Last update : 06/02/26
Duration of the presentations : 15 minutes

Session 1

- Supervisors : Dewallef Pierre, Brereton Clara
- Date : 09/03
- Time : from 13 :30 to 17 :30
- Place : B7a S5

Team	Subject
PANTALONE Damiano HENDRICKX Victor WETKA SAH Aurel Ulrich	Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production (See Reference B.1).
LOUON Nathan KHAI Amine DELVOIE Roméo	Status of Solar Tower Power Plant technology for electricity production (See Reference B.2).
TICHON Quentin PIROUZ Clément TAKOUGOUM ZOGNE Audrey De Jesus	Status of off-shore wind power technology for electricity production (See Reference B.3).
BAIWIR Aymeric GOMONEA George-Andrei DESOLEIL Thomas	Status of biomass combustion power plant technology for electricity production (See Reference B.4).
BOES Hugo HOLLANGE Corentin LINDSEY Alexandre	Status of tidal power plant technology for electricity production (See Reference B.5).
ODDING Luca MAESEN Victor BOCK Benjamin	Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production (See Reference B.6).

Session 2

- Supervisors : Reiter Sigrid, Doppagne Véronique
- Date : 11/03
- Time : from 8 :30 to 12 :30
- Place : B37 S.39

Team	Subject
CHAPELIER Emma JACQUEMIN Jean-Benoit BOULANGER David	Explain what is "Urban sprawl" and what are their drivers (Reference 1.1 Urban sprawl) (A.1).
NJIKAM NSANGOU Louh VAN HOUTE Guillaume SALOUM Yazan	Present the potential energy savings associated with buildings' renovation strategies at the city scale (reference : 1.2 Low energy cities) (A.2).
DEMARET Pierre DJOUKA TAKAM Stella Merveille KERKENI Donia	Present and compare key parameters and strategies to improve transport energy consumption (reference : 1.3 transport) (A.3).
VAN DER ELSTRAETEN Aymeric FREBEL Cyril BASSOU Adam	Explain the concept of "territorial recomposition" and how it can influence the energy consumption due to transport at a regional scale (reference : 1.4 Territorial recomposition) (A.4).
BOVY Victor DURIEUX Thomas SCHIEPERS Nathan	Explain what is a ZEB (Zero Energy Building) and what are the issues of its definition (reference : 1.5 ZEB & ZEN) (A.5).
DONEUX Mathys KHEDHIRI Hiba JüNGER Camille	Explain how the climate and energy mix of a country influence the energy consumption of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).

Session 3

- Supervisors : Dewallef Pierre, Polson Martin
- Date : 25/03
- Time : from 13 :30 to 17 :30
- Place : B37 0.33

Team	Subject
HUBIN Clément GHOMSI KOUAM Jordan Brondon CLAJOT Clément	Status of Stirling dish power plant technology for electricity production (See Reference B.7).
LAMBIET Hugo GRISARD Estelle BIEMAR Mattéo	Status of Natural Gas Combined Cycle (NGCC) technology for electricity production (See Reference B.8).
GERMAY Thomas ALAMI HLIMI Aymen SIMON Elsa	Status of Nuclear power plant technology for electricity production (See Reference B.9).
MIGNON Alexis BOUNAR Sami TSAGO TSAGUE Manoella Stella	Status of Integrated coal Gazeification combined cycle (IGCC) power plant technology for electricity production (See Reference B.10).
JANSSEN Lila Mei FINCK Loïc	Status of Natural Gas cogeneration power plant technology for combined heat and electricity production (See Reference B.11).
PIRSON Mathys ANTOINE Raphaël NARINDER Joti	Status of Carbon Capture and Storage applied on natural gas combined cycle power plants for electricity production (See Reference B.12).

Session 4

- Supervisors : Reiter Sigrid, Polson Martin
- Date : 27/03
- Time : from 8 :30 to 12 :30
- Place : B37 0.36

Team	Subject
JURION Cyril RODE Mathieu SCHMITZ SCHAIR Zoé	Explain what are the environmental and socio-economic impacts of urban sprawl (reference 1.1 Urban sprawl) (A.1).
BENAMEUR Zaid LACHI Titouan LHOEST Guy-Louis	Compare strategies to reduce energy consumption of buildings and transport at the city scale (reference : 1.2 Low energy cities) (A.2).
GUIOT Axel AUPAIX Nathan ALLOUH Abderrahman	Explain how the built density and urban form influence the energy consumption of districts (reference : 1.8 Built density) (A.8).
RYSMAN Hugo KARAMOV Denis COUTANT Tom	Explain the potential for energy mutualisation at the urban block scale and how it can help to achieve zero energy communities (reference : 1.5 ZEB & ZEN) (A.5).
DE BOUW Guillaume MARION Adrien CHARLIER Yoan	Explain how energy is taken into account in life-cycle assessment (LCA) of buildings (references : 1.6 LCA-1 & 1.7 LCA-2) (A.6 and A.7).
DEBRY Romain ROUXHET Léo MORMONT Joyce	Explain how occupants' behaviours and occupation modes influence the energy consumption of a residential building (reference : 1.9 Occupants) (A.9).

Session 5

- Supervisors : Larbanois Antoine, Doppagne Véronique
- Date : 30/03
- Time : from 8 :30 to 12 :30
- Place : B37 S.39

Team	Subject
PLUNUS Violette WILMOTTE Antoine FRANQUET Balian	IPCC Climate Change 2023 synthesis report (see Appendix D.1) : present an summary of Section 2 : "Current Status and Trends"
REMY François BETSCH Matéo EL KHATTOUTI Ayyoub	Demand Response as a way of introducing flexibility into the energy sector : what does it entail ? How can this be implemented in practice ?
LEYEN Benjamin MIDRE Chloé MONVILLE Matteo	Wholesale markets in Europe : present the organisation of the wholesale markets in Europe : the day-ahead and the intraday markets. Explain how these trading floors operate including examples from at least three different European countries.
MADARBUKUS Constance ELMEKKI Sarah KHAZZAKA Gabriel	Electricity sector : present the organisation of the electricity sector in Europe, laying stress on the role of TSO and DSO. Explain the role of all actors involved in the delivery of electricity, from its production to its consumption. Include examples from different European countries.
HOSMANS Liam DOULA Antoine COCHU Chanelle	Balancing markets : present the role of balancing markets in Europe. What are the obligations of BRP, ARP, and BSP ? Explain how the balancing markets are integrated in the European Union (e.g. IGCC initiative).
GIELEN Gauthier COLLIN Thomas	Electricity Interconnectors : what are they ? Present the NEMO and ALEGrO links.

Session 6

- Supervisors : Dewallef Pierre, Doppagne Véronique
- Date : 08/04
- Time : from 8 :30 to 12 :30
- Place : B37 S.39

Team	Subject
MATHIEU Aurélien MORECI Raffaele DEMARCHE Virgile	Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production (See Reference B.1).
LEDENT Sébastien DELHEZ Anaïs DUCULOT Alexis	Status of Solar Tower Power Plant technology for electricity production (See Reference B.2).
SONNET Bastien LEDUC Thomas GARRAUX Aloïs	Status of off-shore wind power technology for electricity production (See Reference B.3).
DRISSI-EL-BOUZAIDI Inès BERBEN Sacha PIZZOLANTE Joséphine	Status of biomass combustion power plant technology for electricity production (See Reference B.4).
GERMEAU Théo PEQUET Louis DE THIBAULT Sophie	Status of Carbon Capture and Storage applied on coal power plants for electricity production (See Reference B.13).
DAUVIN Eliott DIALLO Ibrahim VELAZQUEZ SAEZ Tanguy	Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production (See Reference B.14).

Session 7

- Supervisors : Motiar Rahaman, Brereton Clara
- Date : 09/04
- Time : from 8 :30 to 12 :30
- Place : B37 S.33

Team	Subject
ZENIKHERI Douaa MATHIEU Théo WERBROUCK Sibylle	Explain how biomass can be transformed into fuel. Discuss the use of biodiesel/diesel blends in vehicle applications, and give an overview of the Belgian regulations.
OGER Félicien VERPOORTEN Matthieu BRUHL Margaux	Discuss the economic, environmental and ethical issues of biodiesel production.
KOVACS Tibor NOSSIN Guillaume CATTINI Lola	Discuss the possibilities of electricity storage by batteries. In particular, give an overview of the limitations of these techniques in terms of material resources.
TROQUET Erwann MAZY Arnaud DUMONT Nathan	Give an overview of the use of hydrogen as energy carrier (production, limitations, existing networks and end-use).
LEFORT Antoine CORNETTE Julia MEAN Louis	Explain the general principle of fuel cell technology and their advantages/drawbacks vs. thermo-mechanical systems. Discuss the advantages and drawbacks of high temperature fuel cells (MCFC and SOFC) vs. low temperature fuel cells (AFC and PEMFC).
STEVENS Margot NURUL Ikramul PIRSON Clément	Discuss the differences between fuel cell and battery electric vehicles. Give an overview of advantages and drawbacks of both technologies.

Session 8

— Supervisors : Larbanois Antoine, Gaillard Jérôme
— Date : 13/04
— Time : from 8 :30 to 12 :30
— Place : B37 S.39

Team	Subject
DESMEDT Baptiste COLLIGNON Anaïs RAVEZ Tanguy	EU targets : present and explain the EU 2020 targets, EU 2030 targets, and EU 2050 targets.
SANDOR-CARMONA Léon FAROUZ Assia NOIRHOMME Célestine	IPCC Climate Change 2023 synthesis report (see Appendix D.1) : present a summary of Section 3 : "Long-Term Climate and Development Futures".
DETIENNE Alexandre PIRSON Ephraïm DECAMPS Pierre-Pol	Carbon Capture Technologies : Explain the different types of carbon capture technologies, provide examples of projects, identify the sectors in which they can be applied, and describe how they contribute to the production of e-fuels or e-gas.
VLIEGEN Clara BAYONNET Nicolas DEUSE Louis	Solar photovoltaic (PV) and Electric vehicles : how are these technologies being integrated in the distribution networks ? What challenges (technical AND regulatory) do they pose for the distribution networks ?
PHILIPPART Alexandre EL BOUAYADI Walid VANGEYTE Livius	IPCC Climate Change 2023 synthesis report (see Appendix D.1) : present a summary of Section 4 : "Near-Term Responses in a Changing Climate".
MOURY Sacha HENRY Arthur TIBERI Lucas	Hydrogen : Explain the different methods of producing hydrogen. What are the differences between gray, green, blue, yellow, and pink hydrogen ? What are its advantages and drawbacks compared to other energy vectors ? How can it help reduce carbon emissions ? In which sectors is hydrogen's use most promising, and why ? In which sectors, despite its potential, is hydrogen less appealing, and why ?.

Session 9

- Supervisors : Motiar Rahaman, Gaillard Jérôme
- Date : 16/04
- Time : from 13 :30 to 17 :30
- Place : B28 1.18

Team	Subject
GENOT Louis CASARIL Quentin BERTHOLET Guillaume	Discuss the concept of "Clean coal technology".
MEGUIM KOUEMO Sandra STEWART Matéo MUNDERE NDEKO Wanny-France	Give an overview of the various carbon capture & storage techniques. Discuss their advantages/drawbacks in terms of economy and environmental issues.
JACQUEMIN Justin BROERS Tim DENIS Tom	Explain how to transform solar energy into electricity via steam (Solar Energy Generating Systems). Describe the Mojave Solar Project.
BINI Tom MWABONDET Kessy PROFETA Matteo	Describe the ITER project (nuclear energy).
SANTAMARIA BONNEKAMP Noah BOUTET Eléa DEGROS Dorian	What is coal gasification ? Describe the process in the case of (i) classical gasifiers and (ii) underground processes.
XHROUET Hugo CORDIER Jordan	Give an overview of the shale gas extraction technique. Discuss the environmental issues.

Session 10

- Supervisors : Motiar Rahaman, Brereton Clara
- Date : 17/04
- Time : from 13 :30 to 17 :30
- Place : B37 S.33

Team	Subject
LHOEST Pierre-Arthur TAHIRI-ALAOUI Zaynab PITZ Aurélia	Explain how biomass can be transformed into fuel. Discuss the use of biodiesel/diesel blends in vehicle applications, and give an overview of the Belgian regulations.
INFANTINO Dorian HALUT Médéric DEJAEGERE Noah	Discuss the economic, environmental and ethical issues of biodiesel production.
MARY Elise ADAM Jeanne MANOUSSI Younes	Discuss the possibilities of electricity storage by batteries. In particular, give an overview of the limitations of these techniques in terms of material resources.
VOISIN Augustin BOLLINNE Louis GOLINVAL Thomas	Give an overview of the use of hydrogen as energy carrier (production, limitations, existing networks and end-use).
DEFAYS Félix LEONARD Martin ABDERRAHIM Sami	Explain the general principle of fuel cell technology and their advantages/drawbacks vs. thermo-mechanical systems. Discuss the advantages and drawbacks of high temperature fuel cells (MCFC and SOFC) vs. low temperature fuel cells (AFC and PEMFC).

Appendix A : Sigrid Reiter

Appendix A.1

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Urban sprawl in Europe

The ignored challenge

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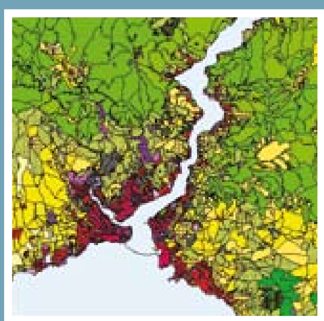

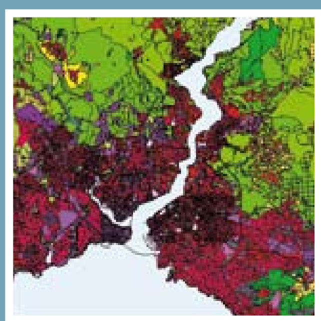

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

European Environment Agency

Urban sprawl in Europe

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EMAS
Verified environmental management
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European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark
Tel.: +45 33 36 71 00
Fax: +45 33 36 71 99
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Contents

Acknowledgements

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The contributors in the project team from the European Topic Centre on Terrestrial Environment were: David Ludlow (lead author, University of the West of England, Bristol), Jaume Fons (task manager), Núria Blanes, Oscar Gómez and Heimo Savolainen, assisted by EEA project officer Agnieszka Romanowicz.

From the JRC, were involved: Marjo Kasanko (task leader), José I. Barredo, Carlo Lavalle, Laura Petrov and Valentina Sagris.

External experts have been consulted throughout the report development. The consultation process included a workshop on the final draft of the report (September 2006). The EEA and JRC wish to acknowledge their valuable input, especially in connection with national, regional and local case studies.

The experts were: Luca Demicheli (APAT — Italian Agency for Environmental Protection and Technical Services), Philippe Doucet (GEPHYRES), Guy Engelen (VITO — Flemish Institute for Technological Research Centre for Integrated Environmental Studies), Andreas Kraemer (Ecologics), Pierre Laconte (Foundation for the Urban Environment; Member of the EEA Scientific Committee) and Henk Ottens (Milieu- en Natuurplanbureau).

This report was conceived, coordinated and edited by Ronan Uhel (EEA).

1 Urban sprawl — a European challenge

1.1 Introduction

Europe is a fascinating and diverse continent, one of the most urbanised on earth. Today, approximately 75 % of the European population live in urban areas, while still enjoying access to extensive natural or semi-natural landscapes. With its stunning urban landscapes, historical cities and cultural treasures, Europe remains one of the world's most desirable and healthy places to live. Moreover, it is the most frequently visited world-travel destination.

The urban future of Europe, however, is a matter of great concern. More than a quarter of the European Union's territory has now been directly affected by urban land use; by 2020, approximately 80 % of Europeans will be living in urban areas, while in seven countries the proportion will be 90 % or more. As a result, the various demands for land in and around cities are becoming increasingly acute. On a daily basis, we all witness rapid, visible and conflicting changes in land use which are shaping landscapes in cities and around them as never before.

Today, society's collective reliance on land and nature for food, raw materials and waste absorption results in a resource demand without precedent in history. In Europe, our consumption patterns are completely different from what they were twenty years ago. Transport, new types of housing, communication, tourism and leisure have emerged as major components of household consumption.

As most of the population live in urban areas, agricultural land uses and their functions in the countryside have consequently evolved. Today, they ensure both the feeding of the city populations and maintenance of a diminishing rural population. Coasts are being urbanised at an accelerating rate, and resident communities are being transformed in order to accommodate these new economies. As a result, our coasts are becoming increasingly intertwined with the hinterland and more dependent on tourism and secondary homes (EEA, 2006).

In this modified landscape, a powerful force is at work: cities are spreading, minimising the time and distances between and in-and-out of the cities. This expansion is occurring in a scattered way throughout Europe's countryside: its name is urban sprawl. Furthermore, it is now rightly regarded as one of the major common challenges facing urban Europe today.

1.2 Why sprawl matters?

Sprawl threatens the very culture of Europe, as it creates environmental, social and economic impacts for both the cities and countryside of Europe. Moreover, it seriously undermines efforts to meet the global challenge of climate change.

Urban sprawl is synonymous with unplanned incremental urban development, characterised by a low density mix of land uses on the urban fringe (Box 1). Classically, urban sprawl is a US phenomenon associated with the rapid low-density outward expansion of US cities, stemming back to the early part of the 20th century. It was fuelled by the rapid growth of private car ownership and the preference for detached houses with gardens.

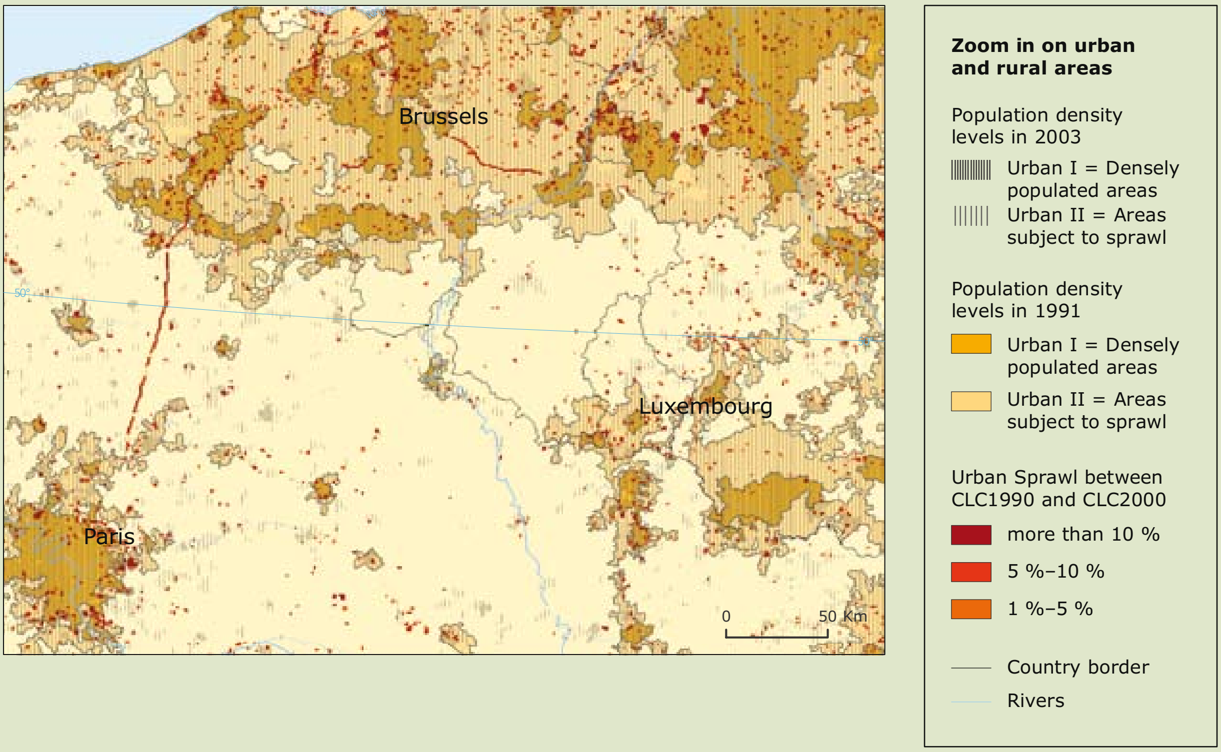
In Europe, cities have traditionally been much more compact, developing a dense historical core shaped before the emergence of modern transport systems. Compared to most American cities, their European counterparts still remain in many cases compact. However, European cities were more compact and less sprawled in the mid 1950s than they are today, and urban sprawl is now a common phenomenon throughout Europe. Moreover, there is no apparent slowing in these trends. The urban areas particularly at risk are in the southern, eastern and central parts of Europe are particularly at risk.

The sprawling nature of Europe's cities is critically important because of the major impacts that are evident in increased energy, land and soil consumption. These impacts threaten both the natural and rural environments, raising greenhouse

Box 1 Urban sprawl — definition

Urban sprawl is commonly used to describe physically expanding urban areas. The European Environment Agency (EEA) has described sprawl as the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas. Sprawl is the leading edge of urban growth and implies little planning control of land subdivision. Development is patchy, scattered and strung out, with a tendency for discontinuity. It leap-frogs over areas, leaving agricultural enclaves. Sprawling cities are the opposite of compact cities — full of empty spaces that indicate the inefficiencies in development and highlight the consequences of uncontrolled growth.

The map of northeast France, Belgium, Luxembourg and northwest Germany illustrates the definition of urban sprawl, and shows the urban areas overlaid with population density. It is clear that low density populated areas extend far beyond the centres of cities, with new urban areas spreading along the Paris-Brussels axis adjacent to the TGV high-speed railway (an effect of the 'beetroot' train stations).



Note: Due to changes in the Eurostat methodology the two datasets (1991 and 2003) differ.

Source: EEA (based on EEA and Eurostat data).

gas emissions that cause climate change, and elevated air and noise pollution levels which often exceed the agreed human safety limits. Thus, urban sprawl produces many adverse impacts that have direct effects on the quality of life for people living in cities.

1.3 Why are cities sprawling?

Historically, the growth of cities has been driven by increasing urban population. However, in Europe today, even where there is little or no population pressure, a variety of factors are still driving sprawl. These are rooted in the desire to realise new lifestyles in suburban environments, outside the inner city.

Global socio-economic forces are interacting with more localised environmental and spatial constraints to generate the common characteristics of urban sprawl evident throughout Europe today. At the same time, sprawl has accelerated in response to improved transportation links and enhanced personal mobility. This has made it possible either to live increasingly farther away from city centres, while retaining all the advantages of a city location, or enabled people to live in one city and work in another.

The mix of forces include both micro and macro socio-economic trends such as the means of transportation, the price of land, individual housing preferences, demographic trends, cultural traditions and constraints, the attractiveness of existing urban areas, and, not least, the application of land use planning policies at both local and regional scales.

Overall, evidence suggests that where unplanned, decentralised development dominates, sprawl will occur in a mechanistic way. Conversely, where growth around the periphery of the city is coordinated by strong urban policy, more compact forms of urban development can be secured.

1.4 Links to EU policies

In essence, through the realisation of the 'internal market', Europe's new prosperity and economic development has put pressure on cities. The role and contribution of cities to Europe's economic growth, jobs and competitiveness, while also delivering social and environmental goals, has been addressed extensively by the EU institutions together with the regional and local authorities (European Commission, 2005). Sustainable urban development appears prominently in many European policy commitments, not least EU regional policy.

To this end substantial EU Cohesion and Structural Funds budget transfers to Member States provide powerful drivers of macro-economic change to support EU integration. However, analysis shows that they can also create inadvertent socio-economic effects that have promoted the development of sprawl. The coordination of land use policies and Structural and Cohesion Funds investments remains key to support the containment of urban sprawl, which is complicated by the fact that EU intervention in many other, if not all, policy domains, impact on or are impacted by urban development.

One illustration of the extent of these interrelationships is the EU commitment to sustainable development and policies to tackle climate change: how can we ensure that the growth of urban greenhouse gas emissions due to the dominance of car transport in the EU's sprawling cities does not threaten to undermine EU Kyoto commitments to reduce greenhouse gas emissions by 2020?

Overall, the EU has an obligation in relation to the wide range of environmental, social and economic impacts of urban sprawl to define a clear and substantial responsibility, and a mandate to take an active lead in the development of new initiatives to counter the impacts of sprawl.

1.5 Who should read this report?

This report is targeted at all those actively involved in the management of Europe's urban areas. The aim is to inform about the impacts of urban sprawl in Europe today and that without concerted action by all agencies to address the underlying causes, the economic social and environmental future of our cities and regions can be compromised.

Subsequent chapters of this report describe the patterns of urban sprawl that have emerged throughout Europe during the post war period (Chapter 2), which are related to the global social and economic trends that form the fundamental drivers of sprawl (Chapter 3). Chapter 4 reviews the evidence of the impacts of urban sprawl, and concludes that the sprawling city creates major and severe impacts in relation to a variety of environmental, social and economic issues affecting not only the city and its region but also the surrounding rural areas. Finally, Chapter 5 examines the principles that could underpin the framework for action at EU level to combat urban sprawl. This would include increased policy coherence built around measures to secure policy integration via close coordination between policies in different domains, better cooperation between different levels of administration, as well as policy definition according to the principles of sustainable development.

2 The extent of urban sprawl in Europe

2.1 The European picture

The process of urbanisation in Europe has evolved as a clear cycle of change during the post-war period from urbanisation to suburbanisation to de-urbanisation and, most recently, to re-urbanisation. Historically, the growth of cities was fundamentally linked to increasing population. In contrast, urban sprawl is a more recent phenomenon and is no longer tied to population

Map 1 Urban expansion in Europe (1990–2000)

Source: EEA, 2005.

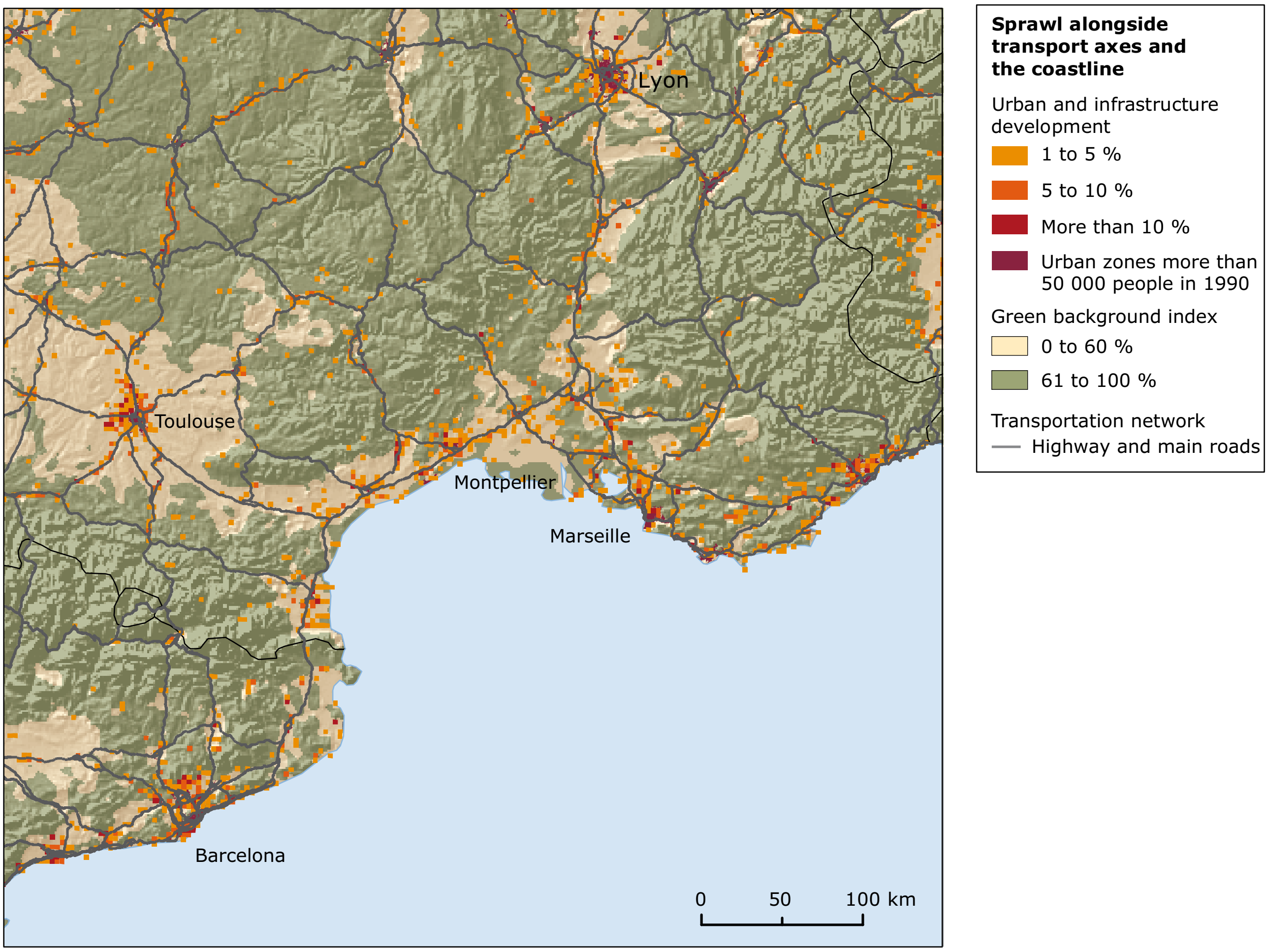
growth as mentioned in Chapter 1. Rather a variety of other powerful factors drive the development of the modern city, including individual housing preferences, increased mobility, commercial investment decisions, and the coherence and effectiveness of land use policies at all levels.

All available evidence demonstrates conclusively that urban sprawl has accompanied the growth of urban areas across Europe over the past 50 years. This is shown from a recent European perspective (Map 1). The areas with the most visible impacts of urban sprawl are in countries or regions with high population density and economic activity (Belgium, the Netherlands, southern and western Germany, northern Italy, the Paris region) and/or rapid economic growth (Ireland, Portugal, eastern Germany, the Madrid region). Sprawl is particularly evident where countries or regions have benefited from EU regional policies. New development patterns can also be observed, around smaller towns or in the countryside, along transportation corridors, and along many parts of the coast usually connected to river valleys. The latter is exemplified by the so-called 'inverse T' of urban sprawl along the Rhône valley down to the Mediterranean coast (Map 2).

Hot spots of urban sprawl are also common along already highly populated coastal strips, such as in the case of Spain where the artificial areas may cover up to 50 % of the total land area (Map 3). This is doubly worrying given the known vulnerability of coastal ecosystems and because the Mediterranean region is classified as one of 34 biodiversity hotspots in the world.

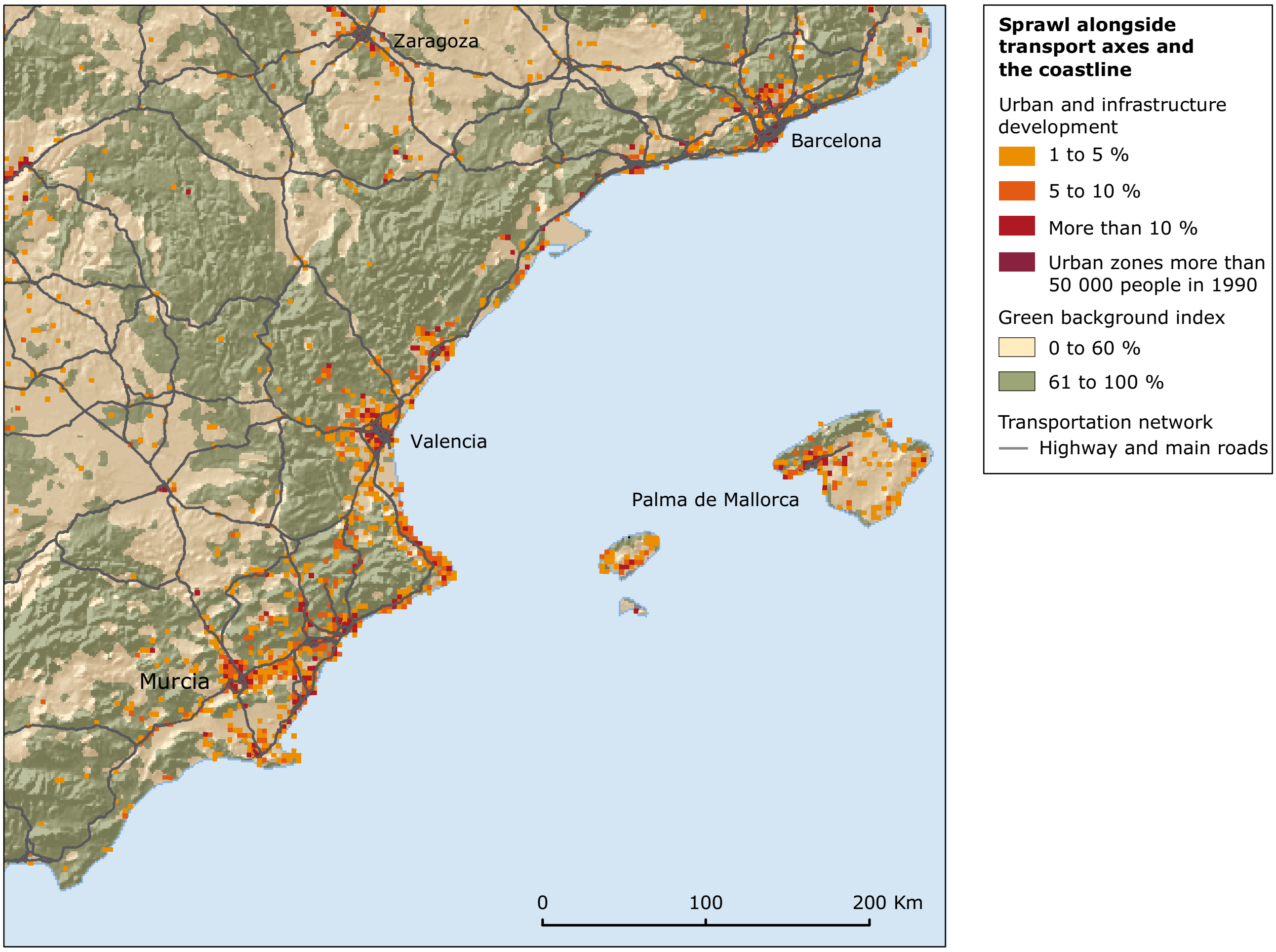
Sprawl may also follow from the expected rapid economic development in many parts of the new Member States, as internal economic dynamism, greater access to EU markets, and Cohesion Fund and Structural Funds investments drive economies. The 2004 accession is too recent to permit full understanding of the potential impacts of urban

Map 2 Urban sprawl along the Rhône corridor: south of France (1990–2000)



Source: EEA.

Map 3 Urban sprawl on the Mediterranean coast: southeast Spain (1990–2000)



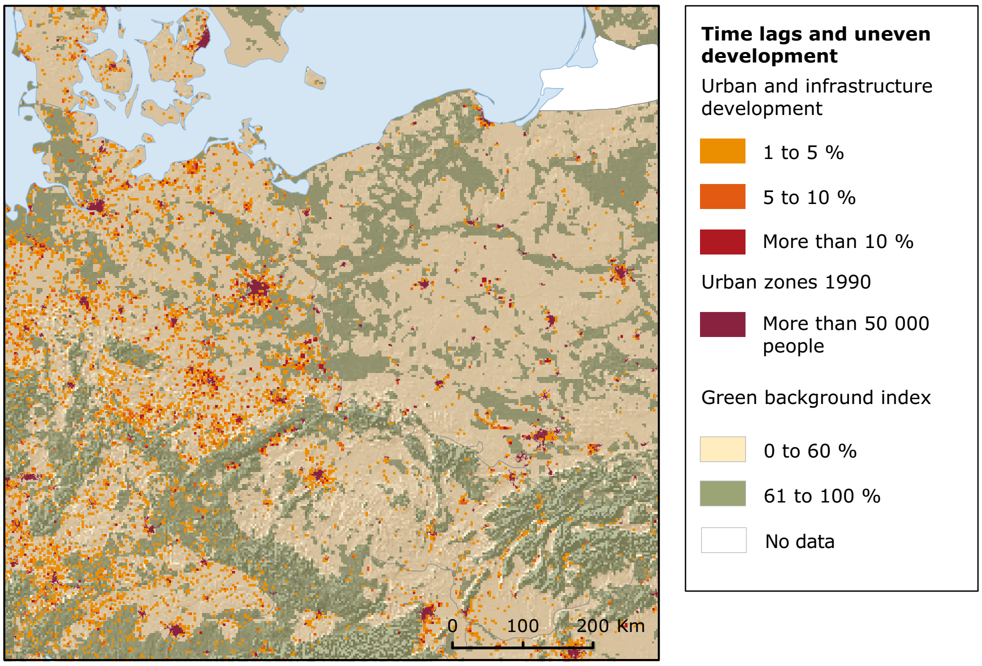
Source: EEA.

sprawl driven by this economic expansion, but some insights can be provided by comparisons between eastern Germany and Poland for the period 1990–2000. East Germany benefited from large monetary transfers from West Germany after unification in 1990, making it one of the most rapidly developing regions in Europe. In contrast, just to the east, in Poland, where EU membership is more recent, there was less development during the period 1990–2000 and the differences in the levels of urban sprawl between Germany and Poland are quite marked (Map 4). This contrast is accentuated by the region history.

As already said, the growth of built-up areas in Europe reached its peak in 1950s–1960s (MOLAND), when the average annual growth rate reached 3.3 % (Figure 1). In subsequent decades the main wave of urban growth has moved farther away from the city centres allowing urban sprawl to extend the urban footprint into the adjacent countryside (Antrop, M., 2004; Sallez & Burgi, 2004; Prud'homme & Nicot, 2004; Couch *et al*., 2005).

Indeed during the ten year period 1990–2000 the growth of urban areas and associated infrastructure throughout Europe consumed more than 8 000 km^2 (a 5.4 % increase during the period), equivalent to complete coverage of the entire territory of the state of Luxembourg. This is equivalent to the consumption of 0.25 % of the combined area of agriculture, forest and natural land. These changes may seem small. However, urban sprawl is concentrated in particular areas which tend to be where the rate of urban growth was already high during the 1970s and 1980s. Moreover, they run alongside the emerging problems of rural depopulation. On a straight extrapolation, a 0.6 % annual increase in urban areas, although apparently small, would lead to a doubling of the amount of urban area in little over a century (EEA, 2005). This needs careful consideration as

Map 4 **Urban sprawl in Germany, Poland and Czech Republic (1990–2000)**



Source: EEA, 2005.

we look ahead to the type of Europe we would like to see in the next 50–100 years, taking into account possible climate change and the many impacts and adaptation challenges it would pose (see Chapter 4, Section 4.1.4).

Historical trends, since the mid-1950s, show that European cities have expanded on average by 78 %, whereas the population has grown by only 33 %. A major consequence of this trend is that European cities have become much less compact. The dense enclosed quarters of the compact city have been replaced by free standing apartment blocks, semi-detached and detached houses. In half of the urban areas studied in the Moland project, more than 90 % of all residential areas built after the mid-1950s were low density areas, with less than 80 % of the land surface covered by buildings, roads and other structures (Figure 2). Only in 5 of the 24 cities, all in southern or central parts of Europe, were more than 50 % of new housing areas (built since the mid-1950s) densely built-up.

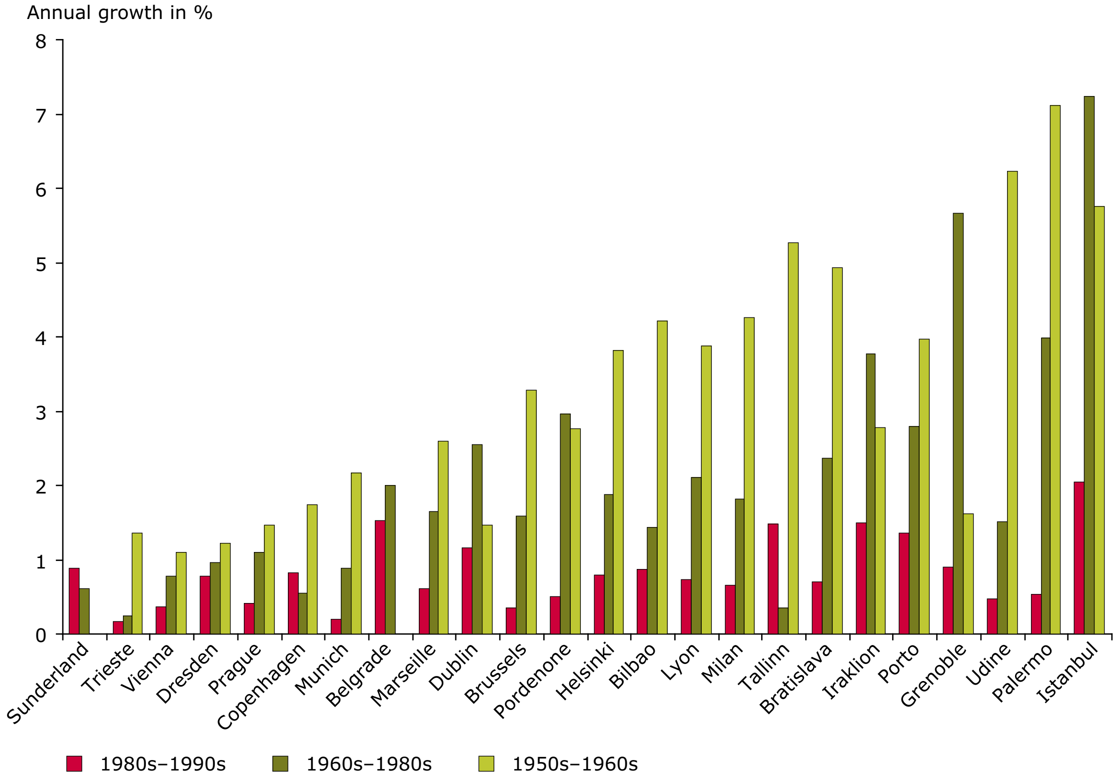
Trends towards new low density environments are also evident in the space consumed per person in the cities of Europe during the past 50 years which has more than doubled. In particular, over the past 20 years the extent of built-up areas in many western and eastern European countries has increased by 20 % while the population has increased by only 6 % (Figure 3).

Sprawl is greater, and in many cases significantly greater, than would be expected on the basis of population growth alone (MOLAND). Only in Munich and Bilbao has population grown more rapidly than in the built-up area. Palermo with 50 % growth in population generated more than 200 % growth in the built-up area (Figure 4).

Although the population is decreasing in many regions of Europe (Map 5 — blue tone), urban areas are still growing in those areas, notably Spain, Portugal and some parts of Italy (Map 5 — dark blue tone). Conversely, moderate increases of population accompanied by a large expansion of urban areas can be observed in Spain, Portugal, Ireland and the Netherlands. Major gains of population (> 10 %, through immigration) can only be observed in western Germany, where the average annual expansion of built-up areas is 47 000 ha/year, growth equivalent over 5 years to the area of Greater Copenhagen.

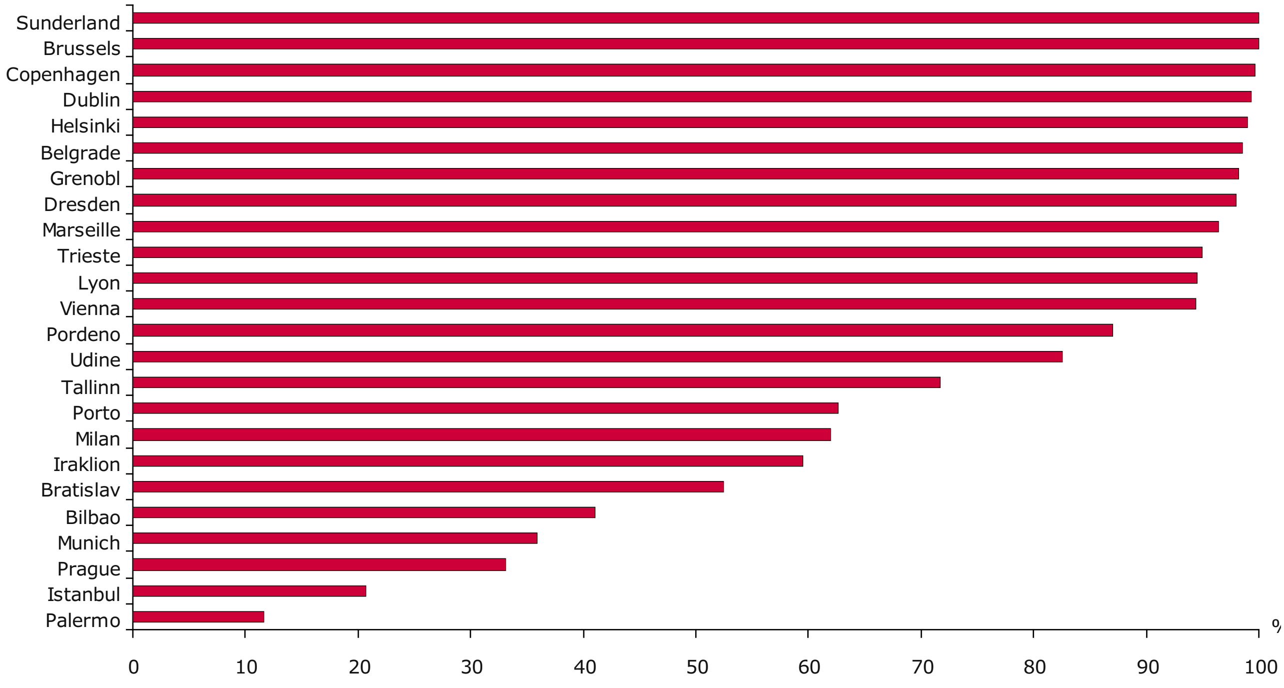
European cites are also remarkably diverse in respect of urban residential densities (Figure 5). Generally, there is a tendency for residential densities to fall towards the north and west of Europe, and the five urban areas with residential densities of at least 10 000 inhabitants/km^2 are all located in southern or southeastern Europe. There is no tendency, however, for urban sprawl to vary with the density of cities, as irrespective of urban

Figure 1 Annual growth of built-up areas from the mid-1950s to the late 1990s, selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 2 Low density residential areas as a proportion of all residential areas built after the mid-1950s, selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

residential density, sprawl is equally evident in the vast majority of the cities examined.

2.2 Regional clusters of sprawling and compact cities

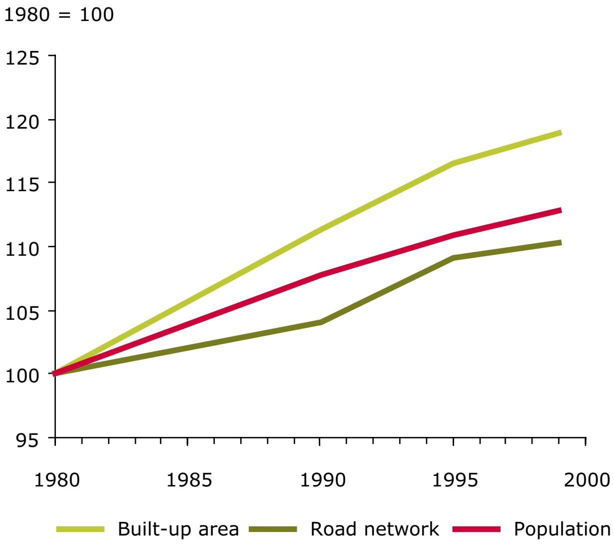
An assessment of the most sprawled and most compact urban areas in Europe can be realised based on the following indicators:

- Growth of built-up areas (1950s–1990s)
- Share of dense residential areas of all residential areas (1990s)
- Share of low density residential areas of all new residential areas (mid-1950s onwards)
- Residential density (1990s)
- The change in growth rates for population and built-up areas (1950s–1990s)
- Available built-up area per person (1990s).

Such indicator analysis for selected cities in Europe, undertaken as part of the MOLAND project, shows the most compact city, Bilbao, is three times denser than the most sprawled city, Udine. Generally the analysis demonstrates certain clustering of cities according to the degree of sprawl or compactness that appear to be more pronounced in certain regions of Europe rather than others (Table 1).

Southern European cities have a long urban tradition in which the urbanisation process has been

Figure 3 **Built-up area, road network and population increases, selected EEA countries**



Note: Countries covered are: Belgium, Czech Republic, Denmark, France, Germany, Latvia, Lithuania, the Netherlands, Poland, Slovakia and Spain.

Source: EEA, 2002.

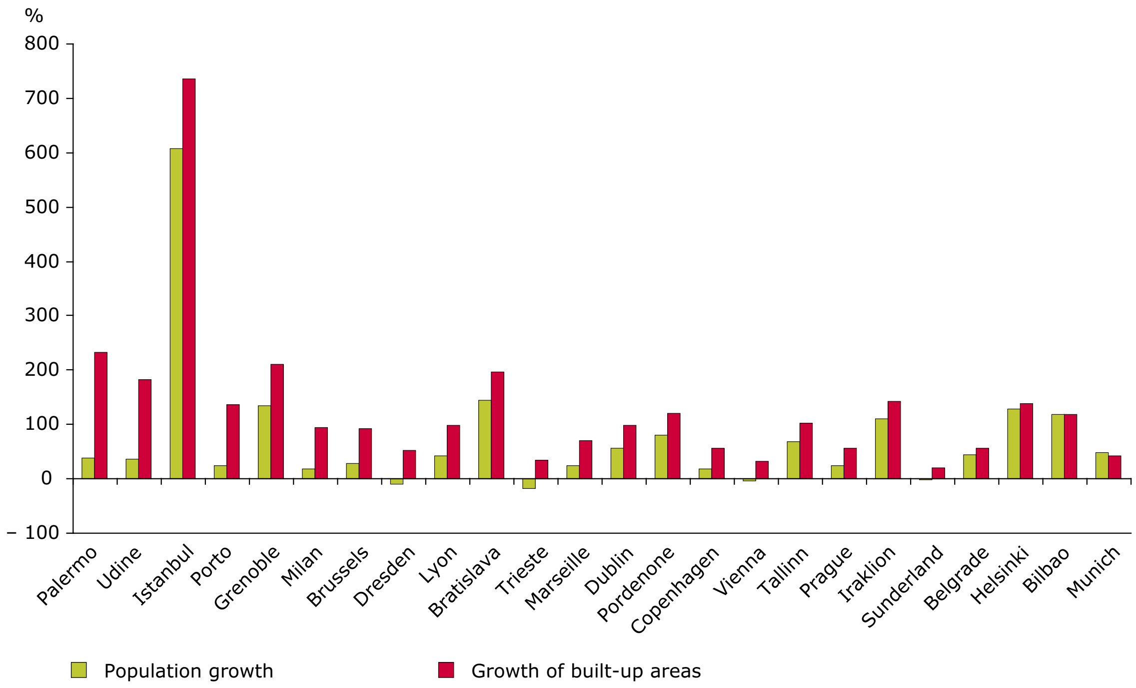
slower, with fewer periods of rapid growth and the cities have been very compact. In recent decades, however, urban sprawl has started to develop at unprecedented rates, and it is most probable that unless land use planning and zoning restrictions are

Table 1 **Distribution of Europe's sprawling and compact cities**

	Southern European cities	Eastern and central European cities	Northern and western European cities
Sprawled		Udine	
		Pordenone	
		Dresden	Helsinki
			Copenhagen
			Dublin
			Brussels
			Grenoble
	Marseille	Trieste	Sunderland
	Porto	Vienna	Lyon
		Bratislava	Tallinn
		Belgrade	
	Iraklion	Prague	
	Palermo	Munich	
	Milan		
	Bilbao		
Compact			

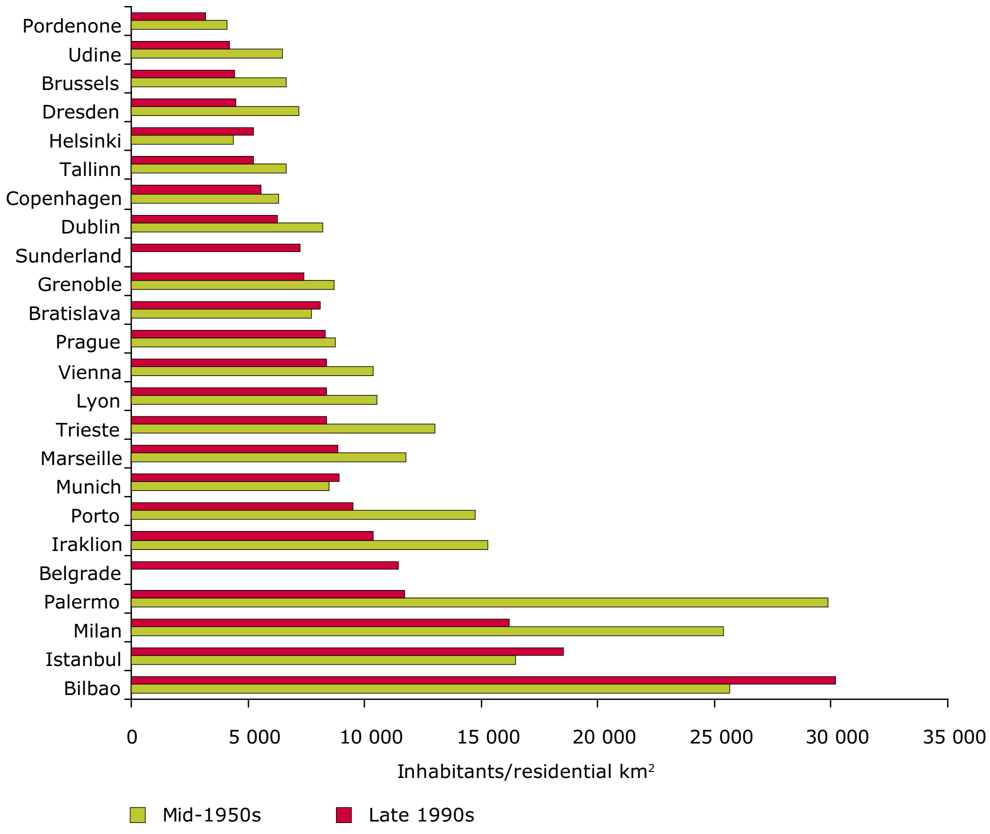
Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 4 **Population growth and the growth of built-up areas (mid-1950s to late 1990s), selected European cities**



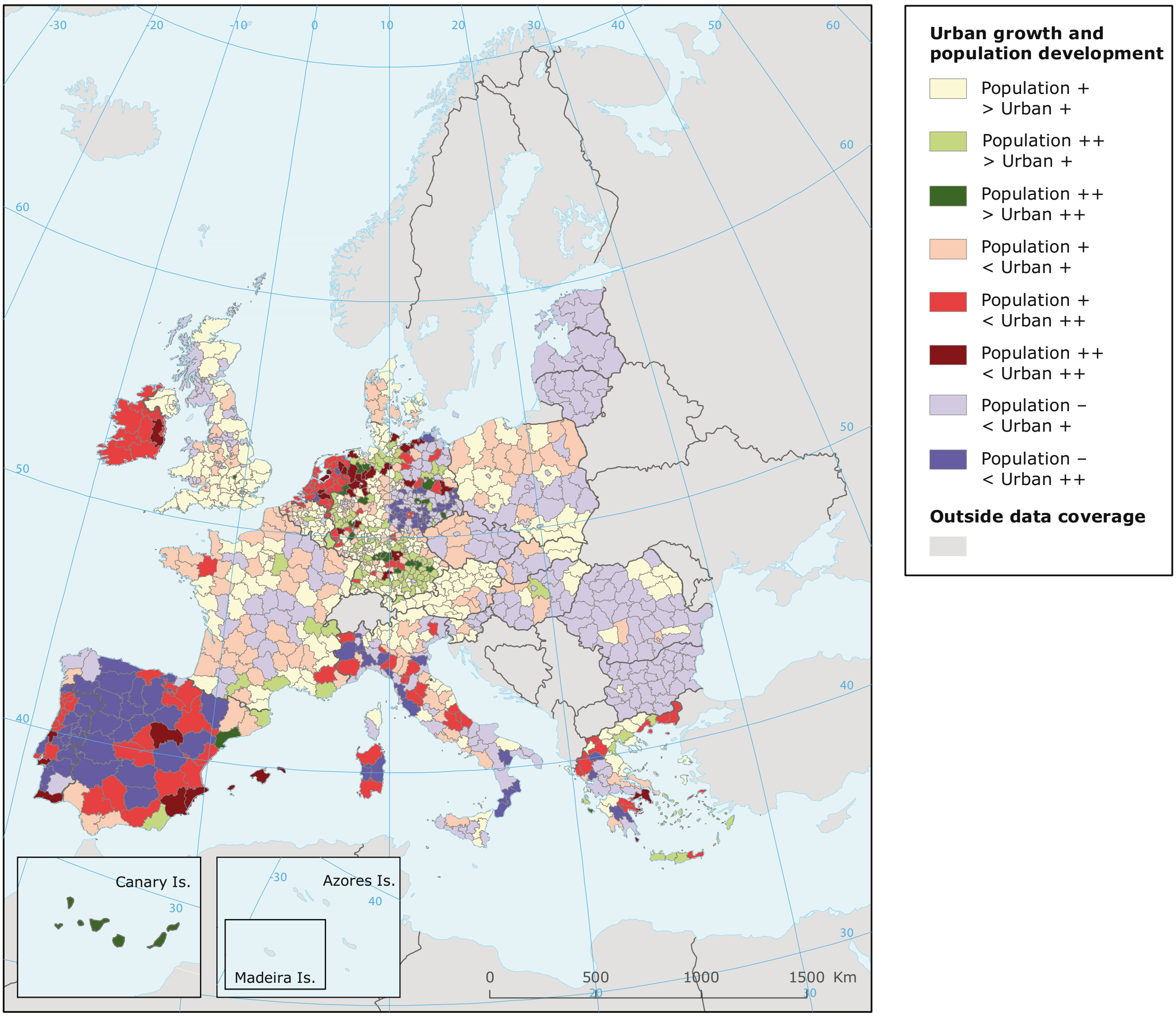
Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure 5 **Residential density in mid-1950s and late 1990s (measured by inhabitants/ residential km²), selected European cities**



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Map 5 Urban growth and population development in Europe (1990–2000)



Source: By courtesy of ESPON, 2006; GeoVille Information Systems (based on EEA and Eurostat data).

more rigorously applied the gap between northern and southern cities will rapidly narrow (Blue Plan, 2005; Munoz, 2003; Dura-Guimera, 2003). Bilbao lies in a class of its own in respect of density and compactness, much of which can be attributed to its location, adjacent to the sea and bordered on two sides by mountains. Nonetheless it is apparent that physical constraints cannot provide the entire explanation of its success, and credit should also be given to the active local planning regime and its well developed transport system.

Clusters of compact cities are also evident in the former socialist countries of central and eastern Europe. The compact urban form and high densities mainly reflect the strong centralised planning regimes and substantial reliance on public transport that prevailed during the communist era (Ott, 2001; Nuissl and Rink, 2005). Today, these cities are facing the same threats of rapid urban sprawl as the southern European cities as the land market is liberated, housing preferences evolve, improving economic prospects create new pressures for low density urban expansion, and less restrictive planning controls prevail. Dresden is an exception amongst ex-socialist cities with a much less compact structure due to the unique circumstances of its wartime experience and subsequent reconstruction.

In northern Italy, small and medium sized cities are also special cases as the whole region has experienced very strong urban sprawl in the past decades and the process continues. The most sprawled cities in the study, Udine and Pordenone, are relatively small cities in the Venezia-Friuli-Giulia region. In smaller cities, in general, densities are lower as the population pressure is lower and in many cases the planning regulations are more permissive allowing more low density building than in large cities.

In general cities in northern and western Europe have less of an urban tradition, and have been more strongly influenced by traditions in which the planning ideal has supported spacious, less compact, garden suburbs (Hall, 2002). This has resulted in much lower densities and more suburban development, particularly as individual housing preferences in north and west European cities have also favoured semi-detached and detached houses.

Along the coastal regions of Europe major population growth is accommodated by continuous sprawling development. During the period 1990–2000, urbanisation of the coast grew approximately 30 % faster than inland areas, with the highest rates of increase (20–35 %) in the coastal zones of Portugal, Ireland and Spain. Many of the mountainous regions of Europe are also under threat from urban impacts, especially where transport routes provide good communications with adjacent lowland regional centres.

All the evidence presented in this section demonstrates that throughout Europe urban areas have expanded considerably more rapidly than the growth of population during the post-war decades. There is no apparent slowing down in these trends. Particularly at risk are the urban areas of the southern, eastern and central parts of Europe where the urban structure has historically been very compact but which in the past few decades have started to grow rapidly outwards.

For these reasons, it is apparent that new policies and tools are necessary to control and channel urban expansion so that urban areas can develop in a more sustainable manner. However, in order to define which sustainable urban planning strategies should be adopted, it is essential in the first place to fully understand the socio-economic drivers that provide the motors of sprawl. This is the focus of the next chapter.

3 The drivers of urban sprawl

3.1 Clusters of drivers

Sustainable urban planning strategies to combat urban sprawl can only be effectively specified when the forces driving urban sprawl are fully understood. Further general analysis shows that residential sprawl and the development of economic activities, in turn linked to the development of transport networks, are intrinsic causes of expanding cities. This is largely a consequence of increasing passenger and freight transport demand throughout Europe, as well as relatively high increases in the price of already urbanised land. The attractiveness of living in the centre of cities has fallen, while the quality of life associated with more 'rural areas' including city suburbs, being closer to nature, has increased. These factors present a planning challenge for small municipalities attempting to maintain their populations and attract small and medium-sized enterprises.

The extremely low price of agricultural land (in most cases good agricultural land) compared to already urbanised land (e.g. brownfield sites) or former industrial sites, is also an important factor underlying urban sprawl. In many development projects, the cost of agricultural land acquisition is relatively low. Thus, it enables greater profits to be made compared to those from already urban land or former industrial waste land, even in cases where no remediation is needed (non-polluted sites). This factor is particularly important in the economic heart of Europe stretching from the United Kingdom down through the Benelux countries, Germany and France (also known as the Pentagon zone). The trend of good agricultural land being deliberately and artificially maintained at a low value is reinforced by the broad use of expropriation tools. A direct side effect of these combined tools — low value, future use not taken into account, and expropriation — is clearly demonstrated by the development of villages near cities for residential or business purposes.

3.1.1 Macro-economic factors

Global economic growth is one of the most powerful drivers of urban sprawl. Globalisation of the economy is today fundamentally interrelated with the development of information and communication technologies (ICT). Both phenomena are beginning to have profound impacts on the spatial distribution of population and employment. Overall, it is likely that ICT will drive urban development towards an even more sprawled future (Audriac, 2005).

Drivers of urban sprawl

Macro-economic factors
- Economic growth
- Globalisation
- European integration

Micro-economic factors
- Rising living standards
- Price of land
- Availability of cheap agricultural land
- Competition between municipalities

Demographic factors
- Population growth
- Increase in household formation

Housing preferences
- More space per person
- Housing preferences

Inner city problems
- Poor air quality
- Noise
- Small apartments
- Unsafe environments
- Social problems
- Lack of green open space
- Poor quality of schools

Transportation
- Private car ownership
- Availability of roads
- Low cost of fuel
- Poor public transport

Regulatory frameworks
- Weak land use planning
- Poor enforcement of existing plans
- Lack of horizontal and vertical coordination and collaboration

EU integration also has far-reaching impacts upon the economies of European cities. In this context, barriers to trade between Member States have been substantially removed and an important feature of this trend is the emergence of the 'super regions' which transcend national boundaries. Furthermore, integration tends to support the development of capital cities, and erode the competitive position of smaller cities and towns. All regions of the EU are intended to benefit from economic growth generated in the new integrated Europe; however, the reality is that new patterns of economic advantage and disadvantage are emerging, as EU action is only one factor amongst many influencing trends in local economies.

EU integration supports investment in longer-distance transport networks to facilitate improved accessibility and mobility. The proposed Trans-European Transport Networks (TEN-T) will greatly influence the future spatial development of urban areas across Europe especially in the EU-10 where natural areas are more prevalent than in the EU-15. In particular, the TEN transportation network is designed to solve some of the existing accessibility problems between EU-15 and the new Member States. However, given the powerful influence that new transport links have in generating development it is vital that current TEN plans fully address all possible impacts of the new infrastructure provision on urban sprawl and on the natural environment.

EU Structural and Cohesion Funds investments throughout Europe can either drive sprawl or support its containment. Investment in new motorways and other road connections readily attracts new development along the line of the improved transport links, frequently exacerbating urban sprawl, as will be seen later in the case study of Dresden-Prague. Alternatively, Structural Funds interventions can be channelled to the redevelopment of deteriorating inner cities making them more attractive for housing and other public and private investments, thereby assisting in the development of more compact cities.

Global competition is also driving efforts to secure economies of scale in the distribution and consumption of goods that have driven changes in the retail sector over the past decades. In the 1950s, most shops were small and located in the middle of residential areas, and the majority of the population did their shopping on foot. Today, major out-of-town shopping centres are the dominant form of retail provision, which together with the surrounding parking areas occupy vast areas of land only accessible by car.

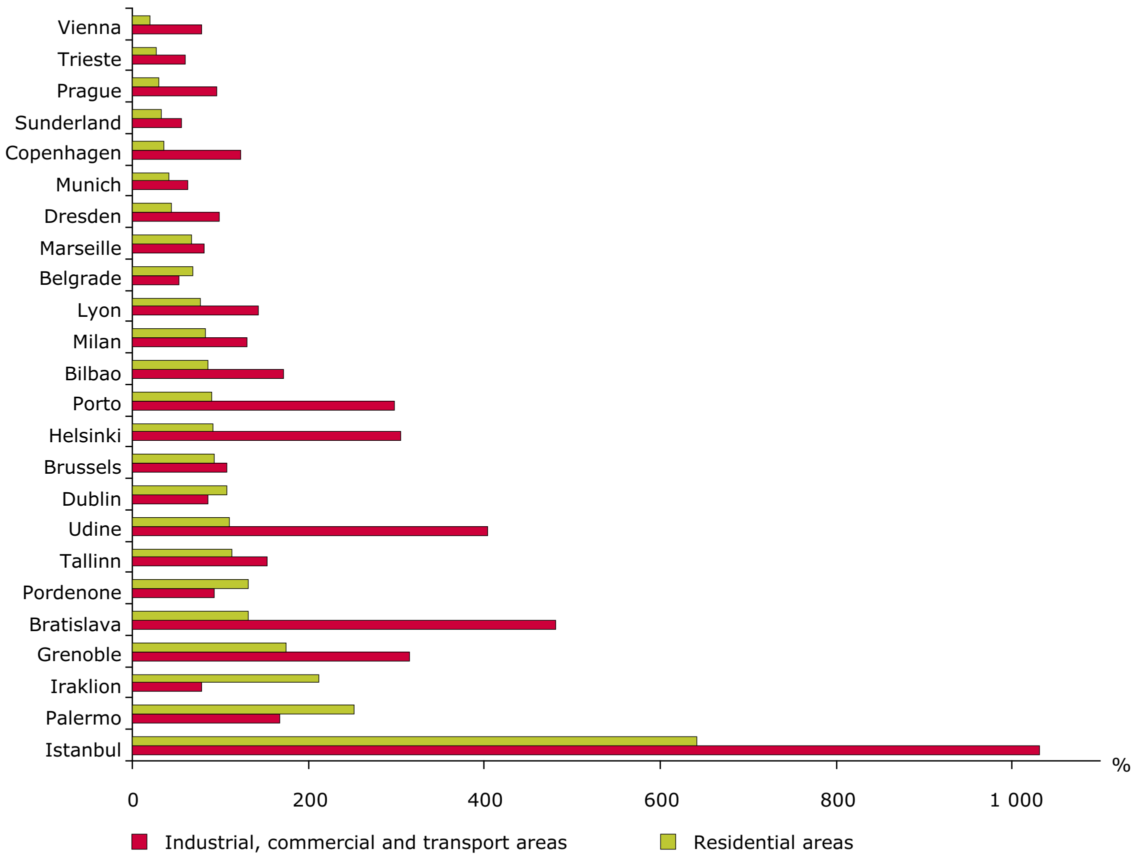
The inter-linkages between residential and industrial/commercial/transport areas in urban development are also critical to the promotion of sprawl. In some cases residential areas promote the development of associated commercial areas. More often new transport links and nodes, and commercial and industrial development facilitate the development of new residential areas in their vicinity. Whatever the relationship it is notable that in most cities industrial, commercial and transport areas are prime motors of sprawl that have outpaced the growth rates of residential areas with on average, growth rates of 100 % above those of residential areas.

The rapid development of transport networks over the past 45 years has impacted particularly strongly outside the historic city centres and these new networks today occupy significantly more space than previous networks. Furthermore, industrial, commercial and transport areas occupy between 25 % and 50 % of all built-up land, and on average one third of urban land is used for these purposes (Figure 6).

In distributional terms, analysis of these land uses shows that in the core of cities the growth of housing and commercial areas are of similar magnitudes, whereas in the immediate vicinity outside the core, the pressures for housing development are generally greater (Figure 7). For all land uses, new development predominantly takes the form of diffuse sprawl, and most new services, other than commercial, and recreation activities are developed outside the core of the city.

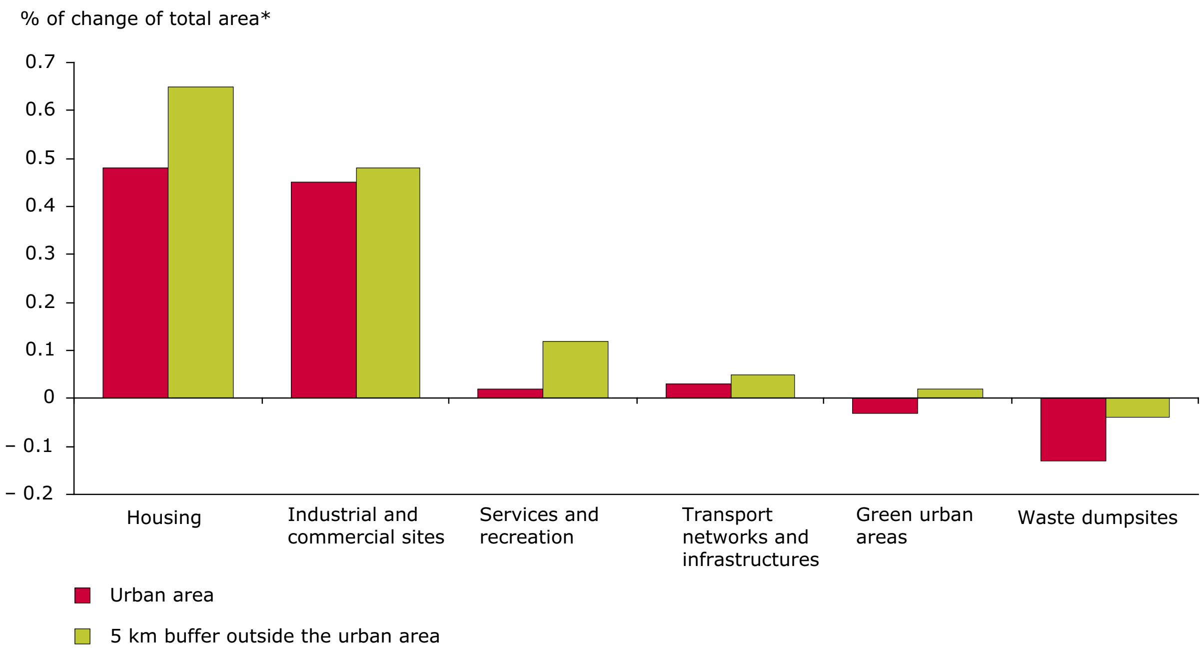
New transport investment, in particular motorway construction, can be a powerful stimulant for new development and sprawl, including shopping centres and residential areas. Land use and transport are inter-dependent in complex ways as development influences mobility patterns. New suburban development without adequate public transportation typically increases the demand for private car use. In contrast the construction of new light rail systems has a tendency to increase housing densities around access points (Handy, 2005). Households make choices between residential areas taking into account the price of housing and the price of commuting between the work place and home. When travel costs fall below a certain threshold and income reaches a certain level the rate of sprawl quickens, and unsurprisingly sprawl is more common in regions where incomes are high and commuting costs are low (Wu, 2006).

Figure 6 Growth rates of residential areas and industrial, commercial and transport areas from the mid-1950s to the end 1990s), selected European cities



Source: MOLAND (JRC) and Kasanko *et al.*, 2006

Figure 7 Functional changes for urban areas greater than 50 000 inhabitants (1990–2000)



Note: * EU-25 except Cyprus, Finland, Malta and Sweden, but with Bulgaria and Romania.

Source: EEA.

3.1.2 Micro-economic factors

From the perspective of land economics, high land prices in the core of the city force developers to seek lower prices in the more peripheral areas. The price of agricultural land is universally much lower than the price of land zoned for housing or the development of services. Agricultural land therefore becomes a highly attractive target for investors and developers. Although planning permission for non-agricultural development increases the value of agricultural land substantially, its price still remains at much lower levels than land in the core urban areas.

Municipalities and public development agencies have a crucial role in the process of conversion of agricultural or natural land to space for housing or commercial development. Throughout the EU, countries they have the responsibility for land use zoning. Competition among municipalities for new income generating jobs and services is great, and many municipalities can be tempted to relax controls on the development of agricultural land and even offer tax benefits to commercial and industrial enterprises to invest in the municipality. Competition of this nature between municipalities fuels urban sprawl.

3.1.3 Social factors

As the evidence presented in Chapter 2 indicates, population growth no longer determines the outward expansion of built-up areas.

Other demographic factors may however increasingly have impacts on urban sprawl. Families with small children are most likely to move to suburban areas and to rural areas outside the city. In contrast the elderly and single are least likely to move out of cities. As the trend towards an increasingly ageing population and smaller households continues, it may be anticipated that some slowing down of the movement from cities to suburbs will occur in the coming decades (Couch & Karecha, 2006).

More and more people in Europe regard a new house, ideally a semi-detached or detached house in the suburban/rural areas outside the city, as the prime investment to be made in their lifetimes. Many wealthier households also actively seek a good investment opportunity. Properties on the peripheries of cities are considered to be better investments because land prices are generally lower than in the core, and the value of property is expected to rise more rapidly outside the urban core (Couch & Karecha, 2006; Wu, 2006). Similar considerations apply in respect of the purchase of second homes, which are not only seen as good investments but also provide additional opportunities for recreation outside the city. The persistence of the suburban ideal underpins the apparently ever increasing demand for houses in the sprawled suburbs and peripheral urban areas, and forms a vital stimulus to urban sprawl.

In contrast to the apparent attractions of the suburbs, the many negative aspects of the inner city cores, including poor environment, social problems and safety issues, create powerful drivers of urban sprawl. City cores are perceived by many as more polluted, noisy and unsafe than the suburbs. The built-up environment is also considered unattractive because of poor urban planning, with areas lacking green open space and sports facilities. Unemployment, poverty, single parent households, drug abuse and minorities with integration problems are also often identified with inner-city areas. These negative environmental factors drive many families with small children out of the city.

As families move out of the city, social segregation begins to intensify. Municipal tax revenues are lowered, and can become insufficient to maintain services such as schools and hospitals. The quality of schools plays a crucial role as parents try to secure the best education for their children. In the inner city a downward cycle of deprivation can readily become established as more and more of the population attempt to move out, reinforcing the problems of those that must remain (Burton, 2000; Couch and Karecha, 2006).

3.2 Pathways to urban sprawl

Deeper understanding of the relationships between the trends that drive urban sprawl, and the specific national, regional and local considerations that fashion the development of the cities and regions of Europe, is essential to redress the adverse effects of sprawl. The prime aim of the following case studies is to permit an assessment of the relative importance and impact of the various forces driving sprawl set against the range of contrasting development outcomes described.

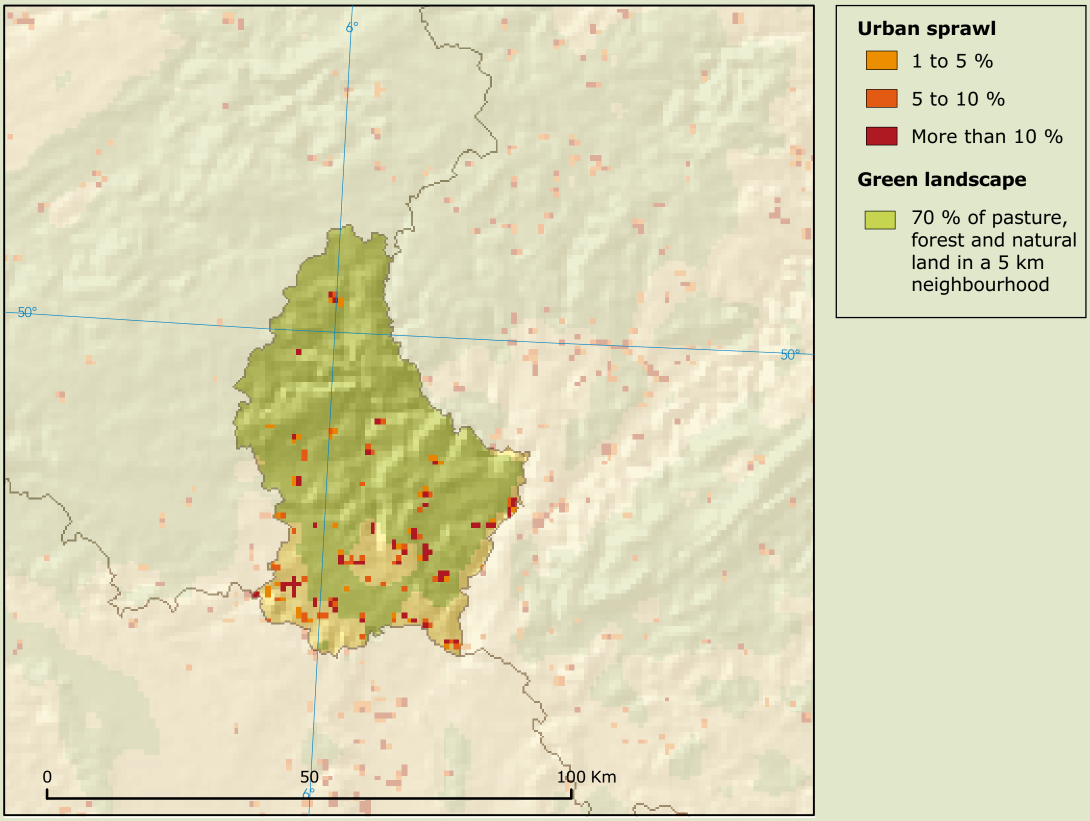
The case studies consistently emphasise the commonality of the key drivers of urban development in terms of economic development, allied in some cases with population growth. Urban development is characterised in terms of a low density space extensive mix of residential, commercial, transport and associated land uses in the urban fringe. However, the case studies also clearly demonstrate city sprawls, the extent to which effective planning strategies control development and how they are applied influence the degree of urban sprawl. Where unplanned, decentralised development dominates, sprawl will occur. Conversely, where growth around the periphery of the city is coordinated by strong urban policy perspectives, more compact forms of urban development will be secured.

The next chapter reviews the multiple, severe and interconnected impacts of urban sprawl in order to fully understand the impacts of sprawl and why it is important for cities not to sprawl. The full range of impacts of sprawl are considered including impacts in respect of environmental resources, natural and protected areas, rural environments, the quality of urban life and health, as well as socio-economic impacts.

Box 2 Luxembourg: new urban traditions, high income and immigration

The expansion of urban areas is the most important land use change in Luxembourg. These changes are mainly concentrated around the existing urban centres of the city of Luxembourg and the old industrial southwest. In both cases the main contributor to this trend is the development of new service industries including financial and EU institutions. The pressure for new residential growth reflects efforts made to attract new inhabitants from the countries bordering Luxembourg and the influx of a growing working population with their families. It also reflects the high income levels in Luxembourg which makes it possible for most inhabitants to live in detached houses. Furthermore, short distances and a relatively small population make commuting a feasible option without excessive congestion.

Map Urban sprawl in Luxembourg driven by socio-economic changes (1990–2000)



Source: EEA.

Box 3 Dublin metropolitan area: rapidly growing economy and population

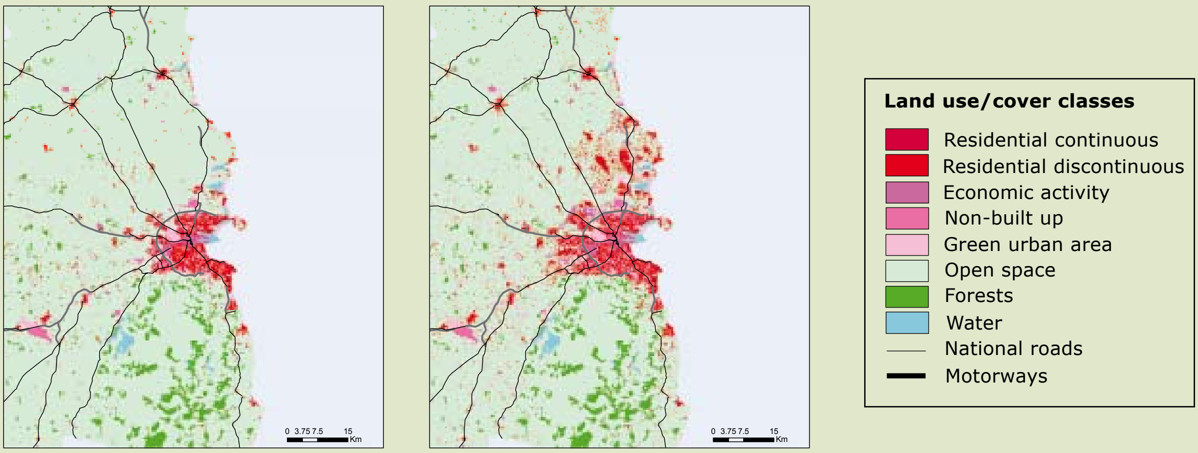
Dublin is a relatively small city by European and international standards. However, it dominates the urban pattern of Ireland in terms of demography, employment and enterprise (Bannon, 2000). The Greater Dublin metropolitan area population was 1 535 000 in 2002, 40 % of the total Irish population. The National Spatial Strategy (2002) suggests that by 2020 the Greater Dublin area population will be in the range of 1.9–2.2 million. The strong growth of the Greater Dublin is a result of the region's role both within Ireland and as a European capital city. Consequently, the Greater Dublin area will need to accommodate 403 000–480 000 additional inhabitants by the year 2020.

Population growth and economic development, as well as house type and price, are predicted to be the main drivers of land use change in the Greater Dublin area during the coming decades. High house prices in Dublin are a significant push factor driving the population towards the rural fringes of the city where it is cheaper to buy or build a house. Another push factor is the small size of apartments in the city centre, forcing families with children needing more space to move out of the city where houses prices are lower and housing more affordable. Personal housing preferences also play an important role as rural living is the Irish housing ideal (Michell, 2004). This preference is realised in single-family houses in open countryside with the benefits of the proximity to the capital or other urban areas. The realisation of this ideal is greatly facilitated by the planning regime which imposes few constraints on the conversion of agricultural areas to low-density housing areas.

Urban–rural migration in the Greater Dublin area has led to the growth of rural towns and villages at the expense of the City of Dublin. The growth of residential areas appears to follow the line of road and rail transport, suggesting a preference for rural living but with the benefits of proximity to urban areas including employment. Another push factor is the transport system in Dublin. Commuting times are long and the lack of orbital roads and rail networks means that to get from one side of the city to the other necessitates a journey through the centre. Often it is quicker to commute from outside Dublin to the centre rather than from one side to the other (Gkartzios and Scott, 2005).

The regional MOLAND model was applied to the Greater Dublin metropolitan region consisting of the following 9 counties: Dublin Co., Kildare, Laois, Longford, Lough, Meath, Offaly, West Meath and Wicklow. According to the 2025 scenario, the outward expansion of residential areas in the Greater Dublin area is estimated to increase by 110 % over the forecast period. In the same period commercial areas will more than double while industrial areas will grow slightly more modestly. The main development axis is to the north from the Greater Dublin area along the seashore as well as inland. To the south little new residential, or industrial or commercial development will take place because of the physical constraints of upland areas. The 2025 scenario also suggests the development of Dublin City to the northwest along the line of the Dublin-Belfast corridor. This development will encourage Dublin City to develop from a mono-centric to poly-centric relationship with the neighbouring cities of Dundalk, Newry and Drogheda. The Greater Dublin Metropolitan area needs land use guidance and zoning as well as new infrastructure if it is going to achieve a more sustainable form of development over the period to 2025.

Map **Dublin 1990 and modelled scenario for 2025**



Source: MOLAND (JRC).

Box 4 Portugal and Spain: threats to the coasts of Europe

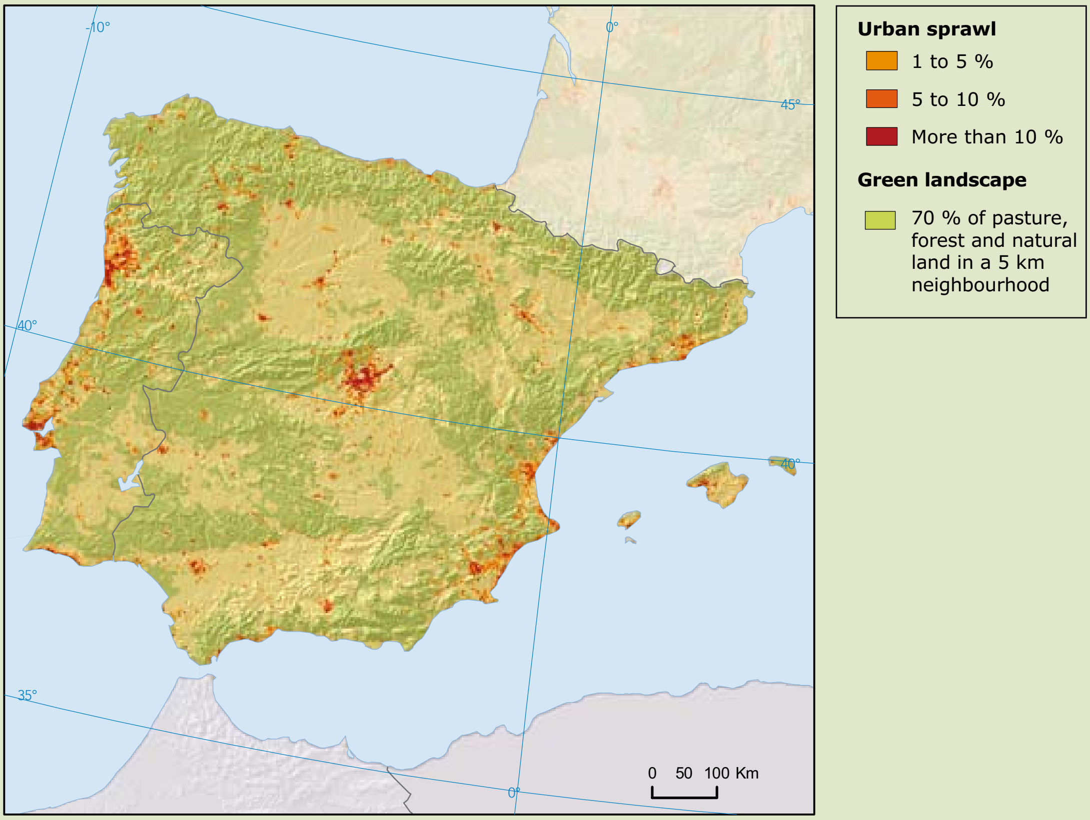
Coastal urbanisation and urban sprawl in coastal zones is no longer necessarily induced and supported by the main coastal cities. By its nature, urban land use along the coasts has become suburban. This new phenomenon, which challenges the state of the environment and sustainability of the coastal areas, is recognised by coastal managers across Europe (CPMR, 2005).

The predominant pattern of residential urbanisation is diffuse settlements adjacent to or disconnected from concentrated urban centres. Residential sprawl is on average responsible for more than 45 % of coastal zone land transformation into artificial surfaces. There is an increasing demand for investment in coastal residences due to tourism and leisure from northern Europe. In addition, there is also domestic demand from the inland population, e.g. the retired. In the past 10 years residential expansion has spread to the coasts of other regional seas, for example the Atlantic coast of Portugal.

Portugal has experienced some of the most rapid increases in urban development in the EU, focused around major cities and the coast. Portugal's urban development is concentrated around the two metropolitan areas of Lisbon and Porto, along the coastline from Lisbon/Setubal to Porto/Viana do Castelo, and more recently along the Algarve coast. In 2000, 50 % of continental Portugal's urban areas were located within 13 km of the coastline, an area which accounts for only 13 % of the total land area. Given the persistently high urban pressures along the coastline, these zones are subject to special development and legal measures.

In Spain, economic growth and tourism has resulted in an increased number of households and second homes particularly along the Mediterranean coast. Illustrative of this phenomenon are the Costa del Sol and Costa Brava which developed significantly during the 1950s and 1960s due to the demand for high quality holidays. This led to the combined development of accommodation, infrastructure and leisure facilities, such as golf courses and marinas. This development is still very intensive today.

Map Polarised urban sprawl around major cities and the coast of Portugal and Spain (1990–2000)



Source: EEA.

Box 5 Madrid region: rapidly growing economy and weak planning framework

The Madrid region is considered to be one of the EU hotspots in urban development in the EU (EEA, 2005). Urbanised land in Madrid grew by 50 % in the 1990s, compared with a national rate of 25 %, and an EU Figure of 5.4 % (Fernández-Galiano, 2006; EEA, 2005). The extraordinary urban development in Madrid region is the result of a number of drivers other than population growth, as the population of the Madrid Autonomous Community had a growth rate of only 5.16 % during the period. There is no single explanation for the intense growth of Madrid in the last few years, rather a number of inter-linked socio-economic factors have produced enormous pressures. The first factor is demand for first and second homes. 513 000 new houses were built in the region in the 1990s (López de Lucio, 2003) even though the population increase for the same period was only 240 000. This housing demand is supported by the current favourable economic situation in Spain combined with low mortgage interest rates across the Euro-zone. Other factors driving the decentralisation process include increased mobility based on a substantially improved transport network, including new toll motorways, three motorway rings around the city, and new and improved metropolitan and train connections. Today both Guadalajara and Toledo can be considered an integral part of the Madrid region due to improved accessibility in the Madrid region, Conversely, in the new low-density residential areas on the periphery of the city new mobility needs are being generated and transport improvements are a priority. The overall effect of the above is a tremendous increase in house prices. More and more people must go further out from the centre to find affordable housing, forcing an ever-growing number of people to commute by car. These socio-economic drivers have promoted an intense decentralisation process in the Madrid region involving both population and economic activity, with a number of territorial impacts, population and employment redistribution, very high rates of housing growth, and the appearance of new urban hubs served by large, decentralised shopping and entertainment malls (López de Lucio, 2003). Today Madrid is a sprawled region, a process that has occurred within the context of a weak spatial planning framework (Munoz, 2003; López de Lucio, 2003; Fernández-Galiano, 2006). The problem of planning is common to a large number of European urban regions, in which the regulatory capacity of municipalities cannot match the enormous forces reshaping the territory (Fernández-Galiano, 2006).

Future development paths: scenarios

Three land use scenarios identified for the region of Madrid describe alternative development paths that form the basis for decisions facing the city planners in delivering a more sustainable Madrid. The alternatives include urban regional development paths based on the idea of competitiveness and free market forces (business-as-usual and scattered scenarios), contrasting with a development path where competitiveness is sought in a more environmentally and socially sustainable way through integrated planning and engagement with stakeholders (compact development scenario). These scenarios are represented as follows:

Business-as-usual: This scenario represents a continuation of very rapid economic growth with low to moderate population growth. The scenario extrapolates the same characteristics and trends identified in the 10 year period 1990–2000.

Compact development: This is an environmental scenario, and is based on an assumption of a 40 % decrease in demand for urban land as compared with the 'business-as-usual' scenario. In this case a more compact development style prevails, representing a departure for current trends. It is probably the least realistic scenario of the three identified.

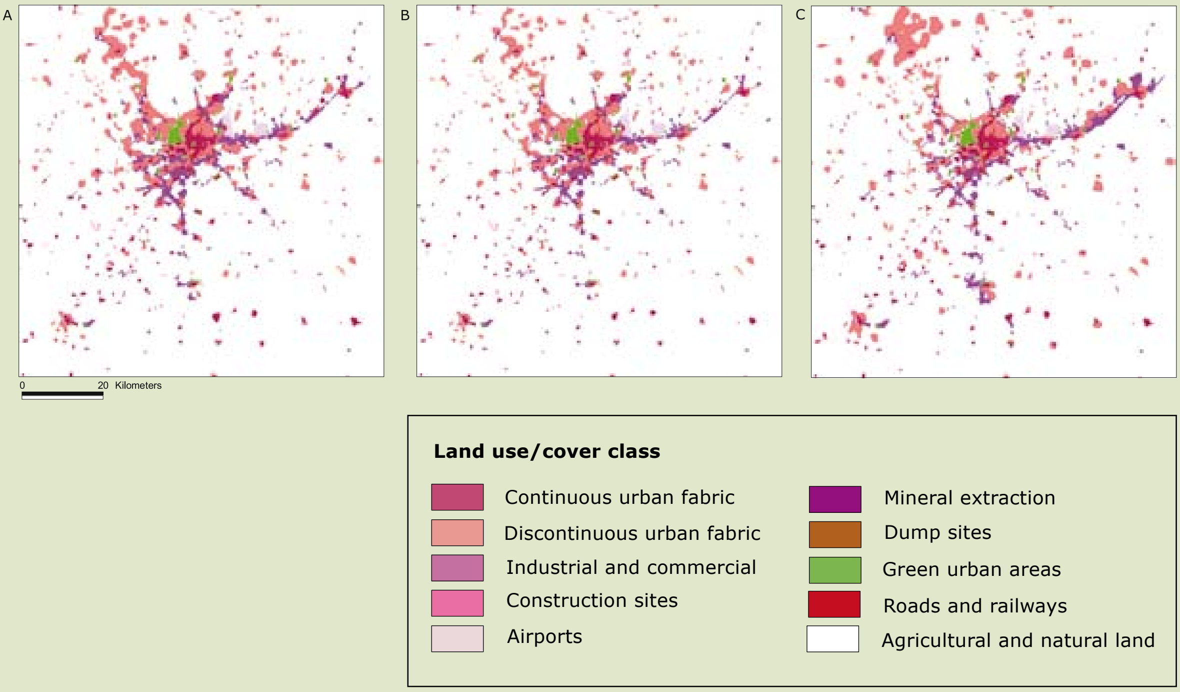
Scattered development: This is a market-led development scenario with greater environmental impacts than the 'business-as-usual' scenario. The scenario is based on more rapid population growth than the business-as-usual case, and assumes a 10 % increase in demand for urban land compared to the 'business-as-usual' scenario. Growth is mainly concentrated in a number of peripheral nodes and the city moves towards a sprawled development style.

The three scenarios show divergent patterns of land use for 2020. However, the business-as-usual scenario shares some common features with the scattered development scenario, as both create severe impacts in terms of additional land consumption and the generation of new commuter movements relying on the private car, as well as other environmental impacts. Overall, urban sprawl is profoundly modifying Madrid in an unsustainable way, and it is clear that the sustainable development of the Madrid region can only be attained by the compact development scenario provided spatial regulation measures are implemented in the short to medium term.

Box 5 (cont.)

Map Development scenarios for the Madrid region 2020

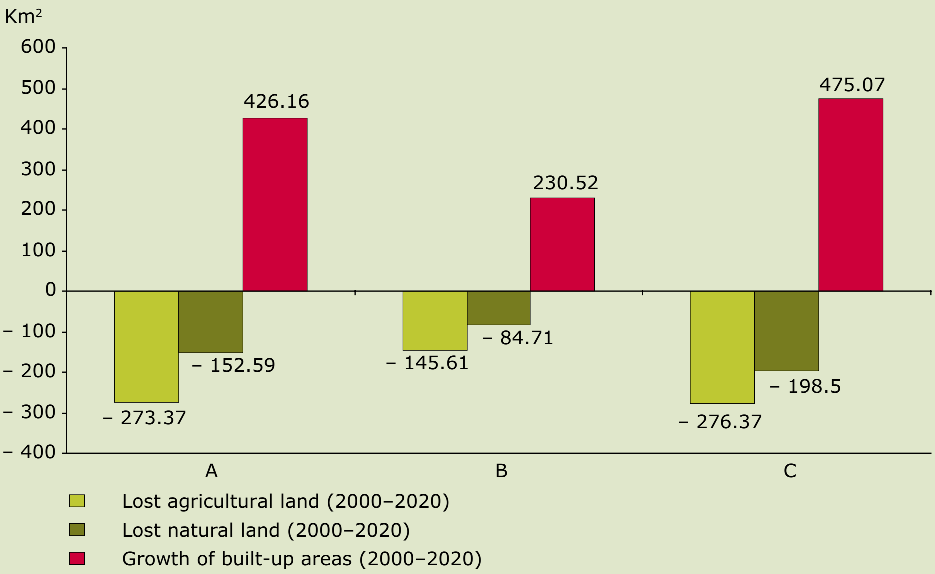
A: Business-as-usual B: Compact development C: Scattered development



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

Figure Land use changes for the Madrid region 2020

A: Business-as-usual B: Compact development C: Scattered development



Source: MOLAND (JRC).

Box 6 Istanbul: European megacity on two continents

Istanbul is a large city at the very edge of Europe, and has a long and turbulent history at the crossroads of European and Asian cultures. Istanbul has always been among the largest cities in the world. At the turn of the 21st century there were approximately 10 million people living in Istanbul, 15 % of the Turkish population. This figure is estimated to grow by 2.5 million people by 2015 based on high birth rates and continuing migration from the countryside. In the past 50 years the growth of Istanbul has been stunning. The built-up area has expanded by 600 % and the population has grown even more, from approximately 1 million to 10 million. Istanbul has always been and still is a very densely populated city. The fact that it is divided by the Straits of Bosporus has created very specific land use development dynamics.

Rapid growth has created numerous problems, such as traffic congestion, pollution (both air and water), unemployment and other social problems, large areas of unregulated housing (50–70 % according to Blue Plan, 2005) and squatter settlements, infrastructure which is lagging behind both the expansion of the city and increasingly restrictive environmental standards (Çağdaş & Berköz, 1996; Erkip, 2000).

What will Istanbul physically look like in 2020? Population growth will remain a key driving force shaping the Istanbul of 2020. Growth of 25 % means 2.5 million new inhabitants, equivalent to the total population of Rome. It is also likely that with the modernisation of the economy and the changes brought by preparations for EU membership, the general standard of living will rise. The improved economic situation will lead to changing housing preferences, with increasing movement out of the city centre to the peripheral parts. (Ergun, 2004; Dökmeci *et al.*, 1996). The new suburbs are typically more spacious, with dominance of larger detached and semi-detached houses, gardens etc. which particularly attract families (Dökmeci & Berköz, 2000). Even the phenomenon of gated cities, which are inhabited by the richest strata and guarded 24 hours a day with full commercial and recreational services have spread to the environs of Istanbul. There are almost 300 gated cities in the immediate vicinity of Istanbul metropolitan municipality (Blue plan, 2005). As a consequence of these developments the population density has dropped. The future of the squatter settlements is an unknown factor, although it is likely that rising living standards (Türkoğlu, 1997) and pressures from the EU will push the authorities to provide proper housing and services to the squatter settlements. The provision of improved housing for these areas will require the accommodation of the same number of people in apartments with at least double or triple the land take.

Residential housing occupies only a part of urban space. Approximately one third is used for commerce, industries and transport purposes. These land use classes tend to grow at a much quicker pace than residential areas when the economy is expanding (Kasanko *et al.*, 2006). As Istanbul will remain the engine of the Turkish economy and will inevitably attract a lot of foreign investment after joining the EU, it is certain that commercial and service related areas will grow very rapidly (Çağdaş & Berköz, 1996) and that new business and office areas will be built to accommodate the growth. The globalisation of the economy and rapid technological development will also create pressures for increases in commercial land. Attempts to alleviate major problems of traffic and congestion will require further space for new transport infrastructure. The Marmaray project linking the European and Asian parts of Istanbul via an underwater railway tunnel and linked to 76 km of combined tube and railway along the coastline will have a drastic impact on future land use in Istanbul.

Future development paths: scenarios

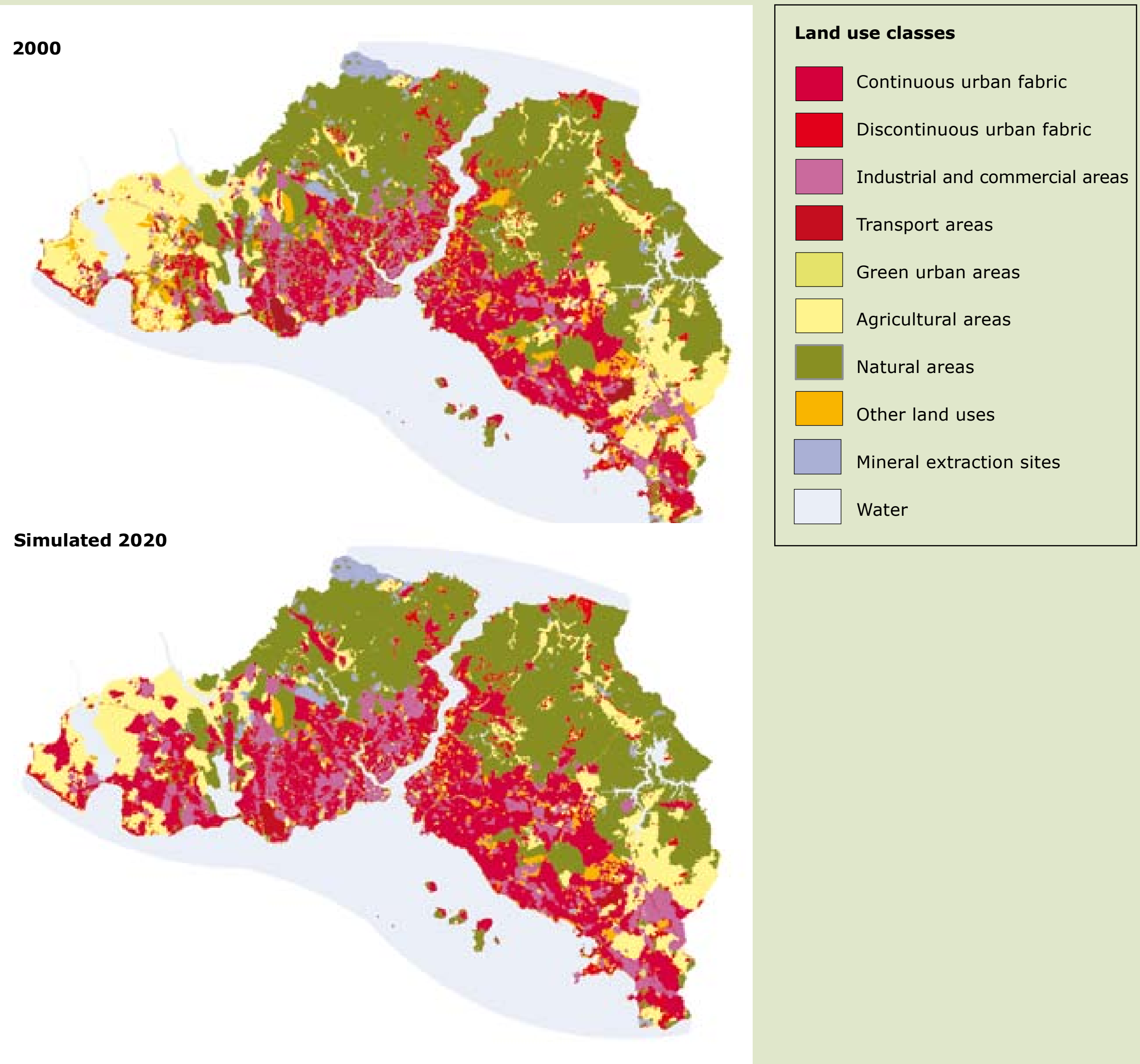
The land use scenario for the year 2020 follows the main trends from 1988 to 2000 with slightly smaller growth expectations. The estimated population growth of 2.5 million inhabitants is comparable to the growth from 1988 to 2000. The simulation was made using the MOLAND model (Barredo *et al.*, 2003; Barredo *et al.*, 2004).

Three clear development tendencies are evident (see Map). First, the filling in of available land within previously built-up areas on both the European and Anatolian sides of Istanbul. Second, the growth along the coastline both westwards and eastwards. This is particularly noticeable on the western side of the European part of Istanbul where large new residential areas are built in the Bükükçekmece area between the two lakes near the coastline. The future Marmaray rail link on the Anatolian side will support the development of the areas close to the coast on the eastern part of the study area. Third, the conservation of the forest area north of Istanbul where there is relatively little new residential development occurring.

Box 6 (cont.)

From an environmental point of view the future developments presented in these simulations are acceptable. Making the urban structure denser and channelling growth along the major transport axes reduces environmental impact, and retains large parts of the natural and agricultural areas in the vicinity of Istanbul. However, it should be emphasised that there are many drivers including housing preferences and land price, which are exerting pressure for less dense future development. Achieving more compact urban development and controlled growth necessitates political agreement on planning and zoning objectives and means of implementing them as well as the control of unauthorised developments.

Map Istanbul 2000 and 2020



Source: MOLAND (JRC) and Kasanko *et al.*, 2006.

4 The impacts of urban sprawl

'Four out of five European citizens live in urban areas and their quality of life is directly influenced by the state of the urban environment' (European Commission, 2006).

Urban development has impacts far beyond the land consumed directly by construction and infrastructure and its immediate surroundings. Economic development and the marginalisation of land by consequent urban development generates the need for new transport infrastructures to link them together, which in turn produces more congestion, and additional costs to society (SACTRA, 1995).

These developments, supported in part by EU budget transfers, have given a powerful economic boost to many disadvantaged regions or regions undergoing restructuring throughout Europe. Some of the most visible impacts, evident in urban sprawl, are apparent in countries or regions with rapid economic growth (Ireland, Portugal, eastern Germany, the Madrid region), regions that have also benefited most from EU regional policies.

New Member States, where little urban sprawl has been detected, may follow the same path of urban development in the coming decades. The environmental impacts will be greater as these areas still possess large amounts of natural landscape. In particular, transport needs are set to grow rapidly in the context of the enlarged EU and the new EU neighbourhood policy. Preliminary analysis indicates that these developments will impact directly on valuable areas of natural landscape.

Experience shows, moreover, that many environmental problems generated by the expansion of our cities create economic and social implications for the city. Urban sprawl and the demise of local shopping and social infrastructures affect many cities with negative effects on the urban economy, as mentioned earlier. Furthermore, environmentally degraded urban areas are less likely to attract new enterprise and services, posing a significant impediment to further local investment. This in turn causes reallocation and the further exacerbation of urban sprawl. Environmental degradation also tends to reduce house prices in the urban core leading to concentrations of socially underprivileged groups, aggravating social exclusion (Austrian EU Presidency, 2006).

The drivers of sprawl and their impacts are fully interconnected and essential to the concept of sustainable development and the associated ecosystems view of the functioning of the city and its surrounding areas. Both concepts inform the analysis of the impacts of urban sprawl in this chapter of the report. The interconnectedness of impacts poses some of the greatest challenges for the design of effective policy solutions to combat the problems of sprawl. However, active urban renewal and redevelopment policies in many urban areas are successfully reversing the deconcentration of urban centres and the decay of central city districts (Working group, 2004).

4.1 Environmental impacts

4.1.1 Natural resources and energy

Urban development involves the substantial consumption of numerous natural resources. The consumption of land and soil are of particular concern as they are mostly non-renewable resources. In contrast to changes in agricultural land use, the development of farmland for new housing or roads tends to be permanent and reversible only at very high costs.

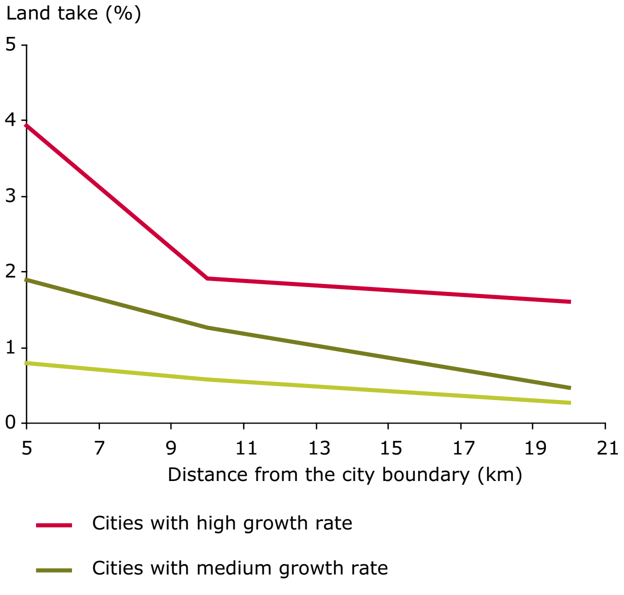
Over the past 20 years, as described in Chapter 2, low density suburban development in the periphery of Europe's cities has become the norm, and the expansion of urban areas in many eastern and western European countries has increased by over three times the growth of population (see Chapter 2, Figures 3 and 4). The problem of the rapid consumption of scarce land resources is graphically illustrated in the widespread sprawl of cities well beyond their boundaries (Figure 8).

Urban sprawl has also produced increased demands for raw materials typically produced in remote locations and requiring transportation. The consumption of concrete in Spain, for example, has increased by 120 % since 1996, reaching a level of 51.5 million tons in 2005. This increased demand reflects major expansion of construction activity in Spain, mainly along the coast and around major cities, where urban sprawl has become endemic. Associated environmental conflicts include the expansion of quarries adjacent to nature reserves and the over-extraction of gravel from river beds.

Urban sprawl and the development of urban land also dramatically transform the properties of soil, reducing its capacity to perform its essential functions. These impacts are evident in the extent of compaction of soil leading to impairment of soil functions; loss of water permeability (soil sealing) which dramatically decreases; loss of soil biodiversity, and reductions of the capacity for the soil to act as a carbon sink. In Germany, for example, it is estimated that 52 % of the soil in built-up areas is sealed (or the equivalent of 15 m^2 per second over a decade). Regions such as Mediterranean coastal areas have experienced 10 % increase in soil sealing during the 1990s. In addition, rainwater which falls on sealed areas is heavily polluted by tire abrasion, dust and high concentrations of heavy metals, which when washed into rivers degrade the hydrological system.

Land use change also alters water/land-surface characteristics which, in turn, modify surface and groundwater interactions (discharge/recharge points), to the point that a majority of the small watersheds affected by urban sprawl show hydrological impairment. If the capacity of certain territories to maintain the ecological and human benefits from ground water diminishes, this could lead to conflicts due to competition for the resource. These conditions generally generate strong migratory flows of people looking for places offering a better quality of life (Delgado, J., 2004). Areas in the southern part of Europe, where desertification processes are at work, are particularly sensitive to such a situation. Reducing groundwater recharge might in addition negatively impact on the hydrological dynamics of wetlands that surround sprawled cities (Salama *et al*., 1999).

Figure 8 Growth of built-up areas outside urban areas (1990–2000)



Source: EEA (CLC 2000, UMZ 2000).

Changes in lifestyle associated with urban sprawl contribute as well to increases in resource use. As mentioned in Chapter 3, people are living increasingly in individual households, which tend to be less efficient, requiring more resources per capita than larger households. For instance, a two-person household uses 300 litres of water per day, two single households use 210 litres each. A two-person household will use 20 % less energy than two single person households. The number of households grew by 11 % between 1990 and 2000, a trend that increases land use and acts as a driver for expansion of urban areas. The general trend is for greater consumption of resources per capita with an associated growth in environmental impact. This adds pressure to the fact that about 60 % of large European cities are already over-exploiting their groundwater resources and water availability.

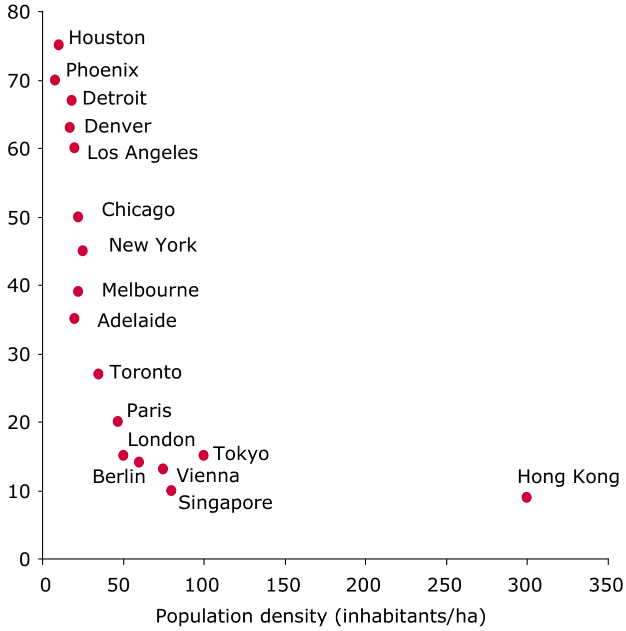
A further consequence of the increasing consumption of land and reductions in population densities as cities sprawl is the growing consumption of energy. Generally, compact urban developments with higher population densities are more energy efficient. Evidence from 17 cities around the world (Figure 9) shows a consistent link between population density and energy consumption, and in particular high energy consumption rates that are associated with lower population densities, characteristic of sprawling environments, dependent on lengthy distribution systems that undermine efficient energy use.

Transport related energy consumption in cities depends on a variety of factors including the nature of the rail and road networks, the extent of the development of mass transportation systems, and the modal split between public and private transport. Evidence shows (Table 2) that there is a significant increase in travel related energy consumption in cities as densities fall. Essentially, the sprawling city is dominated by relatively energy inefficient car use, as the car is frequently the only practical alternative to more energy efficient, but typically inadequate, relatively and increasingly expensive public transportation systems.

Increased transport related energy consumption is in turn leading to an increase in the emission of CO_2 to the atmosphere. The relationship between population densities and CO_2 emissions (Figure 10) is apparent as emissions increase progressively with falling urban densities. Although there are several factors that may explain differentials in CO_2 emissions between cities, including the level of industrial activity and local climatic conditions, the predominance of car borne transportation in sprawling cities is clearly a major factor in the growth of urban green house gas emissions. Urban sprawl therefore poses significant threats to the EU Kyoto commitments to reduce greenhouse gas emissions by 2020.

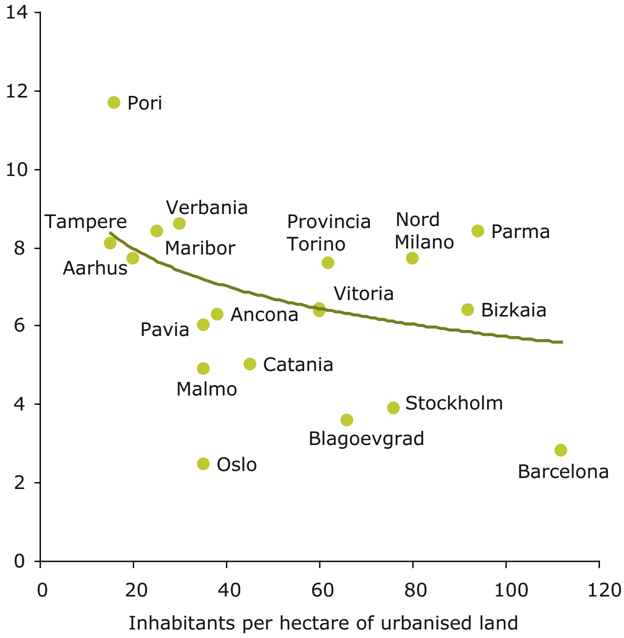
Sprawl also increases the length of trips required to collect municipal waste for processing at increasingly distant waste treatment plants and this is expected to continue as household waste grows 3–4 % annually. The material cycle is becoming geographically decoupled with increasing transport demands, impacting on transport related energy consumption and pollution emissions.

Figure 9 Population density and energy consumption, selected World cities



Source: Adopted from Newman, P. and Kenworthy, J., 1999.

Figure 10 Population density and CO_2 emissions, selected European cities



Source: Adopted from Ambiente Italia, 2003.

Table 2 Population density, energy consumption and cost of transport

Density (population + jobs per hectare)	Annual energy consumption for travel (mega joules per inhabitant)	Cost of transport (% of GDP)
< 25	55 000	12.4
25 to 50	20 200	11.1
50 to 100	13 700	8.6
> 100	12 200	5.7

Source: Adopted from Newman, P. and Kenworthy, J., 1999.

4.1.2 Natural and protected areas

The impacts of sprawl on natural areas are significant. Land sustains a number of ecosystems functions including the production of food, habitat for natural species, recreation, water retention and storage that are interconnected with adjacent land uses. The considerable impact of urban sprawl on natural and protected areas is exacerbated by the increased proximity and accessibility of urban activities to natural areas, imposing stress on ecosystems and species through noise and air pollution.

But even where the direct advance of urban land on natural and protected areas is minimised, the indirect fragmentation impacts of transport and other urban-related infrastructure developments create barrier effects that degrade the ecological functions of natural habitats. Immediate impacts such as the loss of agricultural and natural land or the fragmentation of forests, wetlands and other habitats are well known direct and irreversible impacts.

Urban land fragmentation, with the disruption of migration corridors for wildlife species, isolates these populations and can reduce natural habitats to such an extent that the minimum area required for the viability of species populations is no longer maintained. This process of degradation of ecological networks clearly threatens to undermine the important nature conservation efforts of initiatives such as Natura 2000 (see Box 7).

The environmental impacts of sprawl are evident in a number of ecologically sensitive areas located in coastal zones and mountain areas. Along the European coastal regions urban sprawl is endemic, Moreover, there is little prospect of relief over the next two decades, especially with a predicted increase in population of around 35 million people.

The development related impacts on coastal ecosystems, and their habitats and services, have produced major changes in these coastal zones. The Mediterranean coast, one of the world's 34 biodiversity hotspots, is particularly affected, and the increased demand for water for urban use, competes with irrigation water for agricultural land. This problem has been exacerbated by the increased development of golf courses in Spain, where the over-extraction of groundwater has led to salt water intrusion into the groundwater. Clearly all of this questions the sustainability of, in the long run, the economic development based on tourism that largely fuels this population explosion and urban sprawl.

The mountain ranges of Europe are universally recognised as both the 'water tanks of Europe' and sensitive ecosystems. Currently, they are under severe threat from urban impacts. New transport infrastructures facilitate commuting to the many urban agglomerations with populations over 250 000 inhabitants that lie close to the mountain regions, encouraging urbanisation in the mountain zones. Increased transit and tourist traffic, particularly day tourism from the big cities, also adds to the exploitation of the mountain areas as a natural resource for 'urban consumption' by the lowland populations. More balance is needed in the urban-mountain relationship if the unique ecosystems of these regions are to be conserved.

4.1.3 Rural environments

The growth of European cities in recent years has primarily occurred on former agricultural land (Figure 11). Typically, urban development and agriculture are competing for the same land, as agricultural lands adjacent to existing urban areas are also ideal for urban expansion.

The motivations of farmers in this process are clear as they can secure substantial financial benefits for the sale of farmland for new housing or other urban developments. In Poland, for example, between 2004 and 2006 the price of agricultural land increased on average by 40 %. Around the main cities and new highway developments, increases in price are often much higher (Figure 12).

Soils need to be conserved. They are non-renewable resources and the loss of agricultural land has major impacts on biodiversity with the loss of valuable biotopes for many animals, and particularly birds. Sprawling cities also threaten to consume the best agricultural lands, displacing agricultural activity to both less productive areas (requiring higher inputs of water and fertilisers) and more remote upland locations (with increased risk of soil erosion). In addition, the quality of the agricultural land that is not urbanised but in the vicinity of sprawling cities has also been reduced (Figure 13).

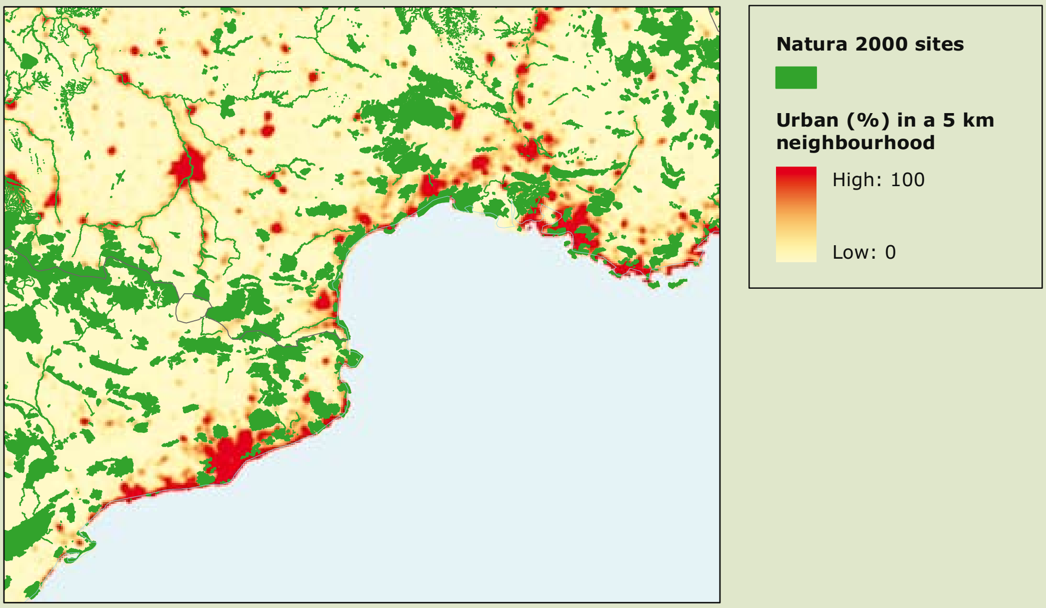
All these characteristic impacts of urban sprawl are well illustrated by the Mediterranean coast. Throughout the region 3 % of farmland was urbanised in the 1990s, and 60 % of this land was of good agriculture quality.

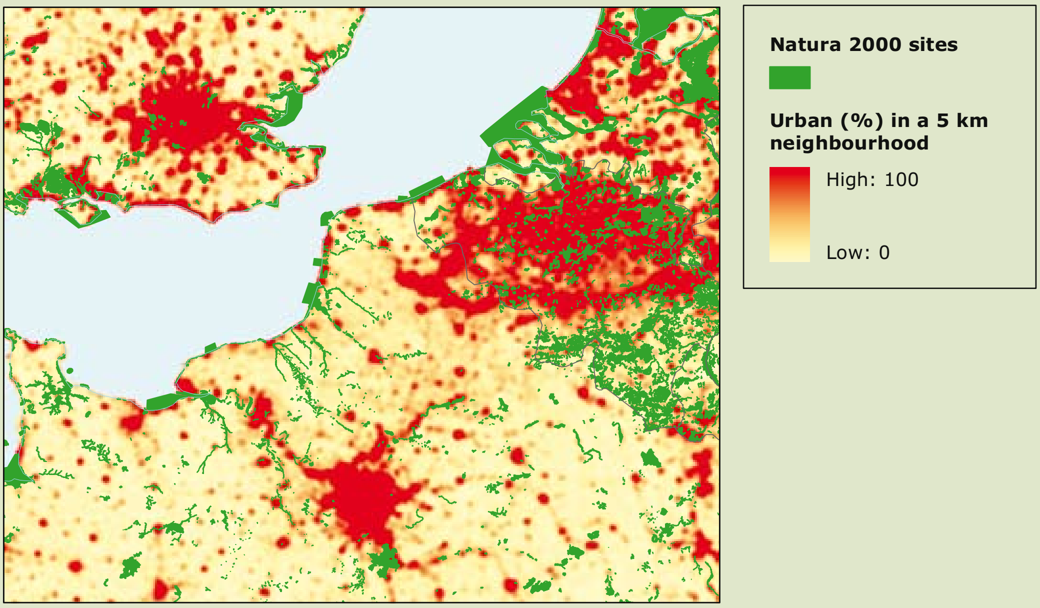
Box 7 Urban pressure on Natura 2000 sites

Pressures on natural areas are derived not only from new land use change but equally from the cumulative effects of land uses in the past. Impacts are generated not only from major urban areas but also from the combined impacts of several small sources that can have equally severe effects.

The map below shows the distribution of urban areas around Natura 2000 sites in the London metropolitan area, northern Belgium, the Netherlands and northern France. To the northeast of Paris, the urban fabric runs along the river Seine, adjacent to Natura 2000 sites. The strong interconnections between urban and natural areas are visible, with 10 % of forests in Belgium and 15 % in Netherlands within 5km of major cities with population in excess of 100,000. In the most extreme cases Natura 2000 sites are completely integrated within the urban areas, and so suffer major pressure from air pollution, noise and human disruption.

Map Urban pressure on Natura 2000 sites in the coastal areas of the English Channel and western Mediterranean





Source: EEA (based on Corine land cover 2000 and Natura 2000 data).

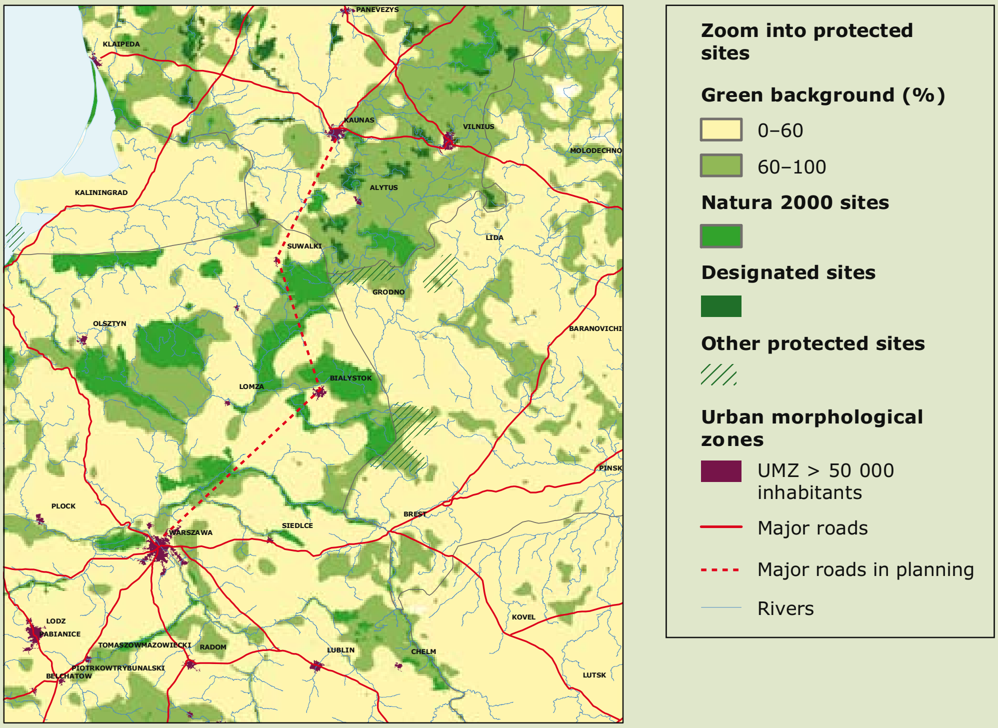
Box 7 (cont.)

Pressures on urban areas are also great on coastal zones, particularly in the western Mediterranean. The map below shows a clear contrast between the expansion of urban areas on the coast and inland. In the case of Barcelona geographic constraints are driving sprawl to the coast, and as a consequence Natura 2000 sites on the coast are becoming more isolated. Elsewhere new urban development is encroaching on inland protected areas. In some localities urbanisation is occurring within Natura 2000 sites.

Impact of transport infrastructure on protected sites: Via Baltica road development, southern part in Lithuania and North-Eastern Poland

Via Baltica is one of the routes planned within the TEN networks to connect the Baltic states and Finland with the rest of the EU. The route commences in Helsinki passing through the Baltic states to Warsaw and beyond. Via Baltica crosses the most important environmental zone in Poland. Unique in Europe, it consists of four very important natural forest and marshland sites (see map sites of environmental interest at regional, national, and European level). The marshes of Biebrza are the only natural wetlands remaining in the whole of Europe, and their protection is a key environmental priority for Poland.

Map Transboundary Environmental Protection Zone: Lithuanian-Polish border



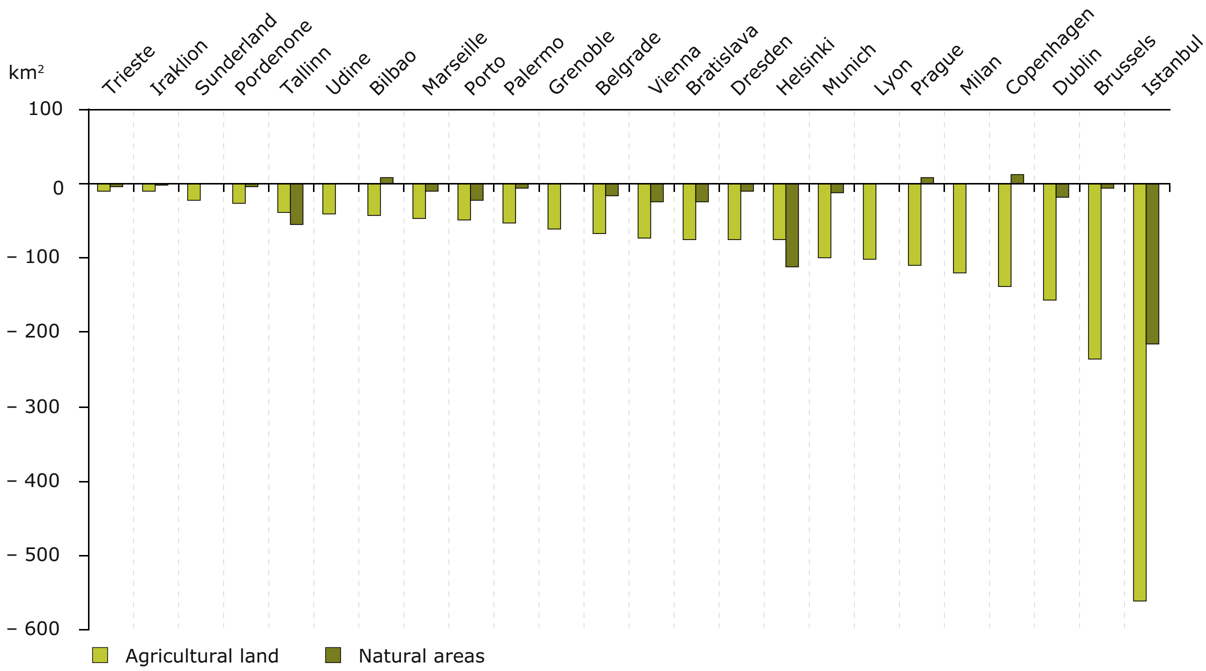
Note: The line indicating major roads in planning is an estimate only.

Source: EEA (based on multiple source data).

The EU funds have now provided financial aid for the Polish government to commit to the construction of this part of the TEN networks, and despite major protests from ecological groups, as well as questions raised at the EU level, most of the plans for the Via Baltica have been accepted.

The proposal is to build a dual carriageway that connects the border zone with the main cities of the region as an extension to the existing national road. The proposal routes part of the road close to the borders of the Biebrza National Park, and part of the route is directed through one of the Natura 2000 sites. To minimise environmental damage the route will be limited to a dual carriageway, instead of a motorway, and elsewhere the route will be tunneled or constructed on raised embankments. Clearly, there are many questions raised regarding the environmental impacts of this section of Via Baltica on the Transboundary Environmental Protection Zone.

Figure 11 Sprawl impacts on agricultural land and natural areas, selected European cities

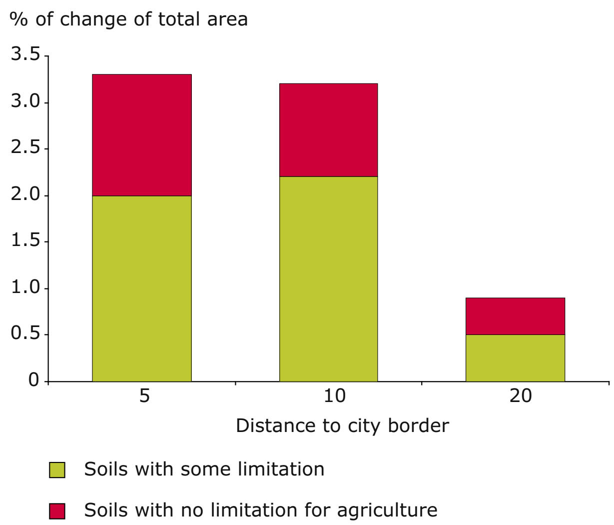


Source: MOLAND (JRC).

Figure 12 Trends in Polish agricultural prices 2000–2004 (Polish Zloty)

Source: Polish Central Statistical Office.

Figure 13 Loss of agricultural land outside urban areas



Source: EEA (CLC 2000, UMZ 2000).

4.1.4 Urban quality of life, hazards and health

As noted earlier, urban sprawl produces many adverse environmental impacts that have direct impacts on the quality of life and human health in cities, such as poor air quality and high noise levels that often exceed the agreed human safety limits.

In the period 1996–2002 significant proportions of the urban population were exposed to air pollutant concentrations in excess of the EU limit values (25–50 % of the urban population for different pollutants). It is estimated that approximately 20 million Europeans suffer from respiratory problems linked to air pollution. In particular, the societal cost of asthma has been estimated at 3 billion euro/year. Although current legislation restricts the emission of harmful substances, certain extreme events facilitated by climatic conditions, or even accidents, are of concern given the large number of people potentially exposed to these threats. Moreover, the impact of air pollution is becoming a global problem as a consequence of long-distance transportation of bio-accumulative substances.

The level of air pollution exposure in the densely developed centres of cities may often be at higher levels than the suburbs due to the greater concentrations and slower movement of traffic. However, the noise produced by all vehicles, and the rapid growth in transport, particularly air and road transport, is more ubiquitous and has resulted in well over 120 million people throughout the EU being exposed to noise levels affecting their well-being.

Sprawl related growth of urban transport and greenhouse gas emissions have major implications for global warming and climate change, with the expectation of increasingly severe weather events in the coming years and increased incidences of river and coastal flooding. The risks from the continued development of these areas in the context of a changing climate is evident in the recent major floods in Europe that have affected large urban populations. The floods in central Europe in August 2002 caused 112 casualties and over 400 000 people were evacuated from their homes. These expected transformations pose major challenges for urban planning that are clearly focussed on the growth of urban sprawl along the coastal fringes throughout Europe, as well as development of sprawling extensions across greenfield sites in the river valleys and lowlands of Europe.

The more general permanent flooding of the coastal regions of Europe due to rising sea levels and climate change is particularly worrying considering the concentration of urban populations along the coasts and the importance of these areas for tourism. The countries of Europe most vulnerable to coastal flooding include the Netherlands and Belgium, where more than 85 % of the coast is under 5 m elevation. Other countries at risk include Germany and Romania where 50 % of the coastline is below 5 m, Poland (30 %) and Denmark (22 %), as well as France, the United Kingdom and Estonia where lowlands cover 10–15 % of the country.

Overall, 9 % of all European coastal zones lie below 5 m elevation. Even with conservative estimates of predictions for sea level rise, a substantial part of the population of Europe living in the coastal regions are highly vulnerable to sea level rise and flooding. It is clear that this is not a specific issue generated by urban sprawl, however, the management of these risks and planning for adaptation will be made more complicated if urban sprawl is not controlled.

Furthermore, the majority of coastal lowlands have ageing defense systems and considerable resources are needed to maintain and improve these systems in order to provide the capacity to withstand the predicted rise in sea levels. In addition and just as important is the fundamental need for new visions for urban and regional planning policy that respond to these challenges. These visions must recognise that continued sprawl in the coastal regions of Europe is fundamentally unsustainable.

Finally, a further emerging issue is worth reporting: urban areas and their hinterlands are becoming increasingly vulnerable to geo-problems controlled by geological processes. The total cost of these problems to society ranges from major hazards (such as volcanic eruptions, earthquakes, floods, land subsidence, landslides) to minor hazards (such as local swelling or shrinking of clays in foundations). Reworking and removal of the soil surface by construction can unbalance watersheds and landscapes, contributing to the loss of biological diversity, ecosystem integrity and productivity, as well as to land degradation and erosion.

4.2 Socio-economic impacts

From a social perspective urban sprawl generates greater segregation of residential development according to income, as mentioned in Chapter 3. Consequently, it can exacerbate urban social and economic divisions. The socio-economic character of suburban and peripheral areas is typified by middle and upper income families with children, who have the necessary mobility and lifestyle to enable them to function effectively in these localities. However, the suburban experience for other groups, including the young and old, who lack mobility and resources can be very different and can reduce social interaction. Furthermore, large segments of urban society are excluded from living in such areas.

Social polarisation associated with urban sprawl is in some cities so apparent that the concept of the 'divided' or 'dual' city has been applied to describe the divisions between the inner city core and the suburban outskirts. In the inner city, poor quality neighbourhoods often house a mix of unemployed people, the elderly poor, single young people and minority ethnic groups, often suffering from the impacts of the selective nature of migration and employment loss.

These socio-economic problems are not, however, unique to city centres. In many cities similar social and economic problems have increasingly developed in the more peripheral areas where post war re-housing schemes are today home to some of the most disadvantaged urban groups and the location of the lowest quality environments.

From an economic perspective urban sprawl is at the very least a more costly form of urban development due to:

- increased household spending on commuting from home to work over longer and longer distances;
- the cost to business of the congestion in sprawled urban areas with inefficient transportation systems;
- the additional costs of the extension of urban infrastructures including utilities and related services, across the urban region.

Urban sprawl inhibits the development of public transport and solutions based on the development of mass transportation systems, and the provision of alternative choices in transportation that are essential to ensure the efficient working of urban environments. These conclusions are reinforced by experience from both Munich and Stockholm where the efficient control of urban sprawl and resulting increase in population densities fosters the use of public transport and reduces the growth of car use (Lyons, 2003; Cameron *et al.*, 2004).

Economic inefficiency is also associated with the market orientated planning regimes that frequently generate sprawling urban areas. Market orientated land use allocations driving urban expansion and the transformation of economic activity often result in the abandonment of former industrial areas. As a result, there are many derelict or underused former industrial zones throughout Europe. In Spain about 50 % of sites contaminated from past industrial activities are located in urban areas (1999), and in Austria it is estimated that abandoned industrial sites cover about 2 % of all urban areas (2004).

Generally, the efficiency savings of more compact city development as compared with market driven suburbanisation can be as high as 20–45 % in land resources, 15—25 % in the construction of local roads and 7–15 % savings in the provision of water and sewage facilities (Burchell *et al.*, 1992).

EU enlargement and the accession of new Member States have in some instances generated economic effects with associated impacts on the development of cities. In Tallinn, for example, over the past 2–3 years the price of apartments has risen considerably during a period of widespread increases in real estate and land market transactions (Box 8). Generally, increased land prices throughout western Europe, as a consequence of urban sprawl and speculation, is attracting investors to new markets in the new Member States. The input of external capital distorts internal markets, particularly in small countries like Estonia which has a small property market and a population of just 1.3 million.

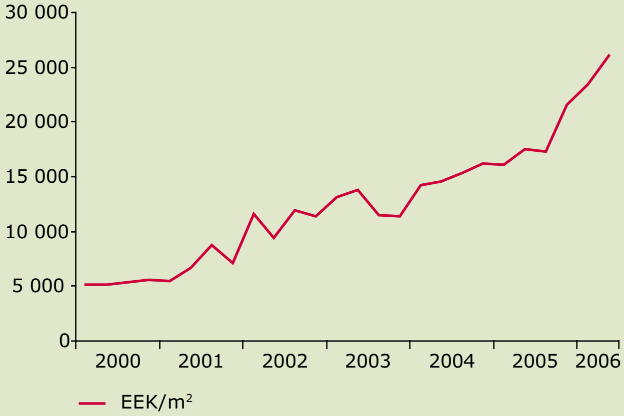
The failure to control urban sprawl at the local level despite the policies and tools that are available supports the case for the development of new initiatives and new policy visions to address these policy failures. The EU has obligations to act to address the impacts of urban sprawl for a wide variety of policy reasons. These include its commitments under environmental treaties to ensure that these impacts do not seriously undermine EU commitments to the Kyoto Protocol on greenhouse gas emissions. Other legal bases for action originate from the fact that some problems of urban sprawl arise from European intervention in other policy domains. Overall, these obligations define a clear responsibility and mandate for the EU to take an active lead in the development of new initiatives to counter the environmental and socio-economic impacts of sprawl.

The following chapter examines the principles that should define the governance framework for action at EU level to combat urban sprawl. This includes policy definition according to the principles of sustainable development, policy coherence built around measures to secure policy integration via close coordination between different policies and initiatives, and better cooperation between different levels of administration.

Box 8 Effects of residential areas pricing on urban sprawl in Tallinn

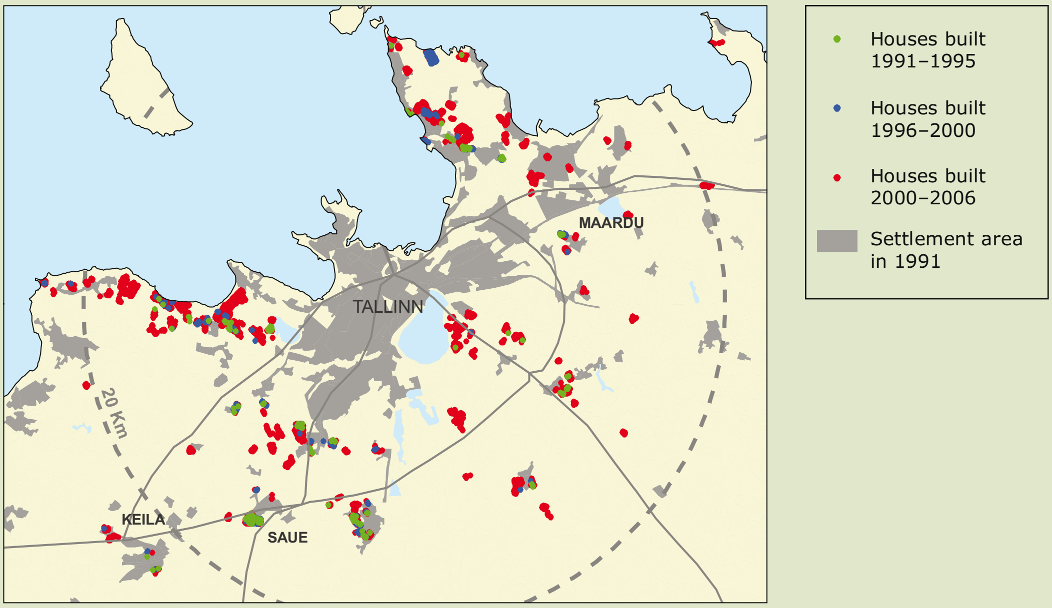
An inventory of the new residential areas (minimum 5 houses or doors in limits of 200 m from each other) in the Tallinn metropolitan area was carried out during January 2006 (Ahas *et al.*, 2006; Tammaru *et al.*, 2006). The construction of the new residential areas has grown exponentially in 1991–2005. One third of all the households living in the suburbs of Tallinn live in the houses that were completed in 2005. The 171 settlements under study consist of 3 400 dwellings housing 5 600 families and 17 200 inhabitants. It becomes evident that 46 % of settlements consist of single-family houses, but only 20 % of the households live in them. New housing is concentrated very close to the capital city, in limits of 10–15 km from city centre. New settlement areas are spatially more scattered into the new small settlements, mainly on the previous farmlands. The majority of new residential areas are located not far from the existing social infrastructure, but they are poorly equipped with it themselves. The local populations living in the city are beginning to realise new opportunities to sell their inner city apartments at higher prices and purchase new housing outside the city. These houses are located in scattered developments approximately 10–15 km from the centre of Tallinn typically on former farmlands. The majority of these new residential areas are located adjacent to the existing social infrastructures but have nonetheless poor social provision.

Figure Tallinn average price of a two-room apartment (EEK/m²)



Source: Estonian Statistical Office, 2006.

Map New settlements in Tallinn metropolitan area, 2006



Source: Tammaru *et al.*, 2006.

5 Responses to urban sprawl

'Creating high quality urban areas requires close coordination between different policies and initiatives, and better cooperation between different levels of administration. Member States have a responsibility to help regional and local authorities to improve the environmental performance of the cities of their country' (Communication from the European Commission to the Council and the European Parliament on Thematic Strategy on the Urban Environment, 2006).

5.1 Initiatives to counter sprawl

This report presents the growing evidence that the drivers of many environmental problems affecting European urban land originate outside the urban territory where the changes are observed. The global market economy, trans-European traffic networks, large-scale demographic and socio-economic changes, cross-boundary pollution, as well as differences in land-planning mechanisms at national, regional and local levels, are the main drivers of change and environmental pressure on, and from, urban areas. As a result, there is now increasing awareness of the benefits of considering urban territory as an integrated unit for stimulating better coordination of policies and analysis of their economic, social and environmental impacts.

Managing cities is a complex and interrelated task which highlights the potential dangers of ad-hoc decision making: the solution to one problem, at one scale, is often the cause of another, at a similar or different scale. It is therefore of prime importance to recognise that while the city is the main focus of socio-economic activity, and the associated pressures and impacts on the environment, it cannot be managed in isolation from forces and decisions that originate well beyond the city borders.

The EU can take a lead role in developing the best frameworks for action at all levels and pave the way for local leaders to do more, as attempted through recent decisions (European Commission, 2005; 2006).

A key dimension of such frameworks is the division of responsibilities between the different levels of city and regional governance. Urban and regional managers at the local level have prime responsibility for the management of the city and its region. But the strategies and instruments to control urban sprawl strongly depend on the interconnectedness between local, regional and national conditions that are increasingly reshaped by the realities of Europe's spatial development. New planning responses to combat urban sprawl therefore would be built on principles that recognise what is locally driven and what should be EU driven.

A further dimension concerns the revision of the thrust of policy at the local level to counter sprawl, and the replacement of the dominant trends of urbanisation ('laissez-faire') with a new urbanism ('creative control') (Laconte P., 2006). At present, planning policy solutions at all levels of governance more typically reflect the logic of economic development rather than a sustainable vision of urban Europe.

New policy interventions to counter sprawl could be focused on the need to supplement the logic of the market and be based on demand-driven rather than supply-driven management. In this context, identifying the necessary spatial trade offs between economic, social and environmental objectives and the key requirements for the sustainable development of Europe's cities requires an improved regional contextualisation of the respective assets that should be maintained, restored or enhanced.

This is the role devolved to spatial development in policy making where the EU can support the envisioning of spatial planning of Europe's cities and regions to effectively address the issue of urban sprawl. This articulated vision of sustainable urban and regional development can provide the context for a range of integrated mutually reinforcing policy responses, offering a new policy coherence to be implemented at all levels. Particular focus can be given to the key EU policy frameworks which can make major contributions to policies to combat urban sprawl, namely transport and cohesion policy.

5.2 The European spatial development perspective

While EU territorial development is the subject of continuing debate, the links between territorial cohesion and economic and social cohesion, two fundamental aims of the European Union (Article 16 of the Treaty), require further clarification and analysis. Many benefits can be secured from a broader vision of cohesion that encompasses the many dimensions of the development of territories, urban areas in particular, and their interrelationships.

Europe has continued to debate the merits of a stronger and more balanced territorial focus for its policies since the Member States and the European Commission presented the European Spatial Development Perspective (ESDP) in 1999. This debate has produced commonly agreed policy orientations focused around better territorial balance and cohesion, improved regional competitiveness, access to markets and knowledge, as well as the prudent management of natural and cultural resources.

These policy orientations reflect the ongoing geographical concentration of many parts of European society in highly urbanised areas. The long-term aim is to see a European territory with many prospering regions and areas, geographically widespread, all playing an important economic role for Europe and providing good quality of life for their citizens. Polycentric spatial development is the main concept underpinning the aims of territorial cohesion. The concept can be described as a bridging mechanism between economic growth and balanced development. Accordingly, polycentric development can bridge the divergent interests of the Member States by encouraging more balanced and coordinated competitiveness. Interest in polycentric development is also fuelled by the hypotheses put forward in the ESDP that polycentric urban systems are more efficient, more sustainable and more equitable than either monocentric urban systems or dispersed small settlements. This process should be considered in conjunction with the perspectives of land prices mentioned earlier in this report. This is particularly pertinent for agricultural land prices in the context of the new intensification of agriculture, driven by the increase of world-market prices and the evident growing demand for biofuels.

One of the central tenets of the ESDP and its follow up studies, notably the Study Programme on European Spatial Planning (SPESP) is that 'many local problems cannot be solved nowadays without an integrated way of looking at towns and countryside, since they tend to be regional problems'. In this context, a territorial dimension has been proposed for the conceptual basis of structural policies after 2007. The Commission has also proposed European territorial cooperation as an objective for Structural Funds interventions for 2007–2013 in support of territorial cohesion within the EU.

At the same time, although the Lisbon Strategy has no explicit territorial dimension, one of its three main priorities calls for Europe to be made an attractive area in which to invest and work. This priority includes considerations relating to access to markets and the provision of services of general interest, as well as to factors relating to the creation of a healthy environment for enterprise and the family. The implementation of the Lisbon Strategy and future structural policies will take place in cities, regions, in national territories and at European level (European Commission, 2005). Therefore, a key question for policy-makers at different levels is to explore, identify, understand and select potential areas for development within their own territory in order to contribute effectively to this overall European strategy.

5.3 Current barriers to addressing urban sprawl

Despite the complexity of urban systems, a piecemeal approach to urban management prevails in many cities; sprawl is seldom tackled as an integrated issue. In turn, issue integration is rarely matched by procedural integration through policy-making, problem analysis and impact assessment, planning, financing and implementation, precisely because of the wide scope of the issues involved. This constraint on effective urban management, already identified as far back as the 1980s (European Commission, 1990), still remains high on political agendas (European Commission, 2006).

In this context, there is a continuing perception of cities as isolated from their wider regional context. In reality, however, the functional influences of cities are recognised as reaching far beyond their immediate boundaries. There are also multidimensional links between urban and rural areas that are becoming more and more apparent. Typically, in Europe today, cities flow imperceptibly across municipal boundaries. This process is at different stages of development in different countries, but it occurs everywhere. At the same time, the responsibility for land use management remains divided between different administrations and this fragmentation of management, frequently exacerbated by the political tensions of neighbouring administrations, may lead to incoherent and uncoordinated land use management.

There are many more dimensions to the management of urban sprawl. Societal behaviour, as mentioned in Chapter 3, is a major factor driving urban development as the desire for detached homes combines with the widespread use of cars. This reflects social values that place great emphasis on individual achievements rather than on group solidarity. Producers of consumer goods or services have made profitable use of this trend through detailed customer socio-cultural typologies and refined market segmentation (Laconte P., 2006).

Illustrative of this reality is the fact that, for the past 20 years, there have been four times more new cars than new babies, and vehicle-kilometres traveled in urban areas by road are predicted to rise by 40 % between 1995 and 2030. Levels of car ownership in the EU-10 are still not at the same levels as for EU-15, suggesting even further growth. If nothing is done, road congestion is expected to increase significantly by 2010 and the costs attributable to congestion will increase to approximately 1 % of Community GDP (EEA, 2006).

The issue of mobility, and accessibility, therefore remains a critical challenge for urban planning and management, as well as a key factor in European territorial cohesion. The challenge is to secure a global approach that takes into account the real impacts of investments directed at the creation and sustainability of local activities and jobs, based on a balanced and polycentric development of European urban areas.

These are challenges that must also be faced at regional, local and European levels, in the framework of the common transport policy and the Trans-European Transport Network (TEN-T). It is worth mentioning, in this respect, that in April 2004 the European Parliament and the Council identified 30 priority projects that represent an investment of EUR 225 billion by 2020, involving, for example, the construction of 12 000 km of highways. Will the history of urban sprawl in the EU-15 repeat itself in the EU-10?

EU regional policy perspectives will play a major role in developing new transport networks during the 2007–2013 period, in accordance with the priority objectives proposed by the Commission, including convergence, regional competitiveness and employment, and territorial cooperation. Impact assessments of the effects on the expansion of city regions generated by these new transport investments will be critical for the attainment of all these priority objectives (Box 9).

That said, it is vital to recall that the very complex nature of urban systems remains the principal barrier for current administrative and political initiatives tackling the problems of urban sprawl. The fundamental challenge remains understanding, in both functional and operational terms, the unsustainable development patterns of our cities so that future unsustainable development can be corrected or avoided. This is still a challenge even for experts studying the most 'sustainable' forms of urban development.

In this context, the relationship between urban compactness and travel patterns (mobility) is central to the debate (Williams K. *et al.*, 2000). However, there are more dimensions, for example, to the simple causal relationship between high-density development and reductions in mobility demand. Current monitoring and analysis of such links could be improved greatly if employment catchment areas were used to define functional urban regions (Laconte P., 2006).

All things considered, the paradigm of the compact city as an immediate antidote to the sprawling city still cannot be fully substantiated. The effectiveness of compaction, as well as centralisation and concentration, have been thoroughly examined, including the various ways in which compaction can be achieved, such as intensification, new high-density development, traditional neighbourhood development etc. However, there are still uncertainties, particularly in the areas of ecological, social and economic impacts (Williams, K. *et al.*, 2000).

5.4 Policy coherence and effectiveness

To be effective policies should deliver what is needed on the basis of clear objectives, in terms of time and with an evaluation of future impacts. Effectiveness also depends on implementing policies in a proportionate manner, on taking decisions at the most appropriate level, and ensuring that decisions taken at regional and local levels are coherent with a broader set of principles for sustainable territorial development across the EU.

The EU has a responsibility and a specific capability to address the wide ranging and powerful pan-

European regional forces generating urban sprawl with impacts beyond the control of urban managers at the local level. For these reasons, policies at all levels need to have an urban dimension that tackles urban sprawl and helps to redress market failures that drive urban sprawl and undermine a sustainable vision for the spatial planning of urban Europe.

The EU white paper on European governance provides the following framework of principles underpinning good governance that assists in defining a framework for intervention to counter sprawl at all levels:

- Policy coherence: ensuring that policies are coherent and not sector-specific and that decisions taken at regional and local levels are coherent with a broader set of principles;
- Responsiveness to local conditions: flexibility in the means provided for implementing legislation and programmes with a strong territorial impact;
- Cooperation in policy development: development of systematic dialogue and increased cooperation with European and national associations of regional and local government.

5.4.1 *Policy coherence*

Policy coherence provides the first principle of good governance through which the EU can support initiatives to counter urban sprawl. Cities can benefit from initiatives and programmes spanning the entire realm of European Commission competence; the framework for trilateral agreements between the EU, national governments and regional/local authorities (COM(2002)709) provides a specific example, and some agreements have already been signed, e.g. Milan (Laconte P., 2006).

However, cities also need a long term sustainable policy vision to help synchronise the many critical success factors, including mobility, access to the natural environment, social and cultural opportunity, and employment, which all form the basis for sustainable urban development. At present, in many cases, the policy vision is poorly articulated permitting a market driven approach to dominate over the interests of sustainable development, a deficiency exacerbated by poor integration between the levels of governance. The EU can set the tone and direction for sectoral policy integration in cities whilst recognising that planning responses to the problem of sprawl must also be sensitive to the local and regional mix of priorities.

As it stands, EU Cohesion Policy (2007–2013) offers an effective framework to build a coordinated and integrated approach to the sustainable development of urban and rural areas. The approach is essential to ameliorate the impacts of urban sprawl and specific actions include:

- coordination of land use policies, as well as Structural and Cohesion Funds investments between urban areas, rural areas, the regions and the national levels to manage urban sprawl. Initiatives to make urban areas and city centres attractive places to live and support the containment of urban sprawl;
- encouragement to Member States to explicitly delegate to cities funds addressing urban issues within Structural Funds operational programmes, with full responsibility throughout the process for the design and implementation of the delegated portion of the programme;
- investments to achieve compliance with EU laws on air quality, waste-water treatment, waste management, water supply and environmental noise. Active management of congestion, transport demand and public transport networks, with a view to improving air quality, reducing noise and encouraging physical activity all of which can assist in addressing the sprawl of cities;
- co-financing of activities under the Structural Funds based on plans that address the key challenges posed by sprawl and the improvement of the overall environmental quality of urban areas.

5.4.2 *Responsiveness to local conditions*

Responsiveness to local conditions provides the second principle of good governance through which the EU can support initiatives to counter urban sprawl. The principle emphasises the need for flexibility in the means provided for implementing EU legislation and programmes with a strong territorial impact.

The EU Urban Thematic Strategy offers an umbrella framework to support actions and solutions developed at the local level to address urban management problems including urban sprawl. The strategy offers a coordinated and integrated approach to assist Member States and local and regional authorities to meet existing environmental obligations, to develop environmental management plans and sustainable urban transport plans, and so to reinforce the environment contribution to the sustainable development of urban areas.

Box 9 Dresden and Prague: economic growth and new transport links

German reunification and the collapse of the communist block led to changes in the economic regime from planned to market economy in both the former east Germany and the Czech Republic. Adaptation to the market economy caused many dramatic changes in traditional economic structures, such as a decrease in GDP and a high rate of unemployment, up to 25 % in Saxony. Towards the end of the 1990s, gradual but sustainable recovery of the economy commenced and political and social reforms took hold. These changes have created completely new driving forces for urban development. EU membership has also led to the growing engagement with European markets and access to EU development schemes e.g. TEN-T, ERDF, Cohesion Fund etc. For the new EU Member States (EU-10) gross domestic product is expected to triple and the number of households is projected to double between 2000 and 2030 (EEA, 2005). But in contrast to economic growth, the demographic trends for EU-10 show significant decreases of population, up to 7 % by 2030 (EEA, 2005). It is clear that all the above-mentioned changes will have a strong impact on land use patterns in the area.

Dresden–Prague: key driving forces for urban development

1950s to 1990s	1990s to present
Economy	
• Planning economy • Emphasis on heavy industry and mining	• Market economy • Foreign (Czech Republic)/western German investments • Emphasis on modern high-tech industries, commerce and services • Construction boom
Population/urbanisation	
• Slowing population growth since the 1970s • Migration to the cities due to industrialisation	• Decrease and ageing population • Migration of rural population into the cities compensates natural decrease of population in cities • Emigration to western Europe for better jobs (Saxony)
Housing and planning policy	
• Limited market for residential and land properties • Land price was not considered in the planning process, dominance of political decisions • Construction of vast areas of block houses for industry workers (especially the Czech Republic)	• Open market for residential and land properties • Private sector interests competing with public interests in the planning process • Low land prices outside cities and people's preference to move to one-family houses
Infrastructure	
• Emphasis on public transport and rail	• Growing importance of motorways

Future development paths: scenarios

Business-as-usual: Extrapolates moderate 1990s trends of land use change, indicating that the land use patterns of the area will not change considerably over the next two decades.

Built-up expansion: Elaborates the socio-economic projections of the European Environmental Agency.

Motorway impact: Evaluates the impact of motorway development (A17/D8 part of TEN Corridor IV).

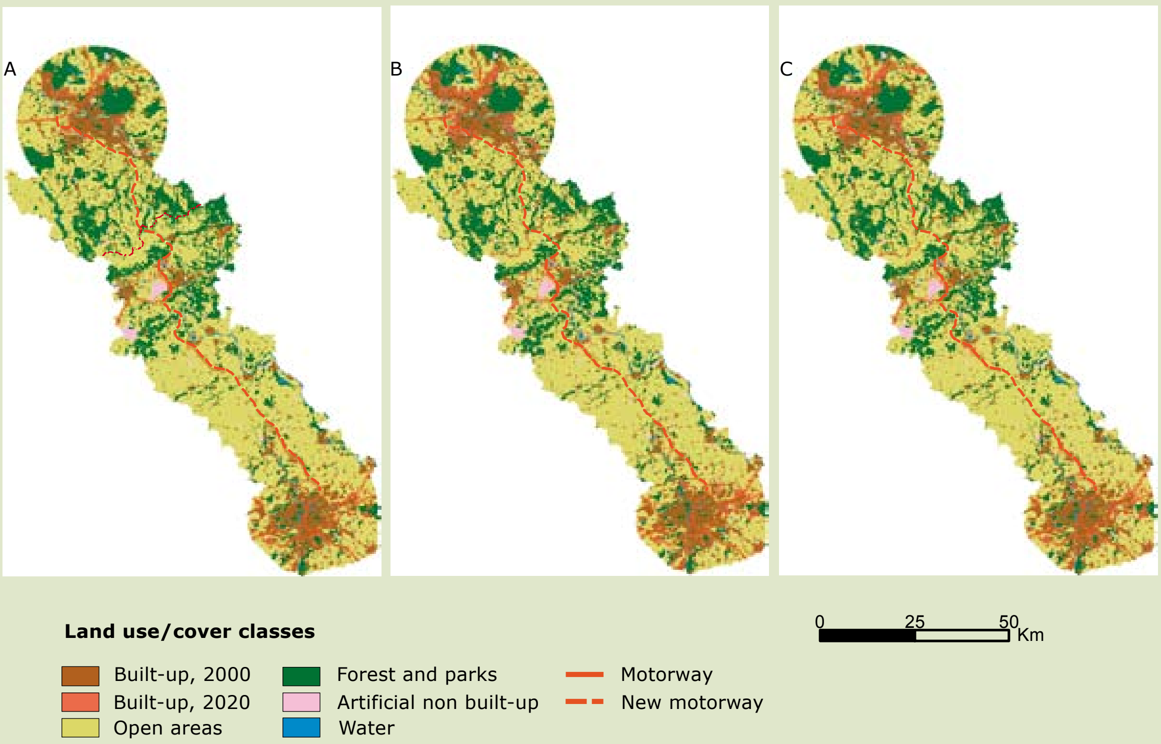
Around Dresden new residential districts are situated adjacent to existing ones and lead to the merging together of former clusters. Construction of the new motorway around the city from west to south creates a new development axis for commercial and industrial areas. The simulation results for Prague show a very different, more clustered type of future development. The radial network of motorways connecting the city to different destinations attracts the development of commercial zones and produces more clustered patterns of growth. The municipalities located in the vicinity of Prague experience intensive residential development and hence it can be assumed that demand for new housing will remain strong.

Box 9 (cont.)

The motorway A17/D8 can reinforce regional development and lead to the establishment of commercial and service areas adjacent to larger settlements and towns. In most cases the future growth pressures of Dresden and Prague will focus on agricultural land and natural areas around both cities.

Map Dresden-Prague: scenarios of urban land use development — late 2000–2020

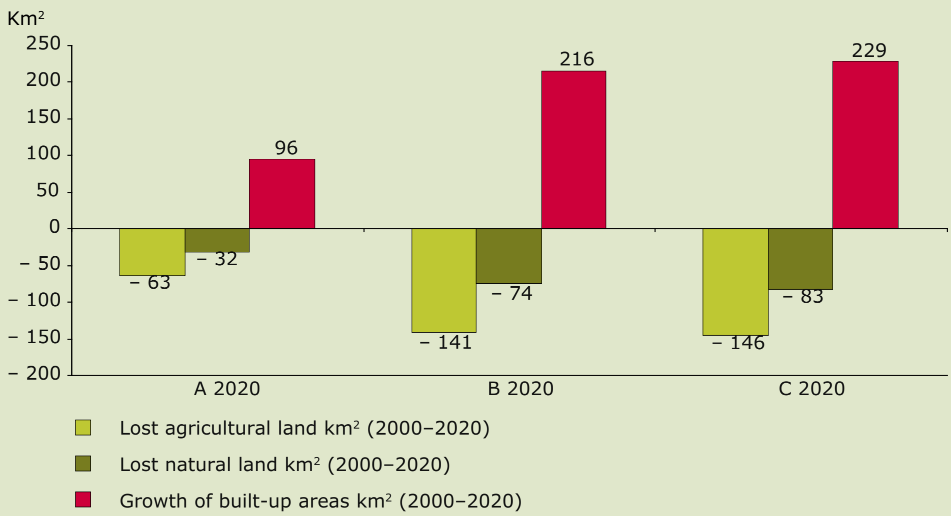
A: Business-as-usual B: Built-up expansion C: Motorway impact



Source: Moland (JRC).

Figure Land use changes in the Dresden-Prague Corridor 2000–2020

A: Business-as-usual B: Built-up expansion C: Motorway impact



Source: Moland (JRC).

The Thematic Strategy provides a context in which good practice experiences of cities in combating urban sprawl can be applied and developed such as:

- the development of long term, consistent plans promoting sustainable development and the limitation of urban sprawl supported by monitoring and evaluation systems to verify results on the ground;
- policies for the the rehabilitation of derelict brownfield sites and renovation of public spaces to assist in the creation of more compact urban forms;
- policies for the avoidance of the use of greenfield sites and complementary urban containment policies;
- identification of the key partners including the private sector and community, as well as local, regional and national government and their mobilisation in the planning, implementation and evaluation of urban development;
- management of the urban-rural interface via cooperation and coordination between urban authorities and rural and regional authorities in promoting sustainable development.

5.4.3 Cooperation in policy development

Cooperation in policy development provides the third principle of good governance through which the EU can support initiatives to counter urban sprawl. At the EU level, the Commission can ensure that regional and local knowledge and conditions are fully taken into account when developing policy proposals. In particular the aim is to develop systematic dialogue and increased cooperation with European and national associations of regional and local government and other local partners including regional and city networks and other NGOs.

The essentials of this approach are based on the development of a reinforced culture of consultation and dialogue, a culture which is adopted by all European Institutions. In some policy sectors, where consultative practices are already well established, the Commission could develop more extensive partnership arrangements. The mobilisation of a broad range of partners with different skills has underpinned the 'Bristol Accord' in which local partnerships including public, private, voluntary and community interests are viewed as essential to deliver sustainable communities.

Such partnerships need to be developed and maintained over the long term based on flexible cooperation between the different territorial levels. Regional and city networks and NGOs can in this manner make more effective contributions to EU policy development.

5.5 Local urban and regional management

The analysis of cities in this report confirms that the success of local planning policies and practices in restricting the physical expansion of built-up areas is critical to efforts to constrain urban sprawl.

The studies have identified planning policies and practices that have successfully restricted the sprawling expansion of built-up areas. Indeed, one fifth of the cities studied increased the density of residential areas from the mid-1950s. At the local level policies of urban containment are widely used in land use planning as a means of reducing urban sprawl and preserving farmland, including policies to limit greenfield and promote brownfield development based on more or less strict land use control.

Given the heterogeneity of the cities considered in this report, the array of policies and other means to limit and prevent urban sprawl is potentially extensive. Further examination of the policies and means to limit urban sprawl in these cities may therefore offer deeper insights into the nature of the effective local management of urban sprawl. The prime aim is to acquire a full understanding of the policies and practices behind the 'success stories' so that this know-how can be made available to all European cities in combating urban sprawl. The following analysis of Munich (Box 10) highlights some best practice experience that can provide catalysts for future integrated approaches to the management of urban sprawl throughout Europe.

The Munich area has remained exceptionally compact when compared to many other European cities. The roots of this success may be traced to the decisions by the city's planners in the post war period to rebuild the historical centre enclosed by a combined park and traffic ring. This was followed in the early 1960s by the replacement of traditional town planning with integrated urban development planning, providing guidelines for all municipal responsibilities including economy, social issues, education, culture as well as town planning.

By the 1990s comprehensive planning concepts were firmly established, based on an integrated urban development plan and focused on the objective of keeping the Munich region compact, urban and green. Fundamental to the attainment of the plan's objectives are a mix of policy initiatives including the reuse of brownfield land, avoidance of expansion, mixed land use development integrating residential and commercial services, improvement of public transport as well as pedestrian and cycling facilities, and reinforcement of regional cooperation.

The Munich case study clearly emphasises the dominant role of local and regional policies in defining the spatial organisation of cities and regions. Munich has successfully adopted and implemented a compact city model in the planning of the city that has effectively contained urban sprawl based on the following key objectives and actions:

- integrated city development plan;
- regional cooperation;
- stakeholders' involvement in city planning;
- emphasis on reuse of vacant brownfields;
- continuously improving public transport with as few new roads as possible;
- compact-urban-green — keep the city compact and urban and green areas green;
- guarantee the necessary resources for implementing the strategies of all relevant policy areas (transport, housing etc.) for both 'business as usual' situations and through major renovation projects.

The lessons from Munich can also provide the good practice basis for sustainable development that many other cities throughout Europe urgently require.

As well as issues concerning the potential for transfer of good practice experience, it is also clear that conflict with policy objectives at national, regional and local levels can also undermine local efforts to combat urban sprawl. The role that EU can play in combating sprawl should therefore be set not only in the context of complementing what is locally driven, but also proactively engaging at all levels, given the evident potential for local policy failure.

5.6 By way of conclusion — combat against urban sprawl

Land use patterns across Europe show that tensions are arising almost everywhere between our need for resources and space and the capacity of the land to support and absorb this need. Urban development is the main driver.

Throughout Europe in the 1990s, changes in land cover were mainly characterised by increases in urban and other artificial land development and forest area, at the expense of agricultural and natural areas. Anticipated growth of the urban population by 5 % in the coming decade, will further fuel these trends. Globalisation, transport networks, socio-demographic changes, societal aspirations for the 'urban culture' and uncoordinated land-planning mechanisms at various levels are the main sources of the environmental unsustainability of our cities.

Scientists, planners and policy-makers are becoming increasingly aware that adequate decisions on urban development cannot be made solely at the local level. This is especially important in a European context where more and more urban areas are becoming connected in order to realise common objectives, such as the Lisbon agenda for growth and competitiveness.

The history of human culture suggests that 'landscape' is one of the earliest and most obvious concepts for perceiving and describing our changing environment, be it artificial or not. It is at the landscape level that changes of land use, naturalness, culture and character become meaningful and recognisable for human interpretation. In that sense, landscape is as much vision as it is reality.

The way we perceive landscapes, the attraction we feel for some of them, and our feelings when conflicts arise over the use of land, are all matters of extreme importance for conservation and future human welfare. A landscape is essentially a photograph of what is going on; it reveals, in short, who we are. With urban sprawl-generated landscapes in continuous flux, we indeed reveal a lot about the footprints we will be leaving for the next generations.

The present report demonstrates, in this context, the potential for local policy to be isolated in overcoming the serious impacts of urban sprawl throughout Europe, a fact which highlights the requirement for urgent action by all responsible agencies and stakeholders. The EU governance white paper defines the preconditions for good governance emphasising the need to assess whether action is needed at the EU level and the principles for action when required.

Box 10 Munich — development of the compact city

Munich is the capital of the Bavarian state and the 3rd largest city in Germany. The MOLAND study area comprises the city of Munich (*Landhauptkapital*) and 44 surrounding municipalities (completely or partially). The total area is 791 km^2 and the resident population in 1990 was 1.69 million inhabitants. From 1955 to 1990 the population has grown by 49 %.

Munich — compact city

The Munich area has remained exceptionally compact if compared to many other European cities (see Chapter 2). It is the only urban area among the 24 urban areas studied where the built-up areas have grown at a clearly slower pace than the population. Another indicator of compactness is the share of continuous residential areas compared with all residential areas built after 1955. In all other Western European cities studied almost all residential areas, built after the 1950s, are discontinuous in character, but in Munich only one third is of this character and two thirds are densely built.

Bavarian planning solutions

Munich was heavily bombed and mostly destroyed in World War II and immediately after the war the city's planners faced a decision whether to completely rebuild or to reconstruct what was destroyed. The outcome, in what later proved to be an excellent decision, was a mix of both approaches. The historical centre was rebuilt largely following the pre-war pattern and style. To ease traffic problems and to increase green urban areas a combined park and traffic ring was constructed around the historical city.

By the early 1960s pressures to find new housing and transport solutions began to mount in Munich. The drivers for change were primarily the increased use of the private car, and strong inward migration from rural areas. At the same time at the Federal level in Germany, the new building law (*Bundesbaugesetz*) took effect. All these factors together influenced the far-sighted decision adopted by the Munich planners to move from traditional town planning to integrated urban development planning, providing guidelines for all municipal activities including economy, social issues, education, culture as well as town planning. The first integrated city-development plan of 1963 paved the way for Munich's modernisation.

In the late 1960s another innovative tool was also adopted as a response to citizens' opposition to the new development plans. The mayor organised an open discussion forum for urban development issues that became a permanent platform where the stakeholders and the city planners could exchange views and opinions. At the same time an independent department was created with the responsibility to coordinate all municipal planning activities, strengthen links with research and stakeholders involvement.

Regional cooperation was seen as the only way of safeguarding the balanced regional development of Munich and the mainly rural neighbouring municipalities. As early as 1950 the majority of the municipalities in the Munich region discussed common urban development issues in the form of a 'Planning Association of Munich's Economic Region' which became the Munich Regional Planning Association. However, this cooperation has remained on a voluntary and consultative basis and no planning authority has been transferred to the regional level, in contrast to other German city-regions.

The 1970s and 1980s were characterised by more incremental developments and the planning vision became less clear. Nonetheless, the steps taken in the earlier period maintained the high planning standards and resulted in a compact and high-quality urban environment. The main objectives of this era were as follows:

- city in equilibrium where various economic, social and environmental interests are in balance;
- development of areas inside the urban structure instead of urban expansion in the periphery supported by economic incentives, and made possible by large brownfields vacated by industry, the military, the Federal Railroads (DBB) and the old airport in Riem;
- strong emphasis on public transport and new road development limited to a minimum;
- preservation of large green recreational areas around the city.

In the 1990s the comprehensive planning concept gained ground and a new version of the integrated urban development plan called 'Munich Perspective' was adopted in 1998. The slogan of the plan is to keep Munich region compact, urban and green. The plan covers economy, social issues, transport, environment and town planning. The main urban structure objectives include continued reuse of brownfields and avoidance of expansion. Mixed land use (residential, commercial, services) is seen as an important way of keeping the

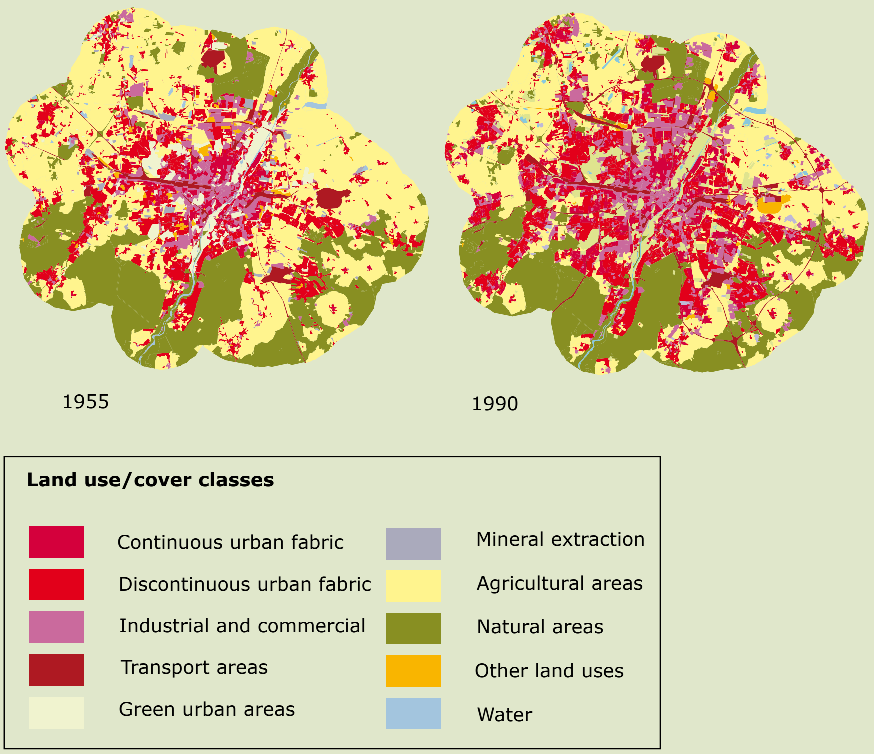
Box 10 (cont.)

city compact. Improvement of public transport as well as pedestrian and cycling facilities and reinforcing regional cooperation are also seen as fundamental for the attainment of the plan objectives.

Key objectives and actions for the compact city

- Integrated city development plan
- Regional cooperation
- Stakeholders' involvement in city planning
- Emphasis on reuse of vacant brownfields
- Continuously improving public transport with as few new roads as possible
- Compact-urban-green — keep the city compact and urban and green areas green
- Guarantee the necessary resources for implementing the strategies of all relevant policy areas (transport, housing etc.) for both 'business as usual' situations and through major renovation projects.

Map Land use changes in Munich urban area from 1955 to 1990



Source: MOLAND (JRC).

It is clear according to the good governance criteria that the EU has specific obligations and a mandate to act and take a lead role in developing the right frameworks for intervention at all levels, and to pave the way for local action. Policies at all levels including local, national and European need to have an urban dimension to tackle urban sprawl and help to redress the market failures that drive urban sprawl. The provision of new visions for the spatial development of Europe's cities and regions is vital for the creation of a range of integrated mutually reinforcing policy responses.

The policy debate on sustainable visions for the spatial planning of urban Europe is already actively underway in the European Parliament. The Parliament's advocacy of the provision of urban green areas and large natural areas to bring citizens closer to nature, can form the *entrée* for wider EU contributions to this debate on the visions. This will set the tone and direction for sectoral policy implementation at all levels, and become the basis for the new urban planning model of city regional development.

In (re)developing integrated spatial planning for the key EU policy frameworks which make major contributions to policies to combat urban sprawl, transport and cohesion policies are without doubt crucially important dimensions for the delivery of positive outcomes. EU Cohesion Policy offers in particular an effective framework to articulate better coordination of land use policies and Structural and Cohesion Funds investments between urban areas, rural areas, and the regions that can effectively manage urban sprawl.

Finally, good governance, in the context of the EU Urban Thematic Strategy, can be translated into the provision of support for actions and solutions developed at the local level to address urban management problems including urban sprawl. In this way the EU can directly assist in the transfer of good practice experience of the management of urban sprawl from one city to another and the dissemination of policy solutions that have proven effective.

The impacts of urban sprawl have for years and decades generated debates among scientists and practitioners, less so among the authorities and policy-makers in charge. We hope, with this report, to contribute to raising further awareness reactions to an issue crucial to Europe's sustainable future.

Annex: Data and methodological approach

A The challenge of scales

The assessment of the phenomena of urban sprawl at the European level requires appropriate information and tools effective at different scales. The issue of urban sprawl must be defined and comprehended in the urban-regional context in which the dynamics of urban sprawl are operational and urban management undertaken. Furthermore, there is a need to broaden the window of inquiry in order to assess the extent of the impacts of urban sprawl across on the political and geographic territory of Europe. This is the challenge of scales as both the information used and tools applied in the assessment of urban sprawl must be effective at these scales.

In this report two main data sets have been used, to establish linkages between the different scales:

- Corine land cover (1990 and 2000). CLC limitations include resolution of urban areas with minimum mapping unit 25 ha and minimum change detection of 5 ha. But CLC is currently the only harmonised spatial data covering all of Europe, with two time references shots for most countries. CLC makes it possible to assess the extent of urban sprawl in Europe, identifying different patterns and hot spots, and providing information about the neighbourhood of these zones so that change in the environmental context can be understood.
- MOLAND (Monitoring Land Use Dynamics) database. This is a comprehensive database of 28 urban areas and 6 wider regions developed by JRC since 1998. MOLAND has four time windows: mid-1950s, late 1960s, mid-1980s and late 1990s. The database includes cities from all EU-15 countries except the Netherlands and Luxemburg, from several EU-10 countries as well as some countries in the pre-accession phase. Most urban areas in the MOLAND database have 0.5 to 2 million inhabitants. The selection of urban areas and regions was influenced by European research interests, for example, the inclusion of areas with Structural Funds subsidies, border regions, areas with specific development dynamics etc. For each urban area detailed information is available on land use/cover changes, but also on socio-economic data from the 1950s. The database provides a wide time frame that is generally lacking at the European level, and the wide distribution of cities is useful to illustrate issues that are not possible with a narrower frame of reference.

It is important to emphasise that both data sources share the same definitions of land cover classes. In the case of MOLAND a more detailed level of subclasses has been derived in view of its higher level of resolution. The common basis of land use classes ensures some comparability of results.

B Definition of urban areas

Urban sprawl is extending urban growth far beyond their administrative boundaries, and in order to ensure that there is full comparability of results between cities the units of analysis need to be clearly defined. In this report urban areas have been defined by morphology and the distribution of urban land across the territory. CLC and MOLAND data sources originate from different projects, and so the definitional bases are slightly different. It should also be borne in mind that both data sources possess different resolutions. Overall, however, general trends, such as direction of change and order of magnitude of built-up areas, are consistent between both data sets. Details are provided in the following paragraphs.

Delineation of urban morphological zones with Corine land cover

Urban morphological zones (UMZ) are defined as built up areas lying less than 200 m apart. Urban areas defined from land cover classes contributing to the urban structure and function are:

- continuous urban fabric (111 according to CLC code);

- discontinuous urban fabric (112 according to CLC code);
- industrial or commercial units (121 according to CLC code);
- green urban areas (141 according to CLC code).

In addition port areas, airports, and sport and leisure facilities, are also included if they are neighbours of the core classes or are contiguous with the core classes.

Once UMZ have been identified according to the procedure outlined above, a second step is undertaken to include road and rail networks, and water courses, if they within 300 m of the UMZ defined in the first step. Finally, forest and scrub (311, 312, 313, 322, 323, 324 CLC code) are also included if they are completely within the core classes.

The UMZ has been delineated for CLC2000 (with reference year 2000). In order to reduce the large number of UMZs identified and work with a relevant subset, only UMZs with more than 100 000 inhabitants have been selected. The allocation of the population has been undertaken as follows:

- EU-25: Population was derived multiplying land cover classes by Population Density Raster provided by JRC. The source data was from Eurostat (2001).
- Non-EU-25: Population data was derived from the CITYPOPULATION (www.citypopulation.de) database, which in turn collects the information from national statistical offices. Data is provided by settlement, and settlements are then aggregated according to UMZ and data from 2001 added.

Urban areas in MOLAND

The area of investigation was selected on the basis of the contiguous artificial surface or core area of the city, plus a peri-urban buffer zone. The former usually corresponds to the Artificial Surface class of the Corine land cover map and equals an area (A). The buffer zone was calculated as follows:

Buffer zone width = $0.25 \times \sqrt{A}$ (square root)

The buffer zone typically extends the urban area by approximately twice the core area. The calculated buffer has often been modified and adapted to the neighbouring structures in order to avoid excluding or cutting land uses of major significance such as an airport, village or, simply, the administrative boundaries. In this report urban area refers to the area that combines the core area and the buffer around it. The urban area is therefore always larger than the city, e.g. Munich includes the city of Munich and 44 surrounding municipalities either completely or partially.

Overview of the main databases used in this report

Data source		**MOLAND**	**Corine land cover 1990**	**Corine land cover 2000**
Responsible authority		JRC	EEA	EEA
Period	**Start date**	1950	1986	1999
	End date	2000	1995	2001
Geographic coverage		28 cities and 6 wider regions in Europe In this study are included: Belgrade, Bilbao, Bratislava, Brussels, Copenhagen, Dresden, Dublin, Grenoble, Helsinki, Iraklion, Istanbul, Lyon, Marseille, Milan, Munich, Palermo, Pordenone, Porto, Prague, Sunderland, Tallinn, Trieste, Udine, Vienna	EU-25 (with the exception of Sweden, Cyprus, Malta), Bulgaria, Croatia, and Romania	EU-25 Member States of the EU and Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Liechtenstein, Macedonia
Spatial resolution		Minimum mapping unit 1 ha for the artificial surfaces and 3 ha for non-artificial surfaces	Minimum mapping unit 25 ha	Minimum mapping unit 25 ha Minimum change detection 5 ha
Temporal coverage		mid-1950s, late 1960s, mid-1980s and late 1990s	1990 +/– 8	2000 +/– 3 years
Quality		Accuracy > = 85 %	Accuracy > = 85 %	Accuracy > = 85 %

C Assessing urban sprawl at the European level: Corine land cover

The assessment of urban sprawl has been undertaken within the framework of the land and ecosystem accounts method developed by the EEA and ETC/TE (EEA, 2006). It is based on the Corine land cover 2000 database which also contains a special data layer of 1990–2000 land cover changes. The land accounting methodology permits the measurement of land use change related to relevant socio-economic land use processes. It is especially relevant the grouping of all possible one-to-one changes between the 44 Corine land cover classes (1892 possible combinations) into 9 major land use process (see box below), called land cover flows, which facilitate the interpretation of the results.

For this report the land cover changes include:

- Urban land management: Change of use e.g. from residential to commercial.
- Urban sprawl: Residential land development (class 1.1 of CLC — urban fabric) with loss of non urban land.
- Sprawl of economic sites and infrastructures: Development of land for economic and infrastructure land uses (including sport and leisure facilities) with loss of non urban land. This can be further subdivided into industrial and commercial sites, services and recreation, transport networks and facilities, and waste disposal sites (see Figure 7 as an example).

Nomenclature of land cover change (Level 1)

LCF1	Urban land management
LCF2	Urban sprawl
LCF3	Extension of economic sites and infrastructures
LCF4	Agricultural rotation and intensification
LCF5	Conversion of land to agriculture
LCF6	Forests creation and management
LCF7	Water body creation and management
LCF8	Changes of land cover due to natural and multiple causes

These land cover changes have been analysed within the UMZs, for reference year 2000. As the focus is at the European scale, results can be aggregated in 1 x 1 km grids (e.g. Maps 1 to 4).

In order to assess the extent of urban sprawl outside the UMZ, 3 buffers were defined:

- 0–5 km outside the boundary of the UMZ;
- 5–10 km outside the boundary of the UMZ;
- 10–20 km outside the boundary of the UMZ.

Within each buffer, urban sprawl was calculated and the results provided as a percentage of the total area (see Figure 8).

D Assessing urban sprawl at regional and local levels: MOLAND

The MOLAND methodology for assessing urban sprawl consists of three phases which are described in the next paragraphs: change detection, understanding changes and the production of scenarios.

Change detection (CHANGE): The objective of change detection is to measure changes in the spatial extent of urban areas and wider regions.

CHANGE produces a reference land use database on the basis of satellite images (IRS) and ancillary data (such as maps, aerial photos etc.), typically for the years 1997 or 1998, and three historical land use databases for selected European urban areas. Historical databases are produced for three time periods: mid-1950s, late 1960s, and mid-1980s depending on the availability of source materials (aerial photos, satellite images etc.).

Understanding (UNDERSTAND): Identifying and testing a number of indicators to be used to measure the 'sustainability of urban and peri-urban areas'. The total number of indicators in the MOLAND indicator databank is approximately 50.

For the purpose of this report the following indicators have been calculated:

- Growth of built-up areas from the 1950s to the late 1990s.

Built-up area includes the following land use classes: residential areas, industrial and commercial and service areas and transport areas. It does not include green urban areas. The indicator has been calculated by taking the extent of the built-up area in the 1990s and the built-up area in the 1950s has been subtracted from that area. The growth is expressed as a percentage.

- Annual growth of built-up areas from the mid-1950s to late 1990s (See above for definition). Growth has been calculated for three time periods:
  1950s–1960s, 1960s–1980s and 1980s–1990s. It has then been divided into an annual percentage.
- Share of low density residential areas compared with all residential areas built after the mid-1950s. In the MOLAND database the residential areas have been classified into two main categories: continuous and discontinuous. The discriminating factor is density. If buildings and other structures cover more than 80 % of the land, the area is classified as continuous residential area and if they cover less than 80 % it is classified as discontinuous residential area. The threshold of 80 % has been used in this context as a boundary between dense and low-density residential areas. The indicator has been calculated by measuring the extent of all residential areas built after the 1950s and low density residential areas built after the 1950s. The share is the percentage of the latter as compared with the former.
- The growth rate of residential, industrial, commercial and transport areas (from the mid-1950s to the end 1990s). The indicator has been calculated by measuring the extent of residential, industrial, commercial and transport areas in the 1990s and comparing with the same areas in the 1950s. Growth is expressed as a percentage.
- City population and built up area growth from 1950s to 1990s. The population statistics have been collected from municipal, regional and national statistical offices. If a municipality is only partially included in the MOLAND database, the population figure for that municipality is proportionally reduced.
- Residential density (measured by inhabitants/ residential km^2). The indicator has been calculated by dividing the total number of the population by the area of residential land use.

Development of scenarios (FORECAST):
Development of 'urban growth' scenarios for a subset of the 25 cities, using state-of-the-art urban cellular automata model.

The MOLAND urban growth model is based on dynamic spatial systems called 'cellular automata'. Inputs to the model are different types of spatially referenced digital data including:

- **Land use maps** showing the distribution of land use types in the area of interest. These maps are derived from the MOLAND reference and historical land use databases.
- **Suitability maps** showing the inherent suitability of the area of interest for different land use types. These maps are created using an overlay analysis of maps of various physical, environmental and institutional factors.
- **Zoning maps** showing the zoning status (i.e. legal constraints) for various land uses in the area of interest. These maps are derived from existing planning maps e.g. master plans, zoning plans, designated areas, protected areas, historic sites, natural reserves, land ownership.
- **Accessibility maps** showing accessibility to transportation networks for the area of interest. These maps are computed from the MOLAND land use and transportation network databases, based on the significance of access to transport networks for the various land uses.
- **Socio-economic data**: for the main administrative regions of the area of interest, comprising demographic statistics i.e. population and income, and data on production and employment for the four main economic sectors e.g. agriculture, industry, commerce, and services.

The outputs from the MOLAND urban model consist of maps showing the predicted evolution of land use in the area of interest over the next twenty years. By varying the inputs into the MOLAND urban model e.g. zoning status, transport networks etc, the model can be used as a powerful planning tool to explore in a realistic way future urban and regional development, under alternative spatial planning and policy scenarios, including the scenario of non-planning.

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Further electronic resources

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European Topic Center on Biological Diversity, http://biodiversity.Eionet.eu.int/.

European Topic Center Terrestrial Environment, http://terrestrial.Eionet.eu.int/.

Monitoring Land Use/Cover Dynamics (MOLAND) http://moland.jrc.it/.

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European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Fax: +45 33 36 71 99

Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

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Appendix A.2

Toward Low Energy Cities

A Case Study of the Urban Area of Liège, Belgium

Sigrid Reiter and Anne-Françoise Marique

Keywords:

buildings
energy consumption
geographic information system (GIS)
industrial ecology
transportation
urban modeling

Summary

Within the framework of sustainable development, it is important to take into account environmental aspects of urban areas related to their energy use. In this article a methodology is proposed for assessing residential energy uses for buildings and transport at the city scale. This method is based on the use of geographic information system (GIS) tools combined with a statistical treatment of urban and transport criteria. The methodology allows us to model building and transport energy use at the city scale, as well as to consider the possible evolution of city energy consumption and to simulate the effects of some strategies of urban renewal. An application is given to study different energy management strategies for the urban area of Liège, Belgium. Building and transport energy consumption are compared at the city scale and their possible evolution in the future is highlighted. Forecast scenarios on future energy policies for Liège's building stock show that the European Directive on the Energy Performance of Buildings and even more selective energy policies applied only to new buildings are not sufficient to widely decrease building energy consumption at the city scale. Renovation of the existing building stock has a much larger positive impact on city energy consumption reductions. The methodology developed in this article can be adapted or reproduced for many other urban regions in Belgium, but also in Europe and even further.

Introduction

In the actual context of growing interest in environmental issues, reducing energy consumption in the building and transport sectors appears as an important policy target. Urban areas are supposed to present high potentialities in terms of energy reduction. This is why the Directive on the Energy Performance of Buildings (EPB; EC 2003) came into force in 2002, with legislation in European Union (EU) member states by 2006. However, existing models and regulations often adopt the perspective of an individual building as an autonomous entity, and neglect the importance of phenomena linked to larger scales (Ratti et al. 2005), while decisions made at the neighborhood level have important consequences on the performance of individual buildings and on the transport habits of the inhabitants (Popovici and Peuportier 2004). Moreover, while politicians, stakeholders, and even citizens are now aware of the issue of energy consumption in buildings, efforts and regulations to control transport needs and consumption remain more limited. Nevertheless, transport and mobility are crucial in terms of urban planning.

This research focuses on energy management at the city level. First, a methodology is elaborated for assessing the energy use of residential buildings and transport of inhabitants at the city scale. Then, an application study uses this methodology to model the energy use of residential buildings and transport of the urban area of Liège, Belgium. This case study compares

Address correspondence to: Sigrid Reiter, University of Liège, Laboratory of Architectural Methodology (LEMA), Chemin des chevreuils 1, Bât. B52, 4000 Liège, Belgium. *Email:* Sigrid.Reiter@ulg.ac.be *Web:* http://www.ulg.ac.be/cms/j_5871/repertoires?uid=U205356

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building and transport energy consumption at the city scale, as well as their possible evolution in the future, depending on forecast scenarios. Moreover, this case study allows us to test some strategies of urban renewal, comparing the effects of the European Directive on Energy Performance of Buildings with even more selective energy policies on new buildings and with renovation strategies on the existing building stock of the urban area of Liège.

The structure of this article is developed in seven sections: *Introduction*, *State of the Art and Method*, *Study Area and Cartographic Work*, *Modeling Energy Consumption at the City Scale*, *Forecast Scenarios*, *Discussion* of the results, and *Conclusion*.

State of the Art and Method

This section proposes a brief survey of the most important references on city energy management and the methodology developed in this research.

State of the Art

Since 1993 the International Energy Agency (IEA) has provided projections about global energy consumption using a World Energy Model. In 2008 the World Energy Outlook recognized that the factors that were influencing city energy use were different from the energy use profiles of the countries the cities were in as a whole (OECD and IEA 2008). Friedman and Cooke (2011) prove the same for New York City, NY, USA, and the U.S. database. The IEA suggests that, in industrialized countries, the energy use per capita of city residents tends to be lower than the national average. In contrast, urban residents in China use more energy per capita than the national average due to higher average incomes and better access to modern services in cities (OECD and IEA 2008).

A lot of scientific articles have already studied energy consumption at the city scale, focusing on relationships between transport energy consumption and building density. Based on data from 32 large cities located all over the world, Newman and Kenworthy (1989, 1999) highlighted a strong inverse relationship between urban density and transport consumption. In studies on Nordic cities, Naess (1996) observed that the use of energy for transportation is reduced with higher urban densities. Banister and colleagues (1997) explain the influence of urban density on energy consumption related to mobility by the average home-to-work distance reduction and the more amenable public transport system in dense urban areas. But Breheny (1995) argues that there is not strong evidence that containment policies promote transport energy savings. In the sample of cities used by Newman and Kenworthy, Breheny and Gordon (1997) demonstrated that the density coefficient and its statistical significance decrease when the petrol price and income are included as explanatory variables. Different studies underline the importance of the price of travel and the influence of socioeconomic factors on transport behaviors (Boarnet and Crane 2001; van de Coevering and Schwanen 2006). Souche (2010), studying 10 cities around the world (through the International Union of Public Transport [IUTP] database), shows that the two variables that are the most statistically significant for transport energy consumption assessment are transport cost and urban density.

On the basis of various case studies, Ewing and Cervero (2001) evaluated quantitatively the impact of urban density, local diversity, local design, and regional accessibility on the mean vehicle travel distances. The elasticity was evaluated at −0.05 for urban density, −0.05 for local diversity, −0.03 for local design, and −0.2 for regional destination accessibility. This means that if the density of a district is multiplied by two, private car commutes are only reduced by 5%. Note that the impact of destination accessibility is larger than the three others parameters combined, suggesting that areas of high accessibility, such as city centers, may produce substantially lower transport energy consumption than dense and mixed developments in less accessible areas. Ewing and colleagues (2008) found that the most compact metropolitan areas in the United States generate 35% shorter mean vehicle travel distances per capita than the most sprawling metropolitan areas. Finally, more compact developments (including density, functional mix, and transit accessibility) can reduce mean vehicle travel per capita by 25% to 30% (Ewing and Cervero 2010).

Various studies argue that more compact urban forms would significantly reduce energy consumption both in the building and transport sectors (Ewing et al. 2008b; Steemers 2003; Urban Task Force 1999). Connecting urban form to building energy use, lower density, and detached housing tend to require more energy than multiunit developments or attached housing (Ewing and Rong 2008; Marique and Reiter 2012b; Steadman et al. 1998; Steemers 2003).

The Method

There are a lot of modeling tools to assess the energy management of a specific building, including TRNSYS (Transient System Simulation Program), EnergyPlus, TAS (Thermal Analysis Software), Simula and COMFIE (Calcul d'Ouvrages Multizones Fixé à une Interface Experte), among others. However, such an approach makes it difficult to generalize the results in order to determine the best strategies on an urban scale. At the neighborhood scale, Steemers (2003) analyzed urban areas of 400 meters (m) × 400 meters in order to establish the relationship between urban form and building energy consumptions. The analysis was based on three geometric parameters: building depth, street prospect, and urban compactness. A similar analysis was performed by Ratti and colleagues (2005). The selected variables were the distance between facades, orientation of the facades, and lighting obstructions. This methodology allows in-depth study of the influence of an urban context on building energy consumption, but is too complex to be applied at the city scale.

On the other hand, there are two types of modeling methods used to predict energy consumption on a larger scale (e.g., for national predictions): the top-down and bottom-up approaches. These methodologies have already been described in detail (Kavgic et al. 2010; Swan and Ugursal 2009). Top-down modeling is generally used to investigate the relationships between the energy and economic sectors, studying the influence of economic variables such as income or fuel prices on the energy consumption of countries. These models lack details on the building stock to be able to quantify the effectiveness of specific energy policy measures on urban energy performance. Bottom-up methods are based on typologies and the component clustering modeling approach. These components can be buildings (Shimoda et al. 2004; Tommerup and Svendsen 2006; Uihlein and Eder 2010), urban blocks (Wallemacq et al. 2011), or neighborhoods (Yamaguchi et al. 2007). This implies that they need extensive databases to support the choice and description of each component of their typologies. This is usually done by a combination of building physics modeling, empirical data (e.g., from housing surveys), statistics on national or regional datasets, and some assumptions about building performance. The bottom-up method is very useful to assess the energy consumption of existing building stocks. One example of the bottom-up method applied to building energy consumption studies is the Energy and Environment Prediction (EEP) model (Jones et al. 2001), based on 100 building types commonly found in England.

The following studies are good examples of a bottom-up modeling approach applied to energy studies related to transport. Boussauw and Witlox (2009) developed a commute-energy performance index and tested it for Flanders and the Brussels capital region in Belgium. This commute-energy performance index is based on statistical data available at the district scale in order to investigate the link between spatial structure and energy consumption for home-to-work travel at the regional scale. Marique and Reiter (2012a) adapted and completed this index to develop a more detailed method for assessing transport consumption at the neighborhood scale. The method takes into account the transport energy consumption of residents for four purposes of travel (work, school, shopping, and leisure). An application of this method and a sensitivity analysis are presented concerning the comparison of four suburban districts located in Belgium (Marique and Reiter 2012a).

The proposed method uses an urban geographic information system (GIS) and statistical treatments of urban and transport data in order to develop an energy model at the city scale. This methodology combines building and transport energy consumption studies as well as top-down and bottom-up modeling approaches. The method combines national statistics, that are not associated with buildings and transport (top-down approach), with local data related to buildings and transport (bottom-up approach). For example, the forecast evolution of demographic data is deducted from global trends of recent years (top-down approach), while the energy consumption of transport and buildings are obtained thanks to empirical data and results of energy modeling (bottom-up approach). This combined approach provides a set of data as accurate as possible and the opportunity to compare different urban design strategies for limiting energy consumption in cities. An application study of this method on the urban area of Liège is developed in the next sections of this article.

Study Area and Cartographic Work

The case study concerns the urban area of Liège, which is a typical regional city (600,000 inhabitants) in Belgium, and more specifically the energy consumption of the residential buildings and transport of residents at the city scale. Spatialization of the urban area of Liège was performed using the Projet Informatique de Cartographie Continue (PICC), a computer project of continued mapping from the Public Service of the Walloon Region of Belgium, providing spatial data in the form of vector map layers that characterize the natural environment (rivers, forests), the built environment (buildings), and the infrastructure (roads, railways, etc.) at a scale of 1/1000.

In the first part of the method, a large number of variables were selected to characterize the energy efficiency of urban areas (including buildings and transport energy consumption) using an extensive literature review on this subject. The cadastral data and several energy criteria taken from the literature (net built density, type of buildings, built compactness, area of urban block, buildings' date of construction, indexes of energy performance for transport consumption, and expected modal shares for alternatives to the car, among others) have been linked through an urban GIS to the PICC data to spatialize these energy criteria through the urban area of Liège. It is important to note that some plots of the PICC found no match in the database of the cadaster. No data were taken into account for the buildings constructed on these plots. Note that these differences arise because the data from the PICC were developed from aerial rectified photographs and the data from the cadaster were developed from digital cadastral maps. These data can be considered acceptable because only 383 buildings could not be taken into account, which represents only 0.2% of the residential building stock of the urban area of Liège.

A statistical treatment of these parameters was performed using a principal component analysis. This methodology (Lebart et al. 1982; Volle 1993) allows crossing a large number of criteria and grouping them according to their similarities. This statistical treatment reduced the number of our selected criteria to characterize the energy performance of the residential building stock of Liège. Six criteria were chosen:

- Buildings' date of construction (before 1930, from 1931 to 1969, from 1970 to 1985, from 1985 to 1996, from 1996 to today), depending on the types of construction related to Belgian regulations. These data are available in the cadaster.
- Building renovation. The cadaster mentions the buildings that have undergone significant upgrades together with the year of the work. The most common energy upgrades consist of adding insulation in the roof and replacing windows. Adding insulation in the slab and the walls is pretty rare in the Walloon region (MRW 2007).

- Type of building (two, three, or four frontages). Indeed, for the same level of insulation, a terraced house uses less energy for heating than a detached house (Marique and Reiter 2012b). These data are available in the cadaster.
- Type of housing (collective or individual). These data are available in the cadaster.
- Index of energy performance for residents' transport for home-to-work travel. This index has been developed by Marique and Reiter (2012a) for the Walloon region.
- Index of energy performance for residents' transport for home-to-school travels. This index has been developed by Marique and Reiter (2012a) for the Walloon region.

The "energy performance index" (IPE) represents the energy used by one person for one trip from home to destination (in kilowatt-hours per person per trip [kWh/person/trip]). It takes into account the distances travelled, the means of transport used, and their relative consumption rates. The IPE is calculated according to equation (1),

$$\text{Energy performance index } (i) = \left(\sum m D_{mi} \times f_m\right) \Big/ T_i, \tag{1}$$

where i represents the territorial unit; m is the means of transport used (diesel car, fuel car, train, bus, bike, on foot); D_{mi} is the total distance travelled by the means of transport m in the district i for home-to-work (or home-to-school) travels; f_m is the consumption factor attributed to the means of transport m; and T_i is the number of workers (or students) in the territorial unit i. Consumption factors (f_m) used in this article were calculated for the Walloon region of Belgium by Marique and Reiter (2012a) on the basis of regional and local data: 0.61 kilowatt-hours per person per kilometer (kWh/person/km) for a diesel car, 0.56 kWh/person/km for a fuel car, 0.45 kWh/person/km for a bus, 0.15 kWh/person/km for a train, and 0 for nonmotorized means of transportation because these do not consume any energy.[1]

The two transport indexes are based on statistical data coming from national censuses, carried out every ten years in Belgium. These data are available at the census block scale for the survey carried out in 1991 and at the individual scale for the last survey carried out in 2001. It should be noted that the transport data based on the first national survey in 1991 are less accurate than the buildings data, based on the cadastral values known for each building, because of the assumption that statistical data are evenly distributed in each census block. Nevertheless, these data are sufficiently accurate for a study at the city scale.

The result of this cartographic work is the spatialization of the six chosen energy criteria through the urban area of Liège. More details on how the GIS was used can be found in the work of Wallemacq and colleagues (2011). Figure 1 presents the mapping of the index of energy performance for home-to-school

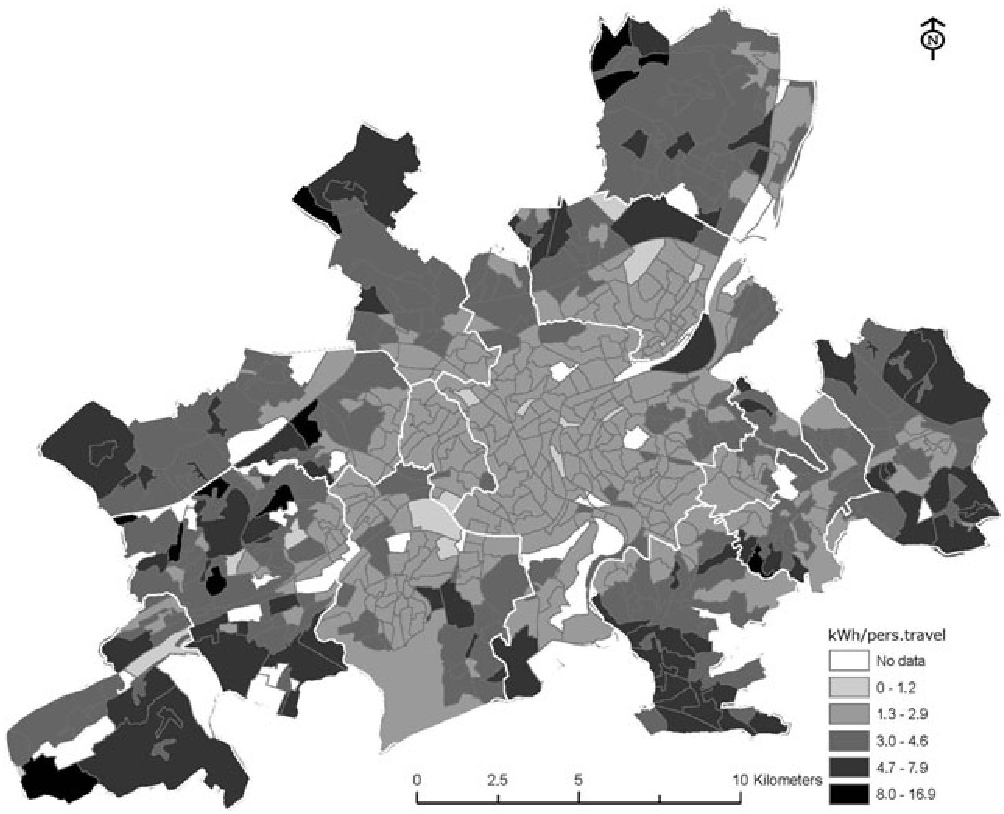

Figure 1 Mapping of the index of energy performance for home-to-school travel (IPE, in kilowatt-hours per worker [kWh/worker] for a one-way trip to school) through the urban area of Liège.

travel through the urban area of Liège (IPE in kilowatt-hours per student for a one-way trip to school). This map shows that peripheral areas tend to generate much more energy consumption than the central areas of the urban zone.

The method used to assess residential energy consumption for buildings and transport is developed and tested for Walloon cities, but it is transposable to other regions and cities. Input data for buildings and transportation models come from national surveys or are collected using a GIS, which are both commonly used tools in numerous regions and countries. Surveys similar to the one used in our model are carried out by, for example, the French National Institute of Statistics (INSEE) in France, the Office for National Statistics (ONS) in the United Kingdom, and the Census and Statistics of Population (IDESCAT) in Catalonia, whereas GISs oriented toward urban planning are now largely used by researchers and territorial communities. It would be interesting to apply the developed method to other case studies of differing urban and transport system layouts to compare their performance.

Modeling Energy Consumption at the City Scale

The city energy modeling is organized into two areas: residential building energy consumption and transport energy consumption of residents.

Residential Building Energy Consumption

For the first topic, a typology of Liège's residential building stock is drawn up by crossing the four chosen building energy criteria: building date of construction, building renovation, type of building, and type of housing. Note that the urban area of Liège has 64,079 terraced houses, 52,314 semidetached houses, 32,478 detached houses, and 13,897 community buildings.

Energy consumption (including heating, hot water, and lighting) is known for each of these types of buildings through empirical surveys on the Walloon building stock (CEEW 2007; ICEDD 2005; Kints 2008). Cooling requirements were neglected because they are minimal in Belgium. In fact, these empirical surveys show that heating represents the largest part of the overall energy consumption of Belgian households (76%). Home appliances, the production of hot water, and cooking represent 10%, 11%, and 3% of the total, respectively. The energy requirements of residential buildings at the city scale were calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the urban area of Liège.

When these values are related to each building, it is possible to establish the actual residential building energy use at the city scale. Moreover, on the basis of the cadaster, we can study the evolution of the energy consumption of the whole urban area of Liège since 1850, which is the first date of construction of a building identified in the cadaster (see figure 2). Before 1931 the dates of building construction are aggregated for periods lasting from 20 to 25 years, which explains the larger width of the bars in that portion of figure 2. This graph shows a very high growth of energy consumption in Liège's urban area during the last century, reaching 6,048 gigawatt-hours (GWh) for the year 2010.[2]

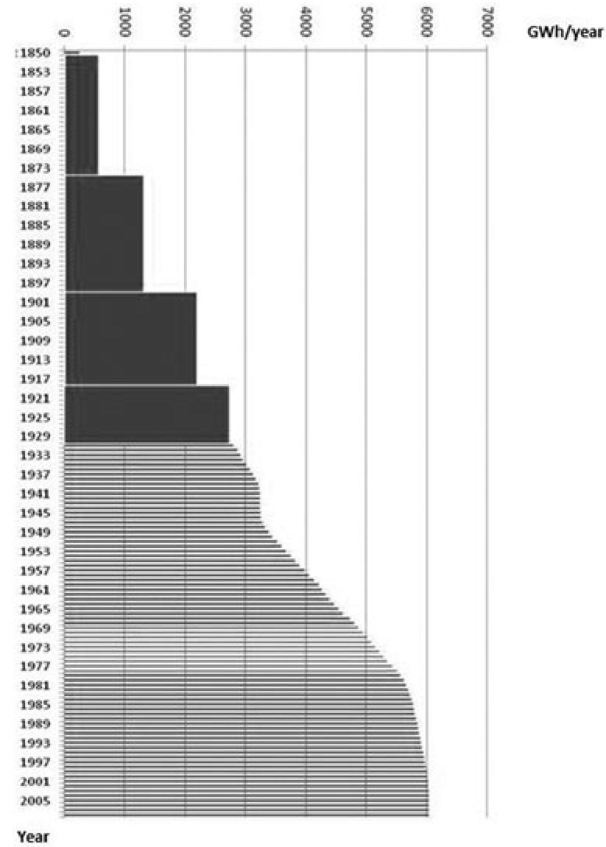

Figure 2 Evolution of the energy consumption of the urban area of Liège (in gigawatt-hours per year [GWh/year]).

Transport Energy Consumption of Residents

For modeling transport energy consumption, we followed the methodology developed by Marique and Reiter (2012a), using values available in each census block about car ownership, travel distances, main mode of transport used, and the number of working days per week and per worker, among others. We have considered the two last Belgian censuses.

The annual consumption of a worker or a student is obtained by the following calculation:

$$\text{IPE} \times \text{annual number of trips (to work or school)},$$

assuming 253 working days per year and 180 school days per year. Finally, the annual consumption calculated for a person is multiplied by the number of workers or students in the area, giving for 2010 a global value for residential transport consumption of 941.9 GWh, from which 841.6 GWh are due to home-to-work travel and 100.3 GWh to home-to-school travel.

Comparing residential energy consumption for buildings and transport at the city scale during the year 2010, building energy consumption was 6,048 GWh, while transport energy consumption accounted only for 941.9 GWh. Thus it is clear that policies to reduce energy consumption must first focus on the existing building stock, because it generates much more energy consumption than residential transport.

Note that home-to-work and home-to-school travel represent only a part of the mobility of a household. Leisure and shopping are two other important purposes of travel (Hubert and Toint 2002). Unfortunately, the Belgian national census does not give information about these purposes of travel. Even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are most often available, the limits of this method arise from the fact that data about only two types of trips (home-to-work and home-to-school travel) are available in the Belgian national census.

Following Hubert (2004), the mean percentages of home-to-work travel and home-to-school travel compared to the total amount of travel in Belgium are 30% and 17% of all trips; moreover, these account for 45% and 9%, respectively, of all the distances travelled. These data were defined through an enquiry of 3,076 workers and 1,619 students. If we add to the transport energy consumption calculated according to the method explained an approximate value for travel for shopping and leisure based on the IPE indexes previously calculated, and taking into account the proportions of transport distances proposed by Hubert (2004), the global energy consumption for residential transport in the city of Liège in 2010 increases greatly and ranges from 1,454.5 GWh to 1,802.2 GWh, depending on whether the IPE for home-to-school or home-to-work travel is used. Nevertheless, this final value for the energy consumption of residential transport in the urban area of Liège remains more than three times lower than the building energy consumption.

Home-to-school travel consumes less energy than home-to-work travel because distances from home to school are shorter than distances from home to work and because the use of public transport is greater for home-to-school travel than home-to-work travel. This first conclusion shows the importance of residential densification of buildings near the main employment areas. A good mix between work, schools, shops, and dwellings in each neighborhood or group of neighborhoods, which allows reduced travel distances, seems to be a good strategy to reduce transport energy consumption.

Forecast Scenarios

The most important actual energy policy measure in the EU is the EPB (Directive 2002/91/EC; EC 2003). It focuses on energy efficiency when new buildings are built or when big buildings (larger than 1,000 square meters [m^2]) undergo a major renovation. However, there might be energy efficient measures that are environmentally efficient and cost effective also on the existing residential building stock, on smaller buildings, and/or lighter renovation processes. Note that in the Danish implementation of the EPB directive, all existing buildings are covered by the energy efficiency measures when they undergo a major renovation (Tommerup and Svendsen 2006). Thus it is useful to model some forecast scenarios to compare the effects of the EPB directive with even more selective energy policies on new buildings and with renovation strategies on the existing building stock.

The demographic data of the population of our study area are known at the census block scale. The simplest hypothesis would estimate that the residential building stock changes proportionally to the population. However, the number of buildings in the urban area of Liège during the last eight years did not increase as rapidly as the population during those years. We have thus established a base curve of the evolution of the built stock according to the statistics of its evolution between 2000 and 2008. This trend is represented by equation (2):

$$Y = 477.35 \ln(x) + 161{,}348 \qquad (2)$$

where x is the forecast year (2000) and Y is the number of buildings. This curve follows very well the recent trend of development of the residential building stock, as the coefficient of determination calculated from the data observed between 2000 and 2008 is 99.7%.

First, six scenarios of residential building energy consumption improvements will be compared. Then, two forecast scenarios for transport energy consumption evolution will be explained. The main assumption of this forecast modeling is that the urban growth is distributed evenly across the different census blocks of the urban area.

Scenario 1: New Buildings Following the Directive on the Energy Performance of Buildings

In this first scenario, the existing building stock remains unchanged, but new buildings are constructed according to the actual standard of the EPB: the building's energy consumption should not exceed 115 kWh/m^2/year. It is therefore the most likely evolution of Liège's building stock if the energy policies are not changed in the future. Following this first scenario, energy consumption for the city of Liège in 2061 is estimated at 6,067.74 GWh/year (see figure 3).

Scenario 2: Strengthening of Energy Policy on New Buildings

Considering that 5% of new housing stock will have low energy (LE) performance (95 kWh/m^2/year), 2% of buildings will have very low energy (VLE) performances (65 kWh/m^2/year), and 1% will reach the standard passive house (50 kWh/m^2/year), building energy consumption decreases by 679 megawatt-hours (MWh) for 2061 compared with the first scenario, which represents a reduction of only 0.01% for a period of 50 years.

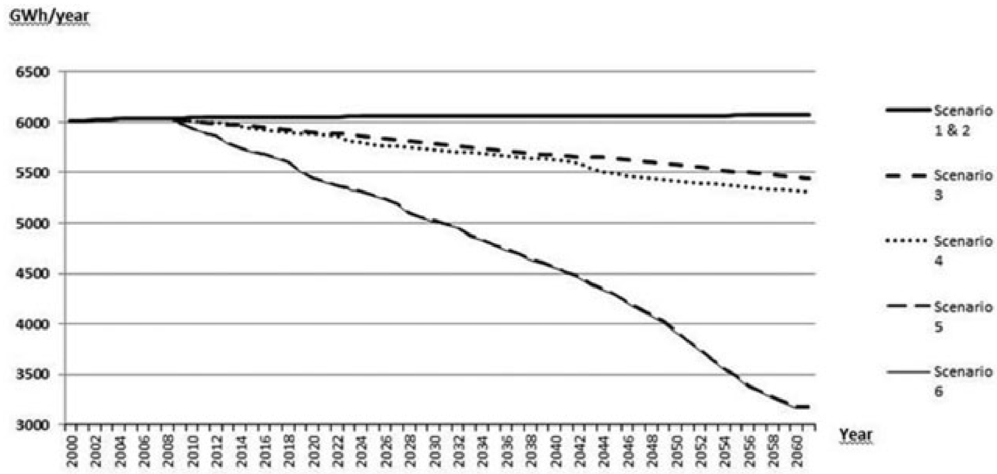

Figure 3 Energy consumption of the urban area of Liège (in gigawatt-hours per year [GWh/year]) from 2000 to 2061, following the six forecast scenarios. The lines showing scenarios 1 and 2 as well as scenarios 5 and 6 are joined because the results are too close at this scale.

Achieving a 10% reduction in energy consumption for all buildings constructed after 2010 would require that the new stock meet the following constructive standards: 63% of buildings achieving the EPB standard, 21% LE buildings, 10% VLE buildings, and 5% passive buildings. Over the whole building stock, this reduction generates a very small decrease in energy consumption (0.06%) compared with scenario 1, corresponding to the actual regulations (see figure 3).

Scenario 3: A 40% Reduction in the Energy Consumption of the Old Building Stock

A rate of renovation of buildings of 0.6% per year is chosen to simulate a realistic policy for energy renovation of the existing building stock equal to two-thirds of the total rate of renovations observed in the Walloon region on an annual basis. It is also assumed that energy management is carried out efficiently: the oldest and least energy efficient buildings are the first to be renovated. Renovating this old building stock will be incorporated as a 40% reduction in energy consumption compared with the initial energy performance of these renovated buildings, which corresponds in the context of the urban area of Liège to roof insulation of the individual terraced houses built before 1930 and to roof insulation and window improvements of detached houses built between 1931 and 1969 that are not yet renovated. Following the work of Verbeek and Hens (2005), insulation of the roof is the most effective and durable measure for an energy performance increase of households in Belgium.

It appears that the renovation of existing buildings can drastically reduce energy consumption across the urban area. The total estimated consumption amounts to 5,439.27 GWh/year in 2061, of which 99.5% is attributed to the existing stock. The decrease in total energy consumption is therefore 10.36% (628.46 GWh/year) compared with 6,067.74 GWh/year for scenario 1 (see figure 3).

Scenario 4: Renovation of the Old Building Stock Reaching the Directive on the Energy Performance of Buildings

This scenario aims to assess the amount of energy that could be saved if the existing building stock was renovated, at a rate of 0.6% per year, to meet the current EPB standard in Belgium (115 kWh/m^2/year),[3] while all the new buildings meet the same energy performance. Following this scenario, the estimated energy consumption for the city of Liège will reach 5,307.20 GWh/year in 2061. That is 760.54 GWh/year (13%) less than scenario 1 (see figure 3).

Scenario 5: Renovation of all the Existing Building Stock Reaching the Directive on the Energy Performance of Buildings

Renovation of all buildings of the residential building stock of Liège to the level of the current EPB standard in Belgium (115 kWh/m^2/year) would result in significant reductions in energy consumption in the urban area (see figure 3). Indeed, the total energy consumption would drop to 3,178.23 GWh/year, which represents a reduction of 47.6% compared with 6,067.74 GWh/year in scenario 1 (where new buildings reach the EPB standard but no renovations are undertaken).

However, to achieve complete renovation of the existing housing stock by 2061, the rate of renovation of the urban area of Liège must increase sharply, to a minimum of 1.92% per year, which would require strong policies to accelerate and strengthen the process of renovating existing buildings.

Scenario 6: All the Existing Building Stock Reaching the Directive on the Energy Performance of Buildings and New Buildings Reaching the Passive Standard

This scenario uses the same renewal policy as scenario 5, but it also assumes that each new dwelling built from 2012 will reach the passive standard (50 kWh/m^2/year). The result of scenario 6 is very close to the previous scenario. The total energy of the urban area in 2061 would be 3,161.57 GWh/year, which represents a reduction of only 0.5% compared with scenario 5.

Scenarios 7 and 8: Forecast Scenarios for Transport Energy Consumption

The evolution of the mean energy performance indexes for home-to-work and home-to-school travel between 1991 and 2001 allowed us to determine the percentage increase in the IPE over ten years: 32.3% for work travel and 8.03% for school travel. Based on this increase for the two IPEs as well as an increase in student numbers of 4.3% and the number of workers of 3% every ten years, the energy consumption for residential transport in 2061 will reach 3,955.3 GWh for home-to-work travel and 187.76 GWh for home-to-school travel, giving a total of 4,140 GWh for these two types of travel. This scenario shows that if the increase in transport consumption in the future is identical to what happened in the past, the total energy consumed at the city scale would greatly increase. In addition, by performing the same approximations for travel for shopping and leisure, the total residential energy consumption for transport would reach between 5,084.32 and 8,183.9 GWh in 2061. Thus, without specific transport policies, urban planning strategies, or important vehicle energy performance improvements, residential energy consumption due to transport is likely to exceed the energy consumption related to the existing building stock in the urban area of Liège.

However, Ewing and colleagues (2008) assume that transport energy consumption in the United States in 2030 will be at the same level as in 2005, because the number of vehicles and the mean vehicle travel will continue to increase while the energy performance of vehicles will be improved. Taking into account this scenario of a steady state of transport energy consumption in the urban area of Liège until 2061 implies that the building energy consumption will remain higher at the city scale than the transport energy consumption, regardless of the chosen scenario for the evolution of the building stock.

Discussion

The studied scenarios show that the actual city energy challenge lies mainly in renovating the existing building stock. Indeed, the first two scenarios and the small difference between scenarios 5 and 6 show that it is not possible to ensure a significant reduction in energy consumption at the city scale by applying only energy policies for new buildings, like the standard EPB already in use, or by enhancing the performance of new buildings to the LE level, VLE level, or even the passive housing standard.

However, scenarios of existing housing stock renewal (scenarios 3 through 5) can significantly reduce the overall consumption of the urban area of Liège in the following proportions:

- A 10.36% energy consumption reduction in 2060 through renovation of the oldest buildings, reducing 40% of their energy consumption at a renovation rate of 0.6% of the building stock per year.
- A 13% energy consumption reduction in 2061 through renovation reaching the EPB level in the oldest buildings at a renovation rate of 0.6% of the building stock per year.
- A 47.6% energy consumption reduction in 2061 through renovation reaching the EPB level of all the existing residential building stock, which corresponds to a renovation rate of 1.92% per year.

Thus the national climate change targets in Belgium will be impossible to reach without a strategic increase in existing housing stock renovation. Finally, at the city scale, the building renovation rate seems to be much more important than the level of insulation reached.

While current energy consumption related to the existing housing stock of the urban area of Liège is significantly higher than the transport energy consumption of residents, the forecast scenarios on transport consumption show that this gap will be reduced and may even be reversed by 2060 if solutions for reducing energy consumption related to residential transport are not implemented. It seems that transport will become an increasing challenge for energy consumption limitation at the city scale. In this respect, favoring more compact urban development while improving the energy performance of vehicles and increasing public transport use should be investigated.

Conclusion

The literature review on city energy consumption shows that density tends to receive the greatest scientific attention, although alone its travel impacts are modest. It is therefore important to make a distinction between density as an isolated parameter and compact development or smart growth, sometimes studied under the term density, that reflect the cumulative effects of various land use factors such as density, functional mix, transit accessibility, walkability, and parking management.

This article presented a methodology to model residential energy use at the city scale, using GIS tools combined with a statistical treatment of urban and transport criteria. This method assesses the energy uses of residential buildings and transport of residents at the city scale. It should help in developing strategies of urban design and urban renewal as well as improving urban management and policy making.

An application of this method was done on the urban area of Liège. This applied study concluded that the EPB and even more selective energy policies on new buildings are not sufficient to greatly decrease the energy consumption of Liège's building stock, and that renovation of the existing building stock has a much greater positive impact on city energy consumption reductions.

The proposed methodology allows comparisons of energy requirements in the building sector and in the transport sector, as well as the ability to test forecast scenarios. This method is thus a powerful tool to highlight which strategy is most efficient in reducing total energy consumption at the city scale. Some further developments of this method are planned, including more precise energy consumption related to travel for leisure and shopping. The methodology developed in this article can be adapted or reproduced for many other territories in Belgium, as well as Europe and beyond.

Acknowledgements

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Notes

1. One kilowatt-hour (kWh) $\approx 3.6 \times 10^6$ joules (J, SI) $\approx 3.412 \times 10^3$ British thermal units (BTU). One kilometer (km, SI) ≈ 0.621 miles (mi).
2. One gigawatt-hour (GWh) $\approx 3.6 \times 10^{12}$ joules (J, SI) $\approx 3.412 \times 10^9$ British thermal units (BTU).
3. One square meter (m^2, SI) ≈ 10.76 square feet (ft^2).

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About the Authors

Sigrid Reiter is a professor at the University of Liège, Liège, Belgium. **Anne-Françoise Marique** is a Ph.D. student at the University of Liège, Liège, Belgium. They work within the research team LEMA (Local Environment Management and Analysis), in the Department ArGEnCo (Architecture, civil engineerinG, Environment and Construction) of the University of Liège.

Appendix A.3

A method for evaluating transport energy consumption in suburban areas

1. INTRODUCTION

The process of urban sprawl, which commonly describes physically expanding urban areas, is a major issue for sustainable development (European Environment Agency, 2006). Urban sprawl is known to represent a significant contribution to the overall energy consumption of a territory for energy needs in buildings and for transport. In fact, for the same standard of insulation, detached houses need more energy for heating than terraced houses (Marique and Reiter, 2010). Moreover, suburban developments have created farther spatial separation of activities, which results in an increase in travel distances and transport energy consumption (Silva et al., 2007). In suburban residential neighborhoods mainly composed of detached houses and often located far away from city centers, car ownership is often high and public transport is generally less available, which tends to favor the use of private cars.

Although the environmental impact of urban sprawl and uncontrollable urbanization are receiving an increasing amount of attention and may give rise to various issues, such as environmental pollution or large-scale climate change (CPDT, 2002; He et al., 2010; Urban Task Force, 1999; Young et al., 1996), and despite the growing importance of the energy issues in public debate, low-density suburban developments continue to grow, regardless of their location. Such developments are found all over Europe, the United States and even emerging countries (Nesamani, 2010; Silva et al., 2007; Yaping and Min, 2009). An evaluation on the sustainability of these suburban neighborhoods is necessary and requires appropriate methods and tools, especially as far as the private transport is concerned. In fact, transport energy consumption is rarely taken into account when the sustainability of these suburban structures is studied, even if sharp fluctuations in oil prices and reduction efforts in greenhouse gases emissions play an important role in current discussions and policies. Even new districts that set themselves up as “eco” or “sustainable” are sometimes built far from city centers and are not necessarily very sound from an ecological point of view because of higher transport energy consumption (Harmaajärvi, 2000).

Section 2 presents a brief review of the literature relating to the interdependences between spatial planning and transport energy consumption. Section 3 describes a quantitative method that was developed to assess transport consumption at the neighborhood scale to create a decision-making tool, to highlight the most efficient strategies needed to promote awareness and to give practical hints on how to reduce energy consumption linked to urban sprawl. Statistical data available at the neighborhood scale and characteristics of cars and public vehicles were used to predict transport needs and assess consumption as far as home-to-work and home-to-school travels are concerned. “Type-profiles” were developed to complete this approach and give an approximation of transport energy consumption related to leisure and commercial purposes. Section 4 presents an application of this method concerning a comparison of four suburban districts located in the Walloon region of Belgium, which confirms that the method is applicable and practical. Finally, Sections 5 and 6 summarize our main findings and discuss the reproducibility and the limits of this approach.

2. BACKGROUND TO THE EVALUATION OF TRANSPORT CONSUMPTION

In the current context of growing interest in environmental issues, reducing energy consumption in the transport sector, which represents 32% of the overall energy in the European Union (the building sector represents 37%), appears as an important policy target (Maïzia et al., 2009). Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, namely through the passing of the European Energy Performance of Buildings Directive (EPBD) and its adaptation to the Member States laws; however, efforts and regulations to control transport needs and consumption are more limited. Nevertheless, although transport and mobility are often neglected, they are crucial in terms of urban sprawl because global oil use has allowed the appearance of sprawling urban forms (Jenks and Burgess, 2002). Therefore, the performances of transport networks determine whether a piece of land is of interest to developers who are likely to expand towns (Halleux, 2008).

Existing scientific work dealing with transport consumption is mainly concerned with dense urban areas, focusing on relationships between transport energy consumption and building density, and this work remains undecided on the effects of densification strategies for the reduction of transport consumption. Maïzia et al. (2009) and Steemers (2003) argue that more compact urban forms would significantly reduce energy consumption both in the building and transport sectors. Based on data from 32 big cities located all over the world, Newman and Kenworthy (1989, 1999) have highlighted a strong inverse relationship between urban density and transport consumption, but their work is only valid for certain conditions and is often criticized by other works (Mindali et al., 2004; Owens, 1995) mainly for methodological reasons. Banister (1992) applied the same kind of approach to British cities and highlighted, on the basis of statistical data obtained from a national survey, that transport energy consumption is slightly higher in London than in smaller cities, which refutes Newman and Kenworthy observations. Boarnet and Crane (2001) are also skeptical on the relationship between urban design and transport behaviors. On the basis of several case studies, they estimate that if the use of the soil and the urban form impact transport behaviors, it is through the price of travel (public transport prices are reduced in dense areas). Gordon and Richardson (1997) demonstrated that if fuel prices are included in the analysis, urban density only plays a limited role on energy consumption in transport. Ewing and Cervero (2001), on the basis of a number of case studies, concluded that the impact of urban density on car travel reduction stays marginal. Elasticity is evaluated at -0.05, which means that if the density of a district is multiplied by two, private car commutes are only reduced by 5% because of the rise of congestion. Finally, Breheny (1995) has emphasized minor reductions in transport energy consumption thanks to the compact city model. His experiments show that, even under very strict conditions that are difficult to reproduce, energy used in transport could only be reduced by 10 to 15%. More recently, Boussauw and Witlox (2009) have developed a commute-energy performance index and tested it for Flanders and the Brussels-capital region in Belgium, including rural and suburban parts of these territories, to investigate the link between spatial structure and energy consumption for home-to-work travels at the regional scale. This method is based on statistical data available at the district scale, taking into account commuting distances, modal shares of non-car travel modes and aspects of infrastructure. This index allows for a better understanding of the energy consumption levels for commuting (home-to-work travels) in cities and less dense areas.

3. THE METHOD

We have developed a quantitative method to assess transport energy consumption, in suburban areas, at the neighborhood scale. Energy consumption in transport is in fact an interesting indicator because it is a composite measure of travel distance, modal choice and journey frequency (Banister, 1998; Muniz and Galindo, 2005). The method takes into account four purposes of travel (work, school, shopping and leisure) and will help us have a better understanding of the regional suburban situation, find the most relevant indicators to reduce transport energy consumption in suburban areas and compare different strategies of intervention in these specific types of structures. It will help to fill the critical lack of evaluation tools that local authorities could use to evaluate new and existing residential developments (Tweed and Jones, 2000), especially those dedicated to transport and location.

The method proposed in this paper only deals with transport energy consumption, which is one of the three parts of an overall method that aims at performing the total energy modeling of suburban areas. The complete package includes the energy assessment of buildings, transport and public lighting, and addresses their influences at the neighborhood scale because, even if the urban context has been mostly neglected in building energy analyses so far, decisions made at the neighborhood level have important consequences on the performance of individual buildings and on the transport habits of the inhabitants (Popovici and Peuportier, 2004). Marique and Reiter (2010; In press) described the first part of the method, dedicated to the energy assessment of suburban houses, at the district scale, and presented its application to three typical suburban districts. The overall method has also the advantage of allowing the comparison between the energy requirements in the building sector and in the transport sector, and thus, for every specific district, to highlight which strategy would be the most efficient to reduce the overall energy consumption.

3.1 Home-to-work travels

To assess energy consumption relating to home-to-work travels, we adapted and completed the performance index developed by Boussauw and Witlox (2009) for Flanders. In fact, the statistical data used in the Flemish commute-energy performance index are also available for the Walloon part of the country. However, other important parameters are not taken into account in the approach developed by Boussauw and Witlox (2009), such as type of fuel, characteristics of the local public transport network in suburban areas (significant differences exist between cities and suburban neighborhoods), number of working days per workers, pre-transportation, etc.

The input data come from the national censuses, which are carried out every ten years in Belgium and are available at the census block scale (the smallest geographical unit in which data are available in Belgium). We have considered the two last censuses, respectively carried out in 1991 and 2001. One-day travel-diary data from male and female heads of households were used. For these households, information was available in each census block about car ownership, travel distances, main mode of transport used, the number of working days per week and per worker, etc. together with their demographic and socioeconomic situation. The survey only concerns two purposes of travel: home-to-work travels and home-to-school travels, which represent the majority of travel.

To determine the total number of kilometers logged annually by various modes of transportation for home-to-work travels, the first step of the method is to combine the number of workers in a census block with the number of travels per week (thought the repartition of the number of working days in the census block), the distance travelled for home-to-work travel (one way) and the modes of transport used (car, bus, train, motorbike, bike or on foot) in this census block. A correction factor was applied to short distances covered by train and long distances covered by bus to keep the relationship between the mode and the distance travelled. As distances travelled per mode of transport are aggregated by census block in the national survey, this correction factor was calculated for each census block, on the basis of the following assumptions: trips by train shorter than 5 kilometers and trips by bus longer than 30 kilometers are spread over the others classes of distances. Non motorized trips (bike, on foot) were not considered in the following calculations because they do not consume any energy. Motorbike trips were neglected because they represent a very small part of home-to-work and home-to-school travels. In addition, if the main mode of transport used was the train, we also took into account travels from the house to the train station to investigate the role of home-to-station travels in total transport energy consumption. The mode of transport used for home-to-station travels was determined by a Geographical Information System (GIS) according to the distance travelled and the bus services available in each district.

Distances covered by diesel cars were separated from those covered by fuel cars according to the regional distribution of the vehicle stock in the Walloon region (55% diesel and 45% fuel cars). The final step of the method consists in allocating consumption factors to the distances covered in each category of vehicles (diesel car, fuel car, bus or train) to convert the distances into energy in terms of kilowatt hour (kWh). The unit of energy, kWh, was chosen to allow a comparison between energy consumption in transport with energy consumption to heat buildings in the overall method (Marique and Reiter, In press). Consumption factors take into account the mean consumption of the vehicles (liter per km), the passenger rate and the characteristics of the fuel (Table 1). For the train, the consumption factor used depends on the production of electricity as trains in Belgium are electric. The value used in this paper was calculated, for Belgium, by CPDT (2005).

Table 1

Consumption factors (per km and per person) used to convert kilometers into kWh, based on regional mean values

	Type of vehicles			
Characteristics	Diesel car	Fuel car	Bus	Train
Consumption per kilometer	0.068 l.	0.080 l.	0.46 l.	-
Occupancy rate	1.2	1.2	10	-
Density of the fuel (/1000 l. in toe)	0.859	0.745	0.859	-
Factor	**0.6134**	**0.6259**	**0.4986**	**0.3888**

Finally, we divided the total amount of energy consumption for home-to-work travels per census block by the working population that lives in the considered area to obtain an index that gives the mean annual energy consumption for home-to-work travels for one worker living in the considered district.

3.2 Home-to-school travels

The method developed for home-to-work travels is also applicable to home-to-school travels because the same types of data are available in the national census. Instead of using the number of working days, we used a mean number of days of school per year. The total amount of energy consumption for home-to-school travels per census block was divided by the number of students living in the census block to give the mean annual energy consumption for home-to-school travels for one student living in the considered census block.

3.3 Others purposes of travel

As previously mentioned, home-to-work and home-to-school travels represent only a part of the mobility of a household. Leisure and shopping are two other important purposes of travel (Hubert and Toint, 2002). Unfortunately, national censuses do not give information about those purposes of travel. As a result, we have developed a simplified calculation to take into account home-to-leisure and home-to-shop travels and compared them to home-to-work and home-to-school travels to give a more complete image of the energy consumption for transport in a district. This approach was based on “type-profiles”. According to socio-economic data, we have established several representative types of households living in a district (a family with two children, two elderly persons, a couple of unemployed people, etc.) and attributed, to each type of households, mobility characteristics for home-to-shop and home-to-leisure travels. These characteristics mainly concerned distances travelled from home to shop or leisure activities (according to the geographical location of each district) and the frequencies of travels (according to the socio-economic composition of the household). The mode of transport used was determined according to hypotheses made on the distances to travel, the distance to bus stops and the bus services available. This required information was collected by using a GIS. Different locations were taken into account: proximity shops, suburban shopping centers and main city centers. Finally, households are now known to try to combine different trips to minimize distances (Wiel, 1997); therefore, a correction factor can be applied to distances to take these “chained trips” into account. At the end, we are still able to distinguish the contribution of each mode in the final results.

4. APPLICATION OF THE METHOD

4.1 Specificities of the Walloon region of Belgium and case studies

Urban sprawl is familiar in many European regions and countries and particularly in the Walloon region of Belgium, where 52% of the building stock is made of detached or semi-detached houses (Kints, 2008). Because of the personal preferences of Walloon households for single family houses with large gardens in a rural environment, and the regulatory framework, which allows this kind of developments to grow, urban sprawl is now a concern in a large part of the regional territory. The Walloon urban sprawl presents several specificities in comparison with the neighboring regions and countries. According to cadastral data (Vanneste et al., 2007), 50% of Walloon census blocks present a mean housing density in the range between 5 and 12 dwellings per hectare, which is very low. In comparison to Flanders, where public authorities are now trying to reduce the size of the plots in new developments, or the Netherlands, where land supplies are historically very limited, land pressure stay limited in the Walloon region and land supplies are still available in large quantity. Moreover, Walloon suburban districts are not developed in continuity with dense urban centers or rural cores but are spread out on the whole regional territory according to land supplies availability and car accessibility (which is high because the transport network is very developed all over the Walloon region).

The majority of those districts are only residential, even if urban sprawl also concerns commercial or industrial functions.

As far as mobility is concerned, the dependence of these suburban areas upon cars is huge. National surveys held every ten years in Belgium show that car ownership is higher in suburban areas than in more densely populated areas (Verhetsel et al., 2007). According to these surveys, distances from home to work are also higher in suburban areas than in more densely populated areas because these neighborhoods are often developed far away from city centers where most of the employment areas are located. Moreover, because of the low population density of the Walloon suburban neighborhoods, public buses are often available at very low frequencies with low commercial speed and do not constitute a credible alternative to individual mobility.

An application of the method is presented concerning the comparison of four existing suburban neighborhoods in the Walloon region of Belgium. Given that urban sprawl is observed throughout the whole region, one representative suburban district has been selected in every urban region identified in Belgium, namely by Sporck et al. (1985), whose aim was to present a typology of the Belgian urban regions and to define their borders. This typology was used in numerous studies and research about urban sprawl, specifically in two statistical censuses held in 1998 and 2007 (Luyten and Van Hecke, 2007; Merenne-Schoumaker et al., 1998). The “operational agglomeration” was based on the morphological agglomeration, or dense urban core. Its limits were determined by the continuity of the building stock and adapted to administrative borders. The “suburbs” were the first suburban area of a city. Areas located further from the city, while keeping strong relationships with it (through home-to-work travels), constituted the “alternating migrants area,” whereas remaining areas were regrouped under the “other areas” term and represent rural and less dense areas located far away from city centers. The main characteristics of the four neighborhoods are presented in Table 2.

Table 2

Main characteristics of the four studied neighborhoods

	Studied areas (suburban neighborhoods)			
Characteristics	Jambes	Fontaine	Rotheux	Tintigny

Urban area	"operational agglomeration"	suburbs"	"alternating migrants"	"other areas"
Main types of houses	Detached houses (pretty new)	Semi-detached and terraced houses	Rural core, farms, detached houses	Detached houses (pretty old)
Distance to city center	6 km	9 km	17 km	29 km
Distance to train station	6 km	9 km	15 km	8 km
Bus services	Low	Good	Low	Very low

4.2 Main results and key indicators

The application of the method developed in section 3 to the four representative suburban neighborhoods presented in section 4.1 gave the following results (Table 3):

Table 3

Index for home-to-work, home-to-school and home-to-shop-and-leisure travels

	Studied areas (suburban neighborhoods)			
Index	Jambes "operational agglomeration"	Fontaine "suburbs"	Rotheux "alterning migrants"	Tintigny "other areas"
Home-to-work kWh/worker.year	4 646	3 945	4 782	5 785
Home-to-school kWh/student.year	888	429	2 152	2 376
Home-to-shop and home-to-leisure kWh/person.year	599	414	1335	2 216

The first main finding of the application of the method to the four case studies was that, in each case, home-to-work travels represent the most important part of the total energy consumption. Home-to-school travels, which were calculated with the same kind of data and the same method, can thus be easily comparable; they consume less energy per capita than home-to-work travels. The first explanation is that distances from home to school are shorter than distances from home to work. Several schools are indeed located in most Walloon towns, even in the more rural ones, whereas work locations remain concentrated in bigger cities and in some suburban business parks. Moreover, the use of public transport is higher for home-to-school travels than for home-to-work ones which could also explain the better results obtained for home-to-school travels.

Home-to-station travels were included in the previous results and represent between 0.9% and 3.7% of home-to-work travels and between 1.1% and 4.8% of home-to-school ones, whereas the modal part of the train was very low. These results show that it is important to take home-to-station travels into account in suburban areas. Moreover, trying to increase the modal part of the train in suburban areas should be a good strategy, but only if alternatives to individual car are proposed for home-to-station travels.

Annual home-to-work and home-to-school energy consumption was higher in the two residential districts located far away from city centers (Tintigny and Rotheux), whereas home-to-work consumption was high in Jambes, but home-to-school consumption was lower than in others districts. As Jambes is located closer to a big city center (6 kilometers), students can more easily use alternative non polluting modes of transport.

Home-to-shop and home-to-leisure travels represent between 62.0% and 96.5% of the annual energy consumption for home-to-school travels, as seen in Table 3. These values mainly depend on the distances to shops, services and leisure. The more equipped the neighborhood and its surrounding are, the smaller the energy consumption rate for home-to-shop and home-to-leisure travels is. As those purposes of travels were calculated according to “type-profiles” and not according to statistical data, results were not as robust as home-to-work and home-to-school consumption but seem to give credible results. Shops and leisure, just as schools, are spread out on the whole region, even in most rural areas (rural core, suburban centers, etc.) which allow for reduced distances from home to destination.

4.3 Sensitivity analyses

Several sensitivity analyses were performed to identify the most relevant indicators that act upon transport energy consumption. Since the main key indicators that seem to be highlighted by the first results were the distance between home and final destination and the bus services, the first sensitivity analysis deals with the location of the districts. If we consider, as a first approach, that all the studied neighborhoods keep their socio-economic characteristics but could now benefit from the same good location than the neighborhood presenting the lowest energy consumption rate (Fontaine neighborhood, close to a city center, good bus services, higher mix in functions), energy consumption relating to home-to-work and home-to-school travels decrease significantly: -55.4% in Tintigny, -22.5% in Jambes and -32.4% in Rotheux, mainly because trips by car are shorter and less numerous. These results highlight that location is paramount as far as transport energy consumption is concerned. To try to isolate the impact of the distance, we then considered that the distances between home and work and between home and school mentioned in the national census were reduced by 10% in a first theoretical calculation and by 20% in a second one. These simulations confirmed that the impact of distances on energy consumption in transport is high (see Table 4). However, these results remain purely theoretical because it is not possible to change the location of existing neighborhoods. Nevertheless, these results show the importance of promoting the implementation of future neighborhoods in areas close to large employment centers and services and increasing the population of these areas when they are already built.

The third type of sensitivity analysis deals with the energy consumption of the vehicles. If we considered that the performances of all the vehicles (fuel consumption per mode) are improved by 10%, which is a credible approach, home-to-work and home-to-school energy consumption decrease from 6.6% to 9.6%. These savings are further improved if the performances of the vehicles are improved by 20%. If only the performances of public buses are improved, resulting savings for home-to-work and home-to-school travels are low: energy consumption only decreases by 1.7% to 2.7% because the modal part of the bus is very low in these districts. Therefore, improving the performances of public vehicles will only give good results in areas where buses are used by a large part of the population.

To favor home-workers is also a credible strategy to reduce transport energy consumption. It was calculated that if 5% of the workers of a district are allowed to work at home, energy consumption savings (home-to-work and home-to-school travels) are in the range of 2.3% to 3.6%, according to the district. If the percentage of “home workers” rises to 10%, energy reductions can reach 6.9%.

The last type of sensitivity analysis deals with modal transfer. If we considered that, in each district, 10% of the workers who used a car to go to work will change their habits and use the bus, then energy consumption (home-to-work and home-to-school travels) are reduced by a maximum of 3%. If the modal transfer rises 20%, energy consumption reductions can reach 5% in one of the four studied areas. If modal transfers deal with home-to-work travels and home-to school travels, energy savings are higher by up to 8%. Therefore, the mode of transport used (car, train or bus) has, in comparison with other strategies, a smaller impact on transport energy consumption relating to home-to-work and home-to-school travels. Even if a car has a level of consumption per kilometer higher than trains or buses, home-to-work travels and home-to-school travels made by train are much longer, and the differences between energy factors for car and for bus is not very important because the bus occupation rate is low.

Table 4

Summary of the sensitivity analyses: energy consumption (home-to-work and home-to-school travels) reductions in % for each scenario tested

	Studied areas (suburban neighborhoods)			
Scenario	Jambes	Fontaine	Rotheux	Tintigny
1.All the districts have the same location as Fontaine	-22.5%	-	-32.4%	-55.4 %
2(a).Distances (home to work and school):-10%	-9.7 %	-9.8 %	-9.6 %	-9.7 %
2(b).Distances (home to work and school): -20%	-19.5 %	- 19.5 %	-19.2 %	-19.4 %
3(a).Performances of vehicles: +10%	-9.0%	-6.6%	-9.6%	-9.6 %
3(b).Performances of vehicles: +20%	-17.9%	-13.2%	-19.2%	-19.1 %
3(c).Performances of the buses only: +20%	-1.7%	-2.7%	-2.1%	-2.1 %
4(a).Home workers: 5%	-3.4%	-2.6%	-3.6%	-2.3 %
4(b).Home workers: 10%	-6.9%	-5.6%	-6.8%	-5.3 %
5(a).Modal transfer (home-to-work): 10%	-2.3%	-1.9%	-2.9%	-1.9 %
5(b).Modal transfer (home-to-work): 20%	-4.2%	-3.9%	-4.6%	-3.3 %
5(c).Modal transfer (home-to-work & school): 10%	-4.0%	-2.5%	-5.0%	-4.6 %
5(d).Modal transfer (home-to-work & school): 20%	-6.7%	-4.9%	-7.8%	-7.4 %

Table 4 summarizes the energy consumption reductions for each sensitivity analyses tested. The results indicate that location is the major impact on energy consumption. Location includes a lot of different factors and it is very difficult to isolate these spatial parameters; however, distances from home to final destination seems to have a huge impact on transport energy consumption. The second most efficient strategy is to improve the vehicles' performances. Mode choice only gives limited results in the existing suburban situation. So, in the debate presented in section 2 about the impact of density on transport energy consumption, our results indicate that distance from home to work, to school and to others activities is paramount. As a result, rather than population and building density, a good mix between work, schools, shops and dwellings, at the living area scale, seems to be the best strategy to reduce transport energy consumption in existing suburban areas.

5. DISCUSSIONS AND PERSPECTIVES

The application of the quantitative method presented in section 3 to four suburban blocks, chosen in each urban region identified by the literature in the Walloon region of Belgium, highlights that energy performances related to transport are low and that the use of public transport is low as well; therefore, suburban districts are very dependent on private cars because cars are more efficient than public transport in these types of structures (low frequencies, low commercial speed, etc.). The sensitivity analyses show, however, that the benefits of several renewal strategies exist: choosing a better location could give significant results as far as energy performances in transport are concerned. Not only is this important for new developments, but also for households who want to reduce their energy consumption and their car and fuel costs. We have also highlighted the great influence of the distance between home and destination, as well as the performances of the vehicles, and the percentage of workers working at home to a lesser extent. We have finally showed that increasing the modal part of buses gives more limited results in the studied areas.

The method is developed and tested for the Walloon region of Belgium, where urban sprawl is a concern in a large portion of the area, but it is transposable to other regions and districts that are also affected by urban sprawl in Europe and beyond, by adjusting parameters, such as those relating to vehicles performances and public transport network, on the basis on local mean values. Input data come from national surveys or are collected using a GIS that are both commonly used tools in numerous regions and countries. Surveys similar to the one used in the case studies were for example carried out by the French National Institute of Statistics

(INSEE) in France, the Office for National Statistics (ONS) in the United Kingdom or the Census and Statistics of Population (IDESCAT) in Catalunya whereas GIS oriented towards urban planning are now largely used by researchers and territorial communities.

Even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are the most often available, the limits of this method arise from the fact that data about only two types of trips (home-to-work and home-to-school travels) are available in national censuses. Those types of travels are not representative of all trips of a household even if they play a founding role in it because they are commuting journeys and affect significantly related trips for leisure or commercial purposes. We have thus developed “type-profiles” to approach this reality but, even if this approach is also used in others research, such as those performed by Cornet et al. (2005), Kritikou et al. (2009) and Saunders et al. (2008), the results obtained are only theoretical and cannot currently be validated by comparing them with in situ measures; therefore, they should be used with caution.

Finally, an interactive decision making tool, accessible on the web, is developed, on the basis of the method presented in this paper. The aim is to transfer the main results of our research to citizens and stakeholders and inject them into policy and decision making. It will help developers to plan new suburban neighborhoods, and public authorities to take location and transport energy consumption into account when issuing authorization to build new districts or transforming exiting ones. Occupants and inhabitants can also use the tool to evaluate transport energy consumption and bus services in their districts and to test the impact of different locations before choosing their future dwelling.

6. CONCLUSIONS

Although the environmental impact of urban sprawl and their associated energy consumption are receiving an increasing amount of attention, low density suburban developments continue to grow all over the world. Aiming to reduce energy consumption linked to urban sprawl, a quantitative method has been developed to assess transport energy consumption relating to home-to-work and home-to-schools travels at the district scale, which was based on statistical data available at the census block scale. A simplified calculation completes the method, as far as home-to-shop and home-to-leisure travels are concerned. The method is flexible and parameterized what makes applicable to different contexts and regions. The application of the method to four existing suburban districts and the sensitivity analyses shows its potential in identifying key parameters and strategies to improve transport energy consumption in suburban areas. A good mix between work, schools, shops and dwellings in each neighborhood, which allows reduced travel distances, seems to be the best strategy to reduce transport energy consumption in suburban areas, whereas means of transport used is only of little impact. As highlighted in this paper, it is particularly crucial that the planning of new districts will be based on proper consideration of the location of the area (distance to work places, schools, etc.) and that public authority could use tools allowing them to better take location into account.

7. ACKNOWLEDGEMENT

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Appendix A.4

URBAN SPRAWL, COMMUTING AND TRAVEL ENERGY CONSUMPTION

INTRODUCTION

The problems associated with energy use, such as global climate change caused by the release of carbon dioxide and other greenhouse gases, are receiving increasingly more attention (Glicksman, 2007). In the transportation sector, which represents approximately 32% of the final energy used in Europe (European Commission, 2008), increases in energy consumption and greenhouse gas emissions due to commuting by car is of particular concern. The rise in individual mobility is namely attributed to the physical expansion of urban areas, commonly referred to as urban sprawl. Due to the combination of rapidly declining transport costs and increasing travel speed (Ewing, 1994), the accessibility of outlying areas and vehicle miles of travel (VMT) per capita have increased substantially over the recent past and have favoured the development of suburban neighbourhoods. Sprawl is believed to be facilitated by car ownership and use and also to contribute to it, in a positive feedback loop that reinforces both low-density development and motorisation (Gilbert and Perl, 2008). The environmental impacts of urban sprawl have been studied in depth and urban sprawl has been identified as a major issue for sustainable development (European Environment Agency, 2006). Although it is often defined in terms of “undesirable” land-use patterns (Ewing, 1994; Urban Task Force, 1999) in the scientific field, sprawl however often induces lower land prices and more affordable housings (Gordon and Richardson, 1997). Low-density developments also mean more room and a higher standard of living for numerous households and constitute one of the preferred living accommodations (Berry and Okulicz-Kozaryn, 2009; Couch and Karecha, 2006; Gordon and Richardson, 1997; Howley, 2009).

Although it is usually argued that more compact urban forms would significantly reduce energy consumption both in the building and transportation sectors (Ewing et al., 2008; Gillham 2002; Newman and Kenworthy, 1999; Steemers 2003), suburban developments continue to grow. An evaluation of the sustainability of suburban neighbourhoods is necessary, and such an evaluation requires appropriate methods and tools, especially regarding private transport. Transport energy consumption is rarely taken into account when the sustainability of suburban structures is studied, even in cases where sharp fluctuations in oil prices and reduction efforts in greenhouse gases emissions play an important role in ongoing discussions and policies. Various scientific articles have already studied the relationships between transport energy consumption and building density. Based on data from 32 big cities located all over the world, Newman and Kenworthy (1999) have highlighted a strong inverse relationship between urban density and transport consumption. But Breheny and Gordon (1997) demonstrated that the density coefficient and its statistical significance decrease when petrol price and income are included as explanatory variables. Different studies underline also the importance of the price of travel and the influence of socio-economic factors on transport behaviours (Boarnet and Crane, 2001; Van de Coevering and Schwanen, 2006). Souche (2010) studying 10 cities around the world (through the IUTP database) showed that the two variables the most statistically significant for transport energy consumption assessment are the transport cost and the urban density. On the basis of various case studies, Ewing and Cervero (2001) evaluated quantitatively the impact of urban density, local diversity, local design and regional accessibility on the mean vehicle travel distances. The elasticity was evaluated at -0.05 for urban density, -0.05 for local diversity, -0.03 for local design and -0.2 for regional destination accessibility. It means that if the density of a district is multiplied by two, private car commutes are only reduced by 5%. Note that the impact of the destination accessibility is larger than the three others parameters combined, suggesting that areas of high accessibility, such as city centres, may produce substantially lower transport energy consumption than dense and mixed developments in less accessible areas. Ewing et al. (2008) found that the most compact metropolitan areas in the US generate 35% less mean vehicle travel distances per capita than the most sprawling metropolitan areas. Ewing and Cervero (2010) showed that a 10% reduction in distance to downtown reduces mean vehicle travel by 2.2% and a 10% increase in nearby jobs reduces mean vehicle travel by 2%. Finally, more compact developments (including density, functional mix, and transit accessibility) can reduce mean vehicle travel per capita by 25-30% (Ewing and Cervero, 2010).

Finally, the issue of scale should also be addressed as existing research and studies mainly consider large and dense urban areas (e.g. Banister, 1992; Ewing and Cervero, 2001; Newman and Kenworthy, 1999) that do not exist in Belgium (with the exception of the city of Brussels). Owens

(1986), for example, found that different characteristics of the spatial structure are important in terms of the energy efficiency across different scales. Regarding the impact of land use on transportation, Van Wee (2002) distinguishes several spatial levels: the direct surroundings of the dwellings, the neighbourhood, the town/city, the region, a sub-set of a country, the entire country and the international scale. In 2008, the World Energy Outlook recognized that the factors that were influencing city energy use were different from the energy use profiles of the countries the cities were in as a whole and suggested that, in industrialized countries, the energy use per capita of city residents tends to be lower than the national average (OECD & IEA 2008). Nonetheless, the issue of geographical scale is often neglected in discussions about the compact city and transport energy savings that too often “elide scale” (Neuman, 2005).

The aim of this paper is to analyse the role of the spatial structure of the territory, and in particular the impact of urban sprawl, on transport energy consumption at the regional and local scale. Urban structure is understood here as the system defined by three main elements: i) the location of work places and services (commercial, education, leisure, etc.), ii) the spatial distribution of population according to the place of residence and iii) infrastructures (transport and technical networks). The aim of this exercise is to understand and address the sustainability of transport in our territories and highlight parameters of paramount importance. This study focuses on home-to-work and home-to-school commuting. Although home-to-work and home-to-school trips are becoming less meaningful in daily travel patterns in the Western world due to the dramatic growth in other activities (Graham, 2000; Lavadinho and Lensel, 2010; Pisarski, 2006), they have more structural power than other forms of travel because they are systematic and repetitive (Dujardin et al., 2011). Amongst all the residential commuting within the Walloon region of Belgium, home-to-work and home-to-school trips account, respectively, for 30% and 17% of trips and for 45% and 9% of the total distance travelled (Hubert, 2004).

In Section 2, the paper presents the study area and the quantitative method used to assess the transport system in Belgium. Three indexes (the energy performance index, the modal share index and the distance travelled index) are developed and mapped in Section 3 to investigate the

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interdependences between urban structure of the territory, urban sprawl and travel energy consumption for commuting at several territorial scales. In Section 4, Section 5 and Section 6, the difference in energy performance between home-to-work and home-to-school trips, the evolution of the performance index between 1991 and 2001 and the most influential parameters are presented and discussed. Section 7 discusses the limitations of the method and Section 8 summarises our main findings.

STUDY AREA AND METHODS

Study area: the Walloon region of Belgium and urban sprawl

Urban sprawl is particularly familiar in the Walloon region of Belgium where numerous suburban residential neighbourhoods have been developed in recent decades. These neighbourhoods are characterised mainly by low-density residential housing, the mono-functionality of the developments (functionality concerns mainly housing but also commercial or industrial developments), the discontinuity with traditional urban cores and the great dependence upon cars (Halleux et al., 2002). Such suburban neighbourhoods are often developed far from city centres where land prices are lower but where public transportation is generally less available. These developments have thus created further spatial separation of activities, which results in an increase in travel distances and transport energy consumption (da Silva et al., 2007). This phenomenon is familiar in Belgium and there are numerous studies dealing with it. However, it remains difficult to spatially represent sprawl. We propose, in this paper, to adopt the definition captured by Van der Haegen and Van Hecke's urban type classification (Sporck et al., 1985; Van der Haegen et al., 1996) (Figure 1). Based on qualitative as well as quantitative data, this classification ranks the 589 Belgian municipalities (262 for the Walloon region) in four categories according to their level of functional urbanisation, morphological and functional criteria. The "operational agglomeration" was based on the morphological agglomeration, or the density of urban cores. Its limits were determined by the continuity of the building stock and adapted to administrative borders. The "suburbs" were the first suburban area of a city. The density of the population remains inferior to 500 inhabitants per square kilometre. Areas located further from the city, while maintaining a strong relationship with the city, namely through home-to-work trips (alternating migrants, or commuters, living in these areas mainly work in the corresponding operational agglomeration), constituted the “alternating migrants area.” Remaining areas were regrouped under the “other areas” term and represent rural and less dense areas located far away from main city centres as well as secondary centres. Urban sprawl is linked to the suburbs and the alternating migrants areas (Brück, 2002). Finally note that the influence of neighbouring countries and regions was not taken into account in Van der Haegen and Van Hecke’s classification.

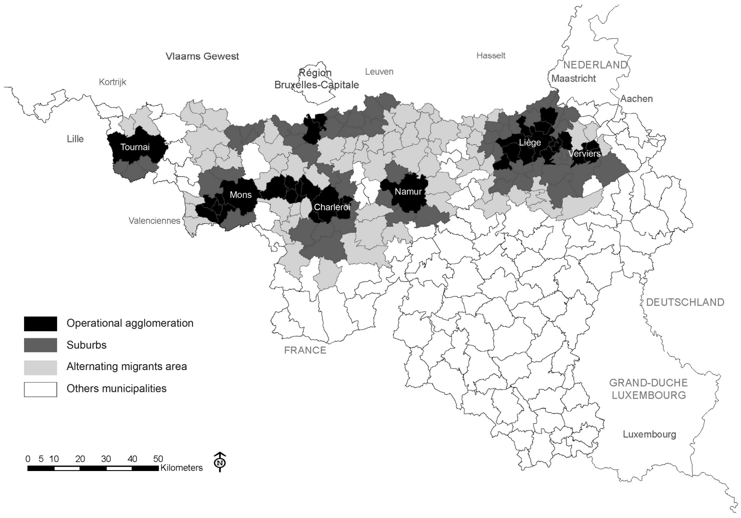

Figure 1: Urban type classification (Sporck et al., 1985; Van der Haegen et al., 1996)

The Method

A quantitative method was developed to assess the energy efficiency of home-to-work and home-to-school trips. The complete methodology and data set are presented in detail by Marique and Reiter (2012a). This method uses empirical data from Belgium’s national census, which is carried out every ten years. We used one-day travel diary data collected from male and female heads of households from the two last surveys, respectively carried out in 1991 and 2001. For these households, information about demographics, socioeconomic status, car ownership, travel distances, the main mode of transportation used and the number of days worked per week and per person is available at the individual (desegregated) scale. These data are available for both home-to-work and home-to-school trips.

These data were also used by Boussauw and Witlox (2009) to develop a commute-energy performance index for Flanders and the Brussels Capital Region of Belgium. To build a locally specific index that is tailored to suburban areas, in addition to Boussauw and Witlox (2009) data, we took into account local characteristics of the public transport network in suburban areas (as significant differences exist between cities and suburban neighbourhoods), the type of vehicles used and the number of working days of the population in the neighbourhood. In this paper, we applied this method to the entire regional territory to investigate the relationships between the spatial structure of the Walloon region of Belgium and the transport energy consumption for home-to-work and home-to-school trips.

Three indexes are derived from this method. The energy performance index (expressed in kWh/travel.person) for a territorial unit represents the mean energy consumption for home-to-work/home-to-school trips for one worker/student living within a particular census block (district). This index takes into account the distances travelled, the means of transport used and their relative consumption rates, expressed by equation (1). In the equation, i represents the territorial unit; m the mean of transport used (diesel car, petrol car, train, bus, bike, on foot); D_{mi} the total distance travelled by the means of transport m in the district i for home-to-work (or home-to-school) trips; f_m the consumption factor attributed to means of transport m and T_i the number of workers (or students) in the territorial unit i.

$$(1)\quad \text{Energy performance index } (i) = \left(\sum_m D_{mi} * f_m\right) / T_i$$

Consumption factors f_m were calculated by Marique and Reiter (2012a) on the basis of regional and local data. Consumption factors are worth 0,56 kWh/person.km for a diesel car, 0,61 kWh/person.km for a petrol car, 0,45 kWh/person.km for a bus, and 0 for non-motorised means of transportation because these do not consume any energy. The consumption factor for a train was recalculated, following Teller et al. (2010). It depends on the production of electricity as trains in Belgium are electric and was calculated by dividing the total energy used to operate trains in Belgium by the total number of passengers-kilometres in the reference year. The consumption factor for the train is worth 0,15 kWh/person.km. Note that this is a mean value that integrates both peak and off-peak hours.

The distance index (in km) represents the mean distance travelled (one way) by one worker/student from home to work/school.

(2) *Distance index (i)* = $\sum_m D_{mi} / T_i$

$$Distance\ index\ (i) = \frac{\Sigma m\, Dmi}{Ti}$$

The modal share index (in %) represents the frequency of use for each mean of transportation per territorial unit, according to equation (3), where ND_n is the number of trips by mode n.

(3) *Modal share index mode n (i)* = $ND_n / \sum_m ND_m$ $Modal\ share\ index\ n\ (i) = \frac{NDn}{\Sigma m\ NDm}$

Indices are calculated at three territorial scale: the census block (or district) scale, the former municipality scale and the municipality scale. In addition to these indexes, the annual energy consumption for home-to-work (or home-to-school) trips is calculated according to equation (4), where TD_i represents the total number of home-to-work (or home-to-school) trips (one way) for all the workers (or students) living within the territorial unit i. This factor takes into account the number of working days for each worker.

(4) *Annual energy consumption (i) = Energy performance index (i)* * TD_i

$$Annual\ energy\ consumption\ (i) = Energy\ performance\ index\ i * TDi$$

Note that the unit of energy chosen to express the energy efficiency of home-to-work and home-to-school trips (kWh) was chosen to allow for a comparison between energy consumption in transport

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and energy consumption in the residential building sector (heating, appliances, electricity, etc.). This method is presented in Marique and Reiter (2012b).

SPATIAL STRUCTURE AND ENERGY CONSUMPTION FOR HOME-TO-WORK TRIPS

Figure 2 presents the energy performance index for home-to-work trips, mapped at the municipality scale (2001 data) for the Walloon region of Belgium. At first glance, the general pattern of this map is similar to Van der Haegen and Van Hecke's urban type classification presented in Figure 1. The two main cities (operational agglomerations) of the region, Charleroi and Liège, show the lowest energy consumption rate (shown in white in Figure 2) whereas suburban and more rural or remote parts of the territory have a much higher energy consumption rate (shown in dark grey and black). The highest transport energy consumption levels are found in two suburban parts of the region: the Brabant Wallon (in the North) and the area south of Luxembourg Province (in the South). These two areas have strong relationships with the metropolitan area of Brussels and Luxembourg-city, respectively, due to the high concentration of employment in these cities. However, the price of land close to these cities is relatively high, which encourages workers to live in remote suburban neighbourhoods and commute longer distances to their places of work. Moreover, public transportation is generally less available in these low-density developments, which results in a higher modal share of the private car.

Table 1 gives the mean value of the energy performance index (kWh/travel.worker) for the three urban types and for the five biggest cities of the Region. Note that Brussels does not belong to the Walloon region, but many workers working in this city live in the Walloon region (see the yellow part on Figure 1). Table 1 highlights that transport energy consumption rises with the distance to city centres where much of the employment is concentrated. Travelled distances were also calculated for the three main urban types. These distances are shorter in operational agglomerations, as compared to the areas with less density. The modal share of the bus is higher in the operational agglomerations whereas the modal share of the train is similar in the three areas. Note that the policy of the Belgian national railway society, tend to close stations located in small towns and to reorganise its offerings around main stations and lines from west to east (Lille – Aachen, along the old industrial basin where many residents and jobs are concentrated) and from south to north (Luxembourg - Brussels).

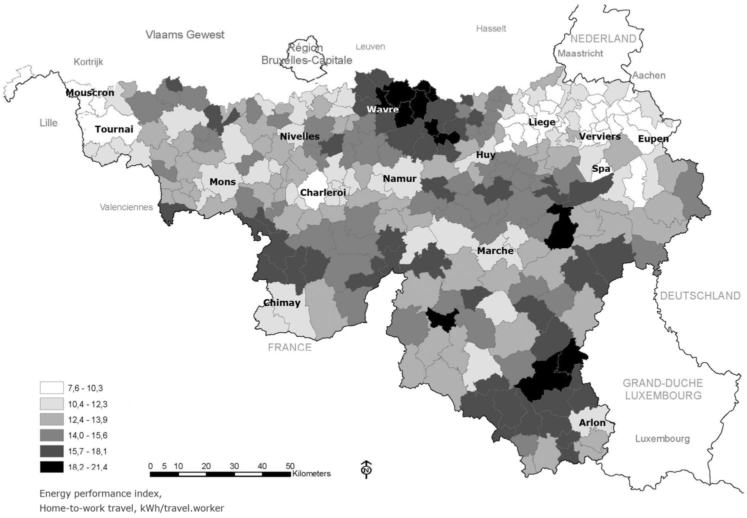

Figure 2: Energy performance index for home-to-work trips (in KWh/travel.worker) at the municipality scale; data: 2001

Table 1: Indexes for home-to-work travel (data: 2001)

	Operational agglomerations	*Suburbs*	*Alternating migrants areas*
Mean energy performance index (kWh/travel.worker)	10,4	12,9	14,2
Brussels (only the part located in the Walloon region, does not include the CBD)	11,5	12,7	15,1
Charleroi	10,3	13,5	13,9
Liège	9,4	12,7	14,0
Mons	12,2	12,9	12,0
Namur	10,8	13,8	14,2
Mean distance for one trip (km)	21,3	25,5	29,5
Mean modal share (bus)	4,0%	1,7%	1,5%

Mean modal share (train)	14,0%	12,7%	15,4%

Calculating and mapping the energy performance index for home-to-work commutes at the former municipality scale (Figure 3) and the local scale refines these initial observations. Outside the main agglomerations, several secondary municipalities and settlements (census blocks or districts) also show lower consumption rates. Most of these are cities and neighbourhoods that are located along the old industrial basin (from west to east: Mouscron, Tournai, Mons, Charleroi, Namur, Huy, Liège, Verviers and Eupen), or smaller towns in the southern, less densely populated part of the Walloon region (Chimay, Marche, Spa and Arlon). These secondary settlements are located outside the influence of the main regional cities. Population density is low, and people typically manage to find employment locally. This local-scale approach thus highlights more local phenomenon linked to the location of secondary employment centres in areas located far from major cities.

In conclusion, two distinct phenomena co-exist: the « metropolisation » and the « territorial recomposition ». Metropolisation induces higher commuting distances in the suburbs of attractive metropolises (such as Luxembourg and Brussels or, to a lesser extent, Lille (in France) and Aachen (in Germany)) where employment is concentrated. Note that these poles are all located outside the Walloon region of Belgium, and three metropolises are located outside of Belgium very close to its border. The influence area of these poles can reach 40 or 50 kilometers. The territorial recomposition occurs mainly occurs in the north part of the region (Brabant wallon) in the suburbs of Brussels. Secondary employments centers were developed over the last years and allow the local population that used to travel to Brussels for work to instead find work closer to their homes. This allows for shorter commuting distances and thus lower scores for the local energy performance index. In the case of territorial recomposition, the suburbanisation of housing is accompanied by a local re-concentration of employment.

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

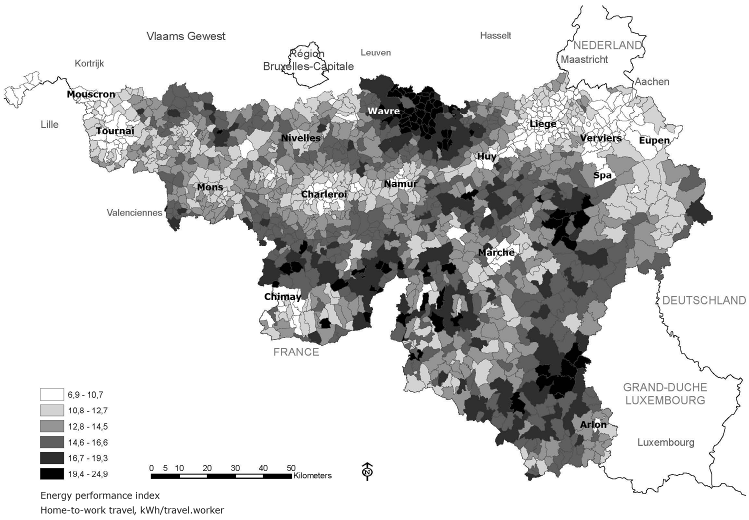

Figure 3: Energy performance index for home-to-work trips (in KWh/travel.worker) at the former municipality scale; data: 2001

The annual transport energy consumption for home-to-work trips per former municipality is mapped in Figure 4. The observations made for the energy performance index are inverted. Former municipalities with high transport energy consumption are strongly linked with areas with high density population and highlight the importance of these areas in terms of potential energy savings. The population affected by the energy-savings measures undertaken in those areas is particularly large. The total annual energy consumption for home-to-work trips in the entire region amounts to 6804 GWh.

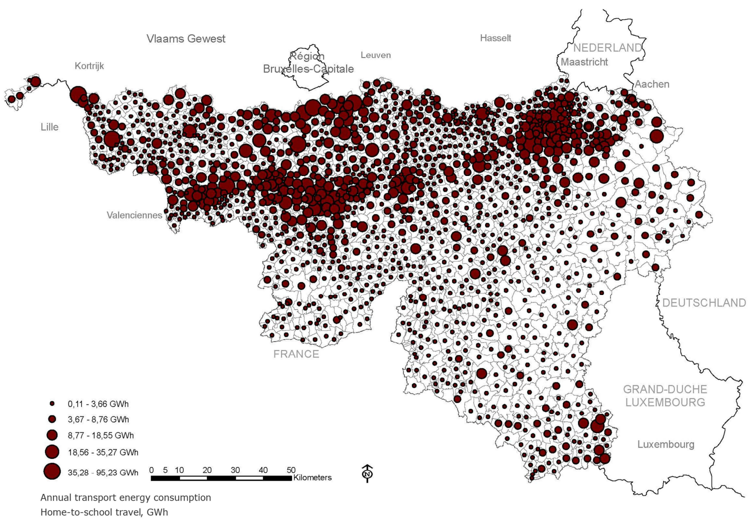

Figure 4: Annual transport energy consumption for home-to-work trips per former municipality; data: 2001

COMPARISON WITH HOME-TO-SCHOOL TRIPS

The method developed in Marique and Reiter (2012a) also allows for discussion of the energy efficiency of home-to-school trips, as data relating to these types of trips are available in the national census. Observations regarding to the relation between the transport energy consumption and the urban structure drawn for home-to-work trips, at the three territorial scales, are also valid for home-to-school trips: lowest energy performance indexes are found in dense urban former municipalities and settlements, located along the former industrial basin (Figure 5). However, home-to-school trips consume much less energy per capita and per travel than home-to-work trips, as shown in Table 2. For example, in 2001, the mean energy performance index for home-to-school trips is worth 3,5 kWh/travel.student, while the mean energy performance index for home-to-work trips was worth 12,1 kWh/travel.worker. The main explanation for this observation is that schools are spread throughout the entire regional territory, even in the most rural municipalities (rural core, suburban centres, etc., are equipped with at least one primary school). This allows for reduced distances from the homes to destinations, whereas work locations remain concentrated in main cities or suburban business centres. For example, the mean distance travelled from home to work is 24,0 kilometres, and the mean distance travelled from home to school is 8,2 kilometres.

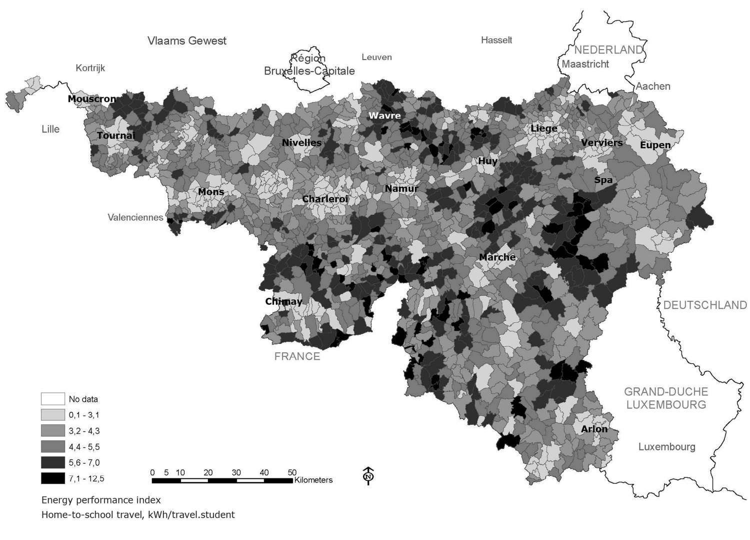

Figure 5: Energy performance index (kWh/travel.student) for home-to-school travels; data: 2001.

Table 2: Indexes for home-to-school travel (data: 2001)

	Operational agglomerations	*Suburbs*	*Alternating migrants areas*
Mean Performance index (kWh/travel.student)	2,7	4,2	4,2
Mean distance for one trip (km)	7,6	11,1	11,2

In terms of modal shares, significant differences are highlighted: the use of non-motorised means of transportation (bike, on foot) is much higher for home-to-school trips (14,7%) than for home-to-work trips (4,7%). The bus is more often used to go to school (21,8%) than to work (only 2,3 %), whereas the use of the train is more or less equivalent for these two types of commutes (6,0 % for home-to-work and 7,6 % for home-to-school). The car is the favourite means of transportation for both purposes of trips with 85,2 % for home-to-work trips and 55,8% for home-to-school trips. Furthermore, the use of car is higher in suburban areas than in central urban areas.

THE EVOLUTION BETWEEN 1991 AND 2001

The evolution of the energy performance index between 1991 and 2001 was calculated for home-to-work trips and mapped in Figure 6. A significant increase in transport energy consumption is highlighted in most former municipalities. This increase is particularly large in the south of the region (the area in relation to the metropolitan area of Luxembourg-city). Many low-density suburban neighbourhoods were developed in this area over the past decade to accommodate the rising number of people that were working in Luxembourg but were not able to pay Luxembourg's price for accommodation (Vanneste et al., 2007). These municipalities often have plenty of building land available at low prices (which is not the case in Luxembourg) but do not offer enough employment opportunities. The annual transport energy consumption for home-to-work trips was worth 5017GWh in 1991, amounting to an increase of 26.2% between 1991 and 2001. The evolution of the annual transport energy consumption for home-to-school trips follows the same trend with an increase of

Marique AF, Dujardin S, Teller J & Reiter S (In press) Urban sprawl, commuting and travel energy consumption. *Proceedings of the Institution of Civil Engineers – Energy*.

23,0%, even if the annual energy consumption is lower overall (589 GWh in 1991 and 766 GWh in 2001). The use of the private car has increased for both purposes of travel (+5,2% for home-to-work and + 11,6% for home-to-school trips) to the detriment of non-motorised modes of transport and buses.

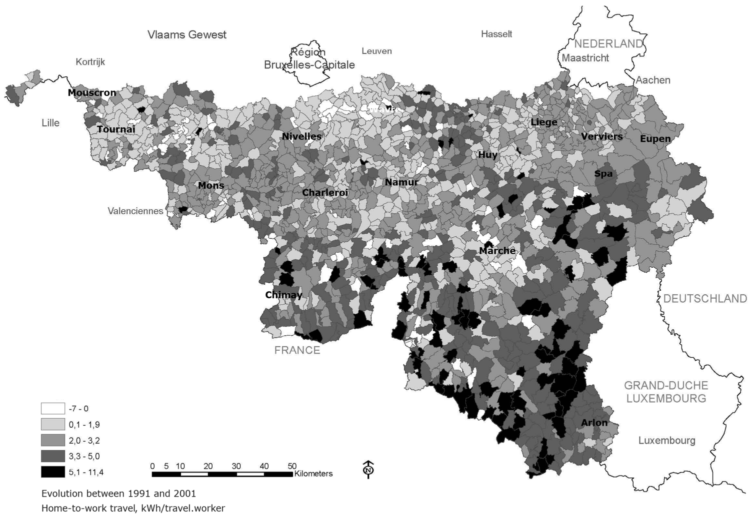

Figure 6: Difference (kWh/travel.worker) between performance indexes for home-to-work trips at the former municipality scale in 2001 and in 1991.

MAIN PARAMETERS

The general pattern of the energy performance index map is very similar to the map presenting the mean travelled distance (see Figure 7 for home-to-work trips). The energy efficiency of home-to-work and home-to-school trips is strongly determined by the distance travelled. Mode choice has less of an impact on the energy performance of those types of commutes. This can partly be explained by the relationship between distance and mode choice. The consumption factor used for the train is approximately four times lower than the consumption factors used for a private car, but trips by train are much longer than trip by car. The location of activities and a mix of functions at the living area scale are thus important strategies for promoting a reduction in transport energy consumption. Promoting more efficient public transportation in these areas could also be a credible strategy for two reasons: more energy efficient vehicles and a better occupation rate could both reduce the consumption factor for the bus.

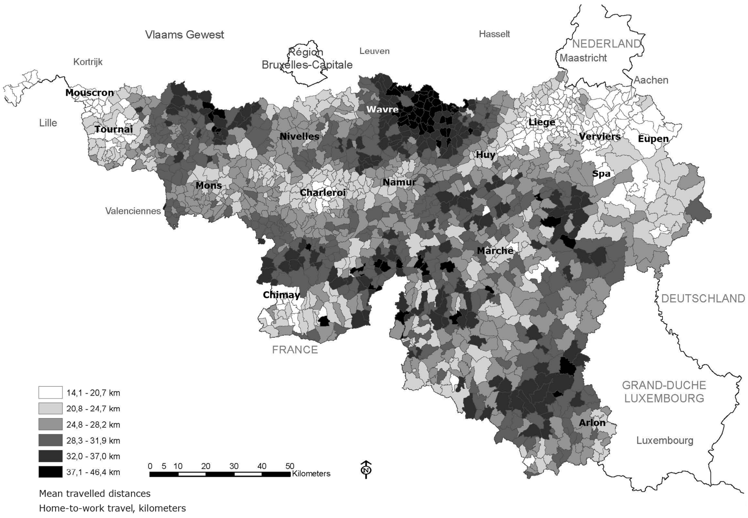

Figure 7: Mean travelled distances from home to work (in kilometres) at the former municipality scale in 2001.

DISCUSSIONS

Several limitations of the proposed method must be acknowledged. First of all, the factors used to convert kilometre per each mode of transportation into kWh are calculated for the entire territory (including urban and rural areas). Factors used for public transport are found to be slightly unfavourable as compared to urban centres. This is explained by the reduced consumption factor per person and per kilometre in urban centres because the occupancy rate of public transport is higher. Moreover, congestion in city centres and above-average speeds on non-congested motorway, which can lead to higher energy consumption rates and vehicle emission (Beevers and Carlslaw, 2005; Department for Transport, 2011; Den Tonkelaar, W. A. M.,1994) are not considered.

Secondly, even if many studies dedicated to transport and energy consumption only focus on home-to-work data because they are the most often available, a limit of the method arise from the fact that data about only two types of trips (home-to-work and home-to-school travels) are available in national censuses. Those types of travels are not representative of all trips of a household even if they play a founding role in it because they are commuting journeys and affect significantly related trips for leisure or commercial purposes. “Type-profiles” such as those performed, on smaller areas, by Saunders et al. (2008) could be developed to take into account those trips in further research.

Thirdly, although the calculations of the indexes lead to quantitative results, analyses are mainly based on visual inspections of the maps to link spatial structure of the territory and transport energy consumption, at different scales. Note that the quantitative data are necessary and that visual analysis alone can lead to misinterpretations of the results. To strengthen the qualitative visual analysis, complementary quantitative methods and techniques could be explored in further analyses. Multivariate regression analyses performed by Marique et al. (in press) for home-to-school trips confirm the qualitative findings highlighted through a qualitative assessment of map patterns

Finally, it should be mentioned that the structure of a territory is not the only parameter that influences energy consumption for commuting. The analyses presented in this paper did not take into account external factors, such as income levels, improvements of the vehicles, behaviours and lifestyles of the commuters, etc., although the authors still believe these factors may influence adults’ mobility behaviours. Due to the huge inertia of the urban structure and market forces (in particular in the neighbouring Luxembourg), major changes in the location of work places and residences can only be considered in the long term. Land use policies should namely favour the reduction of distances through a better mix of functions, at the living area scale, in areas presenting large concentration of local population and be more directives as far as the location of new work places and residences are concerned. In addition to the results presented in this paper, more efficient vehicles, alternative technologies (e.g. hybrid electric vehicles supplied by low-carbon electricity and supported, favourable tax and local charging regimes (Gibbins et al., 2007), hybrid train that uses a battery as an energy storage device (Wen et al., 2007)) and more sustainable behaviours and lifestyles related to transportation should also be encouraged to effectively reduce transport energy consumption and greenhouse gas emissions.

As far as the reproducibility of our approach is concerned, the method is parameterised and, if the same type of empirical survey data exists, it can be reproduced for other territories by adjusting parameters for vehicles, consumption factors, etc.

CONCLUSIONS AND PERSPECTIVES

Using a quantitative method developed to evaluate transport energy consumption and its application to the Walloon region of Belgium, this paper has shown that urban structure (that is to say the system defined by the location of work places and services, the spatial distribution of population according to residence and infrastructures), acts upon travel energy consumption. This study also questioned the issue of scale through an evaluation of the energy efficiency of home-to-work and home-to-school trips at several territorial scales. We have shown that a local-scale approach is useful, as it allows for a more nuanced picture of the energy performance of commuting in urban and suburban areas. The local-scale approach highlights local phenomena, particularly the existence of secondary urban cores characterised by low energy consumption inside suburban territories due to the local re-concentration of employment opportunities and sufficiently large concentration of local population. Two distinct phenomena were highlighted: the “metropolisation”, which results in a longer commuting distance in the suburbs to major employment centres (such as Luxembourg and Brussels), and the “territorial recomposition”, which tends to reduce travelled distances inside suburban or remote territories. In this respect, the current mobility policies should be more context-specific by addressing the sustainability of transport also at the local scale.

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Appendix A.5

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A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale

Anne-Françoise Marique*, Sigrid Reiter

University of Liege, LEMA (Local Environment: Management & Analysis), Chemin des Chevreuils, 1 B52/3, 4000 Liege, Belgium

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A B S T R A C T

Zero-energy buildings (ZEBs) are attracting increasing interest internationally in policies aiming at a more sustainably built environment, the scientific literature and practical applications. Although "zero energy" can be considered at different scales (e.g., community, city), the most common approach adopts only the perspective of the individual building. Moreover, the feasibility of this objective is not really addressed, especially as far as the retrofitting of the existing building stock is concerned. Therefore, this paper aims first to investigate the opportunity to extend the "zero-energy building" concept to the neighbourhood scale by taking into account two main challenges: (1) the impact of urban form on energy needs and the on-site production of renewable energy and (2) the impact of location on transportation energy consumption. It proposes a simplified framework and a calculation method that is then applied to two representative case studies (one urban neighbourhood and one rural neighbourhood) to investigate the feasibility of zero-energy in existing neighbourhoods. The main parameters that act upon the energy balance are identified. The potential of "energy mutualisation" at the neighbourhood scale is highlighted. This paper thereby shows the potentialities of an integrated approach linking transportation and building energy consumptions.

1. Introduction

1.1. Zero-energy at the building scale

The building sector is a major consumer of energy worldwide [1–3]. For example, it represents over 40% of the overall energy consumed in the European Union [1–3]. In the current context of growing interest in environmental issues, reducing energy consumption in the building sector is an important policy target. Politicians, stakeholders and even citizens are now aware of the issue of energy consumption in buildings, especially as a result of the passage of the European Energy Performance of Buildings Directive and its adaptation to the Member States. Its main aim was to establish minimum standards for the energy performance of new buildings and existing buildings larger than 1000 m^2 subject to major renovation [4]. Another major trend commonly proposed to reduce the energy consumption of the existing building stock is the improvement of the thermal performance of the envelope of existing buildings (sometimes in combination with more efficient heating/ventilation systems) [1,3]. As a result, new construction and renovation standards ((very) low-energy standards, passive house standards) [5–7] have been developed to drastically minimise the energy consumption of new and retrofitted buildings and the associated greenhouse gas emissions. During the last few years, "zero-energy buildings" have aroused increasing interest internationally in the scientific literature (e.g., [8–14]), policies aiming at a more sustainable built environment and even concrete applications.

In the literature, the "zero-energy" objective is most often considered on the building scale. Although existing definitions are commonly articulated around an annual energy balance equal to zero (the energy demand of the building is compensated by its renewable production) [10,11], numerous differences exist and several definitions coexist [8,12] depending on such elements as specific local conditions, political targets, connection (or not) to the grid and measures to address energy efficiency before using renewable energy sources. The "zero-energy building" (ZEB) is presented as a general concept that also includes autonomous buildings not connected to energy grids. The term "net zero-energy building" (nZEB) "*underlines the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year*" [8, p. 220]. The concept of a "nearly zero-energy building" is presented by the European Directive on the energy performance of buildings [15] as a "*building that has a very good energy*

* Corresponding author. Tel.: +32 4 366 93 67; fax: +32 4 366 29 09.
E-mail address: afmarique@ulg.ac.be (A.-F. Marique).

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performance. The nearly zero energy or very low amount of energy required should be supplied to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

Other derived concepts are also found in the literature based on various balance metrics [9]. For example, Torcellini and Crawley [9] defined four net zero-energy building balances (net zero primary energy, net zero site energy, net zero energy cost and net zero emissions) and Mohamed et al. [16] investigated them for a single-family house with different heating alternatives. For Voss et al. [10,17], a clear definition, standardised balancing method and international agreements on the meaning of "zero-energy building" (ZEB) are lacking.

To address this issue, Marszal et al. [12] recently proposed a review of the existing ZEB definitions and various calculation methodologies. They highlighted seven main issues to be addressed in further definitions: the metric of the balance, the balancing period, the type of energy use included in the balance, the type of energy balance, the acceptable renewable energy supply options, the connection to the energy infrastructure and finally the requirements for the energy efficiency, the indoor climate and, in the case of grid-connected ZEB, the building-grid interaction. Amongst the more complete existing approaches, Sartori et al. [8] developed a systematic, comprehensive and consistent definition framework for "net zero-energy buildings". They considered "*all the relevant aspects charactering net ZEB and aims at allowing each country to define a consistent (and comparable with others) net ZEB definition in accordance with the country's political targets and specific conditions*" [8, p. 221]. This framework is articulated around two types of annual balances: the import/export balance (balance between delivered and exporter energy) and the load/generation balance (balance between load and generation). The monthly net balance can also be determined according to the same philosophy [8]. Voss et al. also [10] proposed a harmonised terminology and balancing procedure that takes into account the energy balance as well as the energy efficiency and load matching and highlighted that "*it is the optimisation and not the maximisation of electricity exported to the grid that is an essential planning goal for net zero-energy buildings, in addition to the reduction of energy consumption*" [10, p. 55]. These authors proposed a new label (ZEB *x*) allowing the distinction between the need for seasonal compensation (the lower the "*x*" value, the lower this need for compensation). In the same vein, Srinivasan et al. [18] introduced a "renewable emergy balance" as a tool to ensure that buildings are optimised for the reduced consumption of resources and that the use of renewable resources and materials is optimised over the entire lifecycle of the building. Pless and Torcellini [11] ranked the renewable energy sources used in a building to propose a classification grading system for ZEB, based on renewable energy supply options. The goal of this work is to encourage, first, the utilisation of all possible energy-efficient strategies and, then, the use of renewable energy sources and technologies located on the building [19]. Attia et al. [20] developed one of the only decision support building simulation tools that can be used as a proactive guide in the early design stages of residential net zero-energy building design. This tool is designed for a hot climate (Egypt) and allows for the sensitivity analysis of possible variations of nZEB design parameters and elements to inform the decision-making process by illustrating how these variations can affect comfort and energy performance.

As far as policies are concerned, the ZEB is currently receiving an increasing amount of attention in several countries [12–14]. In Europe, the recasting of the European Performance of Buildings Directive (EPBD) requires all new buildings, built in Member States, to be "nearly zero-energy" buildings (nZEB) by 2020. As a consequence, Member States are currently implementing this objective into their own national regulations [14]. The zero objective will then be extended to existing buildings undergoing major retrofitting works [15]. In the United States of America, the Energy Independence and Security Act (2007) [21], which concerns the energy policy of the entire country, aims to create a nationwide net zero-energy initiative for houses built after 2020 and commercial buildings built after 2025. The Asia-Pacific Partnership on Clean Development and Climate, a public-private partnership of seven countries (Australia, Canada, China, India, Japan, South Korea and the United States of America), aims also at promoting the development of net zero energy homes [13].

In practice, several buildings have recently been built that prove that "zero energy", at the building scale, is feasible. Most of these existing zero-energy buildings are (small or large) residential buildings and office buildings [17,22]. Fong and Lee [23] showed that the net zero-energy target seems not to be possible for high-rise buildings in Hong Kong. However, they note that it is feasible for low-rise residential buildings in this subtropical climate.

1.2. Zero energy at the neighbourhood/community scale

Generally speaking, most papers investigating energy issues at the neighbourhood/community scale focus on either the impact of urban form on energy consumption in buildings [e.g., 24–26] or the potential of solar energy utilisation for active and passive solar heating as well as photovoltaic electricity production, lighting and related energy supply and demand [e.g., 27–30]. Hachem et al. [31] studied and compared the electricity generation potential of neighbourhoods and their energy performance in terms of heating and cooling and found out that a significant increase in total electricity generation can be achieved by the building integrated photovoltaic systems of housing units of certain shape-site configurations, as compared to their reference case. They also highlighted that the energy load of a building is affected by its orientation and shape. The impact of urban form on transportation energy consumption has also be widely highlighted in the literature, but it is considered either alone [e.g., 32–36] or, in a few studies, in comparison with building energy consumption [e.g., 37–39].

Studies and reports dealing with zero energy at the neighbourhood/community scales are few in number. The framework proposed by Sartori et al. [8] can also be applied to a cluster of buildings. Kennedy and Sgouridis [40] addressed the question of how to define a zero-carbon, low-carbon or carbon-neutral urban development by proposing hierarchical emissions categories. Todorovic [41] investigated the role of simulation tools in the framework of zero-energy urban planning. The National Renewable Energy Laboratory [19, p. 4] defined, in a technical report, a "zero net energy" community (ZEC) as "*one that has greatly reduced energy needs through efficiency gain such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy*". They highlighted [19, p. 1] that "*community scenarios could link transportation, home and the electric grid as well as enable large quantities of renewable power onto the grid*". They also applied the ZEB hierarchical renewable classification proposed by Pless and Torcellini [11] to the concept of community to focus on the mode and location of production of renewables. A community that met the zero energy definition thanks to renewable energies produced within its built environment (or in brownfields) is at the top of the classification (rank A) whereas a community that met the definition through the purchase of renewable energy certificates is ranked C.

Although not specifically dedicated to the "Zero-energy" objectives, several neighbourhood sustainability assessment tools have recently been developed [42]. Examples of these NSA tools are, amongst others, the STAR Community Rating System (Sustainability Tools for Assessing and Rating Communities) [43] and the US Green Building Council's LEED-ND (Leadership in Energy and Environmental Design—Neighbourhood Development) [44] in the

United States, BREEAM Communities (BRE Environmental Assessment Method) in the United Kingdom [45], HQE2R (Haute Qualité Environnementale et Économique dans la Réhabilitation des bâtiments et le Renouvellement des quartiers) in France [46] and CASBEE-UD (Comprehensive Assessment System for Built Environment Efficiency–Urban environment) in Japan [47]. These tools aim to assess and rate communities and neighbourhoods against a set of defined criteria and themes. They propose a checklist of criteria (mainly optional) and a range of various guidelines to help local stakeholders, designers and citizens move towards more sustainability. Although they all include a large theme dedicated to energy, they neither allow a quantitative assessment of energy consumption or GHG emissions nor the evaluation of the energy efficiency of retrofitting scenarios.

As far as concrete projects are concerned, the West Village is a net zero-energy community, including 662 apartments and 343 single-family homes, under construction in Davis, California [48,49]. Another interesting development at the neighbourhood scale is the Beddington Zero (fossil) Energy Development (BedZED) sustainable neighbourhood, which was intended to be the UK's largest mixed-use zero-carbon community. However, the zero objective was not achieved. Others examples of very low energy neighbourhoods include Hammarby Sjosjad, Augustenborg and BO01 in Sweden, Vauban and Kronsberg in Germany, Eva-Lanxmeer in the Netherlands and Vesterbro in Denmark [50]. Finally, IEA-EBC (International Energy Agency's Energy in Buildings and Communities Programme) has currently a few Annexes/projects on zero-energy communities [22].

1.3. Aim of the paper

This paper aims to complete the existing approaches relating to "zero energy" by developing and investigating the opportunities linked to a new simplified framework dedicated to "zero-energy neighbourhoods" and articulated around the following three main challenges:

(1) The major challenge of the adaptation and retrofitting of the existing building stock (especially in the large part of Europe in which the renewal rate of the existing building stock is quite low), in complementarity with the numerous studies dealing with the production of new optimised buildings and communities, and the concrete feasibility of zero-energy in retrofitting.
(2) The impacts of parameters linked to the urban form on the energy efficiency of single buildings as well as on the choice and efficiency of on-site renewable energy sources (e.g., the possible mutualisation of energy supply and demand between individual buildings).
(3) The impact of the location of residences, work places and services on daily mobility patterns and their related energy consumption, which are considered together with building energy consumption because building or retrofitting very efficient buildings could be counterproductive if its location does not allow alternatives to private cars for daily mobility (travel to work, school, shops, etc.) and imposes long travel distances.

As architects and urban planners, we are particularly interested in investigating the possibilities to adapt the existing building stock in order to reach an annual zero-energy balance, at the neighbourhood scale, and in highlighting the main urban and architectural parameters that act upon the energy balance of a neighbourhood. Thus, in the following, we will take into account three main themes directly related to the urban form of existing neighbourhoods: building energy consumption, the on-site production of renewable energies and transportation energy consumption of inhabitants (in order to take into account the location of activities on the territory in the balance).

1.4. Content of the paper

To this extent, Section 2 proposes a simplified framework and a calculation method to assess zero-energy neighbourhoods. An application of the proposed framework is then developed in Section 3 to test its applicability, investigate the feasibility of zero-energy in retrofitting neighbourhoods and highlight key parameters in the annual energy balance of two representative neighbourhoods (in Belgium). Section 4 discusses key challenges to be addressed and perspectives to be investigated in future research. Finally, the research findings and strengths and weaknesses of the proposed framework are summarised in Section 5.

2. A simplified net "zero-energy neighbourhood" framework: method and assumptions

The net "zero-energy neighbourhood" framework (nZEN) proposed in the scope of this paper aims to articulate the three main energy uses (building energy consumption, the production of on-site renewable energy and transportation energy consumption for daily mobility), at the neighbourhood scale. A neighbourhood is understood here as an "urban block" (that is to say the smallest area of a city that is surrounded by streets) or a group of several "urban blocks". We only consider residential neighbourhoods although the general methodology could be extended to industries, shops, etc. Also note that public services energy uses in a neighbourhood (e.g., street lighting, traffic lights) are not assessed. A previous research [38] namely showed that street lighting energy consumption is minimal in comparison with building and transportation energy consumptions.

The nZEN is here described as a neighbourhood in which the annual energy consumption for buildings and transportation of inhabitants is balanced by the production of on-site renewable energy. The main balance is annual, but monthly, daily or hourly balances could also be studied according to the same definitions to better capture the gaps between energy consumption and production by renewable sources. As far as the metric of the system is concerned, the balances are proposed in terms of primary energy. The conversion factors used to convert gross energy into primary energy are 1 for natural gas and petrol and 2.5 for electricity, as stated in the Walloon regulation on the energy performance of buildings [51]. Only the use phase of the neighbourhood is taken into account in these balances (construction and deconstruction phases are not assessed). Note also that a net zero-energy neighbourhood implies interactions among the buildings in the neighbourhood and between the building and transportation energy consumptions. The zero-energy balance is thus considered as a whole, and each building is not necessarily a zero-energy building. Finally, we assume that the neighbourhood has an electric grid that can provide energy to the neighbourhood when on-site generation from renewables is lower than the load. If greater, the on-site production can be sent to the grid.

2.1. Energy consumption in buildings

The methodology used to assess building energy consumption takes into account the annual energy consumption for space heating (E_{SH}), space cooling (E_{CO}), ventilation (E_V), appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}). The neighbourhood's annual energy consumption for buildings (E_B) is calculated using Eq. (1).

$$E_B = E_{SH} + E_{CO} + E_V + E_A + E_C + E_{HW} \quad (1)$$

2.1.1. Energy consumption for space heating, cooling and ventilation

The method developed to assess energy consumption for space heating, cooling and ventilation was extensively presented in a previous paper [38]. This method combines a typological classification of buildings and neighbourhoods and thermal dynamic simulations. This typological approach classified the residential building stock of Belgium and was based on the following factors: common ownership (detached, semi-detached or terraced houses, apartments), the heated area of the dwelling in square meters (m^2), the heating and ventilation systems, the date of construction and the level of insulation, including retrofitting works performed by the owners (e.g., insulation of the roof and/or replacement of the glazing, change of the heating and/or ventilation systems). Thermal simulations were performed for all of the dwelling types of this typological classification of buildings. The results of these energy simulations (E_{SH} and E_V) are stored in a database comprised of the energy consumption of approximately 250,000 buildings. In these thermal simulations, Brussels meteorological data (temperate climate) are used. The minimum temperature in the dwellings is 18 °C, and internal gains are defined according to the surface area of the dwelling. A correction factor is applied to available solar gain according to the neighbourhood type to take into account the reduction of solar gains with increased built density. The net and gross energy consumption and primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are finally calculated by adding the results from the energy consumption analysis for each type of house according to their distribution in the neighbourhood and the neighbourhood type. Cooling (E_{CO}) is not taken into account in the case studies presented in Section 3, in accordance with regional yearbooks [52]. Moreover, the overheating indicator defined in the European Energy Performance of Building Directive [4] as the ratio between the solar and internal gains of a building to transmission and ventilation losses was calculated by [38] for Walloon residential buildings. It remains under the threshold value proposed in the Directive (29.8% under the threshold value for the worst cases), which indicate that the overheating is not unacceptable and does not require the installation of cooling system [4].

2.1.2. Energy consumption for appliances, cooking and domestic hot water

The annual energy consumptions related to appliances (E_A), cooking (E_C) and domestic hot water (E_{HW}) are assumed to depend on the number of inhabitants in the building. In the following application, regional mean values, gathered by a regional institute in charge of environment (the "Cellule Etat de l'Environnement Wallon" [53]), are used; however, in situ surveys could also be implemented in the model. The energy consumptions related to appliances and cooking are 1048 kWh per person per year and 170 kWh per person per year, respectively [53]. The energy consumption for heating water is obtained by multiplying the volume of hot water needed annually at the neighbourhood scale (m^3) by the difference in temperature between cold and hot water and a conversion factor, used to convert kilocalorie into watt-hour. This factor is worth 1.163 kWh/m^3 °C [54]. We consider each inhabitant to need 100 l of cold water (10 °C) and 40 l of hot water (60 °C) per day, in accordance with the regional trends [53].

2.2. Energy consumption for daily mobility

The annual energy consumption for daily mobility (E_{DM}) is assessed using a performance index introduced by Boussauw and Witlox [55] and adapted by Marique and Reiter [56]. This index is expressed in kWh/travel per person and represents, for a territorial unit, the mean energy consumption for travelling for one person living within a particular neighbourhood. This index takes into account the distances travelled, the means of transportation used and their relative consumption rates, as expressed by Eq. (2). In the equation, i represents the territorial unit; m the means of transportation used (diesel car, gasoline car, train, bus, bike, walking); D_{mi} the total distance travelled by the means of transportation m in territorial unit i; f_m the consumption factor attributed to the means of transportation m; and T_i the number of persons in the territorial unit i. The consumption factors depend upon the consumption of the vehicles (litres of fuel per kilometre) and their occupation rate. In the Belgian context [56], these values are 0.56 kWh/person per km for a diesel car, 0.61 kWh/person per km for a non-diesel car, 0.45 kWh/person per km for a bus, 0.15 kWh/person per km for a train and 0 for non-motorised means of transportation, as the latter do not consume any energy [56].

$$\text{Energy performance index } (i) = \sum_{m} \frac{D_{mi} f_m}{T_i} \tag{2}$$

The energy consumption for daily mobility (E_{DM}) is obtained using Eq. (3) by multiplying the energy performance index by the number of people (N) and the number of trips (T) in the neighbourhood.

$$E_{DM} = \text{Energy performance index} \times NT \tag{3}$$

In our nZEN framework, we attribute all travels to and from work and to and from school to the neighbourhood (rather than the portion that is really consumed within the neighborhood) to focus on the impact of residential locations on transportation energy consumption.

Data used in the following case studies come from a national census carried out in Belgium (the General Socio-Economic Survey 2001 [57]). Note that these data only concern home-to-work and home-to-school travel; however, we could use the same methodology with data from an in situ survey account for all travel purpose.

2.3. On-site energy production by renewable sources

On-site energy production via photovoltaic panels (E_{PV}), thermal panels (E_{TH}) and small wind turbines (E_{WT}) are considered when accounting for renewable energy sources. The annual renewable energy produced in the neighbourhood (E_{RP}) is calculated using equation 4.

$$E_{RP} = E_{PV} + E_{TH} + E_{WT} \tag{4}$$

2.3.1. Photovoltaic panels (electricity)

The potential of neighbourhoods for active solar heating and photovoltaic electricity production is obtained using numerical simulations performed with Townscope software [58]. Only photovoltaic panels on roofs are considered because those on facades are less effective in Belgium [59]. Townscope allows the calculation of the direct, diffuse and reflecting solar radiation reaching a point and the radiation distribution on a surface. As calculations are performed under clear-sky conditions, the software is used to determine a first correction factor M (the difference between the values calculated for the assessed neighbourhood and the clean site) to apply to the mean solar radiation MSR for the considered latitude (MSR = 1000 kWh/m^2·year for Belgium [60]). A second factor F is applied to take into account the roof orientation and inclination (Table 1) [61].

The solar energy received by the considered surface is obtained using Eq. (5). The potential of roofs for photovoltaic electricity production (E_{PV}, in kWh per year) is obtained by Eq. (6). In Eq. (6), S represents the surface area of the considered roofs, C the percentage of the roofs covered by panels (maximum 0.80), η_{pv} the efficiency of the photovoltaic panels, η_{inv} the efficiency of the inverter and

Table 1
Values of the correction factor *F*, which accounts for roof orientation and inclination [61].

		Inclination				
		0°	15°	25°	35°	50°
Orientation	East	0.88	0.87	0.85	0.83	0.77
	Southeast	0.88	0.93	0.95	0.95	0.92
	South	0.88	0.96	0.99	1	0.98
	Southwest	0.88	0.93	0.95	0.95	0.92
	West	0.88	0.87	0.85	0.82	0.76

λ a correction factor taking into account electricity losses. In the following case studies, the efficiency of the photovoltaic panels is fixed at 0.145, the efficiency of the inverter at 0.96 and the electricity loss correction factor at 0.2; in accordance to the technical characteristics of the most used type of panels in Wallonia [62].

$$E_{sol} = \text{MSR} \times FM \,(\text{in} \quad \text{kWh/m}^2\text{year}) \quad (5)$$

$$E_{PV} = E_{sol} S C \eta_{pv}(1-) \quad (6)$$

2.3.2. Thermal panels (hot water)

The solar energy received annually by the roof is obtained using Eq. (5), where correction factor *M* is calculated with Townscope and correction factor *F* is defined according to Table 1. Eq. (7) allows the determination of whether the roofs of the houses of the neighbourhoods are adapted to the production of hot water. In Eq. (7), E_{sol} represents the solar energy received by the roofs, *S* the surface area of the panel and η_{th} the efficiency of the thermal panels. We consider that 55% of the production of hot water of each household must be covered through thermal panels (from a technical-economic viewpoint, the optimum is often considered to be between 50% and 60%). Under these conditions, the efficiency of the system is 0.35.

$$E_{TH} = E_{sol} S \eta_{th} \quad (7)$$

2.3.3. Wind turbines

The approximation used to evaluate the annual electricity production of wind turbines (E_{WT}) consists of multiplying the rated power of the wind turbine by the number of operating hours at this rated power, as in Eq. (8), in which *P* is the rated power of the wind turbine and OH the number of operating hours. This value is fixed at 1000 h for a small wind turbine [63].

$$E_{WT} = P \cdot \text{OH} \quad (8)$$

2.4. Annual balance at the neighbourhood scale

The annual energy consumption of the neighbourhood (E_N) is calculated by adding the building energy consumption (E_B) and transportation energy consumption (E_{DM}) and subtracting the on-site renewable energy production (E_{RP}), as shown in Eq. (9).

$$E_N = E_B + E_{DM} - E_{RP} \quad (9)$$

The monthly balances can also be studied according to the same type of equation by replacing the annual energy consumption and production by the corresponding monthly values.

3. Results

3.1. Presentation of the case studies

The case studies chosen are two common archetypes of neighbourhoods (understood as urban blocks, that is to say the smallest area of a city that is surrounded by streets) and are representative of the building stock in Belgium [64]. The two neighbourhoods contain essentially the same number of buildings but in a very different urban form. Each urban form presents its own specificities and characteristics, especially as far as the built density and the types of buildings are concerned, as highlighted on Table 2, and requires personalised solutions regarding the energy efficiency in the building and transportation sectors and the on-site production of renewable energy.

Table 2
Main characteristics of the two case studies.

	Case 1	Case 2
Type	Urban	Suburban
Surface area	0.97 ha	12.02 ha
Population	180 inhabitants	150 inhabitants
Buildings	57	55
Detached houses	7%	75%
Semi-detached houses	17.5%	19.6%
Terraced houses	75.5%	3.6%
Apartments	0%	1.8%
Density	60 dw/ha	5 dw/ha
% of the surface area occupied by buildings	29%	5%

The first case study (Fig. 1) is a dense neighbourhood (60 dwellings per hectare) representative of an old compact industrial urban fabric. This neighbourhood is located close to good transportation networks (trains and buses), work places, schools, shops and services. Buildings are very poorly insulated, because the neighbourhood was built in the 19th century.

The second case study (Fig. 2) is a low-density suburban neighbourhood (5 dwellings per hectare) located in the suburbs (18 km) of the city centre. It is representative of the urban sprawl that began in Belgium in the 1960s. Public transportation is minimal, and car dependency is high. The neighbourhood is comprised of detached houses built between 1930 and 2010. Some retrofitting works (changing of the glazing, roof insulation) has been performed by the owners.

3.2. Annual energy balance

In the current situation, the energy consumption for space heating is quite large in both neighbourhoods (184 kWh/m^2 per year in case 1 and 235 kWh/m^2 per year in case 2), and the annual zero-energy balance cannot be achieved (Table 3). A clear difference is observed between the heating energy requirements of the two neighbourhoods because the first is made up terraced houses, which consume approximately 25% less energy for heating than the less compact urban form. Similarly to the building scale, to

Fig. 1. Case study 1—a representative urban residential neighbourhood (Belgium).

Table 3
Results of the application of the "zero-energy neighbourhood" framework to the two case studies.

		Case study 1	Case study 2
Consumption (kWh)	Space heating and ventilation: *ESH* + *Ev*	1,421,694	2,754,341
	(*ESH* + *Ev*—low-energy retrofitting)	(463,595)	(703,235)
	(*ESH* + *Ev*—passive retrofitting)	(143,156)	(214,074)
	Appliances: *EA*	161,139	155,485
	Cooking: *EC*	26,277	25,355
	Hot water: *EHW*	152,950	127,458
	Daily mobility: *EDM*	339,696	441,072
Production (kWh)	Photovoltaic elec.: *EPV*	139,945	314,669
	Hot water heating: *ETH*	80,417	67,170
	Wind turbine: *EWT*	0	50,000

Fig. 2. Case study 2—a representative suburban residential neighbourhood (Belgium).

achieve a net zero-energy balance at the neighbourhood scale, the energy demand (heating in these case studies herein) must be reduced using energy efficiency measures (a major retrofitting of the envelope of the building). The result must satisfy the (very) low, passive or net zero-energy standards. Moreover, the results show that the zero-energy neighbourhood objective also needs to minimise the energy needs for appliances, cooking and hot water. It is important to emphasise the influence of less energy-consuming devices as well as adapted user behaviours and lifestyles, parameters that have already been studied in detail in other references (e.g., [65–67]).

Energy consumption for daily mobility is also higher (approximately 30%) in the suburban neighbourhood, which is highly dependent on private cars and for which travel for work and school is across large distances. Taking into account energy consumption from daily mobility, as highlighted in our assumptions, the impact of the location of the neighbourhood can be included in the annual balance. This is crucial to avoid simply proposing building or retrofitting zero-energy buildings and neighbourhoods as the optimal solution to create a more sustainable built environment, regardless of their location and the impact of this location on transportation energy consumption. Moreover, the results show that the zero-energy neighbourhood objective also requires the minimisation of the energy needs for daily mobility, even in urban areas.

In contrast, as far as on-site renewable energy production is concerned, the photovoltaic production is higher in the suburban neighbourhood (case 2) because simulations performed with Townscope to calculate solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in this area than in the dense neighbourhood (case 1). Quite interestingly, parametric variations show that if photovoltaic panels are only located on roofs that receive over 90% of the maximum solar energy and if the electricity production is mutualised at the neighbourhood scale, the efficiency (kWh produced per m^2 of panel) increases significantly (+10.7% in case 1 and +5.0% in case 2). The same amount of photovoltaic electricity can thus be produced by installing fewer panels than reported in Table 3, where photovoltaic panels were installed on each building. Thermal energy production is higher in case 1 thanks to the surface areas of the roofs but simulations performed to assess solar radiation on roofs (see Section 2.3.1, above) have shown that the shadowing effect is much lower in the suburban area.

The use of wind turbines in the first case study was not assessed because of the dense context in which it is located. In the suburban case, a small wind turbine produces approximately 50,000 kWh annually. This wind turbine could be located in the centre of the neighbourhood because this location is sufficiently far from existing houses (based on the noise produced by the turbine and the existing regulations); however, this solution would prohibit the future densification of the neighbourhood, which is a possible solution to increasing the sustainability of existing suburban blocks.

In comparison with building and transportation energy consumption, and for the considered climate and context, the on-site generation of renewable energy is often limited, especially in the dense case study. The zero-energy balance cannot be achieved, even if buildings are retrofitted to the passive standard. Therein, intermediate levels of performance (the [very] low, passive or net zero-energy neighbourhoods) could also be promoted, especially as far as interventions in existing neighbourhoods are concerned. Rather than the respect of a zero-energy annual balance, it seems important to promote, above all, the minimisation of building and transportation energy consumptions and the maximisation of renewable energy production.

3.3. Monthly energy balances

An annual balance was used first in this paper. Yearly balances account for the succession of the four seasons and their particularities. However, it is also interesting to investigate shorter periods of time. Monthly production and consumption curves highlight the shift between the production and consumption peaks and between supply and demand, particularly for solar energy (highest in summer) and heating consumption (highest in winter), as highlighted in Fig. 3.

4. Discussion and perspectives for further research

Achieving a net zero-energy balance in the two existing neighbourhoods is very difficult, namely because the building stock

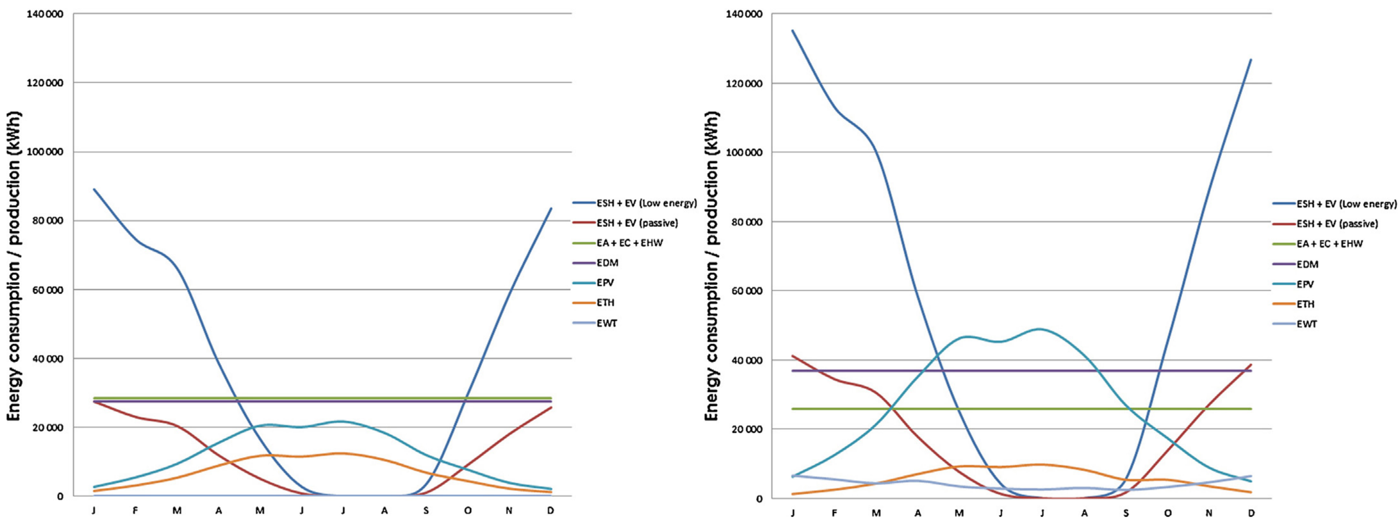

Fig. 3. Monthly production and consumption curves for the two case studies (case study 1 on the left and case study 2 on the right).

is poorly insulated. Intermediate milestone and targets could be proposed to help local communities to move towards more sustainability:

1. Improve the energy efficiency of the building stock (e.g., retrofitting to the passive house standard).
2. Minimize energy demand for buildings and for transportation through occupant behaviour (e.g., adapting the inner temperature of the dwellings, promoting car sharing).
3. Maximise on-site renewable energy production (e.g., installing PV panels).
4. Use off-site renewable energy production (e.g., using district heating and imported renewable energy).

As we highlighted significant differences between the urban and the suburban case studies, these milestones should be differentiated, according to the local opportunities in each neighbourhood.

In this course to reach sustainability in existing neighbourhoods, one of the main advantages of the neighbourhood scale is the potential for an "energy mutualisation" for both energy production and energy consumption. We have namely highlighted the interest of producing photovoltaic electricity at the neighbourhood, rather than at the individual scale. Another example was the pooling of the built envelope in dense urban neighbourhoods that allows to reduce energy needs of terraced houses, in comparison with detached houses. This concept of "pooling", at the neighbourhood scale, provides numerous avenues to increase energy efficiency in our built environment. In the same vein, it should be noted that this "energy mutualisation" or "pooling" at the neighbourhood scale offers interesting perspectives for the compensation of the monthly peaks (as well as hourly peaks) between supply and demand between individual buildings, especially in neighbourhoods presenting a wide variety of functions with different and shifted energy needs (offices, schools, etc., versus residences).

As far as perspectives for further research are concerned, the connection to the grid, the use of smart grids and the storage of energy should be investigated in the future. Cost optimisation should also be considered based on current discussions related to the European Directive on the Energy Performance of Buildings. Finally, we recommend extending the balance to the entire lifecycle of a neighbourhood by including the energy and CO_2 embodied in materials and technical installations (including transportation infrastructure).

5. Conclusions

The goal of this paper was to contribute to the existing literature on the "zero-energy" objective in the building sector by investigating the feasibility of this objective at the neighbourhood scale. The paper presented a simplified framework and a calculation method related to the "net zero-energy neighbourhood", which included building energy consumption and the on-site renewable energy at the neighbourhood scale as well as the impact of urban form and the location of the neighbourhood on transportation energy consumption for daily mobility. These developments were applied to two case studies (one urban neighbourhood and one suburban neighbourhood in Belgium) to highlight the main parameters that act upon the annual energy balance of a neighbourhood and to propose concrete steps to improve the sustainability of existing neighbourhoods. This work highlighted the opportunities for and interest in extending the boundaries of the existing frameworks from the building to the neighbourhood, which mainly concern the impact of urban form and daily mobility. The proposed nZEN framework allows to consider building energy consumption, renewable production and transportation energy consumption as an integrated system, rather than separated topics.

In a more general perspective, this works calls for a better integration of the individual building into its context in policies dealing with energy efficiency. Promoting the building and retrofitting of energy-efficient buildings is a good step towards increased energy efficiency in our built environment (i.e., by imposing mandatory minimum requirements on the energy efficiency of buildings that are crucial to reach a net zero energy balance); however, it is not sufficient. It is also crucial to consider parameters and interactions linked to a larger scale, the urban planning scale, to more effectively achieve the aims of these policies. To this end, the location of new buildings and developments appears to be crucial in the total balance, which includes both building and transportation energy consumption.

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Appendix A.6

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Life-cycle assessment of residential buildings in three different European locations, basic tool

Barbara Rossi [a,*], Anne-Françoise Marique [b], Mauritz Glaumann [c], Sigrid Reiter [b]

[a] MS2F, ArGEnCo Department, University of Liège, Belgium
[b] LEMA, ArGEnCo Department, University of Liège, Belgium
[c] Building, Energy and Environmental Engineering Department, University of Gävle, Sweden

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ABSTRACT

The paper deals with the development of a tool used for the life cycle assessment of residential buildings located in three different European towns: Brussels (Belgium), Coimbra (Portugal) and Luleå (Sweden). The basic tool focuses on the structure and the materials of the buildings and permits the evaluation of the Embodied energy, Embodied carbon and yearly energy consumption. For that purpose, a different set of original data is taken into account for each location, in which the monthly temperatures, energy mix, heating and cooling systems are defined. The energy consumption, being for heating space or water, for cooling or for lighting is transformed into CO_2 emissions to deduce the Operational carbon as well. The influence of the energy mix can therefore be assessed in the basic tool. As a matter of fact, the heating and cooling systems habitually used in the three countries are also of great importance. The District Heating system, is, for instance, incorporated in the basic tool. The presence of solar water heater or photovoltaic panels is also strongly influencing the operational carbon. After a short literature review on building LCA and the description of the basic tool, the software Pleiades + Comfie combined with Equer is used to achieve the complete LCA for one building using two different load bearing frames. The results of the calculations for Brussels climate are verified against these software results. The dependence of the results to parameters such as climate, energy mix and habits is then discussed in the companion paper.

1. Introduction and state-of-the-art

Life Cycle Assessment (LCA) is one of the methods increasingly being used to assess the environmental impacts associated with the production, use, disposal, and recycling of products, including the materials from which they are made. It quantifies the resource use and environmental emissions associated with the product evaluated. LCA was mainly developed for designing low environmental impact products. The interest of using LCA for entire buildings evaluations began to rise in the last decade and, today, several building LCA tools are under development in different countries [1]. But, although the general LCA methodology is well defined [2,3], its application in the building sector still suffers from a lack of standardization [4]. The Technical Committee CEN/TC 350 is currently working on a European standard for the sustainability assessment of buildings using a life cycle approach and quantitative indicators for the environmental performance, social performance and economic performance of buildings.

Some building characteristics to consider when making an LCA are [1,4–11]:

- Each building is a unique product,
- The boundaries of buildings LCA are not clear,
- The long life of buildings in comparison to consumption goods,
- The great impact of the use phase and occupants' behaviour,
- Various function and composition of buildings and their parts (such as the exterior walls for instances),
- Time evolution of environmental performances with functional changes, building retrofit, etc.
- Impact of the surroundings,
- Allocation for recycling.

There exist already some review-papers on the LCA methodology applied to entire buildings [5,12–14], and various previous researches concerned the LCA of residential buildings [4,15–24], including low energy dwellings [25], and LCA studies of office

* Corresponding author.
E-mail addresses: Barbara.Rossi@ulg.ac.be (B. Rossi), afmarique@ulg.ac.be (A.-F. Marique), Mauritz.glaumann@hig.se (M. Glaumann), sigrid.reiter@ulg.ac.be (S. Reiter).

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buildings [17,26]. This review reflects the important developments of LCA studies applied to buildings in the last ten years. However, a lot of modelling challenges remain. Currently LCA gives benefits to retroactively design but has limited use during the design stage [17,18]. Moreover, the building demolition and recycling of materials are rarely addressed in LCA studies of complete buildings [21,27]. These references also show that a great deal of buildings environmental impacts come from their use, primarily water and energy use. Issues such as orientation, insulation, building operation, lighting and appliance use, and so forth are therefore very important. Indeed, the in-use building phase is by far the longest one of the building life cycle. By comprehensively reviewing the existing literature from a entire building life cycle perspective, the phase with the highest environmental impact is the operation phase, representing approximately 62–98% of the life cycle total impacts [28], while the construction phase accounts for a total of 1–20% and the dismantling phase represents less than about 0.2–5%. So, trying to reduce fluxes (energy, water and waste) during the utilisation phase seems to be the first action to achieve. However, in [28] and [29], it is shown that the chosen service life time of the building is crucial for the calculation results and subsequent conclusions drawn from them.

In this study, we will calculate the Embodied carbon and take the recycling potential of the different materials into account. Indeed, the recycling potential is important when compared to the shell embodied materials: it accounts for 29%–40% of the energy used for manufacturing and transporting the building materials [16,21].

The quality (precision, completeness, representativeness) of the data used has a significant impact on the results of an LCA. The existence of uncertainties in input data and modelling as well as the boundaries of the system are often mentioned as a crucial drawback to a clear interpretation of LCA results. To achieve more reliable results the quality of the input data should be analysed and, if necessary, improved but such analyses are often outside the scope of building LCA studies [30]. To understand the reliability of LCAs in the building sector more clearly, the LCA models should be elaborated using data uncertainty estimations. They are particularly important when performing comparative LCA studies [1,29]. Note that Blengini [21] carried out an extensive sensitivity analysis of his LCA study on a multi-family residential building. The impacts were re-calculated by considering different data sources for the two most important materials included in this building: steel and concrete. The differences in terms of global energy requirement of the buildings with two alternative datasets are lower than 8% in comparison with the first dataset. The differences in terms of greenhouse gas (GHG) emissions fall within a range of −15% and +11%. Higher differences occur when other indicators are considered. The conclusions of Blengini [21] on this sensitivity analysis are that the uncertainties relevant to the inventory data of building materials are quite tolerable as far as energy and greenhouse gas emissions are concerned but that the other indicators are less reliable. As far as methods are concerned, three main types of LCA tools can be identified. The first one is the “process analysis” and is based on reliable energy consumption figures for particular processes. This method is often used in research dealing with building structures, as those presented below. The second one is the “input–output analysis” that makes use of national statistical information compiled by governments for the purpose of analysing national economic flows between sectors. Economic flows are then transformed into energy flows using average energy tariffs [24]. This method is less accurate than the first one [31]. To avoid the truncation error due to the delineation of the assessed system and the omission of contributions outside this boundary, a number of researcher have suggested to use a third method, the “hybrid LCA approach”, combining the strengths of process analysis with those of input–output analysis to try to develop a more complete approach [24,31,32].

According to the aim of this study, we have chosen to use a process analysis type based on comprehensive and reliable existing databases (BEES database (http://ws680.nist.gov/bees/) and CRTI (Luxembourg Construction portal, www.crtib.lu)) providing energy consumption and equivalent CO_2 emissions for a quite wide amount of construction materials in Europe. Indeed, the main objective is to focus on the comparison of different structural frames under different climates. The results obtained using the basic tool should thus be lower than those obtained with a hybrid LCA approach but are more pertinent to draw general results regarding the aforementioned comparison of the environmental impacts.

Given the significant consumption of resources in the construction sector, impact categories related to the depletion of non-renewable resources, like land use for example, are also particularly relevant for building related LCA studies. But the models used for inventory analysis or to assess environmental impacts may not be available for all potential impacts or applications, e.g. models generally accepted by the scientific world for the assessment of land use do not exist yet in the literature [33]. It is also worth pointing that some authors take into account the transportation of buildings occupants, assuming that it is part of the building service because it is related to the location of the building and that it is thus contributing to the overall building impacts [22,34]. Nevertheless, those transport distances will not be considered herein. Additionally, in [35], the author demonstrates the need for considering not only the life cycle energy of the building but also the life cycle energy attributable to activities being undertaken by users of the buildings (such as holidays, the replacement rate of items such as washing machine and microwave oven). But because our goal is to investigate the environmental impacts of different structural frames in different locations (characterized by different climate data as well as local energy mixes), the behaviour of the inhabitants is not considered as a variable in the present study. These indicators will not be considered herein. A standard profile of occupation (including internal gains) is defined and assumed to remain unchanged in the three locations to isolate the impact of parameters dealing with the building’s structure and the climate. Our tool focuses on the energy and equivalent CO_2 emissions.

The companion paper is complementary to previous research that compared LCA carried out on buildings with different construction materials or in different climates. Peuportier [15] applied LCA to the comparative evaluation of three single family houses in France: a standard construction made of concrete blocks, a solar house made of stones and wood and a well-insulated wooden frame reference house. This study concluded that the increase of CO_2 emissions of the standard concrete blocks house compared to the well-insulated wooden house represents 18% of the total emissions for the wooden house, but accounting for end-of-life processes may reduce this value. Bôrjesson and Gustavsson [30] studied the greenhouse gas balances of a wood versus concrete multi-storey building from life cycle perspective and concluded also that the concrete-framed building causes higher emissions than the wood-framed one. Comparing the environmental impacts of two dwellings during the entire building life cycle, one in Spain and one in Colombia, Ortiz-Rodriguez et al. showed that the difference in their environmental impacts is not only due to climatic differences but also to the user (energy consumption) habits in each country [36]. Another recent research [37] studied a modular building in two different European locations under the environmental point of view, concluding that the energy mix of the country strongly influences the environmental impacts of this specific modular building. In the companion paper, the LCA of two residential buildings, a traditional masonry house and a steel frame house, is carried out in three different climates: Belgium, Portugal and Sweden. A different life cycle scenario is taken into account for each location, in which the monthly temperatures, buildings insulation thicknesses, energy mix, heating and cooling systems are defined. This study allows us to compare the influence of several parameters on the LCA of residential buildings: the climate related to the temperatures and the buildings insulation thicknesses, the use of different materials, the energy mix and the heating/cooling systems.

The influence of the energy mix of different countries on their GHG emissions is a recent research subject found in the literature, that it is generally studied at national scale, working on demand-profile changes, varying electricity supply and economic issues [38–42]. These studies highlight how a shift in the energy mix toward renewable sources would yield significant reductions in per capita emissions at the national scale, even without reducing energy consumptions, but do not give solutions at the local scale. At the local scale [25], studied the life cycle primary energy analysis of residential buildings (including low energy buildings) and concluded that the operational primary energy varied considerable depending on energy supply systems (cogenerated district heating, heat pumps, electric space heating, etc.) for all the buildings analysed. The choice of energy supply system had a greater effect on the primary energy use than the energy efficiency house envelope measures. The CO_2 emissions from the building operation heavily depend on the carbon content of the fuel used in the supply systems.

Studying the influence of the energetic performance of a building and the influence of occupants' behaviours on the environmental impacts of this building, Blom et al. [23] developed a sensitivity analysis on different electricity mixes. Although each statement depends greatly on the location and the type of building that is considered, the conclusions of this study are that:

- The fraction of the environmental impact due to electricity consumption is higher than the proportion of electricity in the total energy content for all the studied scenarios. Therefore, the electricity mix used in the analysis widely influences the LCA of the building.
- A comparison between the Dutch electricity mix and an alternative electricity mix, using 35% renewable sources, based on European policy goals for 2020, shows that the 35% renewable sources scenario will not significantly reduce all the environmental impacts and will result in a maximum reduction of 14% in the Global warming potential.
- All the renewable energies have not the same environmental impact. The type of sustainable energy sources used to produce electricity greatly influences the environmental impact of the energy mix.

While, in the present paper, a basic tool is implemented and verified against an already validated software, the companion paper studies the influence of the energy mix on the environmental impacts of specific houses, at different LCA stages, allowing to optimize their design. It also shows the complex interactions between building conception, climate, energy mix, materials and energy systems into the building.

2. LCA: the basic tool

2.1. Principles, definitions and tools

The present assessment follows the recommendations of the ISO Standards 14000 series [43] and was made on the basis of a excel sheet developed by Pr. Mauritz Glaumann from the University of Gävle. Amongst other things, the tool was modified to take into account the climate over one year and more complex designs. For example, the energy demand for the space heating evaluation takes into account a scenario including business days and holidays, night and day demanded comfort temperatures, internal heat gains and solar passive heating. Two main impacts are calculated: (1) the Embodied energy/carbon and (2) the Operational energy/carbon (B6 and B7 of [36]).

Embodied energy is an important concept inasmuch as it allows energy efficiency, together with operational energy [35]. Embodied energy represents the energy used for producing building materials (from the extraction of the raw materials to the manufacture of the final product, including transportation) and their implementations in the building. The total embodied energy comprises a direct component (the energy consumed directly at each phase) and an indirect component (the energy required indirectly to support the main processes which is less obvious and more difficult to measure) [24,31]. Operational energy represents the energy used in operating the building, that is to say the energy used for space heating and cooling, hot water, lighting, cooking and others appliances and equipment operation. Similarly, Embodied carbon and Operational carbon respectively represent the equivalent CO_2 emissions due to the extraction, production and transportation of the material and the construction of the buildings and the equivalent CO_2 emissions linked to the operation of the building during its life time.

The procedures and assumptions used herein to evaluate Embodied energy/carbon and Operational energy/carbon are presented in Sections 2.2 and 2.3.

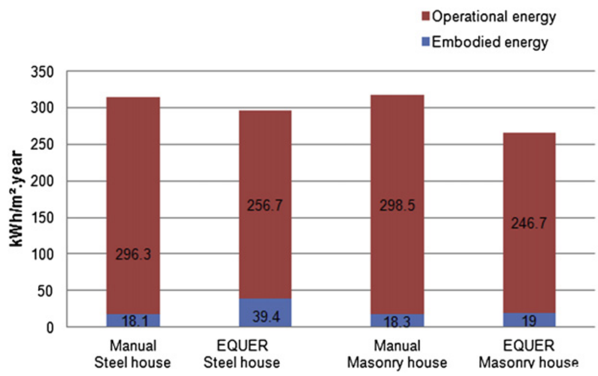

Fig. 1. Operational and embodied energy for the two houses and the two methods.

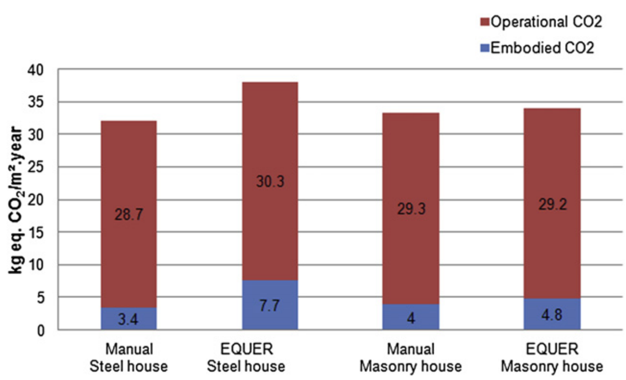

Fig. 2. Operational and embodied carbon for the two houses and the two methods.

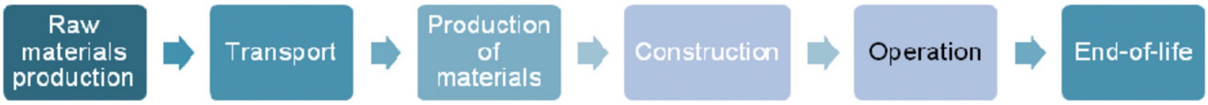

Fig. 3. Steps of the life cycle analysis.

2.2. *Embodied energy and carbon: procedures and assumptions*

The study is a cradle-to-gate study (A1 to A3 of [44]). It covers all the production steps from raw materials "in the earth" (i.e. the cradle) to finished products ready to be shipped from the factory. The non-metallic materials databases are BEES database (http://ws680.nist.gov/bees/) or preferably CRTI (Luxembourg Construction portal, www.crtib.lu) database providing energy consumption and equivalent CO_2 emissions for a quite wide amount of construction materials in Europe.

Transport to and from site (A4) is included in the present study but is only slightly affecting the final results. For instance, if the Ecoinvent database for impacts linked to transportation by trucks is considered, the energy needs for transportation only attain 2% of the embodied energy if a 50 kms distance is considered.

On-site processes (A5), such as the finishing of steel structures (cutting, shot blasting, welding) is not included but, according to steel producers, this step of the analysis is usually negligible [45]. Nevertheless, the net amount of products used for the construction of the building is increased by 5% in order to take into account the losses during construction, due to the vulnerability of products during transport and handling or due to inadequate dimensions.

The end-of-life stages (deconstruction C1, transport C2, reuse and recycling C3, disposal C4) are not included in the analysis for non-metallic material (concrete, insulation, plaster, finishes). As already mentioned for transport to the site, transport to the waste treatment facility might also not have a strong influence on the embodied impacts but are also taken into account. Transport distances are 50 kms to the construction site for all the products and 250 kms are considered between the site and the recycling plant for steel (while only 20 kms are considered for non-metallic materials).

The study includes the credits associated with the steel recycling since it can have a strong influence on the final results [46,47]. Steel is produced using two process routes. The main one is the blast furnace (BF) route (basic oxygen furnace), whereas secondary steel production process uses the electric arc furnace (EAF) route. Both processes recycle a certain amount of scrap that is melted in the furnace making steel a recyclable material. The absolute recycling potential of steel is 100% but, in reality, the net quantity of scrap introduced in the furnace depends on the steel demand. One important parameter of the analysis, especially for construction steel, is the recovery rate that can attain 60% for rebar while, for profiles, it can raise 100%. Nowadays, industries have resolutely worked to influence the methodology and include the end-of-life (EOL) treatment within the life cycle inventory data for steel. Those data are calculated for the BF route (based on iron ore and steel scrap) and the EAF route (mainly based on steel scrap) on the basis of World or European averages and can be obtained via the Worldsteel facility. It is possible to specify the recovery rate (RR is the percentage of steel that will be recovered at the end-of-life stage) or use the average RR for the considered sector. In the present study, an RR of 95% is considered. This parameter will be discussed throughout this paper.

Replacement, refurbishment and repair of materials and products (B1 to B5) is not taken into account specifically in the analysis. However, the embodied carbon/energy are simply augmented by 5% every 10 years to take that into account. A 50-year service life was considered in the analysis and is also one parameter that will be further discussed.

2.3. *Operational energy and carbon (B6 and B7): procedures and assumptions*

This part of the LCA concerns the Use phase (heating, hot water, ventilation, cooling, lighting, building automation and control, Operation in Fig. 3) in which no maintenance or repair is taken into account (B1 to B5) a part from what is described in the previous paragraph.

2.3.1. *Space heating and cooling*

The well-known heat loss factor (HLF) is provided in Equation (1) below:

$$HLF = \sum_i [U_i A_i] \quad (1)$$

where U_i = heat transfer coefficient of wall i (W/m^2 K) and A_i = surface of wall I (m^2).

The heat transfer coefficient of the windows is calculated differently. Depending on U_{glass} and $U_{profile}$, the value of U_{window} is evaluated for each window included in the building. The average heat transfer coefficient permits the user to calculate the heat loss through each window. This method leads to slightly overestimated results.

Conduction of heat may occur through the walls either inwards or outwards. This heat transfer depends on the temperature difference between the warm and cold sides of the walls. In this study, the energy demand for space heating evaluation takes into account a scenario in which (a) each month is characterized by a minimum and a maximum temperature lasting 12 h a day; (b) the required indoor temperature is considered different during the

Table 1
Total electricity use per country (source: iea.org, 2010).

	Belgium (GWh)	%	Portugal (GWh)	%	Sweden (GWh)	%
Coal	7235	8.5	11196	24.4	2235	1.5
Oil	406	0.5	4148	9.0	873	0.6
Gas	24646	29.0	15199	33.1	603	0.4
Nuclear	45568	53.7	0	0.0	63889	42.6
Hydro	1757	2.1	7296	15.9	69211	46.1
Geothermic/wind/solar/other	5318	6.3	8130	17.7	13217	8.8
Total (in 2008)	84930		45969		150028	

Table 2
Impacts from electricity generation.

	Belgium Equer	% [51]	Portugal Equer	% [51]	Sweden Equer	% [51]
CO_2 (g/kWh)	330.6	255.7	608.1	329.0	30.5	16.9
Primary energy (MJ/kWh)	19.5	6.6	9.9	7.0	13.6	9.9

night and the day; (c) during business days, only 6 h of heating are demanded, after this, the evening is supposed to start, and (d) if negative (after having added the human heat production and solar gains), the energy demand is approximately considered as cooling energy. The energy losses *E* (kWh/yr) through the building envelope is finally provided by Equation (2) below, in which $\Delta Tconf,\ d$ is the demanded temperature during the day (K) and $\Delta Tconf,\ n$ is the one demanded during the night:

$$E = HLF\sum_m\Big[\Big(\Delta T_{comf,d}\cdot h_b\cdot j_b\Big)+\Big(\Delta T_{comf,d}\cdot 12\cdot(j_m-j_b)\Big) + \Big(\Delta T_{comf,n}\cdot(12-h_b)\cdot j_b\Big)+\Big(\Delta T_{comf,n}\cdot 12\cdot j_m\Big)\Big] \quad (2)$$

where h_b = number of hours of occupation during business days (h) and $jb(m)$ = number of business(month) days. The monthly temperatures were used in this analysis for calculating the thermal losses, each day during one month has the same temperature.

The climate definition for the three different locations was obtained via Meteonorm software [48].

The envelope thermal properties and energy consumption of the house was verified against the Belgian regulations [49] although, in Sweden, the insulation thickness was modified in the walls, roof and basement slab of the house in accordance to the climate and regulations. The windows were also attributed a lower U value assuming that, in newly built house, better insulated windows may be used.

Thermal bridges are not taken into account in the basic tool but the comparison with Equer will show that the difference in terms of heat losses remains low.

For the solar gains, namely *S*, a simplified assessment is made. First of all, a proportion of yearly overcast sky days and bright sunny days is calculated on the basis of meteorological data for Belgium (this proportion is equivalent to a weather factor). The mean monthly solar irradiation hitting south, north, east and west oriented vertical surfaces is calculated using weather data for Belgium and the previously cited proportion. Taking into account a dirt factor (0,8), a utility factor (0,6), the G solar value of the window glass, the total yearly solar heating can be calculated. In order to keep the basic tool as simple as possible, for the other locations, the solar gains are multiplied by a coefficient that depends on the solar gains chart provided by the NASA, which is 1 herein for Sweden and 1,3 for Coimbra.

An internal heat gain, called *H*, may result from the heat output of human bodies, lamps, motors and appliances. Human heat gains (HHG), in this study, are evaluated as 75 W during the day and 25 W during the night. Only half of the inhabitants are considered to be inside the house during the day and the total heat gain depends on the chosen scenario. This value may be considered as low seen that, depending on the activity, the human body can release more than 150 W. Typical values for computer, lamps and freezer range between 40 and 100 W also but are not taken into account presently.

The calculation of the energy demand due to ventilation losses, namely *V*, is taken from [50].

In total, the total space heating demand equals

$$SHD = E + V - S - H. \quad (3)$$

2.3.2. Hot water consumption

Each inhabitant is supposed to employ 40 L of hot water per day and the energy demand is calculated subsequently. Cold water consumption is not taken into account.

2.3.3. Building and user electricity

The building electricity is proportional to the heated floor area at a rate of 15 kW/yr. Regarding the user electricity, it is assumed that each person employs 100 W during his stay inside the building, it thus depends on the scenario.

2.3.4. Related CO_2 emissions, i.e., operational carbon

Multiple databases are used in the excel file for the calculation of the materials embodied emissions or “Embodied carbon” (see section 2.2). But CO_2 emissions are also generated during operation and it is the CO_2 emissions that contribute to greenhouse gases and so, those will be displayed. The energy consumption, being for heating space or water, for cooling or for lighting is (via the energy mix for electricity amongst other) transformed into CO_2 emissions. For the regional energy mix, the related impacts were deduced from Ecoinvent database [51]. The energy mixes are gathered from official statistics provided by the International Energy Agency (www.iea.org, see Table 1) and [52]. In Belgium, electricity is thus mainly generated from Nuclear Power and Gas. In Portugal, Natural Gas was first introduced in 1997 and is gaining an increasing share in electricity generation. In Sweden, given the relatively low presence of fossil fuels in the energy mix, low CO_2 emissions are shown.

The impacts (in terms of GHG emissions and primary energy) from electricity generation are thus quite different from country to country. These impacts were calculated using [51] and taken from Equer software (see Table 2).

The Swedish District Heating system also distributes hot water via a grid of pipes to supply space heating and domestic hot water for use. In Luleå, this is the main source for both of them. The underlying central facility is a Combined Heat and Power plant that is nourished by an industrial surplus of the nearby steel mill facility (by-product) and so, the environmental impacts shall be allocated to it. In this case, very low CO_2 emissions are accounted for. In the same line of thoughts, District Cooling via cold water taken from the river is also ensured in Luleå, which is impact free. Moreover, depending on the region, habits and regulations lead to quite dissimilar local water, central heating and cooling systems. The presence of solar flat plate collector or local electricity production

Table 3
Space heating, cooling demand and solar gains calculated with Comfie + Equer and with the basic tool for the masonry house and the steel framed house in Brussels.

	Steel framed house			Masonry house		
	Basic tool	Equer	Δ	Basic tool	Equer	Δ
Space heating + Ventilation losses (kWh/m^2.yr)	55	57.0	3.6%	57	55.0	−3.5%
Cooling demand (kWh/m^2.yr)	3.9	7.0	79.5%	3.7	5.0	35.1%
Solar gains over one year (kW)	4031	4144	2.8%	4031	4144	2.8%

Table 4
Operational and embodied carbon and energy calculated with Equer and with the basic tool calculations for the masonry house and the steel frame house in Brussels.

	Steel framed house			Masonry house		
	Basic tool	Equer	Δ	Basic tool	Equer	Δ
Operational carbon (kg/m^2.yr)	28.7	30.3	5.6%	29.3	29.2	−0.3%
Operational energy (kWh/m^2.yr)	296.3	256.7	−13.4%	298.5	246.7	−17.4%
Embodied carbon (kg/m^2.yr)	3.4	(7.7)	125.1%	4	4.8	20.0%
Embodied energy (kWh/m^2.yr)	18.1	(39.4)	117.7%	18.3	19.0	3.8%

using photovoltaic panels will thus also strongly influence the operational CO_2 emissions, regional scenarios will be considered. All those options are incorporated in the tool.

3. Case-study and preliminary conclusion

The considered house, dedicated to 5 persons, has one floor plus an attic or so-called under-roof space. It accommodates one kitchen, one combined living/dining room, one office, one bathroom, one WC and four bedrooms. The surface area of the house is worth 192 m^2 and the heated volume (100%) is worth 409 m^3. All the information concerning the functional unit, the wall compositions, U-values, ventilation rates, etc is provided in the companion paper. As a matter of fact, one house is considered using two structural systems: masonry and steel frame house. The reference house is firstly modelled in the software Pleiades + Comfie, allowing the user to evaluate the house thermodynamic behaviour. Via Equer, the achievement of the complete LCA is then possible.

Equer software is specialized in LCA of building [53]. It is directly linked with thermal simulation software (Pleiades + Comfie [51].) and geometrical description software that allows the life cycle assessment of a whole building. Equer uses the Oekoinventare 96 life cycle inventory database and derives 12 environmental indicators, among which primary energy consumption and global warming potential (obtained by adding the contribution of all emitted greenhouse gases) will be discussed. These indicators, in majority evaluated according to the CML 1992 methodology [54], correspond to a single building type during its life cycle [55]. The construction, operation and demolition phases can be taken into account. The LCA tool Equer has been compared to seven other building LCA tools in the frame of the European thematic network PRESCO. The calculated CO_2 emissions for a case study were differing by ±10% between the tools, but other environmental indicators like toxicity are more uncertain. Further work is planned to progress towards harmonization of the methods [56]. Equer software is used in the next section to evaluate the validity of the calculations made using the basic tool.

Heating loads (space heating and ventilation losses), cooling demand and solar gains (Table 3) are close together which highlight the validity of the calculations and the assumptions made, as Pleiades + Comfie has been validated by the International energy Agency Bestest (Benchmark for Building Energy Simulation Programs) [57,58].

The basic tool and Equer software give similar results regarding operational carbon and operational energy (Table 4) with a relative difference that doesn't exceed 17,4%. Nevertheless, the calculations include so many different data that it is hard to draw conclusions from a comparison of only two specific buildings. In fact, a comprehensive analysis should compare the single parameters *E, V, S and H* in order to improve the basic tool results but this is out of the scope of this study. Higher differences in embodied carbon and embodied energy highlight the influence of the database on the results, especially for the steel framed house. In fact, the 1996 Oekoinventaere database used in Equer does not provide value for "building" steel elimination and recycling. The comparatively large difference between the embodied impacts of the steel building is explained by different input data. Indeed, the Embodied impacts take the recycling potential of the different materials into account in the basic tool. And, for steel, the recycling potential has an important influence on the accuracy of the results of the basic tool.

It is also worth pointing that the total energy use and total carbon emissions over the life cycle of the house (building + operation phase) are quite similar for the steel frame and for the masonry house (as also illustrated in Figs. 1 and 2) making the results acceptable seen the simplicity of use of the basic tool. So, at least, in an introductory phase, the basic tool can be used for simplified LCA of relatively complicated building and is enough for the comprehension of the relative importance of the embodied impacts, the consequence of a change in the energy mix and local energy harvesting…

The companion paper uses the basic tool presented in this paper to perform the life cycle assessment of a masonry house and a steel framed house in three European locations. The functional unit considered in the LCA and the main assumptions are presented in the companion paper. Then, the influence of several parameters, such as those related to database, heating system and climate are discussed. Finally, we summarize our main findings and discuss their limits and reproducibility. Using one practical case-study, the second part of this paper is dedicated to show that, for instance, such tool could be useful in the pre design phase.

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Appendix A.7

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Life-cycle assessment of residential buildings in three different European locations, case study

Barbara Rossi [a,*], Anne-Françoise Marique [b], Sigrid Reiter [b]

[a] ArGEnCo Department, University of Liège, Liege, Belgium
[b] LEMA, ArGEnCo Department, University of Liège, Belgium

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ABSTRACT

The paper presents the comparative results of the life-cycle assessment (LCA) of one residential building with two constructive systems in Brussels and one steel frame house located in three different European towns: Brussels (Belgium), Coimbra (Portugal) and Luleå (Sweden). In a recent study, a modular building was studied in Coimbra and Luleå. It was shown that in terms of CO_2 emissions, the Use Stage was the most harmful stage during the building life-cycle for Coimbra climate. Contrarily, in Luleå, it was the Product Stage, despite energy consumption being higher than Coimbra, due to the way electricity and heat are generated. In the present study, two structural systems are first compared for the Belgian house: steel frame and traditional masonry. A different life-cycle scenario is taken into account for the steel frame house for the three different locations, in which the monthly temperatures, energy mix, heating and cooling systems are defined. The LCA is carried out using the basic tool described in the companion paper. It is worth recalling that the results obtained with the basic tool were verified against Pleiades + Comfie and Equer software, enabling to carry out a complete LCA, for Brussels. Our results confirm that for all the three climates, the Use Stage (Operational energy) is the most harmful period during the building life-cycle and that the energy mix of the country strongly influences the equivalent CO_2 emissions related to the Use Stage (Operational carbon) and may entirely reverse the conclusions about the life-cycle carbon footprint of the building.

1. Introduction

The total energy use over the life-cycle of a building is an emerging research field although a great number of studies have already been achieved about it. Embodied energy of common construction materials such as timber, steel, glass, insulation or reinforced concrete as well as alternative materials such as phase changing materials is one of the topic currently researched all over the world thanks to the ever-growing concern on sustainability in the construction domain. Two main conclusions can be drawn from current studies about total energy consumption in buildings: (1) the assessment of the Embodied energy in buildings can vary substantially due to a quite high variability in the cradle-to-gate material data as well as regional characteristics (although those differences usually remain tolerable [1]) and (2) the Embodied energy can take an important place in the total life-cycle energy use if passive or zero-energy buildings are considered [2]. In the literature, guidelines for reducing the Embodied energy are also provided usually by selecting low Embodied energy materials, designing lightweight/efficient structures to minimize material consumption, using recycled/reusable materials/components and so by ensuring that materials can be separated, guaranteeing future refurbishment and adaptability instead of demolition, preferring locally sourced materials. The most important one is obviously to design for long life using durable low maintenance materials.

The present study focuses on steel frame residential houses located in three different towns: Brussels (Belgium), Luleå (Sweden) and Coimbra (Portugal). The objective of the study is to compare the Embodied energy with the Operational Energy first of all but also to evaluate the corresponding Operational carbon via assumptions on the local resources used to produce energy for heating, cooling, warming water and supplying electricity. The three regions considered indeed show highly different climates but also very different energy mixes as well as regional characteristics such as the use of solar flat plate collector to heat water in Coimbra or District Heating in Luleå.

Section 2 presents the functional unit considered in the LCA and the main assumptions. Let's recall that the methodology, the

* Corresponding author.
E-mail addresses: barbara.rossi@ulg.ac.be (B. Rossi), afmarique@ulg.ac.be (A.-F. Marique), sigrid.reiter@ulg.ac.be (S. Reiter).

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assumptions, the indicators (Embodied energy/carbon and Operational energy/carbon) and the basic tool used for the LCA are described in the companion paper. In Section 3, the results of the calculations are presented. First of all, two constructive systems are compared in Brussels climate. Secondly, the steel frame house is located in three different European towns and the influence of the climate and energy mixes is assessed. Finally, the main conclusions of both papers are presented and discussed in Section 4.

2. Functional unit

2.1. Reference house

For the purpose of the study, a reference house was designed based on the most common characteristics of typical detached Belgian houses [3]. The considered house has one floor (ground floor), plus an attic or so-called under-roof space. Basement floor is not taken into account in the present study. The house accommodate one kitchen, one combined living/dining room, one office, one bathroom, one WC and four bedrooms. The surface area of the house is worth 192 m^2 and the heated volume (100%) is worth 409 m^3. Figs. 1 and 2 present the plans and a 3D model of the reference house.

2.2. Composition of the envelopes

Even though the traditions may differ from one region to another, we considered the same reference house in the three climates to focus on the influence of materials, climate and energy mix in the analyses. The steel frame was based on the European Light Steel Construction Association recommendations and the masonry model is based on standard usage in Belgium. The insulation thickness used in the reference case is designed according to the current thermal regulations in Belgium [4] that limit the *U*-value of walls, roofs and slabs, respectively to 0.4, 0.3 and 0.4 W/m^2 K (amongst other regulations). Double glazed timber windows and wooden insulated doors were used. The insulation thickness (and windows type) was slightly modified in Sweden to fit the local regulations regarding the energy performance of buildings (the Swedish regulations limit the maximum energy consumption of the building, if it's located in the North part of the country, to 95 kWh/m^2 year), which is more difficult to obtain in Sweden than in Belgium due to its colder climate.

The compositions of the envelopes and the corresponding *U*-value are indicated in Table 1 for each type of external wall of the masonry house and in Table 2 for the steel frame house. Note that the thicknesses are to be understood with care seen that, for steel purlins namely, the quantity of material is somehow transformed into an equivalent thickness during the manual calculations. Thus, the number of purlins per metre must be mentioned during the evaluation. Those dimensions could be somewhat reduced (let's say optimized) by considering for instance sandwich panels in the roof and less high profile in the walls, but this is not the scope of this research. Finally, the design of the house leads to a quantity of steel of 64 kg/m^2 distributed in the different walls as indicated in the Table 3. The interested reader can find more information on cradle-to-gate assessment of steel frame walls, roofs or floors in [5]. The necessary moisture and air barrier are not indicated in the present research nor taken into account in the LCA neither are the plumbing devices, finishes or furniture.

Database used in the LCA manual calculations are mentioned in Tables 1 and 2. BEES is the database included in the **B**uilding for **E**nvironmental and **E**conomic **S**ustainability software developed by the National Institute of Standards and Technology (U.S.) and CRTI is the database published by the Centre de Ressources Henri Tudor. Both databases are freely available online and well documented in terms of sources, functional unit considered and so forth. Comparisons were made against the Inventory of Carbon & Energy database of the University of Bath (Sustainable Energy Research Team) and EcoInvent database in order to assess the level of confidence of our database.

3. Results and discussions

3.1. Masonry house VS steel frame house in Brussels

In the companion paper, the reference house was modelled in the software Pleaides + Comfie [6], allowing the user to evaluate the house thermodynamic behaviour. Via Equer [7], the achievement of the complete LCA was possible. The results were used to verify the validity of the manual calculations indicating the level of confidence to be put in our calculations. This analysis was made for the steel fame and the masonry houses located in Brussels. In the next section, the steel house envelope composition is slightly modified such that the materials embodied CO_2 emissions almost reach the masonry house ones. As a result, the energy consumption of the steel frame house decreases.

Actually, the previous comparison described in the companion paper, intended for validating our manual calculations furthermore showed that both houses construction methods lead to very similar Embodied carbon and Operational energy. So, increasing the insulation thicknesses in order that the steel house reaches the same Embodied carbon permit us to conclude that, if the roof and exterior walls can reach a lower *U*-value, the heat losses are even more decreased for the steel frame house. The space heating demand is thus decreased to 76% of its previous value that equalled 43 kWh/

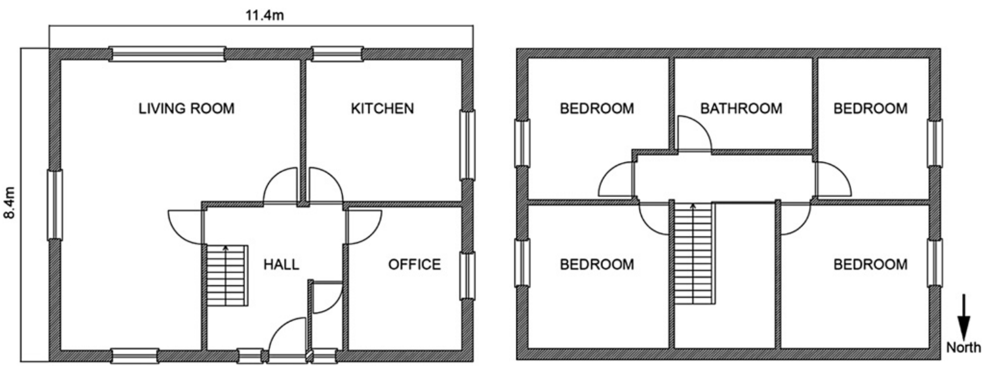

Fig. 1. Plans of the ground and attic floors of the reference house.

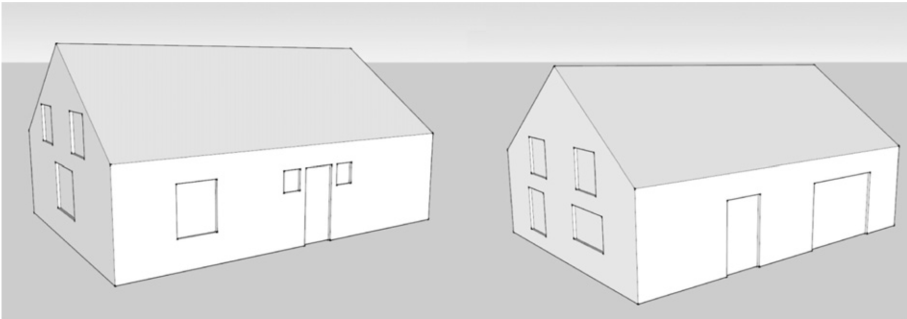

Fig. 2. 3D model of the reference house.

HFA yr if the insulation thickness in the exterior walls, the roof and the slab are respectively increased to 160 mm, 240 mm and 120 mm The results of the manual calculations are indicated in Table 4.

In Fig. 3, both case studies are represented in terms of Embodied carbon (production of materials) whereas Fig. 4 provides the Operational carbon versus Embodied carbon throughout the life-span of the building. These results are coherent with an analysis carried out in the University of Liège on houses presenting various types of envelope [8].

It is then possible to affirm that the Use Stage is the most harmful period during the building life-cycle in terms of Operational carbon. In the same line of thoughts, the energy consumption is the major source of impacts. But the lifetime is crucial to draw general conclusions from the case study. With a very long reference time or a relatively high operational energy use, the embodied impacts can seem comparatively small. And if the lifetime or the operational energy decreases (even by a small percentage), the relative yearly impacts (operational to embodied impact) can rise up to more than 50%.

Coming to the Embodied carbon, it is possible to reach the legislation requirements with fewer materials emissions for the steel house than for the traditional masonry house at least on the basis of the present assumptions, taking into account the recycling credits for steel.

Analysing the share of Embodied energy of each part of the building, it is not possible to make one part responsible for the biggest amount of Embodied energy. The exterior walls, the roof, the ground floor, the intermediate floor have, more or less, the same importance. The ground floor is nevertheless the biggest contributor to the impact mainly because of the reinforced concrete foundation. In the masonry house, the difference in Embodied carbon comes from the roof, intermediate floor and the internal walls. One could claim that the non consideration of the recycling of non-metallic materials leads to overestimated results. For wood, which uptakes CO_2, the end-of-life (burning with energy recovery) increases the Global warming potential impact while producing energy. So the manual calculations would yield even more unfavourable results for the masonry house. For concrete blocks and bricks, used material can be broken down into chips, which can be used for landscaping, or broken down further to be used as aggregate for new construction materials. About 75–80% of secondary and recycled aggregates are thought to end up as sub-base and fill, including use in road building and airfield pavements. Recycled aggregates can also be used to replace a part of the aggregates in concrete. But, recycled aggregate will typically have higher absorption and lower specific gravity than natural aggregate and will produce concrete with slightly higher drying shrinkage and creep. These differences become greater with increasing amounts of recycled fine aggregates. In Ref. [9], the LCA results show that the impacts of cement and aggregate production phases are slightly larger for recycled aggregates concrete than for natural

Table 1
Composition of the envelope of the steel frame house.

	Material	Thickness (mm)		Database
Basement slab	Slab on grade	150		BEES
($U_{SH} = 0.36$ W/m^2 K)	Expanded polystyrene	80		CRTI
	Slab (cement mortar)	60		CRTI
	Plywood sheathing	20		CRTI
	Plaster slab	13		CRTI
External wall	Steel siding	0.8	100%	WORLDSTEEL
($U_{SH} = 0.35$ W/m^2 K)	Rockwool insulation	120		CRTI
	Steel studs	260	2.7–100%	WORLDSTEEL
	Steel internal supports	20	1–50%	WORLDSTEEL
	Plaster board	13		CRTI
Roof	Steel roof tiles	0.8	100%	WORLDSTEEL
($U_{SH} = 0.21$ W/m^2 K)	Steel rafters	60	1–50%	WORLDSTEEL
	Steel purlins	260	2.7–100%	WORLDSTEEL
	Rockwool insulation	200		CRTI
	Steel internal supports	20	1–50%	WORLDSTEEL
	Plaster board	13		CRTI
Floor	Plaster slab	13		CRTI
	Plywood sheathing	20		CRTI
	Rockwool insulation	40	2.7–100%	CRTI
	Steel beams	260	1–50%	WORLDSTEEL
	Steel internal supports	20		WORLDSTEEL
	Plaster board	13		CRTI
Internal walls	Plaster board	13		CRTI
	Rockwool insulation	40		CRTI
	Steel internal supports	40		WORLDSTEEL
	Plaster board	13		CRTI

Table 2
Composition of the envelope of the masonry house.

	Material	Thickness (mm)		Database
Basement slab	Slab on grade	150		BEES
($U_{SH} = 0.35$ W/m^2 K)	Expanded polystyrene	80		CRTI
	Slab (cement mortar)	60		CRTI
	Plywood sheathing	20		CRTI
	Plaster slab	13		CRTI
External wall	Clay brick	100		CRTI
($U_{SH} = 0.37$ W/m^2 K)	Expanded polystyrene	80		CRTI
	Concrete blocks	190		CRTI
	Plaster	13		CRTI
Roof	Ceramic roof tiles	18		CRTI
($U_{SH} = 0.22$ W/m^2 K)	Plywood sheathing	10		CRTI
	Rockwool insulation	180		CRTI
	Timber	230	5%	CRTI
	Timber	19	8%	CRTI
	Plaster board	13		CRTI
Floor	Slab	80		CRTI
	Reinforced light concrete slab	90		CRTI
	Plaster	13		CRTI
Internal walls	Plaster	13		CRTI
	Concrete blocks	190		CRTI
	Plaster	13		CRTI

Table 3
Distribution of the steel weight within the walls.

Wall designation	% of steel
Roof	43
Floor	21
External walls	27
Internal walls	9

aggregates concrete mainly because of transportation. In fact, even if, in an LCA, the original concrete is produced with recycled aggregates, the production of cement is the main contributor to all studied impact categories. It causes approximately 77% of the total energy use and 88% of the total GWP. The main reason for such a situation is a large CO_2 emission during the calcinations process in the clinker production and the fossil fuel usage. The contribution of the aggregate and concrete production and demolition is very small. The same conclusions are drawn in [9]. At this stage, it is important to note that the transportation related to the end-of-life is taken into account with a higher distance for metallic materials than for non-metallic materials. Even though, the preliminary conclusion is still the same.

3.2. Comparative analysis in three different locations

3.2.1. Introduction

To be able to draw general conclusions, it is necessary to conduct a sensitivity analysis of the results to chosen parameters to truly understand their influence on the final values. Herein, the goal is to compare the LCA results of a building located in three different towns and to assess the influence of climate and energy mix. The following parameters (inputs) are thus not included in the sensitivity analysis seen the fact that they don't change the conclusion of the comparative analysis, although having (for some of them) a strong influence on the final results:

(1) Transportation modes and distances could differ from one town to another but as it is only slightly affecting the results, it is thus not considered in the sensitivity analysis;
(2) The energy mix: different energy mixes for electricity production will be considered for the three climates but, in one country, the energy mix will not be modified;
(3) The scenario and envelope composition: naturally, if the occupation scenario, demanded temperature or insulation type are modified, the indicators change consequently. Herein those parameters will be kept constant but the interested reader can refer to [10] and [11] for more information;
(4) The house configuration, the percentage of windows, the house plan, the envelope composition and orientation are of course of great influence on the final results. They will remain unchanged in the present sensitivity analysis;
(5) The presence of local heat/electricity production or energy saving equipment was not investigated in the present paper, although ventilation heat recovery is taken into account because it is becoming a common measure in new built house. Nevertheless, its influence will be briefly discussed;
(6) The carbon payback will be indicated on the next graphs and, naturally, a modification of the lifespan (50 years until now) will influence it.

Table 4
Manual calculations – Masonry house versus steel house (kWh/m^2 yr).

	Masonry	Steel
Building Electricity (including cooling and double flux ventilation)	20.97	21.97
User Electricity	18.79	18.79
Total electricity demand	39.76	40.75
Space heating	44.85	32.38
Ventilation	12.07	12.07
Hot water	5.57	5.57
Total heating demand	62.50	50.02
Heat recovery (double flux ventilation)	−9.05	−9.05
Total bought energy for heating	53.44	40.97
Total energy demand	102.26	90.77
Total bought energy	93.20	81.72
Without user electricity	74.42	62.93

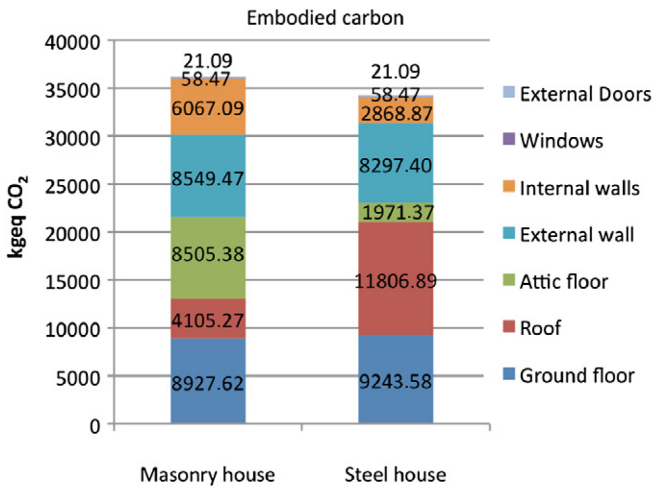

Fig. 3. Manual calculations – Share of each building part in the Embodied carbon – Masonry house versus steel house.

The influence of two important parameters was so therefore assessed since they might have an influence on the main conclusion stated before:

(1) The database: The quality (precision, completeness, representativeness) of the data used can have a significant impact on the results of an LCA. The existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of LCA results. First of all, it can be seen that Equer database (EcoInvent) and the databases used in our manual calculations provide similar results for the masonry house (see the companion paper). The uncertainties in the database yield to tolerable differences as far as these impacts are concerned. Secondly, the steel embodied emissions initially taken as EcoInvent ones in Equer, were replaced by the Worldsteel database (IISI 2002) taking into account the recycling of steel at the end of its life in our manual calculations ([12] and [13]) It was shown that the end-of-life credits have a strong influence on the Embodied carbon/energy of the steel house.
(2) The design of the steel house: It was shown that the quantity of steel used per HFA, that was initially evaluated as 64 kg/m^2, can be increased to approximately 25% of its value, and that, in order to reach the Embodied carbon of the masonry house. Similarly, if the design is modified and the steel quantity increased, the Embodied carbon will increase subsequently in all climates. It is thus concluded that the design of the house presented in this analysis does not affect the final conclusion of the paper.

On top of these considerations, the main conclusions are provided in the next paragraph which highlight the influence of the energy mix and climate.

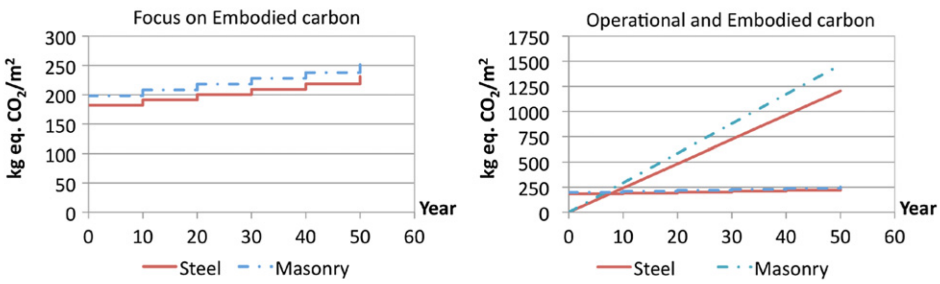

Fig. 4. Manual calculations – Operational and Embodied carbon versus lifespan for steel and masonry houses.

Table 5
Regional scenarios for energy supply.

	Belgium	Portugal	Sweden
Space heating	Natural gas	Oil	District heating
Hot water	Natural gas	Oil	District heating
Cooling	Belgium mix	CO_2 free electricity	District cooling
Building elec.	Belgium mix	Portugal mix (20%)	Sweden mix
User elec.	Belgium mix	Portugal mix (20%)	Sweden mix

3.2.2. *Influence of the energy mix and the climate*

First of all, in [13], it was showed that the electricity mix used in the analysis widely influences the LCA of the building. In the case study provided in the companion paper (masonry house for instance, but the same conclusion can be drawn for the steel house), the fraction of GWP due to electricity consumption (13.14/22.85 = 45%) is higher than the proportion of electricity in the total energy content (39.76/102.26 = 39%) and this fraction raises 72% (215.36/298.5) if the Operational energy is concerned. Secondly, if an alternative electricity mix is considered for the previous analysis, using for instance 35% of renewable sources (based on European policy goals for 2020), it will lead to a GWP and Energy reduction of 10% and 20% respectively.

Besides, the use of one wood furnace as back-up heater in winter can significantly reduce the GWP (up to 12% in this case study), the reason lays of course in the heating system that uses natural gas in Belgium and is therefore highly releasing CO_2. In the frame of this analysis, Oil was also considered for providing heat and how water in Belgium, because it is as popular as the use of natural gas. In this case, the GWP is increased by 12% whereas Primary energy remains more or less the same.

Finally, two more different climates are studied for the steel house with, obviously, their regional energy mixes (see companion paper) and heating systems most likely to be used for each region (see General Direction of Energy and Geology http://www.dgge.pt and [14–17]). The assumptions and results are summarized in Table 5 and Table 6 for the three regions. The Swedish District Heating system, distributing hot water via a grid of pipes to supply space heating and domestic hot water for use, uses a Combined Heat and Power plant that is nourished by an industrial surplus of the nearby steel mill facility (by-product). In this case, very low CO_2 emissions are observed.

To be perfectly clear, in this study, Embodied energy/carbon accounts for all impacts related to Product, Construction, Installation and End-of-Life (only partly), its value remains constant throughout the lifetime of the building. Operational energy/carbon is related to the energy needs during the life of the building and is thus proportional to the lifetime. As a matter of comment, normally, the Embodied impacts that include maintenance, repair or refurbishment should be dependant of the lifetime also. Indeed, depending on the considered moment of replacement or refurbishment, the Embodied energy/carbon is commonly represented using a stair graph.

In Table 7, the results are given in terms of Operational and Embodied energy as well as Operational and Embodied carbon for the three climates. The influence of the energy mix is clearly visible in the Operational carbon line. As for the Fig. 5, it depicts the Operational and Embodied energy/carbon together for the three case studies versus the lifespan.

First of all, in the frame of this study that concerns "ordinary" well-insulated house and not "passive" or "zero-energy" houses, it is possible to affirm that the Use Stage is the most harmful stage (in terms of energy consumption) during the building life-cycle for the three climates, which is also clearly stated in Tables 6 and 7. The total Operational energy (after the whole life which is, indicatively, taken as 50 years herein) is much higher than the Embodied energy.

Secondly, the Embodied carbon payback (the number of years required for the Operational carbon to exceed the Embodied carbon) is smaller than 50 years for Belgium and Portugal, whereas for Sweden, it equals 87 years (see Fig. 5 showing the Operational carbon over the lifespan together with the Embodied carbon although the embodied impacts are more visible in Table 7).

In the same line of thoughts, the Operational energy consumption is the major source of impacts for Belgium and Portugal, even if

Table 6
Results (kWh/m^2 yr).

	Belgium	Portugal	Sweden
Building Electricity (including cooling and double flux ventilation)	21.97	33.44	20.21
User Electricity	18.79	18.79	18.79
Total electricity demand	40.75	52.22	39
Space heating	32.38	11.77	62.57
Ventilation	12.07	6.57	26.15
Hot water	5.57	5.57	5.57
Total heating demand	50.02	23.91	94.29
Heat recovery (double flux ventilation)	−9.05	−4.93	−19.61
Total bought energy for heating	40.97	18.99	74.68
Total energy demand	90.77	76.13	133.29
Total bought energy	81.72	71.21	113.68
Without user electricity	62.93	52.42	94.89

Table 7
Operational and Embodied carbon/energy, Payback.

	Belgium	Portugal	Sweden
Operational carbon (kg/m^2 yr)	24.09	38.72	2.79
Operational energy (kWh/m^2 yr)	274.41	174.72	327.79
Total Embodied carbon (kg/m^2 yr)	4.62	4.62	4.89
Total Embodied energy (kWh/m^2 yr)	24.39	24.39	26.18
Embodied carbon payback	9.59	5.97	87.47
Embodied energy payback	4.44	6.98	4.89

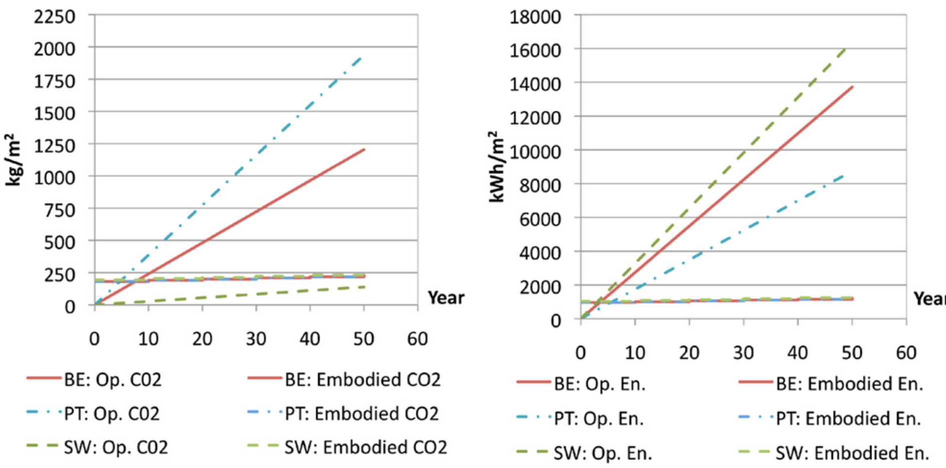

Fig. 5. Operational and Embodied energy/carbon (for the three climates).

the three case studies exhibit a strongly different response to their respective energy mixes combined with a totally different heating demand for the three cases. Especially, the way the electricity supplied to the households has been generated has a strong influence on the results. While for Belgium and Portugal, one could claim that the Embodied carbon is still not the most important contributor to this environmental impact, for Sweden, it is not anymore the case. The very low emissions associated to the production of electricity or heat reveal especially low Operational carbon.

4. Final conclusion

The companion paper described the development of a basic tool used for the life-cycle assessment of buildings located in different European climates. This tool permits the evaluation of the Embodied energy, the Embodied equivalent CO_2 emissions (or Embodied carbon), the Operational energy (or yearly energy consumption of the buildings) and the Operational carbon. The influence of the energy mix (solar water heater, district heating, etc) is included in the basic tool. This simplified tool has been verified thanks to a comparison between our calculations and results of already validated tools: the software Pleiades + Comfie combined with Equer. The basic tool can be used for simplified LCA of relatively complicated building. It provides information on the relative importance of the embodied impacts, on the consequence of a change in the energy mix or local energy harvesting. In addition to the uncertainties linked to LCA presented in the introduction of the companion paper and as in all LCA studies, the results must however be interpreted carefully according to the assumptions used in the calculation. Finally, note that the behaviour of the inhabitants, the economics criteria and the energy consumptions relating to services are beyond the scope of our study, which explains the differences in results of LCA carried out with others methods such as the hybrid LCA.

However, our results confirm the existing literature highlighting that, from an entire building life-cycle perspective, the operation phase represents the highest environmental impact (62–98% of the life-cycle total impacts). So, trying to reduce fluxes (energy, water and waste) during the utilisation phase seems to be the first action to achieve. But how? The usual way encountered in many countries is to decrease the Operational energy by increasing the insulation thickness and air leakage protection leading to very low or even zero-energy houses. But, the present paper and recent researches seem to highlight that the energy mixes strongly influence the Operational carbon especially when district heating is considered. We have shown how a shift in the energy mix towards renewable sources yields significant reductions, even without reducing energy consumptions. This is especially true in Sweden where a very cold weather inducing quite high heating demand is nevertheless responsible for less environmental impacts. In this respect, it should be interesting to investigate the Embodied and Operational energy and carbon of the same houses in radically different climates, including a city of tropical climate. CO_2 free electricity production or solar water heating flat plates can also reduce those impacts but to a shorter extent. The consequence of such decrease is that the Embodied impacts take a more representative place within the buildings life-cycle analysis when the energy mixes are more environmental. And, in those cases, green materials become of great interest. Last, it is worth pointing, that steel frame could lead to less Embodied impacts than masonry when taking into account the recycling credits.

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Appendix A.8

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Retrofitting the Suburbs: Insulation, Density, Urban Form and Location

Anne-Françoise Marique (Corresponding author)
University of Liege (Belgium), Architecture and Urban Planning
Local Environment: Management & Analysis (LEMA),
Chemin des Chevreuils, 1 B52/3 B-4000 Liège (Belgium)
Tel: 32-4366-9367 E-mail: afmarique@ulg.ac.be

Sigrid Reiter
University of Liege (Belgium), Architecture and Urban Planning
Local Environment: Management & Analysis (LEMA),
Chemin des Chevreuils, 1 B52/3 B-4000 Liège (Belgium)
Tel: 32-4366-2909 E-mail: Sigrid.Reiter@ulg.ac.be

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Abstract

The effects of urban sprawl have been well documented, particularly regarding energy consumption. Suburban neighbourhoods are known to be energy inefficient and urban sprawl is considered as a major issue for sustainable development. To improve the energy efficiency of existing suburban urban fabrics is a major challenge that must be addressed to favour a sustainability transition of our built environment. In this context, this paper aims at investigating several scenarios that could be developed to improve the sustainability of existing suburban neighbourhoods: three main types of scenarios (building insulation, density, and urban form) and twelve sub-scenarios, which are focused on the possible evolution of the existing suburban building stocks, are proposed. Quantitative methods developed in previous research are used to assess and compare building and transportation energy consumption of a representative suburban case study. This application aims at investigating two main research questions: (1) "how to intervene in suburban neighbourhoods?" and (2) «where to intervene?" The main results of this application, which are focused on energy efficiency, are then studied in a larger framework to highlight their opportunities and constraints. The main findings of the paper are that, beyond the traditional polarisation of the debates on the energy efficiency of our built environment between the "compact" and the "sprawled" city, a new pragmatic paradigm, which is focused on the smooth densification of existing suburban neighbourhoods, can make them evolve towards greater sustainability.

Keywords: Urban Sprawl, Suburban retrofitting, Energy efficiency, Urban form, Smooth densification

1. Introduction: Urban Sprawl and Energy Efficiency in Urban Planning

The process of urban sprawl, which commonly describes physically expanding urban areas, is a major issue for sustainable development (EEA, 2006). Urban sprawl is known to represent a significant contribution to the overall energy consumption of a territory, particularly for energy needs in buildings and for transport. The environmental effect of urban sprawl and uncontrollable urbanisation are receiving an increasing amount of attention and may lead to various issues such as environmental pollution or large-scale climate change (CPDT, 2002; He et al., 2011; UTF, 1999; Young et al., 1996). However, despite the growing importance of energy issues in public debate, low-density suburban developments continue growing regardless of their location. Even new districts that set themselves up as "eco" or "sustainable" are sometimes built far from city centres and are not necessarily ecological because of the high transport energy consumption (Harmaajärvi, 2000). Such developments are found all over Europe, the United States and even emerging countries (Nesamani, 2012; da Silva et al., 2007; Yaping and Min, 2009)and have become an important part of our contemporary metropolitan areas (Phelps, 2012). An evaluation on the sustainability of these suburban neighbourhoods is necessary and requires the appropriate methods and tools.

The problems of urban sprawl and its numerous environmental, economic and societal effects inevitably refer to the question of "urban form" and its densities and, in particular, the validity of two prevailing and opposite models: the "compact city" and the "sprawled city". The opponents of sprawl articulate the "compact city" model in opposition to the "sprawled city" model using the concepts of centrality, high density, mixed use and performing urban transportation systems. Numerous authors argue that more compact urban forms will significantly reduce the energy consumption in both the building and the transportation sectors (e.g., Ewing et al., 2008; Gillham, 2002; Newman and Kenworthy, 1989 and 1999; Riera and Rey, 2013; Steemers, 2003). However, the concrete feasibility of this model, which is often presented as an ideal urban form, is questionable. In fact, numerous research studies and policies at the national, regional and local levels pretend that it is crucial to favourthe compactness of cities and to thwart urban sprawl but do not propose adequate tools or policies to meet these goals. Moreover, several effects that are related to high compactness (such as congestion, pollution, increase of land prices, etc.) are not adequately addressed. In addition, in numerous European countries, the renewal rate of the building stock is notably low (1 to 2% per year), which implies that the main challenge is this existing building stock and its transition towards greater energy efficiency and greater sustainability. More problematically, this model does not propose any solution for the existing suburban building stock.

The "sprawled city" model dates back from the 19th century and was first developed to reduce the use of urban soil and the production prices. Because the transport costs rapidly declined and the travel speed increased (Ewing, 1994), the mobility levels per capita have substantially increased over the recent past and have favoured the development of suburban neighbourhoods. The sprawl is believed to be facilitated by car ownership and use and to contribute to them in a positive feedback loop that reinforces both low-density development and motorisation (Gilbert and Perl, 2008). Ewing (1994) and Urban Task Force (1999) also defined sprawl in terms of "undesirable" land-use patterns. However, if some authors are clearly critical of suburbs, others propose a more critical conversation (Modarres, 2009). Sprawl often induces lower land prices and more affordable housing (Gordon and Richardson, 1997). The low-density developments mean more space and a higher standard of living for numerous households and constitute one of the preferred living accommodations (Berry and Okulicz-Kozaryn, 2009; Couch and Karecha, 2006; Gordon and Richardson, 1997; Howley, 2009). However, the promotion of this development model even at notably high construction standards (low energy or passive standards that limit the heating energy requirements of buildings at 60 and 15 kWh/m ²year, respectively) will not help to solve numerous problems that are related to urban sprawl, such as soil waterproofing, car dependency or the costs of infrastructure, networks and services.

Three main types of strategies could be investigated to limit the urban sprawl at the regional / national level. The first strategy could consist in an adaptation of the urban planning regulation framework to prohibit the urbanisation of new suburban neighbourhoods in a plain area. However, this strategy seems unrealistic because of its numerous financial consequences (compensation for depreciation, etc.). Moreover, this strategy is only efficient at a large (national) scale. The second strategy, which is often mobilised in the current policies, favours the urban renewal of city centres to propose dwellings that are better adapted to the new comfort and insulation standards (houses with gardens for families, etc.) The third strategy that could be developed follows the same goal as the previous one and consists in building new sustainable neighbourhoods located near good transportation hubs, with have attractive green and public spaces, high quality of life, etc. These last two scenarios could favour a soft transition of our built urban environment towards greater sustainability, but there is one major limitation: they do not consider the future and the possible evolutions of the numerous existing suburban neighbourhoods.

There are intervention scenarios for the existing suburban neighbourhoods to adapt them to climate change, which have been recently developed in the literature, particularly in the United States of America, the United Kingdom and Australia (e.g., Dunham-Jones and Williamson, 2011; Modarres and Kirby, 2012; Rice, 2012; Tachieva, 2012; Williams et al., 2013). These authors propose concrete approaches, at the local level, to retrofit suburbs and increase their sustainability. Amongst various approaches (e.g., an increase in the diversity of functions, good public transportation, a retrofitting of existing networks to increase walking), an increase in the density of both people and uses is often presented as the key means for success. In France, the intensification of suburban areas is also an emerging research topic. A recent French research was dedicated to the issue of Bimby, or "Build In My Back Yard" (Miet and Le Foll, 2013) and specifically proposed to exploit the large land resources available in suburban gardens to accommodate new dwellings. Since the first works on this issue of residential developments in gardens (Whitehand et al., 1991), and despite its potential for suburban intensification and urban compactness, this topic remains relatively little-researched (Sayce et al., 2012). Moreover, and more generally speaking, although one of the main aims of the approaches developed to retrofit suburban areas is to increase their sustainability, their energy efficiency is not evaluated.

In this context, this paper investigates the necessary conditions to improve the energy efficiency of existing suburban areas, by focusing on the impact of urban planning on building and transport energy consumptions at the neighbourhood scale. The following sections present (1) three main retrofitting scenarios that can be investigated to favour this evolution of suburban areas, (2) a quantitative method to assess the energy efficiency of these scenarios regarding thebuilding and transport energy consumptions at the neighbourhood scale, (3) its application to one representative neighbourhood in Belgium and (4) the confrontation between these results, focused on the energy efficiency, with the required practical conditions to achieve the proposed scenarios, such as the regulation framework, the cost and the social acceptability of the proposed measures. Finally, our main findings are summarised to conclude the paper and offer perspectives for further study onsustainability, energy efficiency and retrofitting in the suburbs.

2. Retrofitting Scenarios

In this paper, three main scenarios that address a possible evolution of these existing suburban neighbourhoods are investigated and assessed. These scenarios address the characteristics of buildings and urban form. They do not address parameters that are not directly linked to urban planning. The behaviour of the inhabitants, that is known to have a significant impact on energy consumption, is not discussed in this paper that focused on urban form. The behaviour of the inhabitants in suburban houses has been extensively studied in a previous paper (de Meester et al., 2013).

2.1 Improving the Insulation of the Existing Suburban Building Stock

The first scenario improves the insulation of the existing suburban building stock without any other intervention on the urban form of the existing neighbourhoods (thus, it maintains their characteristics in terms of the density, the diversity of functions, etc.). These scenarios are identified in the following of this paper by the letter “A”. Five sub-scenarios are defined to capture different levels of intervention: A1 -insulating the roof with 20 centimetres of mineral wool, A2 -insulating the roof and replacing the glazing, A3 -retrofitting the entire envelope to fit the actual energy requirements for new buildings, A4 and A5 -retrofitting the entire building envelope to satisfy the low-energy (heating requirements < 60 $kWh/m^2 year$) and the passive (heating requirements < 15 $kWh/m^2 year$) standards, respectively.

2.2 Increasing the Built Density of Existing Suburban Neighbourhoods

The second scenario addresses an increase in the built density of the existing neighbourhoods by constructing new houses or apartments in the gardens, where land opportunities are available. There are identified by the letter “B” in the following of the paper. Four sub-scenarios are defined. In B1, new dwellings are built on the remaining unoccupied plots. In B2, the existing plots are divided to construct new dwellings at the bottom of the plots. In B3, new dwellings (detached houses) are built among the existing houses.In B4, new dwellings (terraced houses) are built among the existing houses. These four sub-scenarios are illustrated on Figure 1.

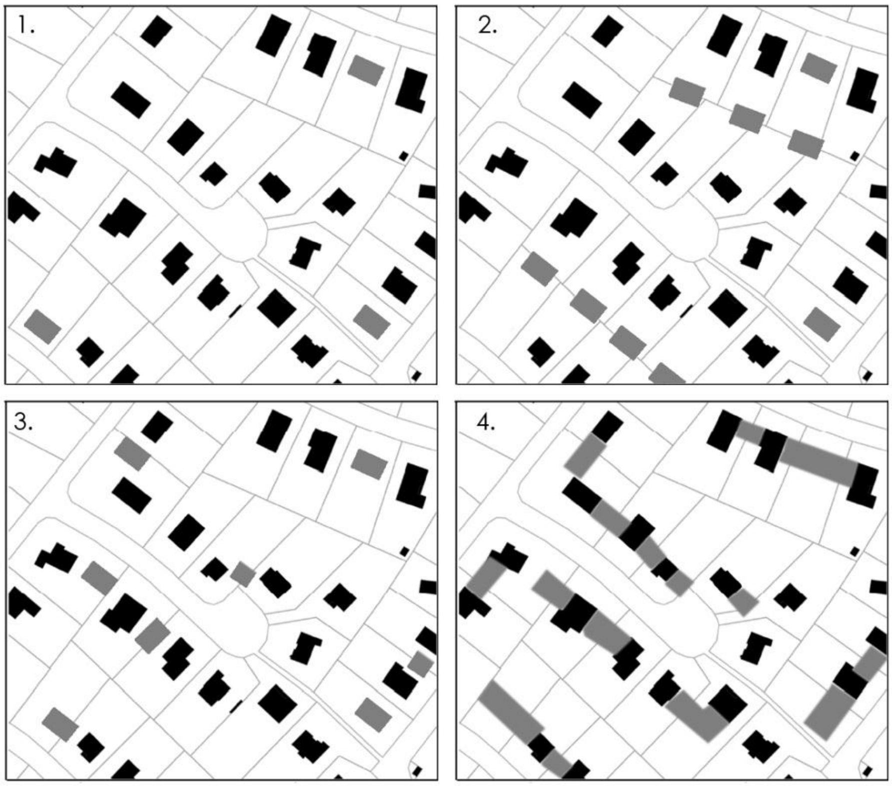

Figure 1. Illustration of the four sub-scenarios that increase the built density of the existing suburban neighbourhoods thanks to the construction of new dwellings in the gardens (the existing houses are in black, and the new dwellings are in grey). In B1, new dwellings are built on the remaining unoccupied plots. In B2, the existing plots are divided to construct new dwellings at the bottom of the plots. In B3, new dwellings (detached houses) are built among the existing houses. In B4, new dwellings (terraced houses) are built among the existing houses.

2.3 Re-Building More Compact Suburban Neighbourhoods

The third scenario is the most theoretical because it implies to demolish existing neighbourhoods and to re-build new neighbourhoods. It investigates the energy efficiency of more compact urban forms than the “detached houses”. This scenario is proposed because it allows the comparison between low-density suburban neighbourhood and more compact urban forms, for one fixed level of insulation, the same number of dwellings and the same built surface area. Scenarios dealing with urban form are identified by the letter “C” in the following of the paper. C1 is the reference case; the urban form of the suburban neighbourhood remains unchanged (the detached houses are built on large individual plots), but the houses are built according to the actual European standard for new buildings, which includes the energy requirements. Two more sub-scenarios are defined. In these sub-scenarios, the number of dwellings and the built surface area remain constant; however, in C2, the dwellings are terraced houses (ground floor + 1 floor) that are organised in the traditional urban blocks, whereas in C3,the dwellings are collective apartment buildings (ground floor + 2 or 3 floors) as illustratedin Figure 2. In the sub-scenarios C2 and C3, the dwellings are built according to the actual standard for new buildings regarding the energy requirements for heating.

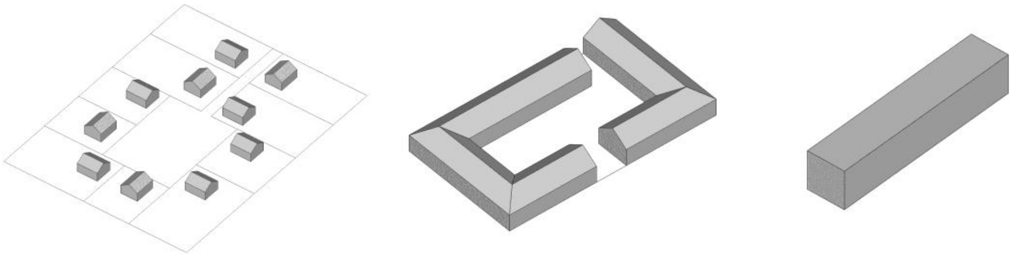

Figure 2. Schematic representation of the reference case and the two sub-scenarios dealing with more compact urban forms. Sub-scenario C1 (illustrated on the left of this image) C1 is the reference case; the urban form of the suburban neighbourhood remains unchanged (the detached houses are built on large individual plots), but the houses are built according to the actual European standard for new buildings, which includes the energy requirements. In sub-scenario C2 (middle), the dwellings are terraced houses (ground floor + 1 floor) that are organised in the traditional urban blocks, whereas in sub-scenario C3 (right), the dwellings are collective apartment buildings (ground floor + 2 or 3 floors).

3. Method and Assumptions

A method was developed to evaluate the energy consumption of the suburban neighbourhoods and the retrofitting scenarios. The first part of the method, which calculates the energy requirements of the buildings and the assumptions that were used are extensively presented in Marique and Reiter (2012a). The methodology combines a typological classification of buildings (based on the common ownership, the number of level and the surface area of the dwelling; see also Marique and Reiter (2012a) for more details), thermal dynamic simulations and statistical treatments of national censuses to assess the annual energy consumption for space heating, space cooling, ventilation, appliances and domestic hot water. The energy consumption and the primary energy consumption for space heating, cooling and ventilation at the neighbourhood scale are calculated by adding the results from the energy simulations for each type of house according to their distribution in the neighbourhood. The energy consumptions of the appliances, for cooking and domestic hot water are not considered in the framework of this paper. Note also that empirical surveys (ICEDD, 2005; Kint, 2008) show that heating represents the largest portion of the overall energy consumption of Belgian households (76%).

The second part of the energy assessment addresses the energy consumption for daily mobility, which is assessed using a commute-energy performance index that was developed by Boussaux and Witlox (2009) and adapted by Marique and Reiter (2012b) for suburban areas.

Assumptions taken into account for the Belgium context were presented extensively in Marique and Reiter (2012b). This index is expressed in kWh/travel.person and represents the mean energy consumption per territorial unit for travel for one person who lives within a particular neighbourhood. This index considers the travelled distances, the means of transport and its relative consumption rates, which are expressed by equation (1). This index was calculated and mapped for the whole Belgium territory, using a GIS tool, at the "census block" scale. In Belgium, the "census block" (or neighbourhood) is the smaller territorial unit in which statistical data are available.

$$Energy\ performance\ index\ (i) = \sum_m \frac{D_{mi} \cdot f_m}{T_i} \tag{1}$$

In equation (1), i is the territorial unit, m is the mean of transport (diesel car, fuel car, train, bus, bike, on foot),*Dmi* is the total distance travelled using the means of transport *m* in the district *i*,*fm* is the consumption factor attributed to the means of transport *m*, and *Ti* is the number of persons in the territorial unit *i*. The consumption factors depend on the consumption of the vehicles (litres of fuel per kilometre) and their occupancy rate. The indices are 0.56 kWh/person.km for a diesel car, 0.61 kWh/p.km for a gasoline car, 0.45 kWh/p.km for a bus, 0.15 kWh/p.km for a train and 0 for non-motorised means of transportation because they do not consume any energy in the following application but can be adapted to each situation and territory because their calculation is entirely parameterised.

The energy consumption for the daily mobility is obtained via equation 2.

$$E_{DM} = Energy\ performance\ index \cdot N \cdot T \tag{2}$$

In equation 2, the energy performance index is multiplied by the number of people *N* and the number of trips *T* in the neighbourhood.

Note that these data only consider the home-to-work and home-to-school travels, but we can use the same methodology for in situ survey data to consider all travel purposes. Although the home-to-work and home-to-school travels are becoming less meaningful in the daily travel patterns in the Western world because of the dramatic growth in other activities (Graham, 2000; Pisarski, 2006), they have more structural power than other travel forms because they are systematic and repetitive.

Using the developed method, the building energy consumption and the transportation energy consumption can be expressed with a common unit (kWh/person.year or kWh/neighbourhood.year), which allows one to consider these two topics together and to include the effect of the location on the daily mobility in the energy balance.

4. Application and Results

Urban sprawl is a concern in a large portion of Wallonia (Belgium). In this region, 52% of the building stock is detached and semi-detached houses (Kints, 2008), and 50% of the census blocks of the region has a mean housing density between five and twelve dwellings per hectare (Vanneste et al., 2007). Suburban neighbourhoods are found everywhere in the region and not only in the suburban municipalities. In this case study, the aforementioned method is applied to one representative suburban neighbourhood of Wallonia. This representative neighbourhood (Figure 3) was selected based on a typological classification of neighbourhoods that was performed to highlight the most representative type of suburban neighbourhoods. Numerous simulations, calculations and sensitivity analyses were performed on several representative neighbourhoods and highlighted that the major trends (highlighted below) remain the same for the suburban neighbourhoods, which shows a built density of 5-12 dwellings per hectare (Marique, 2013).

Figure 3. The selected representative suburban neighbourhood

Currently, the required energy for heatingin buildings is the most important portion of the calculated consumption at the neighbourhood level because the existing suburban building stock in Wallonia is old and poorly insulated. Depending on the available bus services and the distance to the city centre, transportation (only home-to-work and home-to-school travels are considered) represents 11.9-35.9% of the energy consumption of a neighbourhood.

Then, the aforementioned twelve sub-scenarios were applied to this representative neighbourhood to investigate their energy efficiency. Quantitative results are summarized in Table 1 and show that, from an energy viewpoint, all scenarios present interesting results. As stated in Table 1, the energy consumption for heating in buildings is reduced by -7.3% (if only the roofs of the existing buildings are insulated) to -89.8% (if passive retrofitting is promoted). For one fixed insulation level (e.g., the actual fixed energy requirements in the European Directive on the Energy Performance of Buildings as presented in Table 1, although the trends are identical for the low-energy and the passive standards), the most efficient strategies rebuild the neighbourhoods in a more compact urban form (urban blocks or apartment buildings). These scenarios allow a reduction of 68.1% and 70.4%, respectively, in comparison with the

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reference case (detached houses; related to a reduction of 45.2% only), which highlight the low energy efficiency of this type of urban form, even when the detached houses have better insulation (the result is also true for identical insulation levels). An increase in the built density of the existing neighbourhoodsalso improves the energy efficiency of the existing neighbourhoods by constructing new well-insulated houses (B1 to B3). In B4, the results are better because the insulation of new buildings and the building distribution (terraced houses) are mobilised together. Another interesting scenario, which is assimilated into B4, is the building of new collective dwellings in existing neighbourhoods where large land opportunities remains available (for example, in the centre of suburban blocks that were only urbanised on their perimeter). To optimise the energy consumption reductions of the scenarios that increase the built density, it appears necessary to also improve the insulation of the existing buildings. Beside their interest in terms of the energy efficiency, the scenarios that increase the built density avoid the urbanisation of unoccupied land and the construction of new infrastructures.In these scenarios, the new dwellings are developed by increasing the density of the existing neighbourhoodsinstead of developing new low-density neighbourhoods.

Table 1. Reductions in energy consumption for heating in buildings, which were obtained for twelve retrofitting scenarios

A.INSULATION		B.BUILT DENSITY		C.URBAN FORM	
Scenarios	Energy consumption reductions	Scenarios	Energy consumption reductions	Scenarios	Energy consumption reductions
A1.Insulation in the roofs	-7.3%	B1.Unoccupied plots	-5.2%	C1.Detached houses	-45.2%
A2.Insulation in the roofs + double glazing	-14.8%	B2.Bottom of the plots	-17.4%	C2.Urban blocks	-68.1%
A3.Retrofitting to actual standard	-45.2%	B3.Detached houses between existing houses	-12.9%	C3.Apartment buildings	-70.4%
A4.Retrofitting to the low-energy standard	-59.2%	B4.Terraced houses between existing houses	-30.4%		
A5.Retrofitting to the passive standard	-89,8%				

However, the previous scenarios, particularly those that address the density and the construction of new urban forms, cannot be recommended everywhere in the territory. It is crucial to consider the effect of the location of the neighbourhoods on the travelled distances and the transport energy consumption. For example, the building of a mixed and dense neighbourhood andthe increase in density of an existing neighbourhood that is notably badly located (far from the city centre, shops and other services, with notably low bus services) are obviously counter-productive. Thus, the effect of the location of the neighbourhoods was finally investigated using the commute-energy performance index. Marique et al. (2013a; 2013b) highlighted the huge effect of the structure of the territory on the transport energy consumption (Figure 4). In this work, the territory is interpreted as the system defined by three main elements: i) the location of work places and services (commercial, education, leisure, etc.), ii) the spatial distribution of the population according to the place of residence and iii) the infrastructures (the transport and technical networks). The variation of functions (residences, shops, work places, leisure, etc.) in the neighbourhood and the built density have the strongest effect on the variation of the transport energy consumption. The energy efficiency of home-to-work and home-to-school trips is strongly determined by the travelled distance. The mode choice has a smaller effect on the energy performance of those types of commutes. This result can partly be explained by the relationship between the distance and the mode choice.

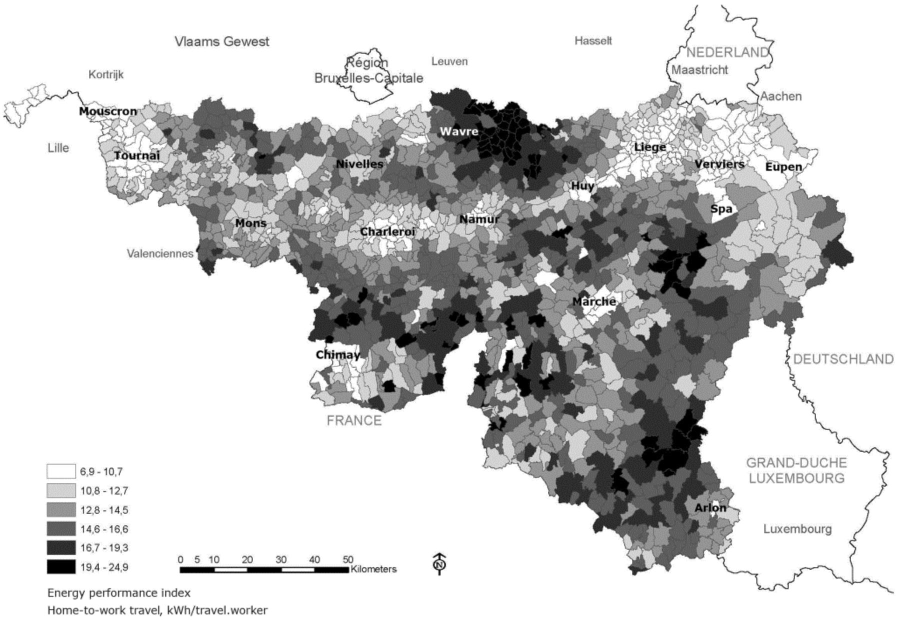

Figure 4. The mapping the commute-energy performance index for home-to-work travel (in kWh/person.travel at the neighbourhood scale shows the variation of the transportation energy consumption (home-to-work travel) according to the location of the neighbourhood.

In this work, these results are mobilised to identify the most appropriate suburban neighbourhoods, where an increase in the built density could be favoured without increasing the energy performance index for commuting. Because suburban neighbourhoods are mainly mono-functional and less dense, this simulation is based on the proximity between one suburban neighbourhood and one or more rural or urban cores, which are dense and present a great variety of functions. The urban and rural cores that we used are defined by the National Institute for Statistics (INS, 2006). Figure 5 highlights in yellow the most appropriate suburban neighbourhoods. The green suburban neighbourhoods are located further from the existing urban or rural cores. In those neighbourhoods, an increase in the built density and the construction of new neighbourhoods is not recommended; because of their location and characteristics, the transport energy consumption is expected to be high (longdistances to travel and few or no alternatives to private cars).

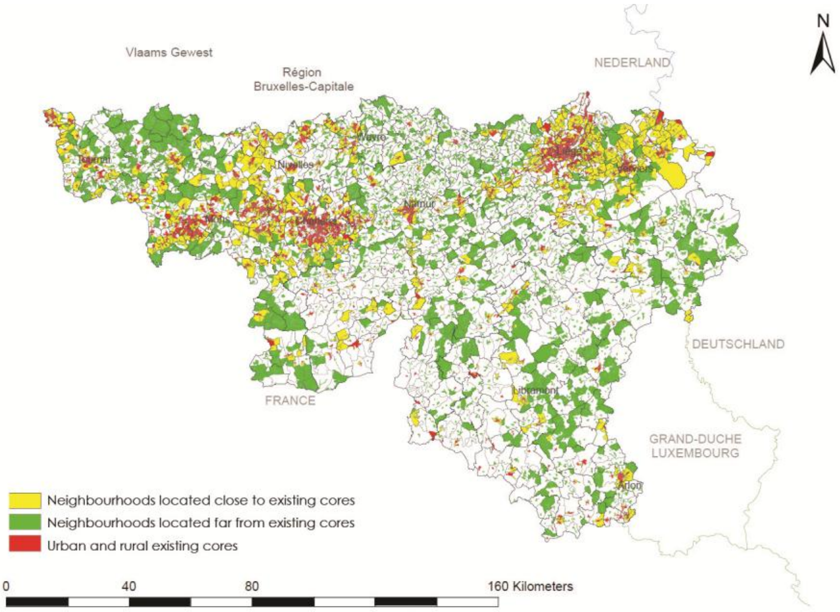

Figure 5. The urban and rural cores (in red), suburban neighbourhoods that are near an urban/rural core (in yellow) and suburban neighbourhoods that are far from the existing cores (in green).

Thus, the scenarios that increase the built density, as well as the building of new neighbourhoods, can be limited to these high-potential areas (neighbourhoods highlighted in yellow on Figure 5). Moreover, these two types of scenarios allow us to recompose locally dense and mixed cores, which have proved their interest in energy efficiency and mode choice in transportation (Marique et al., 2013a, Myung-Jung et al., 2013). This opportunity is interesting particularly because the regional administration has evaluated that 350,000 new dwellings will be built by 2040 to absorb the forecasted demographic growth (+600,000 inhabitants in Wallonia for 2040).

5. Discussion: Retrofitting the Suburbs by Improving Their Energy Efficiency; Key Challenges and Limitations

The results in the first parts of this paper were focused on the energy consumption, which is a crucial topic in the scope of a sustainability transition of suburban areas. This approach is finally completed and moderated by considering the previous study in a broader framework, which considers the economic feasibility of the proposed measures, the regulation framework that allows or does not allow these measures and its societal acceptability.

The cost of the works related to the sub-scenarios that address the insulation of existing buildings increased the insulation level increase (thus, the energy efficiency increase) because of the huge quantity of material to use to reach efficient energy standards. The return on investment must be studied in every particular case to refine this trend. Although there have been financial intensives for several years, this aspect is a major brake to the energy retrofitting of the existing building stock. The division of the existing large plots (mean size = 1,000 m^2) to increase the built density of the existing neighbourhoods allows the owners to sell a part of their plot and gain a considerable amount of money. This option, also investigated in the French

BIMBY research (Miet and Le Foll, 2013) is particularly interesting for households that do not use their entire plot.

We have studied the existing regulation framework (regional and local codes and rules that are related to architecture and urban planning) in Wallonia (Belgium) and this framework is adapted to the scenarios that address the insulation of existing buildings. The only possibly problematic element is the replacement of the facing materials (some colours and materials must be respected according to the local regulations). To increase the built density of existing neighbourhoods is more complicated (except in the sub-scenario B1) because most suburban municipal authorities are reticent to this trend and have adopted specific regulations to avoid increasing the built density of the existing and new suburban neighbourhoods. Because the densification of the existing low-density neighbourhoods is a major preoccupation of the actual regional government (urban planning is a regional matter in Belgium), we can hope for an evolution towards more flexibility in the next few years. Moreover, if the increase in the built density in scenario B1 to scenario B4 can be based on the individual initiatives, scenarios C1 to C3 and the densification of large unoccupied plots in the centre of the existing neighbourhoods request an important intervention of public authorities and private developers to manage the aspects linked to the land properties and build collective development (with various functions, etc.).

Finally, the societal acceptability of the scenarios that increase the built density is also notably problematic. As previously highlighted in the literature, a recent in situ survey in Wallonia (Pierson, 2010) confirms that households in those low-density suburban neighbourhoods are quite reticent to any changes, particularly to increase the built density. Further applied research dedicated to the social representations of housing is necessary to overpass this huge brake.

6. Conclusions and Perspectives

This paper addresses the challenges and conditions of a retrofitting of suburban areas, which was articulated around an increase in the energy efficiency in both the building and the transportation sectors. Two powerful levers were used: (1) urban form, which was considered in addition to the individual building scale, and (2) mobility, to consider the energy used in transportation. Three main types of scenarios (the retrofitting of existing neighbourhoods, increasing the built density and more compact urban forms) and twelve sub-scenarios focused on possible evolutions of the existing suburban building stock were modelled and assessed. The main results of this approach, which were focused on the energy efficiency, were then rethought in a larger framework to highlight the opportunities, the limitations, the constraints and the feasibility of each strategy. These findings show that beyond the traditional polarisation of the debates on energy efficiency of our built environment between the “compact city” and the “sprawled city”, a new pragmatic paradigm, focused on the sustainability transition of suburban areas, particularly by smooth densification in the gardens of existing houses, can make suburban areas evolve towards greater sustainability. However, there are numerous brakes, particularly those that are related to the existing regulation framework and the societal acceptability of an increased density, which should be investigated in further study to be surpassed. These results open avenues for further research on the smooth densification in the suburbs (e.g., energy supply, renewable energy, water heating, ICT).

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Appendix A.9

The influence of occupation modes on building heating loads: the case of a detached house located in a suburban area

Tatiana DE MEESTER[1], Anne-Françoise MARIQUE[2], Sigrid REITER[2]

[1]Architecture et climat, Université catholique de Louvain, Louvain-La-Neuve, Belgium
[2]Local Environment: Management & Analysis (LEMA), University of Liège, Liège, Belgium

ABSTRACT: Occupants' behaviour is known to have a great influence on energetic demand, management and consumptions of a building. However, parameters related to inhabitants' lifestyle are often neglected in energetic studies and researches that often focus on insulation, ventilation or climate. In this context, the aim of the paper is to investigate the influence of three parameters related to human behaviour (the family size and the modes of occupations, the management of the heating system and the management of the heated area) on the housing heating loads of a standard dwelling. The case study chosen for this analysis is a detached house located in a suburban area. Five levels of insulation are tested (no insulation, an intermediate level corresponding to 3 cm of insulation, the current standard for new buildings in the Walloon region of Belgium, the low energy standard and the passive house standard) in order to highlight the impact and the interactions between occupation modes and insulation levels. The relevance of the adaptation of the living area of the house according to the evolution of the family size is finally discussed.

Keywords: thermal simulation, energy consumptions, human behaviour, comfort, building performances

1. INTRODUCTION

The use of mathematical models and simulation tools is often presented as the most credible approach to model the comportment of a building and predict the heating consumptions, in a global vision of sustainability. This approach allows to take into account a large number of parameters which are known to act upon energetic behaviour, management and consumptions of a building and to carry out parametric variations in order to test the impact of different strategies. If the level of insulation, the ventilation or the climate are often discussed in the literature, especially as far as retrofit is concerned, the influence of the composition of the household, its evolution through the whole life cycle of a dwelling or the behaviour of the occupants, which evolve over time while the house remains a fixed and unchanged size, are more rarely debated. However, these parameters have a huge impact on the energetic invoice of a household. Building operations and maintenance, occupant's activities and indoor environmental quality, all related to human behaviour, are indeed known to have an influence as great as or even greater than climate, building envelop and energy systems [1].

In the actual context of growing interests in sustainable development and increasing energy prices, more and more households pay attention to their energetic consumptions, especially as far as heating consumptions are concerned [2] while a large part of the population, and namely elderly owners, stay reluctant to undertake heavy renovation works. The age of the occupants seems namely to have a huge impact on heating loads, and particularly on the occupancy rate and the comfort temperature [3]. Moreover, researches have shown that in general, technical improvements were preferred over behavioural measures and especially shift in consumption. Further, home energy-saving measures seemed to be more acceptable than transport energy-saving measures [4]. The behaviour and preferences of inhabitants and the solutions adopted by the households to reduce their consumptions can thus vary in a wide proportion and cannot be apprehended by one only standard type of household in simulations, as it is generally the case.

In this context, the paper aims at comparing the variations of three parameters related to human behaviours and occupation modes: the family size and the modes of occupations, the management of the heating system (thermostat) and the management of the heated area (the inhabitants occupy the ground floor and the first floor or just the ground floor). These three parameters are then used and combined in order to determine the evolution of the occupancy of the house during its life cycle.

The chosen case study for this analysis is a detached house located in a suburban area because this type of house represents a large part of the building stock and of the total energy consumptions related to housing in the Walloon region of Belgium, where urban sprawl is particularly familiar [5, 6].

The methodology, simulation tools and main assumptions used in this research are summarized in section 2. Then, the impact of the three studied parameters on the evolution of heating loads and internal conditions are presented and finally discussed for five significant levels of insulation.

2. METHODOLOGY AND ASSUMPTIONS

2.1. The TAS thermal simulation software

TAS is a software package for the thermal analysis of buildings. It includes a 3D modeller, a thermal/energy analysis module, a systems/controls simulator and a 2D CFD package. CAD links are also provided into the 3D modeller as well as report generation facilities. It is a complete solution for the thermal simulation of a building, and a powerful design tool in the optimisation of a building's environmental, energy and comfort performance. [7]

2.2. The climate

The climate of the northern part of Europe is a temperate climate. The Brussels' meteorological data are used. Data comprise the hourly data of temperature, humidity, global solar radiation, diffuse solar radiation, cloud cover, dry bulb temperature, wind speed and wind direction. In the analysis of the heating consumptions, a whole typical year is used [8]. The maximum and minimum temperatures, for the considered year are 34.9 °C and -9,1°C.

2.3. The studied building

The studied building is a detached house with a south-east oriented facade. It is a two-storeyed house, located in a suburban area. Figure 1 shows the plans of the 2 floors of the building. The ground floor is composed of a living room, a kitchen, an office, a hall and a cloakroom. The first floor comprises 4 attic bedrooms and an attic bathroom. The windows are located on the 2 gables. One bedroom has a roof window. The house also includes a cellar and an attic. The house has a surface area of 182 m².

2.4. The thermal characteristics

The analysis presented in this paper take into account 5 levels of insulation of the house: a level without insulation (NI) neither in the walls nor in the roof and the slab [9, 10], a level with 3 cm of insulation in the walls, roof and slab (3cm) [9, 10], the current standard (CS) for new buildings in Belgium [9, 10, 11, 12], a low energy level (LE) [9, 10, 13] and the passive house standard (PHS) [9, 10, 12, 14]. The main thermal characteristics of walls and windows are summarized in the Table 1.

Double-glazed windows are used in the four first cases and replaced by triple-glazed windows in the passive house. The natural ventilation (NV) corresponds to the opening of the windows from 5 pm till 6 pm (30 % of the surface of the window opened). The mixed-mode ventilation (with mechanical exhaust (ME)) and the mechanical ventilation (MV) work when the house is occupied. The ventilation has three speeds. The third and the most substantial one corresponds to the requirements of the Belgian ventilation standard [9]. The first speed, the most applied in practice, is worth 1/3 of the third one and is used in our simulations.

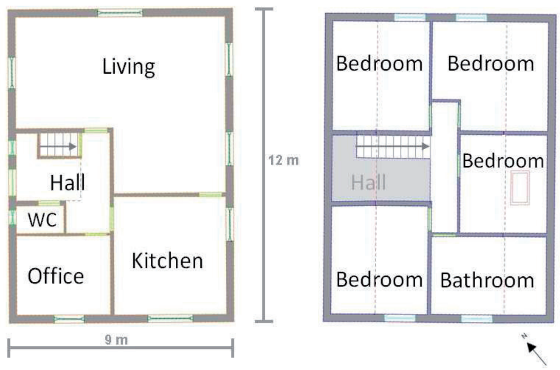

Figure 1: Plans of the ground floor and the attic floor of the studied house

2.5. The internal gains

The more the building is efficient, the more internal conditions have an influence on the heating consumptions of the building. The modelling of internal gains must be representative of the reality. Thanks to the multizone modelling adopted in the analysis, internal gains can be adjusted in each room, according to the moment of the day and the occupation mode.

The following heat emissions are used in the simulations [9, 13] :

- Occupation: 80W per person (the number of person varies from 0 to 5 according to the occupation mode)
- Fridge and deep freeze: 0.85 kWh/day
- Washing-up: 0.3*1.1 kWh/use
  (65 uses/(year.person))
- Appliances: 50kWh/(year.person)
- Television : 150W (1, 2 or 3hours/day)
- Computer: 70W (0, 1, 2 or 10hours/day)
- Cooking: 912W (0.5, 1 or 1.5hours/day)
- Lighting: 6W/m²
- Shower: 1486W/shower (0, 24 or 48 minutes/day)

Table 1: Main thermal properties of the 5 studied levels of insulation.

Levels of insulation	Roof (W/m²K)	External walls (W/m²K)	Ground floor (W/m²K)	Windows (W/m²K)	Airtightness (vol/h)	Ventilation	Annual heating requirement (exigency)
NI	3.586	1.757	1.874	1.22	0.6	NV	-
3cm	0.972	0.758	0.880	1.22	0.6	NV	-
CS	0.3	0.4	0.4	1.22	0.39 (7.8h^{-1} under 50Pa)	NV	-
LE	0.265	0.326	0.395	1.22	0.1 (2h^{-1} under 50Pa)	ME	≤ 60 kWh/(m² a)
PHS	0.129	0.147	0.199	0.774	0.03 (0.6h^{-1} under 50Pa)	MV with heat recovery	≤ 15 kWh/(m² a)

Total internal gains used in each thermal simulation depend on the chosen occupation mode and thus on combinations of the treated parameters. The reference value comes from a monitoring and is worth 2.57 W/m² [15].

2.6. The parametric variations

The study presented in this paper aims at comparing the influence of three parameters related to human behaviour and occupation mode on the heating loads. The studied parameters and their variations are presented below.

The first parameter deals with the family size and the corresponding occupation mode. Two types of family composition are considered and allow to target and to characterize the four following occupation modes.

- Occupation mode 1 (OM1): an active couple works outside the house during the day while their three children go to school.
- Occupation mode 2 (OM2): a self-employed or unemployed couple works/stays at home during the day while their three children go to school.
- Occupation mode 3 (OM3): an active couple without children works/stays outside during the day. Five cases are discussed.
- Occupation mode 4 (OM4): a retired couple, not very active, spends a lot of time at home. Two cases are discussed.

The second parameter deals with the management of the heating system. This modelling is based on three types of management of the thermostat, that depend on the occupation mode. The three studied cases are :

- T1: 20 ℃ in the occupied rooms with a drop to 16 ℃ at night and during the day. The heating season begins the first of October and ends the first of May
- T2: 20 ℃ in the occupied rooms with a drop to 16 ℃ at night. The heating season begin the first of October and ends the first of May.
- T3: 21℃ in the occupied rooms, all over the year , during day and night.

The last parameter is the management of the heated area. The size of a family and its activities evolve over time while the house has a fixed and unchanged size but sometimes, people remove in a part of the house which became too big for them (after the departure of children for example, facing the difficulty of climbing stairs,...). In the simulations, the house is occupied either completely (ground floor and the first floor (GF)) or only partially (just the ground floor (G)). In this case, we consider that the office is transformed into a bedroom.

2.7. The studied cases

Several cases can be arised from the combination of the parameters presented in the previous section. The nine studied cases are summarized in Table 2 (OM is the occupation mode, T1, T2 and T3 are the temperature settings, a cross in the GF column means that both the ground floor and the first floor are occupied (totally or partially) while a cross in the G column means that only the ground floor is occupied).

Table 2: The 9 case studied in the simulations

	OM	GF	G	T1	T2	T3
Case 1.1	1	x		x		
Case 2.2	2	x			x	
Case 3.3	3	x		x		
Case 3.4	3	x			x	
Case 3.5	3		x		x	
Case 3.6	3	x				x
Case 3.7	3		x			x
Case 4.8	4	x				x
Case 4.9	4		x			x

3. RESULTS

The results are presented in 4 parts:

1. the analysis of the 2 cases representing a family with children (case 1.1 and case 2.2),
2. the analysis of the 5 cases representing an active couple without children (cases 3.3 to 3.7),
3. the analysis of the 2 cases representing a retired couple (case 4.8 and case 4.9) and
4. the analysis of the 3 extreme cases representing 3 of the 4 modes (the cases 1.1, 3.4 and 4.9).

Table 3 presents the heating loads of the 9 simulated cases for the 5 levels of insulation. In the first part of the table (part A), the total heating loads calculated for the house are divided by the total surface area of the house (182m²) in each case because if the occupied and heated area changes, the position of the insulation stays the same in each case. In the second part (part B), the total heating loads calculated are divided by the occupied and heated area (182m² if the house is totally occupied by a family (the cases 1.1 and 1.2), 138m² if the ground floor and the first floor are partially occupied by a couple (the cases 3.3, 3.4, 3.6 and 4.8) and 91m² if only the ground floor is occupied by a couple (the cases 3.5, 3.7 and 4.9)).

3.1. OM 1 and 2 : couple with 3 children

Table 3 shows that case 1.1 is more energy-efficient than case 2.2 for all the levels of insulation tested, excepted for the passive case. Proportionally, the biggest difference between these two cases is observed at this passive level: the difference in heating loads between cases 1.1. and 1.2 reaches 2.28 kWh/(m².year) (28.73%). For the other levels of insulation, the difference between the two cases is contained in a range between 0.75% and 8.28% (from 0.45 to 14.98 kWh/(m².year)). This table also reveals the importance of the level of insulation. The change from one level of insulation to another permits a huge reduction in heating loads. Moreover, for both considered cases, the greatest energy reductions are visible when the passive standard is reached. In general, the change from one level of insulation to the higher one is very interesting and has a greater impact than the benefit gained from occupation modes case 1.1 on case 2.2.

3.2. OM3 : active couple without children

If heating loads are divided by the heated area (Part B of Table 3), 4 of the 5 cases relating to the

Table 3: The heating loads of the 9 studied cases (in kWh/m²). The first part of the table (A) presents the total heating loads divided by the total surface area of the house (182m²). The second part (B) presents the heating loads divided by the occupied area (182m², 138m² or 91m² according to the corresp onding occupation mode).

	Case 1.1	Case 2.2	Case 3.3	Case 3.4	Case 3.5	Case 3.6	Case 3.7	Case 4.8	Case 4.9
A.) kWh/m² (Heating loads are divided by the total surface area of the house (182m²))									
NI	180.13	195.11	154.78	170.70	132.19	231.00	178.71	214.71	175.43
3 cm	96.46	101.30	92.94	101.35	88.25	132.15	115.16	122.76	111.96
CS	59.53	59.08	60.50	64.92	59.69	80.75	74.54	74.88	71.62
LE	28.46	31.03	30.18	36.19	31.99	44.82	39.74	40.69	36.99
PHS	7.25	5.16	11.88	13.28	12.76	15.93	15.39	13.54	13.15
B.) kWh/m² (Heating loads are divided by the occupied area (182, 138 or 91m²))									
m²	182	182	138	138	91	138	91	138	91
NI	180.13	195.11	205.40	226.53	265.46	306.55	358.88	310.73	352.28
3 cm	96.46	101.30	123.34	134.50	177.22	175.37	231.25	177.67	224.83
CS	59.53	59.08	80.29	86.15	119.87	107.16	149.68	108.37	143.82
LE	28.46	31.03	40.05	48.02	64.24	59.48	79.79	58.89	74.29
PHS	7.25	5.16	15.76	17.62	25.61	21.14	30.91	19.59	26.41

third occupation mode do not meet the passive house standard. If the heating loads for cases 3.3 to 3.7 are divided by the total surface area of the house, the passive standard is respected. The values of cases 3.6 and 3.7 are indeed nearly beyond the bounds, especially since these cases are considered only with a "speed 1" ventilation rate.

The low energy standard is not reached for case 3.5 and 3.7 (Table 3B) if the occupied area is considered but is reached when the total surface is used (Table 3A).

The heating demands vary a lot according to the occupation mode (Table 3A). The two extreme cases are case 3.5 and case 3.6, The differences between these two cases vary from 98.81 kWh/(m^2.year) for the non insulation case (42.77%) to 3.17 kWh/(m^2.year) for the passive house standard (19.93%). The average of the differences is worth 30.10%. In general, the more the building is insulated, the more the difference between the cases decreases. The impact of behaviour becomes thus less huge and less marked. These two cases develop opposite behaviours. According to Table 3B, the two extreme cases are cases 3.3 and 3.7. The differences between heating loads are contained in a range between 153.18 kWh/(m^2.year) for the non insulated case and 15.15 kWh/(m^2.year) for the passive house standard. The average of the differences is worth 46.89%, which means that a couple, living in a house with 3cm of insulation, with a behaviour similar to case 3.7, can consume as much as a couple living in a non-insulated house with a more responsive and better managed behaviour. In general, if the building has a good insulation, the impact of the behaviour, compared with heated squared meters, can be proportionately as high as the impact of changing from a level of insulation to a better one.

This result highlights the very low equilibrium between comfort and good energy management. If people have very different schedules, it is quite interesting to be able to switch on by remote control the heating and the ventilation which allows to trigger the revival of the heating system. Lowering the day temperature from 20 °C to 16 °C can make a saving of about 10%, by comparing cases 3.3 and 3.4.

A very good insulation will reduce the consequences of the carelessness of people or of their no energy-efficient behaviour. But the reduction of consumptions remains and is thus easily improvable!

3.3. OM4: retired couple not very active

The occupation mode related to retired couple that is not very active and stays at home during the day is less energy-efficient because the house is more often occupied which means more heat, more light, more cooking times. Moreover, thermal comfort is the basis of the notion of comfort for elderly households. This occupation mode requires a great need for heat and that is not negotiable. Note that heating loads predicted by these simulations are low compared to real consumptions generated by some elderly households' behaviours, for example maintaining indoor air temperature at 26℃ all over the year during day and night.

Occupying just a part of the house (here the ground floor), is energetically more interesting. According to Table 3A, if the house is not insulated, the difference between cases 4.8 (the ground floor and the first floor are partially occupied) and 4.9 (the ground floor, only, is occupied) is worth 39.28 kWh/(m^2.year) (18.29%) but this difference is only worth 0.38 kWh/(m^2.year) (2%) in the passive house. According to Table 3B, the average of the differences between these 2 cases is about 21% (contained in a range between 6.83 and 47.16 kWh/(m^2.year)). But these 2 cases do not concern the same surface area and thus the most consumers in terms of kWh/(m².year), the case 4.8, gives the impression to consume less than the case 4.9. It might be interesting to bring in a density factor. Once again, the impact of the occupation mode in terms of kWh/m².year decreases if the insulation of the house is better.

3.4. Comparison between 3 representative occupation modes: synthesis

This section aims at comparing the heating loads results related to 3 extreme occupation modes. The 3 selected cases are case 1.1. (an active couple working outside the house during the day with three children going to school), case 3.4 (an active couple without children working outside the house during the day), and case 4.9 (a retired couple not very active, staying at home with a higher comfort temperature).

The more the building is insulated, the more the occupation mode is marked. The comparison between case 1.1 and case 3.4 (Table 3A) highlights that the difference between heating loads is contained in a range between 5.24% (9.44 kWh/(m^2.year)) for a non-insulated house and 45.42% (6.03 kWh/(m^2.year)) for the passive house standard. The difference in heating loads between the two modes related to a couple without children (cases 3.4 and 4.9) are relatively low. The average of the differences is indeed worth 5.74%. Figure 2 shows that if the building is not insulated, the occupation mode related to the family with three children is the higher consumer of energy. But this occupation mode with children becomes more efficient than the two others modes if the house is insulated. That also reveals the importance of internal gains.

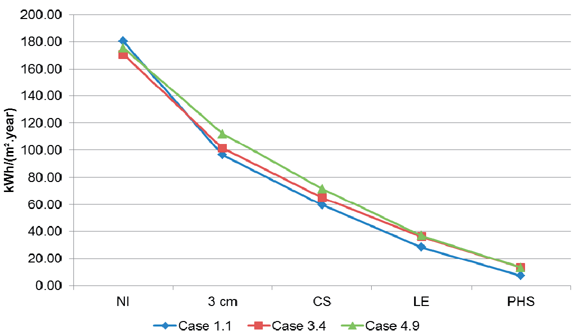

Figure 2: Heating loads (kWh/(m².year)) based on the 5 levels of insulation tested for cases 1.1, 3.4 and 4.9 (In this figure, heating loads are divided by the total surface area of the house (182m²)).

If we consider now the second part of Table 3 (where heating loads are divided by the occupied area), the differences between the three studied cases are more important. The average of the differences between case 1.1 and case 3.4 (range from 10.38 to 46.39 kWh/(m^2.year)) and between case 3.4 and case 4.9 (range from 8.79 to 125.76 kWh/(m^2.year)) are worth 36%. Case 1.1 remains the most interesting one for any level of insulation thanks to the largest heated area, to the numerous internal gains and to the better management of the heating system.

The differences between the cases increase with the level of insulation even if the difference of heating load between cases 3.4 and 4.9 and case 1.1 is more marked if heating loads are divided by the occupied area, as it can be seen on Figure 3.

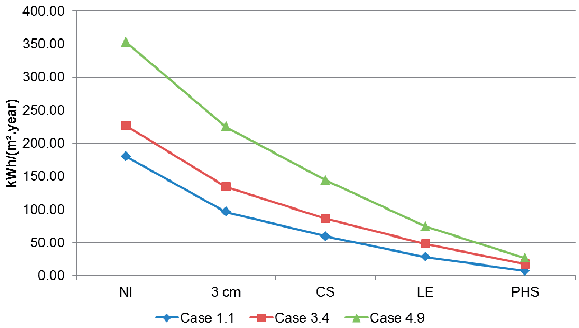

Figure 3: Heating loads (kWh/(m².year)) based on the 5 levels of insulation tested for cases 1.1, 3.4 and 4.9 (In this figure, heating loads are divided by the occupied area).

4. DISCUSSION

This section aims at discussing the impact of these occupation modes during the life cycle of the house. Indeed, several occupation modes can follow one another during the life of a house. To assess their impact on the life expectancy of the studied house, 4 assumptions of occupation are established for a period of time of 100 years and summarized in Table 4. For example, in A1, the house is occupied during 45 years by a family with 3 children (case 1.1) then by an active couple without children (case 3.4) during 30 years and finally by a retired couple (case 4.9) during 25 years.

Table 4 : Years of occupation of each occupation mode, for a life cycle of 100 years : 4 assumptions

	A1	A2	A3	A4
Case 1.1	45	25	60	25
Case 3.4	30	50	25	55
Case 4.9	25	25	15	20
Total	100	100	100	100

Average heating loads calculated for the four scenarii of occupation presented in Table 4, and divided by the heated area, are summarized in Table 5. In two cases (A2 and A4), the requirements of the passive house standard are not met. The more the building is insulated, the more the difference of heating in % increases between the two cases. In the passive house standard, this difference reaches 26.18% (4.51 kWh/(m^2.year)) between A2 and A3, that are the 2 extreme cases.

If the size of family evolves over time, the size of the house and its occupation modes should also be adapted. This strategy would allow to reduce the heating consumptions during the whole life cycle of the building. The aim is to maximize the occupation of the house. But that can lead to significant works of adaptation (extra kitchen, independent entrances, etc.). The insulation and possibilities of thermal improvement of the building must also be taken into account in order to choose the best option.

Table 5 : Average heating loads (in kWh/(m².year)) of a house on his life (100 years) based on the assumptions of occupation modes presented in Table 4.

	A1	A2	A3	A4
NI	237.09	246.37	217.55	240.08
3 cm	139.96	147.57	125.22	143.05
CS	88.59	93.91	78.83	91.03
LE	45.78	49.70	40.22	48.38
PHS	15.15	17.23	12.72	16.79

5. CONCLUSION

Nine types of occupancy of a standard detached house located in a Belgian suburban area have been determined by combining several representative types of households, occupation modes and thermal preferences (management of the thermostat). Thanks to multi-zone thermal simulations performed with a dynamic thermal simulation software (TAS), heating loads have been calculated for these nine case studies and for four combinations of the most representative ones during the life cycle of the building (100 years).

These analyses have highlighted the importance of internal gains related to the different modes of occupation, their influence on heating loads for the studied levels of insulation and the significance to take into account several types of households and occupation modes in thermal studies.

These analyses have particularly highlighted that the more the building is insulated, the more the lifestyle, namely through internal gains, influence proportionally the heating loads even if, in terms of kWh, this impact decreases. These results emphasize that the number of inhabitants and their presence in the house can reduce the heating loads. However, insulation is paramount and increasing the insulation of the house always gives better results than just adapting the occupation mode.

For the studied building, the model that presents the lower heating loads is the active couple working outside with three children, because, in this case, the number of inhabitants is quite adapted to the size of the house. The balance between optimal comfort and good management of the energy is very low and particularly if people have varied schedules. It is thus quite interesting to be able to switch on by remote control the heating and ventilation systems which allows to trigger the revival of the heating.

Last but not least, a more responsible behaviour can easily improve the energy balance of a house. Buildings thermal improvements are also very efficient but take more time and money to be realized. To heighten public awareness of the impact of their lifestyle is thus crucial and can quickly lead to significant reductions in the total energy consumptions of a family.

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Appendix B : Pierre Dewallef

Appendix B.0

Assessing the cost of electricity

Prof. Pierre Dewallef

January 2013

1 Introduction

In today's mostly liberalized electricity market, the economics of a power plant are evaluated as any other industrial investment. Typically, an investor is looking to satisfy a certain level of return for his investment. Example target can be the return on equity (ROE) or the internal rate of return (IRR). However, both indexes depend upon:

- the market price of electricity and
- the production cost of electricity including the interest and amortization cost, the fuel cost and the operation and maintenance cost.

While some uncertainties remain on the fuel cost, the bigger risk is certainly on the market price of electricity as, in a liberalized economy, this price can fluctuate widely.

When a technology is new, the construction cost can be significantly more important than for well established technology. High construction cost combined with uncertain electricity prices is often an important barrier to convince investors to spend some money in new technologies. This is especially the case in the actual framework for reduction of green house gases emissions where new (yet costly) technologies must be put in place to deal with the climate change. In order to ensure the development of these new technologies, active policies must be put in place to promote *clean power generation*.

A possible way to promote clean power generation is to allocate subsidies to guarantee a minimum value for the market price of electricity. Doing so, it is easier for investors to decide whether or not to invest in a given technology. As the technology develops, production cost goes down and efficiency and reliability go up allowing the cost of electricity to go down and to become compatible, on the long term with the market price of electricity.

It is therefore of paramount interest for policy makers to update their knowledge about production cost of electricity so as to guarantee that subsidies are well allocated at all time.

2 Production cost of electricity

The production cost of electricity (COE) is usually expressed in € per MWh[1] and depends upon:

- the capital cost of the project itself made of
  - the power plant construction cost,
  - the interest rate and return on equity (the balance between interest rate and return of equity depends upon the financing structure),
  - the equivalent utilization time of the plant at rated output,
- the fuel cost,
- the operation and maintenance cost.

The interest rate is the return expected by the financing organism (i.e., the bank) and the return on equity is the return expected by investors in his capital. Both are linked to the risk of the project and the weighted average cost of capital (WACC). For sake of simplicity, an average discount rate is defined which takes into account the WACC, the risk of the project and the financing structure.

The equivalent utilization time of the plant at rated output is the electrical energy generated by a plant in a period of time divided by the electrical energy which could be produced by the plant working at rated output during a year. This definition allows correction to be made for part load operation in order to compare different projects on a similar basis.

The fuel cost per unit of electricity produced is proportional to the specific price of the fuel and inversely propotional to the average electrical efficiency of the installation (which must not be confused with the efficiency at rated output).

Operation and maintenance costs consist of fixed costs of operation, maintenance and administration (staff, insurance,...), and the variable costs of operation and maintenance (cost of repair, consumables, spare parts,...).

The cost of electricity is assessed by adding the capital cost, fuel cost and operation and maintenance costs. However, as the various costs are incurred at different times, they have to be corrected to a single reference time for financial calculation. The conversion used is referred to as the present value.

The cost of electricity expressed in € /MWh is calculated as:

$$COE = \frac{C \cdot \psi}{P \cdot T_{eq}} + \frac{Y_F}{\bar{\eta}} + \frac{U_{fix}}{P \cdot T_{eq}} + u_{var} \text{ and } \psi = \frac{d}{1-(1+d)^{-N}} \tag{1}$$

where:

- C is the total capital requirements to be written off (€),

[1] A MWh (mega watt-hour) represents the energy corresponding to a power of one mega watt produced during one hour. It corresponds to 3,6 billion J.

- ψ is the annuity factor used to take into account the interest rate and return on equity (correction based on the present value method),
- d is the average discount rate in percent per annum,
- N is the amortization in years that is often taken as the life time of the power plant (typically 20 years),
- P is the rated power output (MW),
- T_{eq} is the equivalent utilization time at rated power output in hours par annum,
- Y_F is the price of fuel expressed in € per MWh of primary energy (based on the lower heating value),
- $\bar{\eta}$ is the average net plant efficiency in percent,
- U_{fix} is the fixed cost of operation, maintenance and administration,
- u_{var} is the variable cost of operation expressed in € per MWh.

It is interesting to note that the cost of electricity is made of fixed costs (capital costs, interest costs, fixed cost of operation) and variable costs (fuel cost, variable cost of operation). If the market price of the electricity is falling below the variable cost, the power plant must be shut down because no contribution to the fixed costs can be generated.

3 Cost data

This section presents a series of standard data whose purpose is to constitute a starting point for the study. They can be completed by data gathered in the literature and on the internet.

The power plant net efficiencies mentioned below refer to the fuel lower heating value (LHV) while fuel costs and specific CO_2 emissions refer to higher heating values (HHV).

Type of plant	P (MW)	C (€/kW)	$\bar{\eta}$ (%)	T_{eq} (h/a)	u_{var} (€/MWh)	U_{fix} (€/kW/a)
NGCC [2]	(800 MW)	550-650	55-59	5000	2-3	8 - 10
IGCC [3]	(800 MW)	1300-1500	42-47	5000	4-6	10 - 12
PCSPP [4]	(800 MW)	1200-1400	42-47	6000	2,5-3,5	15 - 19
Nuclear (PWR [5])	(1250 MW)	2000-3000	35	7000	2	30 - 50
CCS [6] on NGCC	(450 MW)	800-950	50-55	5000	4-5	10 - 12
CCS on PCPP	(450 MW)	1800-2100	35-40	5000	5-7	20 - 25
CCS on IGCC	(450 MW)	1600-1900	37-42	5000	4-6	15 - 20
Biomass	(30 MW)	2500-3000	28-32	5000	5-7	30 - 35
Photovoltaic	(1 MW)	2500-3000	-	1500	2-3	15 - 20
Solar tower	(60 MW)	2500-3000	-	2500	10-20	100 - 120
CSP [7]	(1 MW)	6000-7000	-	2000	5-10	15 - 20
Stirling Dish	(1 MW)	4000-5000	-	2000	5-10	15 - 20
Off-shore Wind Turbine	(5 MW)	1500-2000	-	2500	15-18	35 - 40
On-shore Wind Turbine	(3 MW)	1200-1500	-	2000	12-15	30 - 35
OTEC [8] Power Plants	(60 MW)	6000-7000	-	5000	15-18	50 - 60
Natural gas cogeneration (Gas Turbine)	(20 MW)	600-800	-	5000	5-8	10 - 12
Natural gas cogeneration (Reciprocating engine)	(1 MW)	800-1000	-	4000	10-12	10 - 12
Tidal Power Plants	(60 MW)	5000-9000	-	3000	20-30	60 - 70

Table 1: Specific price, net efficiency, equivalent utilization time, fixed and variable costs for operation and maintenance of various power plants

[2] Natural Gas Combined Cycle
[3] Integrated coal Gazeification Combined Cycle
[4] Pulverized Coal Steam Power Plant
[5] Pressurized Water Reactor
[6] Carbon Capture and Storage
[7] Concentrated Solar Photovoltaic
[8] Ocean Thermal Energy Conversion

Type of fuel	density ($kg\,m^{-3}$)	LHV ($MJ\,kg^{-1}$)	HHV ($MJ\,kg^{-1}$)	Y_F (€/MWh)	CO_2 (kgCO2/MWh)
Natural gas	0.8	50	55	30	251
Coal	800	32.5	32.5	10	378
Nuclear fuel	-	-	-	1.5	0
Wood chips	320	12	20	25	0 - 20
Wood pellets	600	16	20	35	30

Table 2: Density, lower and higher heating value, specific price and specific CO_2 emissions of various fuels

Appendix B.1

Status of Concentrated Solar Photovoltaic (CSP) technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **concentrated solar photovoltaic technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.2

Status of Solar Tower Power Plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **solar tower power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.3

Status of off-shore wind power technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **off-shore wind power technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.4

Status of biomass combustion power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **biomass combustion power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.5

Status of tidal power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **tidal power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.6

Status of ocean thermal energy conversion (OTEC) power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **ocean thermal energy conversion power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.7

Status of Stirling dish power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Stirling dish power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.8

Status of Natural Gas Combined Cycle (NGCC) technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Natural Gas Combined Cycle power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.9

Status of Nuclear power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Nuclear power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.10

Status of Integrated coal Gazeification combined cycle (IGCC) power plant technology for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Integrated coal Gazeification combined cycle power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.11

Status of Natural Gas cogeneration power plant technology for combined heat and electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **Natural Gas cogeneration power plant technology**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.12

Status of Carbon Capture and Storage applied on natural gas combined cycle power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on natural gas combined cycle**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.13

Status of Carbon Capture and Storage applied on coal power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on coal power plants**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix B.14

Status of Carbon Capture and Storage applied on integrated coal gasification combined cycle (IGCC) power plants for electricity production

Academic year 2012-13

1 Context

A group of policy makers working for public authorities is looking for an update regarding the different technologies for electricity production. Their scope is to obtain synthetic information for electricity production cost, energy yield, potential CO_2 emissions reduction and technological status (under development, tested, mature,...) in order to best allocate subsidies for clean power generation.

2 Problem

You have been contacted by this group to make a 15 minutes presentation on the status of **carbon capture and storage applied on integrated coal gasification combined cycle power plants**. Your intervention must present the main aspects of the technology and mention the principal advantages and drawbacks in terms of potential production for the European Union, intermittency, security of supply and technological maturity.

Your presentation must contain an assessment of the electricity production cost together with a prospective of the calculated cost (decreasing, stable, increasing). The potential CO_2 emissions reduction resulting from the development of the technology must be presented as well. The reference case will be a natural gas combined cycle.

For your cost calculations you will assume an amortization time equal to the duration of the installation (i.e., 20 years) and a weighted average cost of capital of 7%.

3 Practical information

The presentation must be done in English and must not last more than 15 minutes. Due to the time restriction, the length of the presentation should not exceed 15 to 20 slides.

A document is available on the website (entitled *Assessing the cost of electricity*) which explains in details the methodology to be used for the calculation of the electricity production cost. This document is considered as a starting point and completing the cost information supplied by additional information gathered from the literature of from the internet is welcome.

When writing your presentation, you can suppose that your audience has a solid technical background in energy production and already knows the methodology for the assessment of the cost of electricity. Always mention your source when you present cost information and, at the end of the presentation, you will supply a list of references.

For further information, you can contact Prof. Pierre Dewallef (p.dewallef@ulg.ac.be).

Appendix C : Manuel de Villena Miguel

Appendix C.1

[1] - https://eur-lex.europa.eu/resource.html?uri=cellar:c7e47f46-faa4-11e6-8a35-01aa75ed71a1.0014.02/DOC_1&format=PDF

Appendix C.2

[2] - https://eur-lex.europa.eu/resource.html?uri=cellar:c7e47f46-faa4-11e6-8a35-01aa75ed71a1.0014.02/DOC_2&format=PDF

Appendix C.3

[3] - https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016PC0861R(01)&from=EN

Appendix C.4

[4] - http://cadmus.eui.eu/bitstream/handle/1814/57264/RSCAS_2018_TechnicalReport.pdf?sequence=1

Appendix C.5

[5] - https://www.ipcc.ch/sr15/

Appendix C.6

[6] - https://electricity.network-codes.eu/network_codes/

Appendix C.7

[7] - https://electricity.network-codes.eu/network_codes/cacm/

Appendix C.8

[8] - https://fsr.eui.eu/eu-electricity-network-codes/

Appendix C.9

[9] - https://docstore.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenario_Report_2018_Final.pdf

Appendix C.10

[10] - http://fsr.eui.eu/wp-content/uploads/QM-AX-18-017-EN-N.pdf

Appendix C.11

[11] - https://www.consorziobiogas.it/wp-content/uploads/2017/11/Ecofys_Gas-for-Climate.-How-gas-can-h
Feb2018.pdf

Appendix C.12

[12] - https://www.grtgaz.com/sites/default/files/2020-12/03_Etude_100GazEnR_BATweb2.pdf

Appendix D : Larbanois Antoine

Appendix D.1

Climate Change 2023
Synthesis Report

These Sections should be cited as:
IPCC, 2023: Sections. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

Section 1
Introduction

1. Introduction

This Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6) summarises the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation, based on the peer-reviewed scientific, technical and socio-economic literature since the publication of the IPCC's Fifth Assessment Report (AR5) in 2014.

The assessment is undertaken within the context of the evolving international landscape, in particular, developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement. It reflects the increasing diversity of those involved in climate action.

This report integrates the main findings of the AR6 Working Group reports[58] and the three AR6 Special Reports[59]. It recognizes the interdependence of climate, ecosystems and biodiversity, and human societies; the value of diverse forms of knowledge; and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development. Building on multiple analytical frameworks, including those from the physical and social sciences, this report identifies opportunities for transformative action which are effective, feasible, just and equitable using concepts of systems transitions and resilient development pathways[60]. Different regional classification schemes[61] are used for physical, social and economic aspects, reflecting the underlying literature.

After this introduction, Section 2, '*Current Status and Trends*', opens with the assessment of observational evidence for our changing climate, historical and current drivers of human-induced climate change, and its impacts. It assesses the current implementation of adaptation and mitigation response options. Section 3, '*Long-Term Climate and Development Futures*', provides a long-term assessment of climate change to 2100 and beyond in a broad range of socio-economic futures. It considers long-term characteristics, impacts, risks and costs in adaptation and mitigation pathways in the context of sustainable development. Section 4, '*Near- Term Responses in a Changing Climate*', assesses opportunities for scaling up effective action in the period up to 2040, in the context of climate pledges, and commitments, and the pursuit of sustainable development.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[62]. The scientific findings are drawn from the underlying reports and arise from their Summary for Policymakers (hereafter SPM), Technical Summary (hereafter TS), and underlying chapters and are indicated by {} brackets. Figure 1.1 shows the Synthesis Report Figures Key, a guide to visual icons that are used across multiple figures within this report.

58 The three Working Group contributions to AR6 are: Climate Change 2021: The Physical Science Basis; Climate Change 2022: Impacts, Adaptation and Vulnerability; and Climate Change 2022: Mitigation of Climate Change, respectively. Their assessments cover scientific literature accepted for publication respectively by 31 January 2021, 1 September 2021 and 11 October 2021.

59 The three Special Reports are : Global Warming of 1.5°C (2018): an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land (2019): an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); and The Ocean and Cryosphere in a Changing Climate (2019) (SROCC). The Special Reports cover scientific literature accepted for publication respectively by 15 May 2018, 7 April 2019 and 15 May 2019.

60 The Glossary (Annex I) includes definitions of these, and other terms and concepts used in this report drawn from the AR6 joint Working Group Glossary.

61 Depending on the climate information context, geographical regions in AR6 may refer to larger areas, such as sub-continents and oceanic regions, or to typological regions, such as monsoon regions, coastlines, mountain ranges or cities. A new set of standard AR6 WGI reference land and ocean regions have been defined. WGIII allocates countries to geographical regions, based on the UN Statistics Division Classification {*WGI 1.4.5, WGI 10.1, WGI 11.9, WGI 12.1–12.4, WGI Atlas.1.3.3–1.3.4*}.

62 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; more likely than not >50-100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100% and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood also is typeset in italics: for example, very likely. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

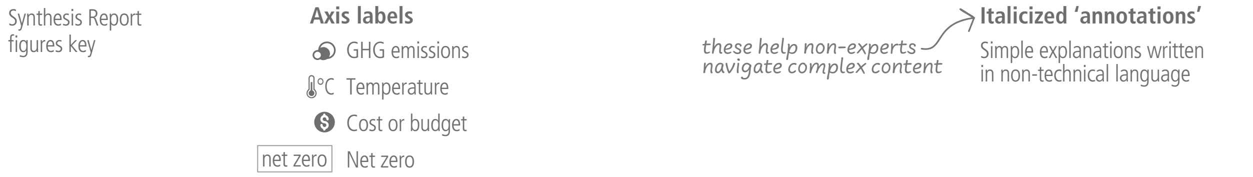


Figure 1.1: The Synthesis Report figures key.

Section 2
Current Status and Trends

Section 2: Current Status and Trends

2.1 Observed Changes, Impacts and Attribution

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase over 2010–2019, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and between individuals (*high confidence*). Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts on food and water security, human health and on economies and society and related losses and damages[63] to nature and people (*high confidence*). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (*high confidence*).

2.1.1. Observed Warming and its Causes

Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09 [0.95 to 1.20]°C)[64], with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88 [0.68 to 1.01]°C)[65]. Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling (Figure 2.1). Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10]°C higher than 1850–1900. Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[66] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs[67] contributed a warming of 1.0°C to 2.0°C, and other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural (solar and volcanic) drivers changed global surface temperature by ±0.1°C and internal variability changed it by ±0.2°C. {*WGI SPM A.1, WGI SPM A.1.2, WGI SPM A.1.3, WGI SPM A.2.2, WGI Figure SPM.2; SRCCL TS.2*}

Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities. Land and ocean sinks have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*). In 2019, atmospheric CO_2 concentrations reached 410 parts per million (ppm), CH_4 reached 1866 parts per billion (ppb) and nitrous oxide (N_2O) reached 332 ppb[68]. Other major contributors to warming are tropospheric ozone (O_3) and halogenated gases. Concentrations of CH_4 and N_2O have increased to levels unprecedented in at least 800,000 years (*very high confidence*), and there is *high confidence* that current CO_2 concentrations are higher than at any time over at least the past two million years. Since 1750, increases in CO_2 (47%) and CH_4 (156%) concentrations far exceed – and increases in N_2O (23%) are similar to – the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (*very high confidence*). The net cooling effect which arises from anthropogenic aerosols peaked in the late 20th century (*high confidence*). {*WGI SPM A1.1, WGI SPM A1.3, WGI SPM A.2.1, WGI Figure SPM.2, WGI TS 2.2, WGI 2ES, WGI Figure 6.1*}

[63] In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic. (See Annex I: Glossary)

[64] The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22]°C). Additionally, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5 {*WGI SPM A1.2 and footnote 10*}

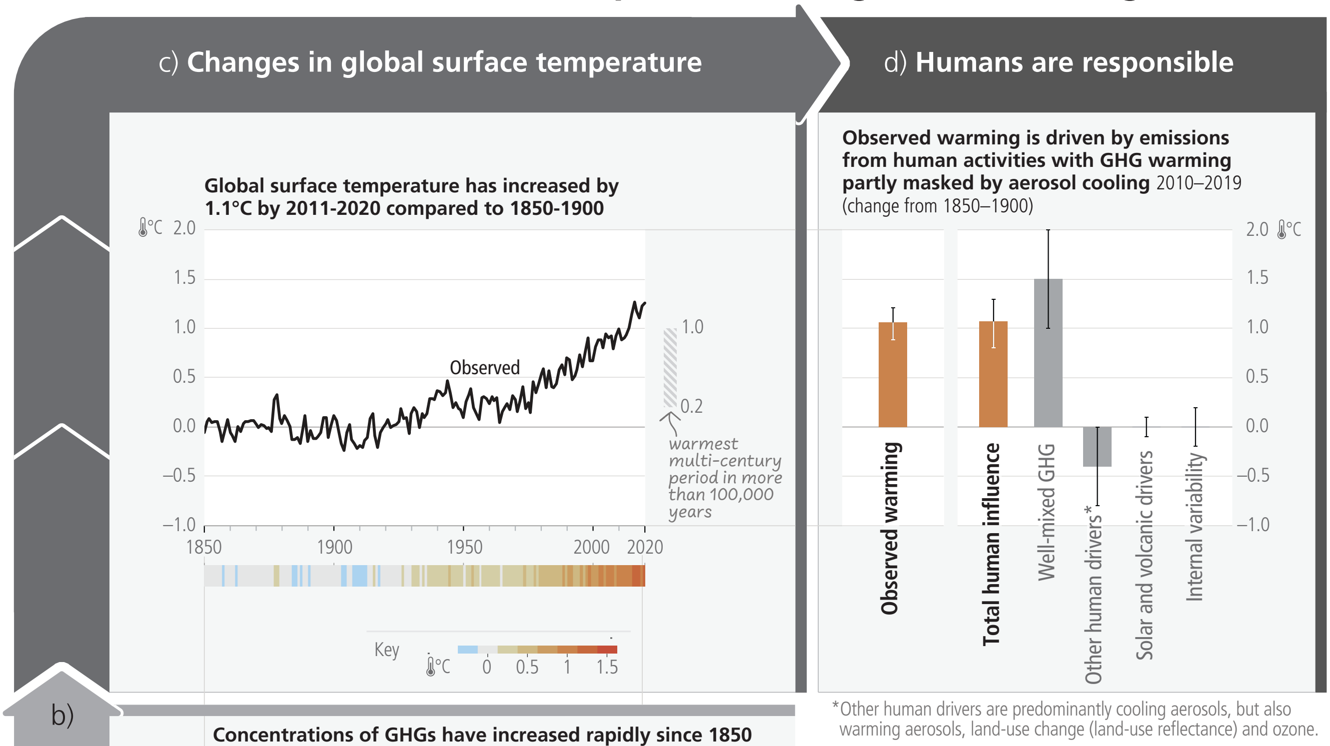
[65] For 1850–1900 to 2013–2022 the updated calculations are 1.15 [1.00 to 1.25]°C for global surface temperature, 1.65 [1.36 to 1.90]°C for land temperatures and 0.93 [0.73 to 1.04]°C for ocean temperatures above 1850–1900 using the exact same datasets (updated by 2 years) and methods as employed in WGI.

[66] The period distinction with the observed assessment arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21]°C. {*WGI SPM footnote 11*}

[67] Contributions from emissions to the 2010–2019 warming relative to 1850–1900 assessed from radiative forcing studies are: CO_2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C.

[68] For 2021 (the most recent year for which final numbers are available) concentrations using the same observational products and methods as in AR6 WGI are: 415 ppm CO_2; 1896 ppb CH_4; and 335 ppb N_2O. Note that the CO_2 is reported here using the WMO-CO_2-X2007 scale to be consistent with WGI. Operational CO_2 reporting has since been updated to use the WMO-CO_2-X2019 scale.

Human activities are responsible for global warming



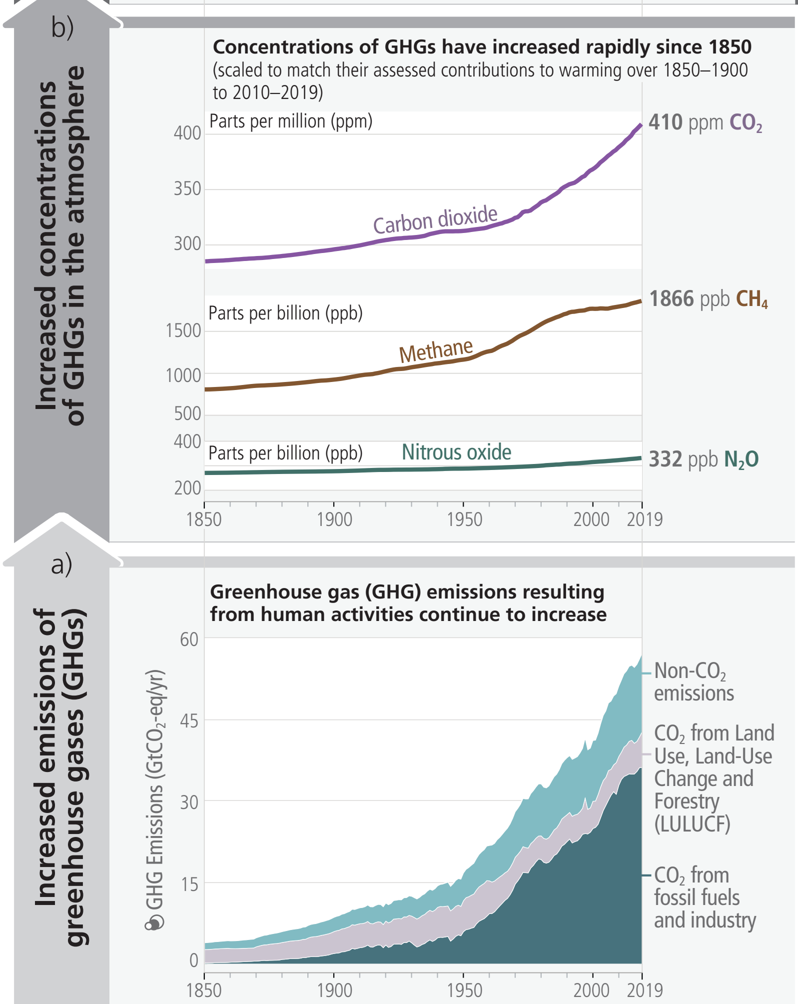


Figure 2.1: The causal chain from emissions to resulting warming of the climate system. Emissions of GHG have increased rapidly over recent decades **(panel (a))**. Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) (dark green); net CO_2 from land use, land-use change and forestry (CO_2-LULUCF) (green); CH_4; N_2O; and fluorinated gases (HFCs, PFCs, SF_6, NF_3) (light blue). These emissions have led to increases in the atmospheric concentrations of several GHGs including the three major well-mixed GHGs CO_2, CH_4 and N_2O **(panel (b)**, annual values). To indicate their relative importance each subpanel's vertical extent for CO_2, CH_4 and N_2O is scaled to match the assessed individual direct effect (and, in the case of CH_4 indirect effect via atmospheric chemistry impacts on tropospheric ozone) of historical emissions on temperature change from 1850–1900 to 2010–2019. This estimate arises from an assessment of effective radiative forcing and climate sensitivity. The global surface temperature (shown as annual anomalies from a 1850–1900 baseline) has increased by around 1.1°C since 1850–1900 **(panel (c))**. The vertical bar on the right shows the estimated temperature *(very likely range)* during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). Prior to that, the next most recent warm period was about 125,000 years ago, when the assessed multi-century temperature range [0.5°C to 1.5°C] overlaps the observations of the most recent decade. These past warm periods were caused by slow (multi-millennial) orbital variations. Formal detection and attribution studies synthesise information from climate models and observations and show that the best estimate is that all the warming observed between 1850–1900 and 2010–2019 is caused by humans **(panel (d))**. The panel shows temperature change attributed to: total human influence; its decomposition into changes in GHG concentrations and other human drivers (aerosols, ozone and land-use change (land-use reflectance)); solar and volcanic drivers; and internal climate variability. Whiskers show *likely* ranges. *{WGI SPM A.2.2, WGI Figure SPM.1, WGI Figure SPM.2, WGI TS2.2, WGI 2.1; WGIII Figure SPM.1, WGIII A.III.II.2.5.1}*

Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 (1.3% yr^{-1}) was lower than that between 2000 and 2009 (2.1% yr^{-1})[69]**.** Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400 ±240 $GtCO_2$. Of these, more than half (58%) occurred between 1850 and 1989 [1400 ±195 $GtCO_2$], and about 42% between 1990 and 2019 [1000 ±90 $GtCO_2$]. Global net anthropogenic GHG emissions have been estimated to be 59±6.6 $GtCO_2$-eq in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990. By 2019, the largest growth in gross emissions occurred in CO_2 from fossil fuels and industry (CO_2-FFI) followed by CH_4, whereas the highest relative growth occurred in fluorinated gases (F-gases), starting from low levels in 1990. (*high confidence*) {*WGIII SPM B1.1, WGIII SPM B.1.2, WGIII SPM B.1.3, WGIII Figure SPM.1, WGIII Figure SPM.2*}

Regional contributions to global human-caused GHG emissions continue to differ widely. Historical contributions of CO_2 emissions vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI (1650 ± 73 $GtCO_2$-eq) and net CO_2-LULUCF (760 ± 220 $GtCO_2$-eq) emissions (Figure 2.2). Variations in regional and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. Average per capita net anthropogenic GHG emissions in 2019 ranged from 2.6 tCO_2-eq to 19 tCO_2-eq across regions (Figure 2.2). Least Developed Countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF. Around 48% of the global population in 2019 lives in countries emitting on average more than 6 tCO_2-eq per capita, 35% of the global population live in countries emitting more than 9 tCO_2-eq per capita[70] (excluding CO_2-LULUCF) while another 41% live in countries emitting less than 3 tCO_2-eq per capita. A substantial share of the population in these low-emitting countries lack access to modern energy services. (*high confidence*) {*WGIII SPM B.3, WGIII SPM B3.1, WGIII SPM B.3.2, WGIII SPM B.3.3*}

Net GHG emissions have increased since 2010 across all major sectors (*high confidence*). In 2019, approximately 34% (20 $GtCO_2$-eq) of net global GHG emissions came from the energy sector, 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from AFOLU, 15% (8.7 $GtCO_2$-eq) from transport and 6% (3.3 $GtCO_2$-eq) from buildings[71] (*high confidence*). Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%) but remained roughly constant at about 2% yr^{-1} in the transport sector (*high confidence*). About half of total net AFOLU emissions are from CO_2 LULUCF, predominantly from deforestation (*medium confidence*). Land overall constituted a net sink of –6.6 (±4.6) $GtCO_2$ yr^{-1} for the period 2010–2019[72] (*medium confidence*). {*WGIII SPM B.2, WGIII SPM B.2.1, WGIII SPM B.2.2, WGIII TS 5.6.1*}

Human-caused climate change is a consequence of more than a century of net GHG emissions from energy use, land-use and land use change, lifestyle and patterns of consumption, and production. Emissions reductions in CO_2 from fossil fuels and industrial processes (CO_2-FFI), due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. The 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions, while the middle 40% contribute 40–53%, and the bottom 50% contribute 13–15%. An increasing share of emissions can be attributed to urban areas (a rise from about 62% to 67–72% of the global share between 2015 and 2020). The drivers of urban GHG emissions[73] are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {*WGIII SPM B.2, WGIII SPM B.2.3, WGIII SPM B.3.4, WGIII SPM D.1.1*}

[69] GHG emission metrics are used to express emissions of different GHGs in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalents (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The AR6 WGI and WGIII reports contain updated emission metric values, evaluations of different metrics with regard to mitigation objectives, and assess new approaches to aggregating gases. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {*WGI SPM D.1.8, WGI 7.6; WGIII SPM B.1, WGIII Cross-Chapter Box 2.2*} (*Annex I: Glossary*)

[70] Territorial emissions

[71] GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur. {*WGIII SPM footnote 8*}

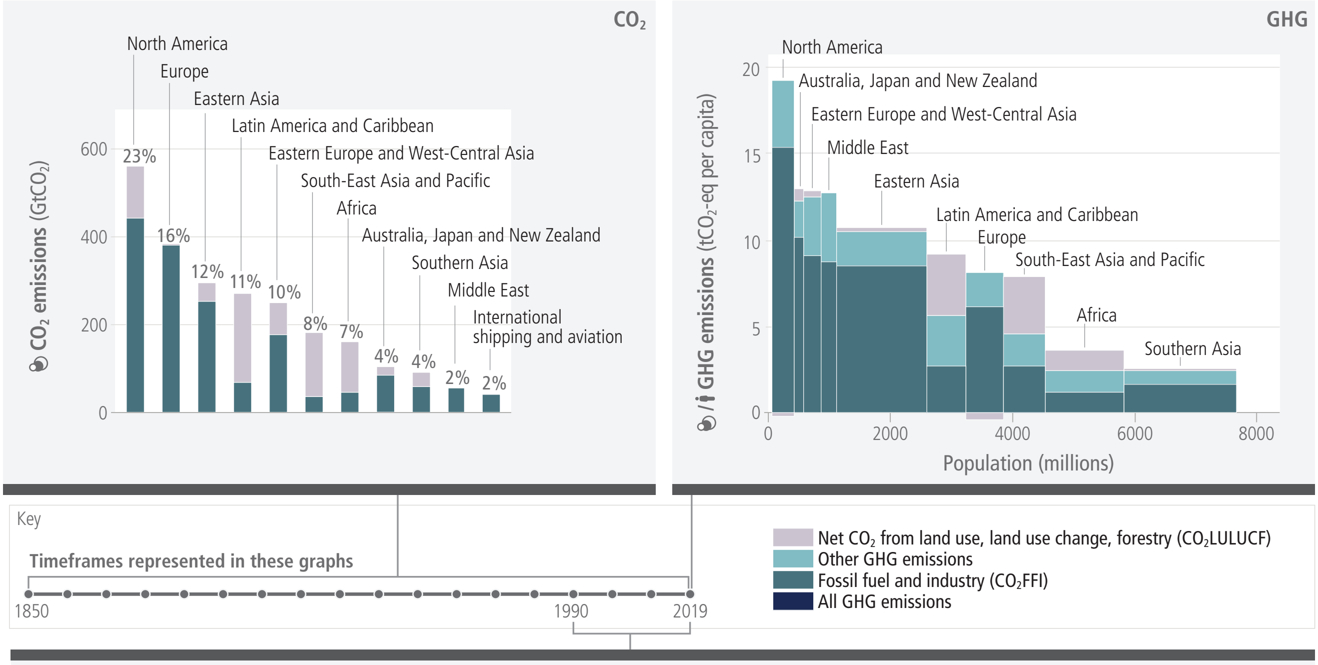
[72] Comprising a gross sink of -12.5 (±3.2) $GtCO_2$ yr^{-1} resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO_2-LULUCF emissions +5.9 (±4.1) $GtCO_2$ yr^{-1} based on book-keeping models. {*WGIII SPM Footnote 14*}

[73] This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {*WGIII SPM footnote 15*}

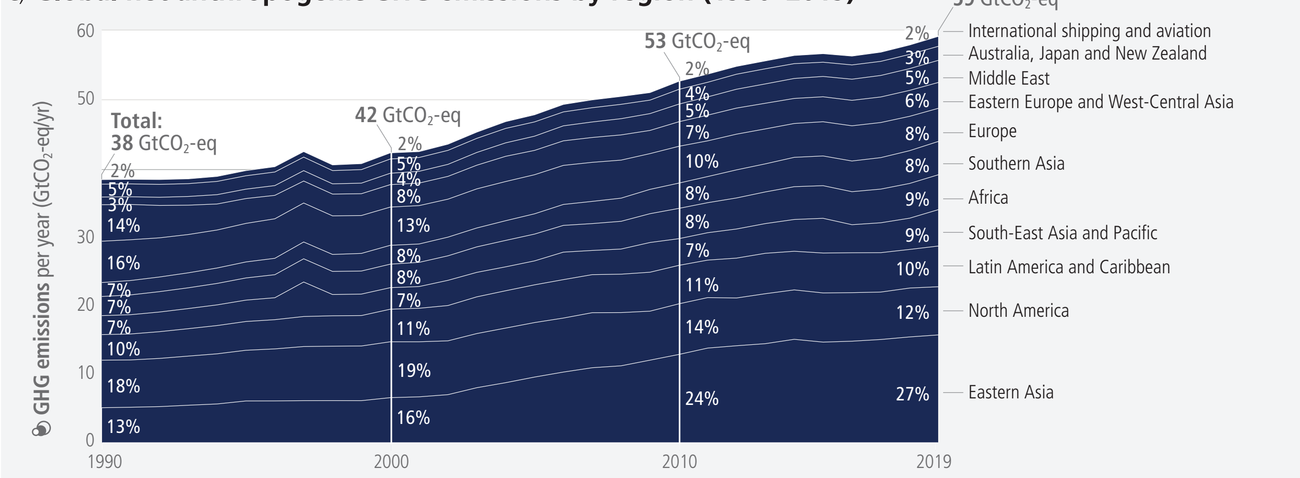
Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850

a) **Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)**

b) **Net anthropogenic GHG emissions per capita and for total population, per region (2019)**



c) **Global net anthropogenic GHG emissions by region (1990–2019)**



d) **Regional indicators (2019) and regional production vs consumption accounting (2018)**

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita ($USD1000_{PPP}$ 2017 per person) [1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019 [2] (production basis)										
GHG emissions intensity (tCO_2-eq / $USD1000_{PPP}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO_2-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2FFI, 2018, per person										
Production-based emissions (tCO_2FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO_2FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2FFI, CO_2LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in WGIII Annex II, Part I.

Section 2

Figure 2.2: Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019. Panel (a) shows the share of historical cumulative net anthropogenic CO_2 emissions per region from 1850 to 2019 in $GtCO_2$. This includes CO_2-FFI and CO_2-LULUCF. Other GHG emissions are not included. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel (b)** shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2-FFI; net CO_2-LULUCF; and other GHG emissions (CH_4, N_2O, fluorinated gases, expressed in CO_2-eq using GWP100-AR6). The height of each rectangle shows per capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO_2-LULUCF is below the axis, indicating net CO_2 removals rather than emissions. **Panel (c)** shows global net anthropogenic GHG emissions by region (in $GtCO_2$-eq yr^{-1} (GWP100-AR6)) for the time period 1990–2019. Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II of WGIII. **Panel (d)** shows population, gross domestic product (GDP) per person, emission indicators by region in 2019 for total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO_2-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included. *{WGIII Figure SPM.2}*

2.1.2. Observed Climate System Changes and Impacts to Date

It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred (Table 2.1). The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years. It is *very likely* that GHG emissions were the main driver[74] of tropospheric warming and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of stratospheric cooling between 1979 and the mid-1990s. It is *virtually certain* that the global upper ocean (0-700m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*). Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1]mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to –4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971 (Figure 3.4). Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019. Human influence has also *very likely* contributed to decreased Northern Hemisphere spring snow cover and surface melting of the Greenland ice sheet. It is *virtually* certain that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. {*WGI SPM A.1, WGI SPM A.1.3, WGI SPM A.1.5, WGI SPM A.1.6, WG1 SPM A1.7, WGI SPM A.2, WG1.SPM A.4.2; SROCC SPM.A.1, SROCC SPM A.2*}

Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5 (Figure 2.3). It is *virtually* certain that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s (Figure 2.3), while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-caused climate change is the main driver of these changes. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006. The frequency and intensity of heavy precipitation events have increased since the 1950s over most land areas for which observational data are sufficient for trend analysis (*high confidence*), and human-caused climate change is *likely* the main driver (Figure 2.3). Human-caused climate change has contributed to increases in agricultural and ecological droughts in some regions due to increased land evapotranspiration (*medium confidence*) (Figure 2.3). It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. {*WGI SPM A.3, WGI SPM A3.1, WGI SPM A3.2; WGI SPM A3.4; SRCCL SPM.A.2.2; SROCC SPM. A.2*}

Climate change has caused substantial damages, and increasingly irreversible[75] losses, in terrestrial, freshwater, cryospheric and coastal and open ocean ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Biological responses including changes in geographic placement and shifting seasonal timing are often not sufficient to cope with recent climate change (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*) and mass mortality events on land and in the ocean (*very high confidence*). Impacts on some ecosystems are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). Impacts in ecosystems from slow-onset processes such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human-caused climate change (*high confidence*). Climate change has contributed to desertification and exacerbated land degradation, particularly in low lying coastal areas, river deltas, drylands and in permafrost areas (*high confidence*). Nearly 50% of coastal wetlands have been lost over the last 100 years, as a result of the combined effects of localised human pressures, sea level rise, warming and extreme climate events (*high confidence*). {*WGII SPM B.1.1, WGII SPM B.1.2, WGII Figure SPM.2.A, WGII TS.B.1; SRCCL SPM A.1.5, SRCCL SPM A.2, SRCCL SPM A.2.6, SRCCL Figure SPM.1; SROCC SPM A.6.1, SROCC SPM, A.6.4, SROCC SPM A.7*}

74 'Main driver' means responsible for more than 50% of the change. {*WGI SPM footnote 12*}

75 See Annex I: Glossary.

Table 2.1: Assessment of observed changes in large-scale indicators of mean climate across climate system components, and their attribution to human influence. The colour coding indicates the assessed confidence in / likelihood[76] of the observed change and the human contribution as a driver or main driver (specified in that case) where available (see colour key). Otherwise, explanatory text is provided. {*WGI Table TS.1*}

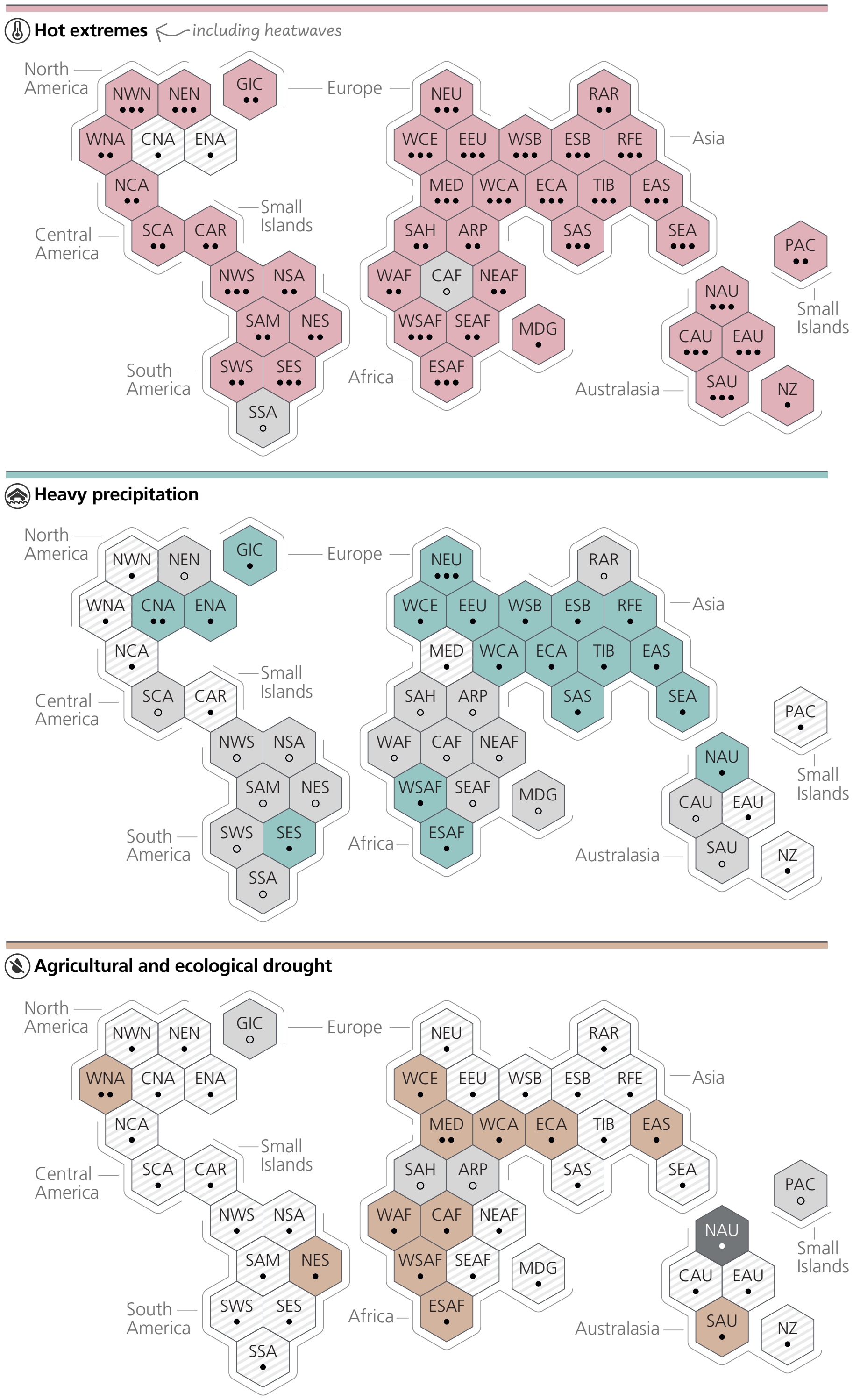
Change in indicator		Observed change assessment	Human contribution assessment
Atmosphere and water cycle	Warming of global mean surface air temperature since 1850-1900		*likely* range of human contribution ([0.8-1.3°C]) encompasses the very likely range of observed warming ([0.9-1.2°C])
	Warming of the troposphere since 1979		Main driver
	Cooling of the lower stratosphere since the mid-20th century		Main driver 1979 - mid-1990s
	Large-scale precipitation and upper troposphere humidity changes since 1979		
	Expansion of the zonal mean Hadley Circulation since the 1980s		Southern Hemisphere
Ocean	Ocean heat content increase since the 1970s		Main driver
	Salinity changes since the mid-20th century		
	Global mean sea level rise since 1970		Main driver
Cryosphere	Arctic sea ice loss since 1979		Main driver
	Reduction in Northern Hemisphere springtime snow cover since 1950		
	Greenland ice sheet mass loss since 1990s		
	Antarctic ice sheet mass loss since 1990s		*Limited evidence & medium agreement*
	Retreat of glaciers		Main driver
Carbon cycle	Increased amplitude of the seasonal cycle of atmospheric CO_2 since the early 1960s		Main driver
	Acidification of the global surface ocean		Main driver
Land climate	Mean surface air temperature over land (about 40% larger than global mean warming)		Main driver
Synthesis	Warming of the global climate system since preindustrial times		

Key: *medium confidence* | *likely / high confidence* | *very likely* | *extremely likely* | *virtually certain* | fact

[76] Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language.

Climate change has impacted human and natural systems across the world with those who have generally least contributed to climate change being most vulnerable

a) **Synthesis of assessment of observed change in hot extremes, heavy precipitation and drought, and confidence in human contribution to the observed changes in the world's regions**



Dimension of Risk: **Hazard**

Key

Type of observed change since the 1950s

- Increase
- Decrease
- Limited data and/or literature
- Low agreement in the type of change

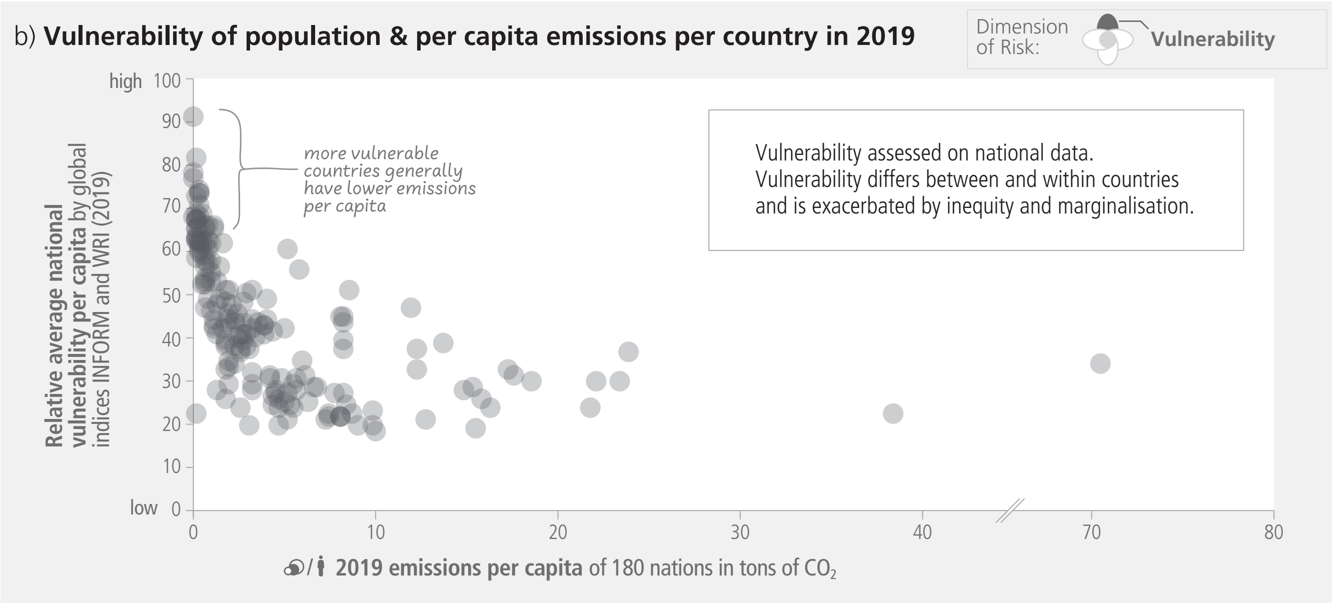
Confidence in human contribution to the observed change

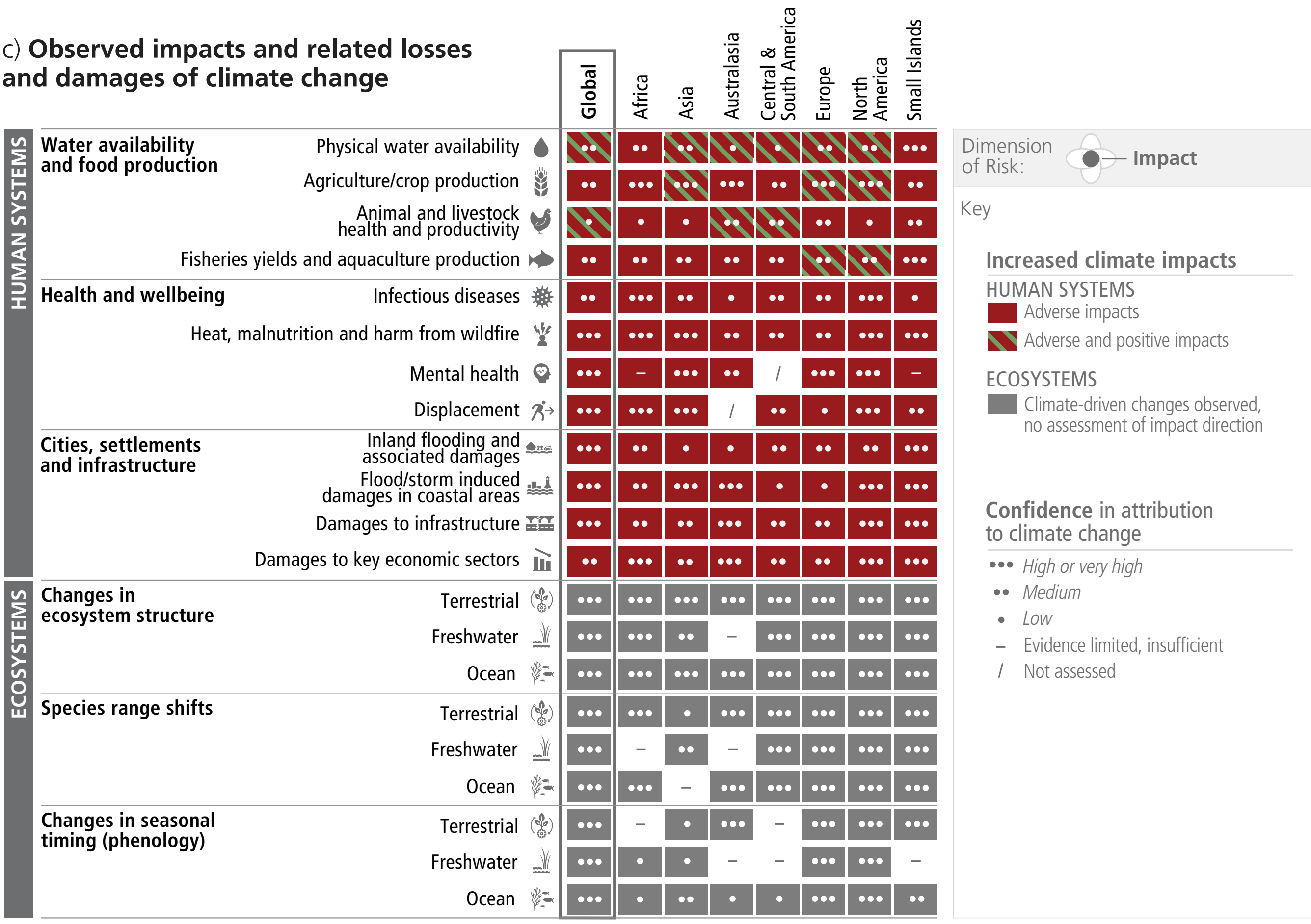
- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence

Each hexagon corresponds to a region

NWN North-Western North America

IPCC AR6 WGI reference regions: **North America: NWN** (North-Western North America), **NEN** (North-Eastern North America), **WNA** (Western North America), **CNA** (Central North America), **ENA** (Eastern North America), **Central America: NCA** (Northern Central America), **SCA** (Southern Central America), **CAR** (Caribbean), **South America: NWS** (North-Western South America), **NSA** (Northern South America), **NES** (North-Eastern South America), **SAM** (South American Monsoon), **SWS** (South-Western South America), **SES** (South-Eastern South America), **SSA** (Southern South America), **Europe: GIC** (Greenland/Iceland), **NEU** (Northern Europe), **WCE** (Western and Central Europe), **EEU** (Eastern Europe), **MED** (Mediterranean), **Africa: MED** (Mediterranean), **SAH** (Sahara), **WAF** (Western Africa), **CAF** (Central Africa), **NEAF** (North Eastern Africa), **SEAF** (South Eastern Africa), **WSAF** (West Southern Africa), **ESAF** (East Southern Africa), **MDG** (Madagascar), **Asia: RAR** (Russian Arctic), **WSB** (West Siberia), **ESB** (East Siberia), **RFE** (Russian Far East), **WCA** (West Central Asia), **ECA** (East Central Asia), **TIB** (Tibetan Plateau), **EAS** (East Asia), **ARP** (Arabian Peninsula), **SAS** (South Asia), **SEA** (South East Asia), **Australasia: NAU** (Northern Australia), **CAU** (Central Australia), **EAU** (Eastern Australia), **SAU** (Southern Australia), **NZ** (New Zealand), **Small Islands: CAR** (Caribbean), **PAC** (Pacific Small Islands)


b) Vulnerability of population & per capita emissions per country in 2019
Dimension of Risk:
Vulnerability
high
low
100
90
80
70
60
50
40
30
20
10
0
Relative average national vulnerability per capita by global indices INFORM and WRI (2019)
more vulnerable countries generally have lower emissions per capita
Vulnerability assessed on national data.
Vulnerability differs between and within countries
and is exacerbated by inequity and marginalisation.
0
10
20
30
40
70
80
2019 emissions per capita of 180 nations in tons of CO2


c) Observed impacts and related losses and damages of climate change
Global
Africa
Asia
Australasia
Central & South America
Europe
North America
Small Islands
HUMAN SYSTEMS
Water availability and food production
Physical water availability
Agriculture/crop production
Animal and livestock health and productivity
Fisheries yields and aquaculture production
Health and wellbeing
Infectious diseases
Heat, malnutrition and harm from wildfire
Mental health
Displacement
Cities, settlements and infrastructure
Inland flooding and associated damages
Flood/storm induced damages in coastal areas
Damages to infrastructure
Damages to key economic sectors
ECOSYSTEMS
Changes in ecosystem structure
Terrestrial
Freshwater
Ocean
Species range shifts
Terrestrial
Freshwater
Ocean
Changes in seasonal timing (phenology)
Terrestrial
Freshwater
Ocean
Dimension of Risk:
Impact
Key
Increased climate impacts
HUMAN SYSTEMS
Adverse impacts
Adverse and positive impacts
ECOSYSTEMS
Climate-driven changes observed, no assessment of impact direction
Confidence in attribution to climate change
••• High or very high
•• Medium
• Low
– Evidence limited, insufficient
/ Not assessed

Section 2

Figure 2.3: Both vulnerability to current climate extremes and historical contribution to climate change are highly heterogeneous with many of those who have least contributed to climate change to date being most vulnerable to its impacts. Panel (a) The IPCC AR6 WGI inhabited regions are displayed as hexagons with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The colours in each panel represent the four outcomes of the assessment on observed changes. Striped hexagons (white and light-grey) are used where there is *low agreement* in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least *medium confidence* in the observed change. The confidence level for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for *high confidence*, two dots for *medium confidence* and one dot for *low confidence* (single, filled dot: *limited agreement*; single, empty dot: *limited evidence*). For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand. **Panel (b)** shows the average level of vulnerability amongst a country's population against 2019 CO_2-FFI emissions per- capita per country for the 180 countries for which both sets of metrics are available. Vulnerability information is based on two global indicator systems, namely INFORM and World Risk Index. Countries with a relatively low average vulnerability often have groups with high vulnerability within their population and vice versa. The underlying data includes, for example, information on poverty, inequality, health care infrastructure or insurance coverage. **Panel (c)** Observed impacts on ecosystems and human systems attributed to climate change at global and regional scales. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. For human systems, the direction of impacts is assessed and both adverse and positive impacts have been observed e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item (for more details and methodology see WGII SMTS.1). Physical water availability includes balance of water available from various sources including ground water, water quality and demand for water. Global mental health and displacement assessments reflect only assessed regions. Confidence levels reflect the assessment of attribution of the observed impact to climate change. *{WGI Figure SPM.3, Table TS.5, Interactive Atlas; WGII Figure SPM.2, WGII SMTS.1, WGII 8.3.1, Figure 8.5; ; WGIII 2.2.3}*

Climate change has reduced food security and affected water security due to warming, changing precipitation patterns, reduction and loss of cryospheric elements, and greater frequency and intensity of climatic extremes, thereby hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth in agricultural productivity over the past 50 years globally (*medium confidence*), with related negative crop yield impacts mainly recorded in mid- and low latitude regions, and some positive impacts in some high latitude regions (*high confidence*). Ocean warming in the 20th century and beyond has contributed to an overall decrease in maximum catch potential (*medium confidence*), compounding the impacts from overfishing for some fish stocks (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Current levels of global warming are associated with moderate risks from increased dryland water scarcity (*high confidence*). Roughly half of the world's population currently experiences severe water scarcity for at least some part of the year due to a combination of climatic and non-climatic drivers (*medium confidence*) (Figure 2.3). Unsustainable agricultural expansion, driven in part by unbalanced diets[77], increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[78] and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, LDCs, Small Islands and the Arctic, and for small-scale food producers, low-income households and Indigenous Peoples globally (*high confidence*). {*WGII SPM B.1.3, WGII SPM.B.2.3, WGII Figure SPM.2, WGII TS B.2.3, WGII TS Figure TS. 6; SRCCL SPM A.2.8, SRCCL SPM A.5.3; SROCC SPM A.5.4., SROCC SPM A.7.1, SROCC SPM A.8.1, SROCC Figure SPM.2*}

In urban settings, climate change has caused adverse impacts on human health, livelihoods and key infrastructure (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also worsened air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Urban infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events[79], with resulting economic losses, disruptions of services and impacts to well-being (*high confidence*). Observed impacts are concentrated amongst economically and socially marginalised urban residents, e.g., those living in informal settlements (*high confidence*). Cities intensify human-caused warming locally (*very high confidence*), while urbanisation also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). {*WGI SPM C.2.6; WGII SPM B.1.5, WGII Figure TS.9, WGII 6 ES*}

Climate change has adversely affected human physical health globally and mental health in assessed regions (*very high confidence*), and is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from extreme events (*very high confidence*), and loss of livelihoods and culture

[77] Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-GHG emissions systems, as described in SRCCL. {*WGII SPM Footnote 32*}

[78] Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and is used to assess the need for humanitarian action. {*WGII SPM, footnote 30*}

[79] Slow-onset events are described among the climatic-impact drivers of the AR6 WGI and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization. {*WGII SPM footnote 29*}

(*high confidence*) (Figure 2.3). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). Climate and weather extremes are increasingly driving displacement in Africa, Asia, North America (*high confidence*), and Central and South America (*medium confidence*) (Figure 2.3), with small island states in the Caribbean and South Pacific being disproportionately affected relative to their small population size (*high confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {*WGII SPM B.1.4, WGII SPM B.1.7*}

Human influence has *likely* increased the chance of compound extreme events[80] since the 1950s. Concurrent and repeated climate hazards have occurred in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Compound extreme events include increases in the frequency of concurrent heatwaves and droughts (*high confidence*); fire weather in some regions (*medium confidence*); and compound flooding in some locations (*medium confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Compound climate hazards can overwhelm adaptive capacity and substantially increase damage (*high confidence*)*)*. {*WGI SPM A.3.5; WGII SPM. B.5.1, WGII TS.C.11.3*}

Economic impacts attributable to climate change are increasingly affecting peoples' livelihoods and are causing economic and societal impacts across national boundaries (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism, and through outdoor labour productivity (*high confidence*) with some exceptions of positive impacts in regions with low energy demand and comparative advantages in agricultural markets and tourism (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). Tropical cyclones have reduced economic growth in the short-term (*high confidence*). Event attribution studies and physical understanding indicate that human-caused climate change increases heavy precipitation associated with tropical cyclones (*high confidence*). Wildfires in many regions have affected built assets, economic activity, and health (*medium* to *high confidence*). In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). {*WGI SPM A.3.4; WGII SPM B.1.6, WGII SPM B.5.2, WGII SPM B.5.3*}

Climate change has caused widespread adverse impacts and related losses and damages to nature and people (*high confidence*). Losses and damages are unequally distributed across systems, regions and sectors (*high confidence*). Cultural losses, related to tangible and intangible heritage, threaten adaptive capacity and may result in irrevocable losses of sense of belonging, valued cultural practices, identity and home, particularly for Indigenous Peoples and those more directly reliant on the environment for subsistence (*medium confidence*). For example, changes in snow cover, lake and river ice, and permafrost in many Arctic regions, are harming the livelihoods and cultural identity of Arctic residents including Indigenous populations (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to well-being (*high confidence*). {*WGII SPM B.1, WGII SPM B.1.2, WGII SPM.B.1.5, WGII SPM C.3.5, WGII TS.B.1.6; SROCC SPM A.7.1*}

Across sectors and regions, the most vulnerable people and systems have been disproportionately affected by the impacts of climate change (*high confidence*). LDCs and SIDS who have much lower per capita emissions (1.7 tCO_2-eq, 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq) excluding CO_2-LULUCF, also have high vulnerability to climatic hazards, with global hotspots of high human vulnerability observed in West-, Central- and East Africa, South Asia, Central and South America, SIDS and the Arctic (*high confidence*). Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalisation linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). In the Arctic and in some high mountain regions, negative impacts of cryosphere change have been especially felt among Indigenous Peoples (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalisation, historical and ongoing patterns of inequity such as colonialism, and governance[81] (*high confidence*). {*WGII SPM B.1, WGII SPM B.2, WGII SPM B.2.4; WGIII SPM B.3.1; SROCC SPM A.7.1, SROCC SPM A.7.2*}

80 See Annex 1: Glossary.

81 Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local. {*WGII SPM Footnote 31*}

2.2 Responses Undertaken to Date

International climate agreements, rising national ambitions for climate action, along with rising public awareness are accelerating efforts to address climate change at multiple levels of governance. Mitigation policies have contributed to a decrease in global energy and carbon intensity, with several countries achieving GHG emission reductions for over a decade. Low-emission technologies are becoming more affordable, with many low or zero emissions options now available for energy, buildings, transport, and industry. Adaptation planning and implementation progress has generated multiple benefits, with effective adaptation options having the potential to reduce climate risks and contribute to sustainable development. Global tracked finance for mitigation and adaptation has seen an upward trend since AR5, but falls short of needs. (*high confidence*)

2.2.1. Global Policy Setting

The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging the development and implementation of climate policies at multiple levels of governance (*high confidence*). The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). The Paris Agreement, adopted under the UNFCCC, with near universal participation, has led to policy development and target-setting at national and sub-national levels, particularly in relation to mitigation but also for adaptation, as well as enhanced transparency of climate action and support (*medium confidence*). Nationally Determined Contributions (NDCs), required under the Paris Agreement, have required countries to articulate their priorities and ambition with respect to climate action. {*WGII 17.4, WGII TS D.1.1; WGIII SPM B.5.1, WGIII SPM E.6*}

Loss & Damage[82] was formally recognized in 2013 through establishment of the Warsaw International Mechanism on Loss and Damage (WIM), and in 2015, Article 8 of the Paris Agreement provided a legal basis for the WIM. There is improved understanding of both economic and non-economic losses and damages, which is informing international climate policy and which has highlighted that losses and damages are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries (*high confidence*). {*WGII SPM C.3.5, WGII Cross-Chapter Box LOSS*}

Other recent global agreements that influence responses to climate change include the Sendai Framework for Disaster Risk Reduction (2015-2030), the finance-oriented Addis Ababa Action Agenda (2015) and the New Urban Agenda (2016), and the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (2016), among others. In addition, the 2030 Agenda for Sustainable Development, adopted in 2015 by UN member states, sets out 17 Sustainable Development Goals (SDGs) and seeks to align efforts globally to prioritise ending extreme poverty, protect the planet and promote more peaceful, prosperous and inclusive societies. If achieved, these agreements would reduce climate change, and the impacts on health, well-being, migration, and conflict, among others (*very high confidence*). {*WGII TS.A.1, WGII 7 ES*}

Since AR5, rising public awareness and an increasing diversity of actors, have overall helped accelerate political commitment and global efforts to address climate change (*medium confidence*). Mass social movements have emerged as catalysing agents in some regions, often building on prior movements including Indigenous Peoples-led movements, youth movements, human rights movements, gender activism, and climate litigation, which is raising awareness and, in some cases, has influenced the outcome and ambition of climate governance (*medium confidence*). Engaging Indigenous Peoples and local communities using just-transition and rights-based decision-making approaches, implemented through collective and participatory decision-making processes has enabled deeper ambition and accelerated action in different ways, and at all scales, depending on national circumstances (*medium confidence*). The media helps shape the public discourse about climate change. This can usefully build public support to accelerate climate action (*medium evidence, high agreement*). In some instances, public discourses of media and organised counter movements have impeded climate action, exacerbating helplessness and disinformation and fuelling polarisation, with negative implications for climate action (*medium confidence*). {*WGII SPM C.5.1, WGII SPM D.2, WGII TS.D.9, WGII TS.D.9.7, WGII TS.E.2.1, WGII 18.4; WGIII SPM D.3.3, WGIII SPM E.3.3, WGIII TS.6.1, WGIII 6.7, WGIII 13 ES, WGIII Box.13.7*}

2.2.2. Mitigation Actions to Date

There has been a consistent expansion of policies and laws addressing mitigation since AR5 (*high confidence*). Climate governance supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Many regulatory and economic instruments have already been deployed successfully (*high confidence*). By 2020, laws primarily focussed on reducing GHG emissions existed in 56 countries covering 53% of global emissions (*medium confidence*). The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). Policy coverage is uneven across sectors and remains limited for emissions from agriculture, and from industrial materials and feedstocks (*high confidence*). {*WGIII SPM B.5, WGIII SPM B.5.2, WGIII SPM E.3, WGIII SPM E.4*}

Practical experience has informed economic instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, alignment with distributional goals, and social acceptance (*high confidence*). Low-emission technological innovation is strengthened through the combination of technology-push policies, together with policies that create incentives for behaviour change and market opportunities (*high confidence*) (Section 4.8.3). Comprehensive and consistent policy packages have been found to be more effective

82 See Annex I: Glossary.

than single policies (*high confidence*). Combining mitigation with policies to shift development pathways, policies that induce lifestyle or behaviour changes, for example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and enhanced active mobility (*high confidence*). Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. Effective governance enhances regulatory certainty, creating specialised organisations and creating the context to mobilise finance (*medium confidence*). These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence*). {*WGIII SPM E.2.2, WGIII SPM E.3, WGIII SPM E.3.1, WGIII SPM E.4.2, WGIII SPM E.4.3, WGIII SPM E.4.4*}

The unit costs of several low-emission technologies, including solar, wind and lithium-ion batteries, have fallen consistently since 2010 (Figure 2.4). Design and process innovations in combination with the use of digital technologies have led to near-commercial availability of many low or zero emissions options in buildings, transport and industry. From 2010-2019, there have been sustained decreases in the unit costs of solar energy (by 85%), wind energy (by 55%), and lithium-ion batteries (by 85%), and large increases in their deployment, e.g., >10× for solar and >100× for electric vehicles (EVs), albeit varying widely across regions (Figure 2.4). Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. (*high confidence*) {*WGIII SPM B.4, WGIII SPM B.4.1, WGIII SPM C.4.2, WGIII SPM C.5.2, WGIII SPM C.7.2, WGIII SPM C.8, WGIII Figure SPM.3, WGIII Figure SPM.3*}

For almost all basic materials – primary metals, building materials and chemicals – many low- to zero-GHG intensity production processes are at the pilot to near-commercial and in some cases commercial stage but they are not yet established industrial practice. Integrated design in construction and retrofit of buildings has led to increasing examples of zero energy or zero carbon buildings. Technological innovation made possible the widespread adoption of LED lighting. Digital technologies including sensors, the internet of things, robotics, and artificial intelligence can improve energy management in all sectors; they can increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities. However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices. Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective and are generally supported by the public, and this enables expanded deployment in many regions. (*high confidence*) {*WGIII SPM B.4.3, WGIII SPM C.5.2, WGIII SPM C.7.2, WGIII SPM E.1.1, WGIII TS.6.5*}

The magnitude of global climate finance flows has increased and financing channels have broadened (*high confidence*). Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20, but average growth has slowed since 2018 (*medium confidence*) and most climate finance stays within national borders (*high confidence*). Markets for green bonds, environmental, social and governance and sustainable finance products have expanded significantly since AR5 (*high confidence*). Investors, central banks, and financial regulators are driving increased awareness of climate risk to support climate policy development and implementation (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions (*high confidence*). {*WGIII SPM B.5.4, WGIII SPM E.5, WGIII TS.6.3, WGIII TS.6.4*}

Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). Equity and distributional impacts of carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). The mix of policy instruments which reduced costs and stimulated adoption of solar energy, wind energy and lithium-ion batteries includes public R&D, funding for demonstration and pilot projects, and demand-pull instruments such as deployment subsidies to attain scale (*high confidence*) (Figure 2.4). {*WGIII SPM B.4.1, WGIII SPM B.5.2, WGIII SPM E.4.2, WG III TS.3*}

Mitigation actions, supported by policies, have contributed to a decrease in global energy and carbon intensity between 2010 and 2019, with a growing number of countries achieving absolute GHG emission reductions for more than a decade (*high confidence*). While global net GHG emissions have increased since 2010, global energy intensity (total primary energy per unit GDP) decreased by 2% yr^{-1} between 2010 and 2019. Global carbon intensity (CO_2-FFI per unit primary energy) also decreased by 0.3% yr^{-1}, mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables, and with large regional variations over the same period. In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). At least 18 countries have sustained production-based CO_2 and GHG and consumption-based CO_2 absolute emission reductions for longer than 10 years since 2005 through energy supply decarbonization, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure (*high confidence*). Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved reduction rates of around 4% yr^{-1} for several years consecutively (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several $GtCO_2$-eq yr^{-1} (*medium confidence*).

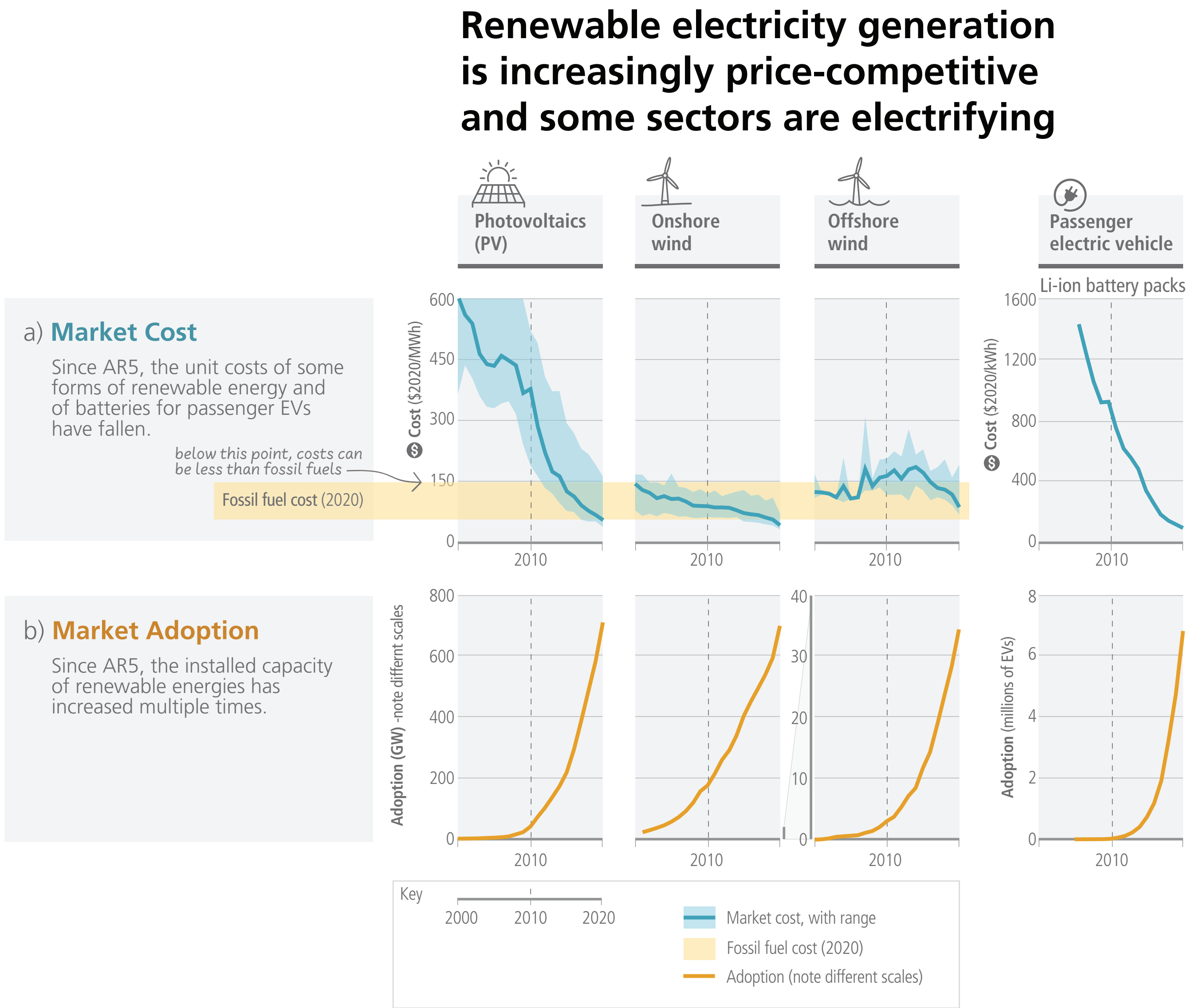


Figure 2.4: Unit cost reductions and use in some rapidly changing mitigation technologies. The **top panel (a)** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Yellow shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD 55 to 148 per MWh). In 2020, the levelised costs of energy (LCOE) of the three renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment. The **bottom panel (b)** shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change over the past decade. The electricity production share reflects different capacity factors; for example, for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the WGIII report are not included as they do not meet these criteria. {*WGIII Figure SPM.3*, *WGIII 2.5, 6.4*}

At least 1.8 $GtCO_2$-eq yr^{-1} of avoided emissions can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments (*medium confidence*). Growing numbers of laws and executive orders have impacted global emissions and are estimated to have resulted in 5.9 $GtCO_2$-eq yr^{-1} of avoided emissions in 2016 *(medium confidence)*. These reductions have only partly offset global emissions growth (*high confidence*). {*WGIII SPM B.1, WGIII SPM B.2.4, WGIII SPM B.3.5, WGIII SPM B.5.1, WGIII SPM B.5.3, WGIII 1.3.2, WGIII 2.2.3*}

2.2.3. Adaptation Actions to Date

Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). The ambition, scope and progress on adaptation have risen among governments at the local, national and international levels, along with businesses, communities and civil society (*high confidence*). Various tools, measures and processes are available that can enable, accelerate and sustain adaptation implementation (*high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*) and pilot projects and local experiments are being implemented in different sectors (*high confidence*). {*WGII SPM C.1, WGII SPM.C.1.1, WGII TS.D.1.3, WGII TS.D.10*}

Adaptation to water-related risks and impacts make up the majority (~60%) of all documented[83] adaptation (*high confidence*). A large number of these adaptation responses are in the agriculture sector and these include on-farm water management, water storage, soil moisture conservation, and irrigation. Other adaptations in agriculture include cultivar improvements, agroforestry, community-based adaptation and farm and landscape diversification among others (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems, enhancing natural water retention such as by restoring wetlands and rivers, and land use planning such as no build zones or upstream forest management, can reduce flood risk (*medium confidence*). Some land-related adaptation actions such as sustainable food production, improved and sustainable forest management, soil organic carbon management, ecosystem conservation and land restoration, reduced deforestation and degradation, and reduced food loss and waste are being undertaken, and can have mitigation co-benefits (*high confidence*). Adaptation actions that increase the resilience of biodiversity and ecosystem services to climate change include responses like minimising additional stresses or disturbances, reducing fragmentation, increasing natural habitat extent, connectivity and heterogeneity, and protecting small-scale refugia where microclimate conditions can allow species to persist (*high confidence*). Most innovations in urban adaptation have occurred through advances in disaster risk management, social safety nets and green/blue infrastructure (*medium confidence*). Many adaptation measures that benefit health and well-being are found in other sectors (e.g., food, livelihoods, social protection, water and sanitation, infrastructure) (*high confidence*). {*WGII SPM C.2.1, WGII SPM C.2.2, WGII TS.D.1.2, WGII TS.D.1.4, WGII TS.D.4.2, WGII TS.D.8.3, WGII 4 ES; SRCCL SPM B.1.1*}

Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {*WGII SPM C1.1*}

Globally tracked adaptation finance has shown an upward trend since AR5, but represents only a small portion of total climate finance, is uneven and has developed heterogeneously across regions and sectors (*high confidence*). Adaptation finance has come predominantly from public sources, largely through grants, concessional and non-concessional instruments (*very high confidence*). Globally, private-sector financing of adaptation from a variety of sources such as commercial financial institutions, institutional investors, other private equity, non-financial corporations, as well as communities and households has been limited, especially in developing countries (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Innovations in adaptation and resilience finance, such as forecast-based/anticipatory financing systems and regional risk insurance pools, have been piloted and are growing in scale (*high confidence*). {*WGII SPM C.3.2, WGII SPM C.5.4; WGII TS.D.1.6, WGII Cross-Chapter Box FINANCE; WGIII SPM E.5.4*}

There are adaptation options which are effective[84] in reducing climate risks[85] for specific contexts, sectors and regions and contribute positively to sustainable development and other societal goals. In the agriculture sector, cultivar improvements, on-farm water management and storage, soil moisture conservation, irrigation[86], agroforestry, community-based adaptation, and farm and landscape level diversification, and sustainable land management approaches, provide multiple benefits and reduce climate risks. Reduction of food loss and waste, and adaptation measures in support of balanced diets contribute to nutrition, health, and biodiversity benefits. (*high confidence*) {*WGII SPM C.2, WGII SPM C.2.1, WGII SPM C.2.2; SRCCL B.2, SRCCL SPM C.2.1*}

Ecosystem-based Adaptation[87] approaches such as urban greening, restoration of wetlands and upstream forest ecosystems reduce a range of climate change risks, including flood risks, urban heat and provide multiple co-benefits. Some land-based adaptation options provide immediate benefits (e.g., conservation of peatlands,

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83 Documented adaptation refers to published literature on adaptation policies, measures and actions that has been implemented and documented in peer reviewed literature, as opposed to adaptation that may have been planned, but not implemented.

84 Effectiveness refers here to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

85 See Annex I: Glossary.

86 Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*).

87 EbA is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), see Annex I: Glossary.

wetlands, rangelands, mangroves and forests); while afforestation and reforestation, restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils take more time to deliver measurable results. Significant synergies exist between adaptation and mitigation, for example through sustainable land management approaches. Agroecological principles and practices and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services. (*high confidence*) {*WGII SPM C.2.1*, *WGII SPM C.2.2*, *WGII SPM C.2.5*, *WGII TS.D.4.1; SRCCL SPM B.1.2*, *SRCCL SPM.B.6.1; SROCC SPM C.2*}

Combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives in case of inland flooding (*medium confidence*) and early warning systems along with flood-proofing of buildings have proven to be cost-effective in the context of coastal flooding under current sea level rise (*high confidence*). Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water, food and vector-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to extreme weather events, and improved early warning systems, surveillance, and vaccine development (*very high confidence*). Adaptation options such as disaster risk management, early warning systems, climate services and social safety nets have broad applicability across multiple sectors (*high confidence*). {*WGII SPM C.2.1*, *WGII SPM C.2.5*, *WGII SPM C.2.9*, *WGII SPM C.2.11*, *WGII SPM C.2.13; SROCC SPM C.3.2*}

Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). {*WGII SPM C.2*}

2.3 Current Mitigation and Adaptation Actions and Policies are not Sufficient

At the time of the present assessment[88] there are gaps between global ambitions and the sum of declared national ambitions. These are further compounded by gaps between declared national ambitions and current implementation for all aspects of climate action. For mitigation, global GHG emissions in 2030 implied by NDCs announced by October 2021 would make it *likely* that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C.[89] Despite progress, adaptation gaps[90] persist, with many initiatives prioritising short-term risk reduction, hindering transformational adaptation. Hard and soft limits to adaptation are being reached in some sectors and regions, while maladaptation is also increasing and disproportionately affecting vulnerable groups. Systemic barriers such as funding, knowledge, and practice gaps, including lack of climate literacy and data hinders adaptation progress. Insufficient financing, especially for adaptation, constraints climate action in particular in developing countries. (*high confidence*)

2.3.1. The Gap Between Mitigation Policies, Pledges and Pathways that Limit Warming to 1.5°C or Below 2°C

Global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26[91] would make it *likely* that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C – if no additional commitments are made or actions taken (Figure 2.5, Table 2.2). A substantial 'emissions gap' exists as global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 would be similar to or only slightly below 2019 emission levels and higher than those associated with modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or to 2°C (>67%), assuming immediate action, which implies deep, rapid, and sustained global GHG emission reductions this decade (*high confidence*) (Table 2.2, Table 3.1, 4.1).[92] The magnitude of the emissions gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs[93] are considered (*high confidence*) (Table 2.2). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1 to 3.4]°C by 2100 (*medium confidence*). If the 'emission gap' is not reduced, global GHG emissions in 2030 consistent with NDCs announced prior to COP26 make it *likely* that warming will exceed 1.5°C during the 21st century, while limiting warming to 2°C (>67%) would imply an unprecedented acceleration of mitigation efforts during 2030–2050 (*medium confidence*) (see Section 4.1, Cross-Section Box.2). {*WGIII SPM B.6, WGIII SPM B.6.1, WGIII SPM B.6.3, WGIII SPM B.6.4, WGIII SPM C.1.1*}

Policies implemented by the end of 2020 are projected to result in higher global GHG emissions in 2030 than those implied by NDCs, indicating an 'implementation gap[94]' (*high confidence*) (Table 2.2, Figure 2.5). Projected global emissions implied by policies implemented by the end of 2020 are 57 (52–60) $GtCO_2$-eq in 2030 (Table 2.2). This points to an implementation gap compared with the NDCs of 4 to 7 $GtCO_2$-eq in 2030 (Table 2.2); without a strengthening of policies, emissions are projected to rise, leading to a median global warming of 2.2°C to 3.5°C (*very likely range*) by 2100 (*medium confidence*) (see Section 3.1.1). {*WGIII SPM B.6.1, WGIII SPM C.1*}

Section 2

[88] The timing of various cut-offs for assessment differs by WG report and the aspect assessed. See footnote 58 in Section 1.

[89] See CSB.2 for a discussion of scenarios and pathways.

[90] See Annex I: Glossary.

[91] NDCs announced prior to COP26 refer to the most recent NDCs submitted to the UNFCCC up to the literature cut-off date of the WGIII report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and the start of COP26. {*WGIII SPM footnote 24*}

[92] Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled pathways that limit warming to 2°C (>67%) based on immediate action are summarised in category C3a in Table 3.1. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table 3.1). {*WGIII SPM footnote 26*}

[93] In this report, 'unconditional' elements of NDCs refer to mitigation efforts put forward without any conditions. 'Conditional' elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC's NDC Synthesis Reports, not by the Paris Agreement. {*WGIII SPM footnote 27*}

[94] Implementation gaps refer to how far currently enacted policies and actions fall short of reaching the pledges. The policy cut-off date in studies used to project GHG emissions of 'policies implemented by the end of 2020' varies between July 2019 and November 2020. {*WGIII Table 4.2, WGIII SPM footnote 25*}

Projected cumulative future CO_2 emissions over the lifetime of existing fossil fuel infrastructure without additional abatement[95] exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C with a likelihood of 83%[96] (see Figure 3.5). Limiting warming to 2°C (>67%) or lower will result in stranded assets. About 80% of coal, 50% of gas, and 30% of oil reserves cannot be burned and emitted if warming is limited to 2°C. Significantly more reserves are expected to remain unburned if warming is limited to 1.5°C. (*high confidence*) {*WGIII SPM B.7, WGIII Box 6.3*}

Table 2.2 Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emissions gaps. Emissions projections for 2030 and gross differences in emissions are based on emissions of 52–56 $GtCO_2$-eq yr–1 in 2019 as assumed in underlying model studies[97]. (*medium confidence*) {*WGIII Table SPM.1*} (*Table 3.1, Cross-Section Box.2*)

Emission and implementation gaps associated with projected global emissions in 2030 under Nationally Determined Contributions (NDCs) and implemented policies

	Implied by policies implemented by the end of 2020 ($GtCO_2$-eq/yr)	Implied by Nationally Determined Contributions (NDCs) announced prior to COP26	
		Unconditional elements ($GtCO_2$-eq/yr)	Including conditional elements ($GtCO_2$-eq/yr)
Median projected global emissions (min–max)*	57 [52–60]	53 [50–57]	50 [47–55]
Implementation gap between implemented policies and NDCs (median)	–	4	7
Emissions gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action	–	10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action	–	19–26	16–23

*Emissions projections for 2030 and gross differences in emissions are based on emissions of 52–56 $GtCO_2$-eq/yr in 2019 as assumed in underlying model studies. (*medium confidence*)

[95] Abatement here refers to human interventions that reduce the amount of GHGs that are released from fossil fuel infrastructure to the atmosphere. {*WGIII SPM footnote 34*}

[96] WGI provides carbon budgets that are in line with limiting global warming to temperature limits with different likelihoods, such as 50%, 67% or 83%. {*WGI Table SPM.2*}

[97] The 2019 range of harmonised GHG emissions across the pathways [53–58 $GtCO_2$-eq] is within the uncertainty ranges of 2019 emissions assessed in WGIII Chapter 2 [53–66 $GtCO_2$-eq].

Projected global GHG emissions from NDCs announced prior to COP26 would make it *likely* that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C

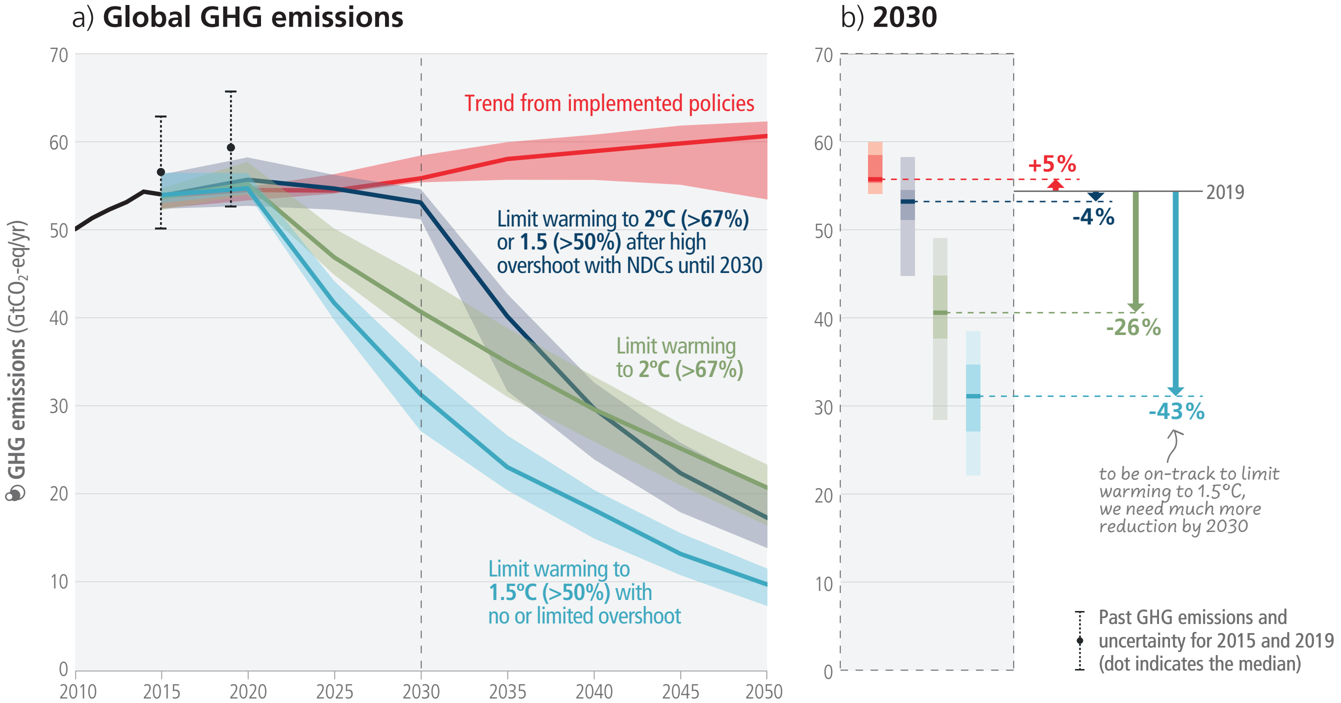


Figure 2.5 Global GHG emissions of modelled pathways (funnels in Panel a), and projected emission outcomes from near-term policy assessments for 2030 (Panel b). Panel a shows global GHG emissions over 2015-2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5–C7, WGIII Table SPM.2).
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, WGIII Table SPM.2) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, WGIII Table SPM.2).
- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020 (C3a, WGIII Table SPM.2).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, WGIII Table SPM.2 C1).

All these pathways assume immediate action after 2020. Past GHG emissions for 2010-2015 used to project global warming outcomes of the modelled pathways are shown by a black line. **Panel b** shows a snapshot of the GHG emission ranges of the modelled pathways in 2030 and projected emissions outcomes from near-term policy assessments in 2030 from WGIII Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are CO_2-equivalent using GWP100 from AR6 WGI. {*WGIII Figure SPM.4, WGIII 3.5, 4.2, Table 4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4*} (*Table 3.1, Cross-Section Box.2*)

Cross-Section Box.1: Understanding Net Zero CO_2 and Net Zero GHG Emissions

Limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching net zero or net negative CO_2 emissions, along with strong reductions in other GHG emissions (see 3.3.2). Future additional warming will depend on future emissions, with total warming dominated by past and future cumulative CO_2 emissions. {*WGI SPM D.1.1, WGI Figure SPM.4; SR1.5 SPM A.2.2*}

Reaching net zero CO_2 emissions is different from reaching net zero GHG emissions. The timing of net zero for a basket of GHGs depends on the emissions metric, such as global warming potential over a 100-year period, chosen to convert non-CO_2 emissions into CO_2-equivalent (*high confidence*). However, for a given emissions pathway, the physical climate response is independent of the metric chosen (*high confidence*). {*WGI SPM D.1.8; WGIII Box TS.6, WGIII Cross-Chapter Box 2*}

Achieving global net zero GHG emissions requires all remaining CO_2 and metric-weighted[98] non-CO_2 GHG emissions to be counterbalanced by durably stored CO_2 removals (*high confidence*). Some non-CO_2 emissions, such as CH_4 and N_2O from agriculture, cannot be fully eliminated using existing and anticipated technical measures. {*WGIII SPM C.2.4, WGIII SPM C.11.4, WGIII Cross-Chapter Box 3*}

Global net zero CO_2 or GHG emissions can be achieved even if some sectors and regions are net emitters, provided that others reach net negative emissions (see Figure 4.1). The potential and cost of achieving net zero or even net negative emissions vary by sector and region. If and when net zero emissions for a given sector or region are reached depends on multiple factors, including the potential to reduce GHG emissions and undertake carbon dioxide removal, the associated costs, and the availability of policy mechanisms to balance emissions and removals between sectors and countries. (*high confidence*) {*WGIII Box TS.6, WGIII Cross-Chapter Box 3*}

The adoption and implementation of net zero emission targets by countries and regions also depend on equity and capacity considerations (*high confidence*). The formulation of net zero pathways by countries will benefit from clarity on scope, plans-of-action, and fairness. Achieving net zero emission targets relies on policies, institutions, and milestones against which to track progress. Least-cost global modelled pathways have been shown to distribute the mitigation effort unevenly, and the incorporation of equity principles could change the country-level timing of net zero (*high confidence*). The Paris Agreement also recognizes that peaking of emissions will occur later in developing countries than developed countries (Article 4.1). {*WGIII Box TS.6, WGIII Cross-Chapter Box 3, WGIII 14.3*}

More information on country-level net zero pledges is provided in Section 2.3.1, on the timing of global net zero emissions in Section 3.3.2, and on sectoral aspects of net zero in Section 4.1.

[98] See footnote 12 above.

Many countries have signalled an intention to achieve net zero GHG or net zero CO_2 emissions by around mid-century (Cross-Section Box.1). More than 100 countries have either adopted, announced or are discussing net zero GHG or net zero CO_2 emissions commitments, covering more than two-thirds of global GHG emissions. A growing number of cities are setting climate targets, including net zero GHG targets. Many companies and institutions have also announced net zero emissions targets in recent years. The various net zero emission pledges differ across countries in terms of scope and specificity, and limited policies are to date in place to deliver on them. {*WGIII SPM C.6.4*, *WGIII TS.4.1*, *WGIII Table TS.1*, *WGIII 13.9*, *WGIII 14.3*, *WGIII 14.5*}

All mitigation strategies face implementation challenges, including technology risks, scaling, and costs (*high confidence*). Almost all mitigation options also face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance (*medium confidence*). The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes (*medium confidence*). {*WGIII SPM C.3.6*, *WGIII SPM E.1.1*, *WGIII SPM E.2.1*, *WGIII SPM E.3.3*}

The adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity (*medium confidence*). In many countries, especially those with limited institutional capacity, several adverse side-effects have been observed as a result of diffusion of low-emission technology, e.g., low-value employment, and dependency on foreign knowledge and suppliers (*medium confidence*). Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy (*medium confidence*). Persistent and region-specific barriers also continue to hamper the economic and political feasibility of deploying AFOLU mitigation options (*medium confidence*). Barriers to implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, low incomes and the lack of access to alternative sources of income, and the risk of reversal (*high confidence*). {*WGIII SPM B.4.2*, *WGIII SPM C.9.1*, *WGIII SPM C.9.3*}

2.3.2. Adaptation Gaps and Barriers

Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). While progress in adaptation implementation is observed across all sectors and regions *(very high confidence)*, many adaptation initiatives prioritise immediate and near-term climate risk reduction, e.g., through hard flood protection, which reduces the opportunity for transformational adaptation[99] (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, and focused more on planning rather than implementation (*high confidence*). Further, observed adaptation is unequally distributed across regions and the largest adaptation gaps exist among lower population income groups (*high confidence*). In the urban context, the largest adaptation gaps exist in projects that manage complex risks, for example in the food–energy–water–health nexus or the inter-relationships of air quality and climate risk (*high confidence*). Many funding, knowledge and practice gaps remain for effective implementation, monitoring and evaluation and current adaptation efforts are not expected to meet existing goals (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). {*WGII SPM C.1*, *WGII SPM C.1.2*, *WGII SPM C.4.1*, *WGII TS.D.1.3*, *WGII TS.D.1.4*}

Soft and hard adaptation limits[100] have already been reached in some sectors and regions, in spite of adaptation having buffered some climate impacts (*high confidence*). Ecosystems already reaching hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*), resulting from financial, governance, institutional and policy constraints and can be overcome by addressing these constraints (*high confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {*WGII SPM C.3*, *WGII SPM C.3.1*, *WGII SPM C.3.2*, *WGII SPM C.3.3*, *WGII SPM.C.3.4*, *WGII 16 ES*}

Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. (*high confidence*) {*WGII SPM.C.3.5*}

There is increased evidence of maladaptation[101] in various sectors and regions. Examples of maladaptation are observed in urban areas (e.g., new urban infrastructure that cannot be adjusted easily or affordably), agriculture (e.g., using high-cost irrigation in areas projected to have more intense drought conditions), ecosystems (e.g. fire suppression in naturally

[99] See Annex I: Glossary.

[100] Adaptation limit: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions. Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks. Soft adaptation limit - Options are currently not available to avoid intolerable risks through adaptive action.

[101] Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence. See Annex I: Glossary.

fire-adapted ecosystems, or hard defences against flooding) and human settlements (e.g. stranded assets and vulnerable communities that cannot afford to shift away or adapt and require an increase in social safety nets). Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, people living in informal settlements), reinforcing and entrenching existing inequities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {*WGII SPM C.4, WGII SPM C.4.3, WGII TS.D.3.1*}

Systemic barriers constrain the implementation of adaptation options in vulnerable sectors, regions and social groups (*high confidence*). Key barriers include limited resources, lack of private-sector and civic engagement, insufficient mobilisation of finance, lack of political commitment, limited research and/or slow and low uptake of adaptation science and a low sense of urgency. Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in this decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). Prioritisation of options and transitions from incremental to transformational adaptation are limited due to vested interests, economic lock-ins, institutional path dependencies and prevalent practices, cultures, norms and belief systems (*high confidence*). Many funding, knowledge and practice gaps remain for effective implementation, monitoring and evaluation of adaptation (*high confidence*), including, lack of climate literacy at all levels and limited availability of data and information (*medium confidence*); for example for Africa, severe climate data constraints and inequities in research funding and leadership reduce adaptive capacity (*very high confidence*). {*WGII SPM C.1.2, WGII SPM C.3.1, WGII TS.D.1.3, WGII TS.D.1.5, WGII TS.D.2.4*}

2.3.3. Lack of Finance as a Barrier to Climate Action

Insufficient financing, and a lack of political frameworks and incentives for finance, are key causes of the implementation gaps for both mitigation and adaptation (*high confidence*). Financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD 100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). The overwhelming majority of tracked climate finance is directed towards mitigation (*very high confidence*). Nevertheless, average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Challenges remain for green bonds and similar products, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries (*high confidence*). {*WGII SPM C.3.2, WGII SPM C.5.4; WGIII SPM B.5.4, WGIII SPM E.5.1*}

Current global financial flows for adaptation including from public and private finance sources, are insufficient for and constrain implementation of adaptation options, especially in developing countries (*high confidence*). There are widening disparities between the estimated costs of adaptation and the documented finance allocated to adaptation (*high confidence*). Adaptation finance needs are estimated to be higher than those assessed in AR5, and the enhanced mobilisation of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Annual finance flows targeting adaptation for Africa, for example, are billions of USD less than the lowest adaptation cost estimates for near-term climate change (*high confidence*). Adverse climate impacts can further reduce the availability of financial resources by causing losses and damages and impeding national economic growth, thereby further increasing financial constraints for adaptation particularly for developing countries and LDCs (*medium confidence*). {*WGII SPM C.1.2, WGII SPM C.3.2, WGII SPM C.5.4, WGII TS.D.1.6*}

Without effective mitigation and adaptation, losses and damages will continue to disproportionately affect the poorest and most vulnerable populations. Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action {WGIII SPM. E.5.3}. Many developing countries lack comprehensive data at the scale needed and lack adequate financial resources needed for adaptation for reducing associated economic and non-economic losses and damages. (*high confidence*) {*WGII Cross-Chapter Box LOSS, WGII SPM C.3.1, WGII SPM C.3.2, WGII TS.D.1.3, WGII TS.D.1.5; WGIII SPM E.5.3*}

There are barriers to redirecting capital towards climate action both within and outside the global financial sector. These barriers include: the inadequate assessment of climate-related risks and investment opportunities, regional mismatch between available capital and investment needs, home bias factors, country indebtedness levels, economic vulnerability, and limited institutional capacities. Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments that are inconsistent with ambition levels; limited institutional capacity to ensure safeguards; standardisation, aggregation, scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM E.5.2; SR1.5 SPM D.5.2*}

Cross-Section Box.2: Scenarios, Global Warming Levels, and Risks

Modelled scenarios and pathways[102] are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies and are based on a range of assumptions, including socio-economic variables and mitigation options. These are quantitative projections and are neither predictions nor forecasts. Global modelled emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures[103]. {*WGI Box SPM.1; WGII Box SPM.1; WGIII Box SPM.1; SROCC Box SPM.1; SRCCL Box SPM.1*}

Socio-economic Development, Scenarios, and Pathways

The five Shared Socio-economic Pathways (SSP1 to SSP5) were designed to span a range of challenges to climate change mitigation and adaptation. For the assessment of climate impacts, risk and adaptation, the SSPs are used for future exposure, vulnerability and challenges to adaptation. Depending on levels of GHG mitigation, modelled emissions scenarios based on the SSPs can be consistent with low or high warming levels[104]. There are many different mitigation strategies that could be consistent with different levels of global warming in 2100 (see Figure 4.1). {*WGI Box SPM.1; WGII Box SPM.1; WGIII Box SPM.1, WGIII Box TS.5, WGIII Annex III; SRCCL Box SPM.1, SRCCL Figure SPM.2*}

WGI assessed the climate response to five illustrative scenarios based on SSPs[105] that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. These scenarios combine socio-economic assumptions, levels of climate mitigation, land use and air pollution controls for aerosols and non-CH_4 ozone precursors. The high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5) have CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively[106]. The intermediate GHG emissions scenario (SSP2-4.5) has CO_2 emissions remaining around current levels until the middle of the century. The very low and low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6) have CO_2 emissions declining to net zero around 2050 and 2070, respectively, followed by varying levels of net negative CO_2 emissions. In addition, Representative Concentration Pathways (RCPs)[107] were used by WGI and WGII to assess regional climate changes, impacts and risks. {*WGI Box SPM.1*} (*Cross-Section Box.2 Figure 1*)

In WGIII, a large number of global modelled emissions pathways were assessed, of which 1202 pathways were categorised based on their projected global warming over the 21st century, with categories ranging from pathways that limit warming to 1.5°C with more than 50% likelihood[108] with no or limited overshoot (C1) to pathways that exceed 4°C (C8). Methods to project global warming associated with the modelled pathways were updated to ensure consistency with the AR6 WGI assessment of the climate system response[109]. {*WGIII Box SPM.1, WGIII Table 3.1*} (*Table 3.1, Cross-Section Box.2 Figure 1*)

[102] In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. WGI primarily used the term scenarios and WGIII mostly used the term modelled emissions and mitigation pathways. The SYR primarily uses scenarios when referring to WGI and modelled emissions and mitigation pathways when referring to WGIII. {*WGI Box SPM.1; WGIII footnote 44*}

[103] Around half of all modelled global emissions pathways assume cost-effective approaches that rely on least-cost mitigation/abatement options globally. The other half look at existing policies and regionally and sectorally differentiated actions. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5–95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth range from 2.5 to 3.5% per year in the 2019–2050 period and 1.3 to 2.1% per year in the 2050–2100 (5–95th percentile). {*WGIII Box SPM.1*}

[104] High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socio-economic Pathway SSP3, may render modelled pathways that limit warming to 2°C (> 67%) or lower infeasible (*medium confidence*). {*WGIII SPM C.1.4; SRCCL Box SPM.1*}

[105] SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. {*WGI SPM footnote 22*}

[106] Very high emission scenarios have become less *likely* but cannot be ruled out. Temperature levels > 4°C may result from very high emission scenarios, but can also occur from lower emission scenarios if climate sensitivity or carbon cycle feedbacks are higher than the best estimate. {*WGIII SPM C.1.3*}

[107] RCP-based scenarios are referred to as RCPy, where 'y' refers to the approximate level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. {*WGII SPM footnote 21*}

[108] Denoted '>50%' in this report.

[109] The climate response to emissions is investigated with climate models, paleoclimatic insights and other lines of evidence. The assessment outcomes are used to categorise thousands of scenarios via simple physically-based climate models (emulators). {*WGI TS.1.2.2*}

Global Warming Levels (GWLs)

For many climate and risk variables, the geographical patterns of changes in climatic impact-drivers[110] and climate impacts for a level of global warming[111] are common to all scenarios considered and independent of timing when that level is reached. This motivates the use of GWLs as a dimension of integration. {*WGI Box SPM.1.4, WGI TS.1.3.2; WGII Box SPM.1*} (*Figure 3.1*, *Figure 3.2*)

Risks

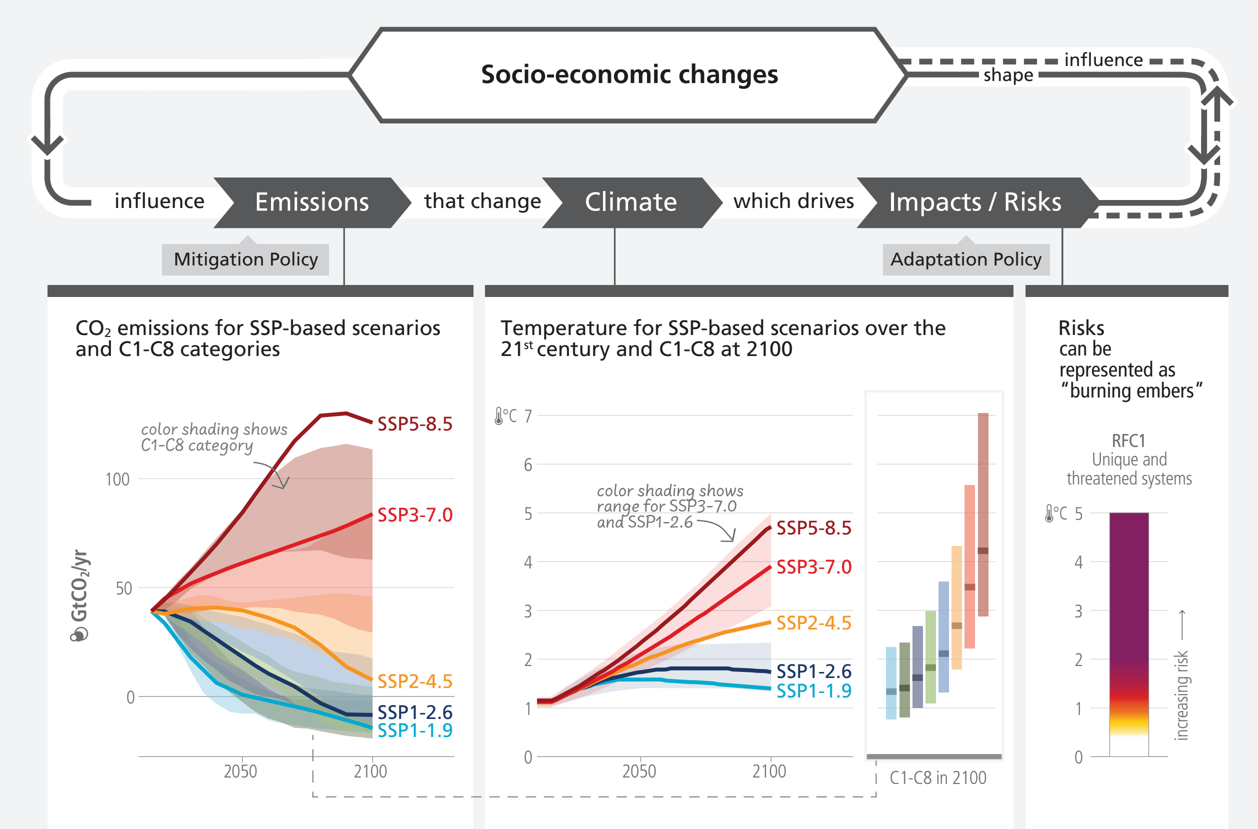
Dynamic interactions between climate-related hazards, exposure and vulnerability of the affected human society, species, or ecosystems result in risks arising from climate change. AR6 assesses key risks across sectors and regions as well as providing an updated assessment of the Reasons for Concern (RFCs) – five globally aggregated categories of risk that evaluate risk accrual with increasing global surface temperature. Risks can also arise from climate change mitigation or adaptation responses when the response does not achieve its intended objective, or when it results in adverse effects for other societal objectives. {*WGII SPM A, WGII Figure SPM.3, WGII Box TS.1, WGII Figure TS.4; SR1.5 Figure SPM.2; SROCC Errata Figure SPM.3; SRCCL Figure SPM.2*} (*3.1.2, Cross-Section Box.2 Figure 1, Figure 3.3*)

[110] See Annex I: Glossary

[111] See Annex I: Glossary. Here, global warming is the 20-year average global surface temperature relative to 1850–1900. The assessed time of when a certain global warming level is reached under a particular scenario is defined here as the mid-point of the first 20-year running average period during which the assessed average global surface temperature change exceeds the level of global warming. {*WGI SPM footnote 26, Cross-Section Box TS.1*}

Scenarios and warming levels structure our understanding across the cause-effect chain from emissions to climate change and risks

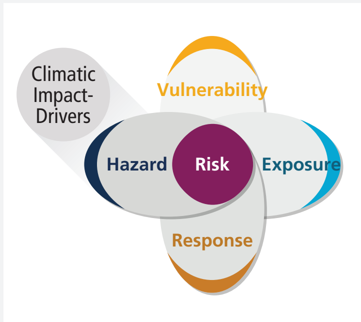
a) AR6 integrated assessment framework on future climate, impacts and mitigation



b) Scenarios and pathways across AR6 Working Group reports

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

c) Determinants of risk



* The terminology SSPx-y is used, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100.

** The AR5 scenarios (RCPy), which partly inform the AR6 WGI and WGII assessments, are indexed to a similar set of approximate 2100 radiative forcing levels (in W m^{-2}). The SSP scenarios cover a broader range of GHG and air pollutant futures than the RCPs. They are similar but not identical, with differences in concentration trajectories for different GHGs. The overall radiative forcing tends to be higher for the SSPs compared to the RCPs with the same label (*medium confidence*). {*WGI TS.1.3.1*}

*** Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

Cross-Section Box.2 Figure 1: Schematic of the AR6 framework for assessing future greenhouse gas emissions, climate change, risks, impacts and mitigation. Panel (a) The integrated framework encompasses socio-economic development and policy, emissions pathways and global surface temperature responses to the five scenarios considered by WGI (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and eight global mean temperature change categorisations (C1–C8) assessed by WGIII, and the WGII risk assessment. The dashed arrow indicates that the influence from impacts/risks to socio-economic changes is not yet considered in the scenarios assessed in the AR6. Emissions include GHGs, aerosols, and ozone precursors. CO_2 emissions are shown as an example on the left. The assessed global surface temperature changes across the 21st century relative to 1850-1900 for the five GHG emissions scenarios are shown as an example in the centre. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0. Projected temperature outcomes at 2100 relative to 1850-1900 are shown for C1 to C8 categories with median (line) and the combined *very likely* range across scenarios (bar). On the right, future risks due to increasing warming are represented by an example 'burning ember' figure (see 3.1.2 for the definition of RFC1). **Panel (b)** Description and relationship of scenarios considered across AR6 Working Group reports. **Panel (c)** Illustration of risk arising from the interaction of hazard (driven by changes in climatic impact-drivers) with vulnerability, exposure and response to climate change. {*WGI TS1.4, Figure 4.11; WGII Figure 1.5, WGII Figure 14.8; WGIII Table SPM.2, WGIII Figure 3.11*}

Section 3
Long-Term Climate and Development Futures

Section 3: Long-Term Climate and Development Futures

3.1 Long-Term Climate Change, Impacts and Related Risks

Future warming will be driven by future emissions and will affect all major climate system components, with every region experiencing multiple and co-occurring changes. Many climate-related risks are assessed to be higher than in previous assessments, and projected long-term impacts are up to multiple times higher than currently observed. Multiple climatic and non-climatic risks will interact, resulting in compounding and cascading risks across sectors and regions. Sea level rise, as well as other irreversible changes, will continue for thousands of years, at rates depending on future emissions. (*high confidence*)

3.1.1. Long-term Climate Change

The uncertainty range on assessed future changes in global surface temperature is narrower than in the AR5. For the first time in an IPCC assessment cycle, multi-model projections of global surface temperature, ocean warming and sea level are constrained using observations and the assessed climate sensitivity. The *likely* range of equilibrium climate sensitivity has been narrowed to 2.5°C to 4.0°C (with a best estimate of 3.0°C) based on multiple lines of evidence[112], including improved understanding of cloud feedbacks. For related emissions scenarios, this leads to narrower uncertainty ranges for long-term projected global temperature change than in AR5. {*WGI A.4, WGI Box SPM.1, WGI TS.3.2, WGI 4.3*}

Future warming depends on future GHG emissions, with cumulative net CO_2 dominating. The assessed best estimates and *very likely* ranges of warming for 2081-2100 with respect to 1850–1900 vary from 1.4 [1.0 to 1.8]°C in the very low GHG emissions scenario (SSP1-1.9) to 2.7 [2.1 to 3.5]°C in the intermediate GHG emissions scenario (SSP2-4.5) and 4.4 [3.3 to 5.7]°C in the very high GHG emissions scenario (SSP5-8.5)[113]. {*WGI SPM B.1.1, WGI Table SPM.1, WGI Figure SPM.4*} (*Cross-Section Box.2 Figure 1*)

Modelled pathways consistent with the continuation of policies implemented by the end of 2020 lead to global warming of 3.2 [2.2 to 3.5]°C (5–95% range) by 2100 (*medium confidence*) (see also Section 2.3.1). Pathways of >4°C (≥50%) by 2100 would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). However, such warming could occur in emissions pathways consistent with policies implemented by the end of 2020 if climate sensitivity or carbon cycle feedbacks are higher than the best estimate (*high confidence*). {*WGIII SPM C.1.3*}

Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid, and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end of century (*high confidence*). The best estimate of reaching 1.5°C of global warming lies in the first half of the 2030s in most of the considered scenarios and modelled pathways[114]. In the very low GHG emissions scenario (SSP1-1.9), CO_2 emissions reach net zero around 2050 and the best-estimate end-of-century warming is 1.4°C, after a temporary overshoot (see Section 3.3.4) of no more than 0.1°C above 1.5°C global warming. Global warming of 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other GHG emissions occur in the coming decades. Deep, rapid, and sustained reductions in GHG emissions would lead to improvements in air quality within a few years, to reductions in trends of global surface temperature discernible after around 20 years, and over longer time periods for many other climate impact-drivers[115] (*high confidence*). Targeted reductions of air pollutant emissions lead to more rapid improvements in air quality compared to reductions in GHG emissions only, but in the long term, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions (*high confidence*)[116]. {*WGI SPM B.1, WGI SPM B.1.3, WGI SPM D.1, WGI SPM D.2, WGI Figure SPM.4, WGI Table SPM.1, WGI Cross-Section Box TS.1; WGIII SPM C.3, WGIII Table SPM.2, WGIII Figure SPM.5, WGIII Box SPM.1 Figure 1, WGIII Table 3.2*} (*Table 3.1, Cross-Section Box.2 Figure 1*)

Changes in short-lived climate forcers (SLCF) resulting from the five considered scenarios lead to an additional net global warming in the near and long term (*high confidence*). Simultaneous stringent climate change mitigation and air pollution control

[112] Understanding of climate processes, the instrumental record, paleoclimates and model-based emergent constraints (see Annex I: Glossary). {*WGI SPM footnote 21*}

[113] The best estimates [and *very likely* ranges] for the different scenarios are: 1.4 [1.0 to 1.8]°C (SSP1-1.9); 1.8 [1.3 to 2.4]°C (SSP1-2.6); 2.7 [2.1 to 3.5]°C (SSP2-4.5); 3.6 [2.8 to 4.6]°C (SSP3-7.0); and 4.4 [3.3 to 5.7]°C (SSP5-8.5). {*WGI Table SPM.1*} (*Cross-Section Box.2*)

[114] In the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5, SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9). In all scenarios considered by WGI except the very high emissions scenario, the midpoint of the first 20-year running average period during which the assessed global warming reaches 1.5°C lies in the first half of the 2030s. In the very high GHG emissions scenario, this mid-point is in the late 2020s. The median five-year interval at which a 1.5°C global warming level is reached (50% probability) in categories of modelled pathways considered in WGIII is 2030–2035. {*WGI SPM B.1.3, WGI Cross-Section Box TS.1, WGIII Table 3.2*} (*Cross-Section Box.2*)

[115] See Cross-Section Box.2.

[116] Based on additional scenarios.

policies limit this additional warming and lead to strong benefits for air quality (*high confidence*). In high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5), combined changes in SLCF emissions, such as CH_4, aerosol and ozone precursors, lead to a net global warming by 2100 of *likely* 0.4°C to 0.9°C relative to 2019. This is due to projected increases in atmospheric concentration of CH_4, tropospheric ozone, hydrofluorocarbons and, when strong air pollution control is considered, reductions of cooling aerosols. In low and very low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6), air pollution control policies, reductions in CH_4 and other ozone precursors lead to a net cooling, whereas reductions in anthropogenic cooling aerosols lead to a net warming (*high confidence*). Altogether, this causes a *likely* net warming of 0.0°C to 0.3°C due to SLCF changes in 2100 relative to 2019 and strong reductions in global surface ozone and particulate matter (*high confidence*). {*WGI SPM D.1.7, WGI Box TS.7*} (*Cross-Section Box.2*)

Continued GHG emissions will further affect all major climate system components, and many changes will be irreversible on centennial to millennial time scales. Many changes in the climate system become larger in direct relation to increasing global warming. With every additional increment of global warming, changes in extremes continue to become larger. Additional warming will lead to more frequent and intense marine heatwaves and is projected to further amplify permafrost thawing and loss of seasonal snow cover, glaciers, land ice and Arctic sea ice (*high confidence*). Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation[117], and very wet and very dry weather and climate events and seasons (*high confidence*). The portion of global land experiencing detectable changes in seasonal mean precipitation is projected to increase (*medium confidence*) with more variable precipitation and surface water flows over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). Many changes due to past and future GHG emissions are irreversible[118] on centennial to millennial time scales, especially in the ocean, ice sheets and global sea level (see 3.1.3). Ocean acidification (*virtually certain*), ocean deoxygenation (*high confidence*) and global mean sea level (*virtually certain*) will continue to increase in the 21st century, at rates dependent on future emissions. {*WGI SPM B.2, WGI SPM B.2.2, WGI SPM B.2.3, WGI SPM B.2.5, WGI SPM B.3, WGI SPM B.3.1, WGI SPM B.3.2, WGI SPM B.4, WGI SPM B.5, WGI SPM B.5.1, WGI SPM B.5.3, WGI Figure SPM.8*} (*Figure 3.1*)

With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Increases in hot and decreases in cold climatic impact-drivers, such as temperature extremes, are projected in all regions (*high confidence*). At 1.5°C global warming, heavy precipitation and flooding events are projected to intensify and become more frequent in most regions in Africa, Asia (*high confidence*), North America (*medium* to *high confidence*) and Europe (*medium confidence*). At 2°C or above, these changes expand to more regions and/or become more significant (*high confidence*), and more frequent and/or severe agricultural and ecological droughts are projected in Europe, Africa, Australasia and North, Central and South America (*medium* to *high confidence*). Other projected regional changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), and increases in aridity and fire weather[119] (*medium* to *high confidence*). Compound heatwaves and droughts become *likely* more frequent, including concurrently at multiple locations (*high confidence*). {*WGI SPM C.2, WGI SPM C.2.1, WGI SPM C.2.2, WGI SPM C.2.3, WGI SPM C.2.4, WGI SPM C.2.7*}

117 Particularly over South and South East Asia, East Asia and West Africa apart from the far west Sahel. {*WGI SPM B.3.3*}

118 See Annex I: Glossary.

119 See Annex I: Glossary.

With every increment of global warming, regional changes in mean climate and extremes become more widespread and pronounced

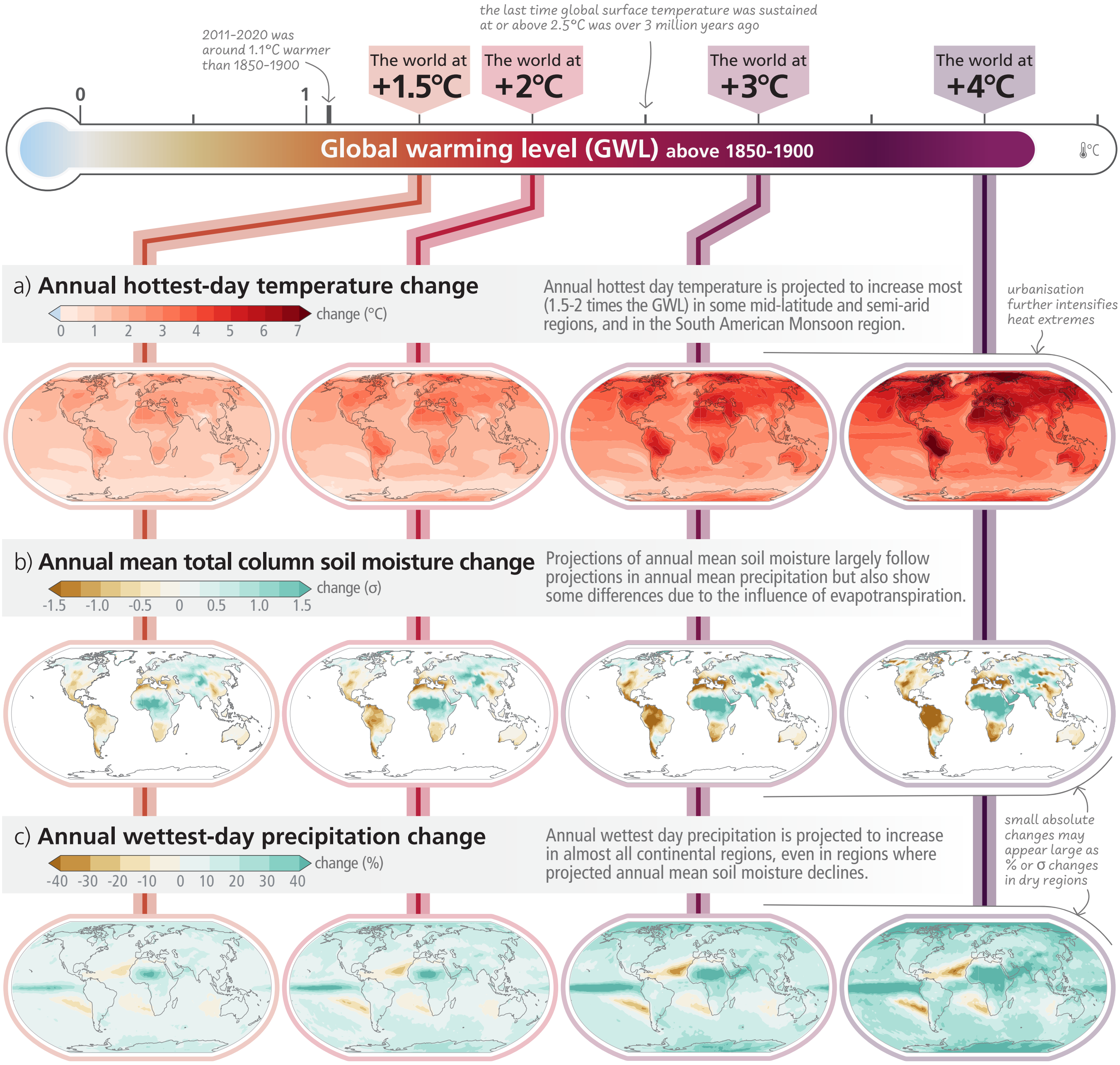


Figure 3.1: Projected changes of annual maximum daily temperature, annual mean total column soil moisture CMIP and annual maximum daily precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850-1900. Simulated (a) annual maximum temperature change (°C), **(b)** annual mean total column soil moisture (standard deviation), **(c)** annual maximum daily precipitation change (%). Changes correspond to CMIP6 multi-model median changes. In panels (b) and (c), large positive relative changes in dry regions may correspond to small absolute changes. In panel (b), the unit is the standard deviation of interannual variability in soil moisture during 1850-1900. Standard deviation is a widely used metric in characterising drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850-1900. The WGI Interactive Atlas (https://interactive-atlas.ipcc.ch/) can be used to explore additional changes in the climate system across the range of global warming levels presented in this figure. {*WGI Figure SPM.5, WGI Figure TS.5, WGI Figure 11.11, WGI Figure 11.16, WGI Figure 11.19*} (*Cross-Section Box.2*)

3.1.2 Impacts and Related Risks

For a given level of warming, many climate-related risks are assessed to be higher than in AR5 (*high confidence*). Levels of risk[120] for all Reasons for Concern[121] (RFCs) are assessed to become high to very high at lower global warming levels compared to what was assessed in AR5 (*high confidence*). This is based upon recent evidence of observed impacts, improved process understanding, and new knowledge on exposure and vulnerability of human and natural systems, including limits to adaptation. Depending on the level of global warming, the assessed long-term impacts will be up to multiple times higher than currently observed (*high confidence*) for 127 identified key risks, e.g., in terms of the number of affected people and species. Risks, including cascading risks (see 3.1.3) and risks from overshoot (see 3.3.4), are projected to become increasingly severe with every increment of global warming (*very high confidence*). {*WGII SPM B.3.3, WGII SPM B.4, WGII SPM B.5, WGII 16.6.3; SRCCL SPM A5.3*} (*Figure 3.2*, *Figure 3.3*)

Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present (1.1°C) but lower than at 2°C (*high confidence*) (see Section 2.1.2). Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C. In terrestrial ecosystems, 3 to 14% of the tens of thousands of species assessed will *likely* face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states and Least Developed Countries (*high confidence*). {*WGII SPM B.3, WGII SPM B.4.1, WGII TS.C.4.2; SR1.5 SPM A.3, SR1.5 SPM B.4.2, SR1.5 SPM B.5, SR1.5 SPM B.5.1*} (*Figure 3.3*)

At 2°C of global warming, overall risk levels associated with the unequal distribution of impacts (RFC3), global aggregate impacts (RFC4) and large-scale singular events (RFC5) would be transitioning to high (*medium confidence*), those associated with extreme weather events (RFC2) would be transitioning to very high (*medium confidence*), and those associated with unique and threatened systems (RFC1) would be very high (*high confidence*) (Figure 3.3, panel a). With about 2°C warming, climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (*high confidence*). For example, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20% (*medium confidence*). Climate change risks to cities, settlements and key infrastructure will rise sharply in the mid and long term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). {*WGII SPM B.3.3, WGII SPM B.4.2, WGII SPM B.4.5, WGII TS C.3.3, WGII TS.C.12.2*} (*Figure 3.3*)

At global warming of 3°C, additional risks in many sectors and regions reach high or very high levels, implying widespread systemic impacts, irreversible change and many additional adaptation limits (see Section 3.2) (*high confidence*). For example, very high extinction risk for endemic species in biodiversity hotspots is projected to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C, compared to 1.5°C global warming without adaptation (*medium confidence*). {*WGII SPM B.4.1, WGII SPM B.4.2, WGII Figure SPM.3, WGII TS Appendix AII, WGII Appendix I Global to Regional Atlas Figure AI.46*} (*Figure 3.2*, *Figure 3.3*)

Global warming of 4°C and above is projected to lead to far-reaching impacts on natural and human systems (*high confidence*). Beyond 4°C of warming, projected impacts on natural systems include local extinction of ~50% of tropical marine species (*medium confidence*) and biome shifts across 35% of global land area (*medium confidence*). At this level of warming, approximately 10% of the global land area is projected to face both increasing high and decreasing low extreme streamflow, affecting, without additional adaptation, over 2.1 billion people (*medium confidence*) and about 4 billion people are projected to experience water scarcity (*medium confidence*). At 4°C of warming, the global burned area is projected to increase by 50 to 70% and the fire frequency by ~30% compared to today (*medium confidence*). {*WGII SPM B.4.1, WGII SPM B.4.2, WGII TS.C.1.2, WGII TS.C.2.3, WGII TS.C.4.1, WGII TS.C.4.4*} (*Figure 3.2*, *Figure 3.3*)

[120] Undetectable risk level indicates no associated impacts are detectable and attributable to climate change; moderate risk indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. {*WGII Figure SPM.3*}

[121] The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories (WGII Figure SPM.3). RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet instability or thermohaline circulation slowing. Assessment methods include a structured expert elicitation based on the literature described in WGII SM16.6 and are identical to AR5 but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. For further explanations of global risk levels and Reasons for Concern, see WGII TS.AII. {*WGII Figure SPM.3*}

Projected adverse impacts and related losses and damages from climate change escalate with every increment of global warming (*very high confidence*), but they will also strongly depend on socio-economic development trajectories and adaptation actions to reduce vulnerability and exposure (*high confidence*). For example, development pathways with higher demand for food, animal feed, and water, more resource-intensive consumption and production, and limited technological improvements result in higher risks from water scarcity in drylands, land degradation and food insecurity (*high confidence*). Changes in, for example, demography or investments in health systems have effect on a variety of health-related outcomes including heat-related morbidity and mortality (Figure 3.3 Panel d). {*WGII SPM B.3, WGII SPM B.4, WGII Figure SPM.3; SRCCL SPM A.6*}

With every increment of warming, climate change impacts and risks will become increasingly complex and more difficult to manage. Many regions are projected to experience an increase in the probability of compound events with higher global warming, such as concurrent heatwaves and droughts, compound flooding and fire weather. In addition, multiple climatic and non-climatic risk drivers such as biodiversity loss or violent conflict will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Furthermore, risks can arise from some responses that are intended to reduce the risks of climate change, e.g., adverse side effects of some emission reduction and carbon dioxide removal (CDR) measures (see 3.4.1). (*high confidence*) {*WGI SPM C.2.7, WGI Figure SPM.6, WGI TS.4.3; WGII SPM B.1.7, WGII B.2.2, WGII SPM B.5, WGII SPM B.5.4, WGII SPM C.4.2, WGII SPM B.5, WGII CCB2*}

Solar Radiation Modification (SRM) approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood. SRM has the potential to offset warming within one or two decades and ameliorate some climate hazards but would not restore climate to a previous state, and substantial residual or overcompensating climate change would occur at regional and seasonal scales (*high confidence*). Effects of SRM would depend on the specific approach used[122], and a sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*). SRM would not stop atmospheric CO_2 concentrations from increasing nor reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of SRM approaches to reduce climate change risks. Lack of robust and formal SRM governance poses risks as deployment by a limited number of states could create international tensions. {*WGI 4.6; WGII SPM B.5.5; WGIII 14.4.5.1; WGIII 14 Cross-Working Group Box Solar Radiation Modification; SR1.5 SPM C.1.4*}

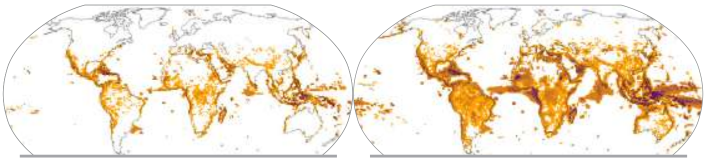
[122] Several SRM approaches have been proposed, including stratospheric aerosol injection, marine cloud brightening, ground-based albedo modifications, and ocean albedo change. See Annex I: Glossary.

Future climate change is projected to increase the severity of impacts across natural and human systems and will increase regional differences

Examples of impacts without additional adaptation

a) Risk of species losses

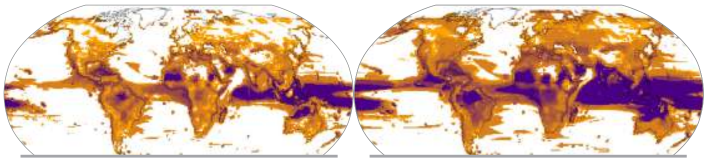
Percentage of animal species and seagrasses exposed to potentially dangerous temperature conditions[1, 2]



1.5°C | 2.0°C

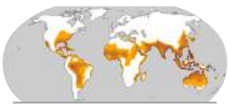
[1]Projected temperature conditions above the estimated historical (1850-2005) maximum mean annual temperature experienced by each species, assuming no species relocation.

[2]Includes 30,652 species of birds, mammals, reptiles, amphibians, marine fish, benthic marine invertebrates, krill, cephalopods, corals, and seagrasses.

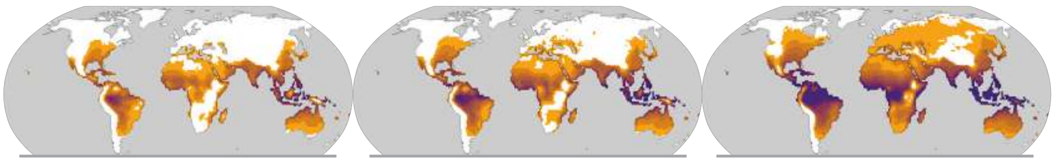


3.0°C | 4.0°C

b) Heat-humidity risks to human health



Historical 1991–2005



1.7 – 2.3°C | 2.4 – 3.1°C | 4.2 – 5.4°C

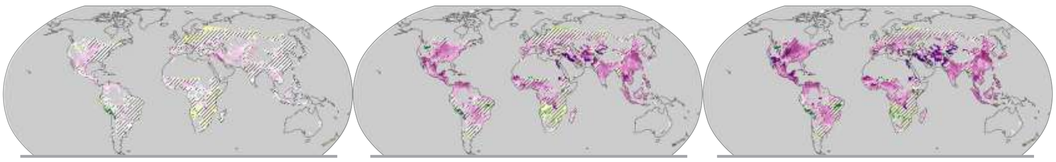
Days per year where combined temperature and humidity conditions pose a risk of mortality to individuals[3]

[3]Projected regional impacts utilize a global threshold beyond which daily mean surface air temperature and relative humidity may induce hyperthermia that poses a risk of mortality. The duration and intensity of heatwaves are not presented here. Heat-related health outcomes vary by location and are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability. The threshold used in these maps is based on a single study that synthesized data from 783 cases to determine the relationship between heat-humidity conditions and mortality drawn largely from observations in temperate climates.

c) Food production impacts

c1) Maize yield[4]

Changes (%) in yield

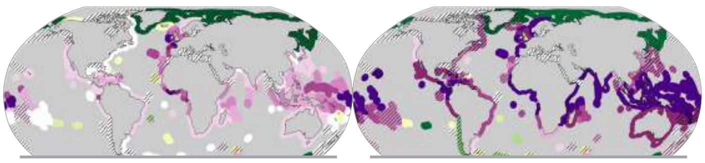


1.6 – 2.4°C | 3.3 – 4.8°C | 3.9 – 6.0°C

[4]Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO_2 enhancement of growth and water retention in currently cultivated areas. Models assume that irrigated areas are not water-limited. Models do not represent pests, diseases, future agro-technological changes and some extreme climate responses.

c2) Fisheries yield[5]

Changes (%) in maximum catch potential



0.9 – 2.0°C | 3.4 – 5.2°C

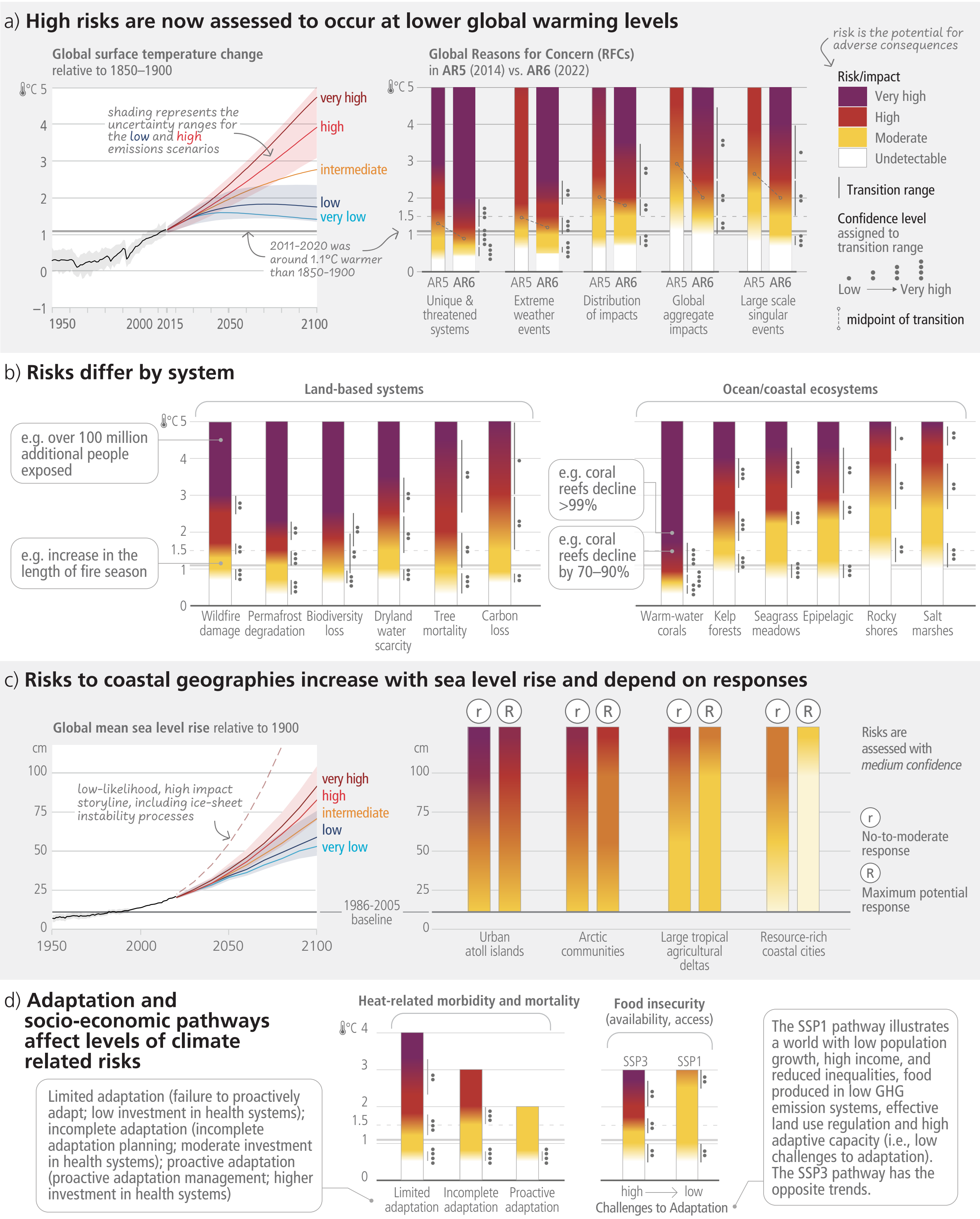
Areas with little or no production, or not assessed

Areas with model disagreement

[5]Projected regional impacts reflect fisheries and marine ecosystem responses to ocean physical and biogeochemical conditions such as temperature, oxygen level and net primary production. Models do not represent changes in fishing activities and some extreme climatic conditions. Projected changes in the Arctic regions have low confidence due to uncertainties associated with modelling multiple interacting drivers and ecosystem responses.

Figure 3.2: Projected risks and impacts of climate change on natural and human systems at different global warming levels (GWLs) relative to 1850-1900 levels. Projected risks and impacts shown on the maps are based on outputs from different subsets of Earth system models that were used to project each impact indicator without additional adaptation. WGII provides further assessment of the impacts on human and natural systems using these projections and additional lines of evidence. **(a)** Risks of species losses as indicated by the percentage of assessed species exposed to potentially dangerous temperature conditions, as defined by conditions beyond the estimated historical (1850–2005) maximum mean annual temperature experienced by each species, at GWLs of 1.5°C, 2°C, 3°C and 4°C. Underpinning projections of temperature are from 21 Earth system models and do not consider extreme events impacting ecosystems such as the Arctic. **(b)** Risk to human health as indicated by the days per year of population exposure to hypothermic conditions that pose a risk of mortality from surface air temperature and humidity conditions for historical period (1991–2005) and at GWLs of 1.7°C to 2.3°C (mean = 1.9°C; 13 climate models), 2.4°C to 3.1°C (2.7°C; 16 climate models) and 4.2°C to 5.4°C (4.7°C; 15 climate models). Interquartile ranges of WGLs by 2081–2100 under RCP2.6, RCP4.5 and RCP8.5. The presented index is consistent with common features found in many indices included within WGI and WGII assessments. **(c)** Impacts on food production: (c1) Changes in maize yield at projected GWLs of 1.6°C to 2.4°C (2.0°C), 3.3°C to 4.8°C (4.1°C) and 3.9°C to 6.0°C (4.9°C). Median yield changes from an ensemble of 12 crop models, each driven by bias-adjusted outputs from 5 Earth system models from the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Maps depict 2080–2099 compared to 1986–2005 for current growing regions (>10 ha), with the corresponding range of future global warming levels shown under SSP1-2.6, SSP3-7.0 and SSP5-8.5, respectively. Hatching indicates areas where <70% of the climate-crop model combinations agree on the sign of impact. (c2) Changes in maximum fisheries catch potential by 2081–2099 relative to 1986-2005 at projected GWLs of 0.9°C to 2.0°C (1.5°C) and 3.4°C to 5.2°C (4.3°C). GWLs by 2081–2100 under RCP2.6 and RCP8.5. Hatching indicates where the two climate-fisheries models disagree in the direction of change. Large relative changes in low yielding regions may correspond to small absolute changes. Biodiversity and fisheries in Antarctica were not analysed due to data limitations. Food security is also affected by crop and fishery failures not presented here. {*WGII Fig. TS.5*, *WGII Fig TS.9*, *WGII Annex I: Global to Regional Atlas Figure AI.15*, *Figure AI.22*, *Figure AI.23*, *Figure AI.29; WGII 7.3.1.2*, *7.2.4.1*, *SROCC Figure SPM.3*} (*3.1.2*, *Cross-Section Box.2*)

Risks are increasing with every increment of warming



e) **Examples of key risks in different regions**

Absence of risk diagrams does not imply absence of risks within a region. The development of synthetic diagrams for Small Islands, Asia and Central and South America was limited due to the paucity of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting few numbers of impact and risk projections for different warming levels.

The risks listed are of at least *medium confidence* level:

Small Islands
- Loss of terrestrial, marine and coastal biodiversity and ecosystem services
- Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure
- Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems
- Reduced habitability of reef and non-reef islands leading to increased displacement
- Risk to water security in almost every small island

North America
- Climate-sensitive mental health outcomes, human mortality and morbidity due to increasing average temperature, weather and climate extremes, and compound climate hazards
- Risk of degradation of marine, coastal and terrestrial ecosystems, including loss of biodiversity, function, and protective services
- Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture, other human uses, and degraded water quality
- Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access
- Risks to well-being, livelihoods and economic activities from cascading and compounding climate hazards, including risks to coastal cities, settlements and infrastructure from sea level rise

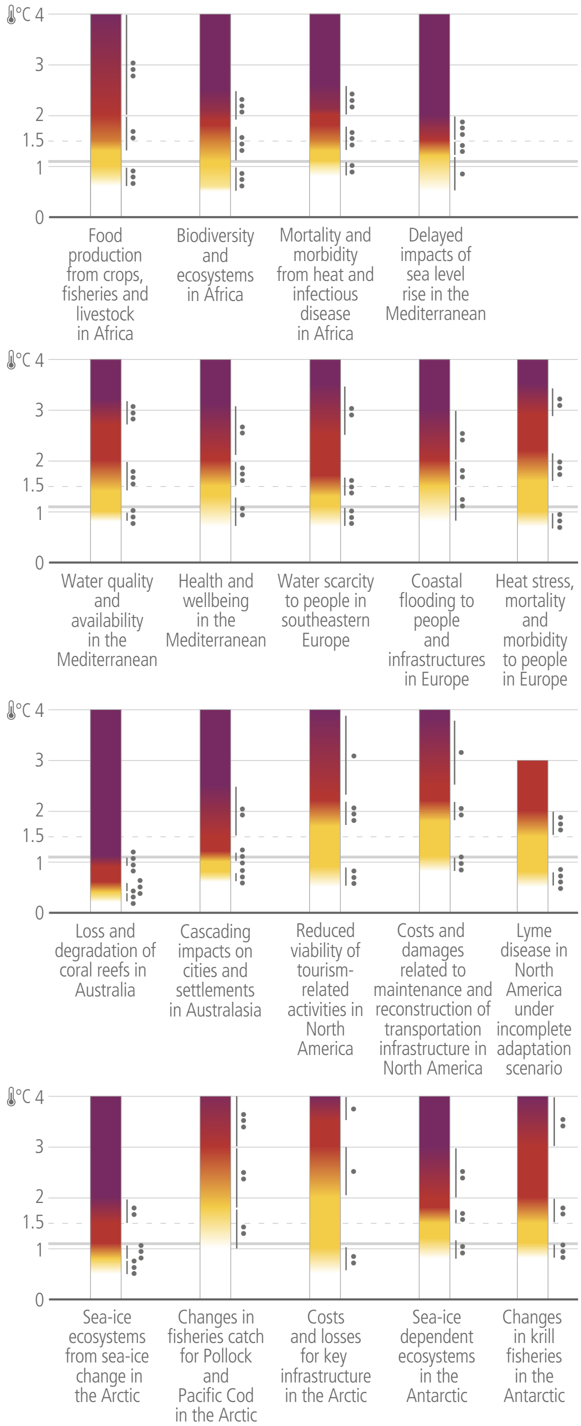
Europe
- Risks to people, economies and infrastructures due to coastal and inland flooding
- Stress and mortality to people due to increasing temperatures and heat extremes
- Marine and terrestrial ecosystems disruptions
- Water scarcity to multiple interconnected sectors
- Losses in crop production, due to compound heat and dry conditions, and extreme weather

Central and South America
- Risk to water security
- Severe health effects due to increasing epidemics, in particular vector-borne diseases
- Coral reef ecosystems degradation due to coral bleaching
- Risk to food security due to frequent/extreme droughts
- Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and coastal erosion

Australasia
- Degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values
- Loss of human and natural systems in low-lying coastal areas due to sea level rise
- Impact on livelihoods and incomes due to decline in agricultural production
- Increase in heat-related mortality and morbidity for people and wildlife
- Loss of alpine biodiversity in Australia due to less snow

Asia
- Urban infrastructure damage and impacts on human well-being and health due to flooding, especially in coastal cities and settlements
- Biodiversity loss and habitat shifts as well as associated disruptions in dependent human systems across freshwater, land, and ocean ecosystems
- More frequent, extensive coral bleaching and subsequent coral mortality induced by ocean warming and acidification, sea level rise, marine heat waves and resource extraction
- Decline in coastal fishery resources due to sea level rise, decrease in precipitation in some parts and increase in temperature
- Risk to food and water security due to increased temperature extremes, rainfall variability and drought

Africa
- Species extinction and reduction or irreversible loss of ecosystems and their services, including freshwater, land and ocean ecosystems
- Risk to food security, risk of malnutrition (micronutrient deficiency), and loss of livelihood due to reduced food production from crops, livestock and fisheries
- Risks to marine ecosystem health and to livelihoods in coastal communities
- Increased human mortality and morbidity due to increased heat and infectious diseases (including vector-borne and diarrhoeal diseases)
- Reduced economic output and growth, and increased inequality and poverty rates
- Increased risk to water and energy security due to drought and heat



Section 3

Figure 3.3: Synthetic risk diagrams of global and sectoral assessments and examples of regional key risks. The burning embers result from a literature based expert elicitation. **Panel (a): Left** - Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. *Very likely* ranges are shown for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0). **Right** - Global Reasons for Concern, comparing AR6 (thick embers) and AR5 (thin embers) assessments. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localised and comprises incremental adjustments to existing practices). However, the transition to a very high-risk level has an emphasis on irreversibility and adaptation limits. The horizontal line denotes the present global warming of 1.1°C which is used to separate the observed, past impacts below the line from the future projected risks above it. Lines connect the midpoints of the transition from moderate to high risk across AR5 and AR6. **Panel (b)**: Risks for land-based systems and ocean/coastal ecosystems. Diagrams shown for each risk assume low to no adaptation. Text bubbles indicate examples of impacts at a given warming level. **Panel (c): Left -** Global mean sea level change in centimetres, relative to 1900. The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and *likely* ranges are shown for SSP1-2.6 and SSP3-7.0. **Right** - Assessment of the combined risk of coastal flooding, erosion and salinization for four illustrative coastal geographies in 2100, due to changing mean and extreme sea levels, under two response scenarios, with respect to the SROCC baseline period (1986–2005) and indicating the IPCC AR6 baseline period (1995–2014). The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). "No-to-moderate response" describes efforts as of today (i.e., no further significant action or new types of actions). "Maximum potential response" represents a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. The assessment criteria include exposure and vulnerability (density of assets, level of degradation of terrestrial and marine buffer ecosystems), coastal hazards (flooding, shoreline erosion, salinization), in-situ responses (hard engineered coastal defences, ecosystem restoration or creation of new natural buffers areas, and subsidence management) and planned relocation. Planned relocation refers to managed retreat or resettlement. Forced displacement is not considered in this assessment. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **Panel (d): Left** - Heat-sensitive human health outcomes under three scenarios of adaptation effectiveness. The diagrams are truncated at the nearest whole °C within the range of temperature change in 2100 under three SSP scenarios. **Right** - Risks associated with food security due to climate change and patterns of socio-economic development. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3) excluding the effects of targeted mitigation and adaptation policies. **Panel (e)**: Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. {*WGI Figure SPM.8; WGII SPM B.3.3, WGII Figure SPM.3, WGII SM 16.6, WGII SM 16.7.4; SROCC Figure SPM.3d, SROCC SPM.5a, SROCC 4SM; SRCCL Figure SPM.2, SRCCL 7.3.1, SRCCL 7 SM*} (*Cross-Section Box.2*)

3.1.3 The Likelihood and Risks of Abrupt and Irreversible Change

The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C to 2.5°C (*medium confidence*) and to very high risk between 2.5°C to 4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*). {*WGI SPM C.3.2, WGI Box TS.9, WGI TS.2.6; WGII Figure SPM.3, WGII SPM B.3.1, WGII SPM B.4.1, WGII SPM B.5.2, WGII Table TS.1, WGII TS.C.1, WGII TS.C.13.3; SROCC SPM B.4*}

Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*). Global mean sea level rise will continue in the 21st century (*virtually certain*), with projected regional relative sea level rise within 20% of the global mean along two-thirds of the global coastline (*medium confidence*). The magnitude, the rate, the timing of threshold exceedances, and the long-term commitment of sea level rise depend on emissions, with higher emissions leading to greater and faster rates of sea level rise. Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 and risks for coastal ecosystems, people and infrastructure will continue to increase beyond 2100 (*high confidence*). At sustained warming levels between 2°C and 3°C, the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia (*limited evidence*). The probability and rate of ice mass loss increase with higher global surface temperatures (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C and 2 to 6 m if limited to 2°C (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: global mean sea level was *very likely* 5 to 25 m higher than today roughly 3 million years ago, when global temperatures were 2.5°C to 4°C higher than 1850–1900 (*medium confidence*). Further examples of unavoidable changes in the climate system due to multi-decadal or longer response timescales include continued glacier melt (*very high confidence*) and permafrost carbon loss (*high confidence*). {*WGI SPM B.5.2, WGI SPM B.5.3, WGI SPM B.5.4, WGI SPM C.2.5, WGI Box TS.4, WGI Box TS.9, WGI 9.5.1; WGII TS C.5; SROCC SPM B.3, SROCC SPM B.6, SROCC SPM B.9*} (*Figure 3.4*)

The probability of low-likelihood outcomes associated with potentially very large impacts increases with higher global warming levels (*high confidence*). Warming substantially above the assessed *very likely* range for a given scenario cannot be ruled out, and there is *high confidence* this would lead to regional changes greater than assessed in many aspects of the climate system. Low-likelihood, high-impact outcomes could occur at regional scales even for global warming within the *very likely* assessed range for a given GHG emissions scenario. Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and in excess of 15 m by 2300 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes[123] and would have severe

[123] This outcome is characterised by deep uncertainty: Its likelihood defies quantitative assessment but is considered due to its high potential impact. {*WGI Box TS.1; WGII Cross-Chapter Box DEEP*}

impacts on populations in low elevation coastal zones. If global warming increases, some compound extreme events[124] will become more frequent, with higher likelihood of unprecedented intensities, durations or spatial extent (*high confidence*). The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would *very likely* cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities. A sequence of large explosive volcanic eruptions within decades, as have occurred in the past, is a low-likelihood high-impact event that would lead to substantial cooling globally and regional climate perturbations over several decades. {*WGI SPM B.5.3, WGI SPM C.3, WGI SPM C.3.1, WGI SPM C.3.2, WGI SPM C.3.3, WGI SPM C.3.4, WGI SPM C.3.5, WGI Figure SPM.8, WGI Box TS.3, WGI Figure TS.6, WGI Box 9.4; WGII SPM B.4.5, WGII SPM C.2.8; SROCC SPM B.2.7*} (*Figure 3.4, Cross-Section Box.2*)

3.2 Long-term Adaptation Options and Limits

With increasing warming, adaptation options will become more constrained and less effective. At higher levels of warming, losses and damages will increase, and additional human and natural systems will reach adaptation limits. Integrated, cross-cutting multi-sectoral solutions increase the effectiveness of adaptation. Maladaptation can create lock-ins of vulnerability, exposure and risks but can be avoided by long-term planning and the implementation of adaptation actions that are flexible, multi-sectoral and inclusive. (*high confidence*)

The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions and will decrease with increasing warming (*high confidence*)[125]. For example, common adaptation responses in agriculture – adopting improved cultivars and agronomic practices, and changes in cropping patterns and crop systems – will become less effective from 2°C to higher levels of warming (*high confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Ecosystem-based Adaptation is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Globally, adaptation options related to agroforestry and forestry have a sharp decline in effectiveness at 3°C, with a substantial increase in residual risk (*medium confidence*). {*WGII SPM C.2, WGII SPM C.2.1, WGII SPM C.2.5, WGII SPM C.2.10, WGII Figure TS.6 Panel (e), 4.7.2*}

With increasing global warming, more limits to adaptation will be reached and losses and damages, strongly concentrated among the poorest vulnerable populations, will increase (*high confidence*). Already below 1.5°C, autonomous and evolutionary adaptation responses by terrestrial and aquatic ecosystems will increasingly face hard limits (*high confidence*) (Section 2.1.2). Above 1.5°C, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). Adaptation to address the risks of heat stress, heat mortality and reduced capacities for outdoor work for humans face soft and hard limits across regions that become significantly more severe at 1.5°C, and are particularly relevant for regions with warm climates (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for small islands and for regions dependent on glacier and snow melt (*medium confidence*). By 2°C, soft limits are projected for multiple staple crops, particularly in tropical regions (*high confidence*). By 3°C, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). {*WGII SPM C.3, WGII SPM C.3.3, WGII SPM C.3.4, WGII SPM C.3.5, WGII TS.D.2.2, WGII TS.D.2.3; SR1.5 SPM B.6; SROCC SPM C.1*}

Integrated, cross-cutting multi-sectoral solutions increase the effectiveness of adaptation. For example, inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition. There are a range of cross-cutting adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined. Transitioning from incremental to transformational adaptation, and addressing a range of constraints, primarily in the financial, governance, institutional and policy domains, can help overcome soft adaptation limits. However, adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. (*high confidence*) {*WGII SPM C.2, WGII SPM C.2.6, WGII SPM.C.2.13, WGII SPM C.3.1, WGII SPM.C.3.4, WGII SPM C.3.5, WGII Figure TS.6 Panel (e)*}

Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation. Adaptation options can become maladaptive due to their environmental impacts that constrain ecosystem services and decrease biodiversity and ecosystem resilience to climate change or by causing adverse outcomes for different groups, exacerbating inequity. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and

[124] See Annex I: Glossary. Examples of compound extreme events are concurrent heatwaves and droughts or compound flooding. {*WGI SPM Footnote 18*}

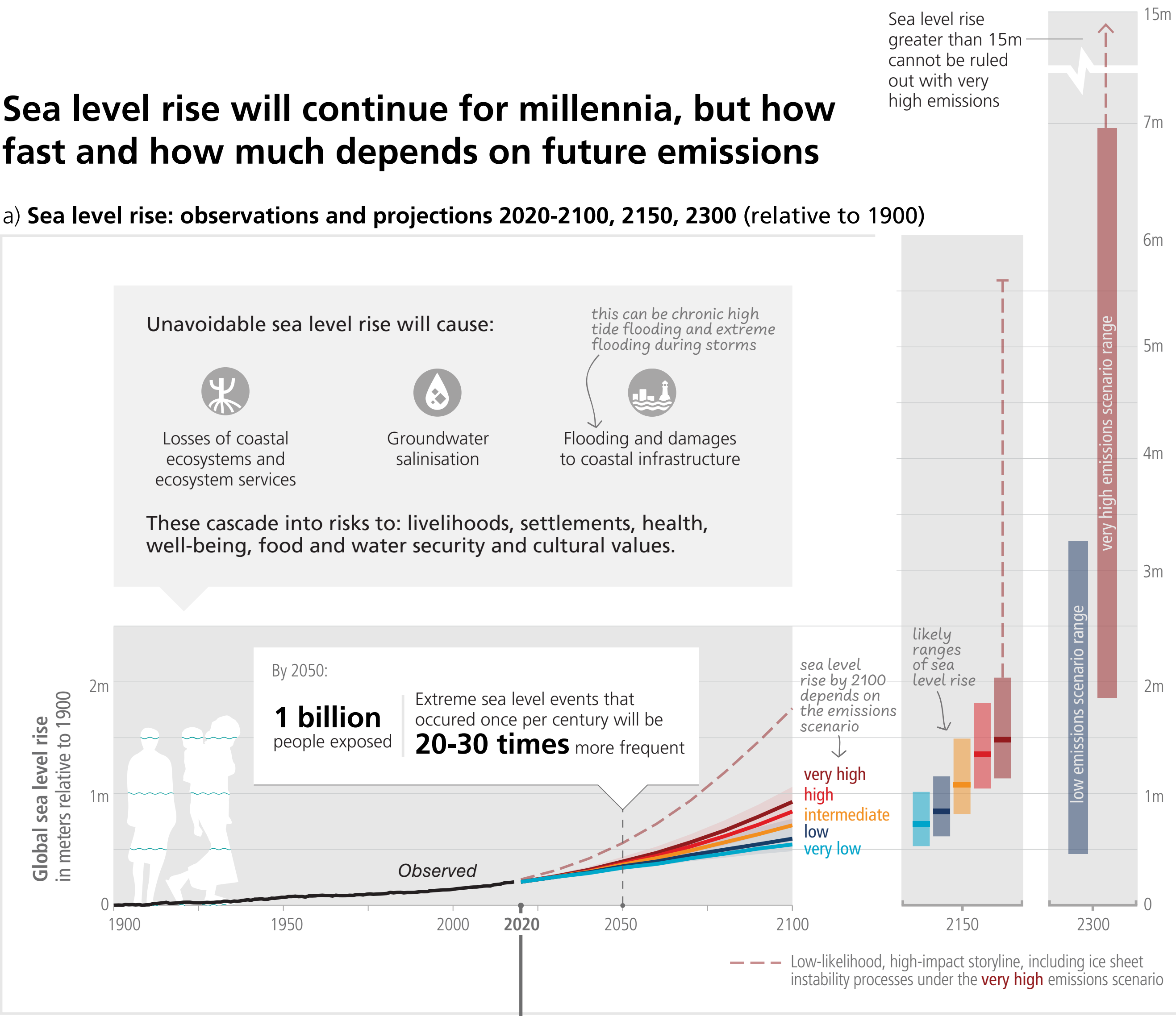
[125] There are limitations to assessing the full scope of adaptation options available in the future since not all possible future adaptation responses can be incorporated in climate impact models, and projections of future adaptation depend on currently available technologies or approaches. {*WGII 4.7.2*}

long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {*WGII SPM C.4, WGII SPM.C.4.1, WGII SPM C.4.2, WGII SPM C.4.3*}

Sea level rise poses a distinctive and severe adaptation challenge as it implies both dealing with slow onset changes and increases in the frequency and magnitude of extreme sea level events (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise (*high confidence*). Responses to ongoing sea level rise and land subsidence include protection, accommodation, advance and planned relocation (*high confidence*). These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and underpinned by inclusive community engagement processes (*high confidence*). Ecosystem-based solutions such as wetlands provide co-benefits for the environment and climate mitigation, and reduce costs for flood defences (*medium confidence)*, but have site-specific physical limits, at least above 1.5ºC of global warming (*high confidence*) and lose effectiveness at high rates of sea level rise beyond 0.5 to 1 cm yr^{-1} (*medium confidence*). Seawalls can be maladaptive as they effectively reduce impacts in the short term but can also result in lock-ins and increase exposure to climate risks in the long term unless they are integrated into a long-term adaptive plan (*high confidence*). {*WGI SPM C.2.5; WGII SPM C.2.8, WGII SPM C.4.1; WGII 13.10, WGII Cross-Chapter Box SLR; SROCC SPM B.9, SROCC SPM C.3.2, SROCC Figure SPM.4, SROCC Figure SPM.5c*} (*Figure 3.4*)

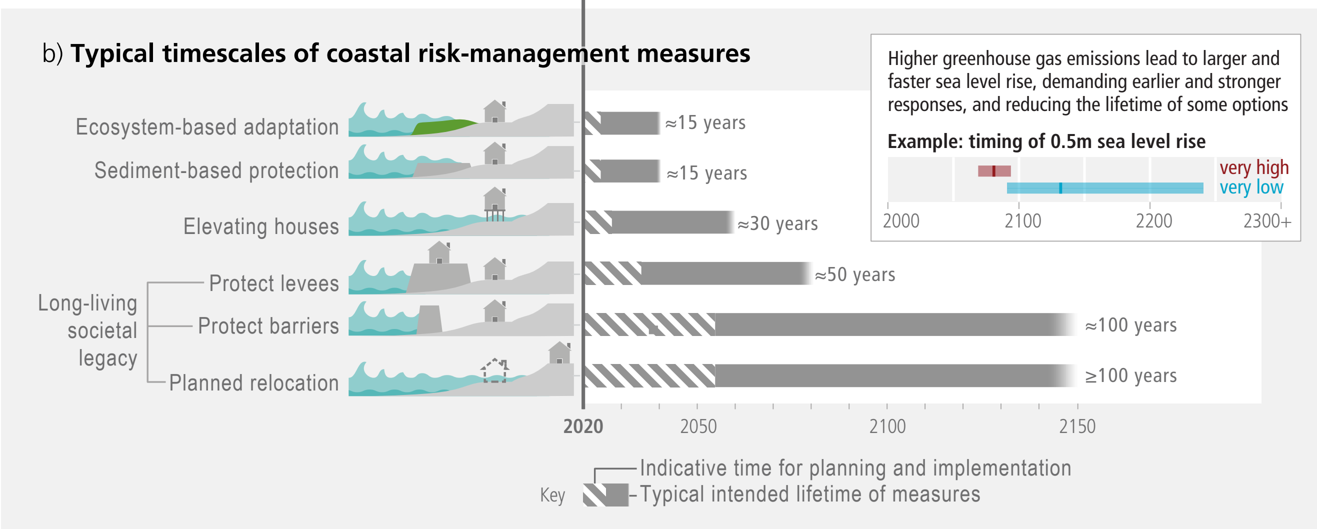
Sea level rise will continue for millennia, but how fast and how much depends on future emissions

a) **Sea level rise: observations and projections 2020-2100, 2150, 2300** (relative to 1900)



Responding to sea level rise requires long-term planning

b) **Typical timescales of coastal risk-management measures**



Section 3

Figure 3.4: Observed and projected global mean sea level change and its impacts, and time scales of coastal risk management. Panel (a): Global mean sea level change in metres relative to 1900. The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 and for 2150 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and median values and *likely* ranges are shown for the considered scenarios. Relative to 1995-2014, the *likely* global mean sea level rise by 2050 is between 0.15 to 0.23 m in the very low GHG emissions scenario (SSP1-1.9) and 0.20 to 0.29 m in the very high GHG emissions scenario (SSP5-8.5); by 2100 between 0.28 to 0.55 m under SSP1-1.9 and 0.63 to 1.01 m under SSP5-8.5; and by 2150 between 0.37 to 0.86 m under SSP1-1.9 and 0.98 to 1.88 m under SSP5-8.5 *(medium confidence)*. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995-2014) to simulated changes relative to 1995-2014. The future changes to 2300 (bars) are based on literature assessment, representing the 17th–83rd percentile range for SSP1-2.6 (0.3 to 3.1 m) and SSP5-8.5 (1.7 to 6.8 m). Red dashed lines: Low-likelihood, high-impact storyline, including ice sheet instability processes. These indicate the potential impact of deeply uncertain processes, and show the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact processes that cannot be ruled out; because of *low confidence* in projections of these processes, this is not part of a *likely* range. IPCC AR6 global and regional sea level projections are hosted at https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool. The low-lying coastal zone is currently home to around 896 million people (nearly 11% of the 2020 global population), projected to reach more than one billion by 2050 across all five SSPs. **Panel (b):** Typical time scales for the planning, implementation (dashed bars) and operational lifetime of current coastal risk-management measures (blue bars). Higher rates of sea level rise demand earlier and stronger responses and reduce the lifetime of measures (inset). As the scale and pace of sea level rise accelerates beyond 2050, long-term adjustments may in some locations be beyond the limits of current adaptation options and for some small islands and low-lying coasts could be an existential risk. {*WGI SPM B.5*, *WGI C.2.5*, *WGI Figure SPM.8*, *WGI 9.6; WGII SPM B.4.5*, *WGII B.5.2*, *WGII C.2.8*, *WGII D.3.3*, *WGII TS.D.7*, *WGII Cross-Chapter Box SLR*} (*Cross-Section Box.2*)

3.3 Mitigation Pathways

Limiting human-caused global warming requires net zero anthropogenic CO_2 emissions. Pathways consistent with 1.5°C and 2°C carbon budgets imply rapid, deep, and in most cases immediate GHG emission reductions in all sectors (*high confidence*). Exceeding a warming level and returning (i.e. overshoot) implies increased risks and potential irreversible impacts; achieving and sustaining global net negative CO_2 emissions would reduce warming (*high confidence*).

3.3.1 Remaining Carbon Budgets

Limiting global temperature increase to a specific level requires limiting cumulative net CO_2 emissions to within a finite carbon budget[126], along with strong reductions in other GHGs. For every 1000 $GtCO_2$ emitted by human activity, global mean temperature rises by *likely* 0.27°C to 0.63°C (best estimate of 0.45°C). This relationship implies that there is a finite carbon budget that cannot be exceeded in order to limit warming to any given level. {*WGI SPM D.1, WGI SPM D.1.1; SR1.5 SPM C.1.3*} (*Figure 3.5*)

The best estimates of the remaining carbon budget (RCB) from the beginning of 2020 for limiting warming to 1.5°C with a 50% likelihood[127] is estimated to be 500 $GtCO_2$; for 2°C (67% likelihood) this is 1150 $GtCO_2$.[128] Remaining carbon budgets have been quantified based on the assessed value of TCRE and its uncertainty, estimates of historical warming, climate system feedbacks such as emissions from thawing permafrost, and the global surface temperature change after global anthropogenic CO_2 emissions reach net zero, as well as variations in projected warming from non-CO_2 emissions due in part to mitigation action. The stronger the reductions in non-CO_2 emissions the lower the resulting temperatures are for a given RCB or the larger RCB for the same level of temperature change. For instance, the RCB for limiting warming to 1.5°C with a 50% likelihood could vary between 300 to 600 $GtCO_2$ depending on non-CO_2 warming[129]. Limiting warming to 2°C with a 67% (or 83%) likelihood would imply a RCB of 1150 (900) $GtCO_2$ from the beginning of 2020. To stay below 2°C with a 50% likelihood, the RCB is higher, i.e., 1350 $GtCO_2$[130]. {*WGI SPM D.1.2, WGI Table SPM.2; WGIII Box SPM.1, WGIII Box 3.4; SR1.5 SPM C.1.3*}

If the annual CO_2 emissions between 2020–2030 stayed, on average, at the same level as 2019, the resulting cumulative emissions would almost exhaust the remaining carbon budget for 1.5°C (50%), and exhaust more than a third of the remaining carbon budget for 2°C (67%) (Figure 3.5). Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 (2400 ±240 $GtCO_2$) amount to about four-fifths[131] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$) and to about two-thirds[132] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {*WGI Table SPM.2; WGIII SPM B.1.3, WGIII Table 2.1*}

In scenarios with increasing CO_2 emissions, the land and ocean carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere (*high confidence*). While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decreases with increasing cumulative net CO_2 emissions (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as GHG fluxes from wetlands, permafrost thaw, and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*). In scenarios where CO_2 concentrations peak and decline during the 21st century, the land and ocean begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 in the very low GHG emissions scenario (*medium confidence*)[133]. {*WGI SPM B.4, WGI SPM B.4.1, WGI SPM B.4.2, WGI SPM B.4.3*}

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126 See Annex I: Glossary.

127 This likelihood is based on the uncertainty in transient climate response to cumulative net CO_2 emissions and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels specified. {*WGI Table SPM.1*}

128 Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Most countries report their anthropogenic land CO_2 fluxes including fluxes due to human-caused environmental change (e.g., CO_2 fertilisation) on 'managed' land in their National GHG inventories. Using emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced. {*WGIII SPM Footnote 9, WGIII TS.3, WGIII Cross-Chapter Box 6*}

129 The central case RCB assumes future non-CO_2 warming (the net additional contribution of aerosols and non-CO_2 GHG) of around 0.1°C above 2010–2019 in line with stringent mitigation scenarios. If additional non-CO_2 warming is higher, the RCB for limiting warming to 1.5°C with a 50% likelihood shrinks to around 300 $GtCO_2$. If, however, additional non-CO_2 warming is limited to only 0.05°C (via stronger reductions of CH_4 and N_2O through a combination of deep structural and behavioural changes, e.g., dietary changes), the RCB could be around 600 $GtCO_2$ for 1.5°C warming. {*WGI Table SPM.2, WGI Box TS.7; WGIII Box 3.4*}

130 When adjusted for emissions since previous reports, these RCB estimates are similar to SR1.5 but larger than AR5 values due to methodological improvements. {*WGI SPM D.1.3*}

131 Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

132 See footnote 131.

133 These projected adjustments of carbon sinks to stabilisation or decline of atmospheric CO_2 concentrations are accounted for in calculations of remaining carbon budgets. {*WGI SPM footnote 32*}

Remaining carbon budgets to limit warming to 1.5°C could soon be exhausted, and those for 2°C largely depleted

Remaining carbon budgets are similar to emissions from use of existing and planned fossil fuel infrastructure, without additional abatement

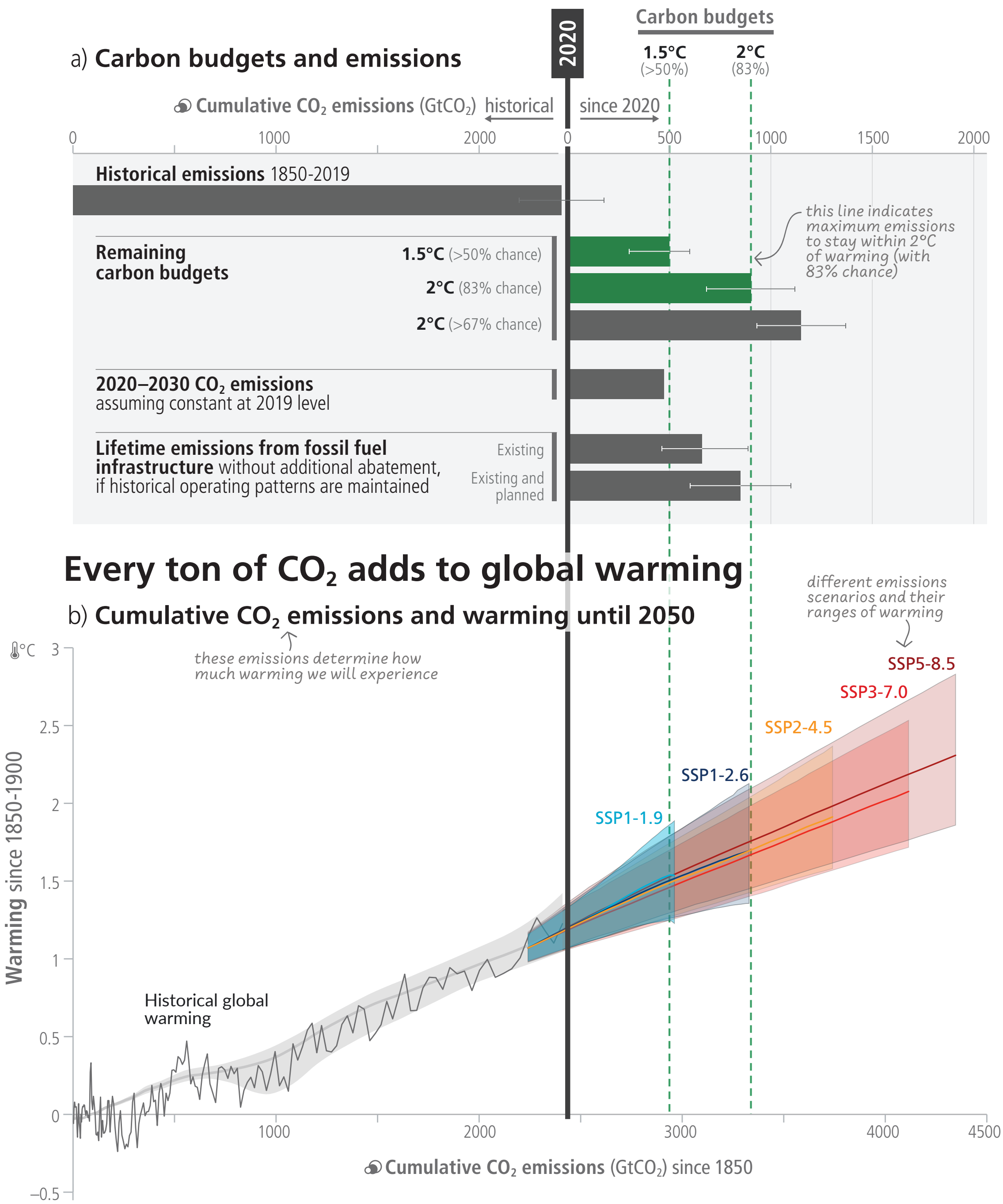

Figure 3.5: Cumulative past, projected, and committed emissions, and associated global temperature changes. Panel (a) Assessed remaining carbon budgets to limit warming *more likely than not* to 1.5°C, to 2°C with a 83% and 67% likelihood, compared to cumulative emissions corresponding to constant 2019 emissions until 2030, existing and planned fossil fuel infrastructures (in $GtCO_2$). For remaining carbon budgets, thin lines indicate the uncertainty due to the contribution of non-CO_2 warming. For lifetime emissions from fossil fuel infrastructure, thin lines indicate the assessed sensitivity range. **Panel (b)** Relationship between cumulative CO_2 emissions and the increase in global surface temperature. Historical data (thin black line) shows historical CO_2 emissions versus observed global surface temperature increase relative to the period 1850-1900. The grey range with its central line shows a corresponding estimate of the human-caused share of historical warming. Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions for the selected scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Projections until 2050 use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcers. {*WGI SPM D.1, WGI Figure SPM.10, WGI Table SPM.2; WGIII SPM B.1, WGIII SPM B.7, WGIII 2.7; SR1.5 SPM C.1.3*}

Table 3.1: Key characteristics of the modelled global emissions pathways. Summary of projected CO_2 and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (columns), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels. Values shown are for the median [p50] and 5–95th percentiles [p5–p95], noting that not all pathways achieve net zero CO_2 or GHGs. {*WGIII Table SPM.2*}

p50 [p5-p95] [1]	Category [2] [# pathways]	Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.	C1 [97]	C1a [50]	C1b [47]	C2 [133]	C3 [311]	C3a [204]	C3b [97]	C4 [159]	C5 [212]	C6 [97]
	Category/ subset label		limit warming to 1.5°C (>50%) with no or limited overshoot	… with net zero GHGs	… without net zero GHGs	return warming to 1.5°C (>50%) after a high overshoot	limit warming to 2°C (>67%)	… with action starting in 2020	… NDCs until 2030	limit warming to 2°C (>50%)	limit warming to 2.5°C (>50%)	limit warming to 3°C (>50%)
GHG emissions reductions from 2019 (%) [3]	2030	Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th-95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019	43 [34-60]	41 [31-59]	48 [35-61]	23 [0-44]	21 [1-42]	27 [13-45]	5 [0-14]	10 [0-27]	6 [-1 to 18]	2 [-10 to 11]
	2040		69 [58-90]	66 [58-89]	70 [62-87]	55 [40-71]	46 [34-63]	47 [35-63]	46 [34-63]	31 [20-5]	18 [4-33]	3 [-14 to 14]
	2050		84 [73-98]	85 [72-100]	84 [76-93]	75 [62-91]	64 [53-77]	63 [52-76]	68 [56-83]	49 [35-65]	29 [11-48]	5 [-2 to 18]
Emissions milestones [4]	Net zero CO_2 (% net zero pathways)	Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th-95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.	2050-2055 (100%) [2035-2070]			2055-2060 (100%) [2045-2070]	2070-2075 (93%) [2055-...]	2070-2075 (91%) [2055-...]	2065-2070 (97%) [2055-2090]	2080-2085 (86%) [2065-...]	...-... (41%) [2080-...]	no net-zero
	Net zero GHGs [5] (% net zero pathways)		2095-2100 (52%) [2050-...]	2070-2075 (100%) [2050-2090]	...-... (0%) [...-...]	2070-2075 (87%) [2055-...]	...-... (30%) [2075-...]	...-... (24%) [2080-...]	...-... (41%) [2075-...]	...-... (31%) [2075-...]	...-... (12%) [2090-...]	no net-zero
Cumulative CO_2 emissions [Gt CO_2] [6]	2020 to net zero CO_2	Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th-95th percentile interval in square brackets.	510 [330-710]	550 [340-760]	460 [320-590]	720 [530-930]	890 [640-1160]	860 [640-1180]	910 [720-1150]	1210 [970-1490]	1780 [1400-2360]	no net-zero
	2020–2100		320 [-210-570]	160 [-220-620]	360 [10-540]	400 [-90-620]	800 [510-1140]	790 [480-1150]	800 [560-1050]	1160 [700-1490]	1780 [1260-2360]	2790 [2440-3520]
Global mean temperature changes 50% probability (°C)	at peak warming	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850-1900, at peak warming and in 2100, for the median value across the scenarios and the 5th-95th percentile interval in square brackets.	1.6 [1.4-1.6]	1.6 [1.4-1.6]	1.6 [1.5-1.6]	1.7 [1.5-1.8]	1.7 [1.6-1.8]	1.7 [1.6-1.8]	1.8 [1.6-1.8]	1.9 [1.7-2.0]	2.2 [1.9-2.5]	no peaking by 2100
	2100		1.3 [1.1-1.5]	1.2 [1.1-1.4]	1.4 [1.3-1.5]	1.4 [1.2-1.5]	1.6 [1.5-1.8]	1.6 [1.5-1.8]	1.6 [1.5-1.7]	1.8 [1.5-2.0]	2.1 [1.9-2.5]	2.7 [2.4-2.9]
Likelihood of peak global warming staying below (%)	<1.5°C	Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th-95th percentile interval in square brackets.	38 [33-58]	38 [34-60]	37 [33-56]	24 [15-42]	20 [13-41]	21 [14-42]	17 [12-35]	11 [7-22]	4 [0-10]	0 [0-0]
	<2.0°C		90 [86-97]	90 [85-97]	89 [87-96]	82 [71-93]	76 [68-91]	78 [69-91]	73 [67-87]	59 [50-77]	37 [18-59]	8 [2-18]
	<3.0°C		100 [99-100]	100 [99-100]	100 [99-100]	100 [99-100]	99 [98-100]	100 [98-100]	99 [98-99]	98 [95-99]	91 [83-98]	71 [53-88]

1 Detailed explanations on the Table are provided in WGIII Box SPM.1 and WGIII Table SPM.2. The relationship between the temperature categories and SSP/RCPs is discussed in Cross-Section Box.2. Values in the table refer to the 50th and [5–95th] percentile values across the pathways falling within a given category as defined in WGIII Box SPM.1. The three dots (…) sign denotes that the value cannot be given (as the value is after 2100 or, for net zero, net zero is not reached). Based on the assessment of climate emulators in AR6 WG I (Chapter 7, Box 7.1), two climate emulators were used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature Change' and 'Likelihood' columns, the non-bracketed values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges in the "likelihood" column, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). These ranges cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty. All global warming levels are relative to 1850-1900.

2 C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in WGIII Figure SPM.4.

3 Global emission reductions in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonised modelled global emissions in 2019 rather than the global emissions reported in WGIII SPM Section B and WGIII Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WGI (see WGIII SPM Footnote 49). Negative values (e.g., in C5, C6) represent an increase in emissions. The modelled GHG emissions in 2019 are 55 [53–58] $GtCO_2$-eq, thus within the uncertainty ranges of estimates for 2019 emissions [53-66] $GtCO_2$-eq (see 2.1.1).

4 Emissions milestones are provided for 5-year intervals in order to be consistent with the underlying 5-year time-step data of the modelled pathways. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile 5-year interval and the upper bound of the 95th percentile 5-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones over the 21st century. Percentiles reported across all pathways in that category include those that do not reach net zero before 2100.

5 For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100-year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. See WGIII Annex III.II.5.

6 Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonised net CO_2 emissions, ensuring consistency with the WG I assessment of the remaining carbon budget. {*WGIII Box 3.4, WGIII SPM Footnote 50*}

3.3.2 Net Zero Emissions: Timing and Implications

From a physical science perspective, limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching net zero or net negative CO_2 emissions, along with strong reductions of other GHG emissions (see Cross-Section Box.1). Global modelled pathways that reach and sustain net zero GHG emissions are projected to result in a gradual decline in surface temperature (*high confidence*). Reaching net zero GHG emissions primarily requires deep reductions in CO_2, methane, and other GHG emissions, and implies net negative CO_2 emissions.[134] Carbon dioxide removal (CDR) will be necessary to achieve net negative CO_2 emissions[135]. Achieving global net zero CO_2 emissions, with remaining anthropogenic CO_2 emissions balanced by durably stored CO_2 from anthropogenic removal, is a requirement to stabilise CO_2-induced global surface temperature increase (see 3.3.3) (*high confidence*). This is different from achieving net zero GHG emissions, where metric-weighted anthropogenic GHG emissions (see Cross-Section Box.1) equal CO_2 removal (*high confidence*). Emissions pathways that reach and sustain net zero GHG emissions defined by the 100-year global warming potential imply net negative CO_2 emissions and are projected to result in a gradual decline in surface temperature after an earlier peak (*high confidence*). While reaching net zero CO_2 or net zero GHG emissions requires deep and rapid reductions in gross emissions, the deployment of CDR to counterbalance hard-to-abate residual emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) is unavoidable (*high confidence*). {*WGI SPM D.1, WGI SPM D.1.1, WGI SPM D.1.8; WGIII SPM C.2, WGIII SPM C.3, WGIII SPM C.11, WGIII Box TS.6; SR1.5 SPM A.2.2*}

In modelled pathways, the timing of net zero CO_2 emissions, followed by net zero GHG emissions, depends on several variables, including the desired climate outcome, the mitigation strategy and the gases covered (*high confidence*). Global net zero CO_2 emissions are reached in the early 2050s in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in pathways that limit warming to 2°C (>67%). While non-CO_2 GHG emissions are strongly reduced in all pathways that limit warming to 2°C (>67%) or lower, residual emissions of CH_4 and N_2O and F-gases of about 8 [5–11] $GtCO_2$-eq yr^{-1} remain at the time of net zero GHG, counterbalanced by net negative CO_2 emissions. As a result, net zero CO_2 would be reached before net zero GHGs (*high confidence*). {*WGIII SPM C.2, WGIII SPM C.2.3, WGIII SPM C.2.4, WGIII Table SPM.2, WGIII 3.3*} *(Figure 3.6)*

[134] Net zero GHG emissions defined by the 100-year global warming potential. See footnote 70.

[135] See Section 3.3.3 and 3.4.1.

Section 3

Global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot reach net zero CO_2 emissions around 2050

Total greenhouse gases (GHG) reach net zero later

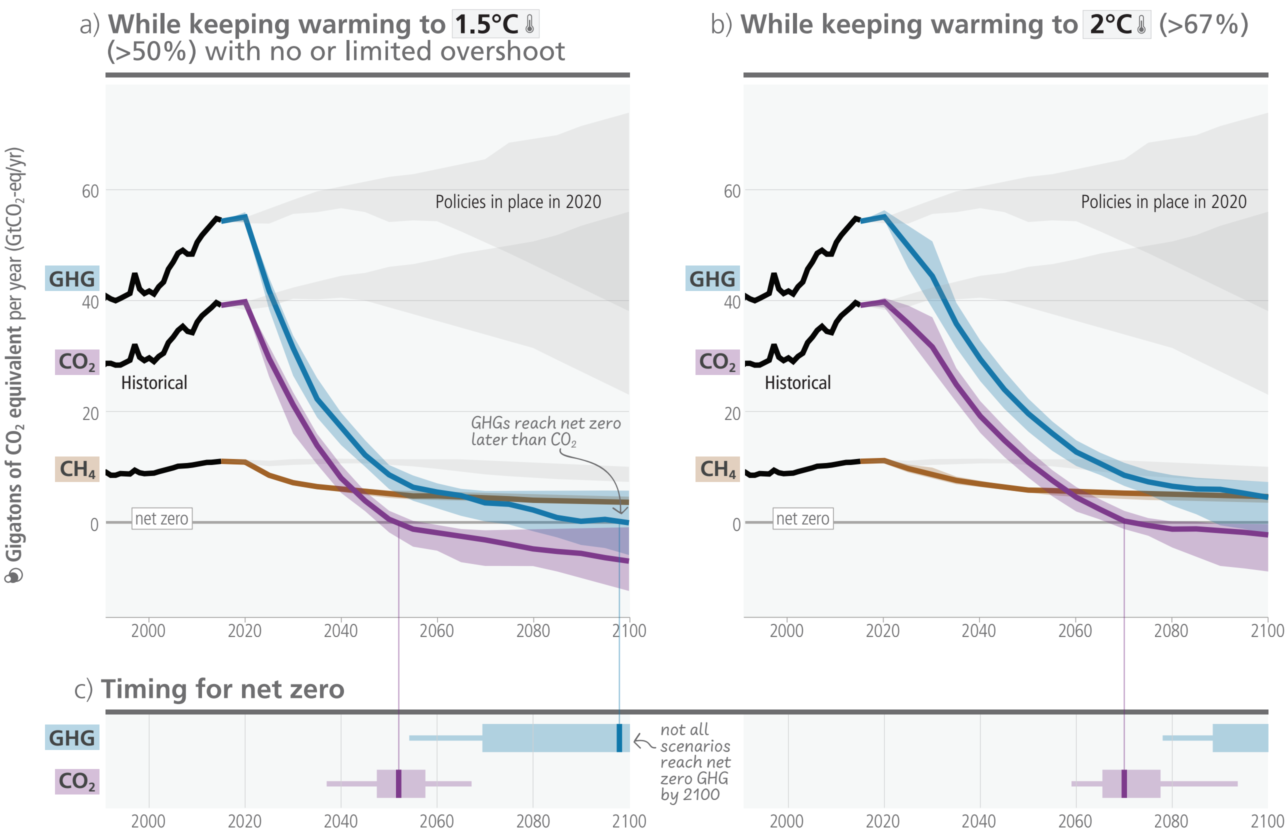

Figure 3.6: Total GHG, CO_2 and CH_4 emissions and timing of reaching net zero in different mitigation pathways. Top row: GHG, CO_2 and CH_4 emissions over time (in $GtCO_2eq$) with historical emissions, projected emissions in line with policies implemented until the end of 2020 (grey), and pathways consistent with temperature goals in colour (blue, purple, and brown, respectively). **Panel (a) (left)** shows pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1) and **Panel (b) (right)** shows pathways that limit warming to 2°C (>67%) (C3). **Bottom row: Panel (c)** shows median (vertical line), *likely* (bar) and *very likely* (thin lines) timing of reaching net zero GHG and CO_2 emissions for global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1) (left) or 2°C (>67%) (C3) (right). {*WGIII Figure SPM.5*}

3.3.3 Sectoral Contributions to Mitigation

All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve rapid and deep and in most cases immediate GHG emissions reductions in all sectors (see also 4.1, 4.5). Reductions in GHG emissions in industry, transport, buildings, and urban areas can be achieved through a combination of energy efficiency and conservation and a transition to low-GHG technologies and energy carriers (see also 4.5, Figure 4.4). Socio-cultural options and behavioural change can reduce global GHG emissions of end-use sectors, with most of the potential in developed countries, if combined with improved infrastructure design and access. (*high confidence*) {*WGIII SPM C.3, WGIII SPM C.5, WGIII SPM C.6, WGIII SPM C.7.3, WGIII SPM C.8, WGIII SPM C.10.2*}

Global modelled mitigation pathways reaching net zero CO_2 and GHG emissions include transitioning from fossil fuels without carbon capture and storage (CCS) to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand-side measures and improving efficiency, reducing non-CO_2 GHG emissions, and CDR[136]. In global modelled pathways that limit warming to 2°C or below, almost all electricity is supplied

[136] CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. *(high confidence)* {*WGIII SPM C.4.6*}

from zero or low-carbon sources in 2050, such as renewables or fossil fuels with CO_2 capture and storage, combined with increased electrification of energy demand. Such pathways meet energy service demand with relatively low energy use, through e.g., enhanced energy efficiency and behavioural changes and increased electrification of energy end use. Modelled global pathways limiting global warming to 1.5°C (>50%) with no or limited overshoot generally implement such changes faster than pathways limiting global warming to 2°C (>67%). (*high confidence*) {*WGIII SPM C.3, WGIII SPM C.3.2, WGIII SPM C.4, WGIII TS.4.2; SR1.5 SPM C.2.2*}

AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced CO_2 removal; however, barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects (see 3.4.1). All assessed modelled pathways that limit warming to 2°C (>67%) or lower by 2100 include land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy. However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by climate change and disturbances such as flood, drought, fire, or pest outbreaks, or future poor management. (*high confidence*) {*WGI SPM B.4.3; WGII SPM B.2.3, WGII SPM B.5.4; WGIII SPM C.9, WGIII SPM C.11.3, WGIII SPM D.2.3, WGIII TS.4.2, 3.4; SR1.5 SPM C.2.5; SRCCL SPM B.1.4, SRCCL SPM B.3, SRCCL SPM B.7*}

In addition to deep, rapid, and sustained emission reductions, CDR can fulfil three complementary roles: lowering net CO_2 or net GHG emissions in the near term; counterbalancing 'hard-to-abate' residual emissions (e.g., some emissions from agriculture, aviation, shipping, industrial processes) to help reach net zero CO_2 or GHG emissions, and achieving net negative CO_2 or GHG emissions if deployed at levels exceeding annual residual emissions (*high confidence*). CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 Gt CO_2 yr^{-1}, e.g., blue carbon management) to higher potential (>3 Gt CO_2 yr^{-1}, e.g., agroforestry); costs range from lower cost (e.g., –45 to 100 USD tCO_2^{-1} for soil carbon sequestration) to higher cost (e.g., 100 to 300 USD tCO_2^{-1} for direct air carbon dioxide capture and storage) (*medium confidence*). Estimated storage timescales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to ten thousand years or more for methods that store carbon in geological formations (*high confidence*). Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints (*high confidence*). {*WGIII SPM C.3.5, WGIII SPM C.11.1, WGIII SPM C.11.4*}

3.3.4 Overshoot Pathways: Increased Risks and Other Implications

Exceeding a specific remaining carbon budget results in higher global warming. Achieving and sustaining net negative global CO_2 emissions could reverse the resulting temperature exceedance (*high confidence*). Continued reductions in emissions of short-lived climate forcers, particularly methane, after peak temperature has been reached, would also further reduce warming (*high confidence*). Only a small number of the most ambitious global modelled pathways limit global warming to 1.5°C (>50%) without overshoot. {*WGI SPM D.1.1, WGI SPM D.1.6, WGI SPM D.1.7; WGIII TS.4.2*}

Overshoot of a warming level results in more adverse impacts, some irreversible, and additional risks for human and natural systems compared to staying below that warming level, with risks growing with the magnitude and duration of overshoot (*high confidence*). Compared to pathways without overshoot, societies and ecosystems would be exposed to greater and more widespread changes in climatic impact-drivers, such as extreme heat and extreme precipitation, with increasing risks to infrastructure, low-lying coastal settlements, and associated livelihoods (*high confidence*). Overshooting 1.5°C will result in irreversible adverse impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet melt, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*). Overshoot increases the risks of severe impacts, such as increased wildfires, mass mortality of trees, drying of peatlands, thawing of permafrost and weakening natural land carbon sinks; such impacts could increase releases of GHGs making temperature reversal more challenging (*medium confidence*). {*WGI SPM C.2, WGI SPM C.2.1, WGI SPM C.2.3; WGII SPM B.6, WGII SPM B.6.1, WGII SPM B.6.2; SR1.5 3.6*}

The larger the overshoot, the more net negative CO_2 emissions needed to return to a given warming level (*high confidence*). Reducing global temperature by removing CO_2 would require net negative emissions of 220 $GtCO_2$ (best estimate, with a *likely* range of 160 to 370 $GtCO_2$) for every tenth of a degree (*medium confidence*). Modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot reach median values of cumulative net negative emissions of 220 $GtCO_2$ by 2100, pathways that return warming to 1.5°C (>50%) after high overshoot reach median values of 360 $GtCO_2$ (*high confidence*).[137] More rapid reduction in CO_2 and non-CO_2 emissions, particularly methane, limits peak warming levels and reduces the requirement for net negative CO_2 emissions and CDR, thereby reducing feasibility and sustainability concerns, and social and environmental risks (*high confidence*). {*WGI SPM D.1.1; WGIII SPM B.6.4, WGIII SPM C.2, WGIII SPM C.2.2, WGIII Table SPM.2*}

[137] Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C to 0.3°C, in both cases for up to several decades. {*WGIII Box SPM.1*}

3.4 Long-Term Interactions Between Adaptation, Mitigation and Sustainable Development

Mitigation and adaptation can lead to synergies and trade-offs with sustainable development (*high confidence*). Accelerated and equitable mitigation and adaptation bring benefits from avoiding damages from climate change and are critical to achieving sustainable development (*high confidence*). Climate resilient development[138] pathways are progressively constrained by every increment of further warming (*very high confidence*). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*).

3.4.1 Synergies and trade-offs, costs and benefits

Mitigation and adaptation options can lead to synergies and trade-offs with other aspects of sustainable development (see also Section 4.6, Figure 4.4). Synergies and trade-offs depend on the pace and magnitude of changes and the development context including inequalities, with consideration of climate justice. The potential or effectiveness of some adaptation and mitigation options decreases as climate change intensifies (see also Sections 3.2, 3.3.3, 4.5). (*high confidence*) {*WGII SPM C.2, WGII Figure SPM.4b; WGIII SPM D.1, WGIII SPM D.1.2, WGIII TS.5.1, WGIII Figure SPM.8; SR1.5 SPM D.3, SR1.5 SPM D.4; SRCCL SPM B.2, SRCCL SPM B.3, SRCCL SPM D.3.2, SRCCL Figure SPM.3*}

In the energy sector, transitions to low-emission systems will have multiple co-benefits, including improvements in air quality and health. There are potential synergies between sustainable development and, for instance, energy efficiency and renewable energy. (*high confidence*) {*WGIII SPM C.4.2, WGIII SPM D.1.3*}

For agriculture, land, and food systems, many land management options and demand-side response options (e.g., dietary choices, reduced post-harvest losses, reduced food waste) can contribute to eradicating poverty and eliminating hunger while promoting good health and well-being, clean water and sanitation, and life on land (*medium confidence)*. In contrast, certain adaptation options that promote intensification of production, such as irrigation, may have negative effects on sustainability (e.g., for biodiversity, ecosystem services, groundwater depletion, and water quality) (*high confidence*). {*WGII TS.D.5.5; WGIII SPM D.10; SRCCL SPM B.2.3*}

Reforestation, improved forest management, soil carbon sequestration, peatland restoration and coastal blue carbon management are examples of CDR methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context[139]. However, afforestation or production of biomass crops for bioenergy with carbon dioxide capture and storage or biochar can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure. (*high confidence*) {*WGII SPM B.5.4, WGII SPM C.2.4; WGIII SPM C.11.2; SR1.5 SPM C.3.4, SR1.5 SPM C.3.5; SRCCL SPM B.3, SRCCL SPM B.7.3, SRCCL Figure SPM.3*}

Modelled pathways that assume using resources more efficiently or shift global development towards sustainability include fewer challenges, such as dependence on CDR and pressure on land and biodiversity, and have the most pronounced synergies with respect to sustainable development (*high confidence*). {*WGIII SPM C.3.6; SR1.5 SPM D.4.2*}

Strengthening climate change mitigation action entails more rapid transitions and higher up-front investments, but brings benefits from avoiding damages from climate change and reduced adaptation costs. The aggregate effects of climate change mitigation on global GDP (excluding damages from climate change and adaptation costs) are small compared to global projected GDP growth. Projected estimates of global aggregate net economic damages and the costs of adaptation generally increase with global warming level. (*high confidence*) {*WGII SPM B.4.6, WGII TS.C.10; WGIII SPM C.12.2, WGIII SPM C.12.3*}

Cost-benefit analysis remains limited in its ability to represent all damages from climate change, including non-monetary damages, or to capture the heterogeneous nature of damages and the risk of catastrophic damages (*high confidence*). Even without accounting for these factors or for the co-benefits of mitigation, the global benefits of limiting warming to 2°C exceed the cost of mitigation (*medium confidence*). This finding is robust against a wide range of assumptions about social preferences on inequalities and discounting over time (*medium confidence*). Limiting global warming to 1.5°C instead of 2°C would increase the costs of mitigation, but also increase the benefits in terms of reduced impacts and related risks (see 3.1.1, 3.1.2) and reduced adaptation needs (*high confidence*)[140]. {*WGII SPM B.4, WGII SPM B.6; WGIII SPM C.12, WGIII SPM C.12.2, WGIII SPM C.12.3 WGIII Box TS.7; SR1.5 SPM B.3, SR1.5 SPM B.5, SR1.5 SPM B.6*}

Considering other sustainable development dimensions, such as the potentially strong economic benefits on human health from air quality improvement, may enhance the estimated benefits of mitigation (*medium confidence*). The economic effects of strengthened mitigation action vary across regions and countries, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation (*high confidence*). Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with implications for near-term actions (Section 4.2), equity (Section 4.4), sustainability (Section 4.6), and finance (Section 4.8) (*high confidence*). {*WGIII SPM C.12.2, WGIII SPM D.3.2, WGIII TS.4.2*}

[138] See Annex I: Glossary.

[139] The impacts, risks, and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). {*WGIII SPM C.11.2*}

[140] The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C. {*WGIII SPM footnote 68*}

3.4.2 Advancing Integrated Climate Action for Sustainable Development

An inclusive, equitable approach to integrating adaptation, mitigation and development can advance sustainable development in the long term (*high confidence*). Integrated responses can harness synergies for sustainable development and reduce trade-offs (*high confidence*). Shifting development pathways towards sustainability and advancing climate resilient development is enabled when governments, civil society and the private sector make development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*) (see also Figure 4.2). Inclusive processes involving local knowledge and Indigenous Knowledge increase these prospects (*high confidence*). However, opportunities for action differ substantially among and within regions, driven by historical and ongoing patterns of development (*very high confidence*). Accelerated financial support for developing countries is critical to enhance mitigation and adaptation action (*high confidence*). {*WGII SPM C.5.4, WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.1.2, WGII SPM D.2, WGII SPM D.3, WGII SPM D.5, WGII SPM D.5.1, WGII SPM D.5.2; WGIII SPM D.1, WGIII SPM D.2, WGIII SPM D.2.4, WGIII SPM E.2.2, WGIII SPM E.2.3, WGIII SPM E.5.3, WGIII Cross-Chapter Box 5*}

Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation and adaptation responses (*medium confidence*). Combining mitigation with action to shift development pathways, such as broader sectoral policies, approaches that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure can significantly increase the adaptive capacity of urban and rural settlements. Coastal cities and settlements play an important role in advancing climate resilient development due to the high number of people living in the Low Elevation Coastal Zone, the escalating and climate compounded risk that they face, and their vital role in national economies and beyond (*high confidence*). {*WGII SPM.D.3, WGII SPM D.3.3; WGIII SPM E.2, WGIII SPM E.2.2; SR1.5 SPM D.6*}

Observed adverse impacts and related losses and damages, projected risks, trends in vulnerability, and adaptation limits demonstrate that transformation for sustainability and climate resilient development action is more urgent than previously assessed (*very high confidence*). Climate resilient development integrates adaptation and GHG mitigation to advance sustainable development for all. Climate resilient development pathways have been constrained by past development, emissions and climate change and are progressively constrained by every increment of warming, in particular beyond 1.5°C (*very high confidence*). Climate resilient development will not be possible in some regions and sub-regions if global warming exceeds 2°C (*medium confidence*). Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, but biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, making climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). {*WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.4, WGII SPM D.4.3, WGII SPM D.5.1; WGIII SPM D.1.1*}

The cumulative scientific evidence is unequivocal: climate change is a threat to human well-being and planetary health (*very high confidence*). Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*). Opportunities for near-term action are assessed in the following section. {*WGII SPM D.5.3; WGIII SPM D.1.1*}

Section 4
Near-Term Responses in a Changing Climate

Section 4 : Near-Term Responses in a Changing Climate

4.1 The Timing and Urgency of Climate Action

Deep, rapid, and sustained mitigation and accelerated implementation of adaptation reduces the risks of climate change for humans and ecosystems. In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action, global GHG emissions are projected to peak in the early 2020s followed by rapid and deep reductions. As adaptation options often have long implementation times, accelerated implementation of adaptation, particularly in this decade, is important to close adaptation gaps. (*high confidence*)

The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions (*very high confidence*). Global warming is *more likely than not* to reach 1.5°C between 2021 and 2040 even under the very low GHG emission scenarios (SSP1-1.9), and *likely* or *very likely* to exceed 1.5°C under higher emissions scenarios[141]. Many adaptation options have medium or high feasibility up to 1.5°C (*medium* to *high confidence*, depending on option), but hard limits to adaptation have already been reached in some ecosystems and the effectiveness of adaptation to reduce climate risk will decrease with increasing warming (*high confidence*). Societal choices and actions implemented in this decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (*high confidence*). Without urgent, effective and equitable adaptation and mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health, and biodiversity, with severe adverse consequences for current and future generations (*high confidence*). {*WGI SPM B.1.3, WGI SPM B.5.1, WGI SPM B.5.2; WGII SPM A, WGII SPM B.4, WGII SPM C.2, WGII SPM C.3.3, WGII Figure SPM.4, WGII SPM D.1, WGII SPM D.5, WGIII SPM D.1.1 SR1.5 SPM D.2.2*}. (*Cross-Section Box.2, Figure 2.1, Figure 2.3*)

In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%), assuming immediate actions, global GHG emissions are projected to peak in the early 2020s followed by rapid and deep GHG emissions reductions (*high confidence*) [142]. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, net global GHG emissions are projected to fall by 43 [34 to 60]%[143] below 2019 levels by 2030, 60 [49 to 77]% by 2035, 69 [58 to 90]% by 2040 and 84 [73 to 98]% by 2050 (*high confidence*) (Section 2.3.1, Table 2.2, Figure 2.5, Table 3.1)[144]. Global modelled pathways that limit warming to 2°C (>67%) have reductions in GHG emissions below 2019 levels of 21 [1 to 42]% by 2030, 35 [22 to 55] % by 2035, 46 [34 to 63] % by 2040 and 64 [53 to 77]% by 2050[145] (*high confidence*). Global GHG emissions associated with NDCs announced prior to COP26 would make it *likely* that warming would exceed 1.5°C (*high confidence*) and limiting warming to 2°C (>67%) would then imply a rapid acceleration of emission reductions during 2030–2050, around 70% faster than in pathways where immediate action is taken to limit warming to 2°C (>67%) (*medium confidence*) (Section 2.3.1) Continued investments in unabated high-emitting infrastructure[146] and limited development and deployment of low-emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {*WGIII SPM B.6.3, WGIII 3.5.2, WGIII SPM B.6, WGIII SPM B.6., WGIII SPM C.1, WGIII SPM C1.1, WGIII Table SPM.2*} (*Cross-Section Box.2*)

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141 In the near term (2021–2040), the 1.5°C global warming level is very *likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5, SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9). The best estimates [and *very likely* ranges] of global warming for the different scenarios in the near term are: 1.5 [1.2 to 1.7]°C (SSP1-1.9); 1.5 [1.2 to 1.8]°C (SSP1-2.6); 1.5 [1.2 to 1.8]°C (SSP2-4.5); 1.5 [1.2 to 1.8]°C (SSP3-7.0); and 1.6[1.3 to 1.9]°C (SSP5-8.5). {*WGI SPM B.1.3, WGI Table SPM.1*} (*Cross-Section Box.2*)

142 Values in parentheses indicate the likelihood of limiting warming to the level specified (see Cross-Section Box.2).

143 Median and very *likely* range [5th to 95th percentile]. {*WGIII SPM footnote 30*}

144 These numbers for CO_2 are 48 [36 to 69]% in 2030, 65 [50 to 96] % in 2035, 80 [61 to109] % in 2040 and 99 [79 to 119]% in 2050.

145 These numbers for CO_2 are 22 [1 to 44]% in 2030, 37 [21 to 59] % in 2035, 51 [36 to 70] % in 2040 and 73 [55 to 90]% in 2050.

146 In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50 to 80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34 [21 to 57]% below 2019 levels by 2030 and by 44 [31 to 63]% in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24 [9 to 53]% below 2019 levels by 2030 and by 37 [20 to 60]% in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). {*WGIII SPM C1.2*, *WGIII Table SPM.2*, *WGIII 3.3; SR1.5 SPM C.1*, *SR1.5 SPM C.1.2*} (*Cross-Section Box.2*)

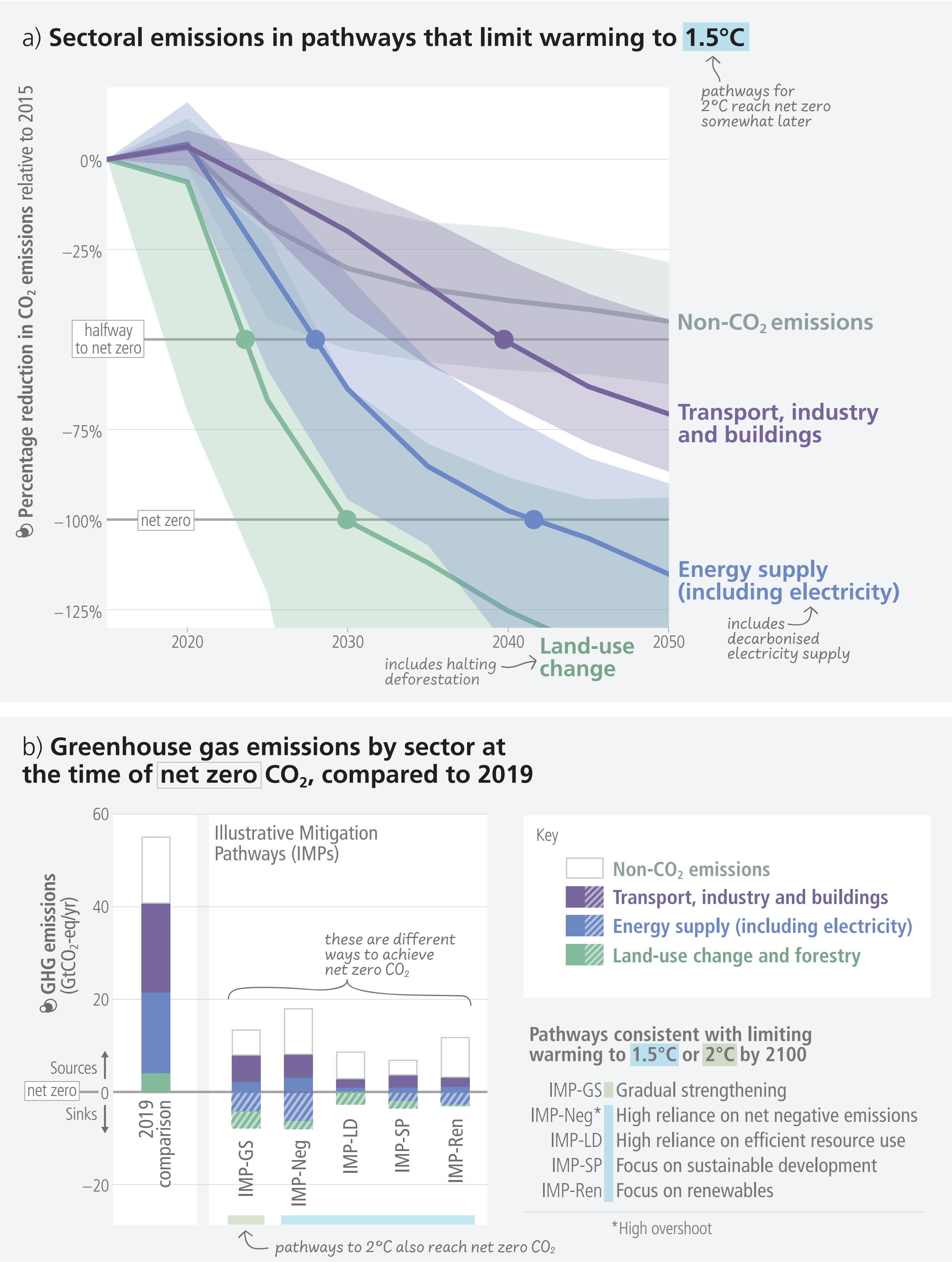
All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve GHG emission reductions in all sectors (*high confidence*). The contributions of different sectors vary across modelled mitigation pathways. In most global modelled mitigation pathways, emissions from land-use, land-use change and forestry, via reforestation and reduced deforestation, and from the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors (Figure 4.1). Strategies can rely on combinations of different options (Figure 4.1, Section 4.5), but doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) {*WGIII SPM C.3*, *WGIII SPM C.3.1*, *WGIII SPM 3.2*, *WGIII SPM C.3.3*} (*Cross-Section Box.2*)

Without rapid, deep and sustained mitigation and accelerated adaptation actions, losses and damages will continue to increase, including projected adverse impacts in Africa, LDCs, SIDS, Central and South America[147], Asia and the Arctic, and will disproportionately affect the most vulnerable populations (*high confidence*). {*WGII SPM C.3.5*, *WGII SPM B.2.4*, *WGII 12.2*, *WGII 10. Box 10.6*, *WGII TS D.7.5*, *WGII Cross-Chapter Box 6 ES*, *WGII Global to Regional Atlas Annex A1.15*, *WGII Global to Regional Atlas Annex A1.27; SR1.5 SPM B.5.3*, *SR 1.5 SPM B.5.7; SRCCL A.5.6*} (*Figure 3.2; Figure 3.3*)

[147] The southern part of Mexico is included in the climatic subregion South Central America (SCA) for WGI. Mexico is assessed as part of North America for WGII. The climate change literature for the SCA region occasionally includes Mexico, and in those cases WGII assessment makes reference to Latin America. Mexico is considered part of Latin America and the Caribbean for WGIII. {*WGII 12.1.1*, *WGIII AII.1.1*}

The transition towards net zero CO_2 will have different pace across different sectors

CO_2 emissions from the electricity/fossil fuel industries sector and land-use change generally reach net zero earlier than other sectors



Section 4

Figure 4.1: Sectoral emissions in pathways that limit warming to 1.5°C. Panel (a) shows sectoral CO_2 and non-CO_2 emissions in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. The horizontal lines illustrate halving 2015 emissions (base year of the pathways) (dashed) and reaching net zero emissions (solid line). The range shows the 5–95th percentile of the emissions across the pathways. The timing strongly differs by sector, with the CO_2 emissions from the electricity/fossil fuel industries sector and land-use change generally reaching net zero earlier. Non-CO_2 emissions from agriculture are also substantially reduced compared to pathways without climate policy but do not typically reach zero. **Panel (b)** Although all pathways include strongly reduced emissions, there are different pathways as indicated by the illustrative mitigation pathways used in IPCC WGIII. The pathways emphasise routes consistent with limiting warming to 1.5°C with a high reliance on net negative emissions (IMP-Neg), high resource efficiency (IMP-LD), a focus on sustainable development (IMP-SP) or renewables (IMP-Ren) and consistent with 2°C based on a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS). Positive (solid filled bars) and negative emissions (hatched bars) for different illustrative mitigation pathways are compared to GHG emissions from the year 2019. The category "energy supply (including electricity)" includes bioenergy with carbon capture and storage and direct air carbon capture and storage. {*WGIII Box TS.5*, *WGIII 3.3*, *WGIII 3.4*, *WGIII 6.6*, *WGIII 10.3*, *WGIII 11.3*} (*Cross-Section Box.2*)

4.2 Benefits of Strengthening Near-Term Action

Accelerated implementation of adaptation will improve well-being by reducing losses and damages, especially for vulnerable populations. Deep, rapid, and sustained mitigation actions would reduce future adaptation costs and losses and damages, enhance sustainable development co-benefits, avoid locking-in emission sources, and reduce stranded assets and irreversible climate changes. These near-term actions involve higher up-front investments and disruptive changes, which can be moderated by a range of enabling conditions and removal or reduction of barriers to feasibility. (*high confidence*)

Accelerated implementation of adaptation responses will bring benefits to human well-being (*high confidence*) (Section 4.3). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in this decade, is important to close adaptation gaps, recognising that constraints remain for some regions. The benefits to vulnerable populations would be high (see Section 4.4). *(high confidence)* {*WGI SPM B.1*, *WGI SPM B.1.3*, *WGI SPM B.2.2*, *WGI SPM B.3; WGII SPM C.1.1*, *WGII SPM C.1.2*, *WGII SPM C.2*, *WGII SPM C.3.1*, *WGII Figure SPM.4b; SROCC SPM C.3.4*, *SROCC Figure 3.4*, *SROCC Figure SPM.5*}

Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). Delayed mitigation action will further increase global warming which will decrease the effectiveness of many adaptation options, including Ecosystem-based Adaptation and many water-related options, as well as increasing mitigation feasibility risks, such as for options based on ecosystems (*high confidence*). Comprehensive, effective, and innovative responses integrating adaptation and mitigation can harness synergies and reduce trade-offs between adaptation and mitigation, as well as in meeting requirements for financing (*very high confidence*) (see Section 4.5, 4.6, 4.8 and 4.9). {*WGII SPM B.3*, *WGII SPM B.4*, *WGII SPM B.6.2*, *WGII SPM C.2*, *WGII SPM C.3*, *WGII SPM D.1*, *WGII SPM D.4.3*, *WGII SPM D.5*, *WG II TS D.1.4*, *WG II TS.D.5*, *WGII TS D.7.5; WGIII SPM B.6.3*, *WGIII SPM B.6.4*, *WGIII SPM C.9*, *WGIII SPM D.2*, *WGIII SPM E.13; SR1.5 SPM C.2.7*, *SR1.5 D.1.3*, *SR1.5 D.5.2*}

Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*). The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*). {*WGI SPM D.1.7*, *WGI SPM D.2.2*, *WGI 6.7*, *WGI TS Box TS.7*, *WGI 6 Box 6.2*, *WGI Figure 6.3*, *WGI Figure 6.16*, *WGI Figure 6.17; WGII TS.D.8.3*, *WGII Cross-Chapter Box HEALTH*, *WGII 5 ES*, *WGII 7 ES; WGII 7.3.1.2; WGIII Figure SPM.8*, *WGIII SPM C.2.3*, *WGIII SPM C.4.2*, *WGIII TS.4.2*}

Challenges from delayed adaptation and mitigation actions include the risk of cost escalation, lock-in of infrastructure, stranded assets, and reduced feasibility and effectiveness of adaptation and mitigation options (*high confidence*). The continued installation of unabated fossil fuel[148] infrastructure will 'lock-in' GHG emissions (*high confidence*). Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*), with globally discounted value projected to be around USD 1 to 4 trillion from 2015 to 2050 (*medium confidence*). Early actions would limit the size of these stranded assets, whereas delayed actions with continued investments in unabated high-emitting infrastructure and limited development and deployment of low-emitting alternatives prior to 2030 would raise future stranded assets to the higher end of the range – thereby acting as barriers and increasing political economy feasibility risks that may jeopardise efforts to limit global warming. (*high confidence*). {*WGIII SPM B.6.3*, *WGIII SPM C.4*, *WGIII Box TS.8*}

[148] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50 to 80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

Scaling-up near-term climate actions (Section 4.1) will mobilise a mix of low-cost and high-cost options. High-cost options, as in energy and infrastructure, are needed to avoid future lock-ins, foster innovation and initiate transformational changes (Figure 4.4). Climate resilient development pathways in support of sustainable development for all are shaped by equity, and social and climate justice (*very high confidence*). Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources. (*high confidence*) {*WGII SPM C.5, WGII SPM D1; WGIII TS.5.2, WGIII 8.3.1, WGIII 8.3.4, WGIII 8.4.1, WGIII 8.6*}

Scaling-up climate action may generate disruptive changes in economic structure with distributional consequences and need to reconcile divergent interests, values and worldviews, within and between countries. Deeper fiscal, financial, institutional and regulatory reforms can offset such adverse effects and unlock mitigation potentials. Societal choices and actions implemented in this decade will determine the extent to which medium and long-term development pathways will deliver higher or lower climate resilient development outcomes. (*high confidence*) {*WGII SPM D.2, WGII SPM D.5, WGII Box TS.8; WGIII SPM D.3, WGIII SPM E.2, WGIII SPM E.3, WGIII SPM E.4, WGIII TS.2, WGIII TS.4.1, WGIII TS.6.4, WGIII 15.2, WGIII 15.6*}

Enabling conditions would need to be strengthened in the near-term and barriers reduced or removed to realise opportunities for deep and rapid adaptation and mitigation actions and climate resilient development (*high confidence*) (Figure 4.2). These enabling conditions are differentiated by national, regional and local circumstances and geographies, according to capabilities, and include: equity and inclusion in climate action (see Section 4.4), rapid and far-reaching transitions in sectors and system (see Section 4.5), measures to achieve synergies and reduce trade-offs with sustainable development goals (see Section 4.6), governance and policy improvements (see Section 4.7), access to finance, improved international cooperation and technology improvements (see Section 4.8), and integration of near-term actions across sectors, systems and regions (see Section 4.9). {*WGII SPM D.2; WGIII SPM E.1, WGIII SPM E.2*}

Barriers to feasibility would need to be reduced or removed to deploy mitigation and adaptation options at scale. Many limits to feasibility and effectiveness of responses can be overcome by addressing a range of barriers, including economic, technological, institutional, social, environmental and geophysical barriers. The feasibility and effectiveness of options increase with integrated, multi-sectoral solutions that differentiate responses based on climate risk, cut across systems and address social inequities. Strengthened near-term actions in modelled cost-effective pathways that limit global warming to 2°C or lower, reduce the overall risk to the feasibility of the system transitions, compared to modelled pathways with delayed or uncoordinated action. (*high confidence*) {*WGII SPM C.2, WGII SPM C.3, WGII SPM C.5; WGIII SPM E.1, WGIII SPM E.1.3*}

Integrating ambitious climate actions with macroeconomic policies under global uncertainty would provide benefits (*high confidence*). This encompasses three main directions: (a) economy-wide mainstreaming packages supporting options to improved sustainable low-emission economic recovery, development and job creation programs (Sections 4.4, 4.5, 4.6, 4.8, 4.9) (b) safety nets and social protection in the transition (Section 4.4, 4.7); and (c) broadened access to finance, technology and capacity-building and coordinated support to low-emission infrastructure ('leap-frog' potential), especially in developing regions, and under debt stress (*high confidence*). (Section 4.8) {*WGII SPM C.2, WGII SPM C.4.1, WGII SPM D.1.3, WGII SPM D.2, WGII SPM D.3.2, WGII SPM E.2.2, WGII SPM E.4, WGII SPM TS.2, WGII SPM TS.5.2, WGII TS.6.4, WGII TS.15, WGII TS Box TS.3; WGIII SPM B.4.2, WGIII SPM C.5.4, WGIII SPM C.6.2, WGIII SPM C.12.2, WGIII SPM D.3.4, WGIII SPM E.4.2, WGIII SPM E.4.5, WGIII SPM E.5.2, WGIII SPM E.5.3, WGIII TS.1, WGIII Box TS.15, WGIII 15.2, WGIII Cross-Chapter Box 1 on COVID in Chapter 1*}

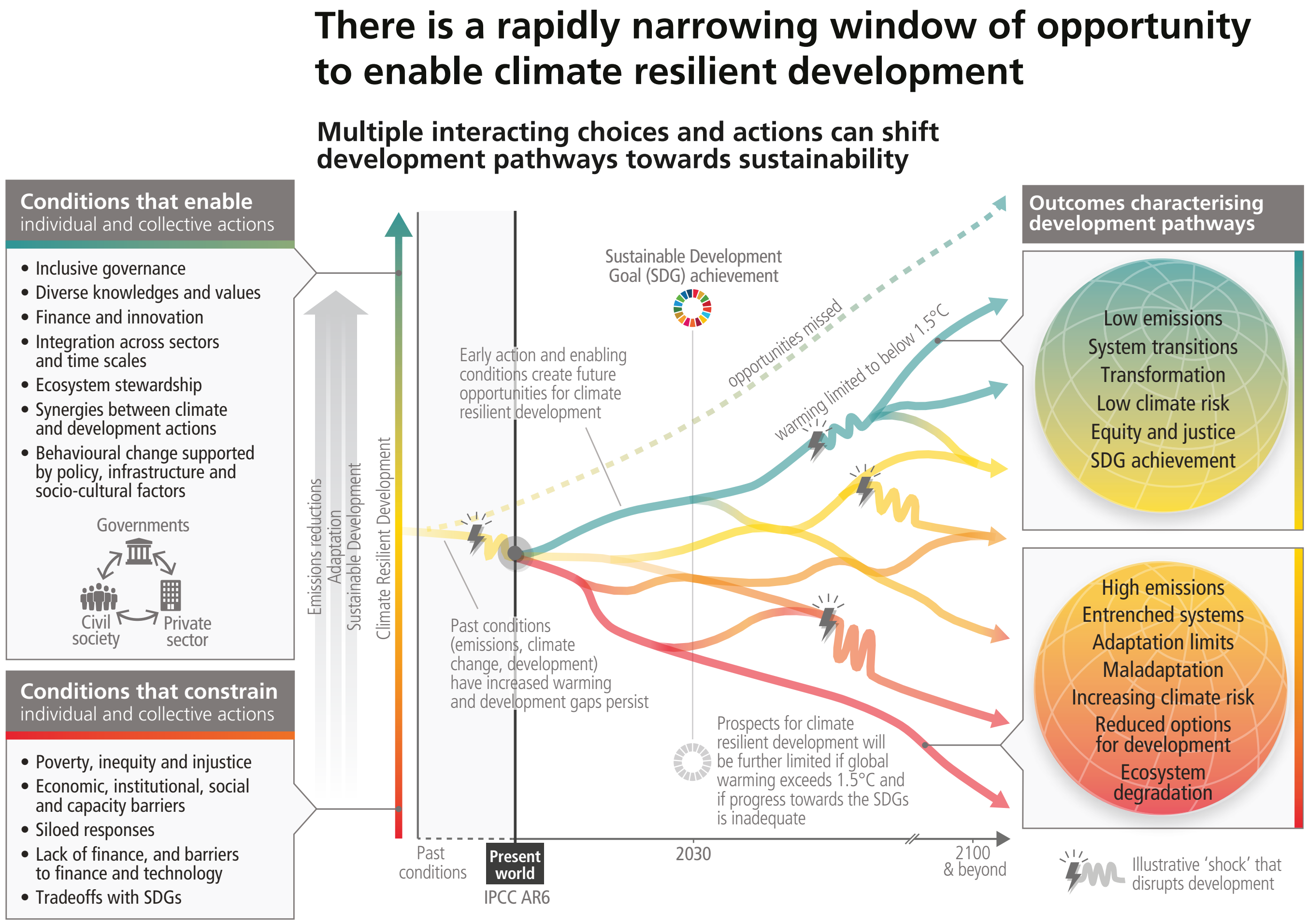


Figure 4.2: The illustrative development pathways (red to green) and associated outcomes (right panel) show that there is a rapidly narrowing window of opportunity to secure a liveable and sustainable future for all. Climate resilient development is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. Diverging pathways illustrate that interacting choices and actions made by diverse government, private sector and civil society actors can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation. Diverse knowledges and values include cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge. Climatic and non-climatic events, such as droughts, floods or pandemics, pose more severe shocks to pathways with lower climate resilient development (red to yellow) than to pathways with higher climate resilient development (green). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, and with every increment of warming, losses and damages will increase. The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Pathways and opportunities for action are shaped by previous actions (or inactions and opportunities missed, dashed pathway), and enabling and constraining conditions (left panel), and take place in the context of climate risks, adaptation limits and development gaps. The longer emissions reductions are delayed, the fewer effective adaptation options. {*WGI SPM B.1; WGII SPM B.1 to B.5, WGII SPM C.2 to 5, WGII SPM D.1 to 5, WGII Figure SPM.3, WGII Figure SPM.4, WGII Figure SPM.5, WGII TS.D.5, WGII 3.1, WGII 3.2, WGII 3.4, WGII 4.2, WGII Figure 4.4, WGII 4.5, WGII 4.6, WGII 4.9; WGIII SPM A, WGIII SPM B1, WGIII SPM B.3, WGIII SPM B.6, WGIII SPM C.4, WGIII SPM D1 to 3, WGIII SPM E.1, WGIII SPM E.2, WGIII SPM E.4, WGIII SPM E.5, WGIII Figure TS.1, WGIII Figure TS.7, WGIII Box TS.3, WGIII Box TS.8, Cross-Working Group Box 1 in Chapter 3, WGIII Cross-Chapter Box 5 in Chapter 4; SR1.5 SPM D.1 to 6; SRCCL SPM D.3*}

4.3 Near-Term Risks

Many changes in the climate system, including extreme events, will become larger in the near term with increasing global warming (*high confidence*). Multiple climatic and non-climatic risks will interact, resulting in increased compounding and cascading impacts becoming more difficult to manage (*high confidence*). Losses and damages will increase with increasing global warming (*very high confidence*), while strongly concentrated among the poorest vulnerable populations (*high confidence*). Continuing with current unsustainable development patterns would increase exposure and vulnerability of ecosystems and people to climate hazards (*high confidence*).

Global warming will continue to increase in the near term (2021–2040) mainly due to increased cumulative CO_2 emissions in nearly all considered scenarios and pathways. In the near term, every region in the world is projected to face further increases in climate hazards (*medium* to *high confidence*, depending on region and hazard), increasing multiple risks to ecosystems and humans (*very high confidence*). In the near term, natural variability[149] will modulate human-caused changes, either attenuating or amplifying projected changes, especially at regional scales, with little effect on centennial global warming. Those modulations are important to consider in adaptation planning. Global surface temperature in any single year can vary above or below the long-term human-induced trend, due to natural variability. By 2030, global surface temperature in any individual year could exceed 1.5°C relative to 1850–1900 with a probability between 40% and 60%, across the five scenarios assessed in WGI (*medium confidence*). The occurrence of individual years with global surface temperature change above a certain level does not imply that this global warming level has been reached. If a large explosive volcanic eruption were to occur in the near term[150] , it would temporarily and partially mask human-caused climate change by reducing global surface temperature and precipitation, especially over land, for one to three years (*medium confidence*). {*WGI SPM B.1.3, WGI SPM B.1.4, WGI SPM C.1, WGI SPM C.2, WGI Cross-Section Box TS.1, WGI Cross-Chapter Box 4.1; WGII SPM B.3, WGII SPM B.3.1; WGIII Box SPM.1 Figure 1*}

The level of risk for humans and ecosystems will depend on near-term trends in vulnerability, exposure, level of socio-economic development and adaptation (*high confidence*). In the near term, many climate-associated risks to natural and human systems depend more strongly on changes in these systems' vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Future exposure to climatic hazards is increasing globally due to socio-economic development trends including growing inequality, and when urbanisation or migration increase exposure (*high confidence*). Urbanisation increases hot extremes (*very high confidence*) and precipitation runoff intensity (*high confidence*). Increasing urbanisation in low-lying and coastal zones will be a major driver of increasing exposure to extreme riverflow events and sea level rise hazards, increasing risks (*high confidence*) (Figure 4.3). Vulnerability will also rise rapidly in low-lying Small Island Developing States and atolls in the context of sea level rise (*high confidence*) (see Figure 3.4 and Figure 4.3). Human vulnerability will concentrate in informal settlements and rapidly growing smaller settlements; and vulnerability in rural areas will be heightened by reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Vulnerability to climate change for ecosystems will be strongly influenced by past, present, and future patterns of human development, including from unsustainable consumption and production, increasing demographic pressures, and persistent unsustainable use and management of land, ocean, and water (*high confidence*). Several near-term risks can be moderated with adaptation (*high confidence*). {*WGI SPM C.2.6; WGII SPM B.2, WGII SPM B.2.3, WGII SPM B.2.5, WGII SPM B.3, WGII SPM B.3.2, WGII TS.C.5.2*} (*Section 4.5 and 3.2*)

Principal hazards and associated risks expected in the near term (at 1.5°C global warming) are:

- Increased intensity and frequency of hot extremes and dangerous heat-humidity conditions, with increased human mortality, morbidity, and labour productivity loss (*high confidence*). {*WGI SPM B.2.2, WGI TS Figure TS.6; WGII SPM B.1.4, WGII SPM B.4.4, WGII Figure SPM.2*}

- Increasing frequency of marine heatwaves will increase risks of biodiversity loss in the oceans, including from mass mortality events (*high confidence*). {*WGI SPM B.2.3; WGII SPM B.1.2, WGII Figure SPM.2; SROCC SPM B.5.1*}

- Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*) and kelp and seagrass ecosystems (*high* to *very high confidence*) and are high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). {*WGII SPM B.3.1*}

- More intense and frequent extreme rainfall and associated flooding in many regions including coastal and other low-lying cities (*medium* to *high confidence*), and increased proportion of and peak wind speeds of intense tropical cyclones (*high confidence*). {*WGI SPM B.2.4, WGI SPM C.2.2, WGI SPM C.2.6, WGI 11.7*}

- High risks from dryland water scarcity, wildfire damage, and permafrost degradation (*medium confidence*). {*SRCCL SPM A.5.3.*}

- Continued sea level rise and increased frequency and magnitude of extreme sea level events encroaching on coastal human settlements and damaging coastal infrastructure *(high confidence)*, committing low-lying coastal ecosystems to submergence and loss (*medium confidence*), expanding land salinization (*very high confidence*), with cascading to risks to livelihoods, health, well-being, cultural values, food and water security (*high confidence*). {*WGI SPM C.2.5, WGI SPM C.2.6; WGII SPM B.3.1, WGII SPM B.5.2; SRCCL SPM A.5.6; SROCC SPM B.3.4, SROCC SPM 3.6, SROCC SPM B.9.1*} (*Figure 3.4, 4.3*)

- Climate change will significantly increase ill health and premature deaths from the near to long term (*high confidence*). Further warming will increase climate-sensitive food-borne, water-borne, and vector-borne disease risks (*high confidence*), and mental health challenges including anxiety and stress (*very high confidence*). {*WGII SPM B.4.4*}

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[149] See Annex I: Glossary. The main internal variability phenomena include El Niño–Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability through their regional influence. The internal variability of global surface temperature in any single year is estimated to be about ±0.25°C (5 to 95% range, *high confidence).* {*WGI SPM footnote 29, WGI SPM footnote 37*}

[150] Based on 2500-year reconstructions, eruptions with a radiative forcing more negative than –1 Wm^{-2}, related to the radiative effect of volcanic stratospheric aerosols in the literature assessed in this report, occur on average twice per century. {*WGI SPM footnote 38*}

- Cryosphere-related changes in floods, landslides, and water availability have the potential to lead to severe consequences for people, infrastructure and the economy in most mountain regions (*high confidence*). {*WGII TS C.4.2*}

- The projected increase in frequency and intensity of heavy precipitation (*high confidence*) will increase rain-generated local flooding (*medium confidence*). {*WGI Figure SPM.6, WGI SPM B.2.2; WGII TS C.4.5*}

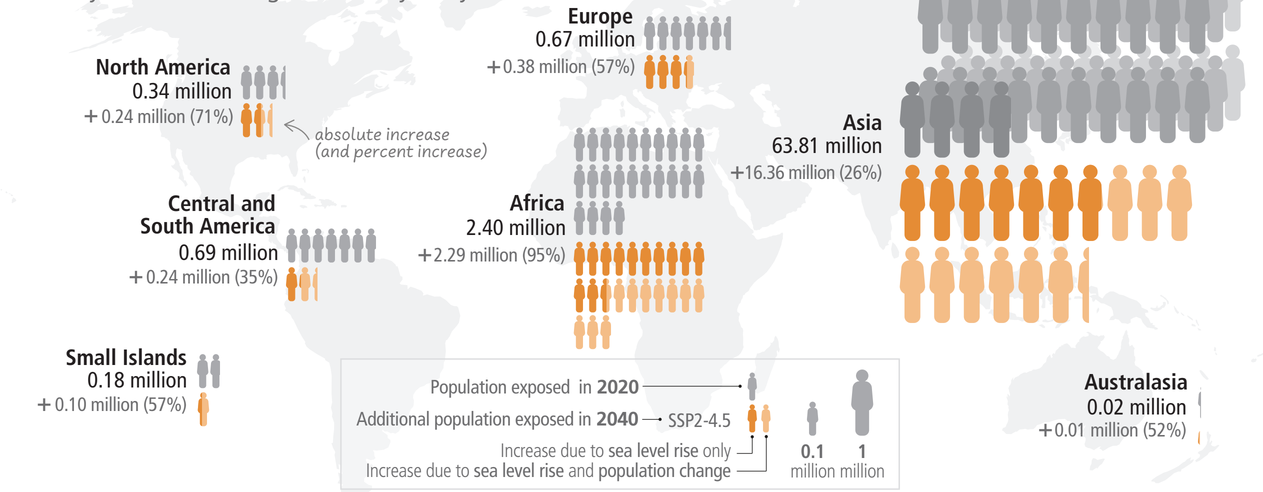
Multiple climate change risks will increasingly compound and cascade in the near term (*high confidence*). Many regions are projected to experience an increase in the probability of compound events with higher global warming (*high confidence*) including concurrent heatwaves and drought. Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*) (Figure 4.3). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Concurrent and cascading risks from climate change to food systems, human settlements, infrastructure and health will make these risks more severe and more difficult to manage, including when interacting with non-climatic risk drivers such as competition for land between urban expansion and food production, and pandemics (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). Increasing transboundary risks are projected across the food, energy and water sectors as impacts from weather and climate extremes propagate through supply-chains, markets, and natural resource flows (*high confidence*) and may interact with impacts from other crises such as pandemics. Risks also arise from some responses intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emissions reduction and carbon dioxide removal measures, such as afforestation of naturally unforested land or poorly implemented bioenergy compounding climate-related risks to biodiversity, food and water security, and livelihoods (*high confidence*) (see Section 3.4.1 and 4.5). {*WGI SPM.2.7; WGII SPM B.2.1, WGII SPM B.5, WGII SPM B.5.1, WGII SPM B.5.2, WGII SPM B.5.3, WGII SPM B.5.4, WGII Cross-Chapter Box COVID in Chapter 7; WGIII SPM C.11.2; SRCCL SPM A.5, SRCCL SPM A.6.5*} (*Figure 4.3*)

With every increment of global warming losses and damages will increase (*very high confidence*), become increasingly difficult to avoid and be strongly concentrated among the poorest vulnerable populations (*high confidence*). Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages will be unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. (*high confidence*). {*WGII SPM B.4, WGII SPM C.3, WGII SPM C.3.5*}

Every region faces more severe and/or frequent compound and cascading climate risks

a) Increase in the population exposed to sea level rise from 2020 to 2040

Exposure to a coastal flooding event that currently occurs on average once every 100 years



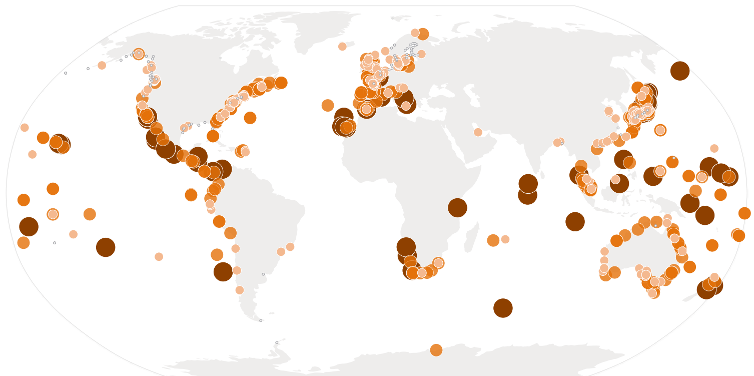
b) Increased frequency of extreme sea level events by 2040

Frequency of events that currently occur on average once every 100 years

The absence of a circle indicates an inability to perform an assessment due to a lack of data.

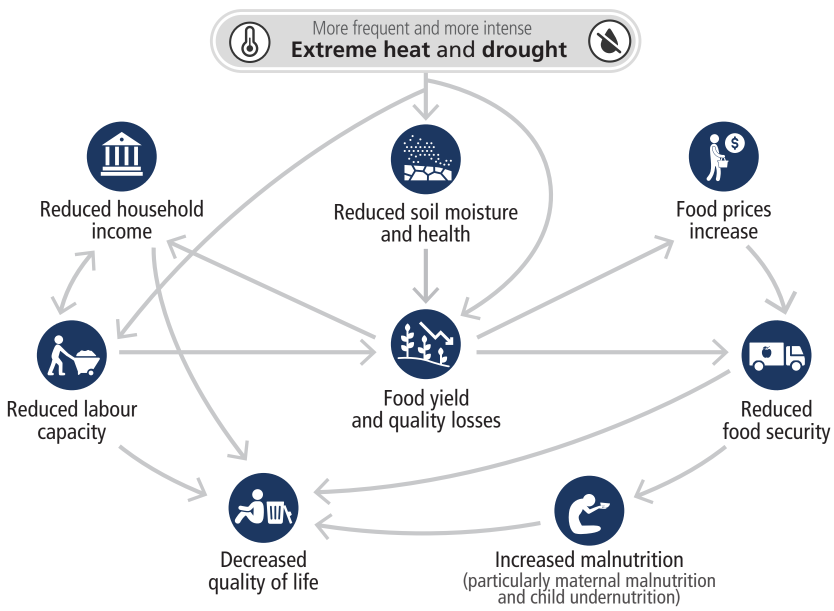
Projected change to 1-in-100 year events under the intermediate SSP2-4.5 scenario

- Annual event
- Decadal event
- Twice-a-century event
- No change



c) Example of complex risk, where impacts from climate extreme events have cascading effects on food, nutrition, livelihoods and well-being of smallholder farmers

Multiple climate change risks will increasingly compound and cascade in the near term



Key

- Bi-directional compounding
- Uni-directional compounding or domino
- Contagion effect on multiple risks

Figure 4.3: Every region faces more severe or frequent compound and/or cascading climate risks in the near term. Changes in risk result from changes in the degree of the hazard, the population exposed, and the degree of vulnerability of people, assets, or ecosystems. **Panel (a)** Coastal flooding events affect many of the highly populated regions of the world where large percentages of the population are exposed. The panel shows near-term projected increase of population exposed to 100-year flooding events depicted as the increase from the year 2020 to 2040 (due to sea level rise and population change), based on the intermediate GHG emissions scenario (SSP2-4.5) and current adaptation measures. Out-migration from coastal areas due to future sea level rise is not considered in the scenario. **Panel (b)** projected median probability in the year 2040 for extreme water levels resulting from a combination of mean sea level rise, tides and storm surges, which have a historical 1% average annual probability. A peak-over-threshold (99.7%) method was applied to the historical tide gauge observations available in the Global Extreme Sea Level Analysis version 2 database, which is the same information as WGI Figure 9.32, except here the panel uses relative sea level projections under SSP2-4.5 for the year 2040 instead of 2050 The absence of a circle indicates an inability to perform an assessment due to a lack of data, but does not indicate absence of increasing frequencies. **Panel (c)** Climate hazards can initiate risk cascades that affect multiple sectors and propagate across regions following complex natural and societal connections. This example of a compound heat wave and a drought event striking an agricultural region shows how multiple risks are interconnected and lead to cascading biophysical, economic, and societal impacts even in distant regions, with vulnerable groups such as smallholder farmers, children and pregnant women particularly impacted. {*WGI Figure 9.32; WGII SPM B4.3, WGII SPM B1.3, WGII SPM B.5.1, WGII TS Figure TS.9, WGII TS Figure TS.10 (c), WGII Fig 5.2, WGII TS.B.2.3, WGII TS.B.2.3, WGII TS.B.3.3, WGII 9.11.1.2*}

4.4 Equity and Inclusion in Climate Change Action

Actions that prioritise equity, climate justice, social justice and inclusion lead to more sustainable outcomes, co-benefits, reduce trade-offs, support transformative change and advance climate resilient development. Adaptation responses are immediately needed to reduce rising climate risks, especially for the most vulnerable. Equity, inclusion and just transitions are key to progress on adaptation and deeper societal ambitions for accelerated mitigation. (*high confidence*)

Adaptation and mitigation actions, across scales, sectors and regions, that prioritise equity, climate justice, rights-based approaches, social justice and inclusivity, lead to more sustainable outcomes, reduce trade-offs, support transformative change and advance climate resilient development (*high confidence*). Redistributive policies across sectors and regions that shield the poor and vulnerable, social safety nets, equity, inclusion and just transitions, at all scales can enable deeper societal ambitions and resolve trade-offs with sustainable development goals.(SDGs), particularly education, hunger, poverty, gender and energy access (*high confidence*). Mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emission reductions (*medium confidence*). Equity, inclusion and just transitions at all scales enable deeper societal ambitions for accelerated mitigation, and climate action more broadly (*high confidence*). The complexity in risk of rising food prices, reduced household incomes, and health and climate-related malnutrition (particularly maternal malnutrition and child undernutrition) and mortality increases with little or low levels of adaptation (*high confidence*). {*WGII SPM B.5.1, WGII SPM C.2.9, WGII SPM D.2.1, WGII TS Box TS.4; WGIII SPM D.3, WGIII SPM D.3.3, WGIII SPM WGIII SPM E.3, SR1.5 SPM D.4.5*} (*Figure 4.3c*)

Regions and people with considerable development constraints have high vulnerability to climatic hazards. Adaptation outcomes for the most vulnerable within and across countries and regions are enhanced through approaches focusing on equity, inclusivity, and rights-based approaches, including 3.3 to 3.6 billion people living in contexts that are highly vulnerable to climate change (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*) and adaptation progress is unevenly distributed with observed adaptation gaps (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). Vulnerability is exacerbated by inequity and marginalisation linked to gender, ethnicity, low income or combinations thereof, especially for many Indigenous Peoples and local communities (*high confidence*). {*WGII SPM B.2, WGII SPM B.2.4, WGII SPM B.3.2, WGII SPM B.3.3, WGII SPM C.1, WGII SPM C.1.2, WGII SPM C.2.9*}

Meaningful participation and inclusive planning, informed by cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge can help address adaptation gaps and avoid maladaptation (*high confidence*). Such actions with flexible pathways may encourage low-regret and timely actions (*very high confidence*). Integrating climate adaptation into social protection programmes, including cash transfers and public works programmes, would increase resilience to climate change, especially when supported by basic services and infrastructure *(high confidence)*. {*WGII SPM C.2.3, WGII SPM C.4.3, WGII SPM C.4.4, WGII SPM C.2.9, WGII WPM D.3*}

Equity, inclusion, just transitions, broad and meaningful participation of all relevant actors in decision making at all scales enable deeper societal ambitions for accelerated mitigation, and climate action more broadly, and build social trust, support transformative changes and an equitable sharing of benefits and burdens (*high confidence*). Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries, including shifting of income and employment during the transition from high to low emissions activities (*high confidence*). While some jobs may be lost, low-emissions development can also open up opportunities to enhance skills and create jobs (*high confidence*). Broadening equitable access to finance, technologies and governance that facilitate mitigation, and consideration of climate justice can help equitable sharing of benefits and burdens, especially for vulnerable countries and communities. {*WGIII SPM D.3, WGIII SPM D.3.2, WGIII SPM D.3.3, WGIII SPM D.3.4, WGIII TS Box TS.4*}

Development priorities among countries also reflect different starting points and contexts, and enabling conditions for shifting development pathways towards increased sustainability will therefore differ, giving rise to different needs (*high confidence*). Implementing just transition principles through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales depending on national circumstances, while in several countries just transition commissions, task forces and national policies have been established (*medium confidence*). {*WGIII SPM D.3.1, WGIII SPM D.3.3*}

Many economic and regulatory instruments have been effective in reducing emissions and practical experience has informed instrument design to improve them while addressing distributional goals and social acceptance (*high confidence*). The design of behavioural interventions, including the way that choices are presented to consumers work synergistically with price signals, making the combination more effective (*medium confidence*). Individuals with high socio-economic status contribute disproportionately to emissions, and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals (*high confidence*). There are options on design of instruments such as taxes, subsidies, prices, and consumption-based approaches, complemented by regulatory instruments to reduce high-emissions consumption while improving equity and societal well-being (*high confidence*). Behaviour and lifestyle changes to help end-users adopt low-GHG-intensive options can be supported by policies, infrastructure and technology with multiple co-benefits for societal well-being (*high confidence*). Broadening equitable access to domestic and international finance, technologies and capacity can also act as a catalyst for accelerating mitigation and shifting development pathways in low-income contexts (*high confidence*). Eradicating extreme poverty, energy poverty, and providing decent living standards to all in these regions in the context of achieving sustainable development objectives, in the near term, can be achieved without significant global emissions growth (*high confidence*). Technology development, transfer, capacity building and financing can support developing countries/ regions leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits (*high confidence*). Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). {*WGII D.2.1, WGIII SPM B.3.3, WGIII SPM.C.8.5, WGIII SPM C.10.2, WGIII SPM C.10.4, WGIII SPM D.3.4, WGIII SPM E.4.2, WGIII TS.5.1, WGIII 5.4, WGIII 5.8, WGIII 15.2*}

4.5 Near-Term Mitigation and Adaptation Actions

Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options. Feasible, effective and low-cost options for mitigation and adaptation are already available, with differences across systems and regions. (*high confidence*)

Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep emissions reductions and secure a liveable and sustainable future for all (*high confidence*). System transitions[151] consistent with pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are more rapid and pronounced in the near-term than in those that limit warming to 2°C (>67%) (*high confidence*). Such a systemic change is unprecedented in terms of scale, but not necessarily in terms of speed (*medium confidence*). The system transitions make possible the transformative adaptation required for high levels of human health and well-being, economic and social resilience, ecosystem health, and planetary health. {*WGII SPM A, WGII Figure SPM.1; WGIII SPM C.3; SR1.5 SPM C.2, SR1.5 SPM C.2.1, SR1.5 SPM C.2, SR1.5 SPM C.5*}

Feasible, effective and low-cost options for mitigation and adaptation are already available (*high confidence*) (Figure 4.4). Mitigation options costing USD 100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half the 2019 level by 2030 (options costing less than USD 20 tCO_2-eq^{-1} are estimated to make up more than half of this potential) (*high confidence*) (Figure 4.4). The availability, feasibility[152] and potential of mitigation or effectiveness of adaptation options in the near term differ across systems and regions (*very high confidence*). {*WGII SPM C.2; WGIII SPM C.12, WGIII SPM E.1.1; SR1.5 SPM B.6*}

Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors by 40 to 70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. (*high confidence*) (Figure 4.4). {*WGIII SPM C.10*}

[151] System transitions involve a wide portfolio of mitigation and adaptation options that enable deep emissions reductions and transformative adaptation in all sectors. This report has a particular focus on the following system transitions: energy; industry; cities, settlements and infrastructure; land, ocean, food and water; health and nutrition; and society, livelihood and economies. {*WGII SPM A, WGII Figure SPM.1, WGII Figure SPM.4; SR1.5 SPM C.2*}

[152] See Annex I: Glossary.

There are multiple opportunities for scaling up climate action

a) Feasibility of climate responses and adaptation, and potential of mitigation options in the near term

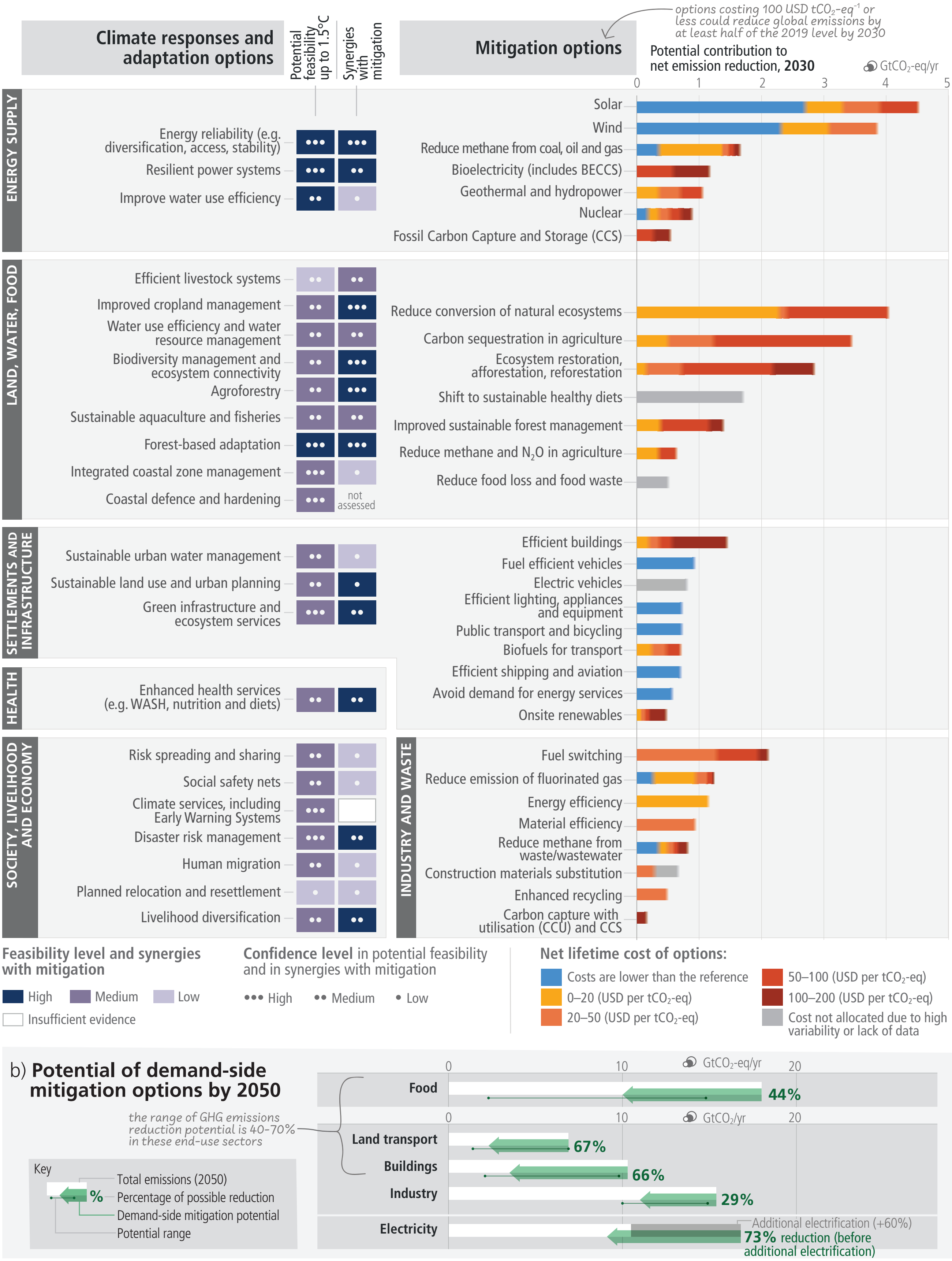


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Figure 4.4: Multiple Opportunities for scaling up climate action. Panel (a) presents selected mitigation and adaptation options across different systems. The left hand side of panel (a) shows climate responses and adaptation options assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. The term response is used here in addition to adaptation because some responses, such as migration, relocation and resettlement may or may not be considered to be adaptation. Migration, when voluntary, safe and orderly, allows reduction of risks to climatic and non-climatic stressors. Forest based adaptation includes sustainable forest management, forest conservation and restoration, reforestation and afforestation. WASH refers to water, sanitation and hygiene. Six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) were used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. The right-hand side of panel (a) provides an overview of selected mitigation options and their estimated costs and potentials in 2030. Relative potentials and costs will vary by place, context and time and in the longer term compared to 2030. Costs are net lifetime discounted monetary costs of avoided greenhouse gas emissions calculated relative to a reference technology. The potential (horizontal axis) is the quantity of net GHG emission reduction that can be achieved by a given mitigation option relative to a specified emission baseline. Net GHG emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (around 2019) reference scenarios from the AR6 scenarios database (25–75 percentile values). The mitigation potentials are assessed independently for each option and are not necessarily additive. Health system mitigation options are included mostly in settlement and infrastructure (e.g., efficient healthcare buildings) and cannot be identified separately. Fuel switching in industry refers to switching to electricity, hydrogen, bioenergy and natural gas. The length of the solid bars represents the mitigation potential of an option. Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. The uncertainty in the total potential is typically 25–50%. When interpreting this figure, the following should be taken into account: (1) The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors; (2) Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure; and (3) Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included.
Panel (b) displays the indicative potential of demand-side mitigation options for 2050. Potentials are estimated based on approximately 500 bottom-up studies representing all global regions. The baseline (white bar) is provided by the sectoral mean GHG emissions in 2050 of the two scenarios (IEA-STEPS and IP_ModAct) consistent with policies announced by national governments until 2020. The green arrow represents the demand-side emissions reductions potentials. The range in potential is shown by a line connecting dots displaying the highest and the lowest potentials reported in the literature. Food shows demand-side potential of socio-cultural factors and infrastructure use, and changes in land-use patterns enabled by change in food demand. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors (buildings, land transport, food) by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. The last row shows how demand-side mitigation options in other sectors can influence overall electricity demand. The dark grey bar shows the projected increase in electricity demand above the 2050 baseline due to increasing electrification in the other sectors. Based on a bottom-up assessment, this projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of infrastructure use and socio-cultural factors that influence electricity usage in industry, land transport, and buildings (green arrow). {*WGII Figure SPM.4, WGII Cross-Chapter Box FEASIB in Chapter 18; WGIII SPM C.10, WGIII 12.2.1, WGIII 12.2.2, WGIII Figure SPM.6, WGIII Figure SPM.7*}

4.5.1. Energy Systems

Rapid and deep reductions in GHG emissions require major energy system transitions (*high confidence*). Adaptation options can help reduce climate-related risks to the energy system (*very high confidence*). Net zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels[153], and use of Carbon Capture and Storage in the remaining fossil fuel systems; electricity systems that emit no net CO_2; widespread electrification; alternative energy carriers in applications less amenable to electrification; energy conservation and efficiency; and greater integration across the energy system *(high confidence).* Large contributions to emissions reductions can come from options costing less than USD 20 tCO_2-eq^{-1}, including solar and wind energy, energy efficiency improvements, and CH_4 (methane) emissions reductions (from coal mining, oil and gas, and waste) (*medium confidence*).[154] Many of these response options are technically viable and are supported by the public (*high confidence*). Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems (*high confidence*). {*WGII SPM C.2.10; WGIII SPM C.4.1, WGIII SPM C.4.2, WGIII SPM C.12.1, WGIII SPM E.1.1, WGIII TS.5.1*}

Climate change and related extreme events will affect future energy systems, including hydropower production, bioenergy yields, thermal power plant efficiencies, and demands for heating and cooling (*high confidence*). The most feasible energy system adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Energy generation diversification (e.g., wind, solar, small-scale hydroelectric) and demand side management (e.g., storage and energy efficiency improvements) can increase energy reliability and reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {*WGII SPM B.5.3, WGII SPM C.2.10; WGIII TS.5.1*}

4.5.2. Industry

There are several options to reduce industrial emissions that differ by type of industry; many industries are disrupted by climate change, especially from extreme events (*high confidence*). Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and

153 In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50–80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

154 The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates (*medium confidence*). {*WGIII SPM C.12.1*}

transformational changes in production processes (*high confidence*). Light industry and manufacturing can be largely decarbonized through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps), and switching to low- and zero-GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based and other synthetic fuels) (*high confidence*), while deep reduction of cement process emissions will rely on cementitious material substitution and the availability of Carbon Capture and Storage (CCS) until new chemistries are mastered (*high confidence*). Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, Carbon Capture and Utilisation (CCU), direct air CO_2 capture, as well as CCS (*high confidence*). Action to reduce industry sector emissions may change the location of GHG-intensive industries and the organisation of value chains, with distributional effects on employment and economic structure (*medium confidence*). {*WGII TS.B.9.1*, *WGII 16.5.2; WGIII SPM C.5*, *WGIII SPM C.5.2*, *WGIII SPM C.5.3*, *WGIII TS.5.5*}

Many industrial and service sectors are negatively affected by climate change through supply and operational disruptions, especially from extreme events (*high confidence*), and will require adaptation efforts. Water intensive industries (e.g., mining) can undertake measures to reduce water stress, such as water recycling and reuse, using brackish or saline sources, working to improve water use efficiency. However, residual risks will remain, especially at higher levels of warming (*medium confidence*). {*WGII TS.B.9.1, WGII 16.5.2, WGII 4.6.3*} (*Section 3.2*)

4.5.3. Cities, Settlements and Infrastructure

Urban systems are critical for achieving deep emissions reductions and advancing climate resilient development, particularly when this involves integrated planning that incorporates physical, natural and social infrastructure (*high confidence*). Deep emissions reductions and integrated adaptation actions are advanced by: integrated, inclusive land use planning and decision-making; compact urban form by co-locating jobs and housing; reducing or changing urban energy and material consumption; electrification in combination with low emissions sources; improved water and waste management infrastructure; and enhancing carbon uptake and storage in the urban environment (e.g. bio-based building materials, permeable surfaces and urban green and blue infrastructure). Cities can achieve net zero emissions if emissions are reduced within and outside of their administrative boundaries through supply chains, creating beneficial cascading effects across other sectors. (*high confidence*) {*WGII SPM C.5.6, WGII SPM D.1.3, WGII SPM D.3; WGIII SPM C.6, WGIII SPM C.6.2*, *WGIII TS 5.4*, *SR1.5 SPM C.2.4*}

Considering climate change impacts and risks (e.g., through climate services) in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being. Effective mitigation can be advanced at each of the design, construction, retrofit, use and disposal stages for buildings. Mitigation interventions for buildings include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions; at the use phase, highly efficient appliances/equipment, the optimisation of the use of buildings and their supply with low-emission energy sources; and at the disposal phase, recycling and re-using construction materials. Sufficiency[155] measures can limit the demand for energy and materials over the lifecycle of buildings and appliances. (*high confidence*) {*WGII SPM C.2.5; WGIII SPM C.7.2*}

Transport-related GHG emissions can be reduced by demand-side options and low-GHG emissions technologies. Changes in urban form, reallocation of street space for cycling and walking, digitalisation (e.g., teleworking) and programs that encourage changes in consumer behaviour (e.g. transport, pricing) can reduce demand for transport services and support the shift to more energy efficient transport modes (*high confidence*). Electric vehicles powered by low-emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Costs of electrified vehicles are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). The environmental footprint of battery production and growing concerns about critical minerals can be addressed by material and supply diversification strategies, energy and material efficiency improvements, and circular material flows (*medium confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and compliment conventional electric rail systems (*medium confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low-emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design standards do not account for changing climate conditions (*high confidence*). {*WGII SPM B.2.5; WGIII SPM C.6.2, WGIII SPM C.8, WGIII SPM C.8.1, WGIII SPM C.8.2, WGIII SPM C.10.2*, *WGIII SPM C.10.3*, *WGIII SPM C.10.4*}

Green/natural and blue infrastructure such as urban forestry, green roofs, ponds and lakes, and river restoration can mitigate climate change through carbon uptake and storage, avoided emissions, and reduced energy use while reducing risk from extreme events such as heatwaves, heavy precipitation and droughts, and advancing co-benefits for health, well-being and livelihoods (*medium confidence*). Urban greening can provide local cooling (*very high confidence*). Combining green/natural and grey/physical infrastructure adaptation responses has potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). Globally, more financing is directed at grey/physical infrastructure than green/natural infrastructure and social infrastructure (*medium confidence*), and there is limited evidence of investment in informal settlements (*medium* to *high confidence*). The greatest gains in well-being in urban areas can be achieved by prioritising finance to reduce climate risk for low-income

[155] A set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries. {*WGIII Annex I*}

and marginalised communities including people living in informal settlements (*high confidence*). {*WGII SPM C.2.5, WGII SPM C.2.6, WGII SPM C.2.7, WGII SPM D.3.2, WGII TS.E.1.4, WGII Cross-Chapter Box FEAS; WGIII SPM C.6, WGIII SPM C.6.2, WGIII SPM D.1.3, WGIII SPM D.2.1*}

Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes. (*high confidence*) {*WGII SPM C.2.8*}

4.5.4. Land, Ocean, Food, and Water

There is substantial mitigation and adaptation potential from options in agriculture, forestry and other land use, and in the oceans, that could be upscaled in the near term across most regions (*high confidence*) (Figure 4.5). Conservation, improved management, and restoration of forests and other ecosystems offer the largest share of economic mitigation potential, with reduced deforestation in tropical regions having the highest total mitigation potential. Ecosystem restoration, reforestation, and afforestation can lead to trade-offs due to competing demands on land. Minimizing trade-offs requires integrated approaches to meet multiple objectives including food security. Demand-side measures (shifting to sustainable healthy diets and reducing food loss/waste) and sustainable agricultural intensification can reduce ecosystem conversion and CH_4 and N_2O emissions, and free up land for reforestation and ecosystem restoration. Sustainably sourced agriculture and forest products, including long-lived wood products, can be used instead of more GHG-intensive products in other sectors. Effective adaptation options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture. These AFOLU response options require integration of biophysical, socioeconomic and other enabling factors. The effectiveness of ecosystem-based adaptation and most water-related adaptation options declines with increasing warming (see 3.2). (*high confidence*) {*WGII SPM C.2.1, WGII SPM C.2.2, WGII SPM C.2.5; WGIII SPM C.9.1; SRCCL SPM B.1.1, SRCCL SPM B.5.4, SRCCL SPM D.1; SROCC SPM C*}

Some options, such as conservation of high-carbon ecosystems (e.g., peatlands, wetlands, rangelands, mangroves and forests), have immediate impacts while others, such as restoration of high-carbon ecosystems, reclamation of degraded soils or afforestation, take decades to deliver measurable results (*high confidence*). Many sustainable land management technologies and practices are financially profitable in three to ten years (*medium confidence*). {*SRCCL SPM B.1.2, SRCCL SPM D.2.2*}

Maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30–50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). The services and options provided by terrestrial, freshwater, coastal and ocean ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors (*high confidence*). {*WGII SPM C.2.4, WGII SPM D.4; SROCC SPM C.2*}

Large-scale land conversion for bioenergy, biochar, or afforestation can increase risks to biodiversity, water and food security. In contrast, restoring natural forests and drained peatlands, and improving sustainability of managed forests enhances the resilience of carbon stocks and sinks and reduces ecosystem vulnerability to climate change. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful adaptation across forests and other ecosystems. (*high confidence*) {*WGII SPM B.5.4, WGII SPM C.2.3, WGII SPM C.2.4; WGIII SPM D.2.3; SRCCL B.7.3, SRCCL SPM C.4.3, SRCCL TS.7*}

Natural rivers, wetlands and upstream forests reduce flood risk in most circumstances (*high confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*), but hard defences against flooding or sea level rise can also be maladaptive (*high confidence*). {*WGII SPM C.2.1, WGII SPM C.4.1, WGII SPM C.4.2, WGII SPM C.2.5*}

Protection and restoration of coastal 'blue carbon' ecosystems (e.g., mangroves, tidal marshes and seagrass meadows) could reduce emissions and/or increase carbon uptake and storage (*medium confidence*). Coastal wetlands protect against coastal erosion and flooding (*very high confidence*). Strengthening precautionary approaches, such as rebuilding overexploited or depleted fisheries, and responsiveness of existing fisheries management strategies reduces negative climate change impacts on fisheries, with benefits for regional economies and livelihoods (*medium confidence*). Ecosystem-based management in fisheries and aquaculture supports food security, biodiversity, human health and well-being (*high confidence*). {*WGII SPM C.2.2, WGII SPM C.2; SROCC SPM C2.3, SROCC SPM C.2.4*}

4.5.5. Health and Nutrition

Human health will benefit from integrated mitigation and adaptation options that mainstream health into food, infrastructure, social protection, and water policies (*very high confidence*). Balanced and sustainable healthy diets[156] and reduced food loss and waste present important opportunities for adaptation and mitigation while generating significant co-benefits in terms of biodiversity and human health *(high confidence*). Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, health insurance, financial incentives, and awareness-raising campaigns, can potentially influence food demand, reduce food waste, reduce healthcare costs, contribute to lower GHG emissions and enhance adaptive capacity (*high confidence*).

[156] Balanced diets refer to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

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Improved access to clean energy sources and technologies, and shifts to active mobility (e.g., walking and cycling) and public transport can deliver socioeconomic, air quality and health benefits, especially for women and children (*high confidence*). {*WGII SPM C.2.2, WGII SPM C.2.11, WGII Cross-Chapter Box HEALTH; WGIII SPM C.2.2, WGIII SPM C.4.2, WGIII SPM C.9.1, WGIII SPM C.10.4, WGIII SPM D.1.3, WGIII Figure SPM.6, WGIII Figure SPM.8; SRCCL SPM B.6.2, SRCCL SPM B.6.3, SRCCL B.4.6, SRCCL SPM C.2.4*}

Effective adaptation options exist to help protect human health and well-being (*high confidence*). Health Action Plans that include early warning and response systems are effective for extreme heat (*high confidence*). Effective options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance and access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). A key pathway to climate resilience in the health sector is universal access to healthcare (*high confidence*). {*WGII SPM C.2.11, WGII 7.4.6*}

4.5.6 Society, Livelihoods, and Economies

Enhancing knowledge on risks and available adaptation options promotes societal responses, and behaviour and lifestyle changes supported by policies, infrastructure and technology can help reduce global GHG emissions (*high confidence*). Climate literacy and information provided through climate services and community approaches, including those that are informed by Indigenous Knowledge and local knowledge, can accelerate behavioural changes and planning (*high confidence*). Educational and information programmes, using the arts, participatory modelling and citizen science can facilitate awareness, heighten risk perception, and influence behaviours (*high confidence*). The way choices are presented can enable adoption of low GHG intensive socio-cultural options, such as shifts to balanced, sustainable healthy diets, reduced food waste, and active mobility (*high confidence*). Judicious labelling, framing, and communication of social norms can increase the effect of mandates, subsidies, or taxes (*medium confidence*). {*WGII SPM C.5.3, WGII TS.D.10.1; WGIII SPM C.10, WGIII SPM C.10.2, WGIII SPM C.10.3, WGIII SPM E.2.2, WGIII Figure SPM.6, WGIII TS.6.1, 5.4; SR1.5 SPM D.5.6; SROCC SPM C.4*}

A range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing approaches, have broad applicability across sectors and provide greater risk reduction benefits when combined (*high confidence*). Climate services that are demand-driven and inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). Policy mixes that include weather and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems combined with effective contingency plans, can reduce vulnerability and exposure of human systems (*high confidence*). Integrating climate adaptation into social protection programs, including cash transfers and public works programs, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure (*high confidence*). Social safety nets can build adaptive capacities, reduce socioeconomic vulnerability, and reduce risk linked to hazards *(robust evidence, medium agreement).* {*WGII SPM C.2.9, WGII SPM C.2.13, WGII Cross-Chapter Box FEASIB in Chapter 18; SRCCL SPM C.1.4, SRCCL SPM D.1.2*}

Reducing future risks of involuntary migration and displacement due to climate change is possible through cooperative, international efforts to enhance institutional adaptive capacity and sustainable development (*high confidence*). Increasing adaptive capacity minimises risk associated with involuntary migration and immobility and improves the degree of choice under which migration decisions are made, while policy interventions can remove barriers and expand the alternatives for safe, orderly and regular migration that allows vulnerable people to adapt to climate change (*high confidence*). {*WGII SPM C.2.12, WGII TS.D.8.6, WGII Cross-Chapter Box MIGRATE in Chapter 7*}

Accelerating commitment and follow-through by the private sector is promoted for instance by building business cases for adaptation, accountability and transparency mechanisms, and monitoring and evaluation of adaptation progress (*medium confidence*). Integrated pathways for managing climate risks will be most suitable when so-called 'low-regret' anticipatory options are established jointly across sectors in a timely manner and are feasible and effective in their local context, and when path dependencies and maladaptations across sectors are avoided (*high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {*WGII SPM C.5.1, WGII SPM C.5.2, WGII TS.D.10.4*}

4.6 Co-Benefits of Adaptation and Mitigation for Sustainable Development Goals

Mitigation and adaptation actions have more synergies than trade-offs with Sustainable Development Goals (SDGs). Synergies and trade-offs depend on context and scale of implementation. Potential trade-offs can be compensated or avoided with additional policies, investments and financial partnerships. (*high confidence*)

Many mitigation and adaptation actions have multiple synergies with Sustainable Development Goals (SDGs), but some actions can also have trade-offs. Potential synergies with SDGs exceed potential trade-offs. Synergies and trade-offs are context specific and depend on: means and scale of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of actions, governance, and policy design. Eradicating extreme poverty, energy poverty, and providing decent living standards to all, consistent with near-term sustainable development objectives, can be achieved without significant global emissions growth. (*high confidence*) {*WGII SPM C.2.3, WGII Figure SPM.4b; WGIII SPM B.3.3, WGIII SPM C.9.2, WGIII SPM D.1.2, WGIII SPM D.1.4, WGIII Figure SPM.8*} (*Figure 4.5*)

Several mitigation and adaptation options can harness near-term synergies and reduce trade-offs to advance sustainable development in energy, urban and land systems (Figure 4.5) (*high confidence*). Clean energy supply systems have multiple co-benefits, including improvements in air quality and health. Heat Health Action Plans that include early warning and response systems, approaches that mainstream health into food, livelihoods, social protection, water and sanitation benefit health and well-being. There are potential synergies between multiple Sustainable Development Goals and sustainable land use and urban planning with more green spaces, reduced air pollution, and demand-side mitigation including shifts to balanced, sustainable healthy diets. Electrification combined with low-GHG energy, and shifts to public transport can enhance health, employment, and can contribute to energy security and deliver equity. Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change can generate multiple additional benefits, such as agricultural productivity, food security, and biodiversity conservation. (*high confidence*) {*WGII SPM C.1.1, WGII C.2.4, WGII SPM D.1, WGII Figure SPM.4, WGII Cross-Chapter Box HEALTH in Chapter 17, WGII Cross-Chapter Box FEASIB in Chapter 18; WGIII SPM C.4.2, WGIII SPM D.1.3, WGIII SPM D.2, WGIII Figure SPM.8; SRCCL SPM B.4.6*}

When implementing mitigation and adaptation together, and taking trade-offs into account, multiple co-benefits and synergies for human well-being as well as ecosystem and planetary health can be realised (*high confidence*). There is a strong link between sustainable development, vulnerability and climate risks. Social safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. Land restoration contributes to mitigation and adaptation with synergies via enhanced ecosystem services and with economically positive returns and co-benefits for poverty reduction and improved livelihoods. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, technology transfer, investments; governance, development, context specific gender-based and other social equity considerations with meaningful participation of Indigenous Peoples, local communities and vulnerable populations. (*high confidence*). {*WGII SPM C.2.9, WGII SPM C.5.6, WGII SPM D.5.2, WGII Cross-Chapter Box on Gender in Chapter 18; WGIII SPM C.9.2, WGIII SPM D.1.2, WGIII SPM D.1.4, WGIII SPM D.2; SRCCL SPM D.2.2, SRCCL TS.4*}

Context relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include but are not limited to social, economic, environmental, cultural, or political circumstances, resource endowment, capabilities, international environment, and prior development. n regions with high dependency on fossil fuels for, among other things, revenue and employment generation, mitigating risks for sustainable development requires policies that promote economic and energy sector diversification and considerations of just transitions principles, processes and practices (*high confidence*). For individuals and households in low-lying coastal areas, in Small Islands, and smallholder farmers transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). Effective governance is needed to limit trade-offs of some mitigation options such as large scale afforestation and bioenergy options due to risks from their deployment for food systems, biodiversity, other ecosystem functions and services, and livelihoods (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {*WGII SPM B.5.4, WGII SPM C.3.1, WGII SPM C.3.4; WGIII SPM D.1.3, WGIII SPM E.4.2; SR1.5 SPM C.3.4, SR1.5 SPM C.3.5, SR1.5 SPM Figure SPM.4, SR1.5 SPM D.4.3, SR1.5 SPM D.4.4*}

Near-term adaptation and mitigation actions have more synergies than trade-offs with Sustainable Development Goals (SDGs)

Synergies and trade-offs depend on context and scale

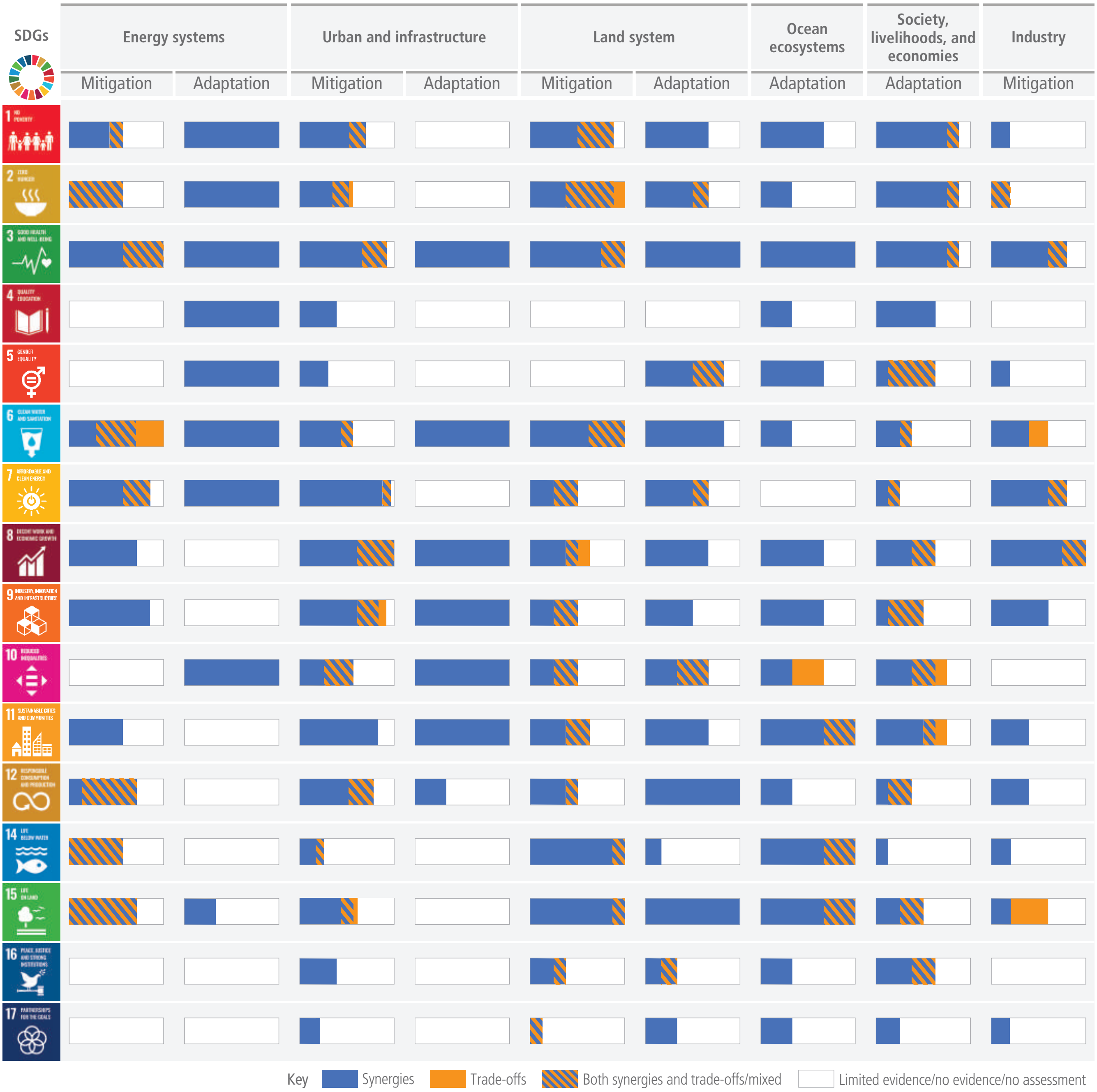

Figure 4.5: Potential synergies and trade-offs between the portfolio of climate change mitigation and adaptation options and the Sustainable Development Goals (SDGs). This figure presents a high-level summary of potential synergies and trade-offs assessed in WGII Figure SPM.4b and WGIII Figure SPM.8, based on the qualitative and quantitative assessment of each individual mitigation or option. The SDGs serve as an analytical framework for the assessment of different sustainable development dimensions, which extend beyond the time frame of 2030 SDG targets. Synergies and trade-offs across all individual options within a sector/system are aggregated into sector/system potentials for the whole mitigation or adaptation portfolio. The length of each bar represents the total number of mitigation or adaptation options under each system/sector. The number of adaptation and mitigation options vary across system/sector, and have been normalised to 100% so that bars are comparable across mitigation, adaptation, system/sector, and SDGs. Positive links shown in WGII Figure SPM.4b and WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of synergies, represented here by the blue proportion within the bars. Negative links shown in WGII Figure SPM.4b and WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of trade-offs and is represented by orange proportion within the bars. 'Both synergies and trade-offs' shown in WGII Figure SPM.4b WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of 'both synergies and trade-off', represented by the striped proportion within the bars. The 'white' proportion within the bar indicates limited evidence/ no evidence/ not assessed. Energy systems comprise all mitigation options listed in WGIII Figure SPM.8 and WGII Figure SPM.4b for adaptation. Urban and infrastructure comprises all mitigation options listed

in WGIII Figure SPM.8 under Urban systems, under Buildings and under Transport and adaptation options listed in WGII Figure SPM.4b under Urban and infrastructure systems. Land system comprises mitigation options listed in WGIII Figure SPM.8 under AFOLU and adaptation options listed in WGII Figure SPM.4b under Land and ocean systems: forest-based adaptation, agroforestry, biodiversity management and ecosystem connectivity, improved cropland management, efficient livestock management, water use efficiency and water resource management. Ocean ecosystems comprises adaptation options listed in WGII Figure SPM.4b under Land and ocean systems: coastal defence and hardening, integrated coastal zone management and sustainable aquaculture and fisheries. Society, livelihood and economies comprises adaptation options listed in WGII Figure SPM.4b under Cross-sectoral; Industry comprises all those mitigation options listed in WGIII Figure SPM.8 under Industry. SDG 13 (Climate Action) is not listed because mitigation/ adaptation is being considered in terms of interaction with SDGs and not vice versa (SPM SR1.5 Figure SPM.4 caption). The bars denote the strength of the connection and do not consider the strength of the impact on the SDGs. The synergies and trade-offs differ depending on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources. For the sake of uniformity, we are not reporting the confidence levels because there is knowledge gap in adaptation option wise relation with SDGs and their confidence level which is evident from WGII fig SPM.4b. {*WGII Figure SPM.4b; WGIII Figure SPM.8*}

4.7 Governance and Policy for Near-Term Climate Change Action

Effective climate action requires political commitment, well-aligned multi-level governance and institutional frameworks, laws, policies and strategies. It needs clear goals, adequate finance and financing tools, coordination across multiple policy domains, and inclusive governance processes. Many mitigation and adaptation policy instruments have been deployed successfully, and could support deep emissions reductions and climate resilience if scaled up and applied widely, depending on national circumstances. Adaptation and mitigation action benefits from drawing on diverse knowledge. (*high confidence*)

Effective climate governance enables mitigation and adaptation by providing overall direction based on national circumstances, setting targets and priorities, mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. Effective governance enhances monitoring and evaluation and regulatory certainty, prioritising inclusive, transparent and equitable decision-making, and improves access to finance and technology (*high confidence*). These functions can be promoted by climate-relevant laws and plans, which are growing in number across sectors and regions, advancing mitigation outcomes and adaptation benefits (*high confidence*). Climate laws have been growing in number and have helped deliver mitigation and adaptation outcomes (*medium confidence*). {*WGII SPM C.5, WGII SPM C.5.1, WGII SPM C5.4, WGII SPM C.5.6; WGIII SPM B.5.2, WGIII SPM E.3.1*}

Effective municipal, national and sub-national climate institutions, such as expert and co-ordinating bodies, enable co-produced, multi-scale decision-processes, build consensus for action among diverse interests, and inform strategy settings (*high confidence*). This requires adequate institutional capacity at all levels (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, participatory processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). Policy support is influenced by Indigenous Peoples, businesses, and actors in civil society, including, youth, labour, media, and local communities, and effectiveness is enhanced by partnerships between many different groups in society (*high confidence*). Climate-related litigation is growing, with a large number of cases in some developed countries and with a much smaller number in some developing countries, and in some cases has influenced the outcome and ambition of climate governance (*medium confidence*). {*WGII SPM C2.6, WGII SPM C.5.2, WGII SPM C.5.5, WGII SPM C.5.6, WGII SPM D.3.1; WGIII SPM E3.2, WGIII SPM E.3.3*}

Effective climate governance is enabled by inclusive decision processes, allocation of appropriate resources, and institutional review, monitoring and evaluation (*high confidence*). Multi-level, hybrid and cross-sector governance facilitates appropriate consideration for co-benefits and trade-offs, particularly in land sectors where decision processes range from farm level to national scale (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability. {*WGII SPM C.5.5, WGII SPM C.5.6, WGII SPM D.1.1, WGII SPM D.2, WGII SPM D.3.2; SRCCL SPM C.3, SRCCL TS.1*}

Drawing on diverse knowledge and partnerships, including with women, youth, Indigenous Peoples, local communities, and ethnic minorities can facilitate climate resilient development and has allowed locally appropriate and socially acceptable solutions (*high confidence*). {*WGII SPM D.2, D.2.1*}

Many regulatory and economic instruments have already been deployed successfully. These instruments could support deep emissions reductions if scaled up and applied more widely. Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, and equity. (*high confidence*) {*WGII SPM E.4; WGIII SPM E.4.2*}

Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, can improve mitigation outcomes in sectoral applications (*high confidence*), and regulatory instruments that include flexibility mechanisms can reduce costs of cutting emissions (*medium confidence*). {*WGII SPM C.5.4; WGIII SPM E.4.1*}

Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Revenue from carbon taxes or emissions trading can be used for equity and distributional goals, for example to support low-income households, among other approaches (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage (*medium confidence*). {*WGIII SPM E4.2, WGIII SPM E.4.6*}

Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits such as improved public revenue, macroeconomic and sustainability performance; subsidy removal can have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases, can be mitigated by measures such as re-distributing revenue saved, and depend on national circumstances (*high confidence*). Fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emissions by 1–4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {*WGIII SPM E.4.2*}

National policies to support technology development, and participation in international markets for emission reduction, can bring positive spillover effects for other countries (*medium confidence*), although reduced demand for fossil fuels as a result of climate policy could result in costs to exporting countries (*high confidence*). Economy-wide packages can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Examples are public spending commitments; pricing reforms; and investment in education and training, R&D and infrastructure (*high confidence*). Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances (*high confidence*). {*WGIII SPM E4.4, WGIII SPM 4.5, WGIII SPM 4.6*}

4.8 Strengthening the Response: Finance, International Cooperation and Technology

Finance, international cooperation and technology are critical enablers for accelerated climate action. If climate goals are to be achieved, both adaptation and mitigation financing would have to increase many-fold. There is sufficient global capital to close the global investment gaps but there are barriers to redirect capital to climate action. Barriers include institutional, regulatory and market access barriers, which can be reduced to address the needs and opportunities, economic vulnerability and indebtedness in many developing countries. Enhancing international cooperation is possible through multiple channels. Enhancing technology innovation systems is key to accelerate the widespread adoption of technologies and practices. (*high confidence*)

4.8.1. Finance for Mitigation and Adaptation Actions

Improved availability and access to finance[157] will enable accelerated climate action (*very high confidence*). Addressing needs and gaps and broadening equitable access to domestic and international finance, when combined with other supportive actions, can act as a catalyst for accelerating mitigation and shifting development pathways (*high confidence*). Climate resilient development is enabled by increased international cooperation including improved access to financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*). {*WGII SPM C.1.2, WGII SPM C.3.2, WGII SPM C.5, WGII SPM C.5.4, WGII SPM D.2, WGII SPM D.3.2, WGII SPM D.5, WGII SPM D.5.2; WGIII SPM B.4.2,WGIII SPM B.5, WGIII SPM B.5.4, WGIII SPM C.4.2, WGIII SPM C.7.3, WGIII SPM C.8.5, WGIII SPM D.1.2, WGIII SPM D.2.4, WGIII SPM D.3.4, WGIII SPM E.2.3, WGIII SPM E.3.1, WGIII SPM E.5, WGIII SPM E.5.1, WGIII SPM E.5.2, WGIII SPM E.5.3, WGIII SPM E.5.4, WGIII SPM E.6.2*}

Both adaptation and mitigation finance need to increase many-fold, to address rising climate risks and to accelerate investments in emissions reduction (*high confidence*). Increased finance would address soft limits to adaptation and rising climate risks while also averting some related losses and damages, particularly in vulnerable developing countries (*high confidence*). Enhanced mobilisation of and access to finance, together with building capacity, are essential for implementation of adaptation actions and to reduce adaptation gaps given rising risks and costs, especially for the most vulnerable groups, regions and sectors (*high confidence*). Public finance is an important enabler of adaptation and mitigation, and can also leverage private finance (*high confidence*). Adaptation funding predominately comes from public sources, and public mechanisms and finance can leverage private sector finance by addressing real and perceived regulatory, cost and market barriers, for instance via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). Average annual modelled mitigation investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a large need for financial, technical, and human resources for adaptation (*high confidence*). {*WGII SPM C.1.2, WGII SPM C2.11, WGII SPM C.3, WGII SPM C.3.2, WGII SPM C3.5, WGII SPM C.5, WGII SPM C.5.4, WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.1.2, WGII SPM C.5.4; WGIII SPM D.2.4, WGIII SPM E.5, WGIII SPM E.5.1, WGIII 15.2*} *(Section 2.3.2, 2.3.3, 4.4, Figure 4.6)*

[157] Finance can originate from diverse sources, singly or in combination: public or private, local, national or international, bilateral or multilateral, and alternative sources (e.g., philanthropic, carbon offsets). It can be in the form of grants, technical assistance, loans (concessional and non-concessional), bonds, equity, risk insurance and financial guarantees (of various types).

There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector and in the context of economic vulnerabilities and indebtedness facing many developing countries (*high confidence*). For shifts in private finance, options include better assessment of climate-related risks and investment opportunities within the financial system, reducing sectoral and regional mismatches between available capital and investment needs, improving the risk-return profiles of climate investments, and developing institutional capacities and local capital markets. Macroeconomic barriers include, amongst others, indebtedness and economic vulnerability of developing regions. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM E.4.2, WGIII SPM E.5, WGIII SPM E.5.2, WGIII SPM E.5.3*}

Scaling up financial flows requires clear signalling from governments and the international community (*high confidence*). Tracked financial flows fall short of the levels needed for adaptation and to achieve mitigation goals across all sectors and regions (*high confidence*). These gaps create many opportunities and the challenge of closing gaps is largest in developing countries (*high confidence*). This includes a stronger alignment of public finance, lowering real and perceived regulatory, cost and market barriers, and higher levels of public finance to lower the risks associated with low-emission investments. Up-front risks deter economically sound low carbon projects, and developing local capital markets are an option. Investors, financial intermediaries, central banks and financial regulators can shift the systemic underpricing of climate-related risks. A robust labelling of bonds and transparency is needed to attract savers. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM B.5.4, WGIII SPM E.4, WGIII SPM E.5.4, WGIII 15.2, WGIII 15.6.1, WGIII 15.6.2, WGIII 15.6.7*}

The largest climate finance gaps and opportunities are in developing countries (*high confidence*). Accelerated support from developed countries and multilateral institutions is a critical enabler to enhance mitigation and adaptation action and can address inequities in finance, including its costs, terms and conditions, and economic vulnerability to climate change. Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, e.g., in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy. Options for scaling up mitigation and adaptation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD 100 billion-a-year goal of the Paris Agreement; increase the use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes. A coordinated effort to make the post-pandemic recovery sustainable over the long term through increased flows of financing over this decade can accelerate climate action, including in developing regions facing high debt costs, debt distress and macroeconomic uncertainty. (*high confidence*) {*WGII SPM C.5.2, WGII SPM C.5.4, WGII SPM C.6.5, WGII SPM D.2, WGII TS.D.10.2; WGIII SPM E.5, WGIII SPM E.5.3, WGIII TS.6.4, WGIII Box TS.1, WGIII 15.2, WGIII 15.6*}

4.8.2. International Cooperation and Coordination

International cooperation is a critical enabler for achieving ambitious climate change mitigation goals and climate resilient development (*high confidence*). Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for developing countries, vulnerable regions, sectors and groups and aligning finance flows for climate action to be consistent with ambition levels and funding needs (*high confidence*). While agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol and Paris Agreement, are helping (Section 2.2.1), international financial, technology and capacity building support to developing countries will enable greater implementation and more ambitious actions (*medium confidence*). By integrating equity and climate justice, national and international policies can help to facilitate shifting development pathways towards sustainability, especially by mobilising and enhancing access to finance for vulnerable regions, sectors and communities (*high confidence*). International cooperation and coordination, including combined policy packages, may be particularly important for sustainability transitions in emissions-intensive and highly traded basic materials industries that are exposed to international competition (*high confidence*). The large majority of emission modelling studies assume significant international cooperation to secure financial flows and address inequality and poverty issues in pathways limiting global warming. There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation (*high confidence*). Delayed global cooperation increases policy costs across regions (*high confidence*). {*WGII SPM D.2, WGII SPM D.3.1, WGII SPM D.5.2; WGIII SPM D.3.4, WGIII SPM C5.4, WGIII SPM C.12.2, WGIII SPM E.6, WGIII SPM E.6.1, WGIII E.5.4, WGIII TS.4.2, WGIII TS.6.2; SR1.5 SPM D.6.3, SR1.5 SPM D.7, SR1.5 SPM D.7.3*}

The transboundary nature of many climate change risks (e.g., for supply chains, markets and natural resource flows in food, fisheries, energy and water, and potential for conflict) increases the need for climate-informed transboundary management, cooperation, responses and solutions through multi-national or regional governance processes (*high confidence*). Multilateral governance efforts can help reconcile contested interests, world views and values about how to address climate change. International environment and sectoral agreements, and initiatives in some cases, may help to stimulate low GHG investment and reduce emissions (such as ozone depletion, transboundary air pollution and atmospheric emissions of mercury). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation through deployment of low-emissions fuels, for example through stricter efficiency and carbon intensity standards. Transnational partnerships can also stimulate policy development, low-emissions technology diffusion, emission reductions and adaptation, by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors, though uncertainties remain over their costs, feasibility, and effectiveness. International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investment and reduce emissions. (*medium confidence*) {*WGII SPM B.5.3, WGII SPM C.5.6, WGII TS.E.5.4, WGII TS.E.5.5; WGIII SPM C.8.4, WGIII SPM E.6.3, WGIII SPM E.6.4, WGIII SPM E.6.4, WGIII TS.5.3*}

Higher mitigation investment flows required for all sectors and regions to limit global warming

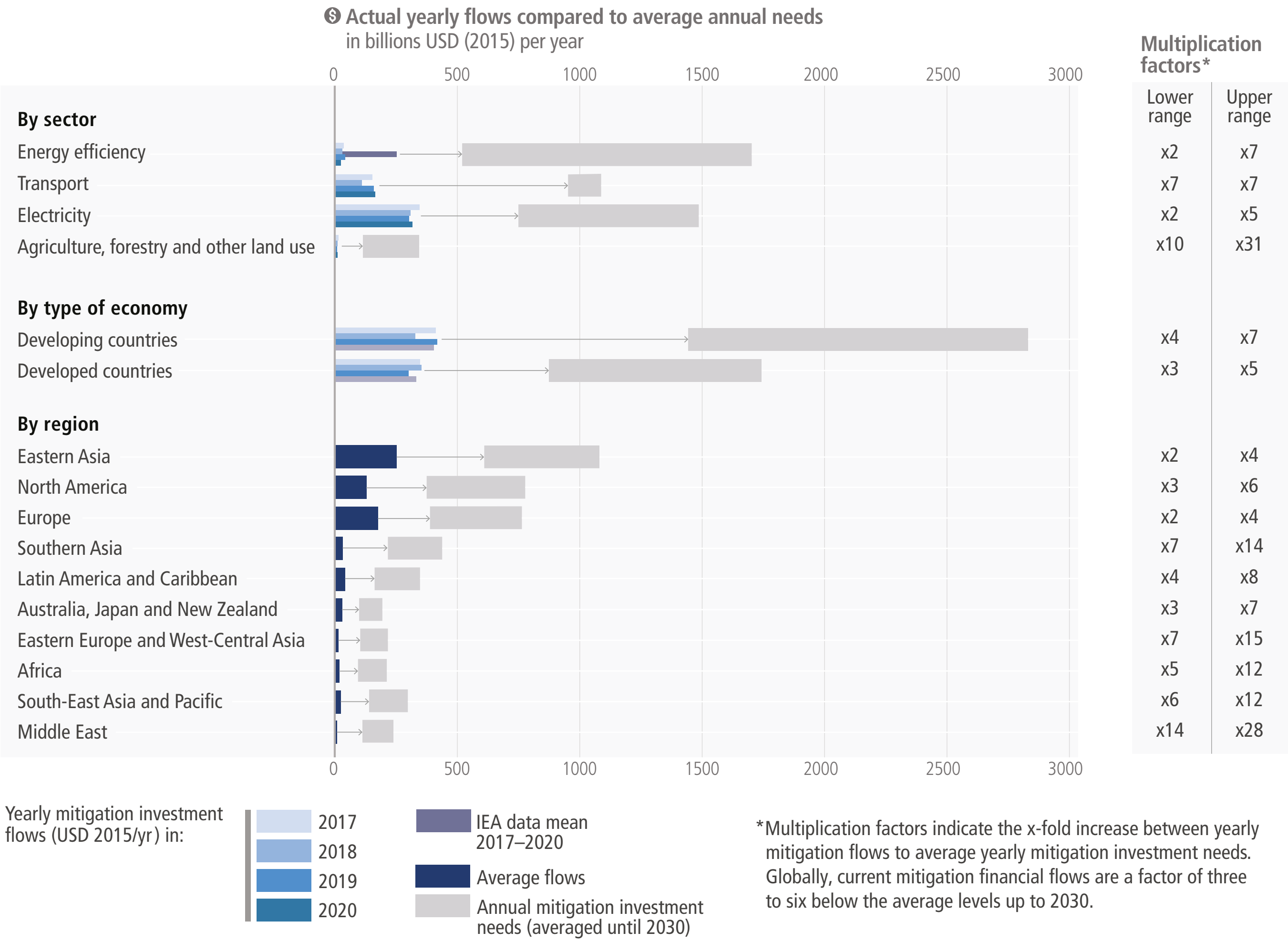

Figure 4.6: Breakdown of average mitigation investment flows and investment needs until 2030 (USD billion). Mitigation investment flows and investment needs by sector (energy efficiency, transport, electricity, and agriculture, forestry and other land use), by type of economy, and by region (see WGIII Annex II Part I Section 1 for the classification schemes for countries and areas). The blue bars display data on mitigation investment flows for four years: 2017, 2018, 2019 and 2020 by sector and by type of economy. For the regional breakdown, the annual average mitigation investment flows for 2017–2019 are shown. The grey bars show the minimum and maximum level of global annual mitigation investment needs in the assessed scenarios. This has been averaged until 2030. The multiplication factors show the ratio of global average early mitigation investment needs (averaged until 2030) and current yearly mitigation flows (averaged for 2017/18–2020). The lower multiplication factor refers to the lower end of the range of investment needs. The upper multiplication factor refers to the upper range of investment needs. Given the multiple sources and lack of harmonised methodologies, the data can be considered only if indicative of the size and pattern of investment needs. {*WGIII Figure TS.25, WGIII 15.3, WGIII 15.4, WGIII 15.5, WGIII Table 15.2, WGIII Table 15.3, WGIII Table 15.4*}

4.8.3. Technology Innovation, Adoption, Diffusion and Transfer

Enhancing technology innovation systems can provide opportunities to lower emissions growth and create social and environmental co-benefits. Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Support for successful low-carbon technological innovation includes public policies such as training and R&D, complemented by regulatory and market-based instruments that create incentives and market opportunities such as appliance performance standards and building codes. (*high confidence*) {*WGIII SPM B.4, WGIII SPM B.4.4, WGIII SPM E.4.3, WGIII SPM E4.4*}

International cooperation on innovation systems and technology development and transfer, accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies and align these with other development objectives (*high confidence*). Choice architecture can help end-users adopt technology and low-GHG-intensive options (*high confidence*). Adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity building (*medium confidence*). {*WGIII SPM B.4.2, WGIII SPM E.6.2, WGIII SPM C.10.4, WGIII 16.5*}

International cooperation on innovation works best when tailored to and beneficial for local value chains, when partners collaborate on an equal footing, and when capacity building is an integral part of the effort (*medium confidence*). {*WGIII SPM E.4.4, WGIII SPM E.6.2*}

Technological innovation can have trade-offs that include externalities such as new and greater environmental impacts and social inequalities; rebound effects leading to lower net emission reductions or even emission increases; and overdependence on foreign knowledge and providers (*high confidence*). Appropriately designed policies and governance have helped address distributional impacts and rebound effects (*high confidence*). For example, digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services (*high confidence*). However, societal digitalization can induce greater consumption of goods and energy and increased electronic waste as well as negatively impacting labour markets and worsening inequalities between and within countries (*medium confidence*). Digitalisation requires appropriate governance and policies in order to enhance mitigation potential (*high confidence*). Effective policy packages can help to realise synergies, avoid trade-offs and/or reduce rebound effects: these might include a mix of efficiency targets, performance standards, information provision, carbon pricing, finance and technical assistance (*high confidence*). {*WGIII SPM B.4.2, WGIII SPM B.4.3, WGIII SPM E.4.4, WGIII TS 6.5, WGIII Cross-Chapter Box 11 on Digitalization in Chapter 16*}

Technology transfer to expand use of digital technologies for land use monitoring, sustainable land management, and improved agricultural productivity supports reduced emissions from deforestation and land use change while also improving GHG accounting and standardisation (*medium confidence*). {*SRCCL SPM C.2.1, SRCCL SPM D.1.2, SRCCL SPM D.1.4, SRCCL 7.4.4, SRCCL 7.4.6*}

4.9 Integration of Near-Term Actions Across Sectors and Systems

The feasibility, effectiveness and benefits of mitigation and adaptation actions are increased when multi-sectoral solutions are undertaken that cut across systems. When such options are combined with broader sustainable development objectives, they can yield greater benefits for human well-being, social equity and justice, and ecosystem and planetary health. (*high confidence*)

Climate resilient development strategies that treat climate, ecosystems and biodiversity, and human society as parts of an integrated system are the most effective (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Climate resilient development is enabled when decision-making processes and actions are integrated across sectors (*very high confidence*). Synergies with and progress towards the Sustainable Development Goals enhance prospects for climate resilient development. Choices and actions that treat humans and ecosystems as an integrated system build on diverse knowledge about climate risk, equitable, just and inclusive approaches, and ecosystem stewardship. {*WGII SPM B.2, WGII Figure SPM.5, WGII SPM D.2, WGII SPM D2.1, WGII SPM 2.2, WGII SPM D4, WGII SPM D4.1, WGII SPM D4.2, WGII SPM D5.2, WGII Figure SPM.5*}

Approaches that align goals and actions across sectors provide opportunities for multiple and large-scale benefits and avoided damages in the near term. Such measures can also achieve greater benefits through cascading effects across sectors (*medium confidence*). For example, the feasibility of using land for both agriculture and centralised solar production can increase when such options are combined (*high confidence*). Similarly, integrated transport and energy infrastructure planning and operations can together reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors (*high confidence*). The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries (*very high confidence*). Integrated design approaches to the construction and retrofit of buildings provide increasing examples of zero energy or zero carbon buildings in several regions. To minimise maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret and timely actions that keep options open, ensure benefits in multiple sectors and systems and suggest the available solution space for adapting to long-term climate change (*very high confidence*). Trade-offs in terms of employment, water use, land-use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, with frameworks for integrated policy implementation (*high confidence*). {*WGII SPM C.2, WGII SPM C.4.4; WGIII SPM C.6.3, WGIII SPM C.6, WGIII SPM C.7.2, WGIII SPM C.8.5, WGIII SPM D.1.2, WGIII SPM D.1.5, WGIII SPM E.1.2*}

Mitigation and adaptation when implemented together, and combined with broader sustainable development objectives, would yield multiple benefits for human well-being as well as ecosystem and planetary health (*high confidence*). The range of such positive interactions is significant in the landscape of near-term climate policies across regions, sectors and systems. For example, AFOLU mitigation actions in land-use change and forestry, when sustainably implemented, can provide large-scale GHG emission reductions and removals that simultaneously benefit biodiversity, food security, wood supply and other ecosystem services but cannot fully compensate for delayed mitigation action in other sectors. Adaptation measures in land, ocean and ecosystems similarly can have widespread benefits for food security, nutrition, health and well-being, ecosystems and biodiversity. Equally, urban systems are critical, interconnected sites for climate resilient development; urban policies that implement multiple interventions can yield adaptation or mitigation gains with equity and human well-being. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation. Effective action in all of the above areas will require near-term political commitment and follow-through, social cooperation, finance, and more integrated cross-sectoral policies and support and actions. (*high confidence*). {*WGII SPM C.1, WG II SPM C.2, WGII SPM C.2, WGII SPM C.5, WGII SPM D.2, WGII SPM D.3.2, WGII SPM D.3.3, WGII Figure SPM.4; WGIII SPM C.6.3, WGIII SPM C.8.2, WGIII SPM C.9, WGIII SPM C.9.1, WGIII SPM C.9.2, WGIII SPM D.2, WGIII SPM D.2.4, WGIII SPM D.3.2, WGIII SPM E.1, WGIII SPM E.2.4, WGIII Figure SPM.8, WGIII TS.7, WGIII TS Figure TS.29: SRCCL ES 7.4.8, SRCCL SPM B.6*} (*3.4, 4.4*)