# Technical Summary

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**This summary should be cited as:**

Edenhofer O., R. Pichs-Madruga, Y. Sokona, S. Kadner, J.C. Minx, S. Brunner, S. Agrawala, G. Baiocchi, I.A. Bashmakov, G. Blanco, J. Broome, T. Bruckner, M. Bustamante, L. Clarke, M. Conte Grand, F. Creutzig, X. Cruz-Núñez, S. Dhakal, N.K. Dubash, P. Eickemeier, E. Farahani, M. Fischedick, M. Fleurbaey, R. Gerlagh, L. Gómez-Echeverri, S. Gupta, J. Harnisch, K. Jiang, F. Jotzo, S. Kartha, S. Klasen, C. Kolstad, V. Krey, H. Kunreuther, O. Lucon, O. Masera, Y. Mulugetta, R.B. Norgaard, A. Patt, N.H. Ravindranath, K. Riahi, J. Roy, A. Sagar, R. Schaeffer, S. Schlömer, K.C. Seto, K. Seyboth, R. Sims, P. Smith, E. Somanathan, R. Stavins, C. von Stechow, T. Sterner, T. Sugiyama, S. Suh, D. Ürge-Vorsatz, K. Urama, A. Venables, D.G. Victor, E. Weber, D. Zhou, J. Zou, and T. Zwickel, 2014: Technical Summary. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

# Contents

# TS.1 Introduction and framing

'Mitigation', in the context of climate change, is a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs). One of the central messages from Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) is that the consequences of unchecked climate change for humans and natural ecosystems are already apparent and increasing. The most vulnerable systems are already experiencing adverse effects. Past GHG emissions have already put the planet on a track for substantial further changes in climate, and while there are many uncertainties in factors such as the sensitivity of the climate system many scenarios lead to substantial climate impacts, including direct harms to human and ecological well-being that exceed the ability of those systems to adapt fully.

Because mitigation is intended to reduce the harmful effects of climate change, it is part of a broader policy framework that also includes adaptation to climate impacts. Mitigation, together with adaptation to climate change, contributes to the objective expressed in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) to stabilize "greenhouse gas concentrations in the atmosphere at a level to prevent dangerous anthropogenic interference with the climate system […] within a time frame sufficient to allow ecosystems to adapt […] to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". However, Article 2 is hard to interpret, as concepts such as 'dangerous' and 'sustainable' have different meanings in different decision contexts (see Box TS.1).[1] Moreover, natural science is unable to predict precisely the response of the climate system to rising GHG

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[1] Boxes throughout this summary provide background information on main research concepts and methods that were used to generate insight.

## Box TS.1 | Many disciplines aid decision making on climate change

Something is dangerous if it leads to a significant risk of considerable harm. Judging whether human interference in the climate system is dangerous therefore divides into two tasks. One is to estimate the risk in material terms: what the material consequences of human interference might be and how likely they are. The other is to set a value on the risk: to judge how harmful it will be.

The first is a task for natural science, but the second is not [Section 3.1]. As the Synthesis Report of AR4 states, "Determining what constitutes 'dangerous anthropogenic interference with the climate system' in relation to Article 2 of the UNFCCC involves value judgements". Judgements of value (valuations) are called for, not just here, but at almost every turn in decision making about climate change [3.2]. For example, setting a target for mitigation involves judging the value of losses to people's well-being in the future, and comparing it with the value of benefits enjoyed now. Choosing whether to site wind turbines on land or at sea requires a judgement of the value of landscape in comparison with the extra cost of marine turbines. To estimate the social cost of carbon is to value the harm that GHG emissions do [3.9.4].

Different values often conflict, and they are often hard to weigh against each other. Moreover, they often involve the conflicting interests of different people, and are subject to much debate and disagreement. Decision makers must therefore find ways to mediate among different interests and values, and also among differing viewpoints about values. [3.4, 3.5]

Social sciences and humanities can contribute to this process by improving our understanding of values in ways that are illustrated in the boxes contained in this summary. The sciences of human and social behaviour—among them psychology, political science, sociology, and non-normative branches of economics—investigate the values people have, how they change through time, how they can be influenced by political processes, and how the process of making decisions affects their acceptability. Other disciplines, including ethics (moral philosophy), decision theory, risk analysis, and the normative branch of economics, investigate, analyze, and clarify values themselves [2.5, 3.4, 3.5, 3.6]. These disciplines offer practical ways of measuring some values and trading off conflicting interests. For example, the discipline of public health often measures health by means of 'disability-adjusted life years' [3.4.5]. Economics uses measures of social value that are generally based on monetary valuation but can take account of principles of distributive justice [3.6, 4.2, 4.7, 4.8]. These normative disciplines also offer practical decision-making tools, such as expected utility theory, decision analysis, cost-benefit and cost-effectiveness analysis, and the structured use of expert judgment [2.5, 3.6, 3.7, 3.9].

There is a further element to decision making. People and countries have rights and owe duties towards each other. These are matters of justice, equity, or fairness. They fall within the subject matter of moral and political philosophy, jurisprudence, and economics. For example, some have argued that countries owe restitution for the harms that result from their past GHG emissions, and it has been debated, on jurisprudential and other grounds, whether restitution is owed only for harms that result from negligent or blameworthy GHG emissions. [3.3, 4.6] concentrations nor fully understand the harm it will impose on individuals, societies, and ecosystems. Article 2 requires that societies balance a variety of considerations—some rooted in the impacts of climate change itself and others in the potential costs of mitigation and adaptation. The difficulty of that task is compounded by the need to develop a consensus on fundamental issues such as the level of risk that societies are willing to accept and impose on others, strategies for sharing costs, and how to balance the numerous tradeoffs that arise because mitigation intersects with many other goals of societies. Such issues are inherently value-laden and involve different actors who have varied interests and disparate decision-making power.

The Working Group III (WGIII) contribution to the IPCC's Fifth Assessment Report (AR5) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. It builds upon the WGIII contribution to the IPCC's Fourth Assessment Report (AR4), the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and previous reports and incorporates subsequent new findings and research. Throughout, the focus is on the implications of its findings for policy, without being prescriptive about the particular policies that governments and other important participants in the policy process should adopt. In light of the IPCC's mandate, authors in WGIII were guided by several principles when assembling this assessment: (1) to be explicit about mitigation options, (2) to be explicit about their costs and about their risks and opportunities vis-à-vis other development priorities, (3) and to be explicit about the underlying criteria, concepts, and methods for evaluating alternative policies.

The remainder of this summary offers the main findings of this report. The degree of certainty in findings, as in the reports of all three IPCC Working Groups, is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment.[2] Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers. Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bolded finding apply to subsequent statements in the paragraph, unless additional terms are provided. References in [square brackets] indicate chapters, sections, figures, tables, and boxes where supporting evidence in the underlying report can be found.

This section continues with providing a framing of important concepts and methods that help to contextualize the findings presented in subsequent sections. Section TS.2 presents evidence on past trends in stocks and flows of GHGs and the factors that drive emissions at the global, regional, and sectoral scales including economic growth, technology, or population changes. Section TS.3.1 provides findings from studies that analyze the technological, economic, and institutional requirements of long-term mitigation scenarios. Section TS.3.2 provides details on mitigation measures and policies that are used within and across different economic sectors and human settlements. Section TS.4 summarizes insights on the interactions of mitigation policies between governance levels, economic sectors, and instrument types.

**Climate change is a global commons problem that implies the need for international cooperation in tandem with local, national, and regional policies on many distinct matters.** Because the GHG emissions of any agent (individual, company, country) affect every other agent, an effective outcome will not be achieved if individual agents advance their interests independently of others. International cooperation can contribute by defining and allocating rights and responsibilities with respect to the atmosphere [Sections 1.2.4, 3.1, 4.2, 13.2.1]. Moreover, research and development (R&D) in support of mitigation is a public good, which means that international cooperation can play a constructive role in the coordinated development and diffusion of technologies [1.4.4, 3.11, 13.9, 14.4.3]. This gives rise to separate needs for cooperation on R&D, opening up of markets, and the creation of incentives to encourage private firms to develop and deploy new technologies and households to adopt them.

**International cooperation on climate change involves ethical considerations, including equitable effort-sharing.** Countries have contributed differently to the build-up of GHG in the atmosphere, have varying capacities to contribute to mitigation and adaptation, and have different levels of vulnerability to climate impacts. Many less developed countries are exposed to the greatest impacts but have contributed least to the problem. Engaging countries in effective international cooperation may require strategies for sharing the costs and benefits of mitigation in ways that are perceived to be equitable [4.2]. Evidence suggests that perceived fairness can influence the level of cooperation among individuals, and that finding may suggest that processes and outcomes seen as fair will lead to more international cooperation as well [3.10, 13.2.2.4]. Analysis contained in the literature of moral and political philosophy can contribute to resolving ethical questions raised by climate change [3.2, 3.3, 3.4]. These questions include how much overall mitigation is needed to avoid 'dangerous interference with the climate system' (Box

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[2] The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (more likely than not > 50–100 %, and more unlikely than likely 0 –< 50 %) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. For more details, please refer to the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, available at http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

## Box TS.2 | Mitigation brings both market and non-market benefits to humanity

The impacts of mitigation consist in the reduction or elimination of some of the effects of climate change. Mitigation may improve people's livelihood, their health, their access to food or clean water, the amenities of their lives, or the natural environment around them.

Mitigation can improve human well-being through both market and non-market effects. Market effects result from changes in market prices, in people's revenues or net income, or in the quality or availability of market commodities. Non-market effects result from changes in the quality or availability of non-marketed goods such as health, quality of life, culture, environmental quality, natural ecosystems, wildlife, and aesthetic values. Each impact of climate change can generate both market and non-market damages. For example, a heat wave in a rural area may cause heat stress for exposed farm labourers, dry up a wetland that serves as a refuge for migratory birds, or kill some crops and damage others. Avoiding these damages is a benefit of mitigation. [3.9]

Economists often use monetary units to value the damage done by climate change and the benefits of mitigation. The monetized value of a benefit to a person is the amount of income the person would be willing to sacrifice in order to get it, or alternatively the amount she would be willing to accept as adequate compensation for not getting it. The monetized value of a harm is the amount of income she would be willing to sacrifice in order to avoid it, or alternatively the amount she would be willing to accept as adequate compensation for suffering it. Economic measures seek to capture how strongly individuals care about one good or service relative to another, depending on their individual interests, outlook, and economic circumstances. [3.9]

Monetary units can be used in this way to measure costs and benefits that come at different times and to different people. But it cannot be presumed that a dollar to one person at one time can be treated as equivalent to a dollar to a different person or at a different time. Distributional weights may need to be applied between people [3.6.1], and discounting (see Box TS.10) may be appropriate between times. [3.6.2]

TS.1) [3.1], how the effort or cost of mitigating climate change should be shared among countries and between the present and future [3.3, 3.6, 4.6], how to account for such factors as historical responsibility for GHG emissions [3.3, 4.6], and how to choose among alternative policies for mitigation and adaptation [3.4, 3.5, 3.6, 3.7]. Ethical issues of well-being, justice, fairness, and rights are all involved. Ethical analysis can identify the different ethical principles that underlie different viewpoints, and distinguish correct from incorrect ethical reasoning [3.3, 3.4].

**Evaluation of mitigation options requires taking into account many different interests, perspectives, and challenges between and within societies.** Mitigation engages many different agents, such as governments at different levels—regionally [14.1], nationally and locally [15.1], and through international agreements [13.1]—as well as households, firms, and other non-governmental actors. The interconnections between different levels of decision making and among different actors affect the many goals that become linked with climate policy. Indeed, in many countries the policies that have (or could have) the largest impact on emissions are motivated not solely by concerns surrounding climate change. Of particular importance are the interactions and perceived tensions between mitigation and development [4.1, 14.1]. Development involves many activities, such as enhancing access to modern energy services [7.9.1, 14.3.2, 16.8], the building of infrastructures [12.1], ensuring food security [11.1], and eradicating poverty [4.1]. Many of these activities can lead to higher emissions, if achieved by conventional means. Thus, the relationships between development and mitigation can lead to political and ethical conundrums, especially for developing countries, when mitigation is seen as exacerbating urgent development challenges and adversely affecting the current well-being of their populations [4.1]. These conundrums are examined throughout this report, including in special boxes highlighting the concerns of developing countries.

**Economic evaluation can be useful for policy design and be given a foundation in ethics, provided appropriate distributional weights are applied.** While the limitations of economics are widely documented [2.4, 3.5], economics nevertheless provides useful tools for assessing the pros and cons of mitigation and adaptation options. Practical tools that can contribute to decision making include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis, expected utility theory, and methods of decision analysis [2.5, 3.7.2]. Economic valuation (see Box TS.2) can be given a foundation in ethics, provided distributional weights are applied that take proper account of the difference in the value of money to rich and poor people [3.6]. Few empirical applications of economic valuation to climate change have been well-founded in this respect [3.6.1]. The literature provides significant guidance on the social discount rate for consumption (see Box TS.10), which is in effect inter-temporal distributional weighting. It suggests that the social discount rate depends in a well-defined way primarily on the anticipated growth in per capita income and inequality aversion [3.6.2].

**Most climate policies intersect with other societal goals, either positively or negatively, creating the possibility of 'co-benefits'**

## Box TS.3 | Deliberative and intuitive thinking are inputs to effective risk management

When people—from individual voters to key decision makers in firms to senior government policymakers—make choices that involve risk and uncertainty, they rely on deliberative as well intuitive thought processes. Deliberative thinking is characterized by the use of a wide range of formal methods to evaluate alternative choices when probabilities are difficult to specify and/or outcomes are uncertain. They can enable decision makers to compare choices in a systematic manner by taking into account both short and long-term consequences. A strength of these methods is that they help avoid some of the well-known pitfalls of intuitive thinking, such as the tendency of decision makers to favour the status quo. A weakness of these deliberative decision aids is that they are often highly complex and require considerable time and attention.

Most analytically based literature, including reports such as this one, is based on the assumption that individuals undertake deliberative and systematic analyses in comparing options. However, when making mitigation and adaptation choices, people are also likely to engage in intuitive thinking. This kind of thinking has the advantage of requiring less extensive analysis than deliberative thinking. However, relying on one's intuition may not lead one to characterize problems accurately when there is limited past experience. Climate change is a policy challenge in this regard since it involves large numbers of complex actions by many diverse actors, each with their own values, goals, and objectives. Individuals are likely to exhibit well-known patterns of intuitive thinking such as making choices related to risk and uncertainty on the basis of emotional reactions and the use of simplified rules that have been acquired by personal experience. Other tendencies include misjudging probabilities, focusing on short time horizons, and utilizing rules of thumb that selectively attend to subsets of goals and objectives. [2.4]

By recognizing that both deliberative and intuitive modes of decision making are prevalent in the real world, risk management programmes can be developed that achieve their desired impacts. For example, alternative frameworks that do not depend on precise specification of probabilities and outcomes can be considered in designing mitigation and adaptation strategies for climate change. [2.4, 2.5, 2.6]

**or 'adverse side-effects'.** Since the publication of AR4, a substantial body of literature has emerged looking at how countries that engage in mitigation also address other goals, such as local environmental protection or energy security, as a 'co-benefit' and conversely [1.2.1, 6.6.1, 4.8]. This multi-objective perspective is important because it helps to identify areas where political, administrative, stakeholder, and other support for policies that advance multiple goals will be robust. Moreover, in many societies the presence of multiple objectives may make it easier for governments to sustain the political support needed for mitigation [15.2.3]. Measuring the net effect on social welfare (see Box TS.11) requires examining the interaction between climate policies and pre-existing other policies [3.6.3, 6.3.6.5].

**Mitigation efforts generate tradeoffs and synergies with other societal goals that can be evaluated in a sustainable development framework.** The many diverse goals that societies value are often called 'sustainable development'. A comprehensive assessment of climate policy therefore involves going beyond a narrow focus on distinct mitigation and adaptation options and their specific co-benefits and adverse side-effects. Instead it entails incorporating climate issues into the design of comprehensive strategies for equitable and sustainable development at regional, national, and local levels [4.2, 4.5]. Maintaining and advancing human well-being, in particular overcoming poverty and reducing inequalities in living standards, while avoiding unsustainable patterns of consumption and production, are fundamental aspects of equitable and sustainable development [4.4, 4.6, 4.8]. Because these aspects are deeply rooted in how societies formulate and implement economic and social policies generally, they are critical to the adoption of effective climate policy.

**Variations in goals reflect, in part, the fact that humans perceive risks and opportunities differently.** Individuals make their decisions based on different goals and objectives and use a variety of different methods in making choices between alternative options. These choices and their outcomes affect the ability of different societies to cooperate and coordinate. Some groups put greater emphasis on near-term economic development and mitigation costs, while others focus more on the longer-term ramifications of climate change for prosperity. Some are highly risk averse while others are more tolerant of dangers. Some have more resources to adapt to climate change and others have fewer. Some focus on possible catastrophic events while others ignore extreme events as implausible. Some will be relative winners, and some relative losers from particular climate changes. Some have more political power to articulate their preferences and secure their interests and others have less. Since AR4, awareness has grown that such considerations—long the domain of psychology, behavioural economics, political economy, and other disciplines—need to be taken into account in assessing climate policy (see Box TS.3). In addition to the different perceptions of climate change and its risks, a variety of norms can also affect what humans view as acceptable behaviour. Awareness has grown about how such norms spread through social networks and ultimately affect activities, behaviours and lifestyles, and thus development pathways, which can have profound impacts on GHG emissions and mitigation policy. [1.4.2, 2.4, 3.8, 3.10, 4.3]

### Box TS.4 | 'Fat tails': unlikely vs. likely outcomes in understanding the value of mitigation

What has become known as the 'fat-tails' problem relates to uncertainty in the climate system and its implications for mitigation and adaptation policies. By assessing the chain of structural uncertainties that affect the climate system, the resulting compound probability distribution of possible economic damage may have a fat right tail. That means that the probability of damage does not decline with increasing temperature as quickly as the consequences rise.

The significance of fat tails can be illustrated for the distribution of temperature that will result from a doubling of atmospheric carbon dioxide ($CO_2$) (climate sensitivity). IPCC Working Group I (WGI) estimates may be used to calibrate two possible distributions, one fat-tailed and one thin-tailed, that each have a median temperature change of 3 °C and a 15 % probability of a temperature change in excess of 4.5 °C. Although the probability of exceeding 4.5 °C is the same for both distributions, likelihood drops off much more slowly with increasing temperature for the fat-tailed compared to the thin-tailed distribution. For example, the probability of temperatures in excess of 8 °C is nearly ten times greater with the chosen fat-tailed distribution than with the thin-tailed distribution. If temperature changes are characterized by a fat tailed distribution, and events with large impact may occur at higher temperatures, then tail events can dominate the computation of expected damages from climate change.

In developing mitigation and adaptation policies, there is value in recognizing the higher likelihood of tail events and their consequences. In fact, the nature of the probability distribution of temperature change can profoundly change how climate policy is framed and structured. Specifically, fatter tails increase the importance of tail events (such as 8 °C warming). While research attention and much policy discussion have focused on the most likely outcomes, it may be that those in the tail of the probability distribution are more important to consider. [2.5, 3.9.2]

**Effective climate policy involves building institutions and capacity for governance.** While there is strong evidence that a transition to a sustainable and equitable path is technically feasible, charting an effective and viable course for climate change mitigation is not merely a technical exercise. It will involve myriad and sequential decisions among states and civil society actors. Such a process benefits from the education and empowerment of diverse actors to participate in systems of decision making that are designed and implemented with procedural equity as a deliberate objective. This applies at the national as well as international levels, where effective governance relating to global common resources, in particular, is not yet mature. Any given approach has potential winners and losers. The political feasibility of that approach will depend strongly on the distribution of power, resources, and decision-making authority among the potential winners and losers. In a world characterized by profound disparities, procedurally equitable systems of engagement, decision making and governance may help enable a polity to come to equitable solutions to the sustainable development challenge. [4.3]

**Effective risk management of climate change involves considering uncertainties in possible physical impacts as well as human and social responses.** Climate change mitigation and adaptation is a risk management challenge that involves many different decision-making levels and policy choices that interact in complex and often unpredictable ways. Risks and uncertainties arise in natural, social, and technological systems. As Box TS.3 explains, effective risk management strategies not only consider people's values, and their intuitive decision processes but utilize formal models and decision aids for systematically addressing issues of risk and uncertainty [2.4, 2.5]. Research on other such complex and uncertainty-laden policy domains suggest the importance of adopting policies and measures that are robust across a variety of criteria and possible outcomes [2.5]. As detailed in Box TS.4, a special challenge arises with the growing evidence that climate change may result in extreme impacts whose trigger points and outcomes are shrouded in high levels of uncertainty [2.5, 3.9.2]. A risk management strategy for climate change will require integrating responses in mitigation with different time horizons, adaptation to an array of climate impacts, and even possible emergency responses such as 'geoengineering' in the face of extreme climate impacts [1.4.2, 3.3.7, 6.9, 13.4.4]. In the face of potential extreme impacts, the ability to quickly offset warming could help limit some of the most extreme climate impacts although deploying these geoengineering systems could create many other risks (see Section TS.3.1.3). One of the central challenges in developing a risk management strategy is to have it adaptive to new information and different governing institutions [2.5].

## TS.2 Trends in stocks and flows of greenhouse gases and their drivers

*This section summarizes historical GHG emissions trends and their underlying drivers. As in most of the underlying literature, all aggregate GHG emissions estimates are converted to $CO_2$-equivalents based on Global Warming Potentials with a 100-year time horizon ($GWP_{100}$) (Box TS.5). The majority of changes in GHG emissions trends that are observed in this section are related to changes in drivers such as eco-*

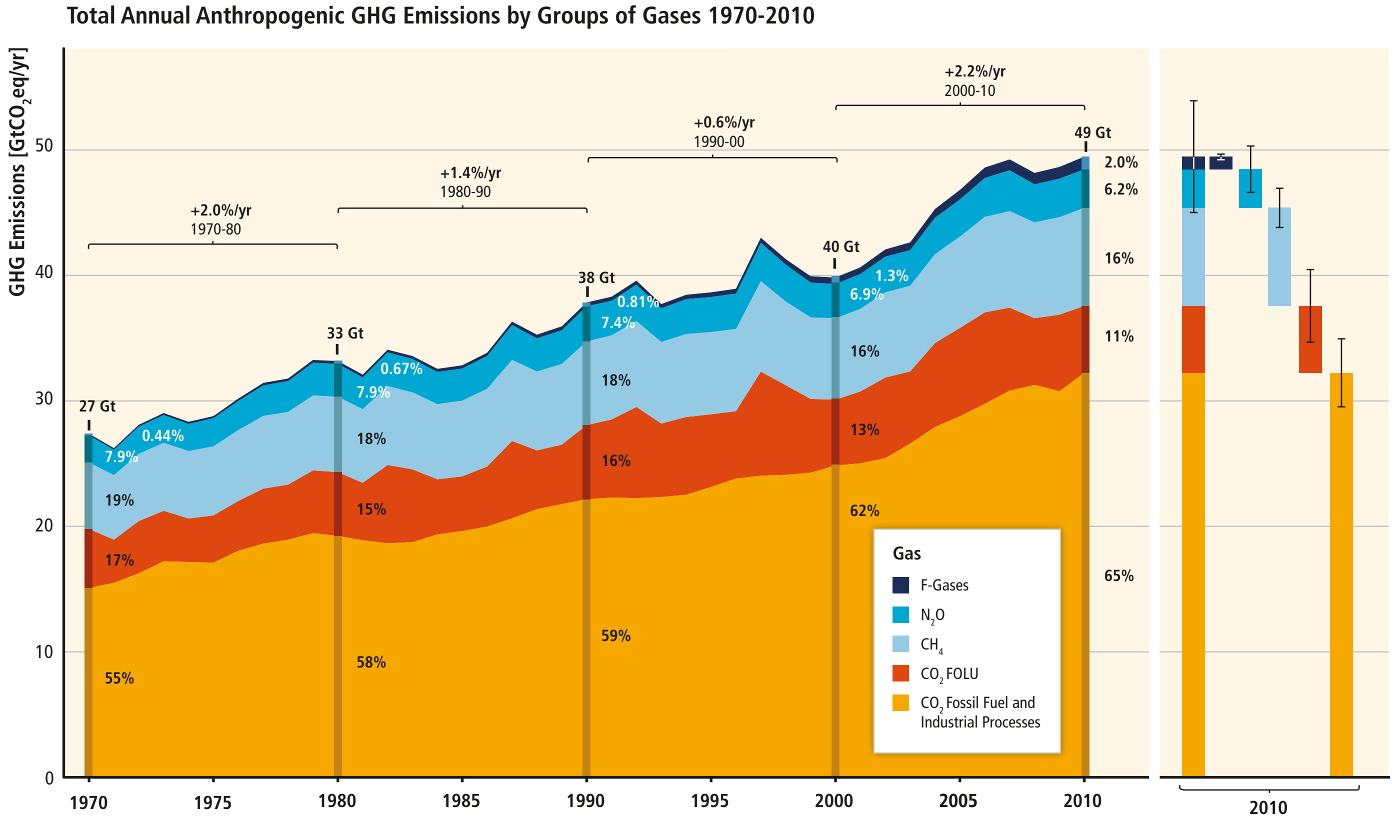

**Figure TS.1 |** Total annual anthropogenic GHG emissions (GtCO$_2$eq/yr) by groups of gases 1970–2010: carbon dioxide (CO$_2$) from fossil fuel combustion and industrial processes; CO$_2$ from Forestry and Other Land Use[4] (FOLU); methane (CH$_4$); nitrous oxide (N$_2$O); fluorinated gases[5] covered under the Kyoto Protocol (F-gases). At the right side of the figure, GHG emissions in 2010 are shown again broken down into these components with the associated uncertainties (90 % confidence interval) indicated by the error bars. Total anthropogenic GHG emissions uncertainties are derived from the individual gas estimates as described in Chapter 5 [5.2.3.6]. Emissions are converted into CO$_2$-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP$_{100}$) from the IPCC Second Assessment Report (SAR). The emissions data from FOLU represents land-based CO$_2$ emissions from forest and peat fires and decay that approximate to the net CO$_2$ flux from FOLU as described in Chapter 11 of this report. Average annual GHG emissions growth rates for the four decades are highlighted with the brackets. The average annual growth rate from 1970 to 2000 is 1.3 %. [Figure 1.3]

*nomic growth, technological change, human behaviour, or population growth. But there are also some smaller changes in GHG emissions estimates that are due to refinements in measurement concepts and methods that have happened since AR4. There is a growing body of literature on uncertainties in global GHG emissions data sets. This section tries to make these uncertainties explicit and reports variations in estimates across global data sets wherever possible.*

## TS.2.1 Greenhouse gas emission trends

**Total anthropogenic GHG emissions have risen more rapidly from 2000 to 2010 than in the previous three decades** (*high confidence*). Total anthropogenic GHG emissions were the highest in human history from 2000 to 2010 and reached 49 (±4.5) gigatonnes CO$_2$-equivalents per year (GtCO$_2$eq/yr) in 2010.[3] Current trends are at the high end of levels that had been projected for this last decade. GHG emissions growth has occurred despite the presence of a wide array of multilateral institutions as well as national policies aimed at mitigation. From 2000 to 2010, GHG emissions grew on average by 1.0 GtCO$_2$eq (2.2 %) per year compared to 0.4 GtCO$_2$eq (1.3 %) per year over the entire period from 1970 to 2000 (Figure TS.1). The global economic crisis 2007/2008 has only temporarily reduced GHG emissions. [1.3, 5.2, 13.3, 15.2.2, Figure 15.1]

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[3] In this summary, uncertainty in historic GHG emissions data is reported using 90 % uncertainty intervals unless otherwise stated. GHG emissions levels are rounded to two significant digits throughout this document; as a consequence, small differences in sums due to rounding may occur.

[4] FOLU (Forestry and Other Land Use)—also referred to as LULUCF (Land Use, Land-Use Change, and Forestry)—is the subset of Agriculture, Forestry, and Other Land Use (AFOLU) emissions and removals of GHGs related to direct human-induced land use, land-use change and forestry activities excluding agricultural emissions (see WGIII AR5 Glossary).

[5] In this report, data on non-CO$_2$ GHGs, including fluorinated gases, are taken from the EDGAR database (see Annex II.9), which covers substances included in the Kyoto Protocol in its first commitment period.

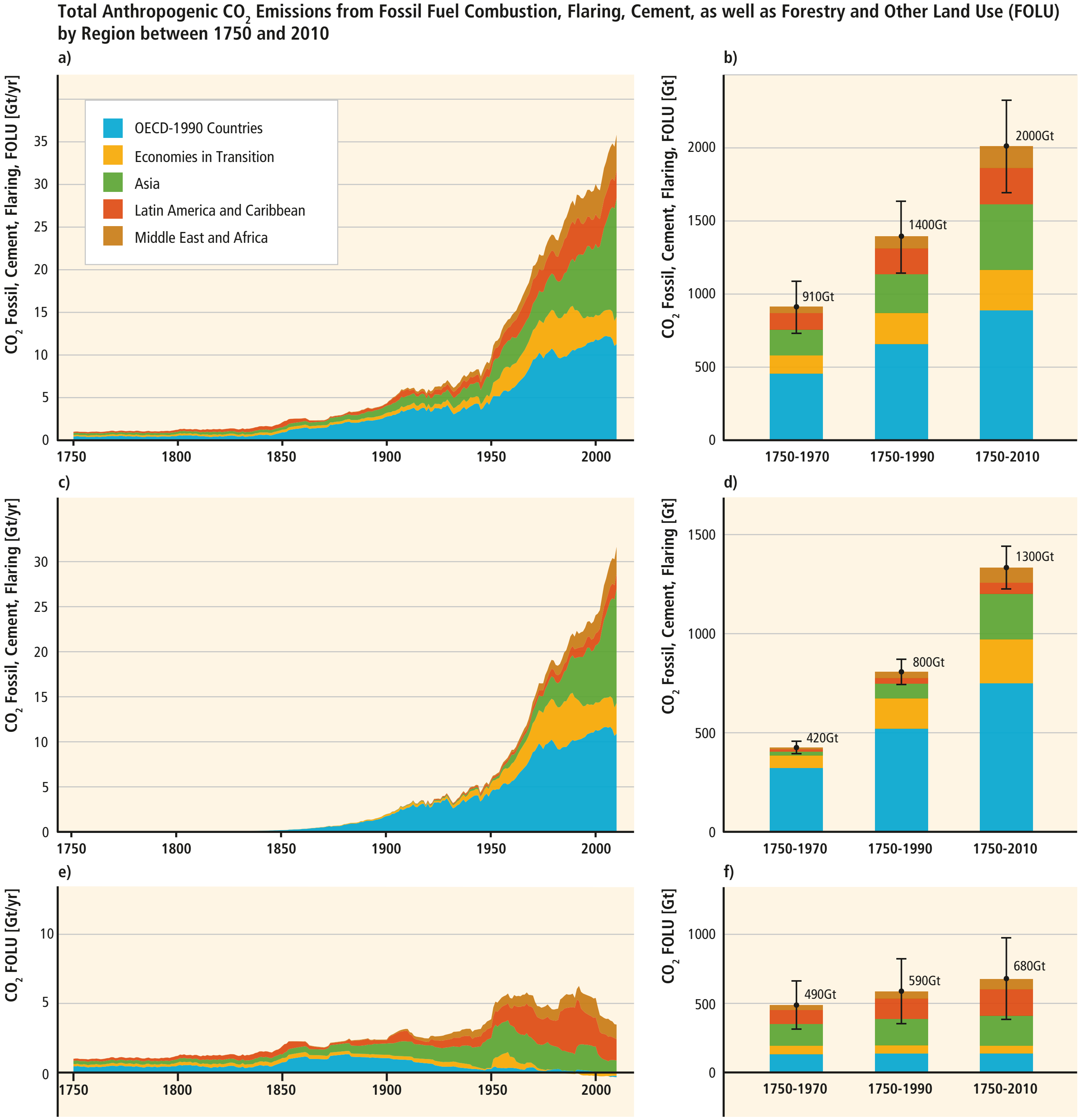

**Figure TS.2 |** Historical anthropogenic $CO_2$ emissions from fossil fuel combustion, flaring, cement, and Forestry and Other Land Use (FOLU)[4] in five major world regions: OECD-1990 (blue); Economies in Transition (yellow); Asia (green); Latin America and Caribbean (red); Middle East and Africa (brown). Emissions are reported in gigatonnes of $CO_2$ per year ($GtCO_2/yr$). Left panels show regional $CO_2$ emissions 1750–2010 from: (a) the sum of all $CO_2$ sources (c+e); (c) fossil fuel combustion, flaring, and cement; and (e) FOLU. The right panels report regional contributions to cumulative $CO_2$ emissions over selected time periods from: (b) the sum of all $CO_2$ sources (d+f); (d) fossil fuel combustion, flaring and cement; and (f) FOLU. Error bars on panels (b), (d) and (f) give an indication of the uncertainty range (90 % confidence interval). See Annex II.2.2 for definitions of regions. [Figure 5.3]

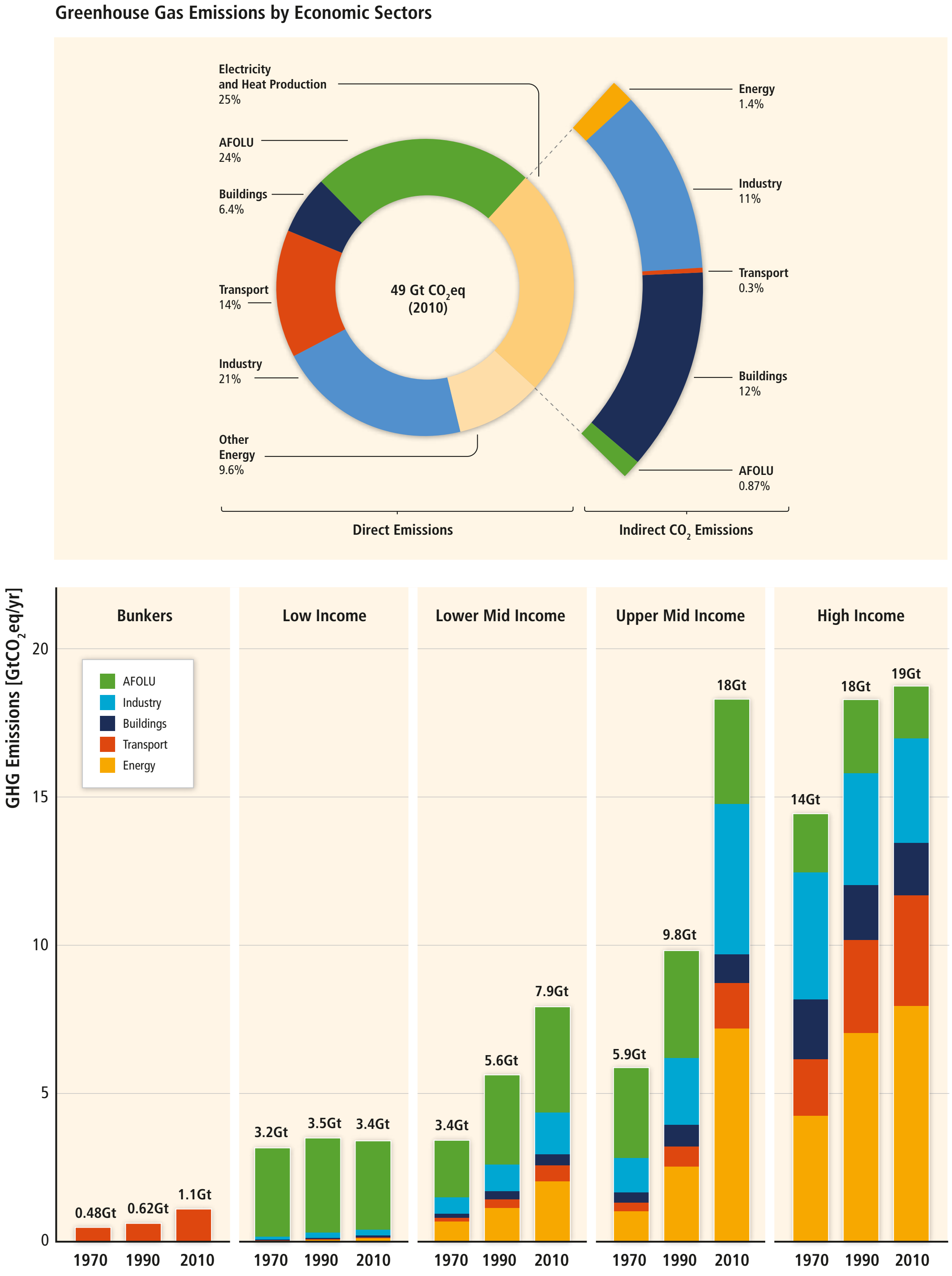

**Figure TS.3 |** Total anthropogenic GHG emissions (GtCO$_2$ eq/yr) by economic sectors and country income groups. Upper panel: Circle shows direct GHG emission shares (in % of total anthropogenic GHG emissions) of five major economic sectors in 2010. Pull-out shows how indirect CO$_2$ emission shares (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other Energy' refers to all GHG emission sources in the energy sector other than electricity and heat production. Lower panel: Total anthropogenic GHG emissions in 1970, 1990 and 2010 by five major economic sectors and country income groups. 'Bunkers' refer to GHG emissions from international transportation and thus are not, under current accounting systems, allocated to any particular nation's territory. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO$_2$ emissions from forest and peat fires and decay that approximate to the net CO$_2$ flux from the Forestry and Other Land Use (FOLU) sub-sector as described in Chapter 11 of this report. Emissions are converted into CO$_2$-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP$_{100}$) from the IPCC Second Assessment Report (SAR). Assignment of countries to income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. Sector definitions are provided in Annex II.9.1. [Figure 1.3, Figure 1.6]

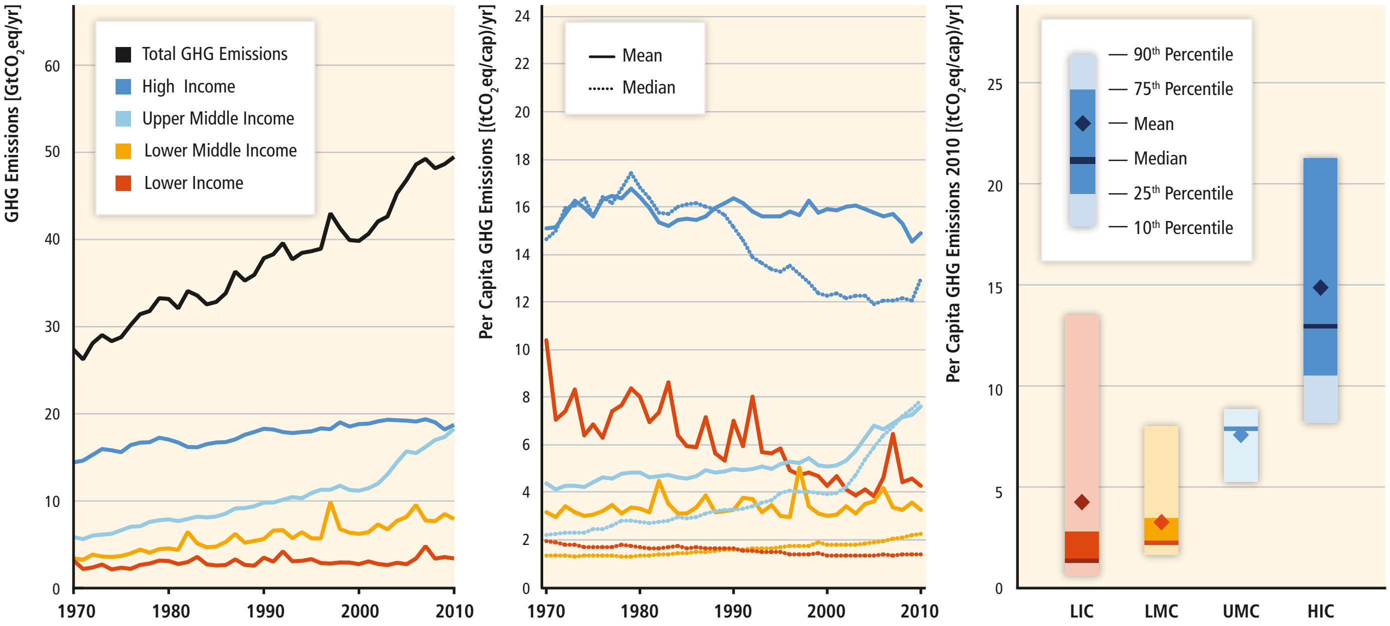

**Figure TS.4 |** Trends in GHG emissions by country income groups. Left panel: Total annual anthropogenic GHG emissions from 1970 to 2010 (GtCO$_2$eq/yr). Middle panel: Trends in annual per capita mean and median GHG emissions from 1970 to 2010 (tCO$_2$eq/cap/yr). Right panel: Distribution of annual per capita GHG emissions in 2010 of countries within each country income group (tCO$_2$/cap/yr). Mean values show the GHG emissions levels weighed by population. Median values describe GHG emissions levels per capita of the country at the 50th percentile of the distribution within each country income group. Emissions are converted into CO$_2$-equivalents based on Global Warming Potentials with a 100-year time horizon (GWP$_{100}$) from the IPCC Second Assessment Report (SAR). Assignment of countries to country income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. [Figures 1.4, 1.8]

**CO$_2$ emissions from fossil fuel combustion and industrial processes contributed about 78 % to the total GHG emissions increase from 1970 to 2010, with similar percentage contribution for the period 2000–2010** (*high confidence*). Fossil fuel-related CO$_2$ emissions reached 32 (±2.7) GtCO$_2$/yr in 2010 and grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Since AR4, the shares of the major groups of GHG emissions have remained stable. Of the 49 (±4.5) GtCO$_2$eq/yr in total anthropogenic GHG emissions in 2010, CO$_2$ remains the major GHG accounting for 76 % (38±3.8 GtCO$_2$eq/yr) of total anthropogenic GHG emissions. 16 % (7.8±1.6 GtCO$_2$eq/yr) come from methane (CH$_4$), 6.2 % (3.1±1.9 GtCO$_2$eq/yr) from nitrous oxide (N$_2$O), and 2.0 % (1.0±0.2 GtCO$_2$eq/yr) from fluorinated gases (Figure TS.1).[5] Using the most recent GWP$_{100}$ values from the AR5 [WGI 8.7] global GHG emissions totals would be slightly higher (52 GtCO$_2$eq/yr) and non-CO$_2$ emission shares would be 20 % for CH$_4$, 5.0 % for N$_2$O and 2.2 % for F-gases. Emission shares are sensitive to the choice of emission metric and time horizon, but this has a small influence on global, long-term trends. If a shorter, 20-year time horizon were used, then the share of CO$_2$ would decline to just over 50 % of total anthropogenic GHG emissions and short-lived gases would rise in relative importance. As detailed in Box TS.5, the choice of emission metric and time horizon involves explicit or implicit value judgements and depends on the purpose of the analysis. [1.2, 3.9, 5.2]

**Over the last four decades total cumulative CO$_2$ emissions have increased by a factor of 2 from about 910 GtCO$_2$ for the period 1750–1970 to about 2000 GtCO$_2$ for 1750–2010** (*high confidence*). In 1970, the cumulative CO$_2$ emissions from fossil fuel combustion, cement production and flaring since 1750 was 420 (±35) GtCO$_2$; in 2010 that cumulative total had tripled to 1300 (±110) GtCO$_2$ (Figure TS.2). Cumulative CO$_2$ emissions associated with FOLU[4] since 1750 increased from about 490 (±180) GtCO$_2$ in 1970 to approximately 680 (±300) GtCO$_2$ in 2010. [5.2]

**Regional patterns of GHG emissions are shifting along with changes in the world economy** (*high confidence*). Since 2000, GHG emissions have been growing in all sectors, except Agriculture, Forestry and Other Land Use (AFOLU)[4] where positive and negative emission changes are reported across different databases and uncertainties in the data are high. More than 75 % of the 10 Gt increase in annual GHG emissions between 2000 and 2010 was emitted in the energy supply (47 %) and industry (30 %) sectors (see Annex II.9.I for sector definitions). 5.9 GtCO$_2$eq of this sectoral increase occurred in upper-middle income countries,[6] where the most rapid economic development and infrastructure expansion has taken place. GHG emissions growth in the other sectors has been more modest in absolute (0.3–1.1 Gt CO$_2$eq) as well as in relative terms (3 %–11 %). [1.3, 5.3, Figure 5.18]

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[6] When countries are assigned to income groups in this summary, the World Bank income classification for 2013 is used. For details see Annex II.2.3.

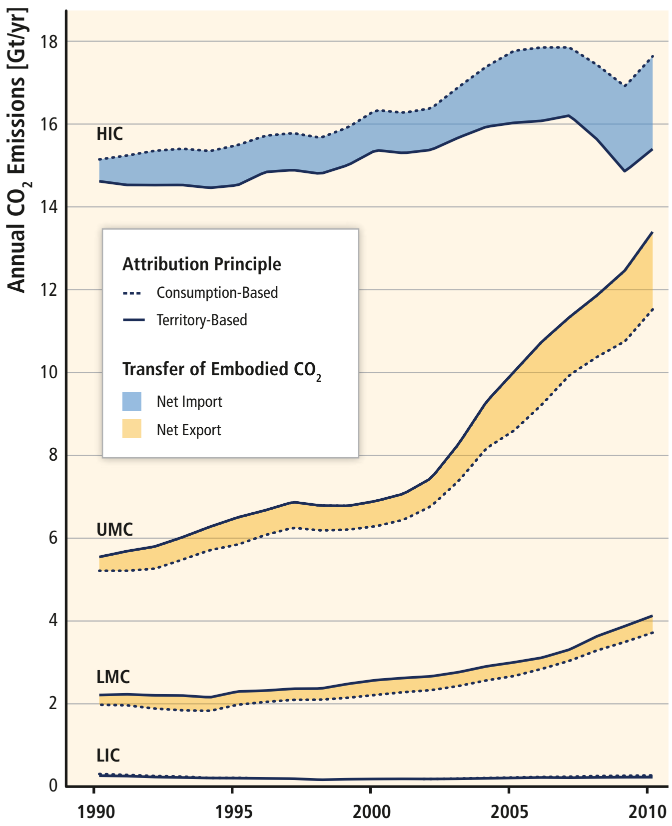

**Figure TS.5 |** Total annual CO$_2$ emissions (GtCO$_2$/yr) from fossil fuel combustion for country income groups attributed on the basis of territory (solid line) and final consumption (dotted line). The shaded areas are the net CO$_2$ trade balances (differences) between each of the four country income groups and the rest of the world. Blue shading indicates that the country income group is a net importer of embodied CO$_2$ emissions, leading to consumption-based emission estimates that are higher than traditional territorial emission estimates. Orange indicates the reverse situation—the country income group is a net exporter of embodied CO$_2$ emissions. Assignment of countries to country income groups is based on the World Bank income classification in 2013. For details see Annex II.2.3. [Figure 1.5]

**Current GHG emission levels are dominated by contributions from the energy supply, AFOLU, and industry sectors; industry and buildings gain considerably in importance if indirect emissions are accounted for** (*robust evidence, high agreement*). Of the 49 (±4.5) GtCO$_2$eq emissions in 2010, 35 % (17 GtCO$_2$eq) of GHG emissions were released in the energy supply sector, 24 % (12 GtCO$_2$eq, net emissions) in AFOLU, 21 % (10 GtCO$_2$eq) in industry, 14 % (7.0 GtCO$_2$eq) in transport, and 6.4 % (3.2 GtCO$_2$eq) in buildings. When indirect emissions from electricity and heat production are assigned to sectors of final energy use, the shares of the industry and buildings sectors in global GHG emissions grow to 31 % and 19 %,[3] respectively (Figure TS.3 upper panel). [1.3, 7.3, 8.2, 9.2, 10.3, 11.2]

**Per capita GHG emissions in 2010 are highly unequal** (*high confidence*). In 2010, median per capita GHG emissions (1.4 tCO$_2$eq/cap/yr) for the group of low-income countries are around nine times lower than median per capita GHG emissions (13 tCO$_2$eq/cap/yr) of high-income countries (Figure TS.4).[6] For low-income countries, the largest part of GHG emissions comes from AFOLU; for high-income countries, GHG emissions are dominated by sources related to energy supply and industry (Figure TS.3 lower panel). There are substantial variations in per capita GHG emissions within country income groups with emissions at the 90th percentile level more than double those at the 10th percentile level. Median per capita emissions better represent the typical country within a country income group comprised of heterogeneous members than mean per capita emissions. Mean per capita GHG emissions are different from median mainly in low-income countries as individual low-income countries have high per capita emissions due to large CO$_2$ emissions from land-use change (Figure TS.4, right panel). [1.3, 5.2, 5.3]

**A growing share of total anthropogenic CO$_2$ emissions is released in the manufacture of products that are traded across international borders** (*medium evidence, high agreement*). Since AR4, several data sets have quantified the difference between traditional 'territorial' and 'consumption-based' emission estimates that assign all emission released in the global production of goods and services to the country of final consumption (Figure TS.5). A growing share of CO$_2$ emissions from fossil fuel combustion in middle income countries is released in the production of goods and services exported, notably from upper middle income countries to high income countries. Total annual industrial CO$_2$ emissions from the non-Annex I group now exceed those of the Annex I group using territorial and consumption-based accounting methods, but per-capita emissions are still markedly higher in the Annex I group. [1.3, 5.3]

**Regardless of the perspective taken, the largest share of anthropogenic CO$_2$ emissions is emitted by a small number of countries** (*high confidence*). In 2010, 10 countries accounted for about 70 % of CO$_2$ emissions from fossil fuel combustion and industrial processes. A similarly small number of countries emit the largest share of consumption-based CO$_2$ emissions as well as cumulative CO$_2$ emissions going back to 1750. [1.3]

**The upward trend in global fossil fuel related CO$_2$ emissions is robust across databases and despite uncertainties** (*high confidence*). Global CO$_2$ emissions from fossil fuel combustion are known within 8 % uncertainty. CO$_2$ emissions related to FOLU have very large uncertainties attached in the order of 50 %. Uncertainty for global emissions of methane (CH$_4$), nitrous oxide (N$_2$O), and the fluorinated gases has been estimated as 20 %, 60 %, and 20 %. Combining these values yields an illustrative total global GHG uncertainty estimate of about 10 % (Figure TS.1). Uncertainties can increase at finer spatial scales and for specific sectors. Attributing GHG emissions to the country of final consumption increases uncertainties, but literature on this topic is just emerging. GHG emissions estimates in the AR4 were 5–10 % higher than the estimates reported here, but lie within the estimated uncertainty range.[3] [5.2]

## Box TS.5 | Emissions metrics depend on value judgements and contain wide uncertainties

Emission metrics provide 'exchange rates' for measuring the contributions of different GHGs to climate change. Such exchange rates serve a variety of purposes, including apportioning mitigation efforts among several gases and aggregating emissions of a variety of GHGs. However, there is no metric that is both conceptually correct and practical to implement. Because of this, the choice of the appropriate metric depends on the application or policy at issue. [3.9.6]

GHGs differ in their physical characteristics. For example, per unit mass in the atmosphere, methane ($CH_4$) causes a stronger instantaneous radiative forcing than $CO_2$, but it remains in the atmosphere for a much shorter time. Thus, the time profiles of climate change brought about by different GHGs are different and consequential. Determining how emissions of different GHGs are compared for mitigation purposes involves comparing the resulting temporal profiles of climate change from each gas and making value judgments about the relative significance to humans of these profiles, which is a process fraught with uncertainty. [3.9.6; WGI 8.7]

A commonly used metric is the Global Warming Potential (GWP). It is defined as the accumulated radiative forcing within a specific time horizon (e.g., 100 years—$GWP_{100}$), caused by emitting one kilogram of the gas, relative to that of the reference gas $CO_2$. This metric is used to transform the effects of different GHG emissions to a common scale ($CO_2$-equivalents).[1] One strength of the GWP is that it can be calculated in a relatively transparent and straightforward manner. However, there are also limitations, including the requirement to use a specific time horizon, the focus on cumulative forcing, and the insensitivity of the metric to the temporal profile of climate effects and its significance to humans. The choice of time horizon is particularly important for short-lived gases, notably methane: when computed with a shorter time horizon for GWP, their share in calculated total warming effect is larger and the mitigation strategy might change as a consequence. [1.2.5]

Many alternative metrics have been proposed in the scientific literature. All of them have advantages and disadvantages, and the choice of metric can make a large difference for the weights given to emissions from particular gases. For instance, methane's $GWP_{100}$ is 28 while its Global Temperature Change Potential (GTP), one alternative metric, is 4 for the same time horizon (AR5 values, see WGI Section 8.7). In terms of aggregate mitigation costs alone, $GWP_{100}$ may perform similarly to other metrics (such as the time-dependent Global Temperature Change Potential or the Global Cost Potential) of reaching a prescribed climate target; however, there may be significant differences in terms of the implied distribution of costs across sectors, regions, and over time. [3.9.6, 6.3.2.5]

An alternative to a single metric for all gases is to adopt a 'multi-basket' approach in which gases are grouped according to their contributions to short and long term climate change. This may solve some problems associated with using a single metric, but the question remains of what relative importance to attach to reducing GHG emissions in the different groups. [3.9.6; WGI 8.7]

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[1] In this summary, all quantities of GHG emissions are expressed in $CO_2$-equivalent ($CO_2eq$) emissions that are calculated based on $GWP_{100}$. Unless otherwise stated, GWP values for different gases are taken from IPCC Second Assessment Report (SAR). Although GWP values have been updated several times since, the SAR values are widely used in policy settings, including the Kyoto Protocol, as well as in many national and international emission accounting systems. Modelling studies show that the changes in $GWP_{100}$ values from SAR to AR4 have little impact on the optimal mitigation strategy at the global level. [6.3.2.5, Annex II.9.1]

## TS.2.2 Greenhouse gas emission drivers

*This section examines the factors that have, historically, been associated with changes in GHG emissions levels. Typically, such analysis is based on a decomposition of total GHG emissions into various components such as growth in the economy (Gross Domestic Product (GDP)/capita), growth in the population (capita), the energy intensity needed per unit of economic output (energy/GDP) and the GHG emissions intensity of that energy (GHGs/energy). As a practical matter, due to data limitations and the fact that most GHG emissions take the form of $CO_2$ from industry and energy, almost all this research focuses on $CO_2$ from those sectors.*

**Globally, economic and population growth continue to be the most important drivers of increases in $CO_2$ emissions from fossil fuel combustion. The contribution of population growth between 2000 and 2010 remained roughly identical to the previous three decades, while the contribution of economic growth has risen sharply** (*high confidence*). Worldwide population increased by 86 % between 1970 and 2010, from 3.7 to 6.9 billion. Over the same period, income as measured through production and/ or consumption per capita has grown by a factor of about two. The exact measurement of global economic growth is difficult because countries use different currencies and converting individual national economic figures into global totals can be done in various ways. With rising population and economic output, emissions of $CO_2$ from fossil fuel combustion have risen as well. Over the last decade, the importance of economic growth as a driver of global $CO_2$ emissions has risen sharply while population growth has remained roughly steady. Due to changes in technology, changes in the economic structure and the mix of energy sources as well as changes in other inputs such as capital and labour, the energy intensity of economic output has steadily declined worldwide. This decline has had an offsetting effect on global $CO_2$ emissions that is nearly of the same magnitude as growth in population (Figure TS.6). There are only a few countries that combine economic growth and decreasing territorial $CO_2$ emissions over longer periods of time. Such decoupling remains largely atypical, especially when considering consumption-based $CO_2$ emissions. [1.3, 5.3]

**Between 2000 and 2010, increased use of coal relative to other energy sources has reversed a long-standing pattern of gradual decarbonization of the world's energy supply** (*high confidence*). Increased use of coal, especially in developing Asia, is exacerbating the burden of energy-related GHG emissions (Figure TS.6). Estimates

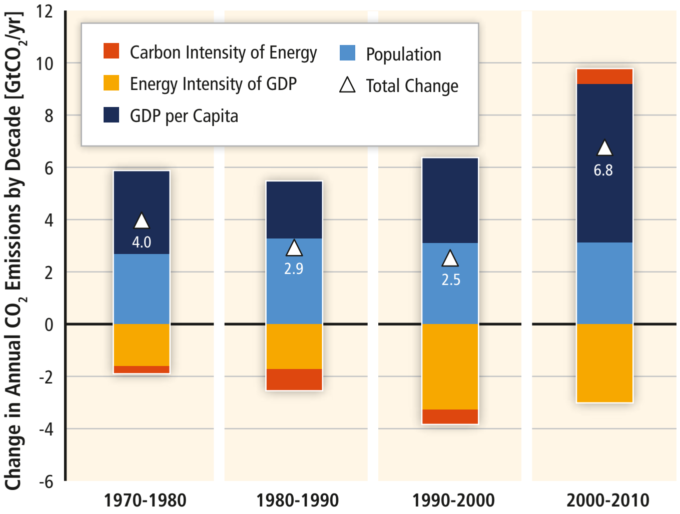

**Figure TS.6 |** Decomposition of the change in total annual $CO_2$ emissions from fossil fuel combustion by decade and four driving factors: population, income (GDP) per capita, energy intensity of GDP and carbon intensity of energy. Total emissions changes are indicated by a triangle. The change in emissions over each decade is measured in gigatonnes of $CO_2$ per year ($GtCO_2$/yr); income is converted into common units using purchasing power parities. [Figure 1.7]

## Box TS.6 | The use of scenarios in this report

Scenarios of how the future might evolve capture key factors of human development that influence GHG emissions and our ability to respond to climate change. Scenarios cover a range of plausible futures, because human development is determined by a myriad of factors including human decision making. Scenarios can be used to integrate knowledge about the drivers of GHG emissions, mitigation options, climate change, and climate impacts.

One important element of scenarios is the projection of the level of human interference with the climate system. To this end, a set of four 'representative concentration pathways' (RCPs) has been developed. These RCPs reach radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 Watts per square meter ($W/m^2$) (corresponding to concentrations of 450, 650, 850, and 1370 ppm $CO_2eq$), respectively, in 2100, covering the range of anthropogenic climate forcing in the 21st century as reported in the literature. The four RCPs are the basis of a new set of climate change projections that have been assessed by WGI AR5. [WGI 6.4, WGI 12.4]

Scenarios of how the future develops without additional and explicit efforts to mitigate climate change ('baseline scenarios') and with the introduction of efforts to limit GHG emissions ('mitigation scenarios'), respectively, generally include socio-economic projections in addition to emission, concentration, and climate change information. WGIII AR5 has assessed the full breadth of baseline and mitigation scenarios in the literature. To this end, it has collected a database of more than 1200 published mitigation and baseline scenarios. In most cases, the underlying socio-economic projections reflect the modelling teams' individual choices about how to conceptualize the future in the absence of climate policy. The baseline scenarios show a wide range of assumptions about economic growth (ranging from threefold to more than eightfold growth in per capita income by 2100), demand for energy (ranging from a 40 % to more than 80 % decline in energy intensity by 2100) and other factors, in particular the carbon intensity of energy. Assumptions about population are an exception: the vast majority of scenarios focus on the low to medium population range of nine to 10 billion people by 2100. Although the range of emissions pathways across baseline scenarios in the literature is broad, it may not represent the full potential range of possibilities (Figure TS.7). [6.3.1]

The concentration outcomes of the baseline and mitigation scenarios assessed by WGIII AR5 cover the full range of RCPs. However, they provide much more detail at the lower end, with many scenarios aiming at concentration levels in the range of 450, 500, and 550 ppm $CO_2eq$ in 2100. The climate change projections of WGI based on RCPs, and the mitigation scenarios assessed by WGIII AR5 can be related to each other through the climate outcomes they imply. [6.2.1]

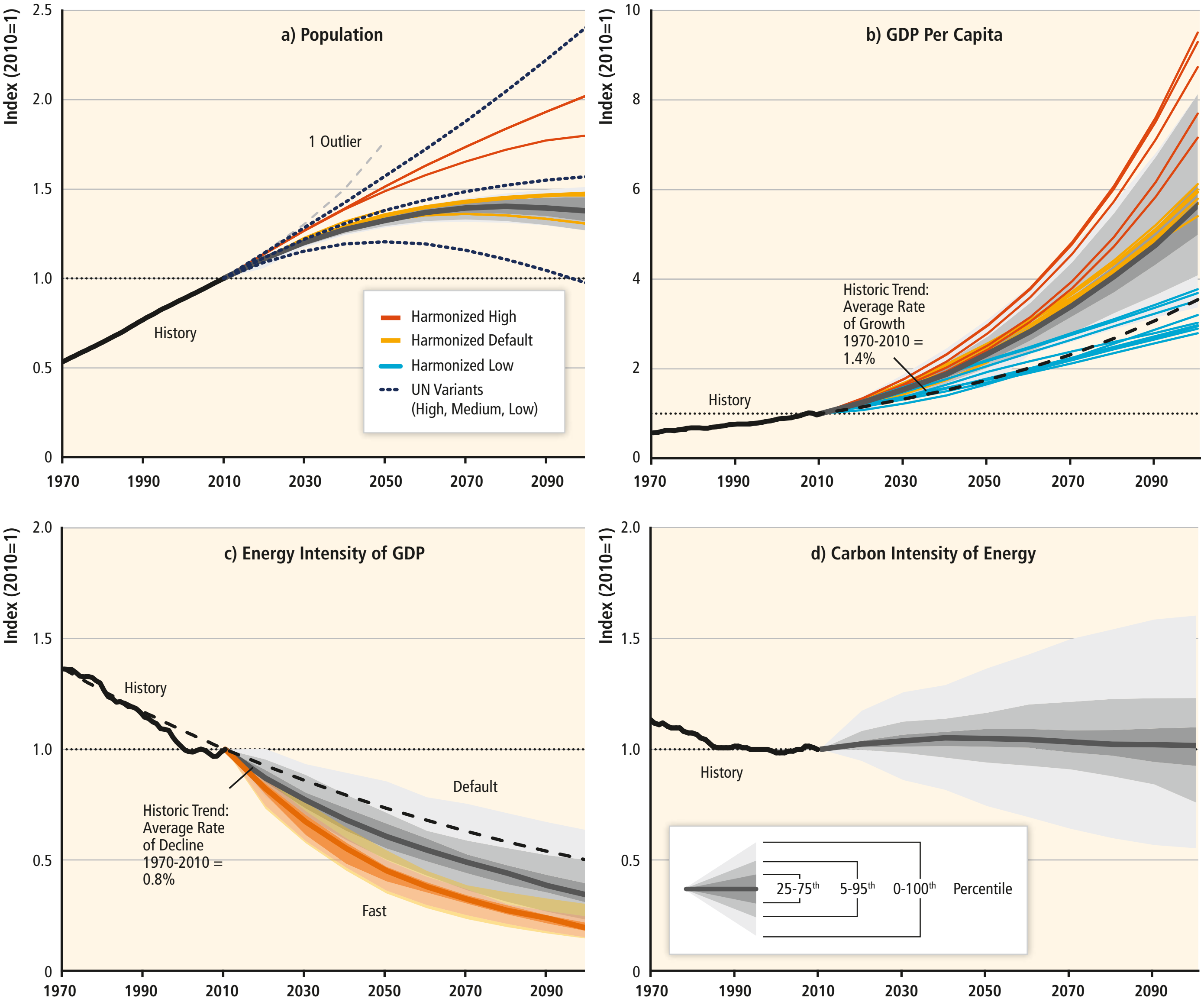

**Figure TS.7 |** Global baseline projection ranges for four emissions driving factors. Scenarios harmonized with respect to a particular factor are depicted with individual lines. Other scenarios are depicted as a range with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full range (lightest), excluding one indicated outlier in panel a). Scenarios are filtered by model and study for each indicator to include only unique projections. Model projections and historic data are normalized to 1 in 2010. GDP is aggregated using base-year market exchange rates. Energy and carbon intensity are measured with respect to total primary energy. [Figure 6.1]

indicate that coal and unconventional gas and oil resources are large; therefore reducing the carbon intensity of energy may not be primarily driven by fossil resource scarcity, but rather by other driving forces such as changes in technology, values, and socio-political choices. [5.3, 7.2, 7.3, 7.4; SRREN Figure 1.7]

**Technological innovations, infrastructural choices, and behaviour affect GHG emissions through productivity growth, energy- and carbon-intensity and consumption patterns** (*medium confidence*). Technological innovation improves labour and resource productivity; it can support economic growth both with increasing and with decreasing GHG emissions. The direction and speed of technological change depends on policies. Technology is also central to the choices of infrastructure and spatial organization, such as in cities, which can have long-lasting effects on GHG emissions. In addition, a wide array of attitudes, values, and norms can inform different lifestyles, consumption preferences, and technological choices all of which, in turn, affect patterns of GHG emissions. [5.3, 5.5, 5.6, 12.3]

**Without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist, driven by growth in global population and economic activities despite improvements in energy supply and end-use technologies** (*high confidence*). Atmospheric concentrations in baseline scenarios collected for this assessment (scenarios without explicit additional efforts to reduce GHG emissions) exceed 450 parts per million (ppm) $CO_2$eq by 2030.[7] They reach $CO_2$eq concentration levels from 750 to more than 1300 ppm $CO_2$eq by 2100 and result in projected global mean surface temperature increases in 2100 from 3.7 to 4.8 °C compared to pre-industrial levels[8] (range based on median climate response; the range is 2.5 °C to 7.8 °C when including climate uncertainty, see Table TS.1).[9] The range of 2100 concentrations corresponds roughly to the range of $CO_2$eq concentrations in the Representative Concentration Pathways (RCP) 6.0 and RCP8.5 pathways (see Box TS.6), with the majority of scenarios falling below the latter. For comparison, the $CO_2$eq concentration in 2011 has been estimated to be 430 ppm (uncertainty range 340–520 ppm).[10] The literature does not systematically explore the full range of uncertainty surrounding development pathways and possible evolution of key drivers such as population, technology, and resources. Nonetheless, the scenarios strongly suggest that absent any explicit mitigation efforts, cumulative $CO_2$ emissions since 2010 will exceed 700 $GtCO_2$ by 2030, 1,500 $GtCO_2$ by 2050, and potentially well over 4,000 $GtCO_2$ by 2100. [6.3.1; WGI Figure SPM.5, WGI 8.5, WGI 12.3]

# TS.3 Mitigation pathways and measures in the context of sustainable development

*This section assesses the literature on mitigation pathways and measures in the context of sustainable development. Section TS 3.1 first examines the anthropogenic GHG emissions trajectories and potential temperature implications of mitigation pathways leading to a range of future atmospheric $CO_2$eq concentrations. It then explores the technological, economic, and institutional requirements of these pathways along with their potential co-benefits and adverse side-effects. Section TS 3.2 examines mitigation options by sector and how they may interact across sectors.*

## TS.3.1 Mitigation pathways

### TS.3.1.1 Understanding mitigation pathways in the context of multiple objectives

**The world's societies will need to both mitigate and adapt to climate change if it is to effectively avoid harmful climate impacts** (*robust evidence, high agreement*). There are demonstrated examples of synergies between mitigation and adaptation [11.5.4, 12.8.1] in which the two strategies are complementary. More generally, the two strategies are related because increasing levels of mitigation imply less future need for adaptation. Although major efforts are now underway to incorporate impacts and adaptation into mitigation scenarios, inherent difficulties associated with quantifying their interdependencies have limited their representation in models used to generate mitigation scenarios assessed in WGIII AR5 (Box TS.7). [2.6.3, 3.7.2.1, 6.3.3]

**There is no single pathway to stabilize $CO_2$eq concentrations at any level; instead, the literature points to a wide range of mitigation pathways that might meet any concentration level** (*high confidence*). Choices, whether deliberated or not, will determine which of these pathways is followed. These choices include, among other things, the emissions pathway to bring atmospheric $CO_2$eq concentrations to a particular level, the degree to which concentrations temporarily exceed (overshoot) the long-term level, the technologies that are deployed to reduce emissions, the degree to which mitigation is coordinated across countries, the policy approaches used to achieve mitigation within and across countries, the treatment of land use, and the manner in which mitigation is meshed with other policy objectives such as sustainable development. A society's development pathway—with its particular socioeconomic, institutional, political, cultural and technological features—enables and constrains the prospects for mitigation. At the national level, change is considered most effective when it reflects country and local visions and approaches to achieving sustainable development according to national circumstances and priorities. [4.2, 6.3–6.8, 11.8]

**Mitigation pathways can be distinguished from one another by a range of outcomes or requirements** (*high confidence*). Decisions about mitigation pathways can be made by weighing the requirements of different pathways against each other. Although measures of aggregate economic costs and benefits have often been put forward as key decision-making factors, they are far from the only outcomes that matter. Mitigation pathways inherently involve a range of synergies and tradeoffs connected with other policy objectives such as energy and food security, energy access, the distribution of economic impacts, local air quality, other environmental factors associated with different technological solutions, and economic competitiveness (Box TS.11). Many of these fall under the umbrella of sustainable development. In addition, requirements such as the rates of up-scaling of energy technologies or the rates of reductions in GHG emissions may provide important insights into the degree of challenge associated with meeting a particular long-term goal. [4.5, 4.8, 6.3, 6.4, 6.6]

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[7] These $CO_2$eq concentrations represent full radiative forcing, including GHGs, halogenated gases, tropospheric ozone, aerosols, mineral dust and albedo change.

[8] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61 °C (5–95 % confidence interval: 0.55 to 0.67 °C) [WGI SPM.E], which is used here as an approximation of the change in global mean surface temperature since pre-industrial times, referred to as the period before 1750.

[9] Provided estimates reflect the 10th to the 90th percentile of baseline scenarios collected for this assessment. The climate uncertainty reflects the 5th to 95th percentile of climate model calculations described in Table TS.1 for each scenario.

[10] This is based on the assessment of total anthropogenic radiative forcing for 2011 relative to 1750 in WGI AR5, i.e., 2.3 $W m^{-2}$, uncertainty range 1.1 to 3.3 $W m^{-2}$. [WGI Figure SPM.5, WGI 8.5, WGI 12.3]

## Box TS.7 | Scenarios from integrated models can help to understand how actions affect outcomes in complex systems

The long-term scenarios assessed in this report were generated primarily by large-scale computer models, referred to here as 'integrated models', because they attempt to represent many of the most important interactions among technologies, relevant human systems (e.g., energy, agriculture, the economic system), and associated GHG emissions in a single integrated framework. A subset of these models is referred to as 'integrated assessment models', or IAMs. IAMs include not only an integrated representation of human systems, but also of important physical processes associated with climate change, such as the carbon cycle, and sometimes representations of impacts from climate change. Some IAMs have the capability of endogenously balancing impacts with mitigation costs, though these models tend to be highly aggregated. Although aggregate models with representations of mitigation and damage costs can be very useful, the focus in this assessment is on integrated models with sufficient sectoral and geographic resolution to understand the evolution of key processes such as energy systems or land systems.

Scenarios from integrated models are invaluable to help understand how possible actions or choices might lead to different future outcomes in these complex systems. They provide quantitative, long-term projections (conditional on our current state of knowledge) of many of the most important characteristics of mitigation pathways while accounting for many of the most important interactions between the various relevant human and natural systems. For example, they provide both regional and global information about emissions pathways, energy and land-use transitions, and aggregate economic costs of mitigation.

At the same time, these integrated models have particular characteristics and limitations that should be considered when interpreting their results. Many integrated models are based on the rational choice paradigm for decision making, excluding the consideration of some behavioural factors. The models approximate cost-effective solutions that minimize the aggregate economic costs of achieving mitigation outcomes, unless they are specifically constrained to behave otherwise. Scenarios from these models capture only some of the dimensions of development pathways that are relevant to mitigation options, often only minimally treating issues such as distributional impacts of mitigation actions and consistency with broader development goals. In addition, the models in this assessment do not effectively account for the interactions between mitigation, adaptation, and climate impacts. For these reasons, mitigation has been assessed independently from climate impacts. Finally, and most fundamentally, integrated models are simplified, stylized, numerical approaches for representing enormously complex physical and social systems, and scenarios from these models are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why output generated from different models—or versions of the same model—can differ, and projections from all models can differ considerably from the reality that unfolds. [3.7, 6.2]

### TS.3.1.2 Short- and long-term requirements of mitigation pathways

**Mitigation scenarios point to a range of technological and behavioral measures that could allow the world's societies to follow GHG emissions pathways consistent with a range of different levels of mitigation** (*high confidence*). As part of this assessment, about 900 mitigation and 300 baseline scenarios have been collected from integrated modelling research groups around the world (Box TS.7). The mitigation scenarios span atmospheric concentration levels in 2100 from 430 ppm $CO_2$eq to above 720 ppm $CO_2$eq, which is roughly comparable to the 2100 forcing levels between the RCP2.6 and RCP6.0 scenarios (Figure TS.8, left panel). Scenarios have been constructed to reach mitigation goals under very different assumptions about energy demands, international cooperation, technologies, the contributions of $CO_2$ and other forcing agents to atmospheric $CO_2$eq concentrations, and the degree to which concentrations temporarily exceed the long-term goal (concentration overshoot, see Box TS.8). Other scenarios were also assessed, including some scenarios with concentrations in 2100 below 430 ppm $CO_2$eq (for a discussion of these scenarios see below). [6.3]

**Limiting atmospheric peak concentrations over the course of the century—not only reaching long-term concentration levels—is critical for limiting transient temperature change** (*high confidence*). Scenarios reaching concentration levels of about 500 ppm $CO_2$eq by 2100 are *more likely than not* to limit temperature change to less than 2 °C relative to pre-industrial levels, unless they temporarily 'overshoot' concentration levels of roughly 530 ppm $CO_2$eq before 2100. In this case, they are *about as likely as not* to achieve that goal. The majority of scenarios reaching long-term concentrations of about 450 ppm $CO_2$eq in 2100 are *likely* to keep temperature change below 2 °C over the course of the century relative to pre-industrial levels (Table TS.1, Box TS.8). Scenarios that reach 530 to 650 ppm $CO_2$eq concentrations by 2100 are *more unlikely than likely* to keep temperature change below 2 °C relative to pre-industrial levels. Scenarios that exceed about 650 ppm $CO_2$eq by 2100 are *unlikely* to limit temperature change to below 2 °C relative to pre-industrial levels. Mitigation

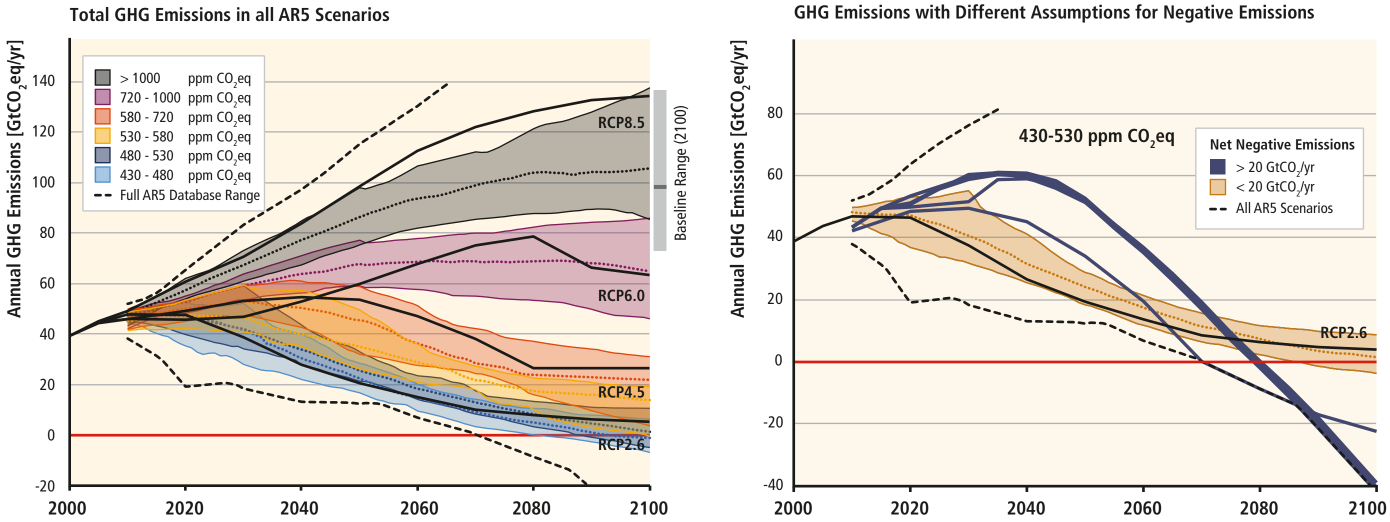

**Figure TS.8 |** Development of total GHG emissions for different long-term concentration levels (left panel) and for scenarios reaching about 450 to about 500 (430–530) ppm $CO_2$eq in 2100 with and without net negative $CO_2$ emissions larger than 20 $GtCO_2$/yr (right panel). Ranges are given for the 10th–90th percentile of scenarios. [Figure 6.7]

scenarios in which temperature increase is *more likely than not* to be less than 1.5 °C relative to pre-industrial levels by 2100 are characterized by concentrations in 2100 of below 430 ppm $CO_2$eq. Temperature peaks during the century and then declines in these scenarios. [6.3]

**Mitigation scenarios reaching about 450 ppm $CO_2$eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm or about 550 ppm $CO_2$eq in 2100** (*high confidence*). Concentration overshoot means that concentrations peak during the century before descending toward their 2100 levels. Overshoot involves less mitigation in the near term, but it also involves more rapid and deeper emissions reductions in the long run. The vast majority of scenarios reaching about 450 ppm $CO_2$eq in 2100 involve concentration overshoot, since most models cannot reach the immediate, near-term emissions reductions that would be necessary to avoid overshoot of these concentration levels. Many scenarios have been constructed to reach about 550 ppm $CO_2$eq by 2100 without overshoot.

**Depending on the level of overshoot, many overshoot scenarios rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and/or afforestation in the second half of the century** (*high confidence*). These and other carbon dioxide removal (CDR) technologies and methods remove $CO_2$ from the atmosphere (negative emissions). Scenarios with overshoot of greater than 0.4 W/m$^2$ (> 35–50 ppm $CO_2$eq concentration) typically deploy CDR technologies to an extent that net global $CO_2$ emissions become negative in the second-half of the century (Figure TS.8, right panel). CDR is also prevalent in many scenarios without concentration overshoot to compensate for residual emissions from sectors where mitigation is more expensive. The availability and potential of BECCS, afforestation, and other CDR technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks. There is uncertainty about the potential for large-scale deployment of BECCS, large-scale afforestation, and other CDR technologies and methods. [6.3, 6.9]

**Reaching atmospheric concentration levels of about 450 to about 500 ppm $CO_2$eq by 2100 will require substantial cuts in anthropogenic GHG emissions by mid-century** (*high confidence*). Scenarios reaching about 450 ppm $CO_2$eq by 2100 are associated with GHG emissions reductions of about 40 % to 70 % by 2050 compared to 2010 and emissions levels near zero $GtCO_2$eq or below in 2100.[11] Scenarios with GHG emissions reductions in 2050 at the lower end of this range are characterized by a greater reliance on CDR technologies beyond mid-century. The majority of scenarios that reach about 500 ppm $CO_2$eq in 2100 without overshooting roughly 530 ppm $CO_2$eq at any point during the century are associated with GHG emissions reductions of 40 % to 55 % by 2050 compared to 2010 (Figure TS.8, left panel; Table TS.1). In contrast, in some scenarios in which concentrations rise to well above 530 ppm $CO_2$eq during the century before descending to concentrations below this level by 2100, emissions rise to as high as 20 % above 2010 levels in 2050. However, these high-overshoot scenarios are characterized by negative global emissions of well over 20 $GtCO_2$ per year in the second half of the century (Figure TS.8, right panel). Cumulative $CO_2$

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[11] This range differs from the range provided for a similar concentration category in AR4 (50 % to 85 % lower than 2000 for $CO_2$ only). Reasons for this difference include that this report has assessed a substantially larger number of scenarios than in AR4 and looks at all GHGs. In addition, a large proportion of the new scenarios include Carbon Dioxide Removal (CDR) technologies and associated increases in concentration overshoot. Other factors include the use of 2100 concentration levels instead of stabilization levels and the shift in reference year from 2000 to 2010.

## Box TS.8 | Assessment of temperature change in the context of mitigation scenarios

Long-term climate goals have been expressed both in terms of concentrations and temperature. Article 2 of the UNFCCC calls for the need to 'stabilize' concentrations of GHGs. Stabilization of concentrations is generally understood to mean that the $CO_2eq$ concentration reaches a specific level and then remains at that level indefinitely until the global carbon and other cycles come into a new equilibrium. The notion of stabilization does not necessarily preclude the possibility that concentrations might exceed, or 'overshoot' the long-term goal before eventually stabilizing at that goal. The possibility of 'overshoot' has important implications for the required GHG emissions reductions to reach a long-term concentration level. Concentration overshoot involves less mitigation in the near term with more rapid and deeper emissions reductions in the long run.

The temperature response of the concentration pathways assessed in this report focuses on transient temperature change over the course of the century. This is an important difference with WGIII AR4, which focused on the long-term equilibrium temperature response, a state that is reached millennia after the stabilization of concentrations. The temperature outcomes in this report are thus not directly comparable to those presented in the WGIII AR4 assessment. One reason that this assessment focuses on transient temperature response is that it is less uncertain than the equilibrium response and correlates more strongly with GHG emissions in the near and medium term. An additional reason is that the mitigation pathways assessed in WGIII AR5 do not extend beyond 2100 and are primarily designed to reach specific concentration goals for the year 2100. The majority of these pathways do not stabilize concentrations in 2100, which makes the assessment of the equilibrium temperature response ambiguous and dependent on assumptions about post-2100 emissions and concentrations.

Transient temperature goals might be defined in terms of the temperature in a specific year (e.g., 2100), or based on never exceeding a particular level. This report explores the implications of both types of goals. The assessment of temperature goals are complicated by the uncertainty that surrounds our understanding of key physical relationships in the earth system, most notably the relationship between concentrations and temperature. It is not possible to state definitively whether any long-term concentration pathway will limit either transient or equilibrium temperature change to below a specified level. It is only possible to express the temperature implications of particular concentration pathways in probabilistic terms, and such estimates will be dependent on the source of the probability distribution of different climate parameters and the climate model used for analysis. This report employs the MAGICC model and a distribution of climate parameters that results in temperature outcomes with dynamics similar to those from the Earth System Models assessed in WGI AR5. For each emissions scenario, a median transient temperature response is calculated to illustrate the variation of temperature due to different emissions pathways. In addition, a transient temperature range for each scenario is provided, reflecting the climate system uncertainties. Information regarding the full distribution of climate parameters was utilized for estimating the likelihood that the scenarios would limit transient temperature change to below specific levels (Table TS.1). Providing the combination of information about the plausible range of temperature outcomes as well as the likelihood of meeting different targets is of critical importance for policymaking, since it facilitates the assessment of different climate objectives from a risk management perspective. [2.5.7.2, 6.3.2]

emissions between 2011 and 2100 are 630–1180 $GtCO_2$ in scenarios reaching about 450 ppm $CO_2eq$ in 2100; they are 960–1550 $GtCO_2$ in scenarios reaching about 500 ppm $CO_2eq$ in 2100. The variation in cumulative $CO_2$ emissions across scenarios is due to differences in the contribution of non-$CO_2$ GHGs and other radiatively active substances as well as the timing of mitigation (Table TS.1). [6.3]

**In order to reach atmospheric concentration levels of about 450 to about 500 ppm $CO_2eq$ by 2100, the majority of mitigation relative to baseline emissions over the course of century will occur in the non-Organisation for Economic Co-operation and Development (OECD) countries** (*high confidence*). In scenarios that attempt to cost-effectively allocate emissions reductions across countries and over time, the total $CO_2eq$ emissions reductions from baseline emissions in non-OECD countries are greater than in OECD countries. This is, in large part, because baseline emissions from the non-OECD countries are projected to be larger than those from the OECD countries, but it also derives from higher carbon intensities in non-OECD countries and different terms of trade structures. In these scenarios, GHG emissions peak earlier in the OECD countries than in the non-OECD countries. [6.3]

**Reaching atmospheric concentration levels of about 450 to about 650 ppm $CO_2eq$ by 2100 will require large-scale changes to global and national energy systems over the coming decades** (*high confidence*). Scenarios reaching atmospheric concentrations levels of about 450 to about 500 ppm $CO_2eq$ by 2100 are characterized by a tripling to nearly a quadrupling of the global share of zero- and low-carbon energy supply from renewables, nuclear energy, fossil energy with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS), by the year 2050 relative to 2010 (about 17 %) (Figure TS.10, left panel). The increase in total global low-carbon energy sup-

**Table TS.1 |** Key characteristics of the scenarios collected and assessed for WGIII AR5. For all parameters, the 10th to 90th percentile of the scenarios is shown.[1, 2] [Table 6.3]

| $CO_2$eq Concentrations in 2100 [ppm $CO_2$eq] Category label (concentration range)[9] | Subcategories | Relative position of the RCPs[5] | Cumulative $CO_2$ emissions[3] [$GtCO_2$] | | Change in $CO_2$eq emissions compared to 2010 in [%][4] | | Temperature change (relative to 1850–1900)[5, 6] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2011–2050 | 2011–2100 | 2050 | 2100 | 2100 Temperature change [°C][7] | Likelihood of staying below temperature level over the 21st century[8] | | | |
| | | | | | | | | 1.5 °C | 2.0 °C | 3.0 °C | 4.0 °C |
| < 430 | Only a limited number of individual model studies have explored levels below 430 ppm $CO_2$eq | | | | | | | | | | |
| **450 (430–480)** | Total range[1, 10] | RCP2.6 | 550–1300 | 630–1180 | −72 to −41 | −118 to −78 | 1.5–1.7 (1.0–2.8) | *More unlikely than likely* | *Likely* | *Likely* | *Likely* |
| **500 (480–530)** | No overshoot of 530 ppm $CO_2$eq | | 860–1180 | 960–1430 | −57 to −42 | −107 to −73 | 1.7–1.9 (1.2–2.9) | *Unlikely* | *More likely than not* | | |
| | Overshoot of 530 ppm $CO_2$eq | | 1130–1530 | 990–1550 | −55 to −25 | −114 to −90 | 1.8–2.0 (1.2–3.3) | | *About as likely as not* | | |
| **550 (530–580)** | No overshoot of 580 ppm $CO_2$eq | | 1070–1460 | 1240–2240 | −47 to −19 | −81 to −59 | 2.0–2.2 (1.4–3.6) | | *More unlikely than likely*[12] | | |
| | Overshoot of 580 ppm $CO_2$eq | | 1420–1750 | 1170–2100 | −16 to 7 | −183 to −86 | 2.1–2.3 (1.4–3.6) | | | | |
| **(580–650)** | Total range | RCP4.5 | 1260–1640 | 1870–2440 | −38 to 24 | −134 to −50 | 2.3–2.6 (1.5–4.2) | | | | |
| **(650–720)** | Total range | | 1310–1750 | 2570–3340 | −11 to 17 | −54 to −21 | 2.6–2.9 (1.8–4.5) | | *Unlikely* | *More likely than not* | |
| **(720–1000)[2]** | Total range | RCP6.0 | 1570–1940 | 3620–4990 | 18 to 54 | −7 to 72 | 3.1–3.7 (2.1–5.8) | *Unlikely*[11] | | *More unlikely than likely* | |
| **>1000[2]** | Total range | RCP8.5 | 1840–2310 | 5350–7010 | 52 to 95 | 74 to 178 | 4.1–4.8 (2.8–7.8) | | *Unlikely*[11] | *Unlikely* | *More unlikely than likely* |

Notes:

[1] The ‘total range’ for the 430–480 ppm $CO_2$eq scenarios corresponds to the range of the 10th–90th percentile of the subcategory of these scenarios shown in Table 6.3.

[2] Baseline scenarios (see TS.2.2) fall into the >1000 and 720–1000 ppm $CO_2$eq categories. The latter category also includes mitigation scenarios. The baseline scenarios in the latter category reach a temperature change of 2.5–5.8 °C above preindustrial in 2100. Together with the baseline scenarios in the >1000 ppm $CO_2$eq category, this leads to an overall 2100 temperature range of 2.5–7.8 °C (range based on median climate response: 3.7–4.8 °C) for baseline scenarios across both concentration categories.

[3] For comparison of the cumulative $CO_2$ emissions estimates assessed here with those presented in WGI AR5, an amount of 515 [445–585] GtC (1890 [1630–2150] $GtCO_2$), was already emitted by 2011 since 1870 [WGI 12.5]. Note that cumulative $CO_2$ emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative $CO_2$ emissions in WGI AR5 are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood [WGI Table SPM.3, WGI SPM.E.8].

[4] The global 2010 emissions are 31 % above the 1990 emissions (consistent with the historic GHG emissions estimates presented in this report). $CO_2$eq emissions include the basket of Kyoto gases ($CO_2$, $CH_4$, $N_2O$ as well as F-gases).

[5] The assessment in WGIII AR5 involves a large number of scenarios published in the scientific literature and is thus not limited to the RCPs. To evaluate the $CO_2$eq concentration and climate implications of these scenarios, the MAGICC model was used in a probabilistic mode (see Annex II). For a comparison between MAGICC model results and the outcomes of the models used in WGI, see Sections WGI 12.4.1.2, WGI 12.4.8 and 6.3.2.6. Reasons for differences with WGI SPM Table.2 include the difference in reference year (1986–2005 vs. 1850–1900 here), difference in reporting year (2081–2100 vs 2100 here), set-up of simulation (CMIP5 concentration-driven versus MAGICC emission-driven here), and the wider set of scenarios (RCPs versus the full set of scenarios in the WGIII AR5 scenario database here).

[6] Temperature change is reported for the year 2100, which is not directly comparable to the equilibrium warming reported in WGIII AR4 [Table 3.5, Chapter 3; see also WGIII AR5 6.3.2]. For the 2100 temperature estimates, the transient climate response (TCR) is the most relevant system property. The assumed 90 % range of the TCR for MAGICC is 1.2–2.6 °C (median 1.8 °C). This compares to the 90 % range of TCR between 1.2–2.4 °C for CMIP5 [WGI 9.7] and an assessed *likely* range of 1–2.5 °C from multiple lines of evidence reported in the WGI AR5 [Box 12.2 in Section 12.5].

[7] Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category. The range of temperature change in the parentheses includes in addition the carbon cycle and climate system uncertainties as represented by the MAGICC model [see 6.3.2.6 for further details]. The temperature data compared to the 1850–1900 reference year was calculated by taking all projected warming relative to 1986–2005, and adding 0.61 °C for 1986–2005 compared to 1850–1900, based on HadCRUT4 [see WGI Table SPM.2].

[8] The assessment in this table is based on the probabilities calculated for the full ensemble of scenarios in WGIII AR5 using MAGICC and the assessment in WGI AR5 of the uncertainty of the temperature projections not covered by climate models. The statements are therefore consistent with the statements in WGI AR5, which are based on the CMIP5 runs of the RCPs and the assessed uncertainties. Hence, the likelihood statements reflect different lines of evidence from both WGs. This WGI method was also applied for scenarios with intermediate concentration levels where no CMIP5 runs are available. The likelihood statements are indicative only [6.3], and follow broadly the terms used by the WGI AR5 SPM for temperature projections: *likely* 66–100 %, *more likely than not* >50–100 %, *about as likely as not* 33–66 %, and *unlikely* 0–33 %. In addition the term *more unlikely than likely* 0–<50 % is used.

[9] The $CO_2$-equivalent concentration includes the forcing of all GHGs including halogenated gases and tropospheric ozone, as well as aerosols and albedo change (calculated on the basis of the total forcing from a simple carbon cycle/climate model, MAGICC).

[10] The vast majority of scenarios in this category overshoot the category boundary of 480 ppm $CO_2$eq concentrations.

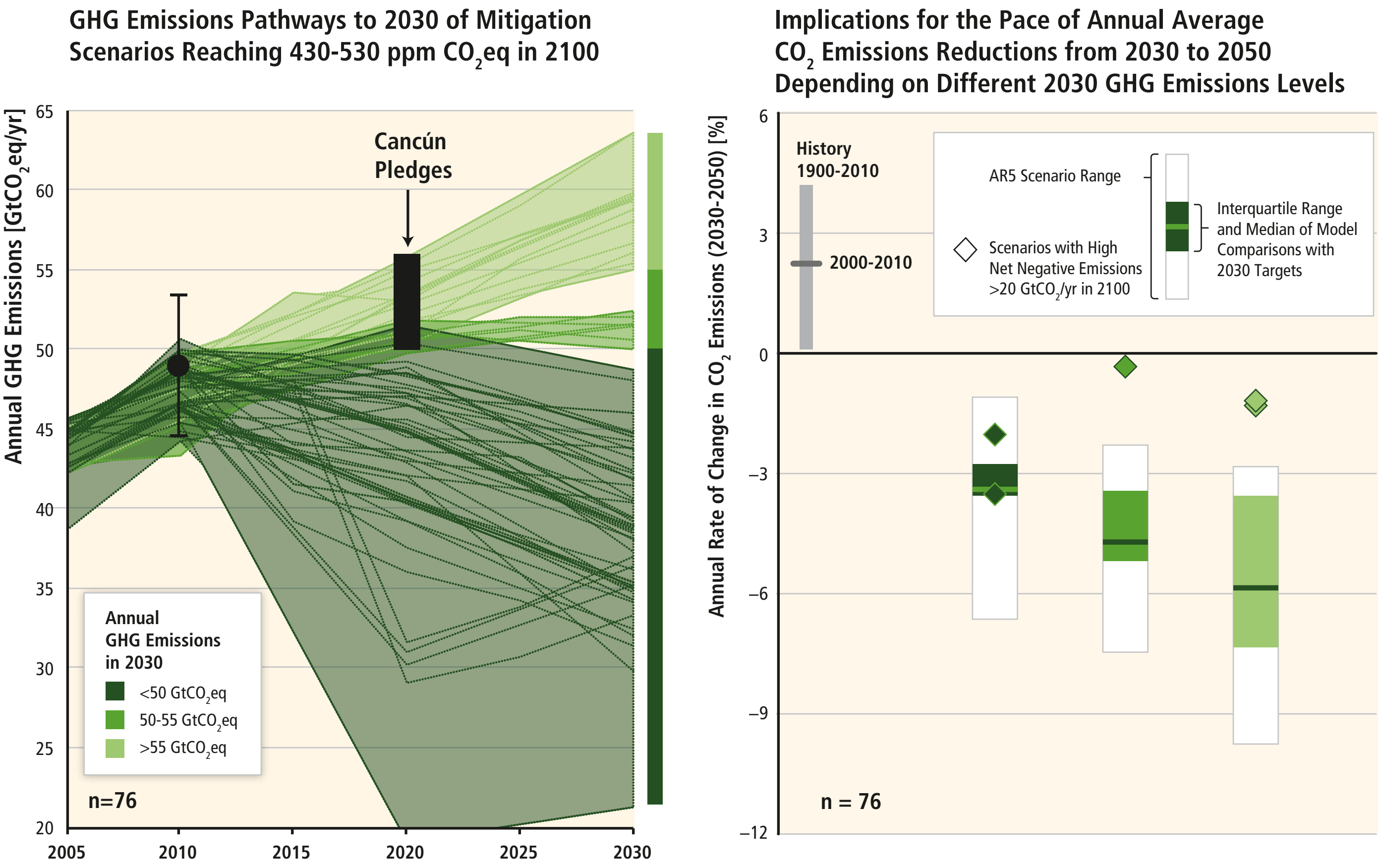
[11] For scenarios in this category no CMIP5 run [WGI Chapter 12, Table 12.3] as well as no MAGICC realization [6.3] stays below the respective temperature level. Still, an *unlikely* assignment is given to reflect uncertainties that might not be reflected by the current climate models.

[12] Scenarios in the 580–650 ppm $CO_2$eq category include both overshoot scenarios and scenarios that do not exceed the concentration level at the high end of the category (like RCP4.5). The latter type of scenarios, in general, have an assessed probability of *more unlikely than likely* to stay below the 2 °C temperature level, while the former are mostly assessed to have an *unlikely* probability of staying below this level.

ply is from three-fold to seven-fold over this same period. Many models could not reach 2100 concentration levels of about 450 ppm $CO_2$eq if the full suite of low-carbon technologies is not available. Studies indicate a large potential for energy demand reductions, but also indicate that demand reductions on their own would not be sufficient to bring about the reductions needed to reach levels of about 650 ppm $CO_2$eq or below by 2100. [6.3, 7.11]

**Mitigation scenarios indicate a potentially critical role for land-related mitigation measures and that a wide range of alternative land transformations may be consistent with similar concentration levels** (*medium confidence*). Land-use dynamics in mitigation scenarios are heavily influenced by the production of bioenergy and the degree to which afforestation is deployed as a negative-emissions, or CDR option. They are, in addition, influenced by forces independent of mitigation such as agricultural productivity improvements and increased demand for food. The range of land-use transformations depicted in mitigation scenarios reflects a wide range of differing assumptions about the evolution of all of these forces. Many scenarios reflect strong increases in the degree of competition for land between food, feed, and energy uses. [6.3, 6.8, 11.4.2]

**Delaying mitigation efforts beyond those in place today through 2030 will increase the challenges of, and reduce the options for, limiting atmospheric concentration levels from about 450 to about 500 ppm $CO_2$eq by the end of the century** (*high confidence*). Cost-effective mitigation scenarios leading to atmospheric concentration levels of about 450 to about 500 ppm $CO_2$eq at the end of the 21st century are typically characterized by annual GHG emissions in 2030 of roughly between 30 $GtCO_2$eq and 50 $GtCO_2$eq. Scenarios with emissions above 55 $GtCO_2$eq in 2030 are characterized by substantially higher rates of emissions reductions from 2030 to 2050 (median emissions reductions of about 6 %/yr as compared to just over 3 %/yr) (Figure TS.9, right panel); much more rapid scale-up of low-carbon energy over this period (more than a tripling compared to a doubling of the low-carbon energy share) (Figure TS.10, right panel);



GHG Emissions Pathways to 2030 of Mitigation Scenarios Reaching 430-530 ppm $CO_2$eq in 2100

Implications for the Pace of Annual Average $CO_2$ Emissions Reductions from 2030 to 2050 Depending on Different 2030 GHG Emissions Levels

**Figure TS.9 |** The implications of different 2030 GHG emissions levels for the rate of $CO_2$ emissions reductions from 2030 to 2050 in mitigation scenarios reaching about 450 to about 500 (430–530) ppm $CO_2$eq concentrations by 2100. The scenarios are grouped according to different emissions levels by 2030 (coloured in different shades of green). The left panel shows the pathways of GHG emissions ($GtCO_2$eq/yr) leading to these 2030 levels. The black bar shows the estimated uncertainty range of GHG emissions implied by the Cancún Pledges. Black dot with whiskers gives historic GHG emission levels and associated uncertainties in 2010 as reported in Figure TS.1. The right panel denotes the average annual $CO_2$ emissions reduction rates for the period 2030–2050. It compares the median and interquartile range across scenarios from recent intermodel comparisons with explicit 2030 interim goals to the range of scenarios in the Scenario Database for WGIII AR5. Annual rates of historical emissions change between 1900–2010 (sustained over a period of 20 years) and the average annual emissions change between 2000–2010 are shown in grey. Note: Scenarios with large net negative global emissions (> 20 $GtCO_2$/yr) are not included in the WGIII AR5 scenario range, but rather shown as independent points. Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with exogenous carbon price assumptions or other policies affecting the timing of mitigation (other than 2030 interim targets) as well as scenarios with 2010 emissions significantly outside the historical range are excluded. [Figure 6.32, 13.13.1.3]

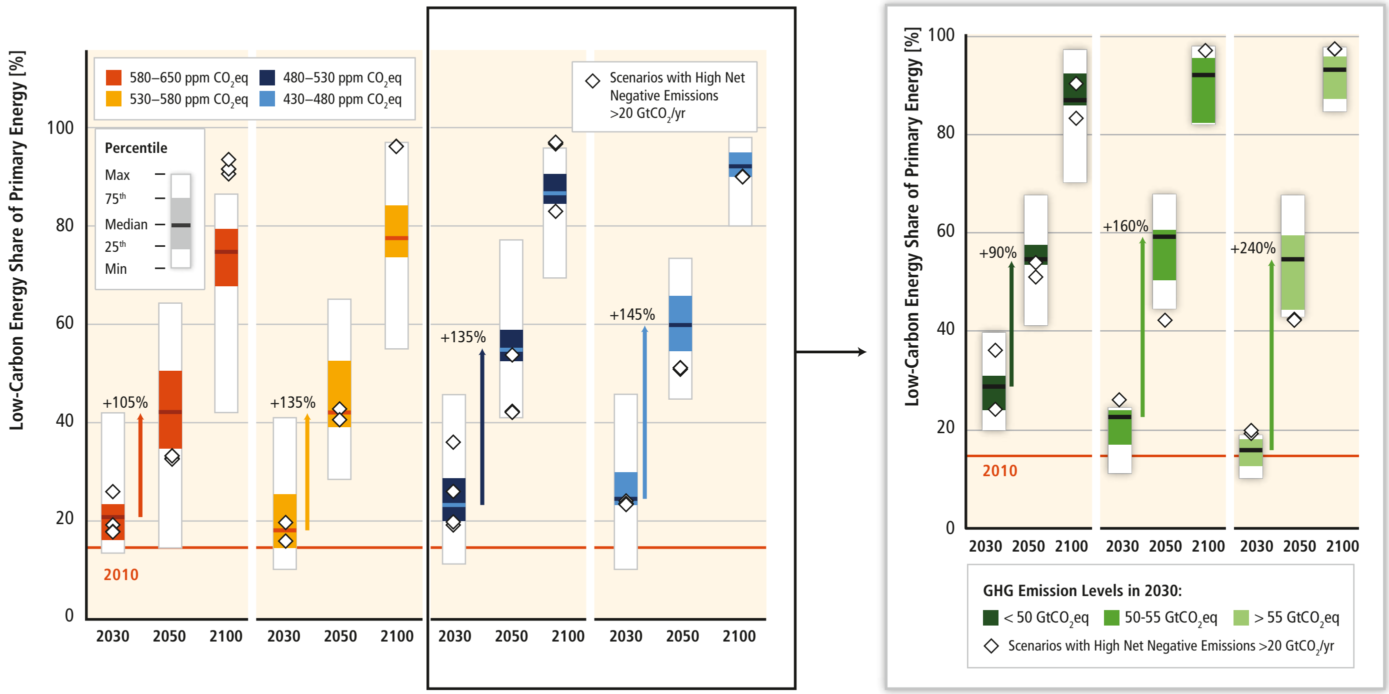


**Figure TS.10 |** The up-scaling of low-carbon energy in scenarios meeting different 2100 CO$_2$eq concentration levels (left panel). The right panel shows the rate of up-scaling subject to different 2030 GHG emissions levels in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO$_2$eq concentrations by 2100. Colored bars show the interquartile range and white bars indicate the full range across the scenarios, excluding those with large, global net negative CO$_2$ emissions (> 20 GtCO$_2$/yr). Scenarios with large net negative global emissions are shown as individual points. The arrows indicate the magnitude of zero- and low-carbon energy supply up-scaling from 2030 to 2050. Zero- and low-carbon energy supply includes renewables, nuclear energy, fossil energy with carbon dioxide capture and storage (CCS), and bioenergy with CCS (BECCS). Note: Only scenarios that apply the full, unconstrained mitigation technology portfolio of the underlying models (default technology assumption) are shown. Scenarios with exogenous carbon price assumptions are excluded in both panels. In the right panel, scenarios with policies affecting the timing of mitigation other than 2030 interim targets are also excluded. [Figure 7.16]

a larger reliance on CDR technologies in the long-term (Figure TS.8, right panel); and higher transitional and long term economic impacts (Table TS.2, orange segments, Figure TS.13, right panel). Due to these increased challenges, many models with 2030 GHG emissions in this range could not produce scenarios reaching atmospheric concentrations levels of about 450 to about 500 ppm CO$_2$eq in 2100. [6.4, 7.11]

**Estimated global GHG emissions levels in 2020 based on the Cancún Pledges are not consistent with cost-effective long-term mitigation trajectories that reach atmospheric concentrations levels of about 450 to about 500 ppm CO$_2$eq by 2100, but they do not preclude the option to meet that goal** (*robust evidence, high agreement*). The Cancún Pledges are broadly consistent with cost-effective scenarios reaching about 550 ppm CO$_2$eq to 650 ppm CO$_2$eq by 2100. Studies confirm that delaying mitigation through 2030 has a substantially larger influence on the subsequent challenges of mitigation than do delays through 2020 (Figures TS.9, TS.11). [6.4]

**Only a limited number of studies have explored scenarios that are *more likely than not* to bring temperature change back to below 1.5 °C by 2100 relative to pre-industrial levels; these scenarios bring atmospheric concentrations to below 430 ppm CO$_2$eq by 2100** (*high confidence*). Assessing this goal is currently difficult because no multi-model study has explored these scenarios. The limited number of published studies exploring this goal have produced associated scenarios that are characterized by (1) immediate mitigation; (2) the rapid up-scaling of the full portfolio of mitigation technologies; and (3) development along a low-energy demand trajectory.[12] [6.3, 7.11]

### TS.3.1.3 Costs, investments and burden sharing

**Globally comprehensive and harmonized mitigation actions would result in significant economic benefits compared to fragmented approaches, but would require establishing effective institutions** (*high confidence*). Economic analysis of mitigation scenarios demonstrates that globally comprehensive and harmonized mitigation actions achieve mitigation at least aggregate economic cost, since they allow mitigation to be undertaken where and when it is least expensive (see Box TS.7, Box TS.9). Most of these mitigation scenarios assume a global carbon price, which reaches all sectors of the economy. Instruments with limited coverage of GHG emissions reductions among sectors and climate policy regimes with fragmented regional

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[12] In these scenarios, the cumulative CO$_2$ emissions range between 680–800 GtCO$_2$ for the period 2011–2050 and between 90–310 GtCO$_2$ for the period 2011–2100. Global CO$_2$eq emissions in 2050 are between 70–95 % below 2010 emissions, and they are between 110–120 % below 2010 emissions in 2100.

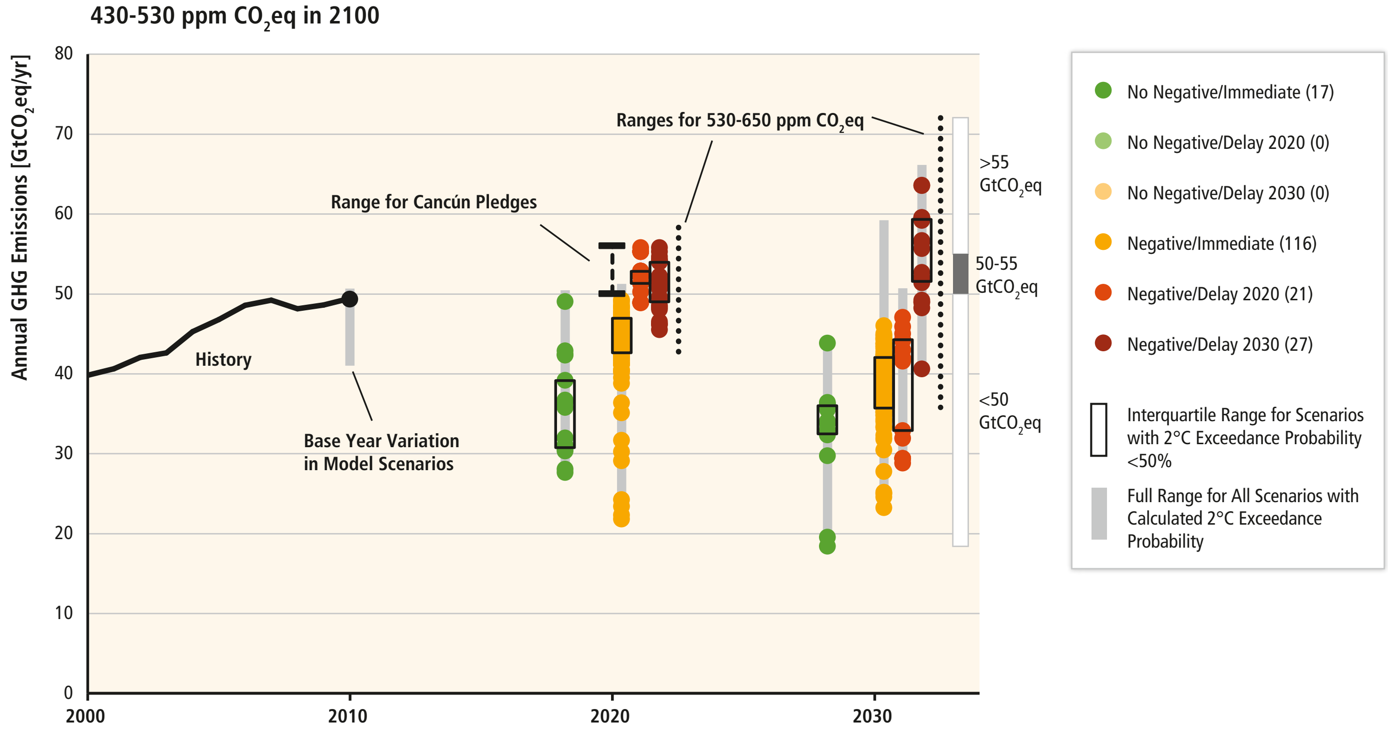


**Figure TS.11 |** Near-term GHG emissions from mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO$_2$eq concentrations by 2100. The Figure includes only scenarios for which temperature exceedance probabilities were calculated. Individual model results are indicated with a data point when 2 °C exceedance probability is below 50 % as assessed by a simple carbon cycle/climate model (MAGICC). Colours refer to scenario classification in terms of whether net CO$_2$ emissions become negative before 2100 (negative vs. no negative) and the timing of international participation in climate mitigation (immediate vs. delay until 2020 vs. delay until 2030). Number of reported individual results is shown in legend. The range of global GHG emissions in 2020 implied by the Cancún Pledges is based on analysis of alternative interpretations of national pledges. Note: In the WGIII AR5 scenario database, only four reported scenarios were produced based on delayed mitigation without net negative emissions while still lying below 530 ppm CO$_2$eq by 2100. They do not appear in the figure, because the model had insufficient coverage of non-gas species to enable a temperature calculation. Delay in these scenarios extended only to 2020, and their emissions fell in the same range as the 'No Negative/Immediate' category. Delay scenarios include both delayed global mitigation and fragmented action scenarios. [Figure 6.31, 13.13.1.3]

action increase aggregate economic costs. These cost increases are higher at more ambitious levels of mitigation. [6.3.6]

**Estimates of the aggregate economic costs of mitigation vary widely, but increase with stringency of mitigation** (*high confidence*). Most cost-effective scenarios collected for this assessment that are based on the assumptions that all countries of the world begin mitigation immediately, there is a single global carbon price applied to well-functioning markets, and key technologies are available, estimate that reaching about 450 ppm CO$_2$eq by 2100 would entail global consumption losses of 1 % to 4 % in 2030 (median: 1.7 %), 2 % to 6 % in 2050 (median: 3.4 %), and 3 % to 11 % in 2100 (median: 4.8 %) relative to consumption in baseline scenarios (those without additional mitigation efforts) that grows anywhere from 300 % to more than 900 % between 2010 and 2100 (baseline consumption growth represents the full range of corresponding baseline scenarios; Figure TS.12; Table TS.2 yellow segments). The consumption losses correspond to an annual average reduction of consumption growth by 0.06 to 0.2 percentage points from 2010 through 2030 (median: 0.09), 0.06 to 0.17 percentage points through 2050 (median: 0.09), and 0.04 to 0.14 percentage points over the century (median: 0.06). These numbers are relative to annual average consumption growth rates in baseline scenarios between 1.9 % and 3.8 % per year through 2050 and between 1.6 % and 3 % per year over the century (Table TS.2, yellow segments). These mitigation cost estimates do not consider the benefits of reduced climate change or co-benefits and adverse side-effects of mitigation (Box TS.9). Costs for maintaining concentrations in the range of 530–650 ppm CO$_2$eq are estimated to be roughly one-third to two-thirds lower than for associated 430–530 ppm CO$_2$eq scenarios. Cost estimates from scenarios can vary substantially across regions. Substantially higher cost estimates have been obtained based on assumptions about less idealized policy implementations and limits on technology availability as discussed below. Both higher and lower estimates have been obtained based on interactions with pre-existing distortions, non-climate market failures, or complementary policies. [6.3.6.2]

**Delaying mitigation efforts beyond those in place today through 2030 or beyond could substantially increase mitigation costs in the decades that follow and the second half of the century** (*high confidence*). Although delays in mitigation by any major emitter will reduce near-term mitigation costs, they will also result in more investment in carbon-intensive infrastructure and then rely on future

**Table TS.2 |** Global mitigation costs in cost-effective scenarios[1] and estimated cost increases due to assumed limited availability of specific technologies and delayed additional mitigation. Cost estimates shown in this table do not consider the benefits of reduced climate change as well as co-benefits and adverse side-effects of mitigation. The yellow columns show consumption losses (Figure TS.12, right panel) and annualized consumption growth reductions in cost-effective scenarios relative to a baseline development without climate policy. The grey columns show the percentage increase in discounted costs[2] over the century, relative to cost-effective scenarios, in scenarios in which technology is constrained relative to default technology assumptions (Figure TS.13, left panel).[3] The orange columns show the increase in mitigation costs over the periods 2030–2050 and 2050–2100, relative to scenarios with immediate mitigation, due to delayed additional mitigation through 2030 (see Figure TS.13, right panel).[4] These scenarios with delayed additional mitigation are grouped by emission levels of less or more than 55 $GtCO_2$eq in 2030, and two concentration ranges in 2100 (430–530 ppm $CO_2$eq and 530–650 ppm $CO_2$eq). In all figures, the median of the scenario set is shown without parentheses, the range between the 16th and 84th percentile of the scenario set is shown in the parentheses, and the number of scenarios in the set is shown in square brackets.[5] [Figures TS.12, TS.13, 6.21, 6.24, 6.25, Annex II.10]

| | Consumption losses in cost-effective scenarios[1] | | | | | | Increase in total discounted mitigation costs in scenarios with limited availability of technologies | | | | Increase in medium- and long-term mitigation costs due to delayed additional mitigation until 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [% reduction in consumption relative to baseline] | | | [percentage point reduction in annualized consumption growth rate] | | | [% increase in total discounted mitigation costs (2015–2100) relative to default technology assumptions] | | | | [% increase in mitigation costs relative to immediate mitigation] | | | |
| **Concentration in 2100 [ppm $CO_2$eq]** | **2030** | **2050** | **2100** | **2010 –2030** | **2010 –2050** | **2010 –2100** | **No CCS** | **Nuclear phase out** | **Limited Solar/ Wind** | **Limited Bioenergy** | **≤55 $GtCO_2$eq** | | **>55 $GtCO_2$eq** | |
| | | | | | | | | | | | **2030–2050** | **2050–2100** | **2030–2050** | **2050–2100** |
| **450 (430–480)** | 1.7<br>(1.0–3.7)<br>[N: 14] | 3.4<br>(2.1–6.2) | 4.8<br>(2.9–11.4) | 0.09<br>(0.06–0.2) | 0.09<br>(0.06–0.17) | 0.06<br>(0.04–0.14) | 138<br>(29–297)<br>[N: 4] | 7<br>(4–18)<br>[N: 8] | 6<br>(2–29)<br>[N: 8] | 64<br>(44–78)<br>[N: 8] | 28<br>(14–50)<br>[N: 34] | 15<br>(5–59) | 44<br>(2–78)<br>[N: 29] | 37<br>(16–82) |
| **500 (480–530)** | 1.7<br>(0.6–2.1)<br>[N: 32] | 2.7<br>(1.5–4.2) | 4.7<br>(2.4–10.6) | 0.09<br>(0.03–0.12) | 0.07<br>(0.04–0.12) | 0.06<br>(0.03–0.13) | N/A | N/A | N/A | N/A | | | | |
| **550 (530–580)** | 0.6<br>(0.2–1.3)<br>[N: 46] | 1.7<br>(1.2–3.3) | 3.8<br>(1.2–7.3) | 0.03<br>(0.01–0.08) | 0.05<br>(0.03–0.08) | 0.04<br>(0.01–0.09) | 39<br>(18–78)<br>[N: 11] | 13<br>(2–23)<br>[N: 10] | 8<br>(5–15)<br>[N: 10] | 18<br>(4–66)<br>[N: 12] | 3<br>(–5–16)<br>[N: 14] | 4<br>(–4–11) | 15<br>(3–32)<br>[N: 10] | 16<br>(5–24) |
| **580–650** | 0.3<br>(0–0.9)<br>[N: 16] | 1.3<br>(0.5–2.0) | 2.3<br>(1.2–4.4) | 0.02<br>(0–0.04) | 0.03<br>(0.01–0.05) | 0.03<br>(0.01–0.05) | N/A | N/A | N/A | N/A | | | | |

Notes:

[1] Cost-effective scenarios assume immediate mitigation in all countries and a single global carbon price. In this analysis, they also impose no additional limitations on technology relative to the models' default technology assumptions.

[2] Percentage increase of net present value of consumption losses in percent of baseline consumption (for scenarios from general equilibrium models) and abatement costs in percent of baseline GDP (for scenarios from partial equilibrium models) for the period 2015–2100, discounted (see Box TS.10) at 5 % per year.

[3] No CCS: CCS is not included in these scenarios. Nuclear phase out: No addition of nuclear power plants beyond those under construction, and operation of existing plants until the end of their lifetime. Limited Solar/Wind: a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios. Limited Bioenergy: a maximum of 100 EJ/yr modern bioenergy supply globally (modern bioenergy used for heat, power, combinations, and industry was around 18 EJ/yr in 2008 [11.13.5]).

[4] Percentage increase of total undiscounted mitigation costs for the periods 2030–2050 and 2050–2100.

[5] The range is determined by the central scenarios encompassing the 16th and 84th percentile of the scenario set. Only scenarios with a time horizon until 2100 are included. Some models that are included in the cost ranges for concentration levels above 530 ppm $CO_2$eq in 2100 could not produce associated scenarios for concentration levels below 530 ppm $CO_2$eq in 2100 with assumptions about limited availability of technologies and/or delayed additional mitigation (see caption of Figure TS.13 for more details).

decision makers to undertake a more rapid, deeper, and costlier future transformation of this infrastructure. Studies have found that aggregate costs, and associated carbon prices, rise more rapidly to higher levels in scenarios with delayed mitigation compared to scenarios where mitigation is undertaken immediately. Recent modelling studies have found that delayed mitigation through 2030 can substantially increase the aggregate costs of meeting 2100 concentrations of about 450 to about 500 ppm $CO_2$eq, particularly in scenarios with emissions greater than 55 $GtCO_2$eq in 2030. (Figure TS.13, right panel; Table TS.2, orange segments) [6.3.6.4]

**The technological options available for mitigation greatly influence mitigation costs and the challenges of reaching atmospheric concentration levels of about 450 to about 550 ppm $CO_2$eq by 2100** (*high confidence*). Many models in recent model intercomparisons could not produce scenarios reaching atmospheric concentrations of about 450 ppm $CO_2$eq by 2100 with broadly pessimistic assumptions about key mitigation technologies. In these studies, the character and availability of CCS and bioenergy were found to have a particularly important influence on the mitigation costs and the challenges of reaching concentration levels in this range. For those models that could produce such scenarios, pessimistic assumptions about these increased discounted global mitigation costs of reaching concentration levels of about 450 and about 550 ppm $CO_2$eq by the end of the century significantly, with the effect being larger for more stringent mitigation scenarios (Figure TS.13, left panel; Table TS.2, grey segments). The studies also showed that reducing energy demand could potentially decrease mitigation costs significantly. [6.3.6.3]

**The distribution of mitigation costs among different countries depends in part on the nature of effort-sharing frameworks and thus need not be the same as the distribution of mitigation efforts. Different effort-sharing frameworks draw upon different ethical principles** (*medium confidence*). In cost-effective scenarios reaching concentrations of about 450 to about 550 ppm $CO_2$eq in 2100, the majority of mitigation investments over the course

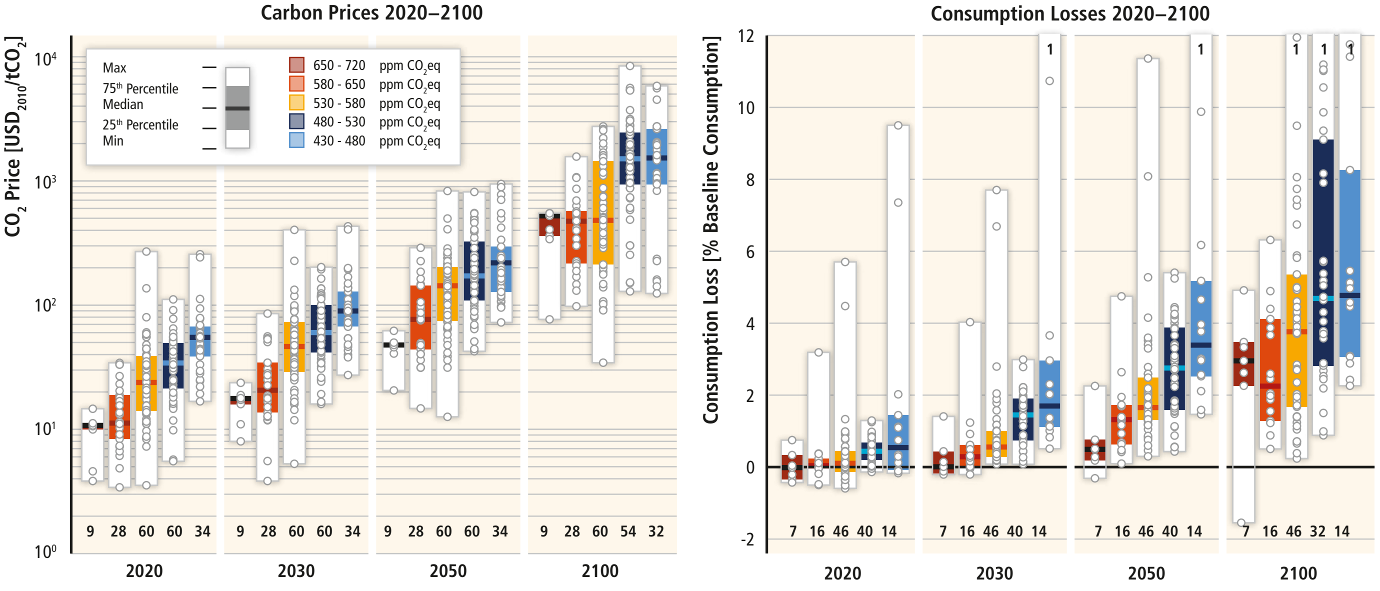


**Figure TS.12 |** Global carbon prices (left panel) and consumption losses (right panel) over time in cost-effective, idealized implementation scenarios. Consumption losses are expressed as the percentage reduction from consumption in the baseline. The number of scenarios included in the boxplots is indicated at the bottom of the panels. The 2030 numbers also apply to 2020 and 2050. The number of scenarios outside the figure range is noted at the top. Note: The figure shows only scenarios that reported consumption losses (a subset of models with full coverage of the economy) or carbon prices, respectively, to 2050 or 2100. Multiple scenarios from the same model with similar characteristics are only represented by a single scenario in the sample. [Figure 6.21]

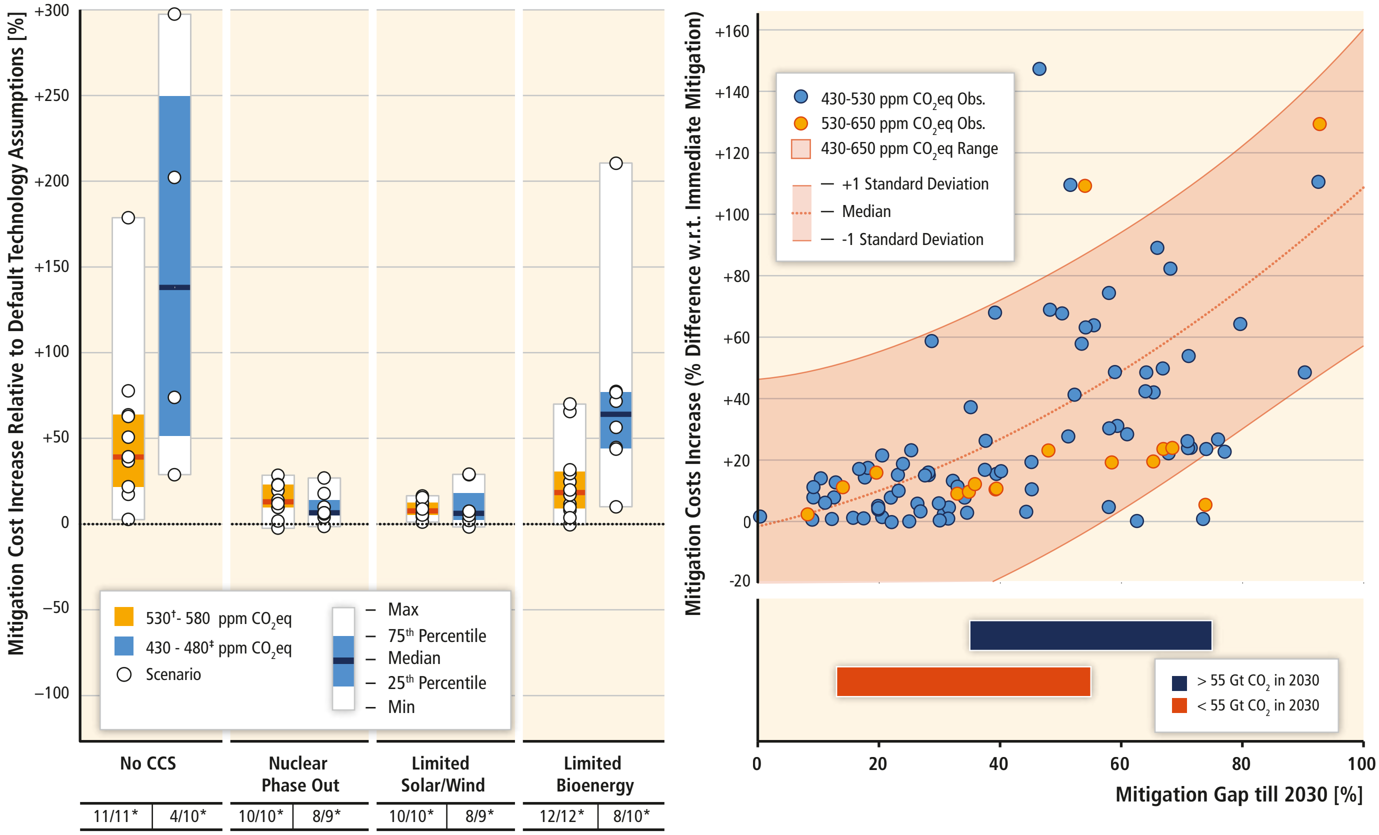
## Box TS.9 | The meaning of 'mitigation cost' in the context of mitigation scenarios

Mitigation costs represent one component of the change in human welfare from climate change mitigation. Mitigation costs are expressed in monetary terms and generally are estimated against baseline scenarios, which typically involve continued, and sometimes substantial, economic growth and no additional and explicit mitigation efforts [3.9.3, 6.3.6]. Because mitigation cost estimates focus only on direct market effects, they do not take into account the welfare value (if any) of co-benefits or adverse side-effects of mitigation actions (Box TS.11) [3.6.3]. Further, these costs do not capture the benefits of reducing climate impacts through mitigation (Box TS.2).

There are a wide variety of metrics of aggregate mitigation costs used by economists, measured in different ways or at different places in the economy, including changes in GDP, consumption losses, equivalent variation and compensating variation, and loss in consumer and producer surplus. Consumption losses are often used as a metric because they emerge from many integrated models and they directly impact welfare. They can be expressed as a reduction in overall consumption relative to consumption in the corresponding baseline scenario in a given year or as a reduction of the average rate of consumption growth in the corresponding baseline scenario over a given time period.

Mitigation costs need to be distinguished from emissions prices. Emissions prices measure the cost of an additional unit of emissions reduction; that is, the marginal cost. In contrast, mitigation costs usually represent the total costs of all mitigation. In addition, emissions prices can interact with other policies and measures, such as regulatory policies directed at GHG reduction. If mitigation is achieved partly by these other measures, emissions prices may not reflect the actual costs of an additional unit of emissions reductions (depending on how additional emissions reductions are induced).

In general, estimates of global aggregate mitigation costs over the coming century from integrated models are based on largely stylized assumptions about both policy approaches and existing markets and policies, and these assumptions have an important influence on cost estimates. For example, cost-effective idealized implementation scenarios assume a uniform price on CO$_2$ and other GHGs in every country and sector across the globe, and constitute the least cost approach in the idealized case of largely efficient markets without market failures other than the climate change externality. Most long-term, global scenarios do not account for the interactions between mitigation and pre-existing or new policies, market failures, and distortions. Climate policies can interact with existing policies to increase or reduce the actual cost of climate policies. [3.6.3.3, 6.3.6.5]



† Scenarios from one model reach concentration levels in 2100 that are slightly below the 530-580 ppm $CO_2$eq category

‡ Scenarios from two models reach concentration levels in 2100 that are slightly above the 430-480 ppm $CO_2$eq category

* Number of models successfully vs. number of models attempting running the respective technology variation scenario

**Figure TS.13 |** Left panel shows the relative increase in net present value mitigation costs (2015–2100, discounted at 5 % per year) from technology portfolio variations relative to a scenario with default technology assumptions. Scenario names on the horizontal axis indicate the technology variation relative to the default assumptions: No CCS = unavailability of carbon dioxide capture and storage (CCS); Nuclear phase out = No addition of nuclear power plants beyond those under construction; existing plants operated until the end of their lifetime; Limited Solar/Wind = a maximum of 20 % global electricity generation from solar and wind power in any year of these scenarios; Limited Bioenergy = a maximum of 100 exajoules per year (EJ/yr) modern bioenergy supply globally. [Figure 6.24] Right panel shows increase in long-term mitigation costs for the period 2050–2100 (sum over undiscounted costs) as a function of reduced near-term mitigation effort, expressed as the relative change between scenarios implementing mitigation immediately and those that correspond to delayed additional mitigation through 2020 or 2030 (referred to here as 'mitigation gap'). The mitigation gap is defined as the difference in cumulative $CO_2$ emissions reductions until 2030 between the immediate and delayed additional mitigation scenarios. The bars in the lower right panel indicate the mitigation gap range where 75 % of scenarios with 2030 emissions above (dark blue) and below (red) 55 $GtCO_2$, respectively, are found. Not all model simulations of delayed additional mitigation until 2030 could reach the lower concentration goals of about 450 or 500 (430–530) ppm $CO_2$eq (for 2030 emissions above 55 $GtCO_2$eq, 29 of 48 attempted simulations could reach the goal; for 2030 emissions below 55 $GtCO_2$eq, 34 of 51 attempted simulations could reach the goal). [Figure 6.25]

of century occur in the non-OECD countries. Some studies exploring particular effort-sharing frameworks, under the assumption of a global carbon market, estimate that the associated financial flows could be in the order of hundred billions of USD per year before mid-century to bring concentrations to between about 450 and about 500 ppm $CO_2$eq in 2100. Most studies assume efficient mechanisms for international carbon markets, in which case economic theory and empirical research suggest that the choice of effort sharing allocations will not meaningfully affect the globally efficient levels of regional abatement or aggregate global costs. Actual approaches to effort-sharing can deviate from this assumption. [3.3, 6.3.6.6, 13.4.2.4]

**Geoengineering denotes two clusters of technologies that are quite distinct: carbon dioxide removal (CDR) and solar radiation management (SRM). Mitigation scenarios assessed in AR5 do not assume any geoengineering options beyond large-scale CDR due to afforestation and BECCS.** CDR techniques include afforestation, using bioenergy along with CCS (BECCS), and enhancing uptake of $CO_2$ by the oceans through iron fertilization or increasing alkalinity. Most terrestrial CDR techniques would require large-scale land-use changes and could involve local and regional risks, while maritime CDR may involve significant transboundary risks for ocean ecosystems, so that its deployment could pose additional challenges for cooperation between countries. With currently known technologies, CDR could not be deployed quickly on a large scale. SRM includes various technologies to offset crudely some of the climatic effects of the build-up of GHGs in the atmosphere. It works by adjusting the planet's heat balance through a small increase in the reflection of incoming sunlight such as by injecting particles or aerosol precursors in the upper atmosphere. SRM has attracted considerable attention, mainly

### Box TS.10 | Future goods should be discounted at an appropriate rate

Investments aimed at mitigating climate change will bear fruit far in the future, much of it more than 100 years from now. To decide whether a particular investment is worthwhile, its future benefits need to be weighed against its present costs. In doing this, economists do not normally take a quantity of commodities at one time as equal in value to the same quantity of the same commodities at a different time. They normally give less value to later commodities than to earlier ones. They 'discount' later commodities, that is to say. The rate at which the weight given to future goods diminishes through time is known as the 'discount rate' on commodities.

There are two types of discount rates used for different purposes. The market discount rate reflects the preferences of presently living people between present and future commodities. The social discount rate is used by society to compare benefits of present members of society with those not yet born. Because living people may be impatient, and because future people do not trade in the market, the market may not accurately reflect the value of commodities that will come to future people relative to those that come to present people. So the social discount rate may differ from the market rate.

The chief reason for social discounting (favouring present people over future people) is that commodities have 'diminishing marginal benefit' and per capita income is expected to increase over time. Diminishing marginal benefit means that the value of extra commodities to society declines as people become better off. If economies continue to grow, people who live later in time will on average be better off—possess more commodities—than people who live earlier. The faster the growth and the greater the degree of diminishing marginal benefit, the greater should be the discount rate on commodities. If per capita growth is expected to be negative (as it is in some countries), the social discount rate may be negative.

Some authors have argued, in addition, that the present generation of people should give less weight to later people's well-being just because they are more remote in time. This factor would add to the social discount rate on commodities.

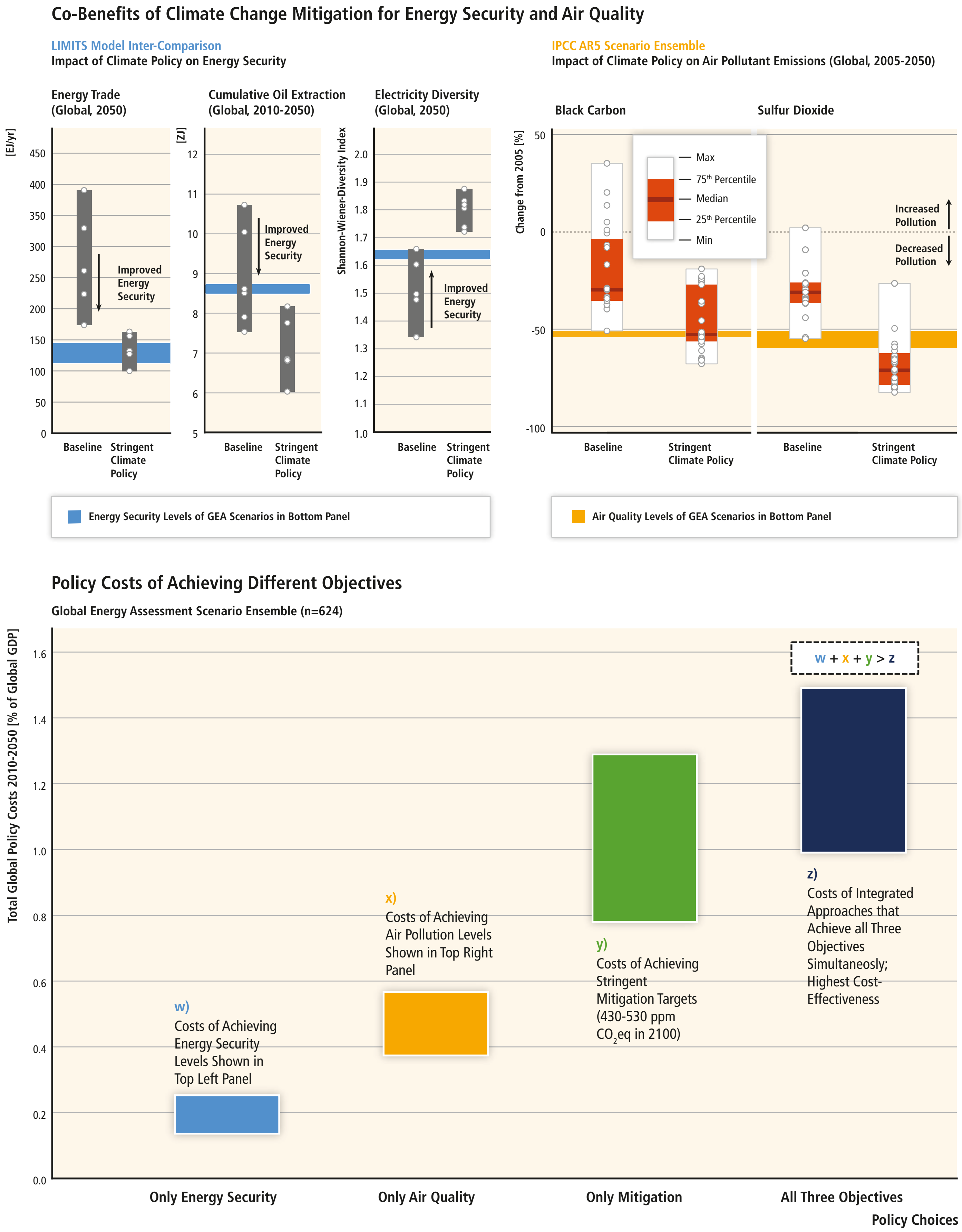
The social discount rate is appropriate for evaluating mitigation projects that are financed by reducing current consumption. If a project is financed partly by 'crowding out' other investments, the benefits of those other investments are lost, and their loss must be counted as an opportunity cost of the mitigation project. If a mitigation project crowds out an exactly equal amount of other investment, then the only issue is whether or not the mitigation investment produces a greater return than the crowded-out investment. This can be tested by evaluating the mitigation investment using a discount rate equal to the return that would have been expected from the crowded out investment. If the market functions well, this will be the market discount rate. [3.6.2]

because of the potential for rapid deployment in case of climate emergency. The suggestion that deployment costs for individual technologies could potentially be low could result in new challenges for international cooperation because nations may be tempted to prematurely deploy unilaterally systems that are perceived to be inexpensive. Consequently, SRM technologies raise questions about costs, risks, governance, and ethical implications of developing and deploying SRM, with special challenges emerging for international institutions, norms and other mechanisms that could coordinate research and restrain testing and deployment. [1.4, 3.3.7, 6.9, 13.4.4]

**Knowledge about the possible beneficial or harmful effects of SRM is highly preliminary.** SRM would have varying impacts on regional climate variables such as temperature and precipitation, and might result in substantial changes in the global hydrological cycle with uncertain regional effects, for example on monsoon precipitation. Non-climate effects could include possible depletion of stratospheric ozone by stratospheric aerosol injections. A few studies have begun to examine climate and non-climate impacts of SRM, but there is very little agreement in the scientific community on the results or on whether the lack of knowledge requires additional research or eventually field testing of SRM-related technologies. [1.4, 3.3.7, 6.9, 13.4.4]

### TS.3.1.4 Implications of mitigation pathways for other objectives

**Mitigation scenarios reaching about 450 to about 500 ppm $CO_2$eq by 2100 show reduced costs for achieving energy security and air quality objectives** (*medium confidence*) (Figure TS.14, lower panel). The mitigation costs of most of the scenarios in this assessment do not consider the economic implications of the cost reductions for these other objectives (Box TS.9). There is a wide range of co-benefits and adverse side-effects other than air quality and energy security (Tables TS.4–8). The impact of mitigation on the overall costs for achieving many of these other objectives as well as the associated welfare implications are less well understood and have not been assessed thoroughly in the literature (Box TS.11). [3.6.3, 4.8, 6.6]


Co-Benefits of Climate Change Mitigation for Energy Security and Air Quality
LIMITS Model Inter-Comparison
Impact of Climate Policy on Energy Security
Energy Trade (Global, 2050)
[EJ/yr]
0
50
100
150
200
250
300
350
400
450
Improved Energy Security
Baseline
Stringent Climate Policy
Cumulative Oil Extraction (Global, 2010-2050)
[ZJ]
5
6
7
8
9
10
11
12
Improved Energy Security
Baseline
Stringent Climate Policy
Electricity Diversity (Global, 2050)
Shannon-Wiener-Diversity Index
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Improved Energy Security
Baseline
Stringent Climate Policy
🟦 Energy Security Levels of GEA Scenarios in Bottom Panel
IPCC AR5 Scenario Ensemble
Impact of Climate Policy on Air Pollutant Emissions (Global, 2005-2050)
Black Carbon
Sulfur Dioxide
Change from 2005 [%]
50
0
-50
-100
Max
75th Percentile
Median
25th Percentile
Min
Increased Pollution
Decreased Pollution
Baseline
Stringent Climate Policy
Baseline
Stringent Climate Policy
🟧 Air Quality Levels of GEA Scenarios in Bottom Panel
Policy Costs of Achieving Different Objectives
Global Energy Assessment Scenario Ensemble (n=624)
Total Global Policy Costs 2010-2050 [% of Global GDP]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
w + x + y > z
w)
Costs of Achieving Energy Security Levels Shown in Top Left Panel
x)
Costs of Achieving Air Pollution Levels Shown in Top Right Panel
y)
Costs of Achieving Stringent Mitigation Targets (430-530 ppm CO$_2$eq in 2100)
z)
Costs of Integrated Approaches that Achieve all Three Objectives Simultaneosly; Highest Cost-Effectiveness
Only Energy Security
Only Air Quality
Only Mitigation
All Three Objectives
Policy Choices

⇒

**Figure TS.14|** Co-benefits of mitigation for energy security and air quality in scenarios with stringent climate policies reaching about 450 to about 500 (430–530) ppm $CO_2$eq concentrations in 2100. Upper panels show co-benefits for different security indicators and air pollutant emissions. Lower panel shows related global policy costs of achieving the energy security, air quality, and mitigation objectives, either alone (w, x, y) or simultaneously (z). Integrated approaches that achieve these objectives simultaneously show the highest cost-effectiveness due to synergies (w + x + y > z). Policy costs are given as the increase in total energy system costs relative to a baseline scenario without additional efforts to reduce GHG emissions beyond those in place today. Costs are indicative and do not represent full uncertainty ranges. [Figure 6.33]

**Mitigation scenarios reaching about 450 to about 500 ppm $CO_2$eq by 2100 show co-benefits for energy security objectives, enhancing the sufficiency of resources to meet national energy demand as well as the resilience of the energy system** (*medium confidence*). These mitigation scenarios show improvements in terms of the diversity of energy sources and reduction of energy imports, resulting in energy systems that are less vulnerable to price volatility and supply disruptions (Figure TS.14, upper left panel). [6.3.6, 6.6, 7.9, 8.7, 9.7, 10.8, 11.13.6, 12.8]

**Mitigation policy could devalue fossil fuel assets and reduce revenues for fossil fuel exporters, but differences between regions and fuels exist** (*high confidence*). Most mitigation scenarios are associated with reduced revenues from coal and oil trade for major exporters (*high confidence*). However, a limited number of studies find that mitigation policies could increase the relative competitiveness of conventional oil vis-à-vis more carbon-intensive unconventional oil and 'coal-to-liquids'. The effect of mitigation on natural gas export revenues is more uncertain, with some studies showing possible benefits for export revenues in the medium term until about 2050 (*medium confidence*). The availability of CCS would reduce the adverse effect of mitigation on the value of fossil fuel assets (*medium confidence*). [6.3.6, 6.6, 14.4.2]

**Fragmented mitigation policy can provide incentives for emission-intensive economic activity to migrate away from a region that undertakes mitigation** (*medium confidence*). Scenario studies have shown that such 'carbon leakage' rates of energy-related emissions are relatively contained, often below 20 % of the emissions reductions. Leakage in land-use emissions could be substantial, though fewer studies have quantified it. While border tax adjustments are seen as enhancing the competitiveness of GHG- and trade-intensive industries within a climate policy regime, they can also entail welfare losses for non-participating, and particularly developing, countries. [5.4, 6.3, 13.8, 14.4]

**Mitigation scenarios leading to atmospheric concentration levels of about 450 to about 500 ppm $CO_2$eq in 2100 are associated with significant co-benefits for air quality and related human health and ecosystem impacts. The benefits from major cuts in air pollutant emissions are particularly high where currently legislated and planned air pollution controls are weak** (*high confidence*). Stringent mitigation policies result in co-controls with major cuts in air pollutant emissions significantly below baseline scenarios (Figure TS.14, upper right panel). Co-benefits for health are particularly high in today's developing world. The extent to which air pollution policies, targeting for example black carbon (BC), can mitigate climate change is uncertain. [5.7, 6.3, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8; WGII 11.9]

**There is a wide range of possible adverse side-effects as well as co-benefits and spillovers from climate policy that have not been well-quantified** (*high confidence*). Whether or not side-effects materialize, and to what extent side-effects materialize, will be case- and site-specific, as they will depend on local circumstances and the scale, scope, and pace of implementation. Important examples include biodiversity conservation, water availability, food security, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries. (Box TS.11)

**Some mitigation policies raise the prices for some energy services and could hamper the ability of societies to expand access to modern energy services to underserved populations** (*low confidence*). **These potential adverse side-effects can be avoided with the adoption of complementary policies** (*medium confidence*). Most notably, about 1.3 billion people worldwide do not have access to electricity and about 3 billion are dependent on traditional solid fuels for cooking and heating with severe adverse effects on health, ecosystems and development. Providing access to modern energy services is an important sustainable development objective. The costs of achieving nearly universal access to electricity and clean fuels for cooking and heating are projected to be between 72 to 95 billion USD per year until 2030 with minimal effects on GHG emissions (*limited evidence, medium agreement*). A transition away from the use of traditional biomass[13] and the more efficient combustion of solid fuels reduce air pollutant emissions, such as sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), and black carbon (BC), and thus yield large health benefits (*high confidence*). [4.3, 6.6, 7.9, 9.3, 9.7, 11.13.6, 16.8]

**The effect of mitigation on water use depends on technological choices and the portfolio of mitigation measures** (*high confidence*). While the switch from fossil energy to renewable energy like photovoltaic (PV) or wind can help reducing water use of the energy system, deployment of other renewables, such as some forms of hydropower, concentrated solar power (CSP), and bioenergy may have adverse effects on water use. [6.6, 7.9, 9.7, 10.8, 11.7, 11.13.6]

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[13] Traditional biomass refers to the biomass — fuelwood, charcoal, agricultural residues, and animal dung — used with the so-called traditional technologies such as open fires for cooking, rustic kilns and ovens for small industries (see Glossary).

## Box TS.11 | Accounting for the co-benefits and adverse side-effects of mitigation

A government policy or a measure intended to achieve one objective (such as mitigation) will also affect other objectives (such as local air quality). To the extent these side-effects are positive, they can be deemed 'co-benefits'; otherwise they are termed 'adverse side-effects'. In this report, co-benefits and adverse side-effects are measured in non-monetary units. Determining the value of these effects to society is a separate issue. The effects of co-benefits on social welfare are not evaluated in most studies, and one reason is that the value of a co-benefit depends on local circumstances and can be positive, zero, or even negative. For example, the value of the extra tonne of sulfur dioxide ($SO_2$) reduction that occurs with mitigation depends greatly on the stringency of existing $SO_2$ control policies: in the case of weak existing $SO_2$ policy, the value of $SO_2$ reductions may be large, but in the case of stringent existing $SO_2$ policy it may be near zero. If $SO_2$ policy is too stringent, the value of the co-benefit may be negative (assuming $SO_2$ policy is not adjusted). While climate policy affects non-climate objectives (Tables TS.4–8) other policies also affect climate change outcomes. [3.6.3, 4.8, 6.6, Glossary]

Mitigation can have many potential co-benefits and adverse side-effects, which makes comprehensive analysis difficult. The direct benefits of climate policy include, for example, intended effects on global mean surface temperature, sea level rise, agricultural productivity, biodiversity, and health effects of global warming [WGII TS]. The co-benefits and adverse side-effects of climate policy could include effects on a partly overlapping set of objectives such as local air pollutant emissions reductions and related health and ecosystem impacts, biodiversity conservation, water availability, energy and food security, energy access, income distribution, efficiency of the taxation system, labour supply and employment, urban sprawl, and the sustainability of the growth of developing countries [3.6, 4.8, 6.6, 15.2].

All these side-effects are important, because a comprehensive evaluation of climate policy needs to account for benefits and costs related to other objectives. If overall social welfare is to be determined and quantified, this would require valuation methods and a consideration of pre-existing efforts to attain the many objectives. Valuation is made difficult by factors such as interaction between climate policies and pre-existing non-climate policies, externalities, and non-competitive behaviour. [3.6.3]

**Mitigation scenarios and sectoral studies show that overall the potential for co-benefits of energy end-use measures outweigh the potential adverse side-effects, whereas the evidence suggests this may not be the case for all energy supply and AFOLU measures** (*high confidence*). (Tables TS.4–8) [4.8, 5.7, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7, 11.13.6, 12.8]

## TS.3.2 Sectoral and cross-sectoral mitigation measures

*Anthropogenic GHG emissions result from a broad set of human activities, most notably those associated with energy supply and consumption and with the use of land for food production and other purposes. A large proportion of emissions arise in urban areas. Mitigation options can be grouped into three broad sectors: (1) energy supply, (2) energy end-use sectors including transport, buildings, industry, and (3) AFOLU. Emissions from human settlements and infrastructures cut across these different sectors. Many mitigation options are linked. The precise set of mitigation actions taken in any sector will depend on a wide range of factors, including their relative economics, policy structures, normative values, and linkages to other policy objectives. The first section examines issues that cut across the sectors and the following subsections examine the sectors themselves.*

### TS.3.2.1 Cross-sectoral mitigation pathways and measures

**Without new mitigation policies GHG emissions are projected to grow in all sectors, except for net $CO_2$ emissions in the AFOLU[14] sector** (*robust evidence, medium agreement*). Energy supply sector emissions are expected to continue to be the major source of GHG emissions in baseline scenarios, ultimately accounting for the significant increases in indirect emissions from electricity use in the buildings and the industry sectors. Deforestation decreases in most of the baseline scenarios, which leads to a decline in net $CO_2$ emissions from the AFOLU sector. In some scenarios the AFOLU sector changes from an emission source to a net emission sink towards the end of the century. (Figure TS.15) [6.3.1.4, 6.8]

**Infrastructure developments and long-lived products that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation** (*robust evidence, high agreement*). This lock-in risk is compounded by the lifetime of the infrastructure, by the difference in emissions associated with alternatives, and

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[14] Net AFOLU $CO_2$ emissions include emissions and removals of $CO_2$ from the AFOLU sector, including land under forestry and, in some assessments, $CO_2$ sinks in agricultural soils.

the magnitude of the investment cost. As a result, lock-in related to infrastructure and spatial planning is the most difficult to eliminate, and thus avoiding options that lock high emission patterns in permanently is an important part of mitigation strategies in regions with rapidly developing infrastructure. In mature or established cities, options are constrained by existing urban forms and infrastructure, and limits on the potential for refurbishing or altering them. However, materials, products and infrastructure with long lifetimes and low lifecycle emissions can ensure positive lock-in as well as avoid emissions through dematerialization (i.e., through reducing the total material inputs required to deliver a final service). [5.6.3, 6.3.6.4, 9.4, 10.4, 12.3, 12.4]

**Systemic and cross-sectoral approaches to mitigation are expected to be more cost-effective and more effective in cutting emissions than sector-by-sector policies** (*medium confidence*). Cost-effective mitigation policies need to employ a system perspective in order to account for inter-dependencies among different economic sectors and to maximize synergistic effects. Stabilizing atmospheric $CO_2$eq concentrations at any level will ultimately require deep reductions in emissions and fundamental changes to both the end-use and supply-side of the energy system as well as changes in land-use practices and industrial processes. In addition, many low-carbon energy supply technologies (including CCS) and their infrastructural requirements face public acceptance issues limiting their deployment. This applies also to the adoption of new technologies, and structural and behavioural change, in the energy end-use sectors (*robust evidence, high agreement*) [7.9.4, 8.7, 9.3.10, 9.8, 10.8, 11.3, 11.13]. Lack of acceptance may have implications not only for mitigation in that particular sector, but also for wider mitigation efforts.

**Integrated models identify three categories of energy system related mitigation measures: the decarbonization of the energy supply sector, final energy demand reductions, and the switch to low-carbon energy carriers, including electricity, in the energy end-use sectors** (*robust evidence, high agreement*) [6.3.4, 6.8, 7.11]. The broad range of sectoral mitigation options available mainly relate to achieving reductions in GHG emissions intensity, energy intensity and changes in activity (Table TS.3) [7.5, 8.3, 8.4, 9.3, 10.4, 12.4]. Direct options in AFOLU involve storing carbon in terrestrial systems (for example, through afforestation) and providing bioenergy feedstocks [11.3, 11.13]. Options to reduce non-$CO_2$ GHG emissions exist across all sectors, but most notably in agriculture, energy supply, and industry.

**Demand reductions in the energy end-use sectors, due to, e.g., efficiency enhancement and behavioural change, are a key miti-**

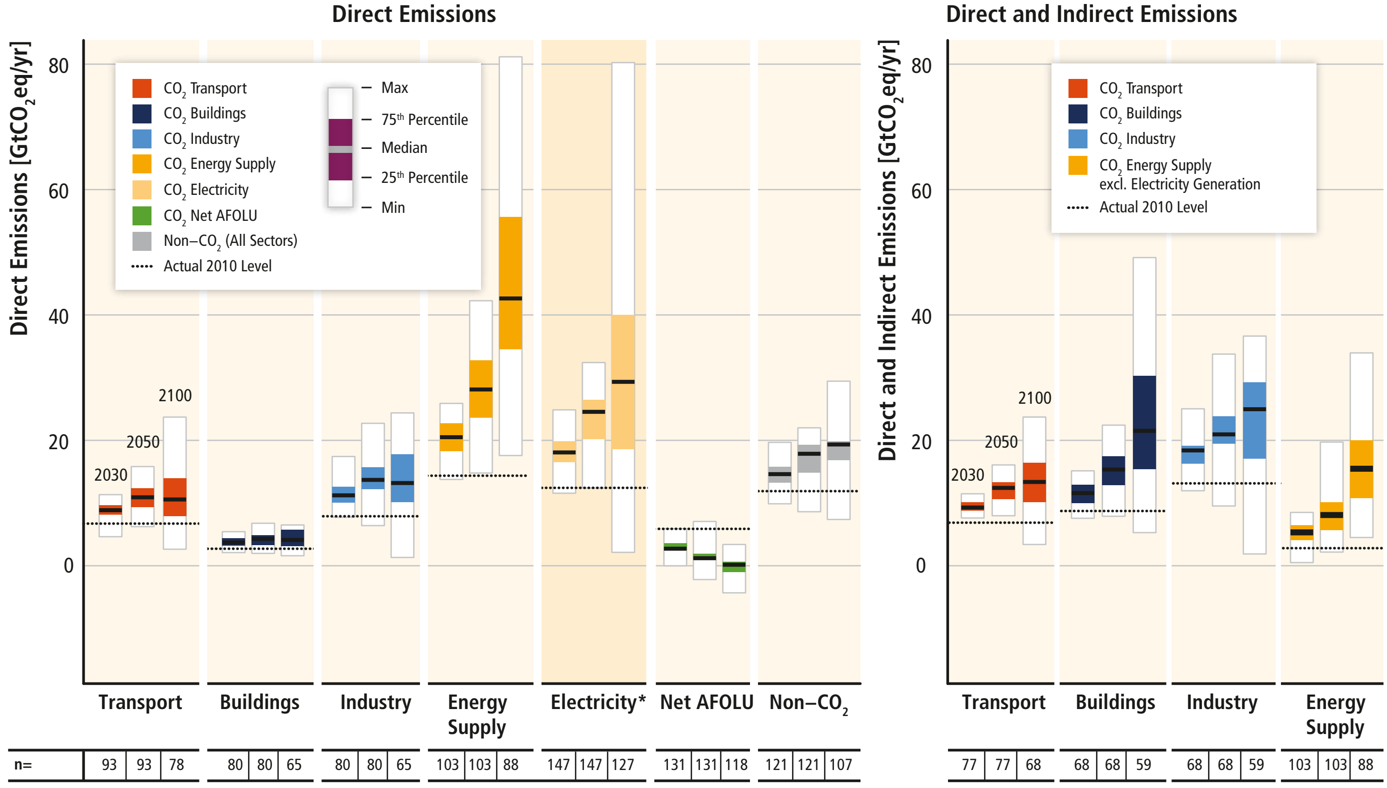
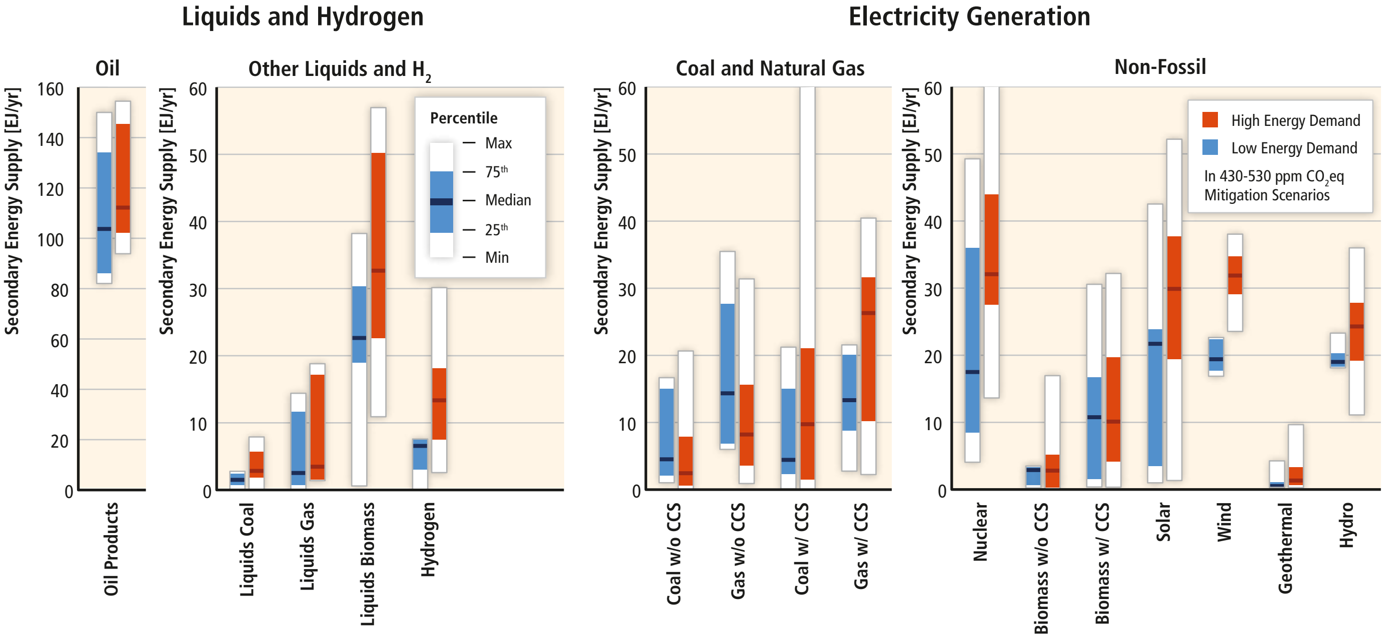


**Figure TS.15 |** Direct (left panel) and direct and indirect emissions (right panel) of $CO_2$ and non-$CO_2$ GHGs across sectors in baseline scenarios. Non-$CO_2$ GHGs are converted to $CO_2$-equivalents based on Global Warming Potentials with a 100-year time horizon from the IPCC Second Assessment Report (SAR) (see Box TS.5). Note that in the case of indirect emissions, only electricity generation emissions are allocated from energy supply to end-use sectors. In the left panel electricity sector emissions are shown (Electricity*) in addition to energy supply sector emissions which they are part of, to illustrate their large role on the energy supply side. The numbers at the bottom refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolutions and time horizons of models. [Figure 6.34]



| 1 | 2 | 3 | 4 |
|---|---|---|---|
| High energy demand scenarios show higher levels of oil supply. | In high energy demand scenarios, alternative liquid and hydrogen technologies are scaled up more rapidly. | High energy demand scenarios show a more rapid up-scaling of CCS technologies but a more rapid phase-out of unabated fossil fuel conversion technologies. | In high energy demand scenarios non-fossil electricity generation technologies are scaled up more rapidly. |

**Figure TS.16 |** Influence of energy demand on the deployment of energy supply technologies in 2050 in mitigation scenarios reaching about 450 to about 500 (430–530) ppm CO$_2$eq concentrations by 2100. Blue bars for 'low energy demand' show the deployment range of scenarios with limited growth of final energy of < 20 % in 2050 compared to 2010. Red bars show the deployment range of technologies in case of 'high energy demand' (> 20 % growth in 2050 compared to 2010). For each technology, the median, interquartile, and full deployment range is displayed. Notes: Scenarios assuming technology restrictions and scenarios with final energy in the base-year outside ± 5 % of 2010 inventories are excluded. Ranges include results from many different integrated models. Multiple scenario results from the same model were averaged to avoid sampling biases; see Chapter 6 for further details. [Figure 7.11]

**gation strategy and affect the scale of the mitigation challenge for the energy supply side** (*high confidence*). Limiting energy demand: (1) increases policy choices by maintaining flexibility in the technology portfolio; (2) reduces the required pace for up-scaling low-carbon energy supply technologies and hedges against related supply-side risks (Figure TS.16); (3) avoids lock-in to new, or potentially premature retirement of, carbon-intensive infrastructures; (4) maximizes co-benefits for other policy objectives, since the potential for co-benefits of energy end-use measures outweighs the potential for adverse side-effects which may not be the case for all supply-side measures (see Tables TS.4–8); and (5) increases the cost-effectiveness of the transformation (as compared to mitigation strategies with higher levels of energy demand) (*medium confidence*). However, energy service demand reductions are unlikely in developing countries or for poorer population segments whose energy service levels are low or partially unmet. [6.3.4, 6.6, 7.11, 10.4]

**Behaviour, lifestyle, and culture have a considerable influence on energy use and associated emissions, with a high mitigation potential in some sectors, in particular when complementing technological and structural change** (*medium evidence, medium agreement*). Emissions can be substantially lowered through: changes in consumption patterns (e.g., mobility demand and mode, energy use in households, choice of longer-lasting products); dietary change and reduction in food wastes; and change of lifestyle (e.g., stabilizing/lowering consumption in some of the most developed countries, sharing economy and other behavioural changes affecting activity) (Table TS.3). [8.1, 8.9, 9.2, 9.3, Box 10.2, 10.4, 11.4, 12.4, 12.6, 12.7]

**Evidence from mitigation scenarios indicates that the decarbonization of energy supply is a key requirement for stabilizing atmospheric CO$_2$eq concentrations below 580 ppm** (*robust evidence, high agreement*). In most long-term mitigation scenarios not exceeding 580 ppm CO$_2$eq by 2100, global energy supply is fully decarbonized at the end of the 21st century with many scenarios relying on a net removal of CO$_2$ from the atmosphere. However, because existing supply systems are largely reliant on carbon-intensive fossil fuels, energy intensity reductions can equal or outweigh decarbonization of energy supply in the near term. In the buildings and industry sector, for example, efficiency improvements are an important strategy for reducing indirect emissions from electricity generation (Figure TS.15). In the long term, the reduction in electricity generation emissions is accompanied by an increase in the share of electricity in end uses (e.g., for

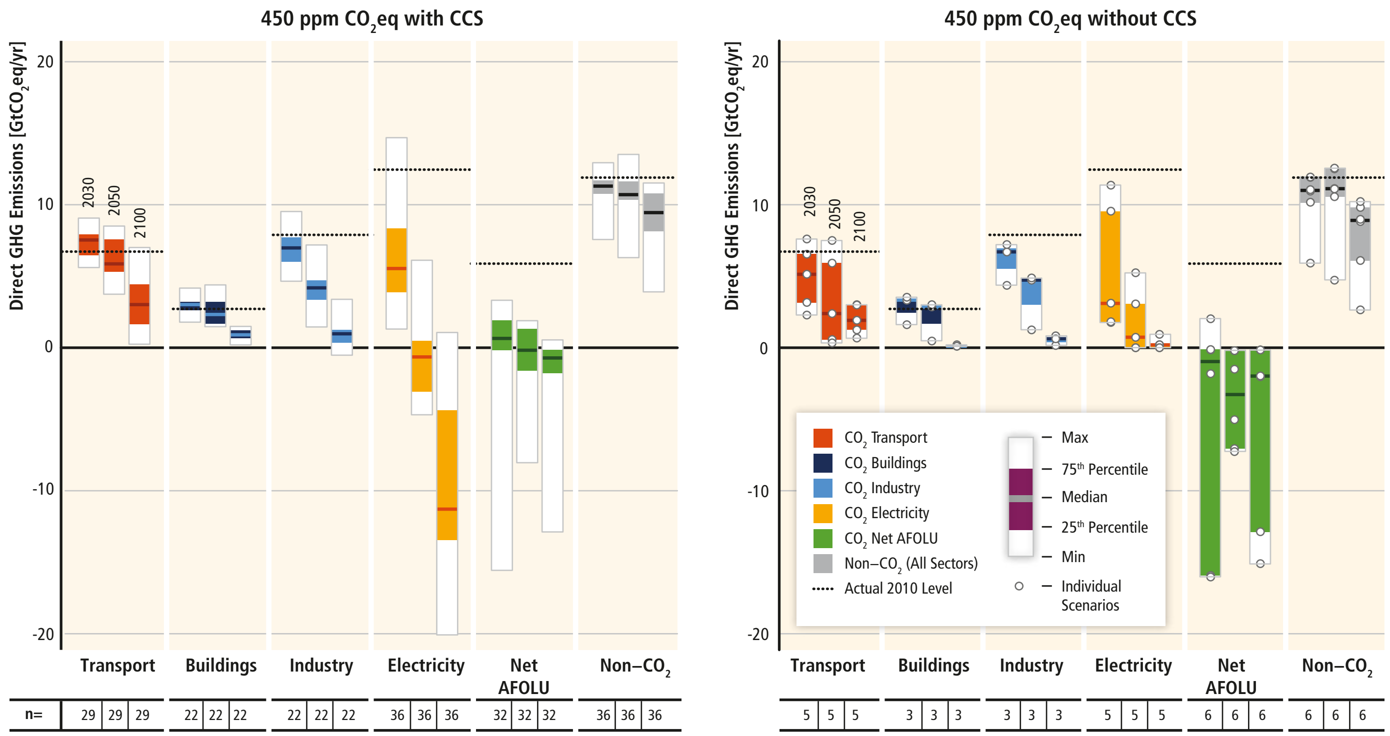


**Figure TS.17 |** Direct emissions of CO$_2$ and non-CO$_2$ GHGs across sectors in mitigation scenarios that reach about 450 (430–480) ppm CO$_2$eq concentrations in 2100 with using carbon dioxide capture and storage (CCS) (left panel) and without using CCS (right panel). The numbers at the bottom of the graphs refer to the number of scenarios included in the ranges that differ across sectors and time due to different sectoral resolutions and time horizons of models. White dots in the right panel refer to emissions of individual scenarios to give a sense of the spread within the ranges shown due to the small number of scenarios. [Figures 6.35]

space and process heating, and potentially for some modes of transport). Deep emissions reductions in transport are generally the last to emerge in integrated modelling studies because of the limited options to switch to low-carbon energy carriers compared to buildings and industry (Figure TS.17). [6.3.4, 6.8, 8.9, 9.8, 10.10, 7.11, Figure 6.17]

**The availability of CDR technologies affects the size of the mitigation challenge for the energy end-use sectors** (*robust evidence, high agreement*) [6.8, 7.11]. There are strong interdependencies in mitigation scenarios between the required pace of decarbonization of energy supply and end-use sectors. The more rapid decarbonization of supply generally provides more flexibility for the end-use sectors. However, barriers to decarbonizing the supply side, resulting for example from a limited availability of CCS to achieve negative emissions when combined with bioenergy, require a more rapid and pervasive decarbonisation of the energy end-use sectors in scenarios achieving low-CO$_2$eq concentration levels (Figure TS.17). The availability of mature large-scale biomass supply for energy, or carbon sequestration technologies in the AFOLU sector also provides flexibility for the development of mitigation technologies in the energy supply and energy end-use sectors [11.3] (*limited evidence, medium agreement*), though there may be adverse impacts on sustainable development.

**Spatial planning can contribute to managing the development of new infrastructure and increasing system-wide efficiencies across sectors** (*robust evidence, high agreement*). Land use, transport choice, housing, and behaviour are strongly interlinked and shaped by infrastructure and urban form. Spatial and land-use planning, such as mixed-zoning, transport-oriented development, increasing density, and co-locating jobs and homes can contribute to mitigation across sectors by (1) reducing emissions from travel demand for both work and leisure, and enabling non-motorized transport, (2) reducing floor space for housing, and hence (3) reducing overall direct and indirect energy use through efficient infrastructure supply. Compact and in-fill development of urban spaces and intelligent densification can save land for agriculture and bioenergy and preserve land carbon stocks. [8.4, 9.10, 10.5, 11.10, 12.2, 12.3]

**Interdependencies exist between adaptation and mitigation at the sectoral level and there are benefits from considering adaptation and mitigation in concert** (*medium evidence, high agreement*). Particular mitigation actions can affect sectoral climate vulnerability, both by influencing exposure to impacts and by altering the capacity to adapt to them [8.5, 11.5]. Other interdependencies include climate impacts on mitigation options, such as forest conservation or hydropower production [11.5.5, 7.7], as well as the effects of particular adaptation options, such as heating or cooling of buildings or establishing more diversified cropping systems in agriculture, on GHG emissions and radiative forcing [11.5.4, 9.5]. There is a growing evidence base for such interdependencies in each sector, but there are substantial knowledge gaps that prevent the generation of integrated results at the cross-sectoral level.

**Table TS.3 |** Main sectoral mitigation measures categorized by key mitigation strategies (in bold) and associated sectoral indicators (highlighted in yellow) as discussed in Chapters 7–12.

| | GHG emissions intensity reduction | Energy intensity reduction by improving technical efficiency | Production and resource efficiency improvement | Structural and systems efficiency improvement | Activity indicator change |
|---|---|---|---|---|---|
| Energy [Section 7.5] | *Emissions/ secondary energy output* | *Energy input/ energy output* | *Embodied energy/ energy output* | – | *Final energy use* |
| | Greater deployment of renewable energy (RE), nuclear energy, and (BE)CCS; fuel switching within the group of fossil fuels; reduction of fugitive (methane) emissions in the fossil fuel chain | Extraction, transport and conversion of fossil fuels; electricity/ heat/ fuel transmission, distribution, and storage; Combined Heat and Power (CHP) or cogeneration (*see Buildings and Human Settlements*) | Energy embodied in manufacturing of energy extraction, conversion, transmission and distribution technologies | Addressing integration needs | Demand from end-use sectors for different energy carriers (*see Transport, Buildings and Industry*) |
| Transport [8.3] | *Emissions/ final energy* | *Final energy/ transport service* | – | *Shares for each mode* | *Total distance per year* |
| | **Fuel carbon intensity ($CO_2$eq/megajoule (MJ)):** Fuel switching to low-carbon fuels e.g., electricity/hydrogen from low-carbon sources (*see Energy*); specific biofuels in various modes (*see AFOLU*) | **Energy intensity (MJ/passenger-km, tonne-km):** Fuel-efficient engines and vehicle designs; more advanced propulsion systems and designs; use of lighter materials in vehicles | Embodied emissions during vehicle manufacture; material efficiency; and recycling of materials (*see Industry*); infrastructure lifecycle emissions (*see Human Settlements*) | Modal shifts from light-duty vehicles (LDVs) to public transit, cycling/walking, and from aviation and heavy-duty vehicles (HDVs) to rail; eco-driving; improved freight logistics; transport (infrastructure) planning | Journey avoidance; higher occupancy/loading rates; reduced transport demand; urban planning (*see Human Settlements*) |
| Buildings [9.3] | *Emissions/ final energy* | *Final energy/ useful energy* | *Embodied energy/ operating energy* | *Useful energy/ energy service* | *Energy service demand* |
| | **Fuel carbon intensity ($CO_2$eq/MJ):** Building-integrated RE technologies; fuel switching to low-carbon fuels, e.g., electricity (*see Energy*) | **Device efficiency:** heating/ cooling (high-performance boilers, ventilation, air-conditioning, heat pumps); water heating; cooking (advanced biomass stoves); lighting; appliances | Building lifetime; component, equipment, and appliance durability; low(er) energy and emission material choice for construction (*see Industry*) | **Systemic efficiency:** integrated design process; low/zero energy buildings; building automation and controls; urban planning; district heating/cooling and CHP; smart meters/grids; commissioning | Behavioural change (e.g., thermostat setting, appliance use); lifestyle change (e.g., per capita dwelling size, adaptive comfort) |
| Industry [10.4] | *Emissions/ final energy* | *Final energy/ material production* | *Material input/ product output* | *Product demand/ service demand* | *Service demand* |
| | **Emissions intensity:** Process emissions reductions; use of waste (e.g., municipal solid waste (MSW)/sewage sludge in cement kilns) and CCS in industry; HFCs replacement and leak repair; fuel switching among fossil fuels to low-carbon electricity (*see Energy*) or biomass (*see AFOLU*) | **Energy efficiency/ best available technologies:** Efficient steam systems; furnace and boiler systems; electric motor (pumps, fans, air compressor, refrigerators, and material handling) and electronic control systems; (waste) heat exchanges; recycling | **Material efficiency:** Reducing yield losses; manufacturing/construction: process innovations, new design approaches, re-using old material (e.g., structural steel); product design (e.g., light weight car design); fly ash substituting clinker | **Product-service efficiency:** More intensive use of products (e.g., car sharing, using products such as clothing for longer, new and more durable products) | Reduced demand for, e.g., products such as clothing; alternative forms of travel leading to reduced demand for car manufacturing |
| Human Settlements [12.4] | *Emissions/ final energy* | *Final energy/ useful energy* | *Material input in infrastructure* | *Useful energy/ energy service* | *Service demand per capita* |
| | Integration of urban renewables; urban-scale fuel switching programmes | Cogeneration, heat cascading, waste to energy | Managed infrastructure supply; reduced primary material input for infrastructure | Compact urban form; increased accessibility; mixed land use | Increasing accessibility: shorter travel time, and more transport mode options |

| | Supply-side improvements | | | Demand-side measures |
|---|---|---|---|---|
| Agriculture, Forestry and Other Land Use (AFOLU) [11.3] | *Emissions/ area or unit product (conserved, restored)* | | | *Animal/crop product consumption per capita* |
| | **Emissions reduction:** of methane (e.g., livestock management) and nitrous oxide (fertilizer and manure management) and prevention of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation (reducing deforestation and forest degradation, fire prevention/control, agroforestry); reduced emissions intensity (GHG/unit product). | **Sequestration:** Increasing the size of existing carbon pools, thereby extracting $CO_2$ from the atmosphere (e.g., afforestation, reforestation, integrated systems, carbon sequestration in soils) | **Substitution:** of biological products for fossil fuels or energy-intensive products, thereby reducing $CO_2$ emissions, e.g., biomass co-firing/CHP (*see Energy*), biofuels (*see Transport*), biomass-based stoves, and insulation products (*see Buildings*) | **Demand-side measures:** Reducing losses and wastes of food; changes in human diets towards less emission-intensive products; use of long-lived wood products |

### TS.3.2.2 Energy supply

**The energy supply sector is the largest contributor to global GHG emissions** (*robust evidence, high agreement*). Annual GHG emissions from the global energy supply sector grew more rapidly between 2000 and 2010 than in the previous decade; their growth accelerated from 1.7 %/yr from 1990–2000 to 3.1 %/yr from 2000–2010. The main contributors to this trend are an increasing demand for energy services and a growing share of coal in the global fuel mix. The energy supply sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-use sectors (industry, transport, buildings, agriculture and forestry). [7.2, 7.3]

**In the baseline scenarios assessed in AR5, direct $CO_2$ emissions from the energy supply sector increase from 14.4 $GtCO_2$/yr in 2010 to 24–33 $GtCO_2$/yr in 2050 (25–75th percentile; full range 15–42 $GtCO_2$/yr), with most of the baseline scenarios assessed in WGIII AR5 showing a significant increase** (*medium evidence, medium agreement*) (Figure TS.15). The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years. The availability of fossil fuels alone will not be sufficient to limit $CO_2$eq concentration to levels such as 450 ppm, 550 ppm, or 650 ppm. [6.3.4, 6.8, 7.11, Figure 6.15]

**The energy supply sector offers a multitude of options to reduce GHG emissions** (*robust evidence, high agreement*). These options include: energy efficiency improvements and fugitive emission reductions in fuel extraction as well as in energy conversion, transmission, and distribution systems; fossil fuel switching; and low-GHG energy supply technologies such as renewable energy (RE), nuclear power, and CCS (Table TS.3). [7.5, 7.8.1, 7.11]

**The stabilization of GHG concentrations at low levels requires a fundamental transformation of the energy supply system, including the long-term phase-out of unabated fossil fuel conversion technologies and their substitution by low-GHG alternatives** (*robust evidence, high agreement*). Concentrations of $CO_2$ in the atmosphere can only be stabilized if global (net) $CO_2$ emissions peak and decline toward zero in the long term. Improving the energy efficiencies of fossil fuel power plants and/or the shift from coal to gas will not by themselves be sufficient to achieve this. Low-GHG energy supply technologies would be necessary if this goal were to be achieved (Figure TS.19). [7.5.1, 7.8.1, 7.11]

**Decarbonizing (i.e., reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels (430–530 ppm $CO_2$eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the buildings, transport, and industry sectors** (*medium evidence, high agreement*) (Figure TS.17). In the majority of mitigation scenarios reaching about 450 ppm $CO_2$eq concentrations by 2100, the share of low-carbon electricity supply (comprising RE, nuclear, fossil fuels with CCS, and BECCS) increases from the current share of around 30 % to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100 (Figures TS.17 and TS.18) [7.14].

**Since AR4, many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale** (*robust evidence, high agreement*). Some technologies are already economically competitive in various settings. Levelized costs of PV systems fell most substantially between 2009 and 2012, and a less extreme trend has been observed for many others RE technologies. Regarding electricity generation alone, RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro, and solar power. Decentralized RE to meet rural energy needs has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV, and wind. Nevertheless, many RE technologies still need direct support (e.g., feed-in tariffs (FITs), RE quota obligations, and tendering/bidding) and/or indirect support (e.g., sufficiently high carbon prices and the internalization of other externalities), if their market shares are to be significantly increased. RE technology policies have been successful in driving the recent growth of RE. Additional enabling policies are needed to address their integration into future energy systems. (*medium evidence, medium agreement*) (Figure TS.19) [7.5.3, 7.6.1, 7.8.2, 7.12, 11.13]

**The use of RE is often associated with co-benefits, including the reduction of air pollution, local employment opportunities, few severe accidents compared to some other energy supply technologies, as well as improved energy access and security** (*medium evidence, medium agreement*) (Table TS.4). At the same time, however, some RE technologies can have technology and location-specific adverse side-effects, which can be reduced to a degree through appropriate technology selection, operational adjustments, and siting of facilities. [7.9]

**Infrastructure and integration challenges vary by RE technology and the characteristics of the existing energy system** (*medium evidence, medium agreement*). Operating experience and studies of medium to high penetrations of RE indicate that integration issues can be managed with various technical and institutional tools. As RE penetrations increase, such issues are more challenging, must be carefully considered in energy supply planning and operations to ensure reliable energy supply, and may result in higher costs. [7.6, 7.8.2]

**Nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist** (*robust evidence, high agree-*

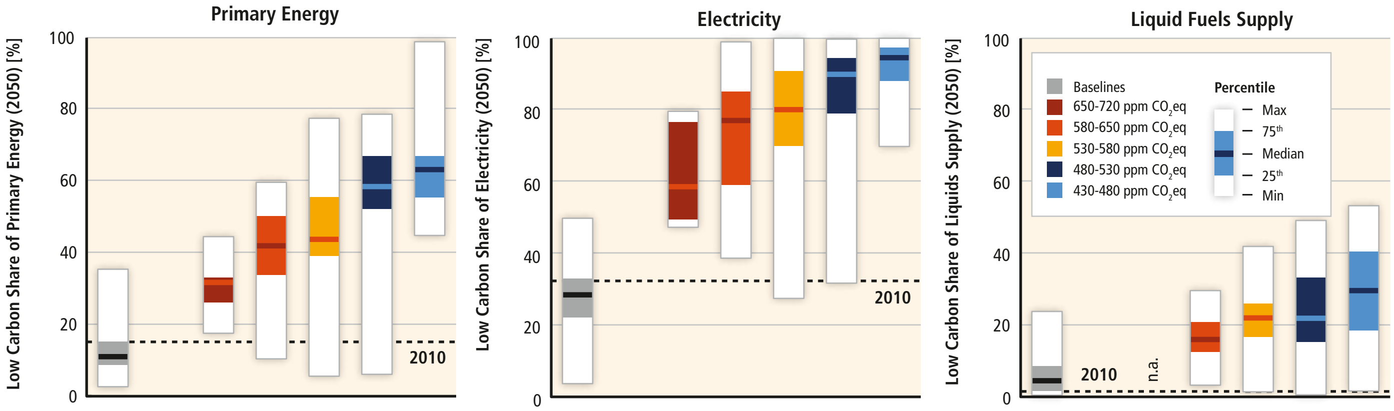


**Figure TS.18 |** Share of low-carbon energy in total primary energy, electricity and liquid fuels supply sectors for the year 2050. Dashed horizontal lines show the low-carbon share for the year 2010. Low-carbon energy includes nuclear, renewables, fossil fuels with carbon dioxide capture and storage (CCS) and bioenergy with CCS. [Figure 7.14]

*ment*) (Figure TS.19). Nuclear electricity accounted for 11 % of the world's electricity generation in 2012, down from a high of 17 % in 1993. Pricing the externalities of GHG emissions (carbon pricing) could improve the competitiveness of nuclear power plants. [7.2, 7.5.4, 7.8.1, 7.12]

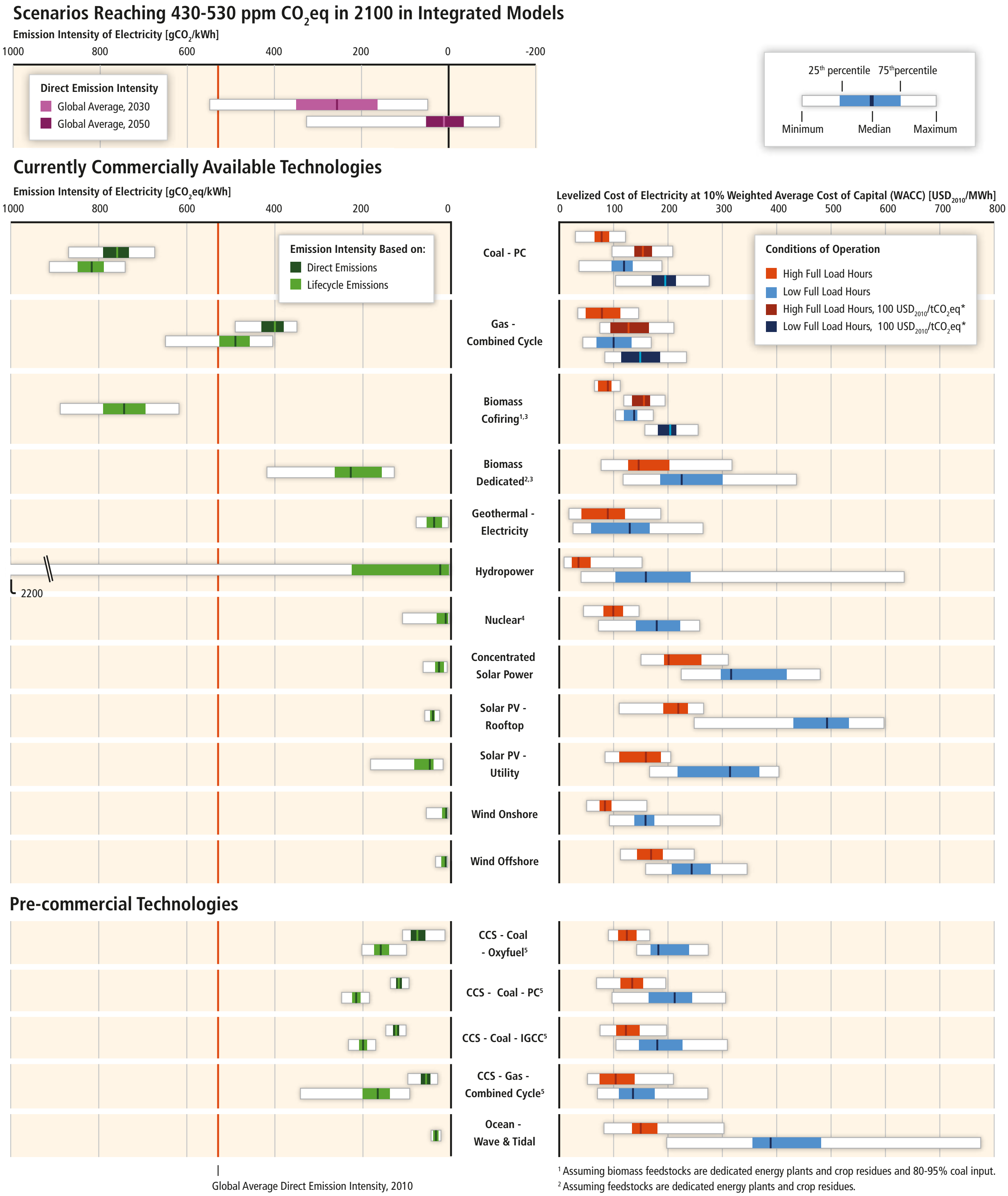
**Barriers and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion** (*robust evidence, high agreement*) (Table TS.4). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal. Investigation of mitigation scenarios not exceeding 580 ppm $CO_2$eq has shown that excluding nuclear power from the available portfolio of technologies would result in only a slight increase in mitigation costs compared to the full technology portfolio (Figure TS.13). If other technologies, such as CCS, are constrained the role of nuclear power expands. [6.3.6, 7.5.4, 7.8.2, 7.9, 7.11]

**GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined cycle power plants or combined heat and power (CHP) plants, provided that natural gas is available and the fugitive emissions associated with its extraction and supply are low or mitigated** (*robust evidence, high agreement*). In mitigation scenarios reaching about 450 ppm $CO_2$eq concentrations by 2100, natural gas power generation without CCS typically acts as a bridge technology, with deployment increasing before peaking and falling to below current levels by 2050 and declining further in the second half of the century (*robust evidence, high agreement*). [7.5.1, 7.8, 7.9, 7.11, 7.12]

**Carbon dioxide capture and storage (CCS) technologies could reduce the lifecycle GHG emissions of fossil fuel power plants** (*medium evidence, medium agreement*). While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, commercial fossil fuel power plant. CCS power plants could be seen in the market if they are required for fossil fuel facilities by regulation or if they become competitive with their unabated counterparts, for instance, if the additional investment and operational costs faced by CCS plants, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). Beyond economic incentives, well-defined regulations concerning short- and long-term responsibilities for storage are essential for a large-scale future deployment of CCS. [7.5.5]

**Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of $CO_2$ storage, as well as risks related to transport and the required up-scaling of infrastructure** (*limited evidence, medium agreement*) (Table TS.4). There is, however, a growing body of literature on how to ensure the integrity of $CO_2$ wells, on the potential consequences of a $CO_2$ pressure build-up within a geologic formation (such as induced seismicity), and on the potential human health and environmental impacts from $CO_2$ that migrates out of the primary injection zone (*limited evidence, medium agreement*). [7.5.5, 7.9, 7.11]

**Combining bioenergy with CCS (BECCS) offers the prospect of energy supply with large-scale net negative emissions, which plays an important role in many low-stabilization scenarios, while it entails challenges and risks** (*limited evidence, medium agreement*). Until 2050, bottom-up studies estimate the economic potential to be between 2–10 $GtCO_2$ per year [11.13]. Some mitigation scenarios show higher deployment of BECCS towards the end of the century. Technological challenges and risks include those associated with the upstream provision of the biomass that is used in the CCS facility, as well as those associated with the CCS technology itself. Currently, no large-scale projects have been financed. [6.9, 7.5.5, 7.9, 11.13]



[1] Assuming biomass feedstocks are dedicated energy plants and crop residues and 80-95% coal input.

[2] Assuming feedstocks are dedicated energy plants and crop residues.

[3] Direct emissions of biomass power plants are not shown explicitly, but included in the lifecycle emissions. Lifecycle emissions include albedo effect.

[4] LCOE of nuclear include front and back-end fuel costs as well as decommissioning costs.

[5] Transport and storage costs of CCS are set to 10 USD$_{2010}$/tCO$_2$.

* Carbon price levied on direct emissions. Effects shown where significant.

**Figure TS.19 |** Specific direct and lifecycle emissions (gCO$_2$eq/ kilowatt hour (kWh)) and levelized cost of electricity (LCOE in USD$_{2010}$/MWh) for various power-generating technologies (see Annex III.2 for data and assumptions and Annex II.3.1 and II.9.3 for methodological issues). The upper left graph shows global averages of specific direct CO$_2$ emissions (gCO$_2$/kWh) of power generation in 2030 and 2050 for the set of about 450 to about 500 (430–530) ppm CO$_2$eq scenarios that are contained in the WG III AR5 Scenario Database (see Annex II.10). The global average of specific direct CO$_2$ emissions (gCO$_2$/kWh) of power generation in 2010 is shown as a vertical line. Note: The inter-comparability of LCOE is limited. For details on general methodological issues and interpretation see Annexes as mentioned above. CCS: CO$_2$ capture and storage; IGCC: Integrated coal gasification combined cycle; PC: Pulverized hard coal; PV: Photovoltaic; WACC: Weighted average cost of capital. [Figure 7.7]

**Table TS.4 |** Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the energy supply sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace, and scale. For possible upstream effects of biomass supply for bioenergy, see Table TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l=limited, m=medium, r=robust; for agreement: l=low, m=medium, h=high. [Table 7.3]

| **Energy Supply** | **Effect on additional objectives/concerns** | | | |
|---|---|---|---|---|
| | **Economic** | **Social** | **Environmental** | **Other** |
| **Nuclear replacing coal power** | ↑ Energy security (reduced exposure to fuel price volatility) (**m**/**m**)<br>↑ Local employment impact (but uncertain net effect) (**l**/**m**)<br>↑ Legacy cost of waste and abandoned reactors (**m**/**h**) | Health impact via<br>↓ Air pollution and coal mining accidents (**m**/**h**)<br>↑ Nuclear accidents and waste treatment, uranium mining and milling (**m**/**l**)<br>↑ Safety and waste concerns (**r**/**h**) | Ecosystem impact via<br>↓ Air pollution (**m**/**h**) and coal mining (**l**/**h**)<br>↑ Nuclear accidents (**m**/**m**) | Proliferation risk (**m**/**m**) |
| **RE (wind, PV, concentrated solar power (CSP), hydro, geothermal, bioenergy) replacing coal** | ↑ Energy security (resource sufficiency, diversity in the near/medium term) (**r**/**m**)<br>↑ Local employment impact (but uncertain net effect) (**m**/**m**)<br>↑ Irrigation, flood control, navigation, water availability (for multipurpose use of reservoirs and regulated rivers) (**m**/**h**)<br>↑ Extra measures to match demand (for PV, wind and some CSP) (**r**/**h**) | Health impact via<br>↓ Air pollution (except bioenergy) (**r**/**h**)<br>↓ Coal mining accidents (**m**/**h**)<br>↑ Contribution to (off-grid) energy access (**m**/**l**)<br>**?** Project-specific public acceptance concerns (e.g., visibility of wind) (**l**/**m**)<br>↑ Threat of displacement (for large hydro) (**m**/**h**) | Ecosystem impact via<br>↓ Air pollution (except bioenergy) (**m**/**h**)<br>↓ Coal mining (**l**/**h**)<br>↑ Habitat impact (for some hydro) (**m**/**m**)<br>↑ Landscape and wildlife impact (for wind) **m**/**m**)<br>↓ Water use (for wind and PV) (**m**/**m**)<br>↑ Water use (for bioenergy, CSP, geothermal, and reservoir hydro) (**m**/**h**) | Higher use of critical metals for PV and direct drive wind turbines (**r**/**m**) |
| **Fossil CCS replacing coal** | ↑↑ Preservation vs. lock-in of human and physical capital in the fossil industry (**m**/**m**) | Health impact via<br>↑ Risk of $CO_2$ leakage (**m**/**m**)<br>↑ Upstream supply-chain activities (**m**/**h**)<br>↑ Safety concerns ($CO_2$ storage and transport) (**m**/**h**) | ↑ Ecosystem impact via upstream supply-chain activities (**m**/**m**)<br>↑ Water use (**m**/**h**) | Long-term monitoring of $CO_2$ storage (**m**/**h**) |
| **BECCS replacing coal** | *See fossil CCS where applicable. For possible upstream effect of biomass supply, see Table TS.8.* | | | |
| **Methane leakage prevention, capture or treatment** | ↑ Energy security (potential to use gas in some cases) (**l**/**h**) | ↓ Health impact via reduced air pollution (**m**/**m**)<br>↑ Occupational safety at coal mines (**m**/**m**) | ↓ Ecosystem impact via reduced air pollution (**l**/**m**) | |

### TS.3.2.3 Transport

**Since AR4, emissions in the global transport sector have grown in spite of more efficient vehicles (road, rail, watercraft, and aircraft) and policies being adopted** (*robust evidence, high agreement*). Road transport dominates overall emissions but aviation could play an increasingly important role in total $CO_2$ emissions in the future. [8.1, 8.3, 8.4]

**The global transport sector accounted for 27% of final energy use and 6.7 $GtCO_2$ direct emissions in 2010, with baseline $CO_2$ emissions projected to increase to 9.3–12 $GtCO_2$/yr in 2050 (25–75th percentile; full range 6.2–16 $GtCO_2$/yr); most of the baseline scenarios assessed in WGIII AR5 foresee a significant increase** (*medium evidence/medium agreement*) (Figure TS.15). Without aggressive and sustained mitigation policies being implemented, transport sector emissions could increase faster than in the other energy end-use sectors and could lead to more than a doubling of $CO_2$ emissions by 2050. [6.8, 8.9, 8.10]

**While the continuing growth in passenger and freight activity constitutes a challenge for future emission reductions, analyses of both sectoral and integrated studies suggest a higher mitigation potential in the transport sector than reported in the AR4** (*medium evidence, medium agreement*). Transport energy demand per capita in developing and emerging economies is far lower than in OECD countries but is expected to increase at a much faster rate in the next decades due to rising incomes and the development of infrastructure. Baseline scenarios thus show increases in transport energy demand from 2010 out to 2050 and beyond. However, sectoral and integrated mitigation scenarios indicate that energy demand reductions of 10–45 % are possible by 2050 relative to baseline (Figure TS.20, left panel) (*medium evidence, medium agreement*). [6.8.4, 8.9.1, 8.9.4, 8.12, Figure 8.9.4]

**A combination of low-carbon fuels, the uptake of improved vehicle and engine performance technologies, behavioural change leading to avoided journeys and modal shifts, investments in related infrastructure and changes in the built environment, together offer a high mitigation potential** (*high confidence*) [8.3, 8.8]. Direct (tank-to-wheel) GHG emissions from passenger and freight transport can be reduced by:

- using fuels with lower carbon intensities ($CO_2$eq/ megajoule (MJ));
- lowering vehicle energy intensities (MJ/passenger-km or MJ/tonne-km);
- encouraging modal shift to lower-carbon passenger and freight transport systems coupled with investment in infrastructure and compact urban form; and
- avoiding journeys where possible (Table TS.3).

Other short-term mitigation strategies include reducing black carbon (BC), aviation contrails, and nitrogen oxides ($NO_x$) emissions. [8.4]

**Strategies to reduce the carbon intensities of fuel and the rate of reducing carbon intensity are constrained by challenges associated with energy storage and the relatively low energy density of low-carbon transport fuels; integrated and sectoral studies broadly agree that opportunities for fuel switching exist in the short term and will grow over time** (*medium evidence, medium agreement*) (Figure TS.20, right panel). Electric, hydrogen, and some biofuel technologies could help reduce the carbon intensity of fuels, but their total mitigation potentials are very uncertain (*medium evidence, medium agreement*). Methane-based fuels are already increasing their share for road vehicles and waterborne craft. Electricity produced from low-carbon sources has near-term potential for electric rail and short- to medium-term potential as electric buses, light-duty and 2-wheel road vehicles are deployed. Hydrogen fuels from low-carbon sources constitute longer-term options. Commercially available liquid and gaseous biofuels already provide co-benefits together with mitigation options that can be increased by technology advances, particularly drop-in biofuels for aircraft. Reducing transport emissions of particulate matter (including BC), tropospheric ozone and aerosol precursors (including $NO_x$) can have human health and mitigation co-benefits in the short term (*medium evidence, medium agreement*). Up to 2030, the majority of integrated studies expect a continued reliance on liquid and gaseous fuels, supported by an increase in the use of biofuels. During the second half of the century, many integrated studies also show substantial shares of electricity and/or hydrogen to fuel electric and fuel-cell light-duty vehicles (LDVs). [8.2, 8.3, 11.13]

**Energy efficiency measures through improved vehicle and engine designs have the largest potential for emissions reduc-**

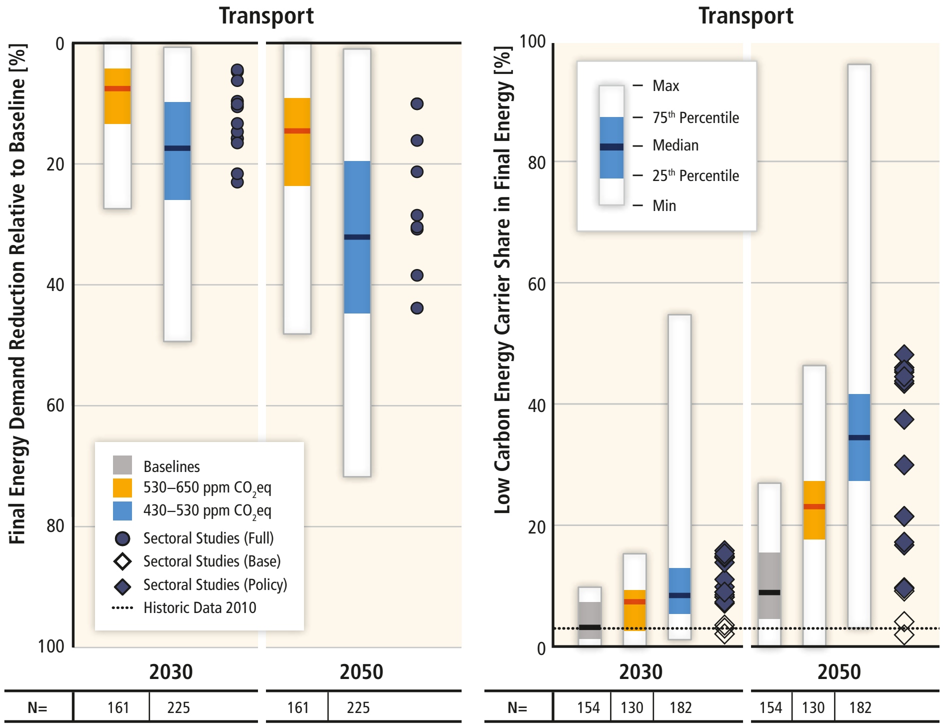


**Figure TS.20 |** Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (including electricity, hydrogen, and liquid biofuels; right panel) in transport by 2030 and 2050 in mitigation scenarios from three different $CO_2$eq concentrations ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 8. Filled circles correspond to sectoral studies with full sectoral coverage. [Figures 6.37 and 6.38]

**tions in the short term** (*high confidence*). Potential energy efficiency and vehicle performance improvements range from 30–50 % relative to 2010 depending on transport mode and vehicle type (Figures TS.21, TS.22). Realizing this efficiency potential will depend on large investments by vehicle manufacturers, which may require strong incentives and regulatory policies in order to achieve GHG emissions reduction goals (*medium evidence, medium agreement*). [8.3, 8.6, 8.9, 8.10]

**Shifts in transport mode and behaviour, impacted by new infrastructure and urban (re)development, can contribute to the reduction of transport emissions** (*medium evidence, low agreement*). Over the medium term (up to 2030) to long term (to 2050 and beyond), urban redevelopment and investments in new infrastructure, linked with integrated urban planning, transit-oriented development, and more compact urban form that supports cycling and walking can all lead to modal shifts. Such mitigation measures are challenging, have uncertain outcomes, and could reduce transport GHG emissions by 20–50 % compared to baseline (*limited evidence, low agreement*). Pricing strategies, when supported by public acceptance initiatives and public and non-motorized transport infrastructures, can reduce travel demand, increase the demand for more efficient vehicles (e. g., where fuel economy standards exist) and induce a shift to low-carbon modes (*medium evidence, medium agreement*). While infrastructure investments may appear expensive at the margin, the case for sustainable urban planning and related policies is reinforced when co-benefits, such as improved health, accessibility, and resilience, are accounted for (Table TS.5). Business initiatives to decarbonize freight transport have begun but will need further support from fiscal, regulatory, and advisory policies to encourage shifting from road to low-carbon modes such as rail or waterborne options where feasible, as well as improving logistics (Figure TS.22). [8.4, 8.5, 8.7, 8.8, 8.9, 8.10]

**Sectoral and integrated studies agree that substantial, sustained, and directed policy interventions could limit transport emissions to be consistent with low concentration goals, but the societal mitigation costs (USD/tCO$_2$eq avoided) remain uncertain** (Figures TS.21, TS.22, TS.23). There is good potential to reduce emissions from LDVs and long-haul heavy-duty vehicles (HDVs) from both lower energy intensity vehicles and fuel switching, and the levelized costs of conserved carbon (LCCC) for efficiency improvements can be very low and negative (*limited evidence, low agreement*). Rail, buses, two-wheel motorbikes, and waterborne craft for freight already have relatively low emissions so their emissions reduction potential is limited. The mitigation cost of electric vehicles is currently high, especially if using grid electricity with a high emissions factor, but their LCCC are expected to decline by 2030. The emissions intensity of aviation could decline by around 50 % in 2030 but the LCCC, although uncertain, are probably over USD 100/tCO$_2$eq. While it is expected that mitigation costs will decrease in the future, the magnitude of such reductions is uncertain. (*limited evidence, low agreement*) [8.6, 8.9]

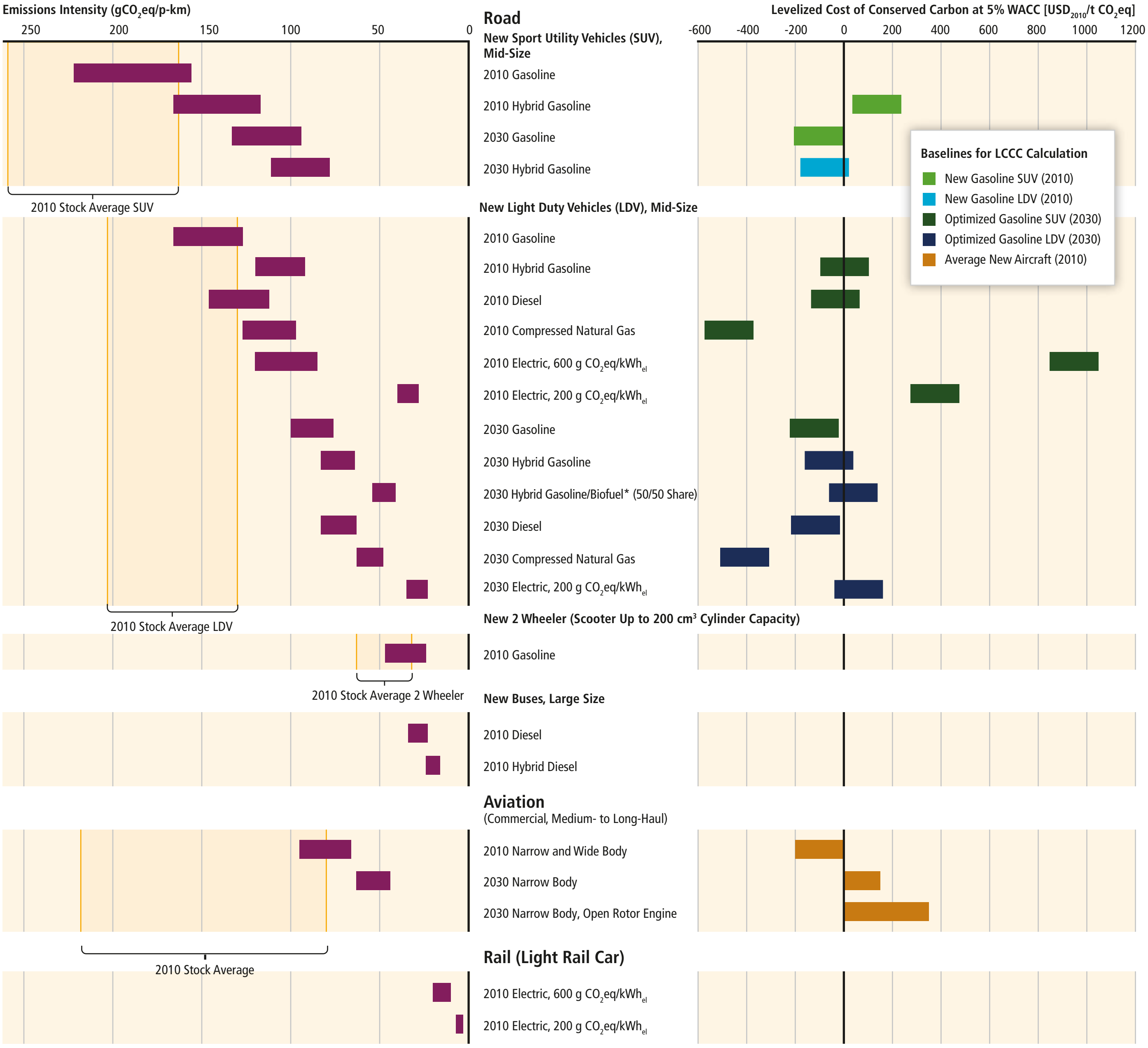
**Barriers to decarbonizing transport for all modes differ across regions but can be overcome, in part, through economic incentives** (*medium evidence, medium agreement*). Financial, institutional, cultural, and legal barriers constrain low-carbon technology uptake and behavioural change. They include the high investment costs needed to build low-emissions transport systems, the slow turnover of stock and infrastructure, and the limited impact of a carbon price on petroleum fuels that are already heavily taxed. Regional differences are likely due to cost and policy constraints. Oil price trends, price instruments on GHG emissions, and other measures such as road pricing and airport charges can provide strong economic incentives for consumers to adopt mitigation measures. [8.8]

**There are regional differences in transport mitigation pathways with major opportunities to shape transport systems and infrastructure around low-carbon options, particularly in developing and emerging countries where most future urban growth will occur** (*robust evidence, high agreement*). Possible transformation pathways vary with region and country due to differences in the dynamics of motorization, age and type of vehicle fleets, existing infrastructure, and urban development processes. Prioritizing infrastructure for pedestrians, integrating non-motorized and transit services, and managing excessive road speed for both urban and rural travellers can create economic and social co-benefits in all regions. For all economies, especially those with high rates of urban growth, investments in public transport systems and low-carbon infrastructure can avoid lock-in to carbon-intensive modes. Established infrastructure may limit the options for modal shift and lead to a greater reliance on advanced vehicle technologies; a slowing of growth in LDV demand is already evident in some OECD countries. (*medium evidence, medium agreement*) [8.4, 8.9]

**A range of strong and mutually supportive policies will be needed for the transport sector to decarbonize and for the co-benefits to be exploited** (*robust evidence, high agreement*). Transport mitigation strategies associated with broader non-climate policies at all government levels can usually target several objectives simultaneously to give lower travel costs, improved access and mobility, better health, greater energy security, improved safety, and increased time savings. Activity reduction measures have the largest potential to realize co-benefits. Realizing the co-benefits depends on the regional context in terms of economic, social, and political feasibility as well as having access to appropriate and cost-effective advanced technologies (Table TS.5). (*medium evidence, high agreement*) Since rebound effects can reduce the CO$_2$ benefits of efficiency improvements and undermine a particular policy, a balanced package of policies, including pricing initiatives, could help to achieve stable price signals, avoid unintended outcomes, and improve access, mobility, productivity, safety, and health (*medium evidence, medium agreement*). [8.4, 8.7, 8.10]

## Passenger Transport

### Currently Commercially Available and Future (2030) Expected Technologies



*Assuming 70% less CO$_2$eq/MJ of Biofuel than per MJ of Gasoline

**Figure TS.21 |** Indicative emissions intensity (tCO$_2$eq/p-km) and levelized costs of conserved carbon (LCCC in USD$_{2010}$/tCO$_2$eq saved) of selected passenger transport technologies. Variations in emissions intensities stem from variation in vehicle efficiencies and occupancy rates. Estimated LCCC for passenger road transport options are point estimates ±100 USD$_{2010}$/tCO$_2$eq based on central estimates of input parameters that are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel CO$_2$eq intensity, vehicle costs, fuel prices). They are derived relative to different baselines (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies, but remain inherently uncertain. LCCC for aviation are taken directly from the literature. Table 8.3 provides additional context (see Annex III.3 for data and assumptions on emissions intensities and cost calculations and Annex II.3.1 for methodological issues on levelized cost metrics). WACC: Weighted average cost of capital. [Table 8.3]

## Freight Transport

### Currently Commercially Available and Future (2030) Expected Technologies

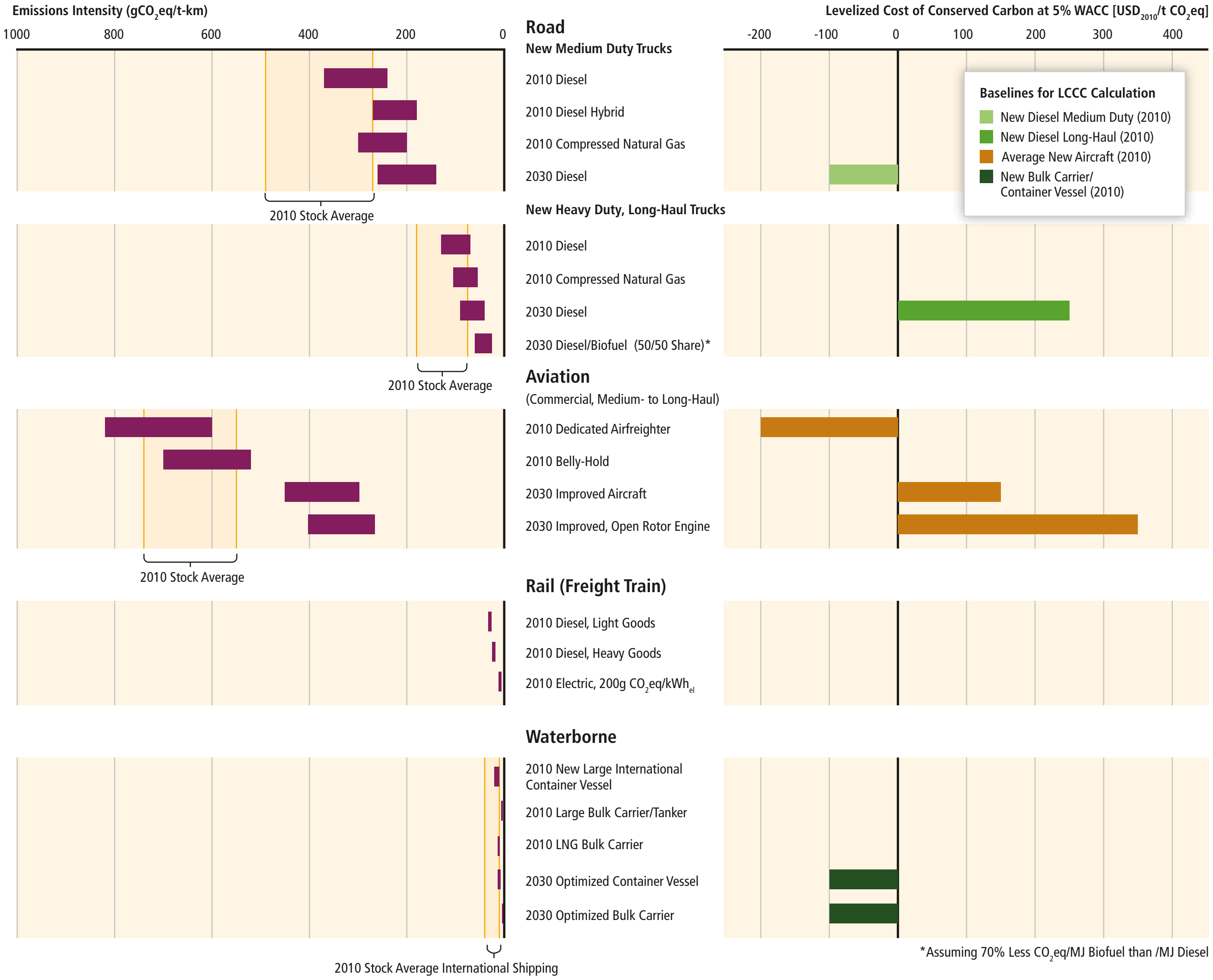


**Figure TS.22 |** Indicative emissions intensity ($tCO_2eq/t\text{-}km$) and levelized costs of conserved carbon (LCCC in $USD_{2010}/tCO_2eq$ saved) of selected freight transport technologies. Variations in emissions intensities largely stem from variation in vehicle efficiencies and load rates. Levelized costs of conserved carbon are taken directly from the literature and are very sensitive to assumptions (e.g., specific improvement in vehicle fuel economy to 2030, specific biofuel $CO_2eq$ intensity, vehicle costs, and fuel prices). They are expressed relative to current baseline technologies (see legend for colour coding) and need to be interpreted accordingly. Estimates for 2030 are based on projections from recent studies but remain inherently uncertain. Table 8.3 provides additional context (see Annex III.3 for data and assumptions on emissions intensities and cost calculations and Annex II.3.1 for methodological issues on levelized cost metrics). LNG: Liquefied natural gas; WACC: Weighted average cost of capital. [Table 8.3]

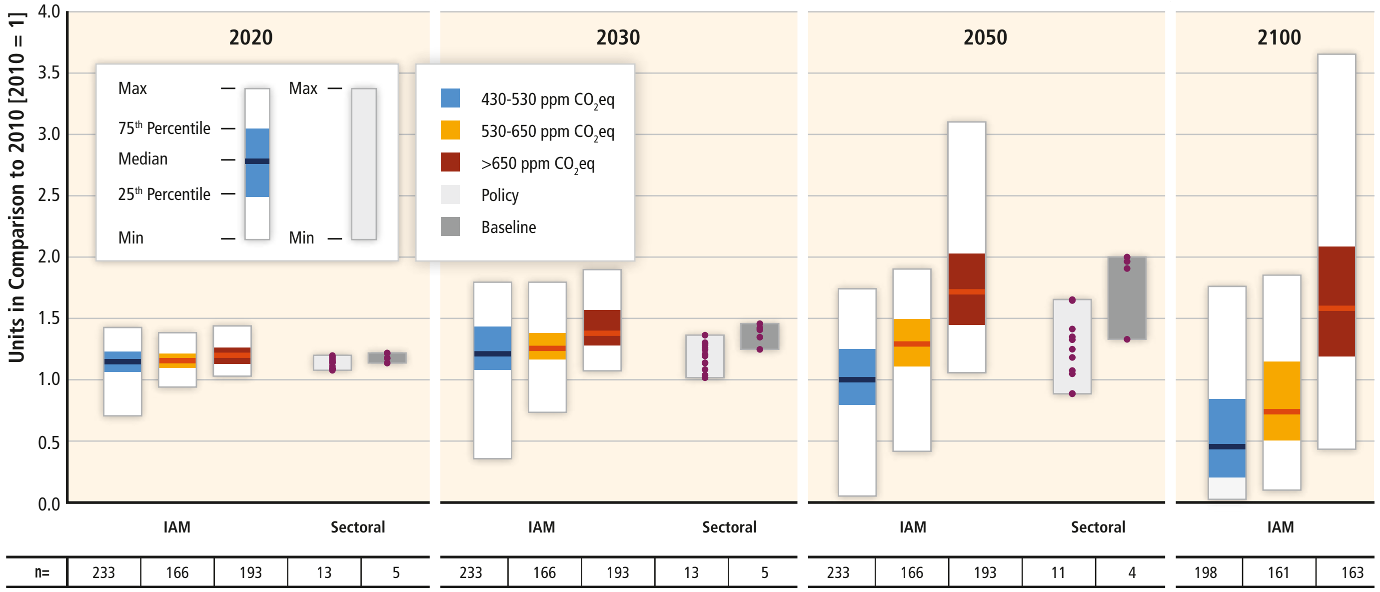


**Figure TS.23 |** Direct global $CO_2$ emissions from all passenger and freight transport are indexed relative to 2010 values for each scenario with integrated model studies grouped by $CO_2$eq concentration levels by 2100, and sectoral studies grouped by baseline and policy categories. [Figure 8.9]

**Table TS.5 |** Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the transport sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern; a question mark (**?**) denotes an uncertain net effect. Co-benefits and adverse side-effects depend on local circumstances as well as on implementation practice, pace and scale. For possible upstream effects of low-carbon electricity, see Table TS.4. For possible upstream effects of biomass supply, see Table TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 8.4]

| **Transport** | **Effect on additional objectives/concerns** | | |
|---|---|---|---|
| | **Economic** | **Social** | **Environmental** |
| **Reduction of fuel carbon intensity: electricity, hydrogen ($H_2$), compressed natural gas (CNG), biofuels, and other fuels** | ↑ Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (**m/m**)<br>↑ Technological spillovers (e.g., battery technologies for consumer electronics) (**l/l**) | Health impact via urban air pollution by<br>? CNG, biofuels: net effect unclear (**m/l**)<br>↓ Electricity, $H_2$: reducing most pollutants (**r/h**)<br>↑ Shift to diesel: potentially increasing pollution (**l/m**)<br>↓ Health impact via reduced noise (electricity and fuel cell LDVs) (**l/m**)<br>↓ Road safety (silent electric LDVs at low speed) (**l/l**) | Ecosystem impact of electricity and hydrogen via<br>↓ Urban air pollution (**m/m**)<br>↑ Material use (unsustainable resource mining) (**l/l**)<br>? Ecosystem impact of biofuels: *see AFOLU* |
| **Reduction of energy intensity** | ↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**m/m**) | ↓ Health impact via reduced urban air pollution (**r/h**)<br>↑ Road safety (via increased crash-worthiness) (**m/m**) | ↓ Ecosystem and biodiversity impact via reduced urban air pollution (**m/h**) |
| **Compact urban form and improved transport infrastructure**<br>**Modal shift** | ↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**m/m**)<br>↑ Productivity (reduced urban congestion and travel times, affordable and accessible transport) (**m/h**)<br>? Employment opportunities in the public transport sector vs. car manufacturing (**l/m**) | Health impact for non-motorized modes via<br>↓ Increased physical activity (**r/h**)<br>↑ Potentially higher exposure to air pollution (**r/h**)<br>↓ Noise (modal shift and travel reduction) (**r/h**)<br>↑ Equitable mobility access to employment opportunities, particularly in developing countries (**r/h**)<br>↑ Road safety (via modal shift and/or infrastructure for pedestrians and cyclists) (**r/h**) | Ecosystem impact via<br>↓ Urban air pollution (**r/h**)<br>↓ Land-use competition (**m/m**) |
| **Journey distance reduction and avoidance** | ↑ Energy security (reduced oil dependence and exposure to oil price volatility) (**r/h**)<br>↑ Productivity (reduced urban congestion, travel times, walking) (**r/h**) | ↓ Health impact (for non-motorized transport modes) (**r/h**) | Ecosystem impact via<br>↓ Urban air pollution (**r/h**)<br>↑ New/shorter shipping routes (**r/h**)<br>↓ Land-use competition from transport infrastructure (**r/h**) |

### TS.3.2.4 Buildings

**GHG emissions from the buildings sector[15] have more than doubled since 1970, accounting for 19 % of global GHG emissions in 2010, including indirect emissions from electricity generation.** The share rises to 25 % if AFOLU emissions are excluded from the total. The buildings sector also accounted for 32 % of total global final energy use, approximately one-third of black carbon emissions, and an eighth to a third of F-gases, with significant uncertainty (*medium evidence, medium agreement*). (Figure TS.3) [9.2]

**Direct and indirect $CO_2$ emissions from buildings are projected to increase from 8.8 $GtCO_2$/yr in 2010 to 13–17 $GtCO_2$/yr in 2050 (25–75th percentile; full range 7.9–22 $GtCO_2$/yr) in baseline scenarios; most of the baseline scenarios assessed in WGIII AR5 show a significant increase** (*medium evidence, medium agreement*) (Figure TS.15) [6.8]. The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years. Without further policies, final energy use of the buildings sector may grow from approximately 120 exajoules per year (EJ/yr) in 2010 to 270 EJ/yr in 2050 [9.9].

**Significant lock-in risks arise from the long lifespans of buildings and related infrastructure** (*robust evidence, high agreement*). If only currently planned policies are implemented, the final energy use in buildings that could be locked-in by 2050, compared to a scenario where today's best practice buildings become the standard in newly built structures and retrofits, is equivalent to approximately 80 % of the final energy use of the buildings sector in 2005. [9.4]

**Improvements in wealth, lifestyle change, the provision of access to modern energy services and adequate housing, and urbanization will drive the increases in building energy demand** (*robust evidence, high agreement*). The manner in which those without access to adequate housing (about 0.8 billion people), modern energy carriers, and sufficient levels of energy services including clean cooking and heating (about 3 billion people) meet these needs will influence the development of building-related emissions. In addition, migration to cities, decreasing household size, increasing levels of wealth, and lifestyle changes, including increasing dwelling size and number and use of appliances, all contribute to considerable increases in building energy services demand. The substantial amount of new construction taking place in developing countries represents both a risk and opportunity from a mitigation perspective. [9.2, 9.4, 9.9]

**Recent advances in technologies, know-how, and policies in the buildings sector, however, make it feasible that the global total sector final energy use stabilizes or even declines by mid-century** (*robust evidence, medium agreement*). Recent advances in technology, design practices and know-how, coupled with behavioural changes, can achieve a two to ten-fold reduction in energy requirements of individual new buildings and a two to four-fold reduction for individual existing buildings largely cost-effectively or sometimes even at net negative costs (see Box TS.12) (*robust evidence, high agreement*). [9.6]

**Advances since AR4 include the widespread demonstration worldwide of very low, or net zero energy buildings both in new construction and retrofits** (*robust evidence, high agreement*). In some jurisdictions, these have already gained important market shares with, for instance, over 25 million $m^2$ of building floorspace in Europe complying with the 'Passivehouse' standard in 2012. However, zero energy/carbon buildings may not always be the most cost-optimal solution, nor even be feasible in certain building types and locations. [9.3]

**High-performance retrofits are key mitigation strategies in countries with existing building stocks, as buildings are very long-lived and a large fraction of 2050 developed country buildings already exists** (*robust evidence, high agreement*). Reductions of heating/cooling energy use by 50–90 % have been achieved using best practices. Strong evidence shows that very low-energy construction and retrofits can be economically attractive. [9.3]

**With ambitious policies it is possible to keep global building energy use constant or significantly reduce it by mid-century compared to baseline scenarios which anticipate an increase of more than two-fold** (*medium evidence, medium agreement*) (Figure TS.24). Detailed building sector studies indicate a larger energy savings potential by 2050 than do integrated studies. The former indicate a potential of up to 70 % of the baseline for heating and cooling only, and around 35–45 % for the whole sector. In general, deeper reductions are possible in thermal energy uses than in other energy services mainly relying on electricity. With respect to additional fuel switching as compared to baseline, both sectoral and integrated studies find modest opportunities. In general, both sectoral and integrated studies indicate that electricity will supply a growing share of building energy demand over the long term, especially if heating demand decreases due to a combination of efficiency gains, better architecture, and climate change. [6.8.4, 9.8.2, Figure 9.19]

**The history of energy efficiency programmes in buildings shows that 25–30 % efficiency improvements have been available at costs substantially lower than those of marginal energy supply** (*robust evidence, high agreement*). Technological progress enables the potential for cost-effective energy efficiency improvements to be maintained, despite continuously improving standards. There has been substantial progress in the adoption of voluntary and mandatory standards since AR4, including ambitious building codes and targets, voluntary construction standards, and appliance standards. At the same time, in both new and retrofitted buildings, as well as in appliances and information, communication and media technology equipment, there have been notable performance and cost improvements. Large

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[15] The buildings sector covers the residential, commercial, public and services sectors; emissions from construction are accounted for in the industry sector.

## Box TS.12 | Negative private mitigation costs

A persistent issue in the analysis of mitigation options and costs is whether there are mitigation opportunities that are privately beneficial—generating private benefits that more than offset the costs of implementation—but which consumers and firms do not voluntarily undertake. There is some evidence of unrealized mitigation opportunities that would have negative private cost. Possible examples include investments in vehicles [8.1], lighting and heating technology in homes and commercial buildings [9.3], as well as industrial processes [10.1].

Examples of negative private costs imply that firms and individuals do not take opportunities to save money. This might be explained in a number of ways. One is that status-quo bias can inhibit the switch to new technologies or products [2.4, 3.10.1]. Another is that firms and individuals may focus on short-term goals and discount future costs and benefits sharply; consumers have been shown to do this when choosing energy conservation measures or investing in energy-efficient technologies [2.4.3, 2.6.5.3, 3.10.1]. Risk aversion and ambiguity aversion may also account for this behaviour when outcomes are uncertain [2.4.3, 3.10.1]. Other possible explanations include: insufficient information on opportunities to conserve energy; asymmetric information—for example, landlords may be unable to convey the value of energy efficiency improvements to renters; split incentives, where one party pays for an investment but another party reaps the benefits; and imperfect credit markets, which make it difficult or expensive to obtain finance for energy savings [3.10.1, 16.4].

Some engineering studies show a large potential for negative-cost mitigation. The extent to which such negative-cost opportunities can actually be realized remains a matter of contention in the literature. Empirical evidence is mixed. [Box 3.10]

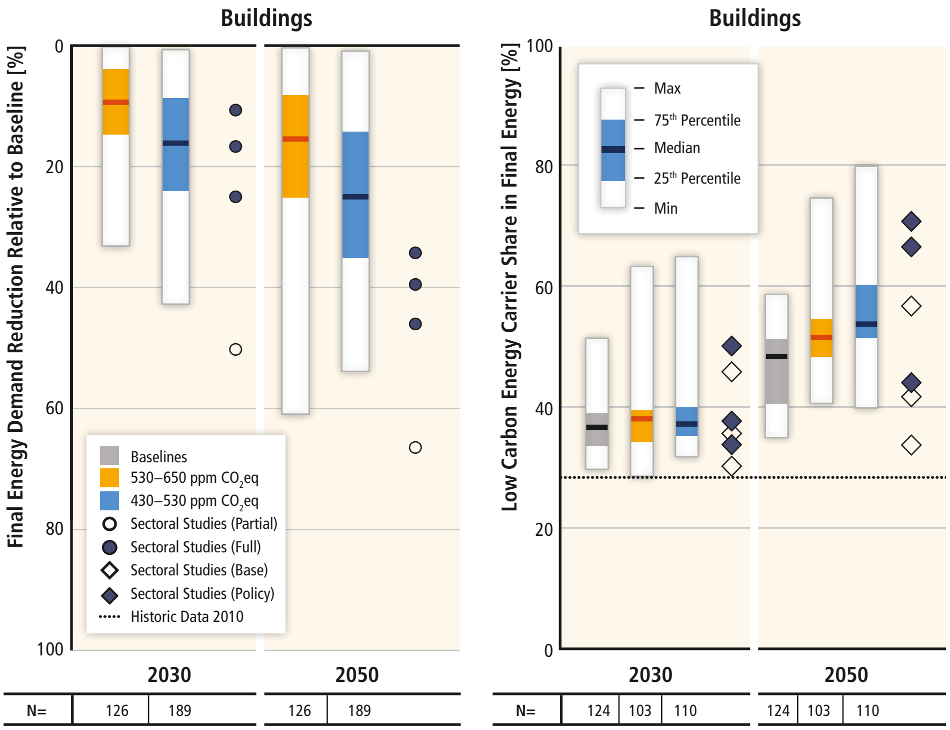

**Figure TS.24 |** Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (from electricity; right panel) in buildings by 2030 and 2050 in mitigation scenarios from three different CO$_2$eq concentrations ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 9. Filled circles correspond to sectoral studies with full sectoral coverage while empty circles correspond to studies with only partial sectoral coverage (e.g., heating and cooling). [Figures 6.37 and 6.38]

reductions in thermal energy use in buildings are possible at costs lower than those of marginal energy supply, with the most cost-effective options including very high-performance new commercial buildings; the same holds for efficiency improvements in some appliances and cooking equipment. [9.5, 9.6, 9.9]

**Lifestyle, culture, and other behavioural changes may lead to further large reductions in building and appliance energy requirements beyond those achievable through technologies and architecture. A three- to five-fold difference in energy use has been shown for provision of similar building-related energy**

**service levels in buildings.** (*limited evidence, high agreement*) For developed countries, scenarios indicate that lifestyle and behavioural changes could reduce energy demand by up to 20 % in the short term and by up to 50 % of present levels by mid-century (*medium evidence, medium agreement*). There is a high risk that emerging countries follow the same path as developed economies in terms of building-related architecture, lifestyle, and behaviour. But the literature suggests that alternative development pathways exist that provide high levels of building services at much lower energy inputs, incorporating strategies such as learning from traditional lifestyles, architecture, and construction techniques. [9.3]

**Most mitigation options in the building sector have considerable and diverse co-benefits** (*robust evidence, high agreement*). These include, but are not limited to: energy security; less need for energy subsidies; health and environmental benefits (due to reduced indoor and outdoor air pollution); productivity and net employment gains; the alleviation of fuel poverty; reduced energy expenditures; increased value for building infrastructure; and improved comfort and services. (Table TS.6) [9.6, 9.7]

**Especially strong barriers in this sector hinder the market-based uptake of cost-effective technologies and practices; as a consequence, programmes and regulation are more effective than pricing instruments alone** (*robust evidence, high agreement*). Barriers include imperfect information and lack of awareness, principal/agent problems and other split incentives, transaction costs, lack of access to financing, insufficient training in all construction-related trades, and cognitive/behavioural barriers. In developing countries, the large informal sector, energy subsidies, corruption, high implicit discount rates, and insufficient service levels are further barriers. Therefore, market forces alone are not expected to achieve the necessary transformation without external stimuli. Policy intervention addressing all stages of the building and appliance lifecycle and use, plus new business and financial models, are essential. [9.8, 9.10]

**A large portfolio of building-specific energy efficiency policies was already highlighted in AR4, but further considerable advances in available instruments and their implementation have occurred since** (*robust evidence, high agreement*). Evidence shows that many building energy efficiency policies worldwide have

**Table TS.6 |** Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the buildings sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. Co-benefits and adverse side-effects depend on local circumstances as well as on implementation practice, pace and scale. For possible upstream effects of fuel switching and RE, see Tables TS.4 and TS.8. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 9.7]

| Buildings | Effect on additional objectives/concerns | | | |
|---|---|---|---|---|
| | Economic | Social | Environmental | Other |
| **Fuel switching, RES incorporation, green roofs, and other measures reducing GHG emissions intensity** | ↑ Energy security (**m/h**)<br>↑ Employment impact (**m/m**)<br>↑ Lower need for energy subsidies (**l/l**)<br>↑ Asset values of buildings (**l/m**) | Fuel poverty (residential) via<br>↓ Energy demand (**m/h**)<br>↑ Energy cost (**l/m**)<br>↓ Energy access (for higher energy cost) (**l/m**)<br>↑ Productive time for women/children (for replaced traditional cookstoves) (**m/h**) | Health impact in residential buildings via<br>↓ Outdoor air pollution (**r/h**)<br>↓ Indoor air pollution (in developing countries) (**r/h**)<br>↓ Fuel poverty (**r/h**)<br>↓ Ecosystem impact (less outdoor air pollution) (**r/h**)<br>↑ Urban biodiversity (for green roofs) (**m/m**) | Reduced Urban Heat Island (UHI) effect (**l/m**) |
| **Retrofits of existing buildings (e.g., cool roof, passive solar, etc.)**<br>**Exemplary new buildings**<br>**Efficient equipment** | ↑ Energy security (**m/h**)<br>↑ Employment impact (**m/m**)<br>↑ Productivity (for commercial buildings) (**m/h**)<br>↑ Lower need for energy subsidies (**l/l**)<br>↑ Asset values of buildings (**l/m**)<br>↑ Disaster resilience (**l/m**) | ↓ Fuel poverty (for retrofits and efficient equipment) (**m/h**)<br>↓ Energy access (higher cost for housing due to the investments needed) (**l/m**)<br>↑ Thermal comfort (for retrofits and exemplary new buildings) (**m/h**)<br>↑ Productive time for women and children (for replaced traditional cookstoves) (**m/h**) | Health impact via<br>↓ Outdoor air pollution (**r/h**)<br>↓ Indoor air pollution (for efficient cookstoves) (**r/h**)<br>↓ Improved indoor environmental conditions (**m/h**)<br>↓ Fuel poverty (**r/h**)<br>↓ Insufficient ventilation (**m/m**)<br>↓ Ecosystem impact (less outdoor air pollution) (**r/h**)<br>↓ Water consumption and sewage production (**l/l**) | Reduced UHI effect (for retrofits and new exemplary buildings) (**l/m**) |
| **Behavioural changes reducing energy demand** | ↑ Energy security (**m/h**)<br>↑ Lower need for energy subsidies (**l/l**) | | ↓ Health impact via less outdoor air pollution (**r/h**) and improved indoor environmental conditions (**m/h**)<br>↓ Ecosystem impact (less outdoor air pollution) (**r/h**) | |

already been saving GHG emissions at large negative costs. Among the most environmentally and cost-effective policies are regulatory instruments such as building and appliance energy performance standards and labels, as well as public leadership programmes and procurement policies. Progress in building codes and appliance standards in some developed countries over the last decade have contributed to stabilizing or even reducing total building energy use, despite growth in population, wealth, and corresponding energy service level demands. Developing countries have also been adopting different effective policies, most notably appliance standards. However, in order to reach ambitious climate goals, these standards need to be substantially strengthened and adopted in further jurisdictions, and to other building and appliance types. Due to larger capital requirements, financing instruments are essential both in developed and developing countries to achieve deep reductions in energy use. [9.10]

### TS.3.2.5 Industry

**In 2010, the industry sector accounted for around 28 % of final energy use, and direct and indirect GHG emissions (the latter being associated with electricity consumption) are larger than the emissions from either the buildings or transport end-use sectors and represent just over 30 % of global GHG emissions in 2010** (the share rises to 40 % if AFOLU emissions are excluded from the total) (*high confidence*). Despite the declining share of industry in global GDP, global industry and waste/wastewater GHG emissions grew from 10 $GtCO_2eq$ in 1990 to 13 $GtCO_2eq$ in 2005 and to 15 $GtCO_2eq$ in 2010 (of which waste/wastewater accounted for 1.4 $GtCO_2eq$). [10.3]

**Carbon dioxide emissions from industry, including direct and indirect emissions as well as process emissions, are projected to increase from 13 $GtCO_2$/yr in 2010 to 20–24 $GtCO_2$/yr in 2050 (25–75th percentile; full range 9.5–34 $GtCO_2$/yr) in baseline scenarios; most of the baseline scenarios assessed in WGIII AR5 show a significant increase** (*medium evidence, medium agreement*) (Figure TS.15) [6.8]. The lower end of the full range is dominated by scenarios with a focus on energy intensity improvements that go well beyond the observed improvements over the past 40 years.

**The wide-scale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in practice, and in non-energy intensive industries, could directly reduce the energy intensity of the industry sector by about 25 % compared to the current level** (*robust evidence, high agreement*). Despite long-standing attention to energy efficiency in industry, many options for improved energy efficiency still remain. Through innovation, additional reductions of about 20 % in energy intensity may potentially be realized (*limited evidence, medium agree-*

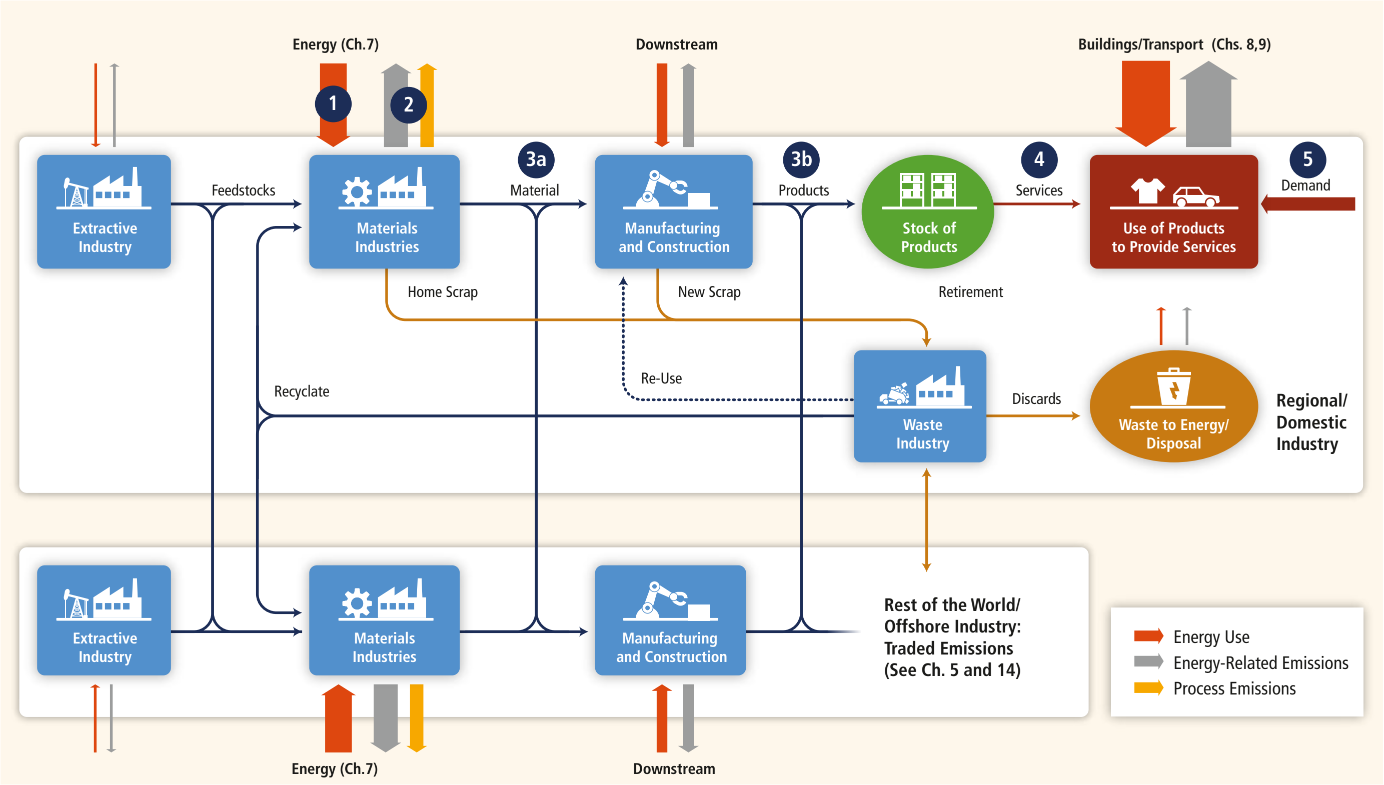

**Figure TS.25 |** A schematic illustration of industrial activity over the supply chain. Options for mitigation in the industry sector are indicated by the circled numbers: (1) energy efficiency; (2) emissions efficiency; (3a) material efficiency in manufacturing; (3b) material efficiency in product design; (4) product-service efficiency; (5) service demand reduction. [Figure 10.2] *ment*). Barriers to implementing energy efficiency relate largely to the initial investment costs and lack of information. Information programmes are a prevalent approach for promoting energy efficiency, followed by economic instruments, regulatory approaches, and voluntary actions. [10.4, 10.7, 10.9, 10.11]

**An absolute reduction in emissions from the industry sector will require deployment of a broad set of mitigation options that go beyond energy efficiency measures** (*medium evidence, high agreement*) [10.4, 10.7]. In the context of continued overall growth in industrial demand, substantial reductions from the sector will require parallel efforts to increase emissions efficiency (e.g., through fuel and feedstock switching or CCS); material use efficiency (e.g., less scrap, new product design); recycling and re-use of materials and products; product-service efficiency (e.g., more intensive use of products through car sharing, longer life for products); radical product innovations (e.g., alternatives to cement); as well as service demand reductions. Lack of policy and experiences in material and product-service efficiency are major barriers. (Table TS.3, Figure TS.25) [10.4, 10.7, 10.11]

**While detailed industry sector studies tend to be more conservative than integrated studies, both identify possible industrial final energy demand savings of around 30 % by 2050 in mitigation scenarios not exceeding 650 ppm $CO_2$eq by 2100 relative to baseline scenarios** (*medium evidence, medium agreement*) (Figure TS.26). Integrated models in general treat the industry sector in a more aggregated fashion and mostly do not explicitly provide detailed sub-sectoral material flows, options for reducing material demand, and price-induced inter-input substitution possibilities. Due to the heterogeneous character of the industry sector, a coherent comparison between sectoral and integrated studies remains difficult. [6.8.4, 10.4, 10.7, 10.10.1, Figure 10.14]

**Mitigation in the industry sector can also be achieved by reducing material and fossil fuel demand by enhanced waste use, which concomitantly reduces direct GHG emissions from waste disposal** (*robust evidence, high agreement*). The hierarchy of waste management places waste reduction at the top, followed by re-use, recycling, and energy recovery. As the share of recycled or reused material is still low, applying waste treatment technologies and recovering energy to reduce demand for fossil fuels can result in direct emission reductions from waste disposal. Globally, only about 20 % of municipal solid waste (MSW) is recycled and about 14 % is treated with energy recovery while the rest is deposited in open dumpsites or landfills. About 47 % of wastewater produced in the domestic and manufacturing sectors is still untreated. The largest cost range is for reducing GHG emissions from landfilling through the treatment of waste by anaerobic digestion. The costs range from negative (see Box TS.12) to very high. Advanced wastewater treatment technologies may enhance GHG emissions reduction in wastewater treatment but they are clustered among the higher cost options (*medium evidence, medium agreement*). (Figure TS.29) [10.4, 10.14]

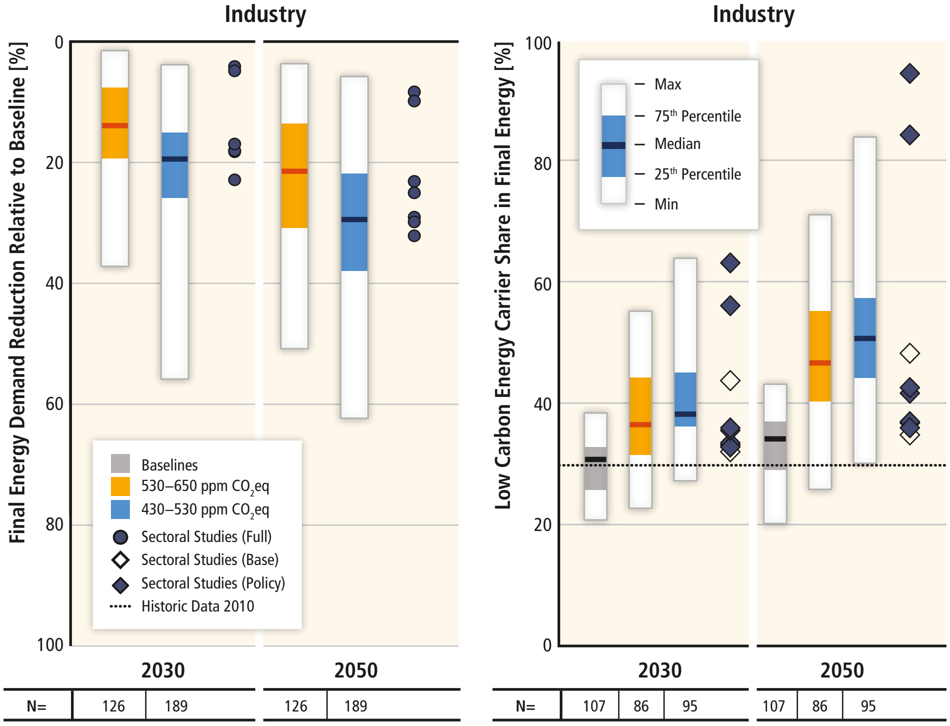

**Figure TS.26 |** Final energy demand reduction relative to baseline (left panel) and development of final low-carbon energy carrier share in final energy (including electricity, heat, hydrogen, and bioenergy; right panel) in industry by 2030 and 2050 in mitigation scenarios from three different $CO_2$eq concentration ranges shown in boxplots (see Section 6.3.2) compared to sectoral studies shown in shapes assessed in Chapter 10. Filled circles correspond to sectoral studies with full sectoral coverage. [Figures 6.37 and 6.38]

**Figure TS.27 |** Indicative $CO_2$ emission intensities for cement (upper panel) and steel (lower panel) production, as well as indicative levelized cost of conserved carbon (LCCC) shown for various production practices/technologies and for 450 ppm $CO_2$eq scenarios of a limited selection of integrated models (for data and methodology, see Annex III). DRI: Direct reduced iron; EAF: Electric arc furnace. [Figures 10.7, 10.8]

**Waste policy and regulation have largely influenced material consumption, but few policies have specifically pursued material efficiency or product-service efficiency** (*robust evidence, high agreement*) [10.11]. Barriers to improving material efficiency include lack of human and institutional capacities to encourage management decisions and public participation. Also, there is a lack of experience and often there are no clear incentives either for suppliers or consumers to address improvements in material or product-service efficiency, or to reduce product demand. [10.9]

**$CO_2$ emissions dominate GHG emissions from industry, but there are also substantial mitigation opportunities for non-$CO_2$ gases**

**Figure TS.28 |** Indicative global $CO_2eq$ emissions for chemicals production (upper panel) and indicative global $CO_2$ emission intensities for paper production (lower panel) as well as indicative levelized cost of conserved carbon (LCCC) shown for various production practices/technologies and for 450 ppm $CO_2eq$ scenarios of a limited selection of integrated models (for data and methodology, see Annex III). [Figures 10.9, 10.10]

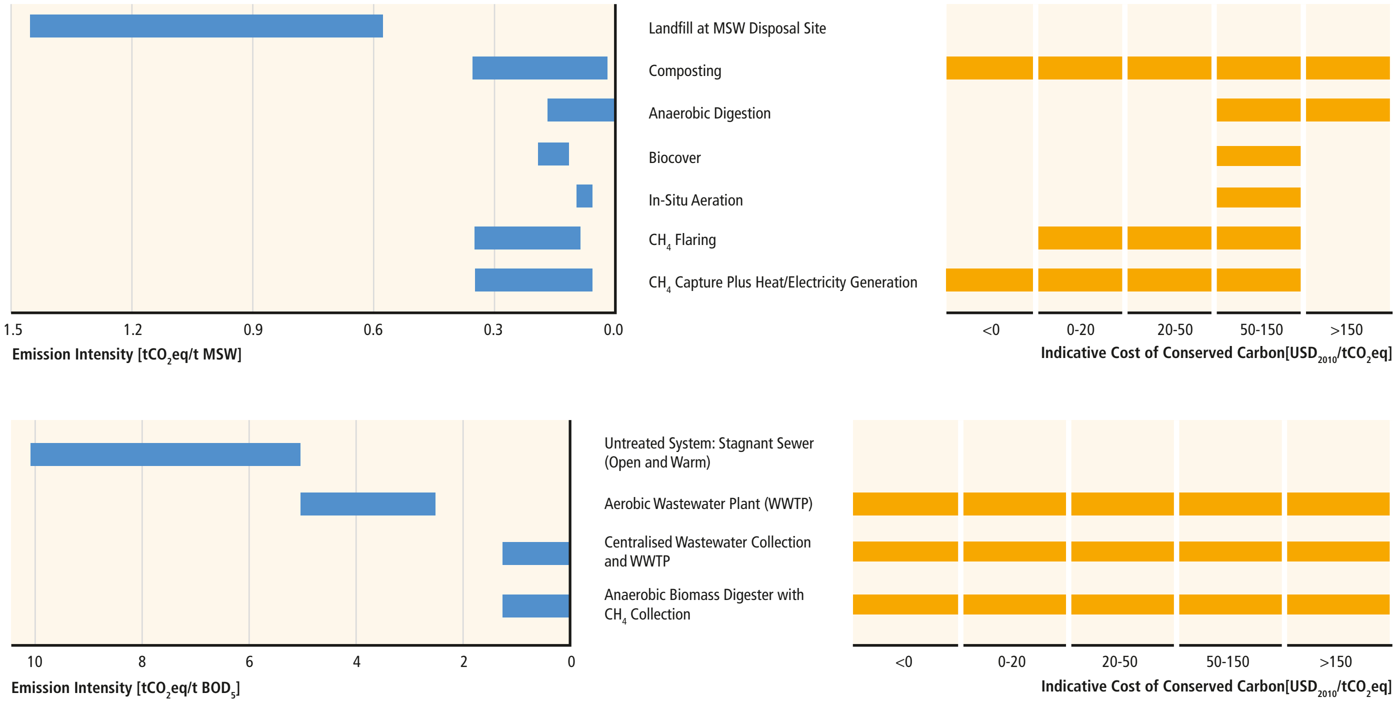

**Figure TS.29|** Indicative $CO_2eq$ emission intensities for waste (upper panel) and wastewater (lower panel) of various practices as well as indicative levelized cost of conserved carbon (for data and methodology, see Annex III). MSW: Municipal solid waste. [Figures 10.19 and 10.20]

(*robust evidence, high agreement*). Methane ($CH_4$), nitrous oxide ($N_2O$) and fluorinated gases (F-gases) from industry accounted for emissions of 0.9 $GtCO_2eq$ in 2010. Key mitigation opportunities comprise, e.g., reduction of hydrofluorocarbon (HFC) emissions by leak repair, refrigerant recovery and recycling, and proper disposal and replacement by alternative refrigerants (ammonia, HC, $CO_2$). $N_2O$ emissions from adipic and nitric acid production can be reduced through the implementation of thermal destruction and secondary catalysts. The reduction of non-$CO_2$ GHGs also faces numerous barriers. Lack of awareness, lack of economic incentives and lack of commercially available technologies (e.g., for HFC recycling and incineration) are typical examples. [Table 10.2, 10.7]

**Systemic approaches and collaborative activities across companies (large energy-intensive industries and Small and Medium Enterprises (SMEs)) and sectors can help to reduce GHG emissions** (*robust evidence, high agreement*). Cross-cutting technologies such as efficient motors, and cross-cutting measures such as reducing air or steam leaks, help to optimize performance of industrial processes and improve plant efficiency very often cost-effectively with both energy savings and emissions benefits. Industrial clusters also help to realize mitigation, particularly from SMEs. [10.4] Cooperation and cross-sectoral collaboration at different levels—for example, sharing of infrastructure, information, waste heat, cooling, etc.—may provide further mitigation potential in certain regions/industry types [10.5].

**Several emission-reducing options in the industrial sector are cost-effective and profitable** (*medium evidence, medium agreement*). While options in cost ranges of 0–20 and 20–50 $USD/tCO_2eq$ and even below 0 $USD/tCO_2eq$ exist, achieving near-zero emissions intensity levels in the industry sector would require the additional realization of long-term step-change options (e.g., CCS), which are associated with higher levelized costs of conserved carbon (LCCC) in the range of 50–150 $USD/tCO_2eq$. Similar cost estimates for implementing material efficiency, product-service efficiency, and service demand reduction strategies are not available. With regard to long-term options, some sector-specific measures allow for significant reductions in specific GHG emissions but may not be applicable at scale, e.g., scrap-based iron and steel production. Decarbonized electricity can play an important role in some subsectors (e.g., chemicals, pulp and paper, and aluminium), but will have limited impact in others (e.g., cement, iron and steel, waste). In general, mitigation costs vary regionally and depend on site-specific conditions. (Figures TS.27, TS.28, TS.29) [10.7]

**Mitigation measures are often associated with co-benefits** (*robust evidence, high agreement*). Co-benefits include enhanced competitiveness through cost-reductions, new business opportunities, better environmental compliance, health benefits through better local air and water quality and better work conditions, and reduced waste, all of which provide multiple indirect private and social benefits (Table TS.7). [10.8]

**There is no single policy that can address the full range of mitigation measures available for industry and overcome associated barriers.** Unless barriers to mitigation in industry are resolved, the pace and extent of mitigation in industry will be limited and even profitable measures will remain untapped (*robust evidence, high agreement*). [10.9, 10.11]

**Table TS.7 |** Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the industry sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace and scale. For possible upstream effects of low-carbon energy supply (includes CCS), see Table TS.4. For possible upstream effects of biomass supply, see Table TS.8. For an assessment of macroeconomic, cross-sectoral, effects associated with mitigation policies (e. g., on energy prices, consumption, growth, and trade), see e. g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Table 10.5]

| **Industry** | **Effect on additional objectives/concerns** | | |
|---|---|---|---|
| | **Economic** | **Social** | **Environmental** |
| **$CO_2$ and non-$CO_2$ GHG emissions intensity reduction** | ↑ Competitiveness and productivity **(m/h)** | ↓ Health impact via reduced local air pollution and better work conditions (for perfluorocarbons from aluminium) **(m/m)** | ↓ Ecosystem impact via reduced local air pollution and reduced water pollution **(m/m)**<br>↑ Water conservation **(l/m)** |
| **Technical energy efficiency improvements via new processes and technologies** | ↑ Energy security (via lower energy intensity) **(m/m)**<br>↑ Employment impact **(l/l)**<br>↑ Competitiveness and productivity **(m/h)**<br>↑ Technological spillovers in developing countries (due to supply chain linkages) **(l/l)** | ↓ Health impact via reduced local pollution **(l/m)**<br>↑ New business opportunities **(m/m)**<br>↑ Water availability and quality **(l/l)**<br>↑ Safety, working conditions and job satisfaction **(m/m)** | Ecosystem impact via:<br>↓ Fossil fuel extraction **(l/l)**<br>↓ Local pollution and waste **(m/m)** |
| **Material efficiency of goods, recycling** | ↓ National sales tax revenue in medium term **(l/l)**<br>↑ Employment impact in waste recycling market **(l/l)**<br>↑ Competitiveness in manufacturing **(l/l)**<br>↑ New infrastructure for industrial clusters **(l/l)** | ↓ Health impacts and safety concerns **(l/m)**<br>↑ New business opportunities **(m/m)**<br>↓ Local conflicts (reduced resource extraction) **(l/m)** | ↓ Ecosystem impact via reduced local air and water pollution and waste material disposal **(m/m)**<br>↓ Use of raw/virgin materials and natural resources implying reduced unsustainable resource mining **(l/l)** |
| **Product demand reductions** | ↓ National sales tax revenue in medium term **(l/l)** | ↑ Wellbeing via diverse lifestyle choices **(l/l)** | ↓ Post-consumption waste **(l/l)** |

### TS.3.2.6 Agriculture, Forestry and Other Land Use (AFOLU)

**Since AR4, GHG emissions from the AFOLU sector have stabilized but the share of total anthropogenic GHG emissions has decreased** (*robust evidence, high agreement*). The average annual total GHG flux from the AFOLU sector was 10–12 $GtCO_2eq$ in 2000–2010, with global emissions of 5.0–5.8 $GtCO_2eq/yr$ from agriculture on average and around 4.3–5.5 $GtCO_2eq/yr$ from forestry and other land uses. Non-$CO_2$ emissions derive largely from agriculture, dominated by $N_2O$ emissions from agricultural soils and $CH_4$ emissions from livestock enteric fermentation, manure management, and emissions from rice paddies, totalling 5.0–5.8 $GtCO_2eq/yr$ in 2010 (*robust evidence, high agreement*). Over recent years, most estimates of FOLU $CO_2$ fluxes indicate a decline in emissions, largely due to decreasing deforestation rates and increased afforestation (*limited evidence, medium agreement*). The absolute levels of emissions from deforestation and degradation have fallen from 1990 to 2010 (*robust evidence, high agreement*). Over the same time period, total emissions for high-income countries decreased while those of low-income countries increased. In general, AFOLU emissions from high-income countries are dominated by agriculture activities while those from low-income countries are dominated by deforestation and degradation. [Figure 1.3, 11.2]

**Net annual baseline $CO_2$ emissions from AFOLU are projected to decline over time with net emissions potentially less than half of the 2010 level by 2050, and the possibility of the AFOLU sector becoming a net sink before the end of century.** However, the uncertainty in historical net AFOLU emissions is larger than for other sectors, and additional uncertainties in projected baseline net AFOLU emissions exist. (*medium evidence, high agreement*) (Figure TS.15) [6.3.1.4, 6.8, Figure 6.5] As in AR4, most projections suggest declining annual net $CO_2$ emissions in the long run. In part, this is driven by technological change, as well as projected declining rates of agriculture area expansion related to the expected slowing in population growth. However, unlike AR4, none of the more recent scenarios projects growth in the near-term. There is also a somewhat larger range of variation later in the century, with some models projecting a stronger net sink starting in 2050 (*limited evidence, medium agreement*). There are few reported projections of baseline global land-related $N_2O$ and $CH_4$ emissions and they indicate an increase over time. Cumulatively, land $CH_4$ emissions are projected to be 44–53 % of total $CH_4$ emissions through 2030, and 41–59 % through 2100, and land $N_2O$ emissions 85–89 % and 85–90 %, respectively (*limited evidence, medium agreement*). [11.9]

**Opportunities for mitigation in the AFOLU sector include supply- and demand-side mitigation options** (*robust evidence, high agreement*). Supply-side measures involve reducing emissions arising from land-use change, in particular reducing deforestation, and land and livestock management, increasing carbon stocks by sequestration in soils and biomass, or the substitution of fossil fuels by biomass for energy production (Table TS.3). Further new supply-side technologies not assessed in AR4, such as biochar or wood products for energy-intensive building materials, could contribute to the mitigation potential of the AFOLU sector, but there are still few studies upon which to make robust estimates. Demand-side measures include dietary change and waste reduction in the food supply chain. Increasing forestry and agricultural production without a commensurate increase in emissions (i.e., one component of sustainable intensification; Figure TS.30) also reduces emissions intensity (i.e., the GHG emissions per unit of product), a mitigation mechanism largely unreported for AFOLU in AR4, which could reduce absolute emissions as long as production volumes do not increase. [11.3, 11.4]

**Among supply-side measures, the most cost-effective forestry options are afforestation, sustainable forest management and reducing deforestation, with large differences in their relative importance across regions; in agriculture, low carbon prices[16] (20 USD/t$CO_2$eq) favour cropland and grazing land management and high carbon prices (100 USD/t$CO_2$eq) favour restoration of organic soils** (*medium evidence, medium agreement*). When considering only studies that cover both forestry and agriculture and include agricultural soil carbon sequestration, the economic mitigation potential in the AFOLU sector is estimated to be 7.18 to 10.6 (full range of all studies: 0.49–10.6) Gt$CO_2$eq/yr in 2030 for mitigation efforts consistent with carbon prices up to 100 USD/ t$CO_2$eq, about a third of which can be achieved at < 20 USD/ t$CO_2$eq (*medium evidence, medium agreement*). The range of global estimates at a given carbon price partly reflects uncertainty surrounding AFOLU mitigation potentials in the literature and the land-use assumptions of the scenarios considered. The ranges of estimates also reflect differences in the GHGs and options considered in the studies. A comparison of estimates of economic mitigation potential in the AFOLU sector published since AR4 is shown in Figure TS.31. [11.6]

**While demand-side measures are under-researched, changes in diet, reductions of losses in the food supply chain, and other measures have a significant, but uncertain, potential to reduce GHG emissions from food production (0.76–8.55 Gt$CO_2$eq/yr by 2050)** (Figure TS.31) (*limited evidence, medium agreement*). Barriers to implementation are substantial, and include concerns about jeopardizing health and well-being, and cultural and societal resistance to behavioural change. However, in countries with a high consumption of animal protein, co-benefits are reflected in positive health impacts resulting from changes in diet (*robust evidence, high agreement*). [11.4.3, 11.6, 11.7, 11.9]

**The mitigation potential of AFOLU is highly dependent on broader factors related to land-use policy and patterns** (*medium evidence, high agreement*). The many possible uses of land can compete or work in synergy. The main barriers to mitigation are institutional (lack of tenure and poor governance), accessibility to financing mechanisms, availability of land and water, and poverty. On the other hand, AFOLU mitigation options can promote innovation, and many technological supply-side mitigation options also increase agricultural and silvicultural efficiency, and can reduce climate vulnerability by improving resilience. Multifunctional systems that allow the delivery of multiple services from land have the capacity to deliver to many policy goals in addition to mitigation, such as improving land tenure, the governance of natural resources, and equity [11.8] (*limited evidence, high agreement*). Recent frameworks, such as those for assessing environmental or ecosystem services, could provide tools for valuing the multiple synergies and tradeoffs that may arise from mitigation actions (Table TS.8) (*medium evidence, medium agreement*). [11.7, 11.8]

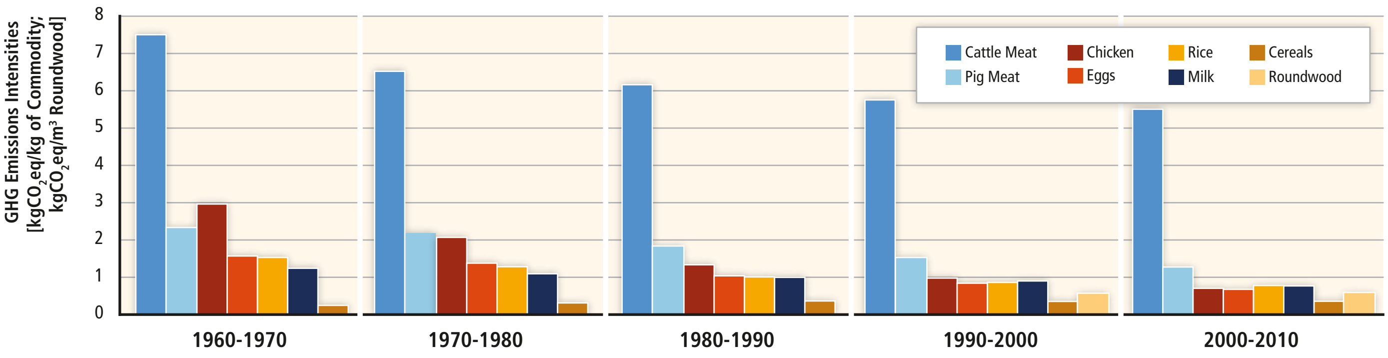

**Figure TS.30 |** GHG emissions intensities of selected major AFOLU commodities for decades 1960s–2000s. (1) Cattle meat, defined as GHG (enteric fermentation + manure management of cattle, dairy and non-dairy)/meat produced; (2) pig meat, defined as GHG (enteric fermentation + manure management of swine, market and breeding)/meat produced; (3) chicken meat, defined as GHG (manure management of chickens)/meat produced; (4) milk, defined as GHG (enteric fermentation + manure management of cattle, dairy)/milk produced; (5) eggs, defined as GHG (manure management of chickens, layers)/egg produced; (6) rice, defined as GHG (rice cultivation)/rice produced; (7) cereals, defined as GHG (synthetic fertilizers)/cereals produced; (8) wood, defined as GHG (carbon loss from harvest)/roundwood produced. [Figure 11.15]

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[16] In many models that are used to assess the economic costs of mitigation, carbon price is used as a proxy to represent the level of effort in mitigation policies (see Glossary).

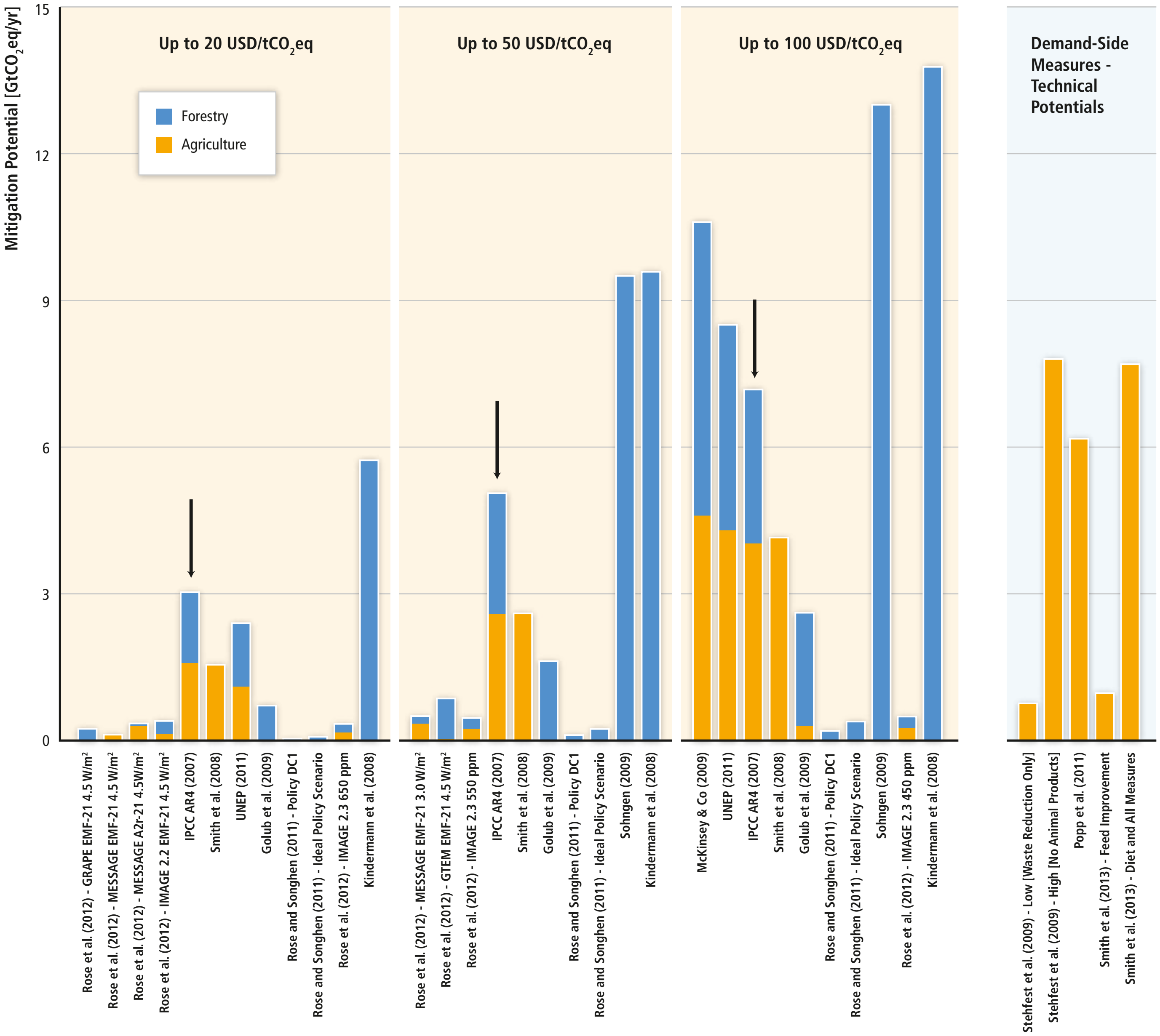

**Figure TS.31 |** Estimates of economic mitigation potentials in the AFOLU sector published since AR4 (AR4 estimates shown for comparison, denoted by black arrows), including bottom-up, sectoral studies, and top-down, multi-sector studies. Supply-side mitigation potentials are estimated for around 2030, ranging from 2025 to 2035, and are for agriculture, forestry or both sectors combined. Studies are aggregated for potentials up to ~20 USD/tCO$_2$eq (actual range 1.64–21.45), up to ~50 USD/tCO$_2$eq (actual range 31.39–50.00), and up to ~100 USD/tCO$_2$eq (actual range 70.0–120.91). Demand-side measures (shown on the right hand side of the figure) are for ~2050 and are not assessed at a specific carbon price, and should be regarded as technical potentials. Smith et al. (2013) values are the mean of the range. Not all studies consider the same measures or the same GHGs. [11.6.2, Figure 11.14]

**Policies governing practices in agriculture as well as forest conservation and management need to account for the needs of both mitigation and adaptation** (*medium evidence, high agreement*). Some mitigation options in the AFOLU sector (such as soil and forest carbon stocks) may be vulnerable to climate change. Economic incentives (e.g., special credit lines for low-carbon agriculture, sustainable agriculture and forestry practices, tradable credits, payment for ecosystem services) and regulatory approaches (e.g., enforcement of environmental law to protect forest carbon stocks by reducing deforestation, set-aside policies, air and water pollution control reducing nitrate load and N$_2$O emissions) have been effective in different cases. Investments in research, development, and diffusion (e.g., increase of resource use-efficiency (fertilizers), livestock improvement, better forestry management practices) could result in synergies between adaptation and mitigation. Successful cases of deforestation reduction in different regions are found to combine different policies such as land planning, regulatory approaches and economic incentives (*limited evidence, high agreement*). [11.3.2, 11.10, 15.11]

**Table TS.8 |** Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the AFOLU sector; arrows pointing up/down denote a positive/negative effect on the respective objective or concern. These effects depend on the specific context (including bio-physic, institutional and socio-economic aspects) as well as on the scale of implementation. For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth, and trade), see e.g., Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. The uncertainty qualifiers in brackets denote the level of evidence and agreement on the respective effects (see TS.1). Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high. [Tables 11.9 and 11.12]

| AFOLU | Effect on additional objectives/concerns | | | |
|---|---|---|---|---|
| | **Economic** | **Social** | **Environmental** | **Institutional** |
| **Supply side:** Forestry, land-based agriculture, livestock, integrated systems, and bioenergy (**marked by** *)<br>**Demand side:** Reduced losses in the food supply chain, changes in human diets, changes in demand for wood and forestry products | * Employment impact via<br>↑ Entrepreneurship development (**m/h**)<br>↓ Use of less labour-intensive technologies in agriculture (**m/m**)<br>↑* Diversification of income sources and access to markets (**r/h**)<br>↑* Additional income to (sustainable) landscape management (**m/h**)<br>↑* Income concentration (**m/m**)<br>↑* Energy security (resource sufficiency) (**m/h**)<br>↑ Innovative financing mechanisms for sustainable resource management (**m/h**)<br>↑ Technology innovation and transfer (**m/m**) | ↑* Food-crops production through integrated systems and sustainable agriculture intensification (**r/m**)<br>↓* Food production (locally) due to large-scale monocultures of non-food crops (**r/l**)<br>↑ Cultural habitats and recreational areas via (sustainable) forest management and conservation (**m/m**)<br>↑* Human health and animal welfare e.g., through less pesticides, reduced burning practices, and practices like agroforestry and silvo-pastoral systems (**m/h**)<br>↓* Human health when using burning practices (in agriculture or bioenergy) (**m/m**)<br>* Gender, intra- and inter-generational equity via<br>↑ Participation and fair benefit sharing (**r/h**)<br>↑ Concentration of benefits (**m/m**) | Provision of ecosystem services via<br>↑ Ecosystem conservation and sustainable management as well as sustainable agriculture (**r/h**)<br>↓* Large scale monocultures (**r/h**)<br>↑* Land-use competition (**r/m**)<br>↑ Soil quality (**r/h**)<br>↓ Erosion (**r/h**)<br>↑ Ecosystem resilience (**m/h**)<br>↑ Albedo and evaporation (**r/h**) | ↑↓* Tenure and use rights at the local level (for indigenous people and local communities) especially when implementing activities in natural forests (**r/h**)<br>↑↓ Access to participative mechanisms for land management decisions (**r/h**)<br>↑ Enforcement of existing policies for sustainable resource management (**r/h**) |

**Reducing Emissions from Deforestation and Forest Degradation (REDD+)[17] can be a very cost-effective policy option for mitigating climate change, if implemented in a sustainable manner** (*limited evidence, medium agreement*). REDD+ includes: reducing emissions from deforestation and forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks. It could supply a large share of global abatement of emissions from the AFOLU sector, especially through reducing deforestation in tropical regions, with potential economic, social and other environmental co-benefits. To assure these co-benefits, the implementation of national REDD+ strategies would need to consider financing mechanisms to local stakeholders, safeguards (such as land rights, conservation of biodiversity and other natural resources), and the appropriate scale and institutional capacity for monitoring and verification. [11.10]

**Bioenergy can play a critical role for mitigation, but there are issues to consider, such as the sustainability of practices and the efficiency of bioenergy systems** (*robust evidence, medium agreement*) [11.4.4, Box 11.5, 11.13.6, 11.13.7]. Barriers to large-scale deployment of bioenergy include concerns about GHG emissions from land, food security, water resources, biodiversity conservation and livelihoods. The scientific debate about the overall climate impact related to land-use competition effects of specific bioenergy pathways remains unresolved (*robust evidence, high agreement*). [11.4.4, 11.13] Bioenergy technologies are diverse and span a wide range of options and technology pathways. Evidence suggests that options with low lifecycle emissions (e.g., sugar cane, Miscanthus, fast growing tree species, and sustainable use of biomass residues), some already available, can reduce GHG emissions; outcomes are site-specific and rely on efficient integrated 'biomass-to-bioenergy systems', and sustainable land-use management and governance. In some regions, specific bioenergy options, such as improved cookstoves, and small-scale biogas and biopower production, could reduce GHG emissions and improve livelihoods and health in the context of sustainable development (*medium evidence, medium agreement*). [11.13]

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[17] UN Programme on Reducing Emissions from Deforestation and Forest Degradation in developing countries, including conservation, sustainable management of forests and enhancement of forest carbon stocks.

### TS.3.2.7 Human settlements, infrastructure, and spatial planning

**Urbanization is a global trend transforming human settlements, societies, and energy use** (*robust evidence, high agreement*). In 1900, when the global population was 1.6 billion, only 13 % of the population, or some 200 million, lived in urban areas. As of 2011, more than 52 % of the world's population—roughly 3.6 billion—lives in urban areas. By 2050, the urban population is expected to increase to 5.6–7.1 billion, or 64–69 % of the world population. [12.2]

**Urban areas account for more than half of global primary energy use and energy-related $CO_2$ emissions** (*medium evidence, high agreement*). The exact share of urban energy and GHG emissions varies with emission accounting frameworks and definitions. Taking account of direct and indirect emissions, urban areas account for 67–76 % of global energy use (central estimate) and 71–76 % of global energy-related $CO_2$ emissions. Taking account of direct emissions only, the urban share of emissions is 44 % (Figure TS.32). [12.2, 12.3]

**No single factor explains variations in per-capita emissions across cities, and there are significant differences in per capita GHG emissions between cities within a single country** (*robust evidence, high agreement*). Urban GHG emissions are influenced by a variety of physical, economic and social factors, development levels, and urbanization histories specific to each city. Key influences on urban GHG emissions include income, population dynamics, urban form, locational factors, economic structure, and market failures. Per capita final energy use and $CO_2$ emissions in cities of Annex I countries tend to be lower than national averages, in cities of non-Annex I countries they tend to be higher. [12.3]

**The majority of infrastructure and urban areas have yet to be built** (*limited evidence, high agreement*). Accounting for trends in declining population densities, and continued economic and population growth, urban land cover is projected to expand by 56–310 % between 2000 and 2030. If the global population increases to 9.3 billion by 2050 and developing countries expand their built environment and infrastructure to current global average levels using available technology of today, the production of infrastructure materials alone would generate about 470 $GtCO_2$ emissions. Currently, average per capita $CO_2$ emissions embodied in the infrastructure of industrialized countries is five times larger than those in developing countries. [12.2, 12.3]

**Infrastructure and urban form are strongly interlinked, and lock in patterns of land use, transport choice, housing, and behaviour** (*medium evidence, high agreement*). Urban form and infrastructure shape long-term land-use management, influence individual transport choice, housing, and behaviour, and affect the system-wide efficiency of a city. Once in place, urban form and infrastructure are difficult to change (Figure TS.33). [12.2, 12.3, 12.4]

**Mitigation options in urban areas vary by urbanization trajectories and are expected to be most effective when policy instruments are bundled** (*robust evidence, high agreement*). For rapidly developing cities, options include shaping their urbanization and infrastructure development towards more sustainable and low-carbon pathways. In mature or established cities, options are constrained by existing urban forms and infrastructure and the potential for refurbishing existing systems and infrastructures. Key mitigation strategies include co-locating high residential with high employment densities,

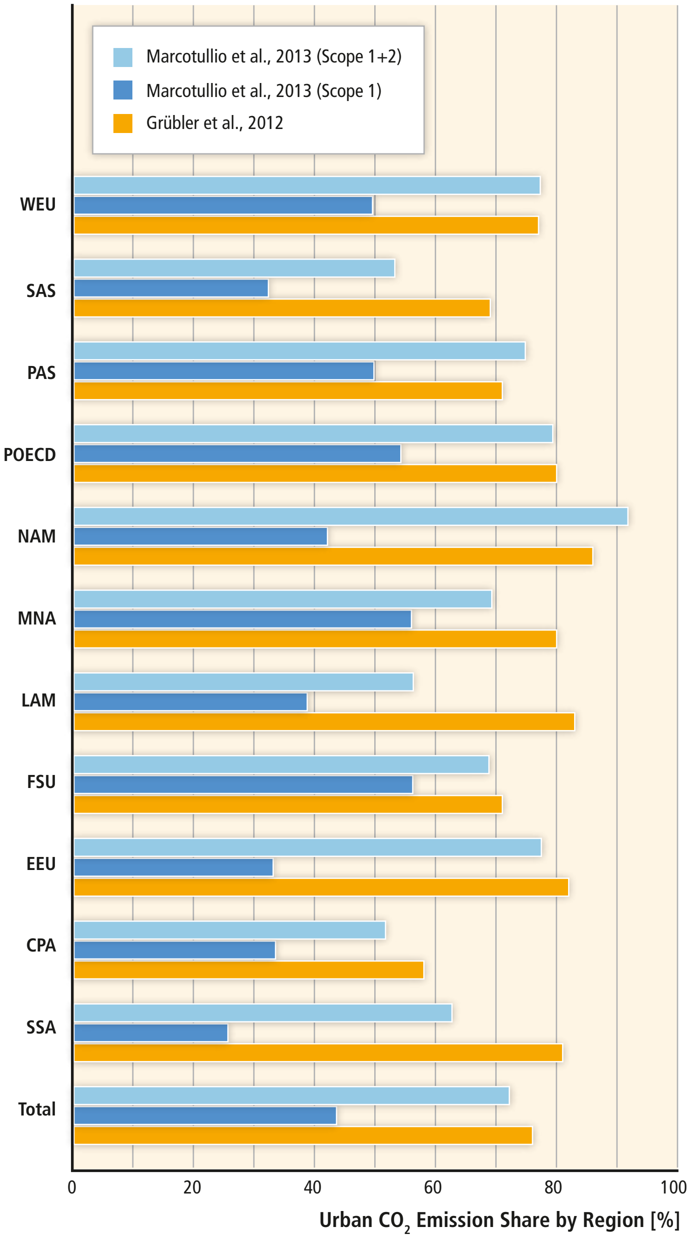


**Figure TS.32 |** Estimated shares of direct (Scope 1) and indirect urban $CO_2$ emissions in total emissions across world regions ($GtCO_2$). Indirect emissions (Scope 2) allocate emissions from thermal power plants to urban areas. CPA: Centrally Planned Asia and China; EEU: Central and Eastern Europe; FSU: Former Soviet Union; LAM: Latin America and Caribbean; MNA: Middle East and North Africa; NAM: North America; PAS: South-East Asia and Pacific; POECD: Pacific OECD; SAS: South Asia; SSA: Sub Saharan Africa; WEU: Western Europe. [12.2.2, Figure 12.4]

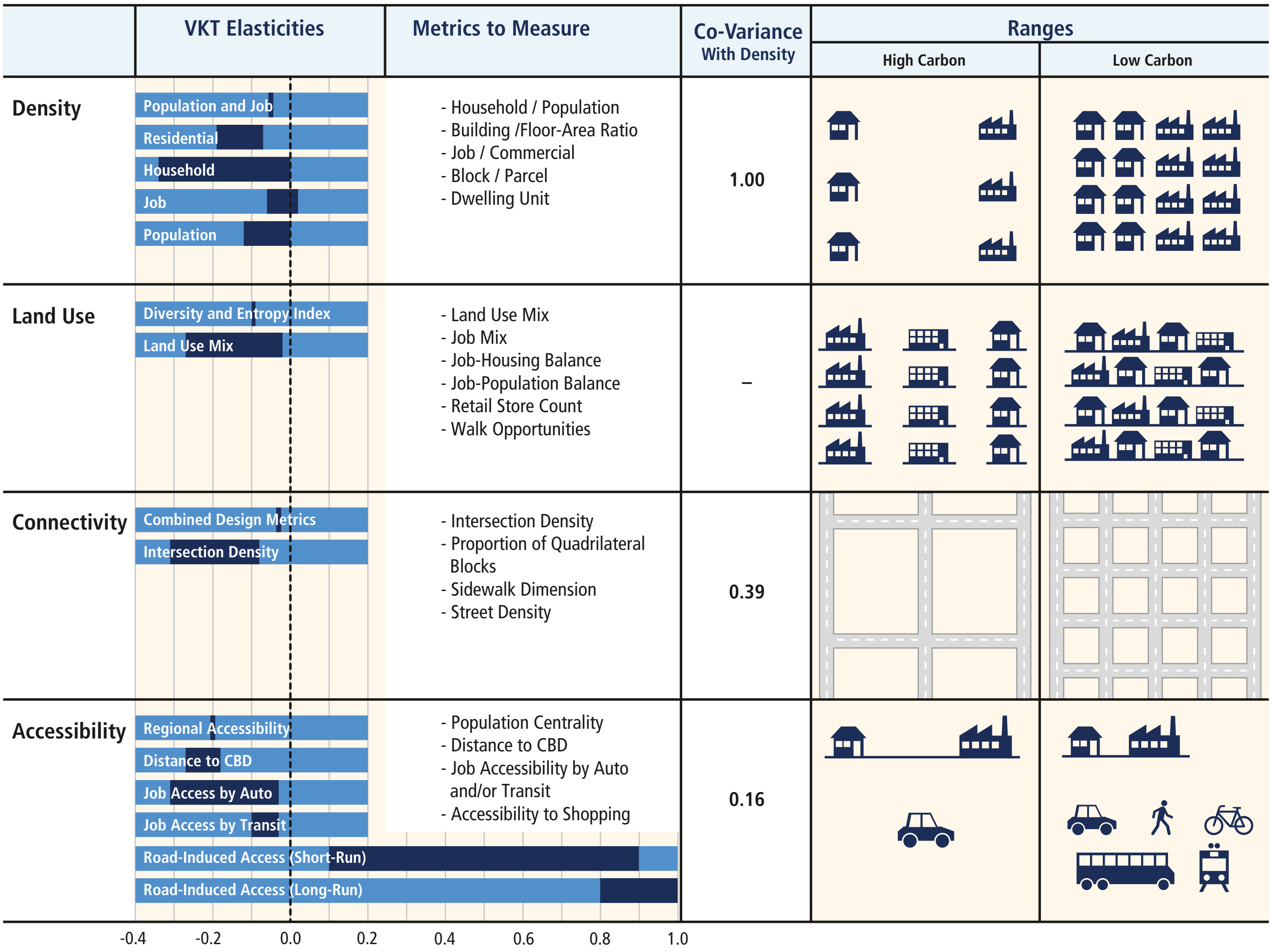


**Figure TS.33 |** Four key aspects of urban form and structure (density, land-use mix, connectivity, and accessibility), their vehicle kilometers travelled (VKT) elasticities, commonly used metrics, and stylized graphics. The dark blue row segments under the VKT elasticities column provide the range of elasticities for the studies included. CBD: Central business district. [Figure 12.14]

achieving high diversity and integration of land uses, increasing accessibility and investing in public transit and other supportive demand-management measures (Figure TS.33). Bundling these strategies can reduce emissions in the short term and generate even higher emissions savings in the long term. [12.4, 12.5]

**The largest opportunities for future urban GHG emissions reduction might be in rapidly urbanizing countries where urban form and infrastructure are not locked-in but where there are often limited governance, technical, financial, and institutional capacities** (*robust evidence, high agreement*). The bulk of future infrastructure and urban growth is expected in small- to medium-size cities in developing countries, where these capacities can be limited or weak. [12.4, 12.5, 12.6, 12.7]

**Thousands of cities are undertaking climate action plans, but their aggregate impact on urban emissions is uncertain** (*robust evidence, high agreement*). Local governments and institutions possess unique opportunities to engage in urban mitigation activities and local mitigation efforts have expanded rapidly. However, little systematic assessment exists regarding the overall extent to which cities are implementing mitigation policies and emissions reduction targets are being achieved, or emissions reduced. Climate action plans include a range of measures across sectors, largely focused on energy efficiency rather than broader land-use planning strategies and cross-sectoral measures to reduce sprawl and promote transit-oriented development (Figure TS.34). [12.6, 12.7, 12.9]

**The feasibility of spatial planning instruments for climate change mitigation is highly dependent on a city's financial and governance capability** (*robust evidence, high agreement*). Drivers of urban GHG emissions are interrelated and can be addressed by a number of regulatory, management, and market-based instruments. Many of these instruments are applicable to cities in both developed and developing countries, but the degree to which they can be implemented varies. In addition, each instrument varies in its potential to generate public revenues or require government expenditures, and the administrative scale at which it can be applied (Figure TS.35). A bun-

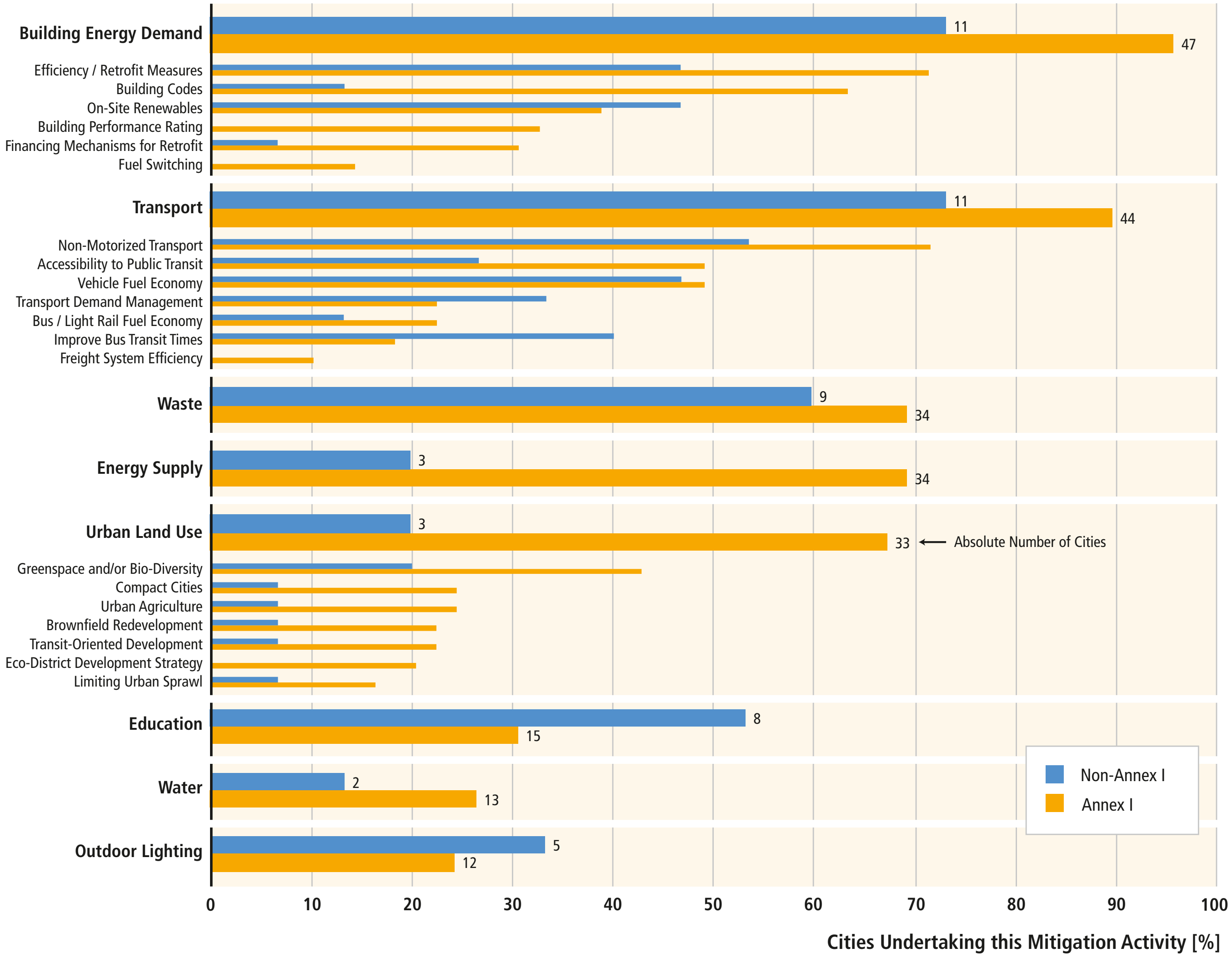


**Figure TS.34 |** Common mitigation measures in Climate Action Plans. [Figure 12.22]

dling of instruments and a high level of coordination across institutions can increase the likelihood of achieving emissions reductions and avoiding unintended outcomes. [12.6, 12.7]

**For designing and implementing climate policies effectively, institutional arrangements, governance mechanisms, and financial resources should be aligned with the goals of reducing urban GHG emissions** (*high confidence*). These goals will reflect the specific challenges facing individual cities and local governments. The following have been identified as key factors: (1) institutional arrangements that facilitate the integration of mitigation with other high-priority urban agendas; (2) a multilevel governance context that empowers cities to promote urban transformations; (3) spatial planning competencies and political will to support integrated land-use and transportation planning; and (4) sufficient financial flows and incentives to adequately support mitigation strategies. [12.6, 12.7]

**Successful implementation of urban climate change mitigation strategies can provide co-benefits** (*robust evidence, high agreement*). Urban areas throughout the world continue to struggle with challenges, including ensuring access to energy, limiting air and water pollution, and maintaining employment opportunities and competitiveness. Action on urban-scale mitigation often depends on the ability to relate climate change mitigation efforts to local co-benefits. The co-benefits of local climate change mitigation can include public savings, air quality and associated health benefits, and productivity increases in urban centres, providing additional motivation for undertaking mitigation activities. [12.5, 12.6, 12.7, 12.8]

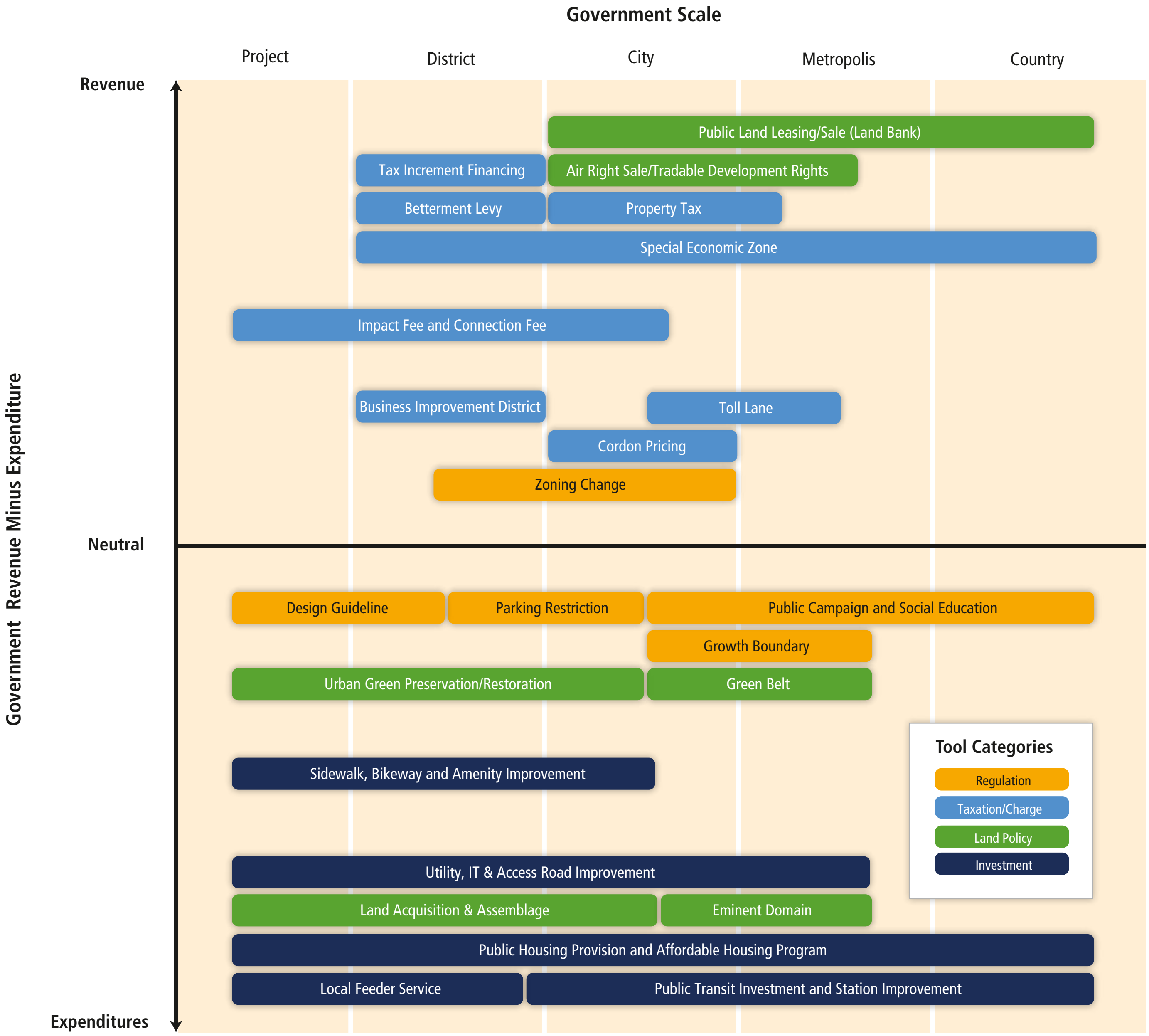


**Figure TS.35 |** Key spatial planning tools and effects on government revenues and expenditures across administrative scales. Figure shows four key spatial planning tools (coded in colours) and the scale of governance at which they are administered (x-axis) as well as how much public revenue or expenditure the government generates by implementing each instrument (y-axis). [Figure 12.20]

# TS.4 Mitigation policies and institutions

*The previous section shows that since AR4 the scholarship on mitigation pathways has begun to consider in much more detail how a variety of real-world considerations—such as institutional and political constraints, uncertainty associated with climate change risks, the availability of technologies and other factors—affect the kinds of policies and measures that are adopted. Those factors have important implications for the design, cost, and effectiveness of mitigation action. This section focuses on how governments and other actors in the private and public sectors design, implement, and evaluate mitigation policies. It considers the 'normative' scientific research on how policies should be designed to meet particular criteria. It also considers research on how policies are actually designed and implemented a field known as 'positive' analysis. The discussion first characterizes fundamental conceptual issues, and then presents a summary of the main findings from WGIII AR5 on local, national, and sectoral policies. Much of the practical policy effort since AR4 has occurred in these contexts. From there the summary looks at ever-higher levels of aggregation, ultimately ending at the global level and cross-cutting investment and finance issues.*

### TS.4.1 Policy design, behaviour and political economy

**There are multiple criteria for evaluating policies**. Policies are frequently assessed according to four criteria [3.7.1, 13.2.2, 15.4.1]:

- Environmental effectiveness—whether policies achieve intended goals in reducing emissions or other pressures on the environment or in improving measured environmental quality.
- Economic effectiveness—the impact of policies on the overall economy. This criterion includes the concept of economic efficiency, the principle of maximizing net economic benefits. Economic welfare also includes the concept of cost-effectiveness, the principle of attaining a given level of environmental performance at lowest aggregate cost.
- Distributional and social impacts—also known as 'distributional equity,' this criterion concerns the allocation of costs and benefits of policies to different groups and sectors within and across economies over time. It includes, often, a special focus on impacts on the least well-off members of societies within countries and around the world.
- Institutional and political feasibility—whether policies can be implemented in light of available institutional capacity, the political constraints that governments face, and other factors that are essential to making a policy viable.

All criteria can be applied with regard to the immediate 'static' impacts of policies and from a long-run 'dynamic' perspective that accounts for the many adjustments in the economic, social and political systems. Criteria may be mutually reinforcing, but there may also be conflicts or tradeoffs among them. Policies designed for maximum environmental effectiveness or economic performance may fare less well on other criteria, for example. Such tradeoffs arise at multiple levels of governing systems. For example, it may be necessary to design international agreements with flexibility so that it is feasible for a large number of diverse countries to accept them, but excessive flexibility may undermine incentives to invest in cost-effective long-term solutions.

**Policymakers make use of many different policy instruments at the same time**. Theory can provide some guidance on the normative advantages and disadvantages of alternative policy instruments in light of the criteria discussed above. The range of different policy instruments includes [3.8, 15.3]:

- Economic incentives, such as taxes, tradable allowances, fines, and subsidies
- Direct regulatory approaches, such as technology or performance standards
- Information programmes, such as labelling and energy audits
- Government provision, for example of new technologies or in state enterprises
- Voluntary actions, initiated by governments, firms, and non-governmental organizations (NGOs)

Since AR4, the inventory of research on these different instruments has grown, mostly with reference to experiences with policies adopted within particular sectors and countries as well as the many interactions between policies. One implication of that research has been that international agreements that aim to coordinate across countries reflect the practicalities on the particular policy choices of national governments and other jurisdictions.

**The diversity in policy goals and instruments highlights differences in how sectors and countries are organized economically and politically as well as the multi-level nature of mitigation**. Since AR4, one theme of research in this area has been that the success of mitigation measures depends in part on the presence of institutions capable of designing and implementing regulatory policies and the willingness of respective publics to accept these policies. Many policies have effects, sometimes unanticipated, across multiple jurisdictions—across cities, regions and countries—because the economic effects of policies and the technological options are not contained within a single jurisdiction. [13.2.2.3, 14.1.3, 15.2, 15.9]

**Interactions between policy instruments can be welfare-enhancing or welfare-degrading**. The chances of welfare-enhancing interactions are particularly high when policy instruments address multiple different market failures—for example, a subsidy or other policy instrument aimed at boosting investment in R&D on less emission-intensive technologies can complement policies aimed at controlling emissions, as can regulatory intervention to support efficient improvement of end-use energy efficiency. By contrast, welfare-degrading interactions are particularly likely when policies are designed to achieve identical goals. Narrowly targeted policies such as support for deployment (rather than R&D) of particular energy technologies that exist in tandem with broader economy-wide policies aimed at reducing emissions (for example, a cap-and-trade emissions scheme) can have the effect of shifting the mitigation effort to particular sectors of the economy in ways that typically result in higher overall costs. [3.8.6, 15.7, 15.8]

**There are a growing number of countries devising policies for adaptation, as well as mitigation, and there may be benefits to considering the two within a common policy framework** (*medium evidence, low agreement*). However, there are divergent views on whether adding adaptation to mitigation measures in the policy portfolio encourages or discourages participation in international cooperation [1.4.5, 13.3.3]. It is recognized that an integrated approach can be valuable, as there exist both synergies and tradeoffs [16.6].

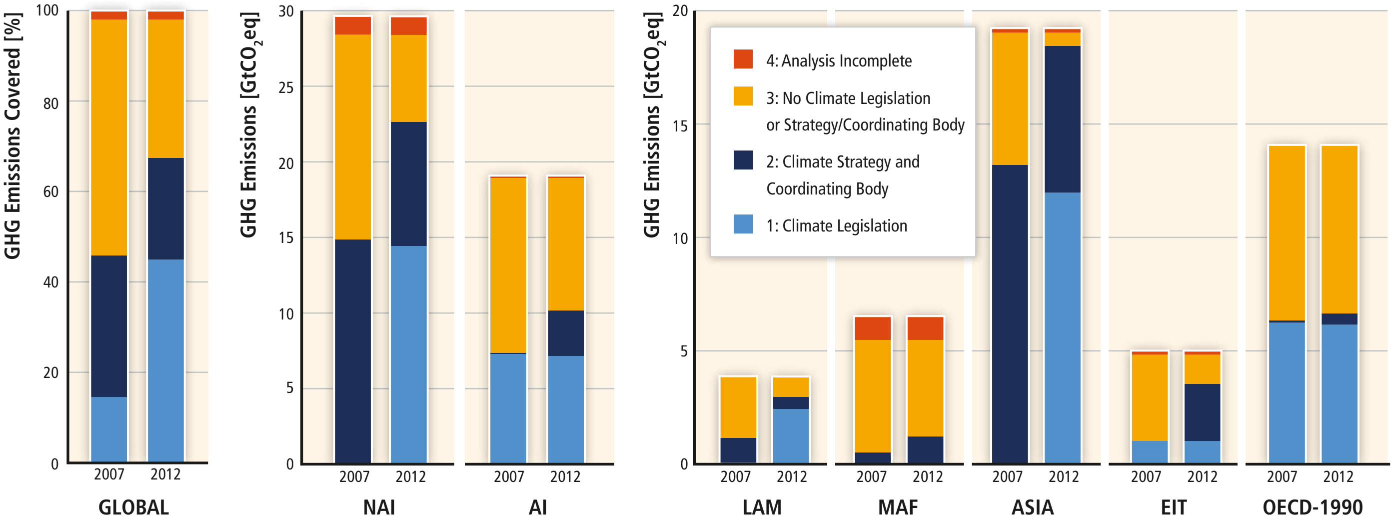
**Traditionally, policy design, implementation, and evaluation has focused on governments as central designers and implementers of policies, but new studies have emerged on government acting in a coordinating role** (*medium confidence*). In these cases, governments themselves seek to advance voluntary approaches, especially when traditional forms of regulation are thought to be inadequate or the best choices of policy instruments and goals is not yet apparent. Examples include voluntary schemes that allow individuals and firms to purchase emission credits that offset the emissions associated with their own activities such as flying and driving. Since AR4, a substantial new literature has emerged to examine these schemes from positive and normative perspectives. [13.12, 15.5.7]

**The successful implementation of policy depends on many factors associated with human and institutional behaviour** (*very high confidence*). One of the challenges in designing effective instruments is that the activities that a policy is intended to affect—such as the choice of energy technologies and carriers and a wide array of agricultural and forestry practices—are also influenced by social norms, decision-making rules, behavioural biases, and institutional processes [2.4, 3.10]. There are examples of policy instruments made more effective by taking these factors into account, such as in the case of financing mechanisms for household investments in energy efficiency and renewable energy that eliminate the need for up-front investment [2.4, 2.6.5.3]. Additionally, the norms that guide acceptable practices could have profound impacts on the baselines against which policy interventions are evaluated, either magnifying or reducing the required level of policy intervention [1.2.4, 4.3, 6.5.2].

**Climate policy can encourage investment that may otherwise be suboptimal because of market imperfections** (*very high confidence*). Many of the options for energy efficiency as well as low-carbon energy provision require high up-front investment that is often magnified by high-risk premiums associated with investments in new technologies. The relevant risks include those associated with future market conditions, regulatory actions, public acceptance, and technology cost and performance. Dedicated financial instruments exist to lower these risks for private actors—for example, credit insurance, feed-in tariffs (FITs), concessional finance, or rebates [16.4]. The design of other mitigation policies can also incorporate elements to help reduce risks, such as a cap-and-trade regime that includes price floors and ceilings [2.6.5, 15.5, 15.6].

## TS.4.2 Sectoral and national policies

**There has been a considerable increase in national and sub-national mitigation plans and strategies since AR4** (Figure TS.36). These plans and strategies are in their early stages of development and implementation in many countries, making it difficult to assess whether and how they will result in appropriate institutional and policy change, and therefore, their impact on future GHG emissions. However, to date these policies, taken together, have not yet achieved a substantial deviation in GHG emissions from the past trend. Theories of institutional change suggest they might play a role in shaping incentives, political contexts, and policy paradigms in a way that encourages



| | GLOBAL | | NAI | | AI | |
|---|---|---|---|---|---|---|
| | 2007 | 2012 | 2007 | 2012 | 2007 | 2012 |
| **1** | 7 (15%) | 22 (44%) | 0 (0%) | 14 (49%) | 7 (38%) | 7 (38%) |
| **2** | 15 (30%) | 11 (23%) | 15 (50%) | 8 (28%) | 0 (0%) | 3 (16%) |
| **3** | 25 (52%) | 15 (30%) | 14 (46%) | 6 (19%) | 12 (61%) | 9 (46%) |
| **4** | 1 (3%) | 1 (3%) | 1 (4%) | 1 (4%) | 0 (1%) | 0 (1%) |

| | LAM | | MAF | | ASIA | | EIT | | OECD-1990 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2007 | 2012 | 2007 | 2012 | 2007 | 2012 | 2007 | 2012 | 2007 | 2012 |
| **1** | 0 (2%) | 2 (63%) | 0 (0%) | 0 (0%) | 0 (0%) | 12 (62%) | 1 (20%) | 1 (20%) | 6 (44%) | 6 (44%) |
| **2** | 1 (28%) | 1 (13%) | 1 (8%) | 1 (19%) | 13 (69%) | 6 (34%) | 0 (0%) | 3 (50%) | 0 (0%) | 0 (3%) |
| **3** | 3 (70%) | 1 (23%) | 5 (76%) | 4 (65%) | 6 (30%) | 1 (3%) | 4 (76%) | 1 (26%) | 8 (55%) | 7 (53%) |
| **4** | 0 (0%) | 0 (0%) | 1 (16%) | 1 (16%) | 0 (1%) | 0 (1%) | 0 (3%) | 0 (3%) | 0 (0%) | 0 (0%) |

**Figure TS.36 |** National climate legislation and strategies in 2007 and 2012. Regions include NAI (Non Annex I countries—developing countries), AI (Annex I countries—developed countries), LAM (Latin America), MAF (Middle East and Africa), ASIA (Asia), EIT (Economies in Transition), OECD-1990; see Annex II.2 for more details. In this figure, climate legislation is defined as mitigation-focused legislation that goes beyond sectoral action alone. Climate strategy is defined as a non-legislative plan or framework aimed at mitigation that encompasses more than a small number of sectors, and that includes a coordinating body charged with implementation. International pledges are not included, nor are sub-national plans and strategies. The panel shows proportion of GHG emissions covered. [Figure 15.1]

GHG emissions reductions in the future [15.1, 15.2]. However, many baseline scenarios (i.e., those without additional mitigation policies) show concentrations that exceed 1000 ppm $CO_2$eq by 2100, which is far from a concentration with a *likely* probability of maintaining temperature increases below 2 °C this century. Mitigation scenarios suggest that a wide range of environmentally effective policies could be enacted that would be consistent with such goals [6.3]. In practice, climate strategies and the policies that result are influenced by political economy factors, sectoral considerations, and the potential for realizing co-benefits. In many countries, mitigation policies have also been actively pursued at state and local levels. [15.2, 15.5, 15.8]

**Since AR4, there is growing political and analytical attention to co-benefits and adverse side-effects of climate policy on other objectives and vice versa that has resulted in an increased focus on policies designed to integrate multiple objectives** (*high confidence*). Co-benefits are often explicitly referenced in climate and sectoral plans and strategies and often enable enhanced political support [15.2]. However, the analytical and empirical underpinnings for many of these interactive effects, and particularly for the associated welfare impacts, are under-developed [1.2, 3.6.3, 4.2, 4.8, 6.6]. The scope for co-benefits is greater in low-income countries, where complementary policies for other objectives, such as air quality, are often weak [5.7, 6.6, 15.2].

**The design of institutions affects the choice and feasibility of policy options as well as the sustainable financing of mitigation measures.** Institutions designed to encourage participation by representatives of new industries and technologies can facilitate transitions to low-GHG emissions pathways [15.2, 15.6]. Policies vary in the extent to which they require new institutional capabilities to be implemented. Carbon taxation, in most settings, can rely mainly on existing tax infrastructure and is administratively easier to implement than many other alternatives such as cap-and-trade systems [15.5]. The extent of institutional innovation required for policies can be a factor in instrument choice, especially in developing countries.

**Sector-specific policies have been more widely used than economy-wide, market-based policies** (*medium evidence, high agreement*). Although economic theory suggests that market-based, economy-wide policies for the singular objective of mitigation would generally be more cost-effective than sector-specific policies, political economy considerations often make economy-wide policies harder to design and implement than sector-specific policies [15.2.3, 15.2.6, 15.5.1]. In some countries, emission trading and taxes have been enacted to address the market externalities associated with GHG emissions, and have contributed to the fulfilment of sector-specific GHG reduction goals (*medium evidence, medium agreement*) [7.12]. In the longer term, GHG pricing can support the adoption of low-GHG energy technologies. Even if economy-wide policies were implemented, sector-specific policies may be needed to overcome sectoral market failures. For example, building codes can require energy-efficient investments where private investments would otherwise not exist [9.10]. In transport, pricing policies that raise the cost of carbon-intensive forms of private transport are more effective when backed by public investment in viable alternatives [8.10]. Table TS.9 presents a range of sector-specific policies that have been implemented in practice. [15.1, 15.2, 15.5, 15.8, 15.9]

**Carbon taxes have been implemented in some countries and—alongside technology and other policies—have contributed to decoupling of emissions from GDP** (*high confidence*). Differentiation by sector, which is quite common, reduces cost-effectiveness that arises from the changes in production methods, consumption patterns, lifestyle shifts, and technology development, but it may increase political feasibility, or be preferred for reasons of competitiveness or distributional equity. In some countries, high carbon and fuel taxes have been made politically feasible by refunding revenues or by lowering other taxes in an environmental fiscal reform. Mitigation policies that raise government revenue (e.g., auctioned emission allowances under a cap-and-trade system or emission taxes) generally have lower social costs than approaches that do not, but this depends on how the revenue is used [3.6.3]. [15.2, 15.5.2, 15.5.3]

**Fuel taxes are an example of a sector-specific policy and are often originally put in place for objectives such as revenue—they are not necessarily designed for the purpose of mitigation** (*high confidence*). In Europe, where fuel taxes are highest, they have contributed to reductions in carbon emissions from the transport sector of roughly 50 % for this group of countries. The short-run response to higher fuel prices is often small, but long-run price elasticities are quite high, or roughly −0.6 to −0.8. This means that in the long run, 10 % higher fuel prices correlate with 7 % reduction in fuel use and emissions. In the transport sector, taxes have the advantage of being progressive or neutral in most countries and strongly progressive in low-income countries. [15.5.2]

**Cap-and-trade systems for GHG emissions are being established in a growing number of countries and regions**. Their environmental effect has so far been limited because caps have either been loose or have not yet been binding (*limited evidence, medium agreement*). There appears to have been a tradeoff between the political feasibility and environmental effectiveness of these programmes, as well as between political feasibility and distributional equity in the allocation of permits. Greater environmental effectiveness through a tighter cap may be combined with a price ceiling that improves political feasibility. [14.4.2, 15.5.3]

**Different factors reduced the price of European Union Emissions Trading System (EU ETS) allowances below anticipated levels, thereby slowing investment in mitigation** (*high confidence*). While the European Union demonstrated that a cross-border cap-and-trade system can work, the low price of EU ETS allowances in recent years provided insufficient incentives for significant additional investment in mitigation. The low price is related to unexpected depth and duration of the economic recession, uncertainty about the long-term reduction targets for GHG emissions, import of credits from the Clean Development Mechanism (CDM), and the interaction with other policy instruments,

**Table TS.9 |** Sector policy instruments. The table brings together evidence on mitigation policy instruments discussed in Chapters 7 to 12. [Table 15.2]

| Policy Instruments | Energy [7.12] | Transport [8.10] | Buildings [9.10] | Industry [10.11] | AFOLU [11.10] | Human Settlements and Infrastructure |
|---|---|---|---|---|---|---|
| **Economic Instruments—Taxes (Carbon taxes may be economy-wide)** | • Carbon taxes | • Fuel taxes<br>• Congestion charges, vehicle registration fees, road tolls<br>• Vehicle taxes | • Carbon and/or energy taxes (either sectoral or economy wide) | • Carbon tax or energy tax<br>• Waste disposal taxes or charges | • Fertilizer or Nitrogen taxes to reduce nitrous oxide | • Sprawl taxes, Impact fees, exactions, split-rate property taxes, tax increment finance, betterment taxes, congestion charges |
| **Economic Instruments—Tradable Allowances (May be economy-wide)** | • Emissions trading (e.g., EU ETS)<br>• Emission credits under CDM<br>• Tradable Green Certificates | • Fuel and vehicle standards | • Tradable certificates for energy efficiency improvements (white certificates) | • Emissions trading<br>• Emission credit under CDM<br>• Tradable Green Certificates | • Emission credits under the Kyoto Protocol's Clean Development Mechanism (CDM)<br>• Compliance schemes outside Kyoto protocol (national schemes)<br>• Voluntary carbon markets | • Urban-scale Cap and Trade |
| **Economic Instruments—Subsidies** | • Fossil fuel subsidy removal<br>• Feed-in-tariffs for renewable energy<br>• Capital subsidies and insurance for 1st generation Carbon Dioxide Capture and Storage (CCS) | • Biofuel subsidies<br>• Vehicle purchase subsidies<br>• Feebates | • Subsidies or Tax exemptions for investment in efficient buildings, retrofits and products<br>• Subsidized loans | • Subsidies (e.g., for energy audits)<br>• Fiscal incentives (e.g., for fuel switching) | • Credit lines for low carbon agriculture, sustainable forestry. | • Special Improvement or Redevelopment Districts |
| **Regulatory Approaches** | • Efficiency or environmental performance standards<br>• Renewable Portfolio standards for renewable energy<br>• Equitable access to electricity grid<br>• Legal status of long term $CO_2$ storage | • Fuel economy performance standards<br>• Fuel quality standards<br>• GHG emission performance standards<br>• Regulatory restrictions to encourage modal shifts (road to rail)<br>• Restriction on use of vehicles in certain areas<br>• Environmental capacity constraints on airports<br>• Urban planning and zoning restrictions | • Building codes and standards<br>• Equipment and appliance standards<br>• Mandates for energy retailers to assist customers invest in energy efficiency | • Energy efficiency standards for equipment<br>• Energy management systems (also voluntary)<br>• Voluntary agreements (where bound by regulation)<br>• Labelling and public procurement regulations | • National policies to support REDD+ including monitoring, reporting and verification<br>• Forest law to reduce deforestation<br>• Air and water pollution control GHG precursors<br>• Land-use planning and governance | • Mixed use zoning<br>• Development restrictions<br>• Affordable housing mandates<br>• Site access controls<br>• Transfer development rights<br>• Design codes<br>• Building codes<br>• Street codes<br>• Design standards |
| **Information Programmes** | | • Fuel labelling<br>• Vehicle efficiency labelling | • Energy audits<br>• Labelling programmes<br>• Energy advice programmes | • Energy audits<br>• Benchmarking<br>• Brokerage for industrial cooperation | • Certification schemes for sustainable forest practices<br>• Information policies to support REDD+ including monitoring, reporting and verification | |
| **Government Provision of Public Goods or Services** | • Research and development<br>• Infrastructure expansion (district heating/cooling or common carrier) | • Investment in transit and human powered transport<br>• Investment in alternative fuel infrastructure<br>• Low emission vehicle procurement | • Public procurement of efficient buildings and appliances | • Training and education<br>• Brokerage for industrial cooperation | • Protection of national, state, and local forests.<br>• Investment in improvement and diffusion of innovative technologies in agriculture and forestry | • Provision of utility infrastructure such as electricity distribution, district heating/cooling and wastewater connections, etc.<br>• Park improvements<br>• Trail improvements<br>• Urban rail |
| **Voluntary Actions** | | | • Labelling programmes for efficient buildings<br>• Product eco-labelling | • Voluntary agreements on energy targets or adoption of energy management systems, or resource efficiency | • Promotion of sustainability by developing standards and educational campaigns | |

particularly related to the expansion of renewable energy as well as regulation on energy efficiency. It has proven to be politically difficult to address this problem by removing GHG emission permits temporarily, tightening the cap, or providing a long-term mitigation goal. [14.4.2]

**Adding a mitigation policy to another may not necessarily enhance mitigation.** For instance, if a cap-and-trade system has a sufficiently stringent cap then other policies such as renewable subsidies have no further impact on total GHG emissions (although they may affect costs and possibly the viability of more stringent future targets). If the cap is loose relative to other policies, it becomes ineffective. This is an example of a negative interaction between policy instruments. Since other policies cannot be 'added on' to a cap-and-trade system, if it is to meet any particular target, a sufficiently low cap is necessary. A carbon tax, on the other hand, can have an additive environmental effect to policies such as subsidies to renewables. [15.7]

**Reduction of subsidies to fossil energy can achieve significant emission reductions at negative social cost** (*very high confidence*). Although political economy barriers are substantial, many countries have reformed their tax and budget systems to reduce fuel subsidies that actually accrue to the relatively wealthy, and utilized lump-sum cash transfers or other mechanisms that are more targeted to the poor. [15.5.3]

**Direct regulatory approaches and information measures are widely used, and are often environmentally effective, though debate remains on the extent of their environmental impacts and cost-effectiveness** (*medium confidence*). Examples of regulatory approaches include energy efficiency standards; examples of information programmes include labelling programmes that can help consumers make better-informed decisions. While such approaches often work at a net social benefit, the scientific literature is divided on whether such policies are implemented with negative private costs (see Box TS.12) to firms and individuals [3.9.3, 15.5.5, 15.5.6]. Since AR4 there has been continued investigation into the 'rebound' effects (see Box TS.13) that arise when higher efficiency leads to lower energy costs and greater consumption. There is general agreement that such rebound effects exist, but there is low agreement in the literature on the magnitude [3.9.5, 5.7.2, 15.5.4].

**There is a distinct role for technology policy as a complement to other mitigation policies** (*high confidence*). Properly implemented technology policies reduce the cost of achieving a given environmental target. Technology policy will be most effective when technology-push policies (e.g., publicly funded R&D) and demand-pull policies (e.g., governmental procurement programmes or performance regulations) are used in a complementary fashion. While technology-push and demand-pull policies are necessary, they are unlikely to be sufficient without complementary framework conditions. Managing social challenges of technology policy change may require innovations in policy and institutional design, including building integrated policies that make complementary use of market incentives, authority, and norms (*medium confidence*). Since AR4, a large number of countries and subnational jurisdictions have introduced support policies for renewable

## Box TS.13 | The rebound effect can reduce energy savings from technological improvement

Technological improvements in energy efficiency (EE) have direct effects on energy consumption and thus GHG emissions, but can cause other changes in consumption, production, and prices that will, in turn, affect GHG emissions. These changes are generally called 'rebound' or 'takeback' because in most cases they reduce the net energy or emissions reduction associated with the efficiency improvement. The size of EE rebound is controversial, with some research papers suggesting little or no rebound and others concluding that it offsets most or all reductions from EE policies [3.9.5, 5.7.2].

Total EE rebound can be broken down into three distinct parts: substitution-effect, income-effect, and economy-wide effect [3.9.5]. In end-use consumption, substitution-effect rebound, or 'direct rebound' assumes that a consumer will make more use of a device if it becomes more energy efficient because it will be cheaper to use. Income-effect rebound or 'indirect rebound', arises if the improvement in EE makes the consumer wealthier and leads her to consume additional products that require energy. Economy-wide rebound refers to impacts beyond the behaviour of the entity benefiting directly from the EE improvement, such as the impact of EE on the price of energy.

Analogous rebound effects for EE improvements in production are substitution towards an input with improved energy efficiency, and substitution among products by consumers when an EE improvement changes the relative prices of goods, as well as an income effect when an EE improvement lowers production costs and creates greater wealth.

Rebound is sometimes confused with the concept of carbon leakage, which often describes the incentive for emissions-intensive economic activity to migrate away from a region that restricts GHGs (or other pollutants) towards areas with fewer or no restrictions on such emissions [5.4.1, 14.4]. Energy efficiency rebound can occur regardless of the geographic scope of the adopted policy. As with leakage, however, the potential for significant rebound illustrates the importance of considering the full equilibrium effects of a mitigation policy [3.9.5, 15.5.4].

energy such as feed-in tariffs and renewable portfolio standards. These have promoted substantial diffusion and innovation of new energy technologies such as wind turbines and photovoltaic panels, but have raised questions about their economic efficiency, and introduced challenges for grid and market integration. [2.6.5, 7.12, 15.6.5]

**Worldwide investment in research in support of mitigation is small relative to overall public research spending** (*medium confidence*). The effectiveness of research support will be greatest if it is increased slowly and steadily rather than dramatically or erratically. It is important that data collection for program evaluation is built into technology policy programmes, because there is limited empirical evidence on the relative effectiveness of different mechanisms for supporting the invention, innovation and diffusion of new technologies. [15.6.2, 15.6.5]

**Government planning and provision can facilitate shifts to less energy- and GHG-intensive infrastructure and lifestyles** (*high confidence*). This applies particularly when there are indivisibilities in the provision of infrastructure as in the energy sector [7.6] (e.g., for electricity transmission and distribution or district heating networks); in the transport sector [8.4] (e.g., for non-motorized or public transport); and in urban planning [12.5]. The provision of adequate infrastructure is important for behavioural change [15.5.6].

**Successful voluntary agreements on mitigation between governments and industries are characterized by a strong institutional framework with capable industrial associations** (*medium confidence*). The strengths of voluntary agreements are speed and flexibility in phasing measures, and facilitation of barrier removal activities for energy efficiency and low-emission technologies. Regulatory threats, even though the threats are not always explicit, are also an important factor for firms to be motivated. There are few environmental impacts without a proper institutional framework. [15.5.7]

## TS.4.3 Development and regional cooperation

**Regional cooperation offers substantial opportunities for mitigation due to geographic proximity, shared infrastructure and policy frameworks, trade, and cross-border investment that would be difficult for countries to implement in isolation** (*high confidence*). Examples of possible regional cooperation policies include regionally-linked development of renewable energy power pools, networks of natural gas supply infrastructure, and coordinated policies on forestry. [14.1]

**At the same time, there is a mismatch between opportunities and capacities to undertake mitigation** (*medium confidence*). The regions with the greatest potential to leapfrog to low-carbon development trajectories are the poorest developing regions where there are few lock-in effects in terms of modern energy systems and urbanization patterns. However, these regions also have the lowest financial, technological, and institutional capacities to embark on such low-carbon development paths (Figure TS.37) and their cost of waiting is high due to unmet energy and development needs. Emerging economies already have more lock-in effects but their rapid build-up of modern energy systems and urban settlements still offers substantial opportunities for low-carbon development. Their capacity to reorient themselves to low-carbon development strategies is higher, but also faces constraints in terms of finance, technology, and the high cost of delaying the installation of new energy capacity. Lastly, industrialized economies have the largest lock-in effects, but the highest capacities to reorient their energy, transport, and urbanizations systems towards low-carbon development. [14.1.3, 14.3.2]

**Regional cooperation has, to date, only had a limited (positive) impact on mitigation** (*medium evidence, high agreement*). Nonetheless, regional cooperation could play an enhanced role in promoting mitigation in the future, particularly if it explicitly incorporates mitigation objectives in trade, infrastructure and energy policies and promotes direct mitigation action at the regional level. [14.4.2, 14.5]

**Most literature suggests that climate-specific regional cooperation agreements in areas of policy have not played an important role in addressing mitigation challenges to date** (*medium confidence*). This is largely related to the low level of regional integration and associated willingness to transfer sovereignty to supra-national regional bodies to enforce binding agreements on mitigation. [14.4.2, 14.4.3]

**Climate-specific regional cooperation using binding regulation-based approaches in areas of deep integration, such as EU directives on energy efficiency, renewable energy, and biofuels, have had some impact on mitigation objectives** (*medium confidence*). Nonetheless, theoretical models and past experience suggest that there is substantial potential to increase the role of climate-specific regional cooperation agreements and associated instruments, including economic instruments and regulatory instruments. In this context it is important to consider carbon leakage of such regional initiatives and ways to address it. [14.4.2, 14.4.1]

**In addition, non-climate-related modes of regional cooperation could have significant implications for mitigation, even if mitigation objectives are not a component** (*medium confidence*). Regional cooperation with non-climate-related objectives but possible mitigation implications, such as trade agreements, cooperation on technology, and cooperation on infrastructure and energy, has to date also had negligible impacts on mitigation. Modest impacts have been found on the level of GHG emissions of members of regional preferential trade areas if these agreements are accompanied with environmental agreements. Creating synergies between adaptation and mitigation can increase the cost-effectiveness of climate change actions. Linking electricity and gas grids at the regional level has also had a modest impact on mitigation as it facilitated greater use of low-carbon and renewable technologies; there is substantial further mitigation potential in such arrangements. [14.4.2]

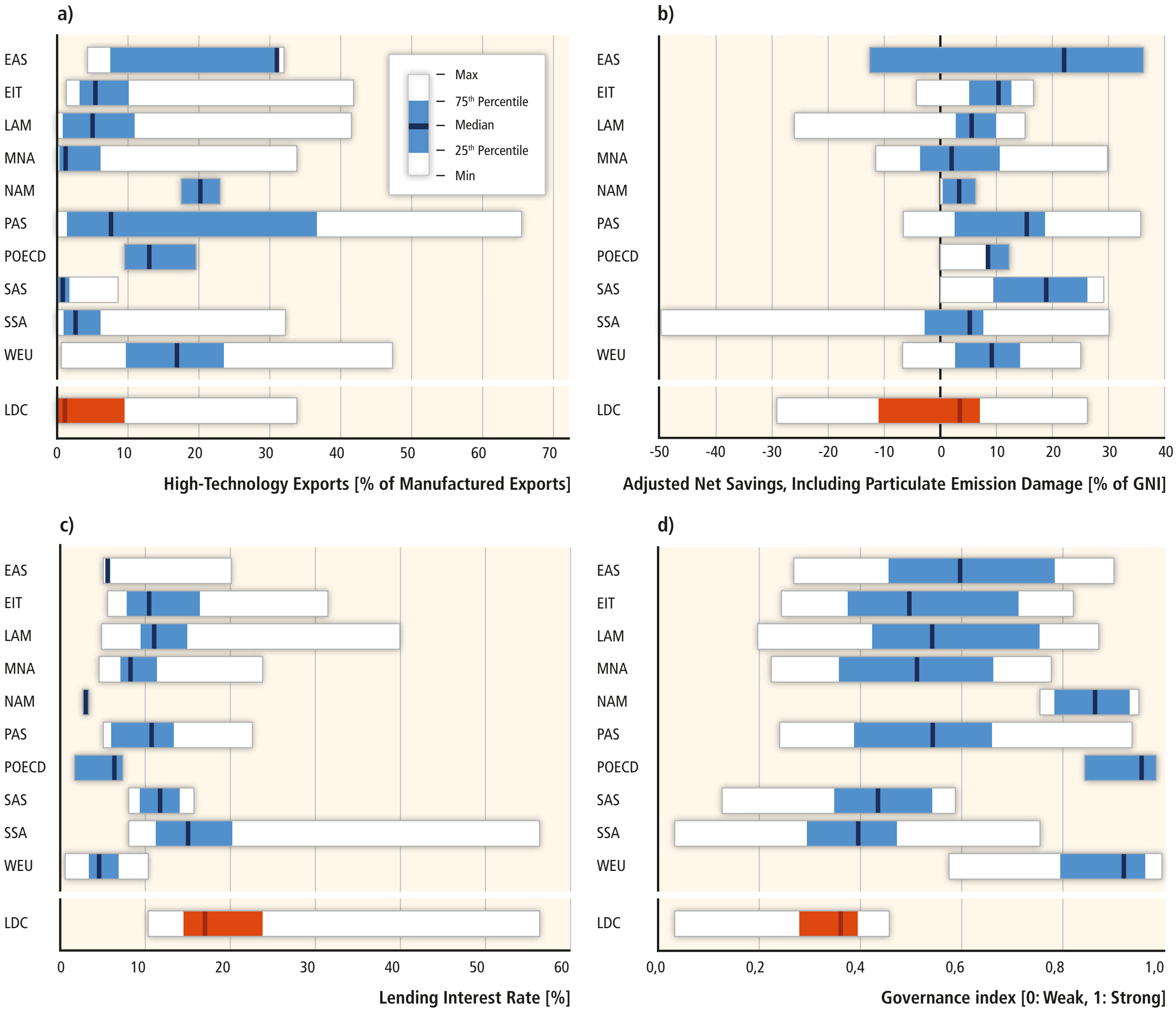
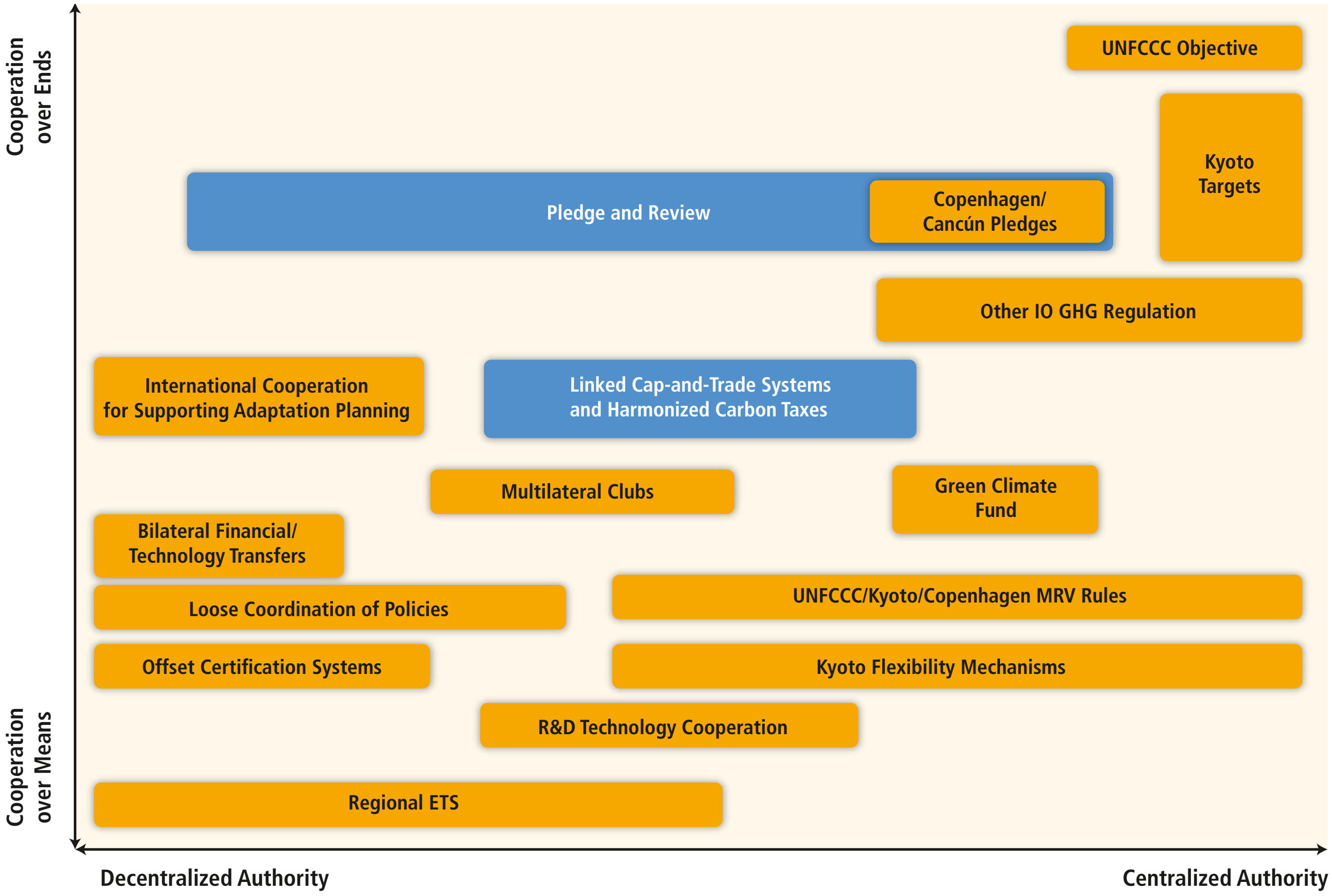


**Figure TS.37 |** Economic and governance indicators affecting regional capacities to embrace mitigation policies. Regions include EAS (East Asia), EIT (Economies in Transition), LAM (Latin America and Caribbean), MNA (Middle East and North Africa), NAM (North America), POECD (Pacific Organisation for Economic Co-operation and Development (OECD)-1990 members), PAS (South East Asia and Pacific), SAS (South Asia), SSA (sub-Saharan Africa), WEU (Western Europe), LDC (least-developed countries). Statistics refer to the year 2010 or the most recent year available. Note: The lending interest rate refers to the average interest rate charged by banks to private sector clients for short- to medium-term financing needs. The governance index is a composite measure of governance indicators compiled from various sources, rescaled to a scale of 0 to 1, with 0 representing weakest governance and 1 representing strongest governance. [Figure 14.2]

## TS.4.4 International cooperation

**Climate change mitigation is a global commons problem that requires international cooperation, but since AR4, scholarship has emerged that emphasizes a more complex and multi-faceted view of climate policy** (*very high confidence*). Two characteristics of climate change necessitate international cooperation: climate change is a global commons problem, and it is characterized by a high degree of heterogeneity in the origins of GHG emissions, mitigation opportunities, climate impacts, and capacity for mitigation and adaptation [13.2.1.1]. Policymaking efforts to date have primarily focused on international cooperation as a task centrally focused on the coordination of national policies that would be adopted with the goal of mitigation. More recent policy developments suggest that there is a more complicated set of relationships between national, regional, and global policymaking, based on a multiplicity of goals, a recognition of policy co-benefits, and barriers to technological innovation and diffusion [1.2, 6.6, 15.2]. A major challenge is assessing whether decentralized policy action is consistent with and can lead to total mitigation efforts that are effective, equitable, and efficient [6.1.2.1, 13.13].



Loose coordination of policies: examples include transnational city networks and Nationally Appropriate Mitigation Actions (NAMAs);
R&D technology cooperation: examples include the Major Economies Forum on Energy and Climate (MEF), Global Methane Initiative (GMI), or Renewable Energy and Energy Efficiency Partnership (REEEP); Other international organization (IO) GHG regulation:
examples include the Montreal Protocol, International Civil Aviation Organization (ICAO), International Maritime Organization (IMO).

**Figure TS.38 |** Alternative forms of international cooperation. The figure represents a compilation of existing and possible forms of international cooperation, based upon a survey of published research, but is not intended to be exhaustive of existing or potential policy architectures, nor is it intended to be prescriptive. Examples in orange are existing agreements. Examples in blue are structures for agreements proposed in the literature. The width of individual boxes indicates the range of possible degrees of centralization for a particular agreement. The degree of centralization indicates the authority an agreement confers on an international institution, not the process of negotiating the agreement. [Figure 13.2]

**International cooperation on climate change has become more institutionally diverse over the past decade** (*very high confidence*). Perceptions of fairness can facilitate cooperation by increasing the legitimacy of an agreement [3.10, 13.2.2.4]. UNFCCC remains a primary international forum for climate negotiations, but other institutions have emerged at multiple scales, namely: global, regional, national, and local [13.3.1, 13.4.1.4, 13.5]. This institutional diversity arises in part from the growing inclusion of climate change issues in other policy arenas (e.g., sustainable development, international trade, and human rights). These and other linkages create opportunities, potential co-benefits, or harms that have not yet been thoroughly examined. Issue linkage also creates the possibility for countries to experiment with different forums of cooperation ('forum shopping'), which may increase negotiation costs and potentially distract from or dilute the performance of international cooperation toward climate goals. [13.3, 13.4, 13.5] Finally, there has been an emergence of new transnational climate-related institutions not centred on sovereign states (e.g., public-private partnerships, private sector governance initiatives, transnational NGO programmes, and city level initiatives) [13.3.1, 13.12].

**Existing and proposed international climate agreements vary in the degree to which their authority is centralized.** As illustrated in Figure TS.38, the range of centralized formalization spans strong multilateral agreements (such as the Kyoto Protocol targets), harmonized national policies (such as the Copenhagen/Cancún pledges), and decentralized but coordinated national policies (such as planned linkages of national and sub-national emissions trading schemes) [13.4.1, 13.4.3]. Four other design elements of international agreements have particular relevance: legal bindingness, goals and targets, flexible mechanisms, and equitable methods for effort-shar-

**Table TS.10 |** Summary of performance assessments of existing and proposed forms of cooperation. Forms of cooperation are evaluated along the four evaluation criteria described in Sections 3.7.1 and 13.2.2. [Table 13.3]

| | **Mode of International Cooperation** | | **Assessment Criteria** | | | |
|---|---|---|---|---|---|---|
| | | | **Environmental Effectiveness** | **Aggregate Economic Performance** | **Distributional Impacts** | **Institutional Feasibility** |
| **Existing Cooperation [13.13.1]** | **UNFCCC** | | Aggregate GHG emissions in Annex I countries declined by 6.0 to 9.2 % below 1990 levels by 2000, a larger reduction than the apparent 'aim' of returning to 1990 levels by 2000. | Authorized joint fulfilment of commitments, multi-gas approach, sources and sinks, and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse effects, and other factors. | Commitments distinguish between Annex I (industrialized) and non-Annex I countries. Principle of 'common but differentiated responsibility.' Commitment to 'equitable and appropriate contributions by each [party].' | Ratified (or equivalent) by 195 countries and regional organizations. Compliance depends on national communications. |
| | **The Kyoto Protocol (KP)** | | Aggregate emissions in Annex I countries were reduced by 8.5 to 13.6 % below 1990 levels by 2011, more than the first commitment period (CP1) collective reduction target of 5.2 %. Reductions occurred mainly in EITs; emissions; increased in some others. Incomplete participation in CP1 (even lower in CP2). | Cost-effectiveness improved by flexible mechanisms (Joint Implementation (JI), CDM, International Emissions Trading (IET)) and domestic policy choice. Cost and benefit estimates depend on baseline, discount rate, participation, leakage, co-benefits, adverse effects, and other factors. | Commitments distinguish between developed and developing countries, but dichotomous distinction correlates only partly (and decreasingly) with historical emissions trends and with changing economic circumstances. Intertemporal equity affected by short-term actions. | Ratified (or equivalent) by 192 countries and regional organizations, but took 7 years to enter into force. Compliance depends on national communications, plus KP compliance system. Later added approaches to enhance measurement, reporting, and verification (MRV). |
| | **The Kyoto Mechanisms** | | About 1.4 billion tCO$_2$eq credits under the CDM, 0.8 billion under JI, and 0.2 billion under IET (through July 2013). Additionality of CDM projects remains an issue but regulatory reform underway. | CDM mobilized low cost options, particularly industrial gases, reducing costs. Underperformance of some project types. Some evidence that technology is transferred to non-Annex I countries. | Limited direct investment from Annex I countries. Domestic investment dominates, leading to concentration of CDM projects in few countries. Limited contributions to local sustainable development. | Helped enable political feasibility of Kyoto Protocol. Has multi-layered governance. Largest carbon markets to date. Has built institutional capacity in developing countries. |
| | **Further Agreements under the UNFCCC** | | Pledges to limit emissions made by all major emitters under Cancun Agreements. Unlikely sufficient to limit temperature change to 2 °C. Depends on treatment of measures beyond current pledges for mitigation and finance. Durban Platform calls for new agreement by 2015, to take effect in 2020, engaging all parties. | Efficiency not assessed. Cost-effectiveness might be improved by market-based policy instruments, inclusion of forestry sector, commitments by more nations than Annex I countries (as envisioned in Durban Platform). | Depends on sources of financing, particularly for actions of developing countries. | Cancún Conference of the Parties (COP) decision; 97 countries made pledges of emission reduction targets or actions for 2020. |
| | **Agreements outside the UNFCCC** | **G8, G20, Major Economies Forum on Energy and Climate (MEF)** | G8 and MEF have recommended emission reduction by all major emitters. G20 may spur GHG reductions by phasing out of fossil fuel subsidies. | Action by all major emitters may reduce leakage and improve cost-effectiveness, if implemented using flexible mechanisms. Potential efficiency gains through subsidy removal. Too early to assess economic performance empirically. | Has not mobilized climate finance. Removing fuel subsidies would be progressive but have negative effects on oil-exporting countries and on those with very low incomes unless other help for the poorest is provided. | Lower participation of countries than UNFCCC, yet covers 70 % of global emissions. Opens possibility for forum-shopping, based on issue preferences. |
| | | **Montreal Protocol on Ozone-Depleting Substances (ODS)** | Spurred emission reductions through ODS phaseouts approximately 5 times the magnitude of Kyoto CP1 targets. Contribution may be negated by high-GWP substitutes, though efforts to phase out HFCs are growing. | Cost-effectiveness supported by multi-gas approach. Some countries used market-based mechanisms to implement domestically. | Later compliance period for phaseouts by developing countries. Montreal Protocol Fund provided finance to developing countries. | Universal participation. but the timing of required actions vary for developed and developing countries |
| | | **Voluntary Carbon Market** | Covers 0.13 billion tCO$_2$eq, but certification remains an issue | Credit prices are heterogeneous, indicating market inefficiencies | [No literature cited.] | Fragmented and non-transparent market. |

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| | Mode of International Cooperation | | Assessment Criteria | | | |
|---|---|---|---|---|---|---|
| | | | **Environmental Effectiveness** | **Aggregate Economic Performance** | **Distributional Impacts** | **Institutional Feasibility** |
| **Proposed Cooperation [13.13.2]** | **Proposed architectures** | **Strong multilateralism** | Tradeoff between ambition (deep) and participation (broad). | More cost-effectivewith greater reliance on market mechanisms. | Multilateralism facilitates integrating distributional impacts into negotiations and may apply equity-based criteria as outlined in Ch. 4 | Depends on number of parties; degree of ambition |
| | | **Harmonized national policies** | Depends on net aggregate change in ambition across countries resulting from harmonization. | More cost-effectivewith greater reliance on market mechanisms. | Depends on specific national policies | Depends on similarity of national policies; more similar may support harmonization but domestic circumstances may vary. National enforcement. |
| | | **Decentralized architectures, coordinated national policies** | Effectiveness depends on quality of standards and credits across countries | Often (though not necessarily) refers to linkage of national cap-and-trade systems, in which case cost effective. | Depends on specific national policies | Depends on similarity of national policies. National enforcement. |
| | **Effort (burden) sharing arrangements** | | Refer to Sections 4.6.2 for discussion of the principles on which effort (burden) sharing arrangements may be based, and Section 6.3.6.6 for quantitative evaluation. | | | |

ing [13.4.2]. Existing and proposed modes of international cooperation are assessed in Table TS.10. [13.13]

**The UNFCCC is currently the only international climate policy venue with broad legitimacy, due in part to its virtually universal membership** (*high confidence*). The UNFCCC continues to evolve institutions and systems for governance of climate change. [13.2.2.4, 13.3.1, 13.4.1.4, 13.5]

**Incentives for international cooperation can interact with other policies** (*medium confidence*). Interactions between proposed and existing policies, which may be counterproductive, inconsequential, or beneficial, are difficult to predict, and have been understudied in the literature [13.2, 13.13, 15.7.4]. The game-theoretic literature on climate change agreements finds that self-enforcing agreements engage and maintain participation and compliance. Self-enforcement can be derived from national benefits due to direct climate benefits, co-benefits of mitigation on other national objectives, technology transfer, and climate finance. [13.3.2]

**Decreasing uncertainty concerning the costs and benefits of mitigation can reduce the willingness of states to make commitments in forums of international cooperation** (*medium confidence*). In some cases, the reduction of uncertainty concerning the costs and benefits of mitigation can make international agreements less effective by creating a disincentive for states to participate [13.3.3, 2.6.4.1]. A second dimension of uncertainty, that concerning whether the policies states implement will in fact achieve desired outcomes, can lessen the willingness of states to agree to commitments regarding those outcomes [2.6.3].

**International cooperation can stimulate public and private investment and the adoption of economic incentives and direct regulations that promote technological innovation** (*medium confidence*). Technology policy can help lower mitigation costs, thereby increasing incentives for participation and compliance with international cooperative efforts, particularly in the long run. Equity issues can be affected by domestic intellectual property rights regimes, which can alter the rate of both technology transfer and the development of new technologies. [13.3, 13.9]

**In the absence of—or as a complement to—a binding, international agreement on climate change, policy linkages between and among existing and nascent international, regional, national, and sub-national climate policies offer potential climate change mitigation and adaptation benefits** (*medium confidence*). Direct and indirect linkages between and among sub-national, national, and regional carbon markets are being pursued to improve market efficiency. Linkage between carbon markets can be stimulated by competition between and among public and private governance regimes, accountability measures, and the desire to learn from policy experiments. Yet integrating climate policies raises a number of concerns about the performance of a system of linked legal rules and economic activities. [13.3.1, 13.5.3, 13.13.2.3] Prominent examples of linkages are among national and regional climate initiatives (e.g., planned linkage between the EU ETS and the Australian Emission Trading Scheme, international offsets planned for recognition by a number of jurisdictions), and national and regional climate initiatives with the Kyoto Protocol (e.g., the EU ETS is linked to international carbon markets through the project-based Kyoto Mechanisms) [13.6, 13.7, Figure 13.4, 14.4.2].

**International trade can promote or discourage international cooperation on climate change** (*high confidence*). Developing constructive relationships between international trade and climate agreements involves considering how existing trade policies and rules can be modified to be more climate-friendly; whether border adjustment measures or other trade measures can be effective in meeting the goals of international climate policy, including participation in and compliance with climate agreements; or whether the UNFCCC, World Trade Organization (WTO), a hybrid of the two, or a new institution is the best forum for a trade-and-climate architecture. [13.8]

**The Montreal Protocol, aimed at protecting the stratospheric ozone layer, achieved reductions in global GHG emissions** (*very high confidence*). The Montreal Protocol set limits on emissions of ozone-depleting gases that are also potent GHGs, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Substitutes for those ozone-depleting gases (such as hydrofluorocarbons (HFCs), which are not ozone-depleting) may also be potent GHGs. Lessons learned from the Montreal Protocol, for example about the effect of financial and technological transfers on broadening participation in an international environmental agreement, could be of value to the design of future international climate change agreements (see Table TS.10). [13.3.3, 13.3.4, 13.13.1.4]

**The Kyoto Protocol was the first binding step toward implementing the principles and goals provided by the UNFCCC, but it has had limited effects on global GHG emissions because some countries did not ratify the Protocol, some Parties did not meet their commitments, and its commitments applied to only a portion of the global economy** (*medium evidence, low agreement*). The Parties collectively surpassed their collective emission reduction target in the first commitment period, but the Protocol credited emissions reductions that would have occurred even in its absence. The Kyoto Protocol does not directly influence the emissions of non-Annex I countries, which have grown rapidly over the past decade. [5.2, 13.13.1.1]

**The flexible mechanisms under the Protocol have cost-saving potential, but their environmental effectiveness is less clear** (*medium confidence*). The CDM, one of the Protocol's flexible mechanisms, created a market for GHG emissions offsets from developing countries, generating credits equivalent to nearly 1.4 $GtCO_2eq$ as of October 2013. The CDM's environmental effectiveness has been mixed due to concerns about the limited additionality of projects, the validity of baselines, the possibility of emissions leakage, and recent credit price decreases. Its distributional impact has been unequal due to the concentration of projects in a limited number of countries. The Protocol's other flexible mechanisms, Joint Implementation (JI) and International Emissions Trading (IET), have been undertaken both by governments and private market participants, but have raised concerns related to government sales of emission units. (Table TS.10) [13.7.2, 13.13.1.2, 14.3.7.1]

**Recent UNFCCC negotiations have sought to include more ambitious contributions from the countries with commitments under the Kyoto Protocol, mitigation contributions from a broader set of countries, and new finance and technology mechanisms.** Under the 2010 Cancún Agreement, developed countries formalized voluntary pledges of quantified, economy-wide GHG emission reduction targets and some developing countries formalized voluntary pledges to mitigation actions. The distributional impact of the agreement will depend in part on the magnitude and sources of financing, although the scientific literature on this point is limited, because financing mechanisms are evolving more rapidly than respective scientific assessments (*limited evidence, low agreement*). Under the 2011 Durban Platform for Enhanced Action, delegates agreed to craft a future legal regime that would be 'applicable to all Parties […] under the Convention' and would include substantial new financial support and technology arrangements to benefit developing countries, but the delegates did not specify means for achieving those ends. [13.5.1.1, 13.13.1.3, 16.2.1]

## TS.4.5 Investment and finance

**A transformation to a low-carbon economy implies new patterns of investment.** A limited number of studies have examined the investment needs for different mitigation scenarios. Information is largely limited to energy use with global total annual investment in the energy sector at about 1200 billion USD. Mitigation scenarios that reach atmospheric $CO_2eq$ concentrations in the range from 430 to 530 ppm $CO_2eq$ by 2100 (without overshoot) show substantial shifts in annual investment flows during the period 2010–2029 if compared to baseline scenarios (Figure TS.39): annual investment in the existing technologies associated with the energy supply sector (e.g., conventional fossil fuelled power plants and fossil fuel extraction) would decline by 30 (2 to 166) billion USD per year (median: –20 % compared to 2010) (*limited evidence, medium agreement*). Investment in low-emissions generation technologies (renewables, nuclear, and power plants with CCS) would increase by 147 (31 to 360) billion USD per year (median: +100 % compared to 2010) during the same period (*limited evidence, medium agreement*) in combination with an increase by 336 (1 to 641) billion USD in energy efficiency investments in the building, transport and industry sectors (*limited evidence, medium agreement*). Higher energy efficiency and the shift to low-emission generation technologies contribute to a reduction in the demand for fossil fuels, thus causing a decline in investment in fossil fuel extraction, transformation and transportation. Scenarios suggest that average annual reduction of investment in fossil fuel extraction in 2010–2029 would be 116 (–8 to 369) billion USD (*limited evidence, medium agreement*). Such spillover effects could yield adverse effects on the revenues of countries that export fossil fuels. Mitigation scenarios also reduce deforestation against current deforestation trends by 50 % reduction with an investment of 21 to 35 billion USD per year (*low confidence*). [16.2.2]

**Estimates of total climate finance range from 343 to 385 billion USD per year between 2010 and 2012** (*medium confidence*). The range is based on 2010, 2011, and 2012 data. Climate finance was almost evenly invested in developed and developing countries. Around 95 % of the total was invested in mitigation (*medium confidence*). The figures reflect the total financial flow for the underlying investments, *not the incremental investment*, i.e., the portion attributed to the mitigation/adaptation cost increment (see Box TS.14). In general, quantitative data on climate finance are limited, relate to different concepts, and are incomplete. [16.2.1.1]

**Depending on definitions and approaches, climate finance flows to developing countries are estimated to range from 39 to 120 billion USD per year during the period 2009 to 2012** (*medium confidence*). The range covers public and private flows for mitigation and adaptation. Public climate finance was 35 to 49 billion USD (2011/2012 USD) (*medium confidence*). Most public climate finance provided to developing countries flows through bilateral and multilateral institutions usually as concessional loans and grants. Under the UNFCCC, climate finance is funding provided to developing countries by Annex II Parties and averaged nearly 10 billion USD per year from 2005 to 2010 (*medium confidence*). Between 2010 and 2012, the ´fast start finance´ provided by some developed countries amounted to over 10 billion USD per year (*medium confidence*). Estimates of international private climate finance flowing to developing countries range from 10 to 72 billion USD (2009/2010 USD) per year, including foreign direct investment as equity and loans in the range of 10 to 37 billion USD (2010 USD and 2008 USD) per year over the period of 2008–2011 (*medium confidence*). Figure TS.40 provides an overview of climate finance, outlining sources and managers of capital, financial instruments, project owners, and projects. [16.2.1.1]

**Within appropriate enabling environments, the private sector, along with the public sector, can play an important role in financing mitigation**. The private sector contribution to total climate finance is estimated at an average of 267 billion USD (74 %) per year in the period 2010 to 2011 and at 224 billion USD (62 %) per year in the

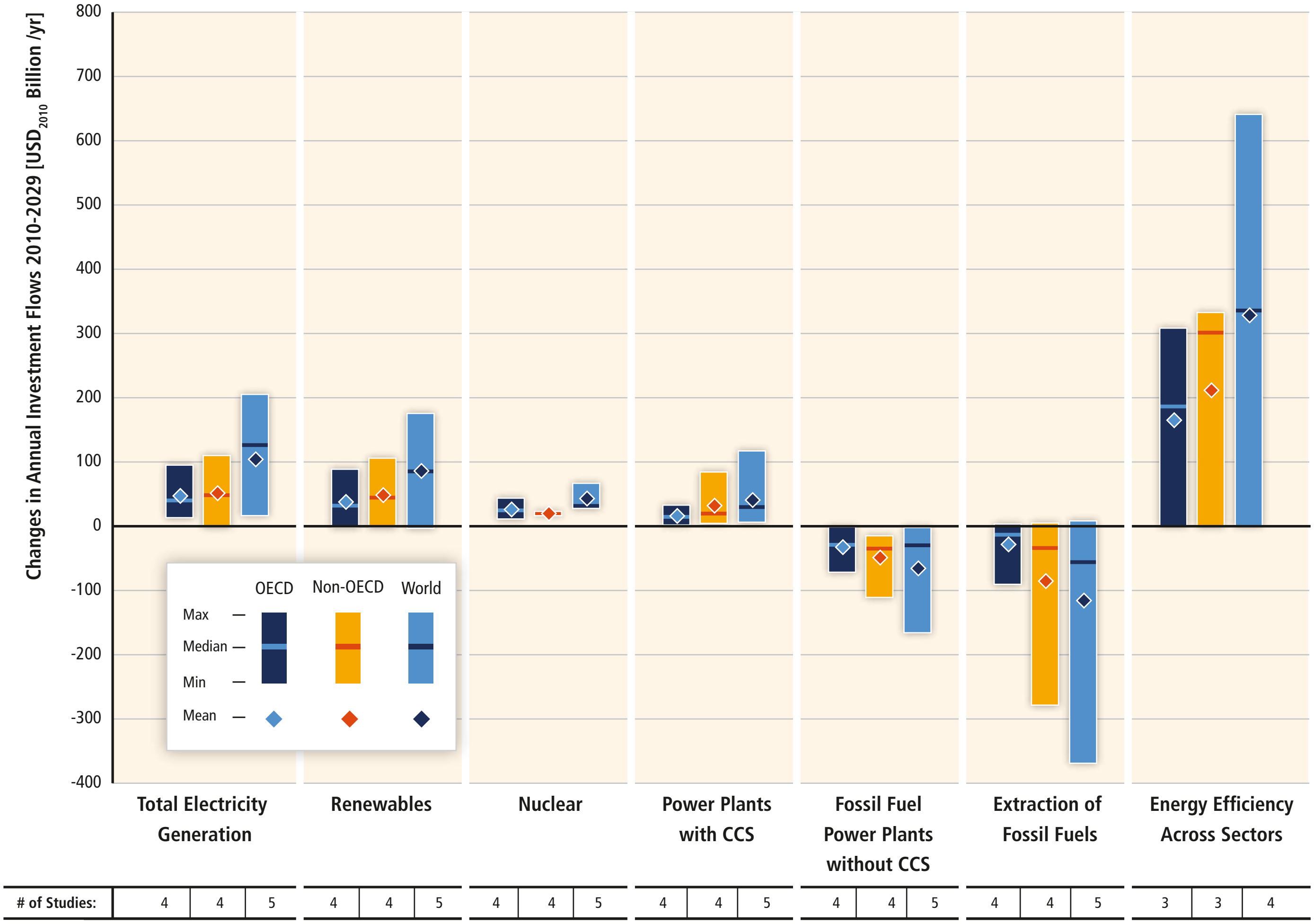

**Figure TS.39 |** Change of average annual investment flows in mitigation scenarios (2010–2029). Investment changes are calculated by a limited number of model studies and model comparisons for mitigation scenarios that reach concentrations within the range of 430–530 ppm $CO_2$eq by 2100 compared to respective average baseline investments. The vertical bars indicate the range between minimum and maximum estimate of investment changes; the horizontal bar indicates the median of model results. Proximity to this median value does not imply higher likelihood because of the different degree of aggregation of model results, low number of studies available and different assumptions in the different studies considered. The numbers in the bottom row show the total number of studies assessed. [Figure 16.3]

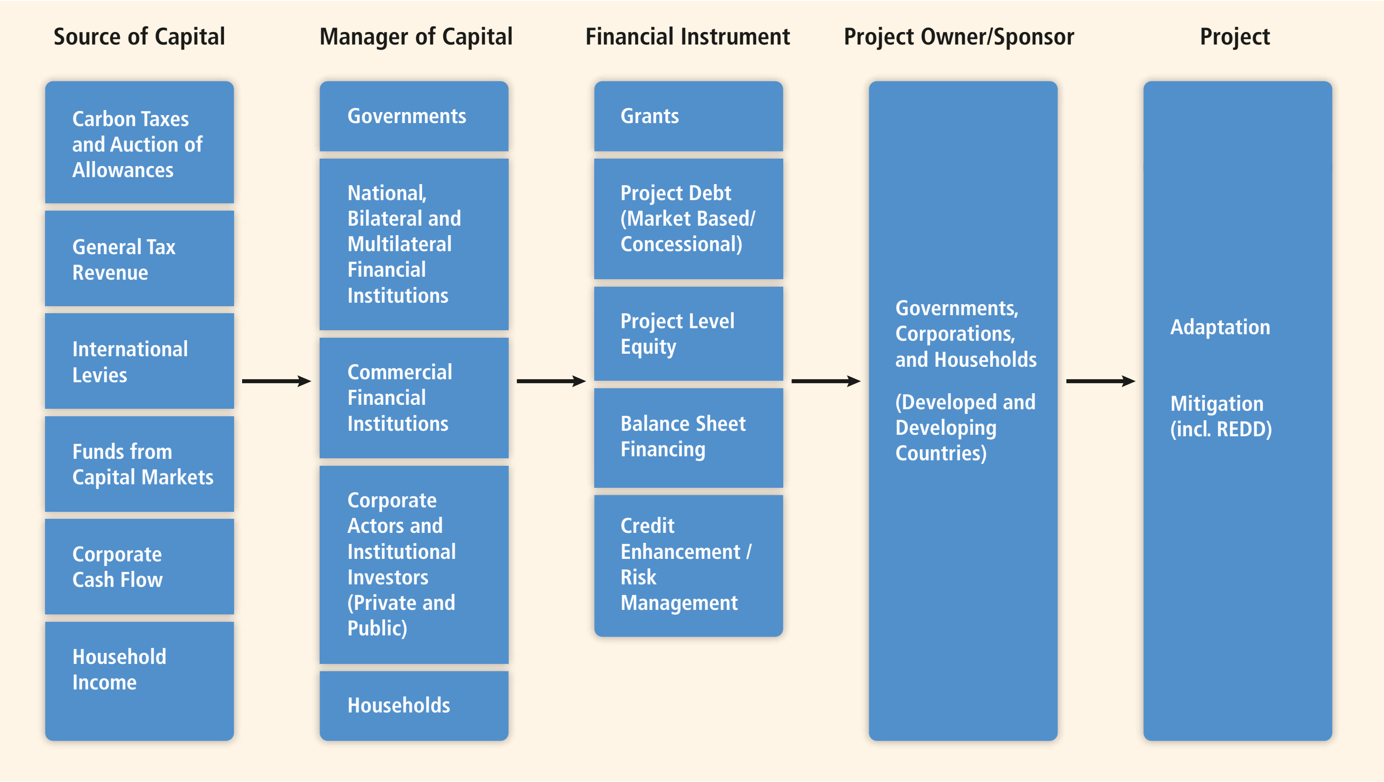

**Figure TS.40 |** Types of climate finance flows. 'Capital' includes all relevant financial flows. The size of the boxes is not related to the magnitude of the financial flow. [Figure 16.1]

## Box TS.14 | There are no agreed definitions of ´climate investment´ and 'climate finance'

'*Total climate finance*' includes all financial flows whose expected effect is to reduce net GHG emissions and/or to enhance resilience to the impacts of climate variability and the projected climate change. This covers private and public funds, domestic and international flows, expenditures for mitigation and adaptation, and adaptation to current climate variability as well as future climate change. It covers the full value of the financial flow rather than the share associated with the climate change benefit. The share associated with the climate change benefit is the incremental cost. The '*total climate finance flowing to developing countries*' is the amount of the total climate finance invested in developing countries that comes from developed countries. This covers private and public funds for mitigation and adaptation. '*Public climate finance provided to developing countries*' is the finance provided by developed countries´ governments and bilateral institutions as well as multilateral institutions for mitigation and adaptation activities in developing countries. '*Private climate finance flowing to developing countries*' is finance and investment by private actors in/from developed countries for mitigation and adaptation activities in developing countries. Under the UNFCCC, climate finance is not well-defined. Annex II Parties provide and mobilize funding for climate-related activities in developing countries.

The '*incremental investment*' is the extra capital required for the initial investment for a mitigation or adaptation project in comparison to a reference project. Incremental investment for mitigation and adaptation projects is not regularly estimated and reported, but estimates are available from models. The '*incremental cost*' reflects the cost of capital of the incremental investment and the change of operating and maintenance costs for a mitigation or adaptation project in comparison to a reference project. It can be calculated as the difference of the net present values of the two projects. Many mitigation measures have higher investment costs and lower operating and maintenance costs than the measures displaced so incremental cost tends to be lower than the incremental investment. Values depend on the incremental investment as well as projected operating costs, including fossil fuel prices, and the discount rate. The '*macroeconomic cost of mitigation policy*' is the reduction of aggregate consumption or GDP induced by the reallocation of investments and expenditures induced by climate policy (see Box TS.9). These costs do not account for the benefit of reducing anthropogenic climate change and should thus be assessed against the economic benefit of avoided climate change impacts. [16.1] period 2011 to 2012 (*limited evidence, medium agreement*) [16.2.1]. In a range of countries, a large share of private sector climate investment relies on low-interest and long-term loans as well as risk guarantees provided by public sector institutions to cover the incremental costs and risks of many mitigation investments. The quality of a country's enabling environment—including the effectiveness of its institutions, regulations and guidelines regarding the private sector, security of property rights, credibility of policies, and other factors—has a substantial impact on whether private firms invest in new technologies and infrastructure [16.3]. By the end of 2012, the 20 largest emitting developed and developing countries with lower risk country grades for private sector investments produced 70 % of global energy related $CO_2$ emissions (*low confidence*). This makes them attractive for international private sector investment in low-carbon technologies. In many other countries, including most least-developed countries, low-carbon investment will often have to rely mainly on domestic sources or international public finance. [16.4.2]

**A main barrier to the deployment of low-carbon technologies is a low risk-adjusted rate of return on investment vis-à-vis high-carbon alternatives** (*high confidence*). Public policies and support instruments can address this either by altering the average rates of return for different investment options, or by creating mechanisms to lessen the risks that private investors face [15.12, 16.3]. Carbon pricing mechanisms (carbon taxes, cap-and-trade systems), as well as renewable energy premiums, FITs, RPSs, investment grants, soft loans and credit insurance can move risk-return profiles into the required direction [16.4]. For some instruments, the presence of substantial uncertainty about their future levels (e.g., the future size of a carbon tax relative to differences in investment and operating costs) can lead to a lessening of the effectiveness and/or efficiency of the instrument. Instruments that create a fixed or immediate incentive to invest in low-emission technologies, such as investment grants, soft loans, or FITs, do not appear to suffer from this problem. [2.6.5]