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The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century

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ABSTRACT

Studies of global environmental change make extensive use of scenarios to explore how the future can evolve under a consistent set of assumptions. The recently developed Shared Socioeconomic Pathways (SSPs) create a framework for the study of climate-related scenario outcomes. Their five narratives span a wide range of worlds that vary in their challenges for climate change mitigation and adaptation. Here we provide background on the quantification that has been selected to serve as the reference, or 'marker', implementation for SSP2. The SSP2 narrative describes a middle-of-the-road development in the mitigation and adaptation challenges space. We explain how the narrative has been translated into quantitative assumptions in the *IIASA Integrated Assessment Modelling Framework*. We show that our SSP2 marker implementation occupies a central position for key metrics along the mitigation and adaptation challenge dimensions. For many dimensions the SSP2 marker implementation also reflects an extension of the historical experience, particularly in terms of carbon and energy intensity improvements in its baseline. This leads to a steady emissions increase over the 21st century, with projected end-of-century warming nearing 4 °C relative to preindustrial levels. On the other hand, SSP2 also shows that global-mean temperature increase can be limited to below 2 °C, pending stringent climate policies throughout the world. The added value of the SSP2 marker implementation for the wider scientific community is that it can serve as a starting point to further explore integrated solutions for achieving multiple societal objectives in light of the climate adaptation and mitigation challenges that society could face over the 21st century.

1. Introduction and background

Studies of global environmental change are characterized by deep uncertainty. Many interdependent factors influence how our world could evolve over time. These include policy choices and societal preferences. As we have no means to predict the future in a highly precise way, scenarios are often used as scientific tools to explore what futures we could foresee, and which decisions today could most robustly lead to desired outcomes (Riahi et al., 2007). In this sense, scenarios are neither predictions nor forecasts. They have instead been described as "stories that happened in the future" (Armstrong and Green, 2012) and are created by projecting a consistent set of assumptions from today into the future. These assumptions determine many of the key characteristics of scenarios: how population grows and develops over time, which levels of education are achieved when, which technologies and energy sources become available, how food is produced and consumed, which world views and social preferences dominate, and much more. The space and dimensions that can be explored are vast, but to make sense scientifically, it is crucial that a single

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scenario is based on a set of assumptions that is internally consistent. To this end, overarching storylines are typically developed that sketch the general context of scenarios; then, within this context or narrative, policies and decisions can be varied.

Recently, narratives have been developed for the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017). These descriptions of alternative futures of societal development span a range of possible worlds that stretch along two climate-change-related dimensions: mitigation and adaptation challenges. Together with the Representative Concentration Pathways (RCPs) from a few years earlier (Moss et al., 2010; van Vuuren et al., 2012), they provide a toolkit for the climate change research community to carry out integrated, multi-disciplinary analysis. The SSPs reflect five different developments of the world that are characterized by varying levels of global challenges [see (Riahi et al., 2016, in press) for an overview]: (1) development under a green growth paradigm (SSP1: Sustainability—Taking the Green Road) (van Vuuren et al., 2017); (2) development along historical patterns (SSP2: Middle of the Road, this study); (3) a regionally heterogeneous development (SSP3: Regional rivalry—A rocky road) (Fujimori et al., 2016, in press); (4) a development which breeds both geographical and social inequalities (SSP4: Inequality—A road divided) (Calvin et al., 2016, in press); and (5) a development path that is dominated by extensive fossil-fuel use (SSP5: Fossil-fuelled development—Taking the highway) (Kriegler et al., 2016, in press).

Here we provide background and information about the quantification of the middle-of-the-road scenario (SSP2) in the Integrated Assessment Modelling (*IAM*) framework of the International Institute for Applied Systems Analysis (*IIASA*). This quantification has been selected as the reference, or 'marker', implementation of SSP2, and its results are made available (together with those of other modelling frameworks) as a resource to the wider community in a public database (https://secure.iiasa.ac.at/web-apps/ene/SspDb). In the SSP taxonomy, SSP2 is a "middle-of-the-road" evolution of future societal developments (Box 1). This means that its objective is to cover the middle ground in terms of mitigation and adaptation challenges between more extreme SSPs, like SSP1 and SSP3 (see Boxes S1 and S2 in Supplementary Information, SI). SSP2 is consistent with development patterns (e.g., final energy intensity improvement rates) that have been observed over the past century, but is not a mere extrapolation of recent trends. The SSP2 narrative stipulates an explicit dynamic pathway informed by past trends, but in which future changes are consistent with middle-of-the-road expectations rather than falling near the upper or lower bounds of possible outcomes (O'Neill et al., 2017). This follows a long tradition of dynamics-as-usual scenarios (see Supplementary Text 1). The bracketing SSP1 depicts a sustainable future in which global cooperation, low population growth and higher incomes result in low challenges of mitigation and adaptation. SSP3 provide a narrative for the other extreme (see Boxes S1 and S2 in SI).

The objective of this paper is to provide a detailed explanation of how the SSP2 narrative was translated into the quantitative scenario that serves as the marker implementation for the evolution of the future global energy and land system in an SSP2 world. For this, we use the *IIASA IAM* framework. This framework comprises a collection of several, unique disciplinary models coupled to each other for the development of comprehensive scenarios. We first provide an overview of the quantitative assumptions that were selected to represent the main characteristics of the SSP2 narrative. Then, we introduce the *IIASA IAM* framework and describe how it has been used to translate the qualitative narratives into a quantitative scenario of the future. The subsequent section describes the baseline developments of the energy and land systems within this scenario in absence of climate change mitigation policy, and also explores the impact of increasing climate policy stringency. Where appropriate, a comparison is made between SSP2 and the bracketing SSP1 and SSP3 implementations within the *IIASA IAM* framework, which represent the two extremes in terms of challenges to mitigation and adaptation. The last section then takes a step back and provides an overview and conclusions, presenting the middle-of-the-road results for SSP2 in the wider context of the SSP1 and SSP3 narratives. This paper thus documents the novel implementation of the SSP2 marker scenario in the *IIASA IAM* framework, and provides a first assessment of how societal assumptions along the SSP dimensions translate in varying mitigation and adaptation challenges.

2. From narratives to quantified scenario characteristics

Quantifying possible evolutions of the energy and land system in an SSP2 world requires the overarching narrative (Box 1) to be translated into quantified assumptions for analysis and modelling. What does "middle-of-the-road" mean exactly, in terms of challenges to adaptation and mitigation? Here we provide a brief overview of SSP2's economic and population developments over the 21st century; these are core drivers of the scenarios, particularly for energy services and food demands. We then continue with a look at the assumptions made for the energy and land-use sectors. It is important to note that some of these core drivers will also be further affected by interactions within the *IIASA IAM*. For example, economic development will be affected by

Box 1. SSP2 narrative of a middle-of-the-road world.

"The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing moderate challenges to mitigation and adaptation, but with significant heterogeneities across and within countries." (O'Neill et al., 2015).

investments in the energy system required to mitigate carbon emissions, and the baseline energy intensity will be affected by energy prices and stringency of climate mitigation action.

2.1. Population and economic development

Population and economic developments have strong implications for the anticipated mitigation and adaptation challenges. For example, a larger, poorer population will have more difficulties to adapt to the detrimental effects of climate change (O'Neill et al., 2014). Understanding how population and economic growth develops in the SSPs therefore already gives a first layer of understanding of the multiple challenges. Population growth evolves in response to how the fertility, mortality, migration, and education of various social strata are assumed to change over time. In SSP2, global population steadily grows to 9.4 billion people around 2070, and slowly declines thereafter (KC and Lutz, 2017). Gross Domestic Product (GDP) follows regional historical trends (Dellink et al., 2017). With global average income reaching about 60 (thousand year-2005 USD/capita, purchasing-power-parity – PPP, i.e., GDP/capita) by the end of the century, SSP2 sees an increase of global average income by a factor 6. The SSP2 GDP projection is thus situated in-between the estimates for SSP1 and SSP3, which reach 2100 global average income levels of 82 and 22 (thousand year-2005 USD/capita PPP), respectively. SSP2 depicts a future of global progress where developing countries achieve significant economic growth. Today, average per capita income in the global North is about five times higher than in the global South (see SI for regional definitions). In SSP2, developing countries reach today's average income levels of the OECD by around 2060–2090, depending on the region. However, modest improvements of educational attainment levels result in declines in education-specific fertility rates, leading to incomplete economic convergence across different world regions. This is particularly an issue for Africa. Overall, both the population and GDP developments in SSP2 are designed to be situated in the middle of the road between SSP1 and SSP3, see KC and Lutz (2017) and Dellink et al. (2017) for details.

2.2. Baseline energy intensity improvements

Energy intensity improvements are among the key distinguishing features of the assumptions of the modelled SSP scenarios – the quantified interpretations of the qualitatively-described narratives. These improvements are driven by advances in energy efficiency and evolving behavioural/lifestyle preferences, which are not explicitly modelled. Historically, the intensity of total final energy (FEI; final energy at the end-use level per dollar of GDP) improved at a rate of about 1.2% globally over the 1971–2010 timeframe. Without this improvement, energy use, and by extension greenhouse gas emissions, would be much higher today than they currently are. Energy intensity improvements thus have important implications for the anticipated challenges for mitigation.

Fig. 1 summarizes the baseline assumptions for SSP1, SSP2, and SSP3 in terms of their energy intensity evolution over the 21st century (globally and for the North and South, respectively), highlighting SSP2's middle-of the road position within this set. The narrative of SSP2 prescribes that technological trends do not shift markedly from historical patterns. In the SSP2 baseline (i.e., when no climate mitigation efforts are assumed), final energy intensity is therefore assumed to continue to improve at approximately the abovementioned average historical rate (i.e., 1.3%, see also Fig. 8, below). In contrast, SSP1 and SSP3 assume more extreme

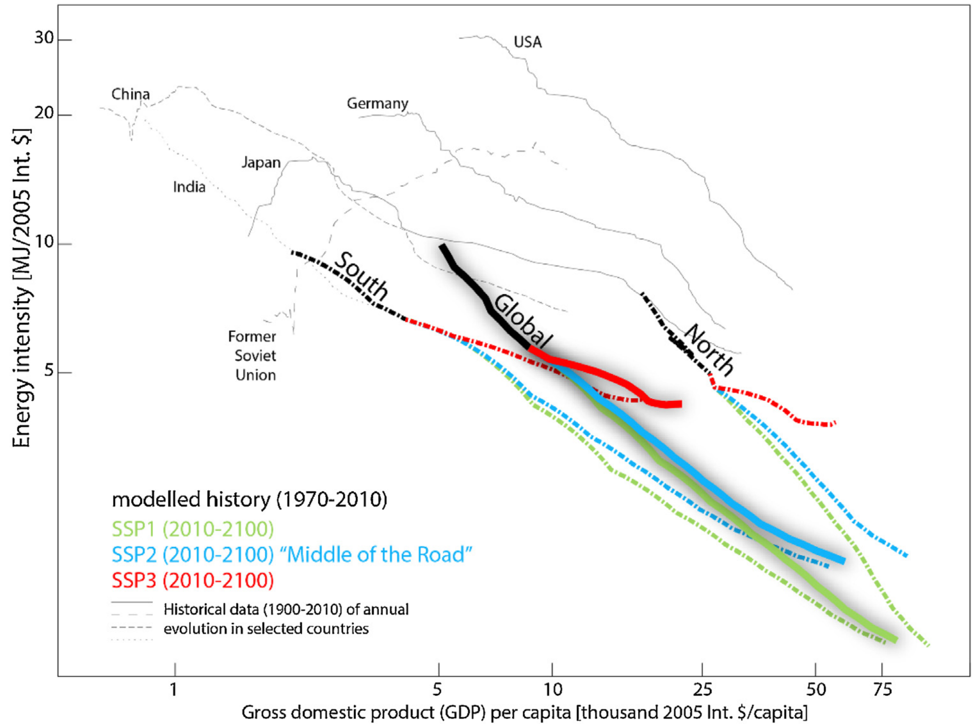


Fig. 1. Historic and future final energy intensity (total final energy use over GDP PPP) development plotted against gross domestic product (GDP PPP) per capita. Thin lines represent annual historical data from 1900 to 2010 for selected countries based on Maddison (2010). Original GDP data from this source has been deflated from 1990 to 2005 using a US GDP deflator and a 10 year moving average has been applied to the energy intensity numbers to smooth high-frequency fluctuations. Global model data (thick solid lines) is provided for SSP1, SSP2 and SSP3 (green, blue, red, respectively) as well as regionally aggregated data for the global North and South (thick dashed lines). Historical data for these regions for the period 1970–2010 originated from World Bank (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evolutions that imply lower and higher challenges to mitigation. The SSP1 no-climate-policy baseline assumes global FEI improvements of 1.7% annually while in the SSP3 baseline FEI is assumed to improve more slowly (0.2% annually).

Fig. 1 also presents historical energy intensity data for key countries, which shows how the future energy intensity improvement rates of the global North and South in the SSP2 baseline compare to historical trends. Fig. 1 also illustrates how regional convergence in terms of economic and technological development is either facilitated (in SSP1) or frustrated (in SSP3), with SSP2 providing a middle ground.

Together with economic and population developments, energy intensity improvements translate into varying levels of energy demand (presented in Section 4.1), which are both an input and an output into the *IIASA IAM* framework. A description of how energy demand has been derived is provided in Supplementary Text 2.

2.3. Fossil energy resources

The availability and costs of fossil fuels will also influence the future direction of the energy system, and therewith future mitigation challenges. Understanding the variations in fossil fuel

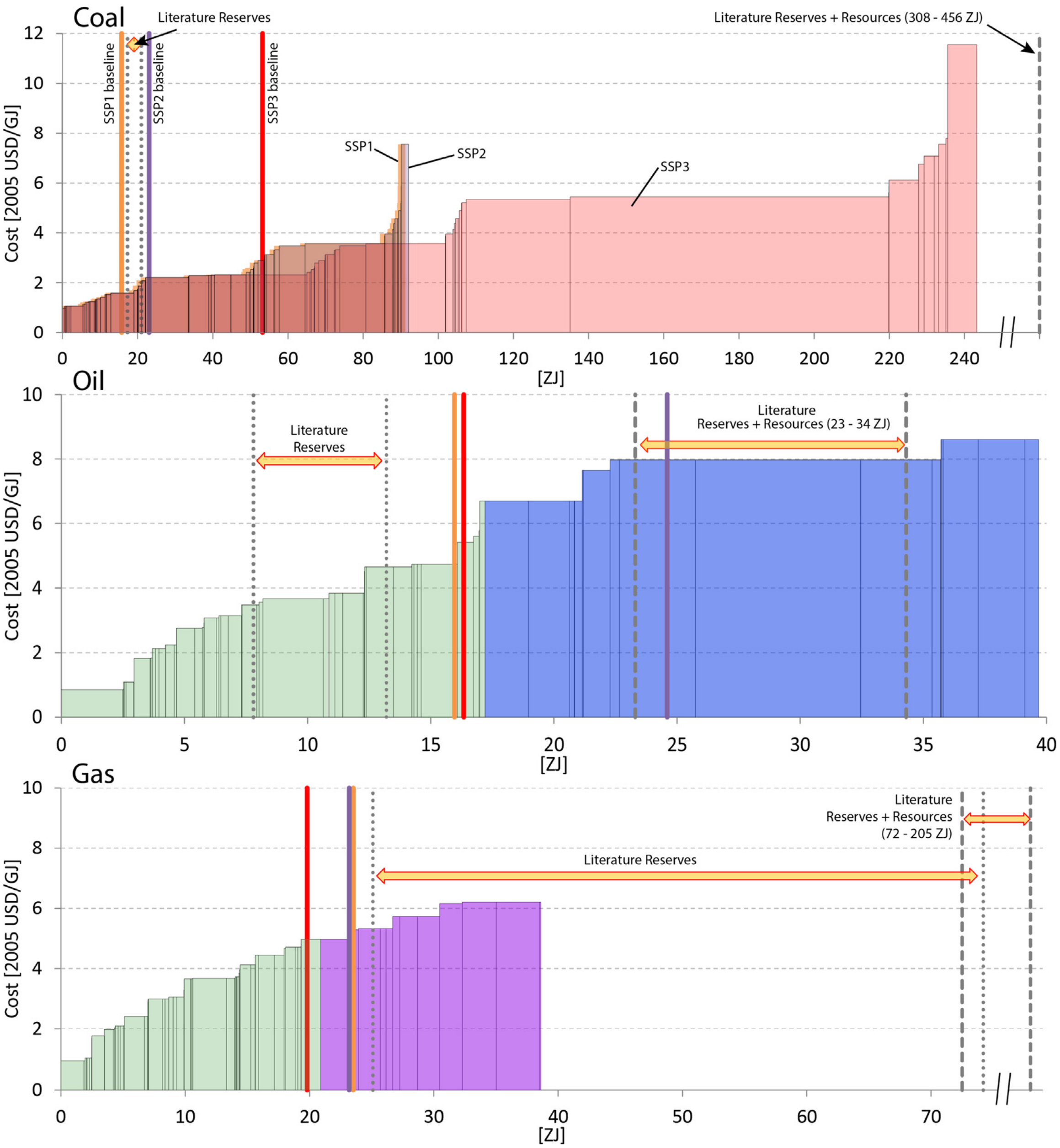


Fig. 2. Cumulative global resource supply curves for coal (top), oil (middle), and gas (bottom) in the *IIASA IAM* framework. Green shaded resources are technically and economically extractable in all SSPs, purple shaded resources are additionally available in SSP1 and SSP2 and blue shaded resources are additionally available in SSP2. Coloured vertical lines represent the cumulative use of each resource between 2010 and 2100 in the SSP baselines (see top panel for colour coding), and are thus the result of the combined effect of our assumptions on fossil resource availability and conversion technologies in the SSP baselines. 'Reserves' are generally defined as being those quantities for which geological and engineering information indicate with reasonable certainty that they can be recovered in the future from known reservoirs under existing economic and operating conditions. 'Resources' are detected quantities that cannot be profitably recovered with current technology, but might be recoverable in the future, as well as those quantities that are geologically possible, but yet to be found. The remainder are 'Undiscovered resources' and, by definition, one can only speculate on their existence. Definitions are based on Rogner et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Storyline elements and their quantitative translation in SSP1, SSP2, and SSP3 baselines. All indicators apply to 2010–2100; Intensity improvements are in FE/GDP annually.

Energy			
	SSP1	**SSP2**	**SSP3**
Energy demand	Total final energy intensity improvement is approx. 1.7% *(Regional range from 1.3% to 2.45%)*	Total final energy improvement is approx. 1.2% *(Regional range from .9% to 2%)*	Total final energy improvement is approx. 0.3% *(Regional range from .2% to .9%)*
Transport	High electrification (*max. 75% of total transport possible*)	Medium electrification (*max. 50% of total transport possible*)	Low electrification (*max 10% of total transport possible*)
Residential & Commercial	High electrification rate: 1.44% *(Regional range from .35% to 4%)*	Medium electrification rate: 1.07% *(Regional range from .23% to 3%)*	Low electrification rate: .87% (*Regional range from .37% to 2%*)
Industry + Feedstocks	High electrification rate: 0.56% (*Regional range from .2% to 1.2%*) High feedstock reduciton rate: -0.33% (*Regional range from -0.51 to 0.59%*)	Medium electrification rate: 0.47% (*Regional range from .07% to 1.08%*) Medium feedstock reduction rate: -0.27% (*Regional range from -0.45% to 0.64%*)	Low electrification rate: .12% (*Regional range from -.03% to 0.71%*) Low feedstock reduction rate: -0.24% (*Regional range from -0.38% to 0.51%*)
Traditional Fuel Use	Phase-out by 2040	Phase-out by 2080	Continued use of traditional biomass
Fossil Energy Resource			
Coal	High cost assumptions	Medium cost assumptions	Low cost assumptions
Other Hydrocarbons	Medium resource availability (*56 ZJ*)	High resource availability (*77 ZJ*)	Low resource availability (*41 ZJ*)
Energy Supply			
Conventional and Unconventional Fossil Fuel Conversion	Low technology learning rate and slow market penetration *(limited cost reduction (0-30% by 2100; 30% for gas only))*	Medium assumptions *(cost reductions between 10% (coal syn-liquids) and 30% (for other coal and gas))*	High learning rate for coal; medium for others; hydrogen is unavailable (cost reductions from 15-20% (for coal-synthetic liquids gas) and up to 50% for coal)
Commercial Biomass Conversion	High technology improvements (cost reductions of 30%-50%)	Medium assumptions *(cost reductions of 20%-40%)*	Low technology improvements (cost reductions of 10%-30%)
Non-bio Renewables Conversion	High technology improvements *(cost reductions between 20%-90%)*	Medium assumptions *(cost reductions between 18%-70%)*	Low technology Improvement *(cost reductions between 10%-30%)*
Nuclear Power	Low assumption (Cost reductions of 15%)	Medium assumptions *(Cost reductions of 30%)*	No learning
CCS (under climate policy only)	Low technological development for fossils; High for biomass *(Cost reductions of 0%-50%)*	Medium assumptions *(Cost reductions of 10%-40%)*	Low technological development (Cost reductions of 10%-27%)

Agriculture and land use			
	SSP1	**SSP2**	**SSP3**
Net deforestation	Afforestation *(No net deforestation by 2050, +3% forest area by 2100 compared to 2010)*	Deforestation/Afforestation (Forest loss of 1% by 2050, back to 2010 area by 2100)	Deforestation *(Net forest loss of 3% by 2050 and 6% by 2100 compared to 2010)*
Land productivity growth			
Crops: Yields	High yield growth *(Annual yield growth from 0.51% p.a. in the North to 0.66% in the South)*	Moderate yield growth *(Annual yield growth from 0.46% p.a. in the North to 0.60% in the South)*	Slow yield growth *(Annual yield growth from 0.35% p.a. in the North to 0.35% in the South)*
Crops: Input intensity	Low intensity *(Elasticity of variable inputs incl. fertilizer use wrt technological change: 0.75)*	Medium intensity *(Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.00)*	High intensity *(Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.25)*
Livestock: Feed conversion efficiency	Enhanced efficiency growth *(Annual feed conversion efficiency change from 0.10% in the North to 0.26% in the South)*	Moderate efficiency growth *(Annual feed conversion efficiency change from 0.10% in the North to 0.24% in the South)*	Slow efficiency growth *(Annual feed conversion efficiency change from 0.07% in the North to 0.14% in the South)*
Livestock: Endogenous productivity growth	High livestock systems transition *(Annually, up to 5% of livestock production systems can be converted to an alternative system or the activity can be abandoned)*	Medium livestock systems transition *(Annually, up to 2.5% of livestock production systems can be converted to an alternative system or the activity can be abandoned)*	Low livestock systems transition *(No adjustment in the ruminant production system structure)*
Environmental impact of food consumption			
Food demand	Slow consumption growth and more sustainable and healthy diets *(Calorie consumption per capita growing – North : 1%, South: 16%. Livestock product share decreases in North by one third but increases in South, leading to a stable share of 15% globally)*	Moderate consumption growth and increasing share of livestock products in the diet *(Calorie consumption per capita growing by 11% in the North and 22% in the South. Livestock product share in the diet growing from 15% to 18%.)*	Substantial consumption growth but lagging demand for animal proteins in diet in the South *(Calorie consumption per capita growing by 5% in the North and 15% in the South. Livestock product share stays at 15%.)*
Losses & Wastes	Fast reduction of losses & wastes (L&W) *(L&W in the processing chains reduced from 12% to 7% in the Oilseed and Pulses sector and from 7% to 2.5% in the dairy sector over 2000 and 2050)*	Medium reduction of losses & wastes (L&W) *(L&W in the processing chains reduced from 12% to 7.5% in the Oilseed and Pulses sector and from 7% to 3% in the dairy sector over 2000 and 2050)*	Slow reduction of losses & wastes (L&W) *(L&W in the processing chains reduced from 12% to 9% in the Oilseed and Pulses sector and from 7% to 4.5% in the dairy sector over 2000 and 2050)*

availability and the underlying extraction cost assumptions across the SSPs is hence useful. Our fossil energy resource assumptions are derived from various sources (Rogner, 1997; Riahi et al., 2012) and are aligned with the storylines of the individual SSPs.

While the physical resource base is identical across the SSPs, considerable differences are assumed regarding the technical and economic availability of overall resources, for example, of unconventional oil and gas. What ultimately determines the attractiveness of a particular type of resource is not just the cost at which it can be brought to the surface, but the cost at which it can be used to provide energy services. Assumptions on fossil energy resources should thus be considered together with those on related conversion technologies. In line with the narratives, technological change in fossil fuel extraction and conversion technologies is assumed to be slowest in SSP1, while comparatively faster technological change occurs in SSP3 thereby considerably enlarging the economic potentials of coal and unconventional hydrocarbons (Table 1 and Fig. 2). However, driven by tendency toward regional fragmentation we assume the focus in SSP3 to be on developing coal technologies which in the longer term leads to a replacement of oil products by synthetic fuels based on coal-to-liquids technologies. In contrast, for SSP2 we assume a continuation of recent trends, focusing more on developing extraction technologies for unconventional hydrocarbon resources, thereby leading to higher potential cumulative oil extraction than in the other SSPs (Fig. 2, middle panel).

The regional distribution of fossil energy resources further contributes to differences between the SSPs, for example, oil is concentrated in the Middle East and North Africa while Russia and former Soviet Union states dominate a large share of conventional gas resources (Supplementary Text 3). The emphasis on coal in SSP3 leads to different regional trade patterns compared to SSP2 where oil continues to be a dominant fuel significantly into the future. All these assumptions together result in different portfolios of fossil resources being available and used in each SSP (see Table S2 in SI). The use of these resources in the various SSPs is discussed later.

2.4. Non-biomass renewable and nuclear resources

Renewable energy resources (solar, wind, hydro, geothermal) along with nuclear offer an alternative to fossil energy. The variation of the potential and cost for non-biomass renewables (in particular solar and wind energy) across our SSPs will thus strongly impact the perceived climate mitigation challenge. Regional resource potentials for solar and wind are classified according to resource quality (annual capacity factor) based on Pietzcker et al. (2014) and Eurek et al. (in review). Regional resource potentials as implemented in the *IIASA IAM* are provided by region and capacity factor for solar PV, concentrating solar power (CSP), and onshore/offshore wind in Johnson et al. (in review). The physical potential of these sources is assumed to be the same across all SSPs. However, the part of the resource that is useable at economically competitive costs is assumed to differ widely. Consistent with the narratives, we assume that SSP1 makes significant progress towards the exploitation of renewables, while there is only little progress in SSP3. SSP2 here follows a central path. In our calculations, technological progress is determined by income developments and narrative-specific assumptions (Table 1). This results for SSP2 in cost reductions for non-biomass renewable technologies (e.g., solar panels, wind turbines) of about 18–70% from 2010 to 2100 (range across all technologies). In the green-growth-driven world of SSP1, these reductions range from 20 to 90%, while in SSP3 they are very modest reaching maximally 30% by 2100. To account for the intermittency of solar and wind energy, renewable integration constraints have been introduced into the *IIASA IAM* (Sullivan et al., 2013). These integration constraints are intended to capture the additional costs and system changes that are required when deploying large shares of variable renewable energy (VRE), including the need for increased generation flexibility and backup capacity to handle uncertain and intermittent VRE generation and increased storage and/or hydrogen production to avoid electricity curtailment.

To allow for a balanced development of the energy portfolio in SSP2, a technological learning rate comparable to fossil based technologies is assumed for nuclear power (30% cost reduction by 2100 over 2010). It is furthermore assumed that operating times improve in developing countries (i.e., the annual full load factor increases from 70% in 2010–85% in 2100), allowing developing countries to gradually catch up with the North, based on per capita income trajectories. A comparison to other SSP implementations is provided in Supplementary Text 4.

2.5. Bioenergy resources and use

Biomass energy is another potentially important renewable energy resource in the *IIASA IAM*. This includes both commercial and non-commercial use. Commercial refers to the use of bioenergy in, for example, power plants or biofuel refineries (see Supplementary Text 5), while non-commercial refers to the use of bioenergy for residential heating and cooking, primarily in rural households of today's developing countries. Bioenergy potentials differ across SSPs as a result of different levels of competition over land for food and fibre, but ultimately only vary to a limited degree (Fig. 3). The drivers underlying this competition are different land-use developments in the SSPs, which are determined by agricultural productivity and global demand for food consumption. Land-use specifics are described in more detail below (Section 2.7). In short, SSP1 experiences low competition between different possible land-use activities compared to SSP3, because agricultural productivity is assumed to increase at almost double the rate in SSP1 compared to SSP3 (0.51–0.66% versus 0.35% per year). Furthermore, food demand is assumed to grow only very slowly in SSP1 compared to SSP3 (Table 1). Reflecting a medium perspective on both these drivers, the land-use competition for bioenergy resources and therewith

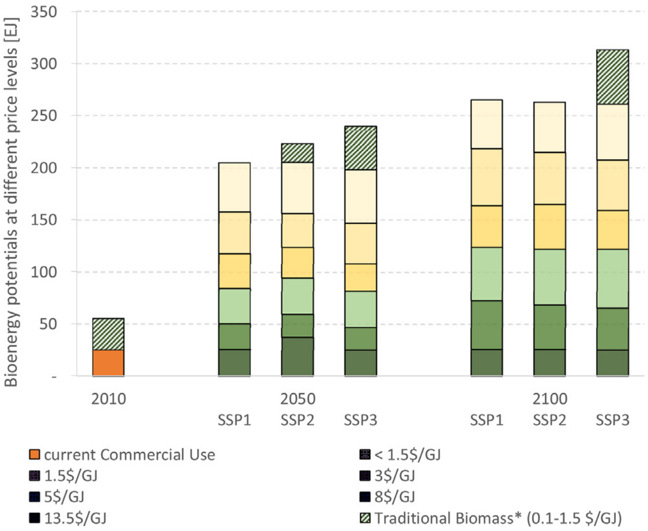


Fig. 3. Availability of bioenergy at different price levels in the *IIASA IAM* framework for the three SSPs.
* Typically non-commercial biomass is not traded or sold, however in some cases there is a market-price range from 0.1–1.5$/GJ (Pachauri et al., 2013) ($ equals 2005 USD).

also the commercial bioenergy potentials in SSP2 are situated in the middle (Fig. 3). Ultimately, the differences in bioenergy potentials across different SSPs remain limited. This is on the one hand due to the fact that substantial amounts of biomass are assumed to be sourced from feedstocks such as traditional forest management or sawmill residues, which do not directly compete with agricultural production and hence are relatively unaffected by the differentiated storylines for that sector. At the same time, just about half of the energy plantations area is assumed to occur at the expense of agricultural land. The other half is projected to take place in otherwise non-cultivated land.

The demand for non-commercial biomass is closely related to the degree of access to modern and clean fuels for poor populations in developing countries, which is derived from the population and GDP projections (Riahi et al., 2012; Pachauri et al., 2013) for each SSP. Adjusted historic traditional biomass consumption (Riahi et al., 2012) was used to determine current biomass demand in rural areas; these quantities were then projected into the future with the help of urbanization trends (Jiang and O'Neill, in press). In SSP3, large shares of the global population are not able to reach income levels that allow for a switch to clean fuels. These populations thus continue to rely on traditional fuels for cooking and heating and hence the demand for non-commercial bioenergy increases throughout the entire century. SSP1, on the other hand, seeks to spur regional development and convergence, and sees the demand for non-commercial bioenergy discontinued by 2040. SSP2 takes up the middle spot in this set, with a gradual decline over the century and a phase out of non-commercial bioenergy by 2080.

2.6. Technology cost developments

Primary energy resources like coal, biomass, and wind, among others, need technologies for their transformation into electricity or other secondary energy forms, such as liquid or gaseous fuels. Assumptions must be made about how the costs of these technologies change over time, and these assumptions are critical as they strongly influence the nature and direction of the baseline evolution of the energy system (Roehrl and Riahi, 2000). Moreover, the quantitative assumptions should be consistent with the overarching qualitative SSP narrative (Table 1). In SSP1, for instance, whose green-growth storyline is more consistent with a sustainable development paradigm, higher rates of technological progress and learning are assumed for renewables and other advanced technologies that may replace fossil fuels (e.g., the potential for electric mobility is assumed to be higher in SSP1 compared to SSP2 or SSP3). In contrast, SSP3 assumes limited progress across a host of advanced technologies, particularly for renewables and hydrogen; more optimistic assumptions are instead made for coal-based technologies, not only for power generation but also for liquid fuels production. Meanwhile, the middle-of-the-road SSP2 narrative is characterized by a fairly balanced view of progress for both conventional fossil and non-fossil technologies. In this sense, technological development in SSP2 is not biased toward any particular technology group. If it were, it would not occupy a middle-of-the-road position between the green-growth and fossil-fuel intensive paradigms of SSP1 and SSP3, respectively. The system-wide, long-term implications of these assumptions will become clearer in Section 4, where the results for the energy supply mix are discussed.

Technological costs vary regionally in all SSPs, reflecting marked differences in engineering and construction costs across countries observed in the real world. Generally, costs start out lower in the developing world and are assumed to converge to those of present-day industrialized countries as the former becomes richer throughout the century (thus, the cost projections consider both labour and capital components). This catch-up in costs is assumed to be fastest in SSP1 and slowest in SSP3 (where differences remain, even in 2100); SSP2 is in between. Estimates for present-day and fully learned-out technology costs are from the Global Energy Assessment (Riahi et al., 2012) and World Energy Outlook (IEA, 2014). A summary of these cost assumptions can be found in Supplementary Figs. S1–S3.

2.7. Land-use developments

Land-use development assumptions influence projected emissions and mitigation potential for the land-use sector and thus contribute to the overall mitigation challenge. They depend on a multitude of factors like agricultural productivities, feed conversion efficiencies, consumption patterns, forest value, and regulations, all of which play out differently across the various SSPs.

Agricultural productivity growth – the key driver of land-use requirements for food production – is fostered by investments into new technologies and policies promoting country-to-country knowledge transfer. We relate productivity growth to per capita GDP growth in each region, which can be considered a proxy for the level of investments into research and development, and at the same time a proxy for the demand growth (Herrero et al., 2014). Because per capita GDP growth differs across regions, so does agricultural productivity. In the SSP2 narrative, for instance, the world remains to a certain degree fragmented economically, but crop yields grow relatively faster in the global South than in the global North, gradually catching up to the yields in today's developed countries (for regional definitions, see Supplementary Table S4). The SSP2 development of crop yields is situated between the slightly faster and substantially slower developments of SSP1 and SSP3, respectively. Importantly, in none of the SSPs, climate change impacts on food production are taken into account. In addition, different assumptions about the character of the yield growth are made for each SSP: e.g., in SSP2 the yield growth is proportional to the growth in input requirements such as fertilizers which has implications for its associated emissions (Valin et al., 2013).

Feed conversion efficiencies (i.e., the land productivity of the livestock sector) are estimated based on past trends calculated by (Soussana et al., 2012) and extrapolated forward based on per capita GDP growth. The detailed livestock sector representation allows for endogenous intensification through production systems transitions (Havlík et al., 2014). SSP2 assumes moderate flexibility of these systems. Important barriers frustrate system changes in SSP3, and education and other infrastructure facilitate the transition in SSP1. Finally, in terms of food consumption, SSP2 occupies a central spot between SSP1 and SSP3 (see Table 1 and Supplementary Text 6). Trade assumptions of agricultural commodities (Supplementary Text 5) are not varied across the SSPs.

3. Implementation framework: SSP scenario development cycle

The large set of assumptions that have been introduced in the previous section and Table 1 have to be assessed in an integrated way in order to produce scenarios that consistently represent all dimensions of the SSPs' broader narratives. To this end, the *IIASA IAM* framework is used. The *IIASA IAM* framework consists of a combination of five different models or modules which complement each other and are specialized in different areas. Here we provide a succinct overview of the components of the framework (see Box 2), and illustrate the interaction between the different models or modules in a typical scenario development cycle.

3.1. Development of baseline scenarios

All models and modules introduced in Box 2, together build the *IIASA IAM* framework. They provide input to and iterate between each other during a typical SSP scenario development cycle. In the previous section, we documented the very first step in such an SSP scenario development cycle: the selection of quantitative assumptions for all important model parameters. Together with inputs on GDP and population, they provide the exogenous SSP inputs that are needed at the start. In the remainder of this section, we describe which further steps are taken within the *IIASA IAM* framework to develop an SSP scenario.

MESSAGE represents the core of the *IIASA IAM* framework (Fig. 4) and its main task is to optimize the energy system so that it can satisfy specified energy demands at the lowest costs. *MESSAGE* carries out this optimization in an iterative setup with *MACRO*, which provides estimates of the macro-economic demand response that results of energy system and services costs computed by *MESSAGE.* For the six commercial end-use demand categories depicted in *MESSAGE* (Table S3), *MACRO* will adjust

Box 2. Description of IIASA Integrated Assessment Modelling framework components.

Energy system

Energy system dynamics are modelled with the ***MESSAGE*** model (**M**odel for **E**nergy **S**upply **S**trategy **A**lternatives and their **G**eneral **E**nvironmental impacts). *MESSAGE* is a global systems engineering optimization model used for long and medium term energy system planning (Messner and Strubegger, 1995; Riahi et al., 2012). *MESSAGE* divides the world into 11 regions, each of which is characterized by a detailed energy system representation. The model's main objective is to optimize the contributions of various energy supply options over time in order to meet specified regional energy demands at the lowest overall discounted cost. *MESSAGE* features a very broad portfolio of energy technologies, covering technologies for resource extraction, fuel conversion, electricity and heat generation as well as end use technologies. These various technologies supply seven different demands (see Supplementary Table S3). Finally, *MESSAGE* also tracks the sources and sinks of greenhouse gases (GHG) and estimates anthropogenic GHG emissions as part of its optimization procedure.

Land-use system

Land-use dynamics are modelled with the ***GLOBIOM*** (**GL**obal **BIO**sphere **M**anagement) model, which is a recursive-dynamic partial-equilibrium model (Havlík et al., 2011). *GLOBIOM* represents the competition between different land-use based activities. It includes a bottom-up representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, incl. comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use. Its spatial equilibrium modelling approach represents bilateral trade based on cost competitiveness. For spatially explicit projections of the change in afforestation, deforestation, forest management, and their related CO_2 emissions, *GLOBIOM* is coupled with the ***G4M*** (**G**lobal **FOR**est **M**odel) model (Kindermann et al., 2006; Kindermann et al., 2008; Gusti, 2010). The spatially explicit *G4M* model compares the income of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, and decides on afforestation, deforestation or alternative management options. As outputs, *G4M* provides estimates of forest area change, carbon uptake and release by forests, and supply of biomass for bioenergy and timber.

Air pollution

Air pollution implications are derived with the help of the ***GAINS*** (**G**reenhouse gas–**A**ir pollution **IN**teractions and **S**ynergies) model. *GAINS* allows for the development of cost-effective emission control strategies to meet environmental objectives on climate, human health and ecosystem impacts until 2030 (Amann et al., 2011). These impacts are considered in a multi-pollutant context, quantifying the contributions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of particulate matter (PM), including fine and coarse PM as well as carbonaceous particles (BC, OC). As a stand-alone model, it also tracks emissions of six greenhouse gases of the Kyoto basket. The *GAINS* model has global coverage and holds essential information about key sources of emissions, environmental policies, and further mitigation opportunities for about 170 country-regions. The model relies on exogenous projections of energy use, industrial production, and agricultural activity for which it distinguishes all key emission sources and several hundred control measures. *GAINS* can develop finely resolved mid-term air pollutant emission trajectories with different levels of mitigation ambition (Cofala et al., 2007; Amann et al., 2013). The results of such scenarios are used as input to global IAM frameworks to characterize air pollution trajectories associated with various long-term energy developments (see further below and, for example, Riahi et al., 2012; Rao et al., 2013).

Macro-economic system

The macro-economic response of the global economy in the *IIASA IAM* framework is captured by the ***MACRO*** model. The form of *MACRO* used in the *IIASA IAM* framework is derived from a long series of models by Manne and Richels (1992). As further described by Messner and Schrattenholzer (2000), MACRO maximizes the intertemporal utility function of a single representative producer-consumer in each world region through optimization. The result is a sequence of optimal savings, investment, and consumption decisions. The main variables of the model are the capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a nested production function with constant elasticity of substitution. It considers the six commercial energy demand categories in *MESSAGE* (see Table S3).

Climate system

The response of the carbon-cycle and climate to anthropogenic climate drivers is modelled with the ***MAGICC*** model (**M**odel for the **A**ssessment of **G**reenhouse-gas **I**nduced **C**limate **C**hange). *MAGICC* is a reduced-complexity coupled global climate and carbon cycle model which calculates projections for atmospheric concentrations of GHGs and other atmospheric climate drivers like air pollutants, together with consistent projections of radiative forcing, global annual-mean surface air temperature, and ocean-heat uptake (Meinshausen et al., 2011a). *MAGICC* is an upwelling-diffusion, energy-balance model, which produces outputs for global- and hemispheric-mean temperature. Here, MAGICC is used in a deterministic setup (Meinshausen et al., 2011b), but also a probabilistic setup (Meinshausen et al., 2009) has been used earlier with the *IIASA IAM* framework (Rogelj et al., 2013a; Rogelj et al., 2013b; Rogelj et al., 2015). Climate feedbacks on the global carbon cycle are accounted for through the interactive coupling of the climate model and a range of gas-cycle models.

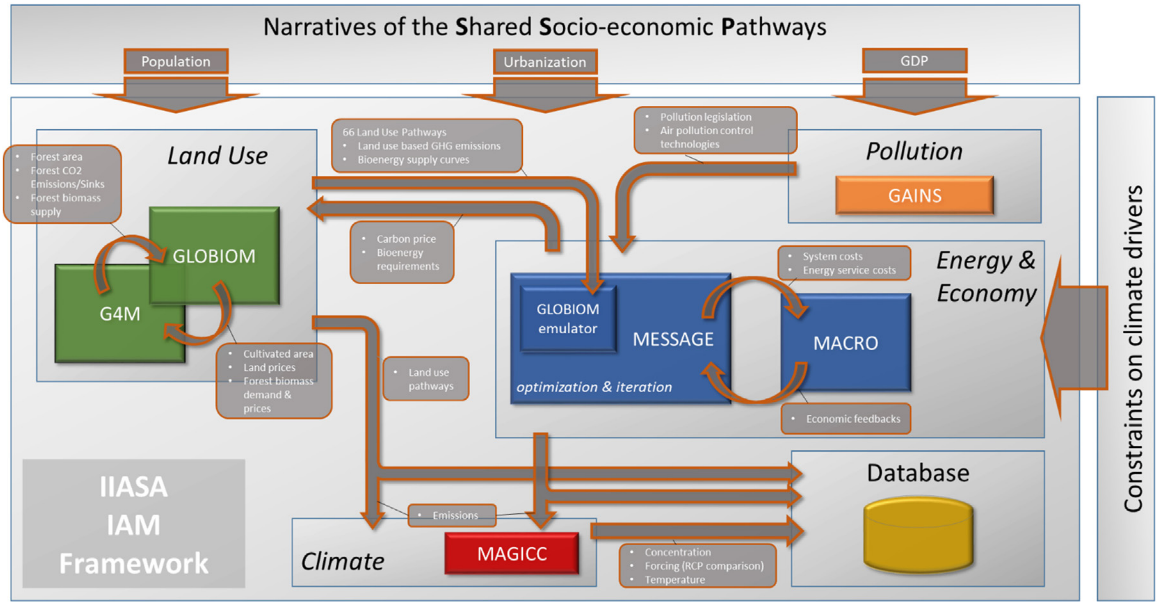


Fig. 4. Overview of the IIASA IAM framework. Coloured boxes represent respective specialized disciplinary models which are integrated for generating internally consistent scenarios.

useful energy demands, until the two models have reached equilibrium. This iteration reflects price-induced energy efficiency improvements that can occur when energy prices increase. *GLOBIOM* provides *MESSAGE* with information on land use and its implications, like the availability and cost of bio-energy, and availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Land Use) sector. To reduce computational costs, *MESSAGE* iteratively queries a *GLOBIOM* emulator which can provide possible land-use outcomes during the optimization process instead of requiring the *GLOBIOM* model to be rerun continuously (see Supplementary Text 7, and Supplementary Figs. S6 and S7). Only once the iteration between *MESSAGE* and *MACRO* has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding online analysis with the full-fledged *GLOBIOM* model. This ensures full consistency in the modelled results from *MESSAGE* and *GLOBIOM*, and also allows the production of a more extensive set of reporting variables. Air pollution implications of the energy system are computed in *MESSAGE* by applying technology-specific pollution coefficients from *GAINS*. In general, cumulative global GHG emissions from all sectors are constrained at different levels to reach desired forcing levels (cf. right-hand side Fig. 4). The climate constraints are thus taken up in the coupled *MESSAGE-GLOBIOM* optimization, and the resulting carbon price is fed back to the full-fledged *GLOBIOM* model for full consistency. Finally, the combined results for land use, energy, and industrial emissions from *MESSAGE* and *GLOBIOM* are merged and fed into *MAGICC*, a global carbon-cycle and climate model, which then provides estimates of the climate implications in terms of atmospheric concentrations, radiative forcing, and global-mean temperature increase. Importantly, climate impacts and impacts of the carbon cycle are currently not accounted for in the *IIASA IAM* framework. The entire framework is linked to an online database infrastructure which allows straightforward visualisation, analysis, comparison and dissemination of results.

3.2. Introduction of climate policy

Climate action within the *IIASA IAM* framework is typically modelled by capping the cumulative amount of CO_2 or other greenhouse gases over the 21st century. Alternative ways to model climate policy are also possible, for example by prescribing carbon prices or renewable energy targets. When applying a climate policy to an SSP narrative, assumptions have to be made about the extent and timing of that policy. To ensure consistency between these policy assumptions and the SSP narratives, shared climate policy storylines (called 'shared climate policy assumptions' – SPA) have been developed (Kriegler et al., 2014), which are complementary to the SSP narratives (Table S5). For each SSP, a particular SPA is recommended. For SSP2, we use SPA2. SPA2 assumes that climate policies targeting emissions from fossil-fuel use and industry are geographically fragmented until 2020 and then converge to a globally uniform carbon price by 2040. For more details see Kriegler et al. (2014) and Riahi et al. (2016, in press). Land-use emissions are controlled by the same regional carbon prices. However, in order to comply with the specification that SSP2 has to be a dynamics-as-usual world, global afforestation or elimination of deforestation before 2030 is not allowed to occur. In our implementation, we adjust the near-term carbon price for land-use emissions in order to avoid this. Also the SPAs reflect the gradation in mitigation challenges between the various SSPs. SPA1, which is applied to SSP1, assumes that fast global action is possible, while SSP3 assumes that a period of fragmented regional action will precede global action (see also, Kriegler et al., 2014).

4. Results summary for the SSP2 marker scenario

This section illustrates some of the salient characteristics of the marker SSP2 implementation in the *IIASA IAM* framework. Results for the SSP2 baseline are the initial focus; this scenario does not include any climate policies beyond those in place today. Such a baseline then provides a reference point against which the effectiveness of climate policies (of varying stringency) can be measured. We first present how the SSP2 energy intensity improvements compare to the bracketing SSP1 and SSP3 scenarios, and then have a closer look at how global energy demand and supply, as well as land use develop over time. The subsequent section analyses the evolution of atmospheric climate-modifying emissions, including GHGs and air pollutants. Finally, we explore transformations in the energy and land-use systems required to limit climate change to targeted levels of anthropogenic radiative forcing over the 21st century. Due to space constraints, this discussion focusses mainly on global developments, but also some information at the level of the global North and South is provided. A full set of scenario results can be found in the publicly available, online database (https://secure.iiasa.ac.at/web-apps/ene/SspDb).

4.1. Baseline energy-system characteristics

4.1.1. Energy demand and supply

The varying energy intensity improvement rates of the SSPs translate into widely diverging levels of baseline energy demand in absence of climate action. Combined with alternative assumptions for fossil resources and energy technologies (see earlier), this leads to markedly different energy system structures, both on the supply and demand sides. On the demand side in particular, all SSPs exhibit a continuous transformation away from inconvenient and low quality fuels (mainly solid fuels) toward more flexible, convenient and higher quality carriers, such as electricity. Yet, while the nature of the demand-side transition may be similar across the SSPs, the pace at which these changes (or this 'modernization') occurs is much faster in SSP1 compared to SSP3; SSP2 lies in the middle (Fig. 5, lower panels).

Final energy demand in SSP2 increases steadily over the 21st century reaching approximately 640 and 970 EJ/yr by 2050 and 2100, respectively (Fig. 5, top left panel). The latter is a 2.7-fold increase from 2010. These 2100 levels are about 300 EJ/yr higher than in SSP1, and about 200 EJ/yr lower than in SSP3. Our SSP1 implementation thus roughly manages to stabilize energy demand growth in the second half of the century. Fig. 5 further illustrates that the SSP2 marker implementation with the *IIASA IAM* framework is situated roughly in the middle between the SSP1 and SSP3 implementations. The differences in baseline energy demand between the SSPs are dominated by the surge in the global South (Supplementary Figs. S10-S12). In SSP2, final energy demand for the industry, residential-and-commercial, and transport sectors increases by approximately 42% by 2100 over 2010 levels in developed countries. The increase is even greater in the South, due to the drastic increase in income levels: final energy demand quadruples over the same period of time, accounting for a global share of 74% by 2100 compared to about 51% in 2010. SSP3 projects a similar final energy demand in 2100 for the global North as today, while SSP1 sees energy demand contract slightly. The bulk of energy demand increase in any SSP is thus projected to come from developing countries.

The results for the primary energy mix of SSP2 (Fig. 5, top-right panel) show that, much like today, fossil energy carriers remain the fuels of choice until the end of the century in an SSP2 world. The assumed moderate investments in renewables limit their role in the future, despite their continued growth. SSP2 sees its share of non-fossil energy in the primary energy mix increase from 17% today (2010) to 23% in 2100. In SSP1 this is higher and in SSP3 lower (Supplementary Figs. S13 and S14). The non-fossil share in SSP1 increases to 31% in 2100 because of an increase in renewables other

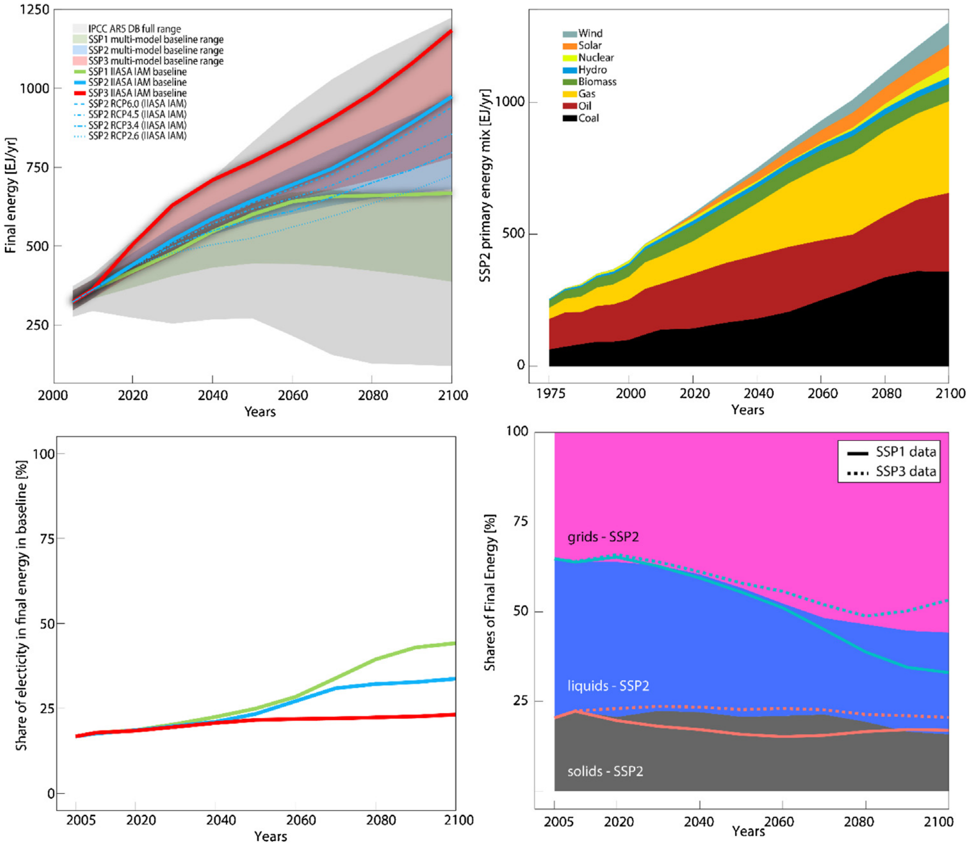


Fig. 5. Energy characteristics and context of the SSP2 marker scenario. Top left: Evolution of final energy demand over the 21st century for baseline SSP1, SSP2, and SSP3 scenarios modelled by the *IIASA IAM* framework (bold green, blue, and red lines), compared to the multi-model range across all respective SSPs submitted by other modelling teams (green, blue, and red shaded areas), as well as the range found in the IPCC AR5 Scenario Database (grey range). Thin lines in different line types represent SSP2 final energy demand for four mitigation pathways modelled with the *IIASA IAM* framework in line with an end-of-century radiative forcing target of 6.0, 4.5, 3.4, and 2.6 W/m2, respectively. Top right: Primary energy mix evolution for the SSP2 marker, modelled by the *IIASA IAM* framework. Bottom left: Share of electricity in final energy in the 3 SSP baselines. Colours as in left-hand panel. Bottom right: Contributions of solids (grey), liquids (blue), and grids (pink) to total final energy in SSP2. Variations for SSP1 and SSP3 are shown by solid and dashed lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than biomass. Finally, on the demand side, the three SSPs differ markedly in terms of their shares of electricity in final energy and the relative shares of final energy that are covered by solids, liquids, or grids (see Fig. 5, bottom panels, and Supplementary Figs. S8–S9).

4.2. Baseline land-use characteristics

4.2.1. Demand and supply of agricultural commodities

Population and economic growth, as well as evolving social preferences (as discussed in Section 2), drive overall demand for agricultural products, and these demands vary across the SSPs (Popp et al., in review). Agricultural commodities like food crops and livestock are traded globally. This continues in SSP2, and in addition agricultural markets continue their long-term trend of slightly decreasing agricultural prices. More rapid technological progress and only moderately increasing demand lead to even more substantial price decreases in SSP1, while slower technological progress and stronger demand lead to increasing commodity prices in SSP3. All these estimates exclude any influence of climate change.

As food crop demand relates to challenges for adaptation, SSP2 also here provides a middle-of-the-road perspective. In this scenario, human consumption of crops (globally) is projected to increase by 41% until 2050 and return to this level by 2100, after peaking around 2070. The year-2100 demand for food crops is projected to be 22% lower in SSP1 and 33% higher in SSP3, relative to SSP2. A further characteristic of the SSP2 baseline is the growing level of livestock consumption, which is considered a luxury good and is therefore associated with higher incomes (Supplementary Text 8). The moderate increase in population together with sustained income growth makes the SSP2 scenario the largest livestock product consumer. In SSP1, the partial shift to less meat-intensive diets in the North and the slowly growing population in the South lead to livestock product consumption that is about a third lower. In SSP3, the decreasing population in the North and slowly growing incomes in the South lead also to livestock product demand which is 7% lower than in SSP2. Overall, increasing food consumption combined with crop demands for animal feed and for other uses leads to a global increase of crop production of 84% in 2100 in SSP2, relative to 2010. This compares to a global increase of 21% and 97% in SSP1 and SSP3, respectively.

4.2.2. Demand and supply of woody biomass

A second main task of the land-use sector is the provision of woody biomass. Two major biomass uses are considered, industrial round wood and biomass for energy production, and these can be sourced from round wood from traditional forests or from biomass from short rotation tree plantations (Supplementary Text 9). Unlike for food, 74% of the demand for industrial round wood was located in the North in 2010. In SSP2, the global demand for industrial round wood is projected to double by 2100, but only half of it would come from the North. This demand is similar in SSP1 (5% lower), and about 20% lower in SSP3. Similar to livestock products, opposite trends in population and economic growth in SSP1 and SSP3 cancel each other out, making the demand highest in SSP2.

Biomass demand for energy amounts to some 55 EJ of primary energy in 2010 and 80% of this demand comes from the South. This is mainly traditional biomass used for cooking and heating. In SSP2, this demand progressively decreases (see earlier). The total energy biomass demand in SSP2 is 8% higher in 2050 compared to 2010. In the second half of the century, the increasing demand for modern bioenergy production results in a net increase of 19% compared to 2010 by the end of the century, reaching 66 EJ. Overall, the commercial biomass deployment by 2100 in the SSP1 baseline is of the same magnitude as in SSP3 (around 74 EJ). The major difference between these two scenarios consists in the deployment of traditional biomass, which is phased out before 2100 in SSP1, while still representing 50 EJ in SSP3. This makes the overall baseline energy biomass demand in SSP3 74% larger compared to SSP1.

4.2.3. Land use evolution

Land use is closely linked to agricultural and forest production (see Supplementary Text 10 and 11), and these influence the natural environment and ecosystem services, such as biodiversity or carbon sequestration. Land use is therefore simultaneously connected to both adaptation and mitigation challenges. Yet, despite the major crop production increases foreseen in SSP2, global cropland only expands by 25% relative to 2010 (Fig. 6). The remainder of the production increase comes from intensification of land use supported by technological change. This requires a doubling of fertilizer use and a 10% increase in irrigation water withdrawals. In SSP1, moderate demand increase and fast

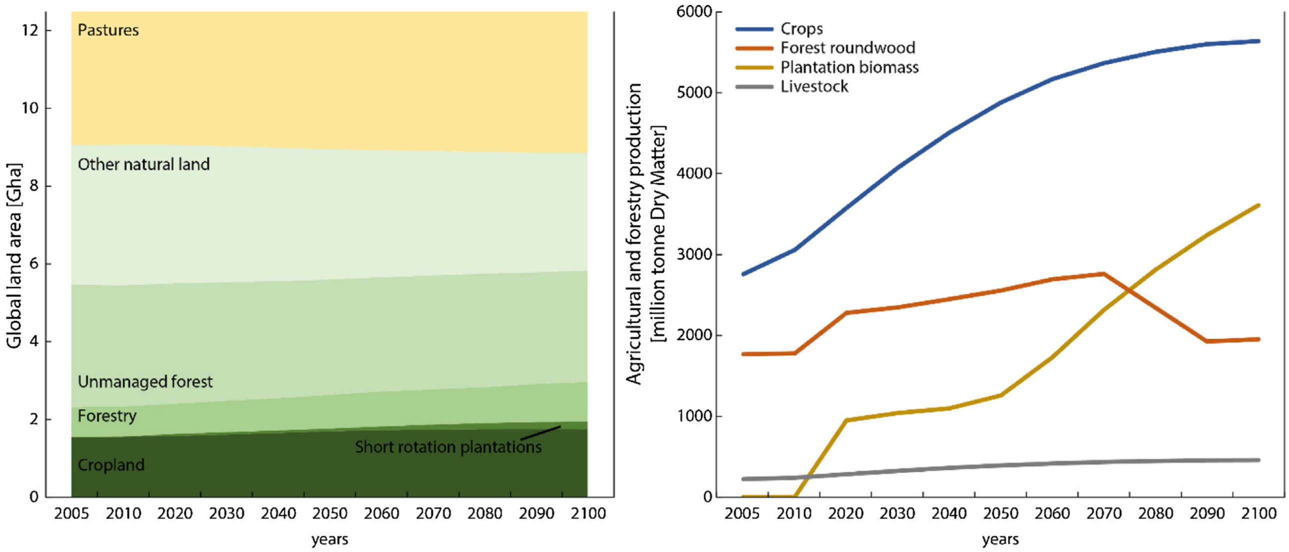


Fig. 6. Land use development in the marker SSP2 baseline scenario. Left panel: evolution of global land area over time. Right panel: agricultural and forestry production over time in units of million tonnes of dry matter. Similar figures of a 2.6 W/m2 mitigation case is provided in Supplementary Figs. S18.

technological progress lead to an increase in cropland area (10% by 2100 from 2010 levels). On the other hand, the slightly higher demand and slower technological progress of SSP3 mean that almost twice as much additional land and irrigation water is required, compared to SSP2. Moreover, although livestock production almost doubles in SSP2, utilized grassland area is projected to expand by only 6% in 2100 compared to 2010 (see Supplementary Text 11). Over the same time period, grassland area in SSP3 increases by more than 3%, despite the lower livestock product demand, whereas in SSP1 substantially lower demand and faster technological change lead to utilized grassland area being 6% lower. In terms of pressure on forests and other natural land, SSP2 represents a middle-of-the-road scenario with a net loss of 607 million hectares by 2100 (compared to 2010), while SSP3 and SSP1 see a loss of 719 million and a gain of 63 million hectares, respectively. These developments are critical for both adaptation and mitigation challenges, because when more land is required for baseline agricultural and forest production, less land remains available to address potential climate impacts on agriculture or implement climate change mitigation activities.

4.3. Climate drivers and climate policy

Up to this point, we presented results for the SSP2 baseline in absence of climate policy. Each SSP baseline, however, can be combined with various levels of climate policy. This leads to a matrix of potential outcomes with various SSP narratives on the horizontal and various climate mitigation levels on the vertical axis. The level of climate mitigation in this matrix is defined as a limit on the total anthropogenic radiative forcing in 2100. Studies in this issue look at limiting radiative forcing to 8.5, 6.0, 4.5, 3.4, and 2.6 W/m^2, and further studies are under way to develop pathways that limit radiative forcing to 2.0 W/m^2 in 2100 or that significantly exceed the targeted end-of-century radiative forcing during earlier decades.

4.3.1. Baseline emission trajectories

Emission trajectories of the SSP2 baseline are the starting point for our climate policy analysis. Fig. 7 illustrates that also in terms of baseline trajectories of GHG and air pollutant emissions, SSP2 is fully consistent with its assigned role of a middle-of-the-road scenario (bold lines in Fig. 7). The marker SSP2 trajectories are

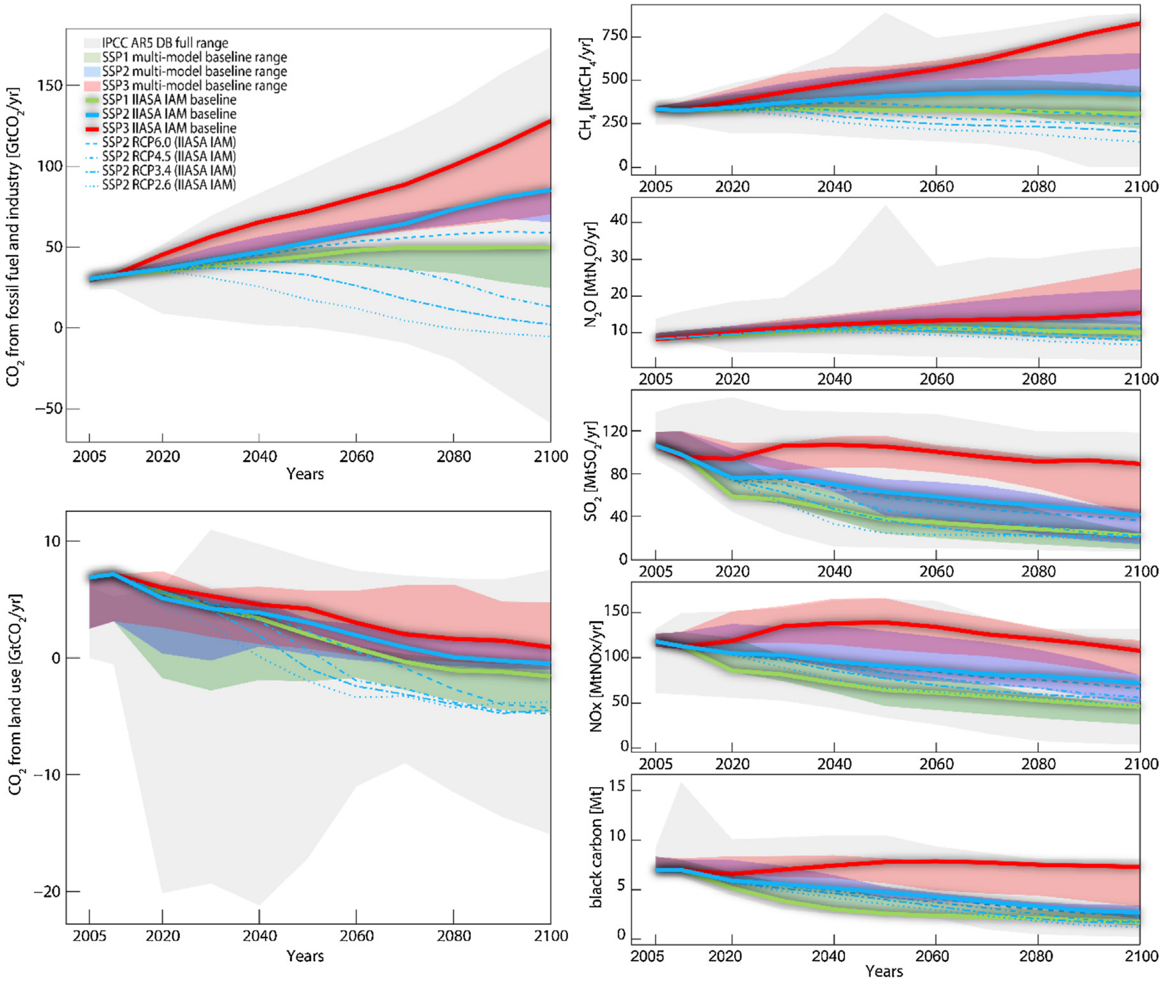


Fig. 7. Global developments for various greenhouse gases and air pollutants. The evolution over the 21st century for baseline SSP1, SSP2, and SSP3 scenarios modelled by the *IIASA IAM* framework is provided in bold green, blue, and red lines. These are compared to the multi-model range across all respective SSPs submitted by other modelling teams (green, blue, and red shaded areas, discussed in the overview paper by Riahi et al., 2016, in press), as well as the range found in the IPCC AR5 Scenario Database (grey range). Thin lines in different line types represent SSP2 emissions for four mitigation pathways modelled with the *IIASA IAM* framework in line with an end-of-century radiative forcing target of 6.0, 4.5, 3.4, and 2.6 W/m^2, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

situated roughly in the middle between SSP1 and SSP3 for all emissions. In terms of total CO_2 emissions, the SSP2 baseline roughly doubles its emissions over the course of the century (from 40 $GtCO_2$ in 2010 to 85 $GtCO_2$ in 2100), landing 44 $GtCO_2$ below the level of SSP3, and 37 $GtCO_2$ above the level of SSP1.

Some air pollutants have also climate impacts, especially sulphur dioxide (SO_2) and black carbon, and their evolutions are partially coupled with CO_2 because they can be emitted from the same sources (Bond et al., 2013; Rogelj et al., 2014b). Baseline evolutions of SSP1, SSP2, and SSP3 show important differences in the projected emissions for SO_2, NO_x, and black carbon over the entire 21st century (Rao et al., 2017). These differences are driven by varying stringency of air pollution legislation and access to clean fuels for cooking, but also because the three SSPs differ strongly in their use of coal as a primary energy source over the 21st century (see earlier and Supplementary Figs. S13 and S14) and in the amount of traditional biomass burnt. Altogether these factors can determine the level of air pollutant emissions over time to a high degree (Rogelj et al., 2014a).

When assessed with the RCP tuning of *MAGICC* (Meinshausen et al., 2011b), the total anthropogenic radiative forcing for the baseline developments of SSP1, SSP2, and SSP3 is estimated to amount to 5.5, 6.5, and 8.1 W/m^2 in 2100 (Table 2). Also here SSP2 thus occupies a central spot. Global-mean temperatures are estimated to rise to about 3.2, 3.8, and 4.5 °C, respectively, by 2100 and relative to pre-industrial levels.

4.3.2. Emission mitigation pathways

The estimated global-mean temperature rise of the baseline scenarios highlights the need for climate change mitigation. Even in a world reigned by a green-growth paradigm (SSP1), median global-mean temperature increases to about 3.2 °C above pre-industrial levels by 2100. Within the SSP framework, no explicit temperature stabilisation targets are defined. Instead, the consequences of limiting total anthropogenic radiative forcing in 2100 to various levels are explored. Here we look at the emissions underlying this radiative forcing.

To limit global-mean temperature at any level, global CO_2 emissions eventually have to become zero at a global scale (Knutti and Rogelj, 2015). Similarly, to limit radiative forcing to increasingly lower levels, emissions have to be steadily reduced. For example, the SSP2 marker baseline has strongly increasing global total GHG emissions (to about 43% and 107% above 2010 levels in 2050 and 2100, respectively). However, achieving a radiative forcing of about 4.5 W/m^2 in 2100 already results in 2050 GHG emissions being about the same level as in 2010, and 61% lower in 2100. Further reducing end-of-century forcing to about 2.6 W/m^2 results in levels of −49% in 2050 and −105% in 2100, respectively, relative to 2010 levels. Also CO_2 emissions from fossil fuel and industry undergo a similar consistent reduction with increasing stringency of the forcing target (Fig. 7).

Land-use CO_2 developments portray a more particular story. For the same intermediate (4.5 W/m^2) and stringent (2.6 W/m^2) mitigation cases as discussed above, land-use CO_2 emissions decrease rapidly in the first half of the century. In the second half, however, the rate of decline slows down, and in our very stringent mitigation case, land-use CO_2 emissions even increase again slightly until 2100 (Supplementary Fig. S16). This reflects the fact that considerable mitigation and productivity improvement options in the land-use sector can be achieved at relatively moderate prices. When taking a sector-wide approach towards climate mitigation, land-use emissions are thus reduced early on, enabling the comparatively later deployment of more costly mitigation technologies in the energy sector, which become cheaper later due to technological learning, discounting and power plant vintaging. The increase in land-use emissions at the end of the century in the most stringent mitigation scenario, is due to the fact that land-use-based mitigation is abandoned in favour of producing and extracting more biomass for use in combination with carbon capture and storage (CCS) in the energy system.

Overall, limiting anthropogenic radiative forcing in 2100 to about 6.0, 4.5, 3.4, and 2.6 W/m^2 leads to a global-mean temperature increase in 2100 relative to pre-industrial levels of about 3.2, 2.6, 2.2, and 1.8 °C, respectively (Table 2).

4.3.3. Mitigation drivers

Emission reductions can be achieved by several means, and carbon and energy intensity improvements are key enabling drivers (Fig. 8). Baseline carbon intensity improvements in SSP2 and SSP3 are very similar, while in SSP1 they are slightly higher due to a more pronounced shift to renewables under a baseline green-growth paradigm. When moving towards increasingly more stringent mitigation scenarios, carbon instensity improvements increase to basically the same level in all three SSPs (about 1.2-1.4%/year for a 2.6 W/m^2 target). However, energy intensity improvements remain vastly different, even under stringent climate target. SSP1 already includes ambitious energy intensity improvements in its baseline, which do not increase much further. Also SSP3 achieves energy intensity improvements, but even in the most stringent mitigation scenario do energy intensity improvements not catch up with any of the other SSP baseline improvements. This contributes to the failure to achieve a 2.6 W/m^2 forcing target under the assumptions of our SSP3 implementation. Also here the middle-of-the-road characteristics of SSP2 are illustrated. Energy intensity improvements in SSP2 increase with increasing stringency of climate mitigation. However, they remain distinctly below the levels achievable under a green-growth paradigm of SSP1. This highlights the issue of path dependency in a broader sense: the path followed in terms of technological and societal development critically influences the chances of achieving certain outcomes.

Carbon intensity improvements are mainly achieved by changes at the supply side of the energy system (although strictly speaking they are also influenced by demand reductions). The contributions of various technologies vary depending on the SSP storyline. On the one hand, primary energy sources shift away from

Table 2

Global climate outcomes of the SSP quantifications by the IIASA IAM framework, assessed with the RCP tuning of the MAGICC climate model (Meinshausen et al., 2011a,b).

	Atmospheric CO_2 concentrations in 2100 [ppm CO_2]	Total anthropogenic forcing in 2100 [W/m^2]	Global-mean temperature increase in 2100 relative to pre-industrial levels [°C]
SSP1 baseline	669	5.5	3.2
SSP2 marker baseline	785	6.5	3.8
SSP2 6.0 W/m^2	700	5.5	3.2
SSP2 4.5 W/m^2	563	4.3	2.6
SSP2 3.4 W/m^2	491	3.5	2.2
SSP2 2.6 W/m^2	426	2.6	1.8
SSP3 baseline	980	8.1	4.5

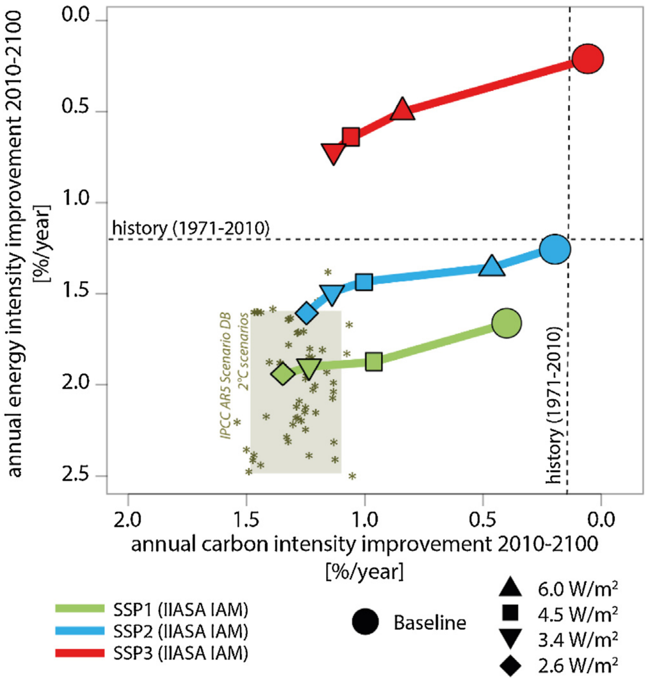


Fig. 8. Annual improvements from 2010 to 2100 of carbon and primary energy intensity for SSP1, SSP2, and SSP3 baselines, as well as four mitigation cases. Improvement rates are calculated as average annual reductions relative to 2010. Figure adapted from Riahi et al. (2016, in press). All SSP results are computed with the *IIASA IAM* framework. 2 °C scenarios limit warming to below 2 °C with at least 66% probability.

fossil fuels in favour of renewables. This is also the case in SSP2 (Supplementary Fig. S15). A further contribution comes from the storage of carbon (CO_2).

In general, despite being a middle-of-the-road world, SSP2 relies to a greater extent on fossil-fuel based CCS as a bridging technology for its climate mitigation compared to SSP1 and SSP3 (Fig. 9, Supplementary Fig. S16 and S17). It is remarkable that even SSP3 relies to a much lesser extent on fossil based CCS than SSP2, despite being a "fossil intensive scenario". This is a consequence of the much higher challenges to mitigation that are specified in the SSP3 narrative. SSP3 is also linked to high inertia in climate policy development: it applies SPA3, which is defined by a long period of geographically fragmented policies (up to 2040) and a limited pricing of land-use emissions (Supplementary Table S5 and Riahi et al. 2016, in press). In such a world, a transition away from a coal-based energy system results in the first place in avoiding the build-up of carbon-intensive infrastructure, because the high inertia in the turnover of the energy system and the limited technological progress would make it otherwise impossible to reduce emissions later on. Moreover, non-biomass renewables are less attractive in SSP3, requiring regions to make use of local possibilities that extensively use bioenergy in combination with carbon capture and storage (BECCS). For intermediate climate targets BECCS deployment is always greater in SSP3 than in SSP1 or SSP2. SSP1 on the other hand faces the lowest challenge to mitigation due to widespread availability of non-biomass renewables and relatively low energy demand. Finally, the absolute CO_2 emissions reduction contribution of the AFOLU (Agriculture, Forestry and Other Land Use) sector is overall small in all three SSPs modelled here, with decreasing relative and absolute contributions going from SSP1 over SSP2 to SSP3 (see Fig. 9). However, its role generally increases when considering all greenhouse gases. In terms of overall climate mitigation challenges, SSP2 is situated between SSP1 and SSP3.

5. Overview and conclusions

As discussed throughout this paper, the marker implementation of SSP2 represents a middle-of-the-road scenario with respect to mitigation and adaptation challenges. These challenges are multi-dimensional and can therefore be described by a wide variety of metrics such as those summarized in Fig. 10, which plots salient characteristics drawn from the *IIASA IAM* interpretations of SSP1, SSP2, and SSP3. For instance, four illustrative metrics that capture adaptation challenges are used here: the gini coefficient, the number of people globally that have no access to clean forms of energy in 2050, the share of the global population that remains illiterate by 2100, and the share of the global population that has

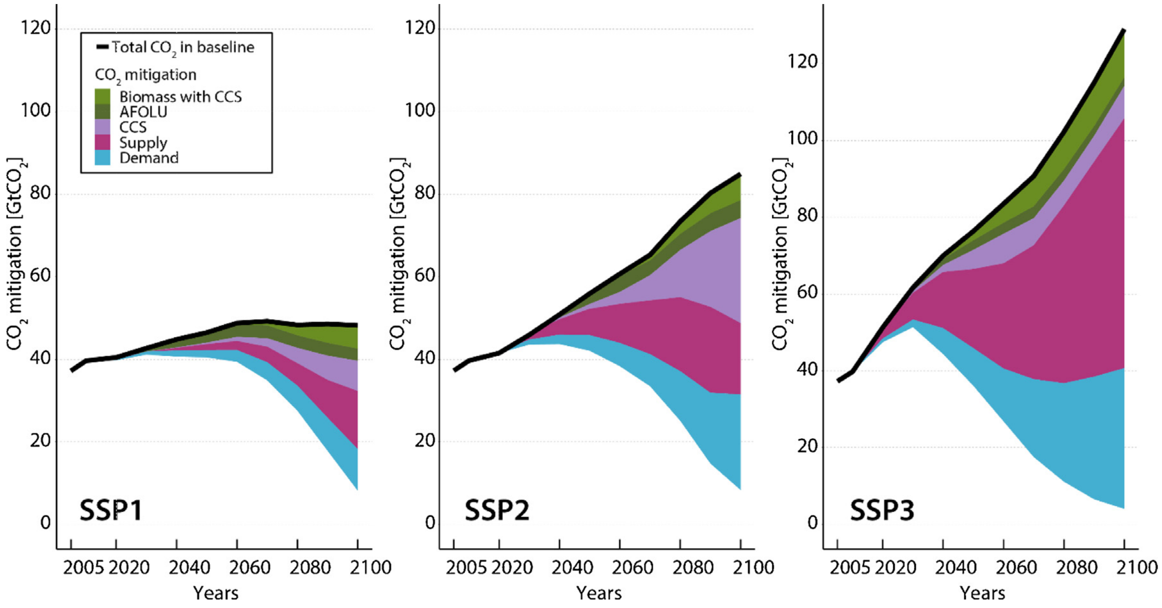


Fig. 9. Mitigation of CO_2 from baseline CO_2 emission levels in SSP1, SSP2, and SSP3 for achieving a global radiative forcing target in 2100 of 4.5 W/m^2, as modelled in the *IIASA IAM* framework. Mitigation contributions show the direct emission reduction contributions for each sector. Supplementary Fig. S19 shows the results for a 2.6 W/m^2 radiative forcing level.

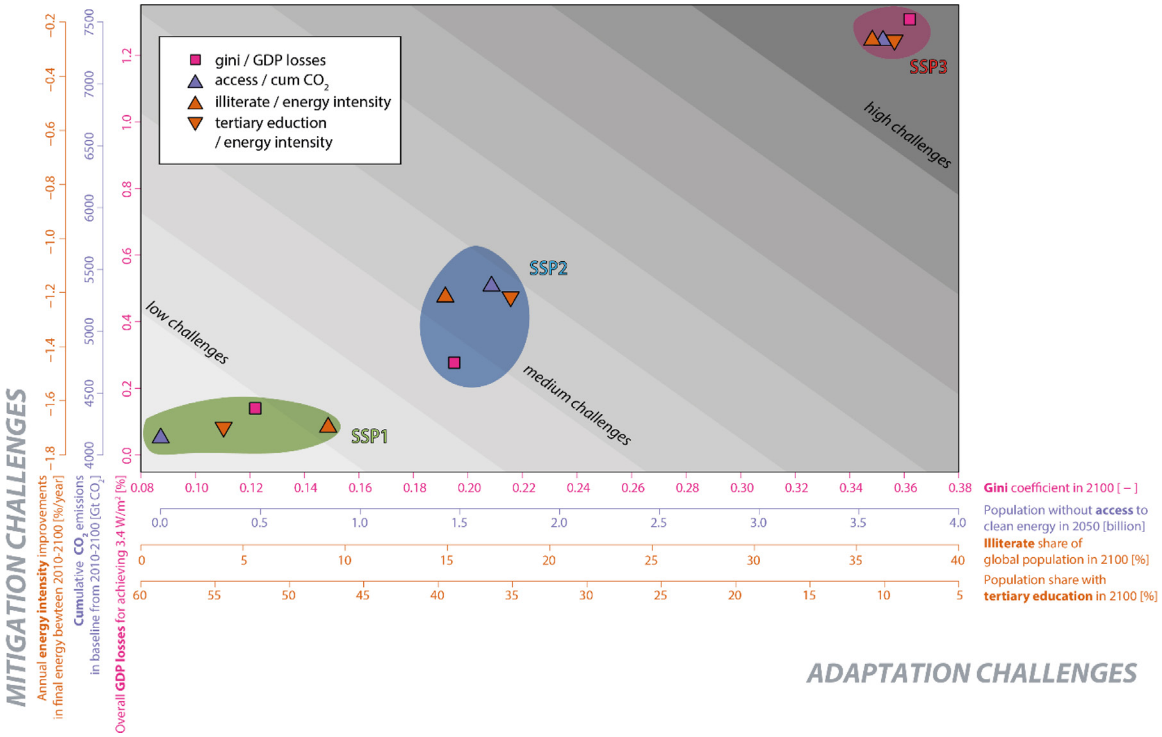
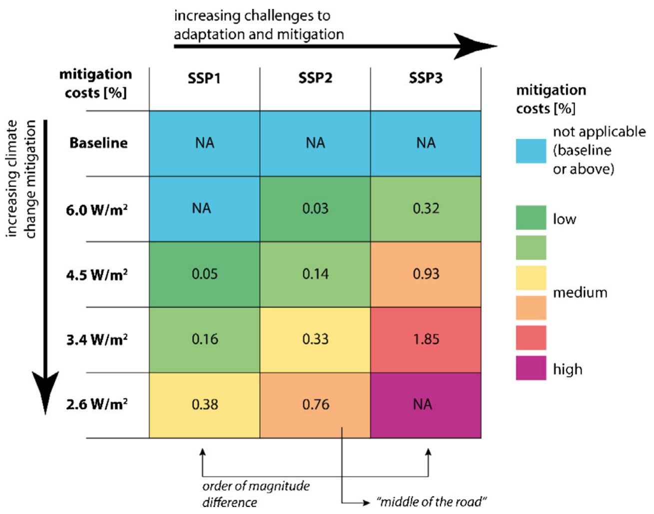


Fig. 10. Positioning of SSP1, SSP2, and SSP3 quantifications in a multi-dimensional mitigation & adaptation challenges space. SSP1 and SSP3 are characterised by low and high challenges, respectively, to mitigation and adaption. SSP2 provides a middle-of-the-road perspective, with medium challenges in both dimensions. Note that this represents a conceptual simplification of the issue, as some of the metrics have implications for both mitigation and adaptation. Nevertheless, they are only listed in one dimension. "Overall GDP losses" are referring to the net present value (5% discount rate) of the GDP loses over the 2010–2100 period.

received tertiary education by 2100. For mitigation challenges, three illustrative metrics are used: the average annual energy intensity improvement rate over the 21st century (2010 to 2100), the amount of cumulative CO_2 emissions in the baseline of each scenario from 2010 to 2100, and the estimated net present value of GDP losses to move from a baseline to a 3.4 W/m^2 world. This selection of metrics is meant to be illustrative and non-exhaustive. Many aspects, including vulnerability, health, exposure, etc., will have to be assessed in subsequent studies by multi-disciplinary research communities. In any event, Fig. 10 makes it quite apparent that SSP2 takes up a central position compared to SSP1 and SSP3 in this multi-dimensional mitigation and adaptation challenges space. SSP2 thus serves its purpose of a middle-of-the-road scenario for the 21st century.

Challenges related to climate mitigation are further illustrated in Fig. 11, where mitigation costs are plotted across a range of climate targets and the three SSPs. These costs are vastly different between the three SSPs. For instance, they are estimated to vary by roughly an order of magnitude between SSP1 and SSP3. This on the one hand illustrates the fundamental importance of the SSP framing narratives for the quantification of mitigation challenges, and on the other hand the fact that SSP1 and SSP3 take up the role of two rather extreme bracketing scenarios within the SSP framework. SSP2 is positioned in the middle-of-the-road between SSP1 and SSP3, with mitigation costs being about a factor six smaller and a factor of two higher compared to SSP3 and SSP1, respectively (Fig. 11). The variation in mitigation costs we find between the three SSPs modelled in the *IIASA IAM* framework roughly covers the 90th percentile range found in all scenarios available in the IPCC AR5 Scenario Database. The latter range represents the spread due to an arbitrary convolution of model and scenario uncertainty. However, this illustrates the importance of selecting baseline development paths when conducting climate change mitigation analyses.



mitigation costs [%]	SSP1	SSP2	SSP3
Baseline	NA	NA	NA
6.0 W/m²	NA	0.03	0.32
4.5 W/m²	0.05	0.14	0.93
3.4 W/m²	0.16	0.33	1.85
2.6 W/m²	0.38	0.76	NA

Fig. 11. Mitigation costs across SSPs and different levels of climate change mitigation. Mitigation costs represent the net present value (discounted at 5%) of the difference in GDP from 2010 to 2100 and are expressed in percent relative to the baseline. Cases marked with NA cannot be achieved in the *IIASA IAM* implementation of the SSPs. A corresponding figure but with carbon prices is provided in Supplementary Fig. S20.

In summary, this paper has shown that the *IIASA IAM* marker implementation of SSP2 provides an internally-consistent interpretation of the middle-of-the-road perspective within the SSP scenario framework. The SSP2 marker implementation occupies a central position along all major mitigation and adaptation challenge dimensions assessed here. For many dimensions the SSP2 marker implementation also reflects an extension of the historical experience, particularly in terms of carbon and energy intensity improvements in its baseline. This feature was not intended from the beginning of the exercise but rather an outcome from the effort to design a scenario with intermediate challenges compared to the other SSPs. These developments lead to a steady increase of carbon emissions over the 21st century, with projected end-of-century warming nearing 4 °C relative to preindustrial levels. With an eye toward global efforts to mitigation climate change, SSP2 also provides an optimistic note: it indicates that options exist for limiting global-mean temperature increase to below 2 °C, and at discounted mitigation costs of about 1%. The SSP framework focusses only on climate change mitigation and adaption; however, the international policy-making community has recently agreed 17 global, overarching Sustainable Development Goals (SDGs) for the coming decades. Owing to its middle-of-the-road perspective, SSP2 offers a useful starting point for further studies exploring solutions to these goals in conjunction with the climate adaptation and mitigation challenges society will face over the 21st century.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004.

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