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# Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century

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ABSTRACT

This paper presents a set of energy and resource intensive scenarios based on the concept of Shared Socio-Economic Pathways (SSPs). The scenario family is characterized by rapid and fossil-fueled development with high socio-economic challenges to mitigation and low socio-economic challenges to adaptation (SSP5). A special focus is placed on the SSP5 marker scenario developed by the REMIND-MAgPIE integrated assessment modeling framework. The SSP5 baseline scenarios exhibit very high levels of fossil fuel use, up to a doubling of global food demand, and up to a tripling of energy demand and greenhouse gas emissions over the course of the century, marking the upper end of the scenario literature in several dimensions. These scenarios are currently the only SSP scenarios that result in a radiative forcing pathway as high as the highest Representative Concentration Pathway (RCP8.5). This paper further investigates the direct impact of mitigation policies on the SSP5 energy, land and emissions dynamics confirming high socio-economic challenges to mitigation in SSP5. Nonetheless, mitigation policies reaching climate forcing levels as low as in the lowest Representative Concentration Pathway (RCP2.6) are accessible in SSP5. The SSP5 scenarios presented in this paper aim to provide useful reference points for future climate change, climate impact, adaption and mitigation analysis, and broader questions of sustainable development.

## 1. Introduction

Climate change and sustainable development are central global and long-term challenges facing humankind today. Scenarios of societal developments over the 21st century are a primary tool for investigating the scope and evolution of these challenges, and therefore have been used in climate change research for a long time (Leggett et al., 1992). In the past years, a new scenario framework for climate change research has been presented that further systematizes the exploration of relevant socio-economic futures for climate policy analysis (Ebi et al., 2014; van Vuuren et al., 2014; O'Neill et al., 2014; Kriegler et al., 2014a). To this end, a set of five

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Shared Socio-Economic Pathways (SSPs) has been developed with different levels of socio-economic challenges to the two generic policy responses to climate change, mitigation and adaption (SSP1 to SSP5; Kriegler et al., 2012; O'Neill et al., 2014; O'Neill et al., 2017). The associated scenarios aim to facilitate and integrate future research on mitigation, adaptation and residual climate impacts and are thus targeting climate change researchers and climate policy analysts. Even though the SSP scenarios were developed for climate change research as primary recipient, they are also highly relevant for investigating broader questions of sustainable development (O'Neill et al., 2017).

This paper describes the energy, land-use, and emissions outcomes in a future unfolding according to SSP5, called "Fossil-Fueled Development". SSP5 is characterized by high socio-economic challenges to mitigation and low socio-economic challenges to adaptation (O'Neill et al., 2017). It describes a world of resource intensive development, where high economic growth is combined with material intensive production and consumption patterns and a strong reliance on abundant fossil fuel resources. This leads to high levels of greenhouse gas emissions, and to large challenges to reduce them in response to climate change. At the same time, the SSP5 narrative foresees a peak and decline in global population, rapid human development, fast income convergence between regions and an increasingly inclusive and globalized economy, giving rise to high and growing adaptive capacity to climate change (see Section 5 of the supplementary online material (SOM) for a full description of the SSP5 narrative reproduced from O'Neill et al. (2017). There have been a number of narratives in the global scenarios literature (Raskin et al., 2005) with some resemblance to the SSP5 narrative including the Market Forces and Markets First Narratives of the Global Scenario Group (Raskin et al., 2010) and the Global Enviromental Outlook (UNEP, 2003), respectively, the global orchestration narrative of the Millennium Ecosystem Assessment (Carpenter et al., 2005), and the A1FI scenario family of the IPCC Special Report on emissions scenarios (Nakićenović and Swart, 2000).

The analysis is part of a multi-model exercise to generate a range of energy-land-economy-climate scenarios for the full set of SSPs with a collection of integrated assessment models (IAMs) (Riahi et al., 2017; Bauer et al., 2017; Popp et al., 2017). To streamline the use of the SSP5 scenario in future applications, a single IAM marker scenario was selected among the SSP5 scenarios—for recommended use in applications which cannot consider the full set of IAM scenarios. The SSP5 marker scenario was developed with the REMIND-MAgPIE integrated assessment modeling framework (Popp et al., 2011; Bauer et al., 2014). Four companion papers in this special issue describe the marker scenarios for the other SSPs (SSP1 IMAGE, van Vuuren et al., 2017; SSP2 MESSAGE-GLOBIOM, Fricko et al., 2017; SSP3 AIM/CGE, Fujimori et al., 2017; SSP4 GCAM, Calvin et al., 2017).

The SSP5 emissions outcomes can be compared with earlier "high emissions" scenarios following storylines with some resemblance to SSP5. This includes in particular the emissions scenario underlying the highest Representative Concentration Pathway (RCP) reaching a radiative forcing of 8.5 $W/m^2$ by the end of the century (RCP8.5; Riahi et al., 2011) and the A1FI scenario family in the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000). We will provide a quantitative comparison of the SSP5 scenarios with those scenarios as well as with the range of baseline and mitigation scenarios in the emissions scenario database of the Fifth Assessment Report (AR5) of Working Group III of the IPCC (IPCC, 2014).

The SSP5 scenario family presented in this study is built around a SSP5 baseline scenario without dedicated climate policy and without impacts of climate change and other dimensions of global environmental change on society. This scenario aims to provide a baseline case for future investigations of mitigation, adaptation and residual climate impacts. Of course, accounting for climate impacts and climate policies can significantly alter the energy, land-use, and emissions outcomes as well as other socio-economic outcomes. In line with the conceptual approach of the new scenario framework (van Vuuren et al., 2014), the impact of policy interventions and climate change can be analyzed with respect to this baseline to explore the contingency of future developments on present and future actions. While much of this analysis is subject to concurrent (e.g., Wiebe et al., 2015) or future research, this study already presents a set of SSP5-based climate change mitigation scenarios. The mitigation scenarios can be used to assess the challenges to mitigation in SSP5 by exploring the socio-economic consequences of reaching increasingly stringent forcing targets.

While the paper focuses on the SSP5 marker scenario developed by REMIND-MAgPIE, it will also explore the impact of model choice and inherently uncertain assumptions about future socio-economic and technological developments on the scenario outcomes. Concerning the uncertainty about socio-economic developments and future technologies, the SSP5 energy, land-use, emissions, and economic outcomes will be compared with SSP1, a sustainability oriented world with low challenges to mitigation and adaptation (O'Neill et al., 2017; van Vuuren et al., 2017) and a middle-of-the road development in SSP2, a world with intermediate challenges to mitigation and adaptation (Fricko et al., 2017). Concerning the impact of model choice and differences in the implementation of the SSP5 narrative, the paper will compare the SSP5 marker scenario with alternative interpretations of SSP5 by the GCAM (Calvin et al., 2017), WITCH-GLOBIOM (Emmerling et al., 2016), and AIM/CGE (Fujimori et al., 2017) integrated assessment models. Still, the deep uncertainty about long-term developments gives rise to a myriad of choices in projecting the energy, land use, and emissions outcomes even within the bounds of the SSP5 narrative. Therefore the range of SSP5 projections may still increase as more SSP5 interpretations from other models or SSP5 model sensitivity studies become available.

Further information about the SSP scenarios can be found at https://secure.iiasa.ac.at/web-apps/ene/SspDb.

## 2. Methods

### 2.1. The REMIND-MAgPIE integrated assessment modeling framework

The REMIND-MAgPIE integrated assessment modeling framework consists of an energy-economy-climate model (REMIND) (Bauer et al., 2008, 2012; Leimbach et al., 2010a,b; Luderer et al., 2013, 2015) coupled to a land-use model (MAgPIE) (Lotze-Campen et al., 2008; Popp et al., 2010, 2014b). REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering based energy system model. It covers eleven world regions, differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach et al., 2010a,b; Mouratiadou et al., 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer et al., 2012, 2016a,b; Klein et al., 2014a; Pietzcker et al., 2014a,b). The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as adjustment costs for rapidly expanding technologies. The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler et al., 2014a,b). Several energy sector policies are represented explicitly (Bertram et al., 2015), including energy-sector fuel taxes and consumer subsidies (Schwanitz et al., 2014). The model also represents trade in energy resources (Bauer et al., 2015).

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014). Agricultural demand includes demand for food (Bodirsky et al., 2015), feed (Weindl et al., 2015), bioenergy (Popp et al., 2011), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production (TC), cropland expansion and production relocation (intra-regionally and inter-regionally through international trade) (Dietrich et al., 2014; Lotze-Campen et al., 2010; Schmitz et al., 2012). MAgPIE derives cell specific land-use patterns, rates of future agricultural yield increases (Dietrich et al., 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (Bodirsky et al., 2012; Popp et al., 2010) and land-use change (Humpenöder et al., 2014; Popp et al., 2014b).

Emissions in the land-use and energy sectors are interlinked by overarching climate policy objectives and the deployment of bioenergy (Klein et al., 2014b; Popp et al., 2014a; Rose et al., 2014). REMIND and MAgPIE models are coupled to establish an equilibrium of bioenergy and emissions markets in an iterative procedure (Bauer et al., 2014). The atmospheric chemistry-climate model MAGICC (Meinshausen et al., 2011) is used to evaluate the climate outcomes of the REMIND-MAgPIE emission pathways. More details about the REMIND-MAgPIE modeling framework and the coupling approach can be found in Section S2 of the SOM.

### 2.2. Implementation of SSPs

REMIND-MAgPIE so far developed integrated energy-land-economy-climate scenarios for SSP5 (Fossil Fueled Development; this article), SSP1 (Sustainability; van Vuuren et al., 2017) and SSP2 (Middle of the Road; Fricko et al., 2017). REMIND-MAgPIE scenarios for SSP3 (Regional Rivalry; Fujimori et al., 2017) and SSP4 (Inequality; Calvin et al., 2017) that are characterized by stronger inter- and intraregional disparities than SSP1, 2, and 5 are a subject of future work.

The interpretation of SSP1, 2 and 5 by REMIND-MAgPIE is based on the SSP narratives (O'Neill et al., 2017) and more detailed energy and land-use specifications developed for the SSP interpretations by IAMs (Riahi et al., 2017). Model assumptions and parameters directly relating to these features were identified, and varied across the three SSPs (Table 1). Further details on the parameter variations are provided in Section S3 of the SOM.

Population projections are an exogenous input to REMIND-MAgPIE and are directly taken from the country-level population projections for SSP1, 2, and 5 (KC and Lutz, 2017). Regional economic output is deduced from the SSP country-level projections of gross domestic product (GDP) by the OECD team (Dellink et al., 2017). GDP is an endogenous variable in REMIND, largely driven by exogenous assumptions about labor productivity increases. Those were adjusted to reproduce the GDP projections in the SSP baseline cases. The mitigation scenarios show an endogenous GDP response to mitigation policies which can serve as a measure for the challenges to mitigation in the individual SSPs (see Section 5).

SSP5 scenarios have also been produced by the AIM/CGE, GCAM, and WITCH-GLOBIOM integrated assessment models. Their implementation of SSP5 is briefly summarized in Section S3.3 of the SOM.

### 2.3. Implementation of mitigation scenarios

The SSP mitigation scenarios were derived by implementing mitigation policies in the SSP baselines aiming at a climate forcing target in 2100. The target levels of anthropogenic climate forcing were chosen to be consistent with the 2100 forcing levels obtained by the Representative Concentration Pathways (RCPs; van Vuuren et al., 2011), i.e., RCP6.0 (Scenario SSP5-6.0; reaching about 5.4 $W/m^2$ as estimated by the reduced-form atmospheric chemistry-climate model MAGICC; Riahi et al., 2017), RCP4.5 (SSP5-4.5; about 4.2 $W/m^2$) and RCP2.6 (SSP5-2.6; 2.6 $W/m^2$). In addition, an intermediate forcing level of 3.4 $W/m^2$ was investigated.

Since such policies are not only characterized by the long term forcing target, but also by other factors such as their regional, sectoral and temporal profile, their qualitative features were harmonized across IAMs by use of shared climate policy assumptions (SPAs, Kriegler et al., 2014a). A detailed discussion of the SPAs can be found in Riahi et al. (2017). In the energy sector, regionally fragmented carbon pricing as implied by existing climate policy pledges was assumed until 2020 (Kriegler et al., 2015), followed by a transition period to globally uniform carbon pricing at the level mandated by the long term forcing target in 2100. The assumptions about the transition period reflected different abilities to establish effective international cooperation to solve environmental problems in the SSPs (see Table 1): full global cooperation after 2020 in SSP1, and transition to a global carbon price from 2020 to 2040 in SSP2 and SSP5. Both SSP1 and SSP5 assume effective institutions to manage land-use, and therefore associated SPAs assume effective pricing of land-use emissions at the level of the energy sector. In SPA2, the control of emissions from land conversion is weaker in the near term so that deforestation is not fully eliminated before 2030. A detailed description of the SPA implementation in REMIND-MAgPIE is provided in Section S4 of the SOM.

The SPAs try to incorporate short term climate policy developments in the long term mitigation scenarios. Although they were formulated before the adoption of the Paris Agreement in December 2015, they are to some extent compatible with the intended nationally determined contributions (NDCs) to the agreement, particularly for SSP2 (SOM Figs. S4.2 and S4.3). Remaining differences are within the range of the uncertainty about the final scope of NDCs and in particular their actual implementation, which will be influenced by the underlying socio-economic pathway the world will follow in the coming decades.

### 2.4. Regional reporting

Scenario outcomes are provided on the global level and the level of five macro-regions: Latin America (LAM), Middle East and

**Table 1**
Overview of the SSP implementation in REMIND-MAgPIE. The table links the implementation settings (right columns) to the associated high level characterization of SSPs in O'Neill et al. (2017) (left columns). HICs stands for High Income Countries. The concrete implementation was based on more detailed specifications of energy and land-use characteristics developed for the IAM interpretations of SSPs (Riahi et al., 2017); SOM Tables S3.1 and S3.5). A detailed quantitative description of the SSP implementation in REMIND-MAgPIE is provided in SOM Section S3.

| Narrative (O'Neill et al., 2017) | | | | REMIND-MAgPIE implementation | | | |
|---|---|---|---|---|---|---|---|
| Indicator | SSP1 – Sustainability | SSP2 – Middle of the Road | SSP5 – Fossil Fueled Development | Parameter | SSP1 | SSP2 | SSP5 |
| **Demographics** | | | | | | | |
| Population growth | Low (medium fertility in HICs) | Medium | Low (high fertility in HICs) | Population | KC and Lutz (2017) | | |
| Migration | Medium | Medium | High | | | | |
| **Economy & lifestyle** | | | | | | | |
| GDP growth (per capita) | High (medium in HICs) | Medium, uneven | High | GDP/cap growth | Dellink et al. (2017) | | |
| Inequality | Reduced | Uneven, reduced moderately | Strongly reduced | GDP/cap convergence | Dellink et al. (2017) | | |
| | | | | Traditional biomass use | Rapid phase-out | Intermediate phase-out | Rapid phase-out |
| Globalization | Connected markets | Semi-open global economy | Strong | Regional capital intensities | Converging | Non-converging | Converging |
| International trade | Moderate | Moderate | High | Capital markets | Global | Global | Global |
| | | | | Energy markets | Global | Global | Global |
| | | | | Agricultural trade | Global | Regional | Global |
| Consumption | Low material consumption | Material intensive | Materialism, Status consumption, High mobility | Energy demand | Low | Medium | High |
| | | | | Transport liquids | Low | Medium | High |
| Diet | Low meat diets | Medium meat consumption | Meat-rich diets | Calories per capita | Low | Medium | High |
| | | | | Livestock share | Low | Medium | High |
| **Technology** | | | | | | | |
| Development | Rapid | Medium, uneven | Rapid | GDP/cap growth | Dellink et al. (2017) | | |
| Energy technology change | Directed away from fossil fuels, toward efficiency, renewables | Some investment in renewables, continued reliance on fossil fuels | Directed toward fossil fuels; alternative sources not actively pursued | Renewable energy | Favorable outlook | Intermediate outlook | Pessimistic outlook |
| | | | | Nuclear energy | Pessimistic | Intermediate | Intermediate |
| | | | | CCS | Intermediate | Intermediate | Favorable |
| **Environment & resources** | | | | | | | |
| Fossil constraints | Preferences shift away from fossil fuels | No reluctance to use unconv. Resources | None | Oil, coal and gas resources | Low | Medium | High |
| Land-use | Strong regulations to avoid environmental tradeoffs | Medium regulations lead to slow decline in the rate of deforestation | Medium regulations lead to slow decline in the rate of deforestation | Forest protection rate | High | Medium | Medium |
| Agriculture | Improvements in ag productivity; rapid diffusion of best practices | Medium pace of tech change in ag sector; entry barriers to ag markets reduced slowly | Highly managed, resource-intensive, rapid increase in productivity | Crop productivity | Endogenous | Endogenous | Endogenous |
| | | | | Livestock productivity | Medium/ high | Medium | High |
| | | | | Nutrient efficiency | High | Medium | Low |
| | | | | Biomass supply (2nd generation) | Low | Medium | High |
| **Policies & institutions** | | | | | | | |
| International cooperation | Effective | Relatively weak | Effective for development, limited for environment | See international trade settings above, and discussion of SPAs in Section 2.3 | | | |
| Environmental (and energy) policy | Improved management of local and global issues; tighter regulation of pollutants | Concern for local pollutants but only moderate success in implementation | Focus on local environment, little concern with global problems | Air pollutant control | High | Medium | High |
| | | | | Bioenergy tax | High | Medium to high | High |
| | | | | Fossil fuel policies (Subsidies/ taxes) | Restrictive | Intermediate | Supportive |

Africa (MAF), Asia not including the Middle East (ASIA), the reforming economies of the former Soviet Union (REF), and the original OECD countries (in 1990) plus European Union and candidate countries (OECD) (Riahi et al., 2017; https://secure.iiasa.ac.at/web-apps/ene/SspDb). Since the native model regions of REMIND-MAgPIE are not perfect subsets of these macro-regions, small deviations between the definition of these regions and the country groups mapped to these regions by REMIND-MAgPIE exist (SOM Section S2.4).

## 3. Energy and food demand and their drivers in SSP5

Energy and food demand are strongly influenced by population and economic developments. Food demand was constructed exogenously based on SSP5 population and economic output trajectories and additional assumptions in the SSP5 narrative (SOM Section S3.2), and remained unchanged between baseline and mitigation cases. Energy demand is an endogenous output of the REMIND model, and differs between baseline and mitigation cases due to changes in energy mix and energy prices.

### 3.1. Population

SSP5 is a world with a fast demographic transition in developing countries driven by improving education, health, and economic conditions, and a stabilization of fertility rates above replacement levels in high income countries due to optimistic economic outlooks (KC and Lutz, 2017). Migration from poorer to wealthier countries further bolsters the dynamic population development in industrialized countries. The starkly different trends in population before and after 2050 are an important feature of SSP5 affecting associated energy, emissions and land use projections. Specifically, in the first half of the century population is increasing in all regions except the reforming economies (REF), and after 2050 it is decreasing in all regions except in the Middle East and Africa (MAF) and high income OECD regions. Globally, population peaks at around 8.6 billion between 2050 and 2060 followed by a decline to 7.4 billion in 2100 (Fig. 1, top row). Overall, global population growth is projected to be similar to SSP1 and slower than in SSP2 and the UN medium projection (United Nations, 2015) in all regions except OECD. It is also similar to the SRES A1FI scenario family (Nakićenović and Swart, 2000), but significantly lower than in the high population RCP8.5 scenario (Riahi et al., 2011).

### 3.2. Economic output

Economic growth is rapid in developing countries and high in industrialized countries, with a strong convergence of income levels between countries. GDP per capita levels by the end of the century are projected to increase by factors of 5 (OECD; annual average growth of 1.8%/yr) to 28 (MAF; 3.8%/yr) relative to 2010, reaching 120 thousand (MAF) to 160 thousand (OECD) US Dollars per year in 2100 (in purchasing power parity (PPP) units; Dellink et al., 2017). This translates into a rapid increase of global economic output from 67 trillion USD in 2010 to 360 trillion USD in 2050 and 1000 trillion USD (PPP) in 2100 (Fig. 1, upper middle row). End of century economic output in SSP5 is almost twice as high as in SSP2 and SSP1, with the strongest differences in OECD due to the compounding effects of significantly higher population and GDP per capita growth. Income convergence between developing and industrialized countries is equally rapid in SSP1 and SSP5, but at lower overall income levels in SSP1 due to less emphasis on economic growth in high income countries. Since the SSP economic output assumptions are specified in PPP units, the GDP values cannot directly be compared to GDP projections based on market exchange rates as reported for emissions scenarios in the literature. However, GDP information in PPP is available for A1FI (Nakićenović and Swart, 2000) and a subset of scenarios in the AR5 scenario database (IPCC, 2014). They all assume slower global economic growth over the 21st century than SSP5.

### 3.3. Energy demand

Historically, energy intensity of economic output decreased and per capita energy use increased with increasing GDP per capita levels (Grübler et al., 2012; Fouquet, 2014). In SSP2 and SSP5, the developing regions MAF, ASIA, and LAM exhibit a roughly constant growth of per capita final energy demand with income, while in the OECD and REF regions, it saturates starting from considerably higher levels of per capita energy use (SOM Fig. S1.1). The resulting final energy intensity improvement rates over the century range from 1.2%/yr in OECD to 2.3%/yr in MAF in line with historic trends in developing and industrialized countries (Grübler et al., 2012; Stern, 2012; IEA, 2015). In the sustainability oriented world described by SSP1, per capita energy demand grows significantly slower with income in the developing regions and even decreases in OECD and REF. As a result, global final energy demand in SSP5 (1170 EJ/yr) is more than twice as high as in SSP1 (470 EJ/yr) by the end of the century, with SSP2 positioned in between these two cases (Fig. 1, lower middle row). This trend in energy demand is confirmed by other interpretations of SSP5 by AIM/CGE, GCAM and WITCH-GLOBIOM, which find global energy demand levels in 2100 between 980 and 1190 EJ/yr (Figs. 3, SOM S1.3). SSP5 final energy demand levels are similar to RCP8.5 (Riahi et al., 2011) and at the upper end of energy demand projections in the AR5 database (IPCC, 2014), but significantly lower than in A1FI (Nakićenović and Swart, 2000).

### 3.4. Food demand

Food demand reflects human metabolic requirements, but food consumption is also a function of economic and social development as consumption patterns, especially the share of livestock products within diets and food waste, change with income (Bodirsky et al., 2015). This is particularly true for SSP5, where diets with high animal and waste shares prevail (Figs. 2 , SOM S3.7). Under this assumption, the income dynamics in SSP5 result in increasing per-capita food demand at household level (including household waste) until late in the century, reaching a global average crop demand of 3250 kcal/cap/day (45% higher than in 2010) and livestock demand of 860 kcal/cap/day (85% higher than in 2010) in 2100 (Fig. 2). By 2100, SSP5 shows substantially higher per-capita food demand (crops and livestock) across all regions compared to SSP2 (3320 kcal/cap/day) and in particular compared to SSP1 (2830 kcal/cap/day) with its emphasis on limiting meat consumption and food waste (SOM Fig. S1.2). Total global food demand by 2100, however, is similar in SSP2 and SSP5 (46 EJ/yr) because population in SSP2 is substantially higher than in SSP5 (Fig. 1, bottom row). In contrast, total food demand in SSP1 (30 EJ/yr) is considerably lower compared to SSP5 and SSP2 because of the coincidence of lower population and lower per-capita food demand in SSP1. Food demand projections in other SSP5 IAM interpretations are lower than in the REMIND-MAgPIE marker scenario (AIM/CGE: 3600 kcal/cap/day, 40 EJ/yr; GCAM: 3420 kcal/cap/day, 39 EJ/yr).

Regional food demand in REMIND-MAgPIE is identical in the baseline and climate policy scenarios, i.e., food demand is insensitive to climate policy intervention. Regional food production, however, differs between baseline and climate policy scenarios because agricultural productivity and trade patterns react to mitigation policies (SOM Figs. S1.9, S1.12).

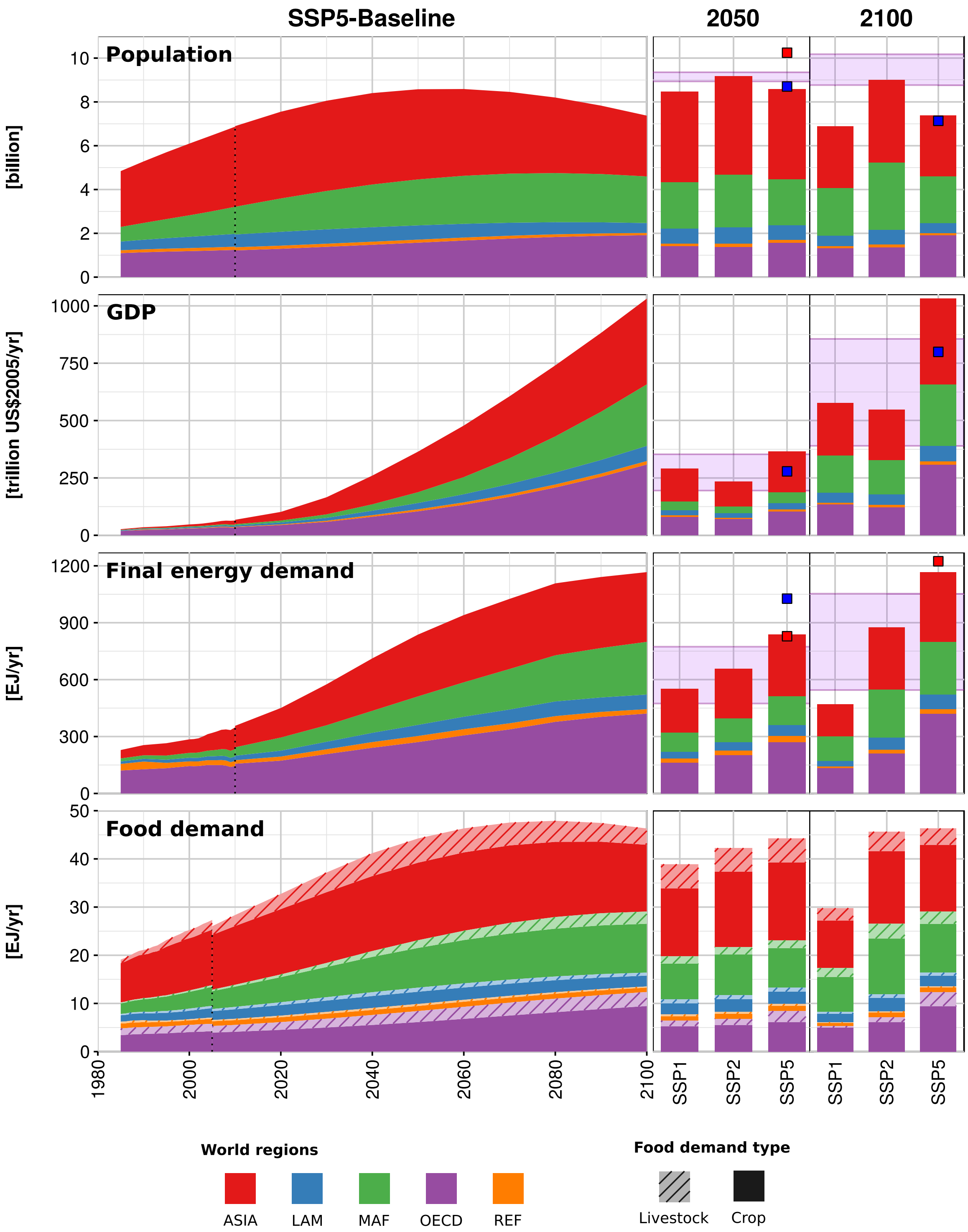

**Fig. 1.** Energy and food demand and their drivers in the REMIND-MAgPIE baseline scenarios. Shown are global population (top row), GDP (in PPP; upper middle row), energy demand (lower middle row), and food demand (bottom row) in SSP5 over the 21st century stacked by SSP region. The figure includes a comparison with SSP1 and SSP2 for the years 2050 and 2100. SSP values are also compared with population, GDP and final energy projections in the RCP8.5 (red marker, Riahi et al., 2011) and SRES A1FI marker scenarios (blue marker, Nakićenović and Swart, 2000) and the 5th to 95th percentile range in the AR5 emissions scenario database (grey bands; IPCC, 2014). Food energy demand was not reported for these scenarios. RCP8.5 population (12.4 billion) and A1FI final energy demand (1570 EJ) are outside the plot range in 2100. The food demand categories of FAO and MAgPIE do not match perfectly, e.g., fish is not included in MAgPIE, causing a small gap between historic food demand (FAO) and our projections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

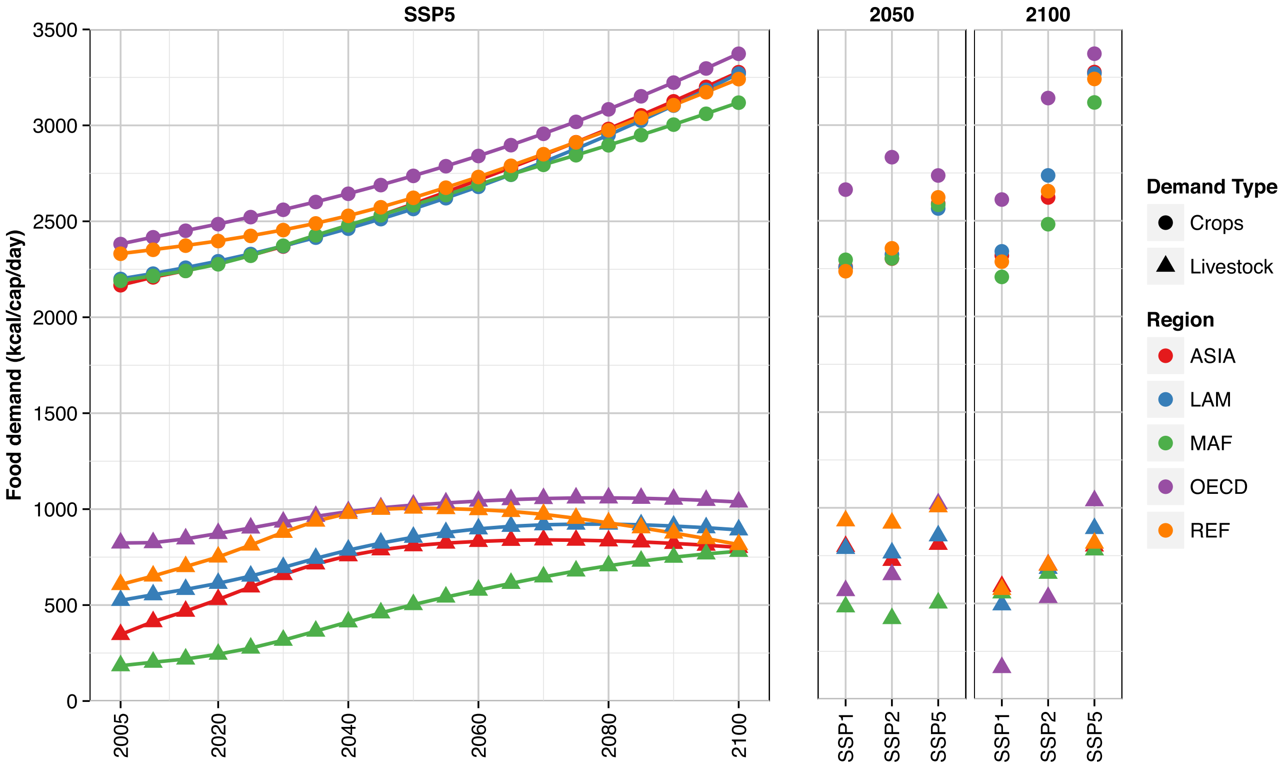

**Fig. 2.** Regional per-capita food demand (kcal/cap/day) in SSP5 over the 21st century assumed by REMIND-MAgPIE. Food demand is split into demand for crops and livestock products. The figure includes a comparison with SSP1 and SSP2 for the years 2050 and 2100.

## 4. Energy, land-use, and emissions outcomes in SSP5

### *4.1. Transformation of the energy system in SSP5*

High economic growth and rapid income convergence lead to fast modernization of energy use (Fig. 3). The final energy consumption of solids is quickly phased out, whereas electricity, transportation fuels and gases consumption grow rapidly. Largest differences to SSP1 and SSP2 occur for transportation fuel consumption driven by rapidly growing passenger transport and freight transportation volumes in SSP5. In the mitigation scenarios, climate policies induce a general decrease in final energy demand, and an acceleration of the modernization of energy use. These general features are shared across the larger set of SSP5 scenarios, with main differences between model projections occurring for liquids consumption due to differences in transportation energy use (SOM Fig. S1.3).

#### *4.1.1. Energy transition in the SSP5 baseline scenarios*

In the absence of climate policy, primary energy supply is dominated by the economics of energy resource availability and energy conversion technologies for the production of electricity, liquids and gases, which strongly depends on the underlying technology and resource assumptions in SSP5 (see Table 1 for an overview and SOM Section S3.1 for a more detailed description of these assumptions). Due to the assumption of plentiful fossil fuel resources, fossil fuels continue to dominate the rapidly growing primary energy supply (Fig. 4). Technological progress, supportive policies and flexible markets are globally increasing the supply of natural gas and also oil in the first half of the century. In the SSP5 marker scenario, oil peaks in 2050 at twice the production rate of 2010. The oil industry is the dominant supplier of liquid fuels until 2050, and continues to be mostly used for the provision of liquids after the peak (SOM Fig. S1.6). Natural gas extraction quadruples and peaks in 2070, driven by rapidly increasing demand for electricity generation in the first half of the century (Fig. 4) and for gaseous fuels, predominantly for space heating (SOM Fig. S1.7). Coal experiences a renaissance as major primary energy source in the second half of the century when its deployment is significantly increased for the production of electricity (Fig. 5) and liquids (SOM Fig. S1.6) in the face of rising costs for oil and gas exploration and high demand for liquid transportation fuels and gases (Figs. 3, SOM S1.6, S1.7). Despite these developments, low local air pollution is limited to low levels due to effective pollutant emissions controls (see also Section 3.4).

Low public acceptance and policy support for renewable energy lead to slower cost improvements and a more limited share of renewable energy technologies than in SSP2 and particularly SSP1. As a result, renewable energy only starts to be deployed at larger scale by the end of the 21st century. Nuclear power is used only to a very limited degree given its high costs relative to coal and gas fired power generation (Figs. 5, SOM S1.5). Other SSP5 baseline scenarios show similar trends. Coal use increases over the 21st century in all baseline scenarios, although the coal renaissance is more limited in GCAM due to a larger and continuously increasing oil supply in the liquids sector (SOM Fig. S1.4). Electricity generation remains fossil fuel based, but models differ most notably on the total amount of electricity, the share of coal vs. gas-fired power generation, and the choice between solar and wind power by the end of the century (SOM Fig. S1.5).

The comparison of the SSP5 marker scenario with SSP1 and SSP2 highlights the fundamental differences regarding the scale of primary energy use and particularly the use of fossil fuels between SSPs (Fig. 4). While RCP8.5 foresees a similar increase in overall

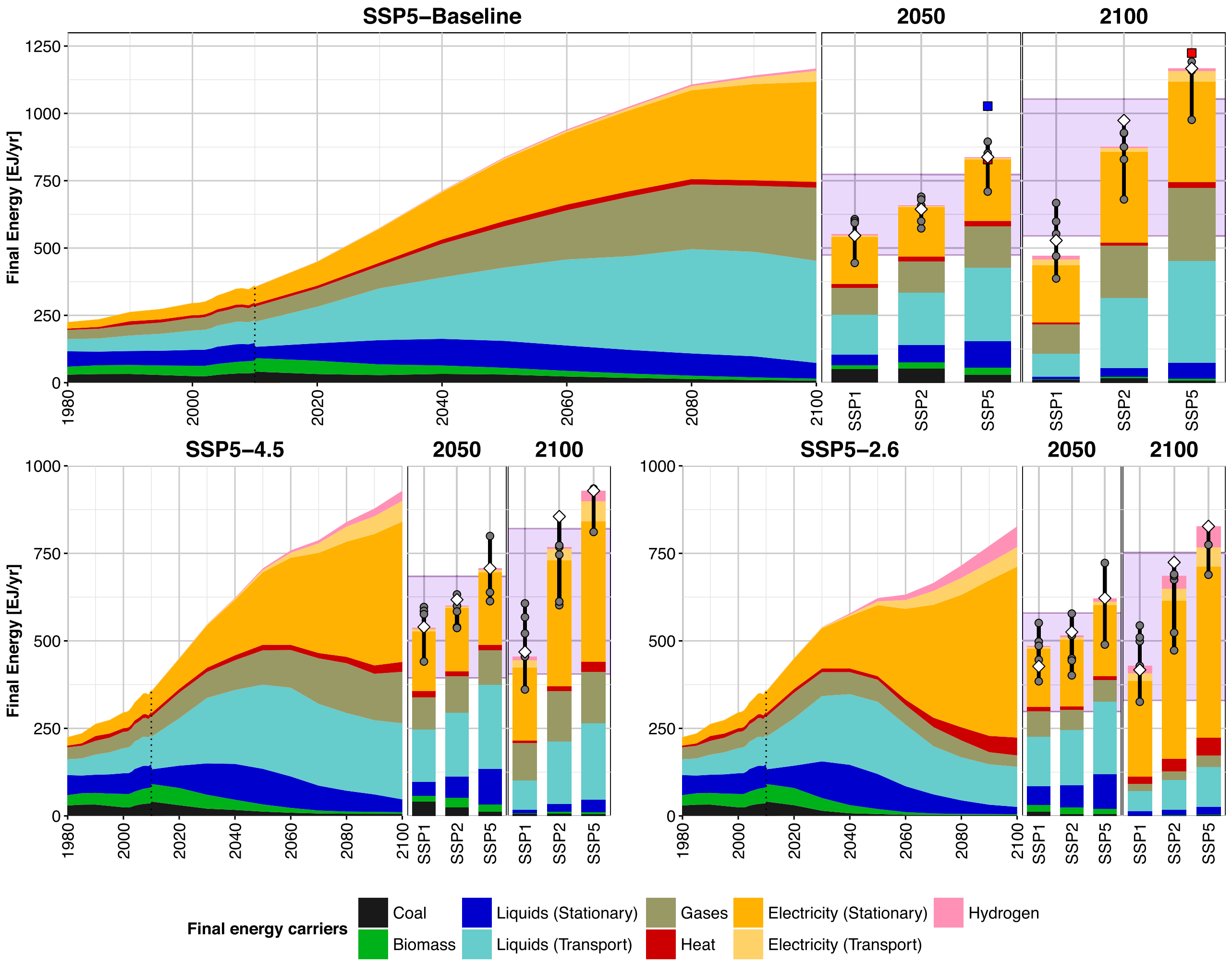

**Fig. 3.** Final energy demand by carrier in the SSP5 baseline scenario (top row) and the 4.5 W/m$^2$ (SSP5-4.5) and 2.6 W/m$^2$ (SSP5-2.6) mitigation cases (bottom row) as derived by REMIND-MAgPIE. Results are compared with SSP1 and SSP2 for the years 2050 and 2100. The dots in the bar plots indicate final energy demand projections across IAMs and the white diamonds represent the SSP marker scenarios. The grey bands show the 5th to 95th percentile range of final energy use in baseline and mitigation scenarios (580–650 ppm CO$_2$e scenarios compared to SSP5-4.5 and 430–480 ppm CO$_2$e to SSP5-2.6) collected in the IPCC AR5 emissions scenario database (IPCC, 2014). SSP5 baseline values are compared with the RCP8.5 (red marker, Riahi et al., 2011) and SRES A1FI marker scenarios (blue marker, value of 1570 EJ in the year 2100 above plot range; Nakićenović and Swart, 2000). Historic data is from IEA (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

primary energy supply compared to the SSP5 baseline, the renaissance of coal is less pronounced due to lower coal to liquids deployment in the 2nd half of the century (Riahi et al., 2011).

International trade of fossil fuels expands rapidly in the globalized energy markets foreseen in SSP5, particularly for gas and later on for coal (SOM Fig. S1.8). In the SSP5 marker scenario, the coal renaissance makes coal by far the largest international energy market in the second half of the 21st century, with traded energy volumes up to five times the size of current oil and gas markets. This allows OECD and REF to become large exporters of coal to Asia and MAF countries, while the role of MAF as largest oil and gas exporter declines. Thus, the geo-politics of international energy markets changes completely over the course of the century in the SSP5 baseline case.

### *4.1.2. Energy transition in the SSP5 mitigation scenarios*

Climate change mitigation requires substantial changes in the scale and structure of primary energy use (Fig. 4). Coal use responds strongest. In the SSP5 marker scenarios, coal-fired power generation and solid coal use are phased out rapidly before 2050 in both the intermediate (SSP5-4.5) and stringent (SSP5-2.6) mitigation cases despite the availability of CCS. This is due to the fact that gas-fired power plants with CCS are economically favored and the amount of CO$_2$ that can be sequestered per year is limited to ca. 27 GtCO$_2$ (SOM Section S3.1.4). Coal CCS only becomes prominent as an end-of-pipe technology in coal to liquids production in SSP5-4.5 (SOM Fig. S1.6). SSP5 mitigation scenarios from other IAMs see a somewhat larger role for Coal CCS, including in the power sector, but even in these cases it is not among the major mitigation options for reaching stringent mitigation targets (SSP5-2.6; SOM Figs. S1.4, S1.5) given the more favorable economics of other options at high carbon prices.

In contrast to coal, the use of oil and gas continues to grow rapidly until 2050 (SSP5-4.5) and 2040 (SSP5-2.6), respectively, due to only moderate short-term climate policies as defined by the shared climate policy assumption for SSP5 (see Section 2.3 and SOM Section S4). In the SSP5-4.5 marker scenario, natural gas continues thereafter to supply most of a significantly reduced demand for gases in the energy end use sectors (Fig. S1.4) and in combination with CCS remains an important source for electricity generation (Fig. 3). Oil plays an even larger role in the liquids sector than in the baseline case given that coal is no longer available as a major substitute, and biofuels only replace a fraction of what was supplied by coal to liquids (SOM Fig. S1.6). Biofuel production is

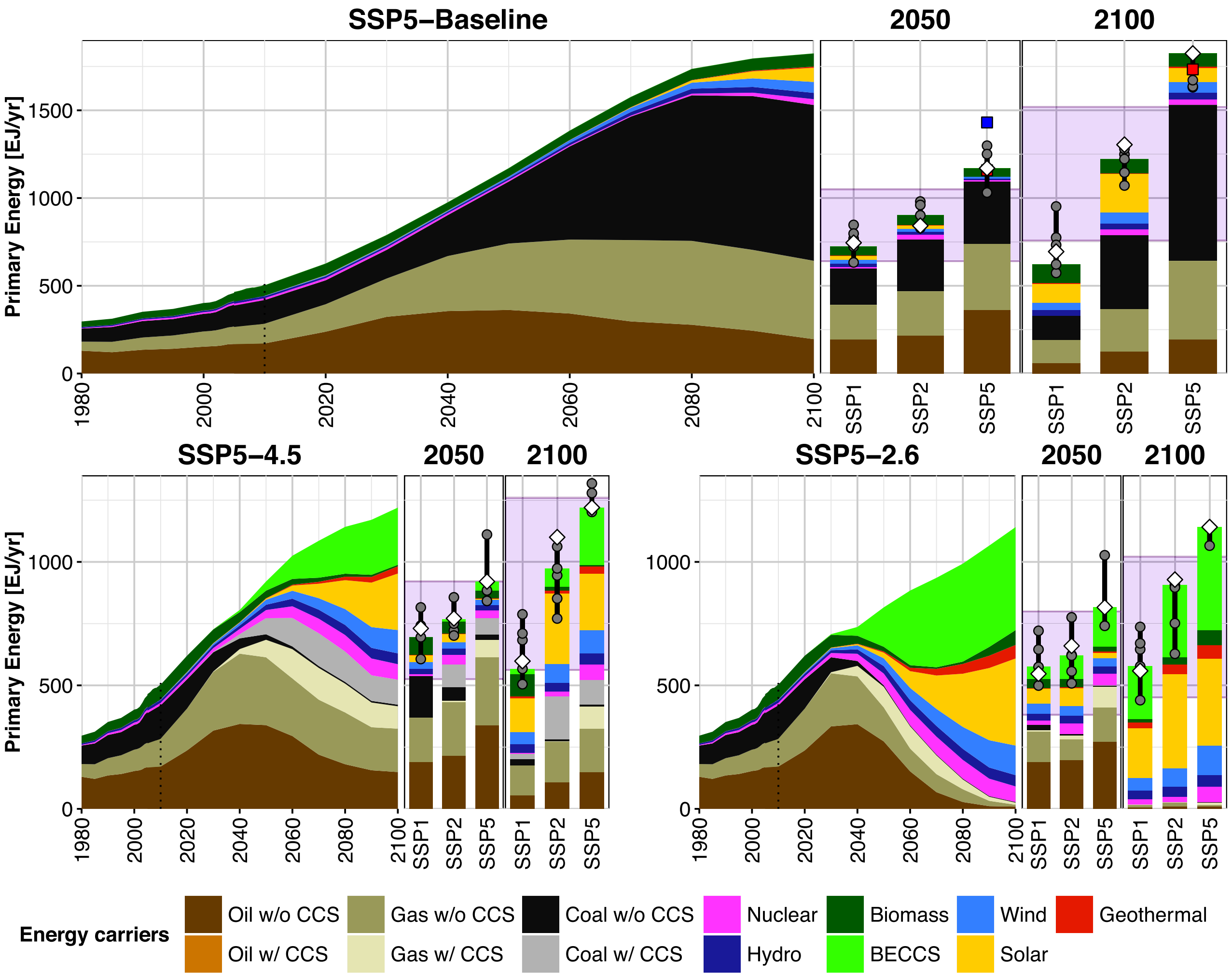

**Fig. 4.** Primary energy supply by source (in direct equivalent units) in the SSP5 baseline scenario (top row) and the 4.5 W/m$^2$ (45) and 2.6 W/m$^2$ (26) mitigation cases (bottom row) as derived by REMIND-MAgPIE. Results are compared with SSP1 and SSP2 for the years 2050 and 2100. The dots in the bar plots indicate primary energy supply projections across IAMs and the white diamonds represent the SSP marker scenarios. The grey bands show the range of primary energy projections in the AR5 scenario database (see Fig. 3 for details). SSP5 baseline values are compared with the RCP8.5 (red marker) and SRES A1FI marker scenarios (blue marker, value of 2070 EJ in 2100 above plot range). Historic data is from IEA (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

combined with CCS (BECCS) to withdraw $CO_2$ from the atmosphere, thus off-setting some of the residual fossil fuel emissions. Even though the SSP5 storyline assumes unfavorable conditions for non-biomass renewables, the strong mitigation pressure leads to massive upscaling of renewables in the power sector after 2050, with wind and solar providing more than two thirds of electricity by the end of the century (Fig. 5). The upscaling is seen across all SSP5 mitigation scenarios. Despite the fact that models differ about the relative share of renewable vs. nuclear power and the residual use of fossil-fuel fired power plants, renewable energy is the largest source of electricity generation by 2100 in all mitigation scenarios, while fossil fuel power generation with CCS is used only to a limited degree in SSP5-2.6 (SOM Fig. S1.5).

In the stringent SSP5-2.6 mitigation case compatible with the objective to limit global warming to 2°C, purpose-grown bioenergy use is strongly increased (Fig. S1.4) to substitute fossil fuels particularly in the transportation sector and – in combination with CCS – to withdraw large amounts of carbon dioxide from the atmosphere to offset excess emissions from fossil fuel use and residual emissions from the agricultural sector (Section 4.3). Residual fossil fuel use in 2100 differs significantly between SSP5 projections, ranging between a complete phase-out (REMIND-MAgPIE marker) and 500 EJ (AIM/CGE) due to different deployment levels of fossil and bioenergy CCS over the century (SOM Fig. S1.4).

Mitigation leads to a collapse of the international coal market and significant reductions of oil and gas trade in the second half of the century (SOM Fig. S1.8). However, oil trade can even increase in the near term compared to the baseline case due to demand reductions in exporter countries and a reduction of unconventional oil supply in importer countries. Bioenergy trade grows significantly during the second half of the century.

### 4.2. Land-use change in SSP5

The SSP5 narrative assumes that land-use change is incompletely regulated, i.e., tropical deforestation continues, although at slowly declining rates over time. Crop yields are rapidly increasing. Barriers to international trade are strongly reduced, and strong globalization leads to high levels of international trade (see

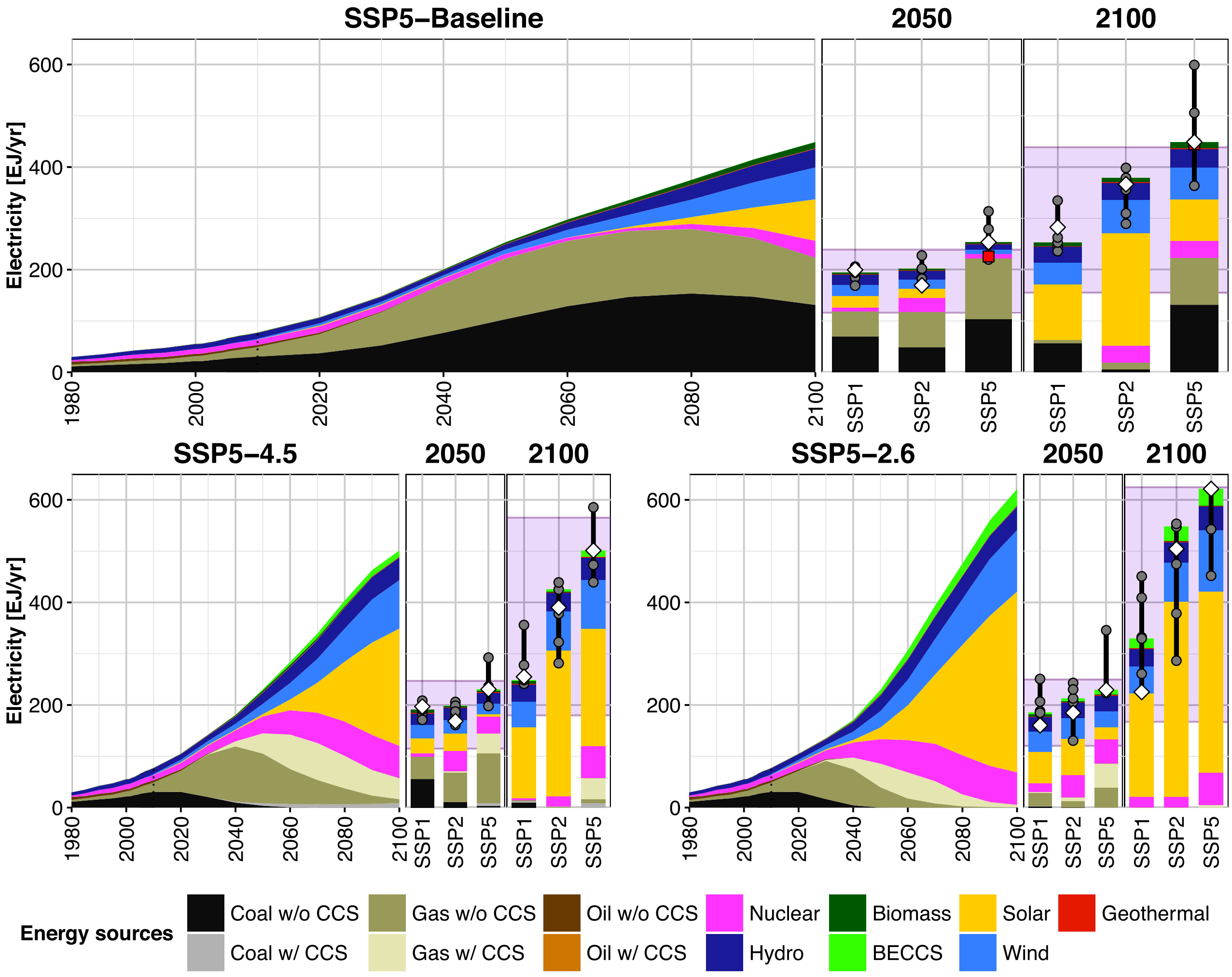

**Fig. 5.** Electricity generation by source in the SSP5 baseline scenario (top row) and the 4.5 W/m$^2$ (45) and 2.6 W/m$^2$ (26) mitigation cases (bottom row) as derived by REMIND-MAgPIE. Results are compared with SSP1 and SSP2 for the years 2050 and 2100. The dots in the bar plots indicate electricity generation projections across IAMs and the white diamonds represent the SSP marker scenarios. The grey bands show the range of electricity projections in the AR5 scenario database (IPCC, 2014; see Fig. 3 for details). SSP5 baseline values are compared with the RCP8.5 scenario (red marker). Historic data is from IEA (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Sections 2.2 and SOM S3.2). These factors greatly affect the land-use dynamics under the increasing food (Figs. 1 and 2) and bioenergy demand (Fig. 4) in SSP5.

*4.2.1. Global land use change*

As a result of the strongly increasing demand for food crops and livestock products (Fig. 1), global cropland expands by about 300 Mha between 2005 and 2100 (peak in 2070 at 400 Mha) in the SSP5-Baseline marker scenario by REMIND-MAgPIE (Fig. 6), accompanied by an increase in global cereal crop yields of ca. 60% between 2005 and 2100 (SOM Fig. S1.9). Cropland expands into forests but also at the expense of pastures. By 2100, the global pasture and forest area in the SSP5 baseline scenario declines by 270 Mha and 220 Mha respectively (Fig. 6).

The spatial distribution of these changes is shown in the land use maps included in the SOM (Fig. S1.10). Net global cropland expansion in the SSP5-Baseline marker scenario is very similar to the RCP 8.5 scenario (290 Mha by 2100; SOM Fig. S1.11). In contrast, however, cropland in the RCP 8.5 scenario expands only into forest and not into pasture areas. The expansion of cropland into pastures in the SSP5-Baseline marker scenario is facilitated by productivity gains in the livestock sector (SOM Fig. S3.8) and related shifts in feeding practices from roughages to more energy-rich feed cultivated on cropland allowing for contraction of pasture area in spite of growing demand for livestock products.

Global land-use change by 2100 in SSP5-Baseline is similar to that in SSP2-Baseline because of similar total food demand (Fig. 1) but differs substantially from land-use change in SSP1-Baseline. In SSP1, food and especially livestock demand markedly decline in the 2nd half of the century resulting in large-scale abandonment of cropland and pasture areas (520 Mha and 230 Mha respectively). Regrowth of natural vegetation on those areas causes terrestrial carbon sequestration, which is reflected in negative CO$_2$ emissions from land-use in SSP1-Baseline (Section 3.4). Biomass plays a minor role in the energy mix of SSP5-Baseline. In 2100, dedicated 2nd generation bioenergy amounts to 3 EJ/yr (Fig. 3) and occupies about 15 Mha (Fig. 6). This is similar in SSP2-Baseline but different in SSP1-Baseline where bioenergy area increases to 140 Mha for producing 35 EJ/yr in 2100.

Demand for dedicated energy crops is substantially higher in climate mitigation scenarios because the combination of bioenergy with CCS can provide energy and concurrently remove CO$_2$ from the atmosphere. In SSP5-4.5 and SSP5-2.6, global bioenergy crop demand increases to 170 EJ/yr and 410 EJ/yr by 2100

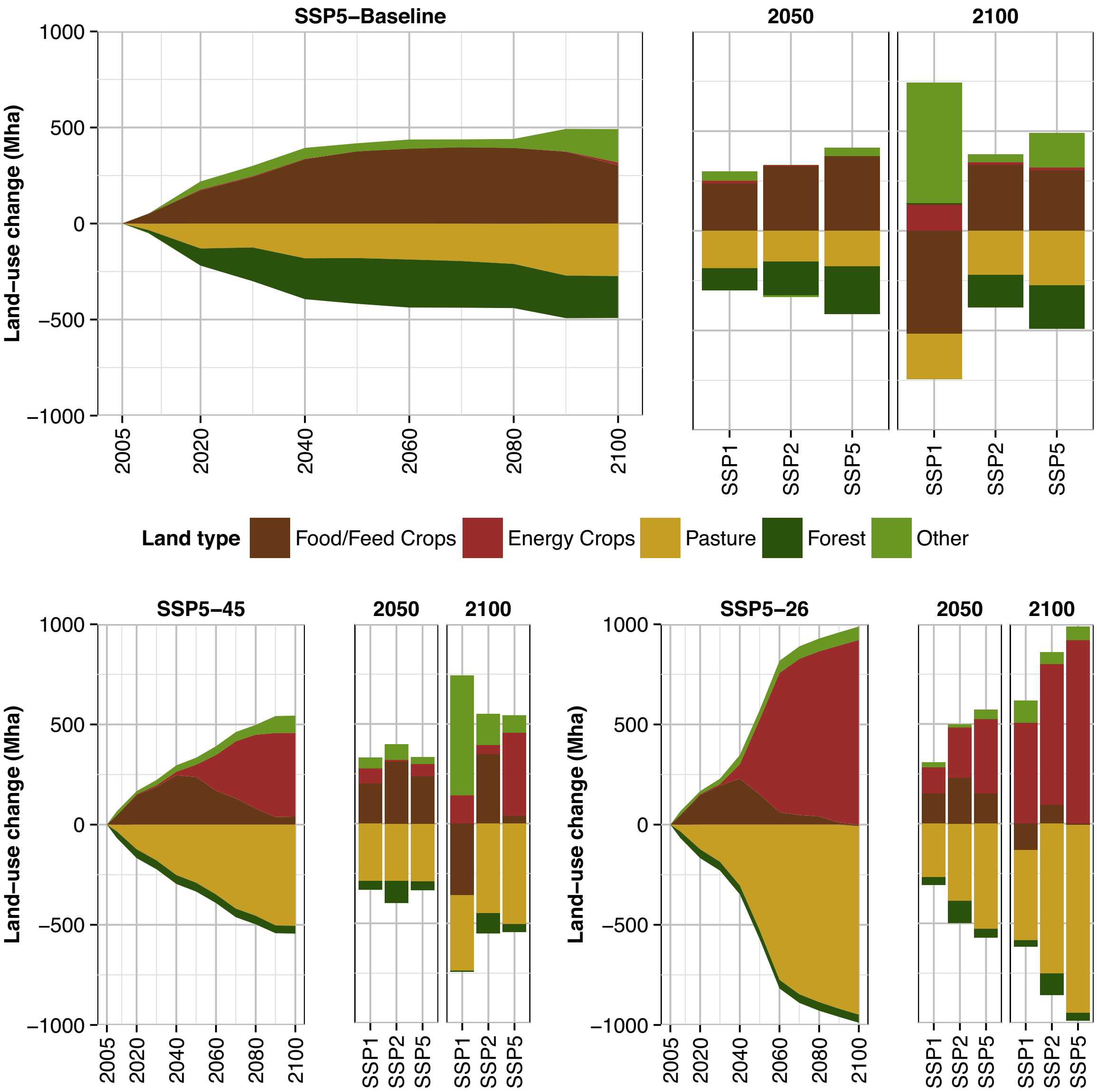

**Fig. 6.** Global land-use change by land type relative to 2010 in the SSP5-Baseline scenario (top row) and the 4.5 W/m$^2$ (45) and 2.6 W/m$^2$ (26) mitigation cases (bottom row) as derived by REMIND-MAgPIE. Results are compared with SSP1-Baseline and SSP2-Baseline for the years 2050 and 2100. "Other" land, which includes non-forest natural vegetation, deserts and abandoned agricultural land, strongly increases in SSP1-Baseline towards the end of the century, associated with regrowth of natural vegetation. If the carbon density of re-growing vegetation exceeds a threshold of 20 tC/ha, "Other" land is reclassified as "Forest".

respectively (Fig. 4). The strong increase of bioenergy demand in mitigation scenarios compared to SSP5-Baseline renders bioenergy the dominant driver for cropland expansion in the second half of the century. By 2100, global bioenergy area amounts to 420 Mha in SSP5-4.5 and 920 Mha in SSP5-2.6 (Fig. 6). These values are comparable to global land requirements for bioenergy crop production in GCAM (SSP5-4.5: 530 Mha; SSP5-2.6: 770 Mha) and AIM/CGE (SSP5-2.6: 910 Mha; the value of 800 Mha in SSP5-4.5 is higher due to higher bioenergy use; see SOM Fig. S1.3) (SOM Fig. S1.11).

In REMIND-MAgPIE, the increase of bioenergy area in the mitigation scenarios is accompanied by higher bioenergy yields than in SSP5-Baseline. Global average bioenergy crop yields in 2100 amount to 22 tDM/ha/yr in SSP5-4.5 and 25 tDM/ha/yr in SSP5-2.6, compared to 11 tDM/ha/yr in SSP5-Baseline (SOM Fig. S1.9). In contrast to SSP5-Baseline, cropland expands primarily into pasture areas in the SSP5 mitigation scenarios because deforestation after 2010 is avoided by pricing $CO_2$ emission from land-use change at the same level as $CO_2$ emissions in the energy sector (Figs. 6, SOM S1.10). In contrast to SSP5, the REMIND-MAgPIE SSP2 mitigation scenarios still show considerable deforestation (about 100 Mha by 2050) because the effective implementation of a carbon pricing scheme in the land-use sector is delayed until 2030 (Section 2.3). In the SSP1 mitigation scenarios, bioenergy is produced primarily on areas that would have been abandoned in SSP1-Baseline, which hampers the regrowth of natural vegetation and associated carbon uptake. Afforestation occurs in the SSP5 mitigation scenarios by GCAM and AIM/CGE (only SSP5-26), but is not accessible as mitigation option in the REMIND-MAgPIE implementation of the SSPs.

While global food/feed crop area increases in the beginning of the century in the REMIND-MAgPIE SSP5 mitigation scenarios, it starts to decline in 2040 in favor of bioenergy and returns to its 2005 level by 2100. To ensure the same food production in climate mitigation scenarios as in SSP5-Baseline, cereal crop yields need to increase at higher pace. Global average cereal crop yields in 2100 are above 5 tDM/ha/yr in SSP5-4.5 and SSP5-2.6, compared to 4.2 tDM/ha/yr in SSP5-Baseline and ca. 2.9 tDM/ha/yr in 2010 (SOM Fig. S1.9). The strong contraction of pasture area in the climate policy scenarios is facilitated by regional shifts in food production according to comparative advantages (SOM Fig. S1.12) and higher investments into agricultural research and development (yield-increasing technological change), which increases the amount of biomass grazed on a certain pasture area (grazing intensity). The GCAM model shows similar pasture dynamics in SSP5-4.5 and SSP5-2.6 as REMIND-MAgPIE, whereas AIM-CGE shows a relatively small decline of pasture areas but strong contraction of other land that is not covered by forest or used for agriculture (Fig. SOM S1.11).

### *4.2.2. Regional land use change patterns*

In the SSP5-Baseline marker scenario, agriculture expands into forests and other natural land primarily in Sub-Saharan Africa (as part of MAF) and Latin America (LAM) (Figs. 7 , SOM S1.10). The MAF region shows the highest increase in crop and livestock demand throughout the 21st century in SSP5 (Fig. 1). The associated cropland expansion in MAF causes the major part of global deforestation by 2100 (Figs. 7, SOM S1.10). Despite the increase in livestock demand, pasture area in MAF is relatively stable throughout the century because of improved feeding efficiencies and a shift from pasture to cropland based feed production (SOM Fig. S3.8). At the same time, MAF becomes the main exporter of livestock products in SSP5-Baseline (SOM Fig. S1.12) due to a combination of strong reduction of barriers for international trade (SOM Fig. S3.11), productivity increases in crop and livestock systems (SOM Fig. S3.8), and the large availability of pastureland in MAF, which accounts in 2005 for about one third of global pasture area. The agricultural area in ASIA in SSP5-Baseline is largely maintained after 2050 (Fig. 7) allowing ASIA to become the main exporter of crops (SOM Fig. S1.12). In the climate mitigation scenarios, bioenergy area expands in all regions except REF. In SSP5-4.5 bioenergy cropland in 2100 is similar in ASIA, LAM, MAF and OECD, whereas in SSP5-2.6 bioenergy production occupies substantially more land in ASIA and MAF than in LAM and OECD (Fig. 7). The large-scale production of bioenergy in the mitigation scenarios has repercussions on agricultural trade patterns. In MAF, the extensive livestock production on pasture areas in SSP5-Baseline is displaced by bioenergy production in SSP5-2.6 (Fig. 7). Thus, livestock production for export is shifted to other regions such as ASIA (SOM Fig. S1.12).

### *4.3. Development of emissions in SSP5*

The SSP5 baseline scenario exhibits a tripling of well-mixed greenhouse gas (WMGHG) emissions from 50 $GtCO_2$-eq in 2010 to ca. 150 $GtCO_2$-eq towards the end of the century (Figs. 8 , SOM S1.13; range of 125–150 $GtCO_2$eq/yr across the four SSP5 interpretations by IAMs). This massive increase is mostly driven by the strong reliance on fossil fuels consistent with the narrative of SSP5. In the SSP5-Baseline marker scenario, fossil fuel emissions peak between 2080 and 2090 as even the abundant coal, oil and gas resources in SSP5 become depleted (Fig. 4). The SSP5 emissions exceed SSP2 emissions by more than 75% and SSP1 emissions by more than a factor three mainly due to the very different developments in the energy sector. There are also major differences in land-use $CO_2$ emissions which fall to zero (SSP2 and SSP5) or even turn negative due to $CO_2$ uptake from vegetation regrowth (SSP1) by the end of the century. In terms of regional breakdown, the largest share of WMGHG emissions comes from the ASIA and OECD regions, contributing more than a third of emissions each throughout the century (SOM Fig. S1.14). The WMGHG emissions from the MAF region increase seven fold until 2100 catching up with OECD emissions by the end of the century.

The emissions scenario associated with RCP8.5 (Riahi et al., 2011) and the SRES A1FI scenario family (Nakićenović and Swart, 2000) come closest to SSP5 within the previous generations of scenarios. Compared to these scenarios, the SSP5 marker scenario shows higher $CO_2$ emissions due to its larger coal use

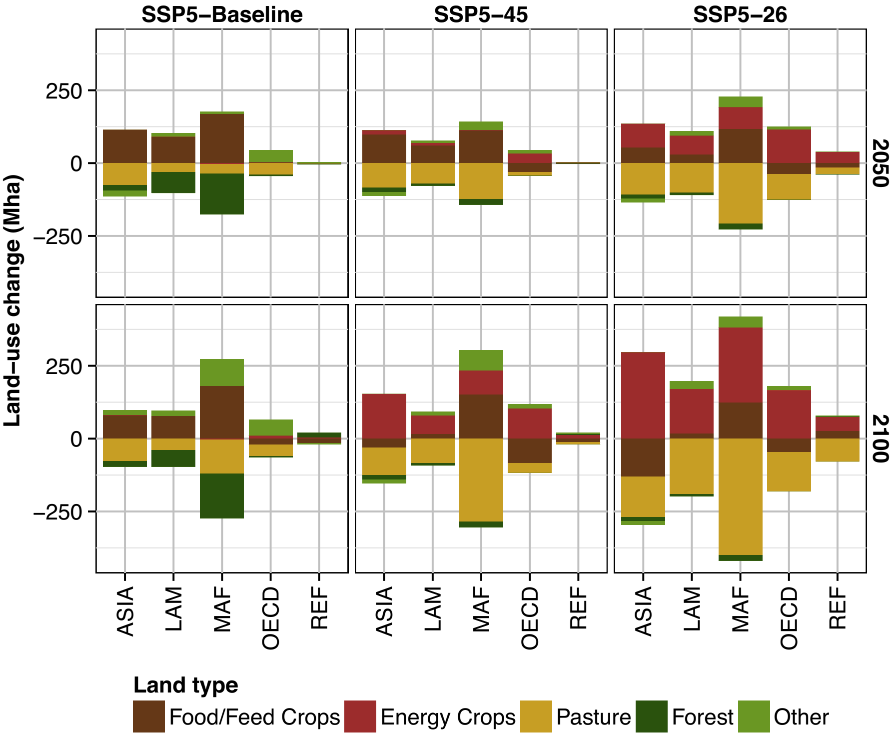

**Fig. 7.** Regional land-use change in SSP5-Baseline, SSP5-4.5 and SSP5-2.6 by 2050 and 2100 as derived by REMIND-MAgPIE.

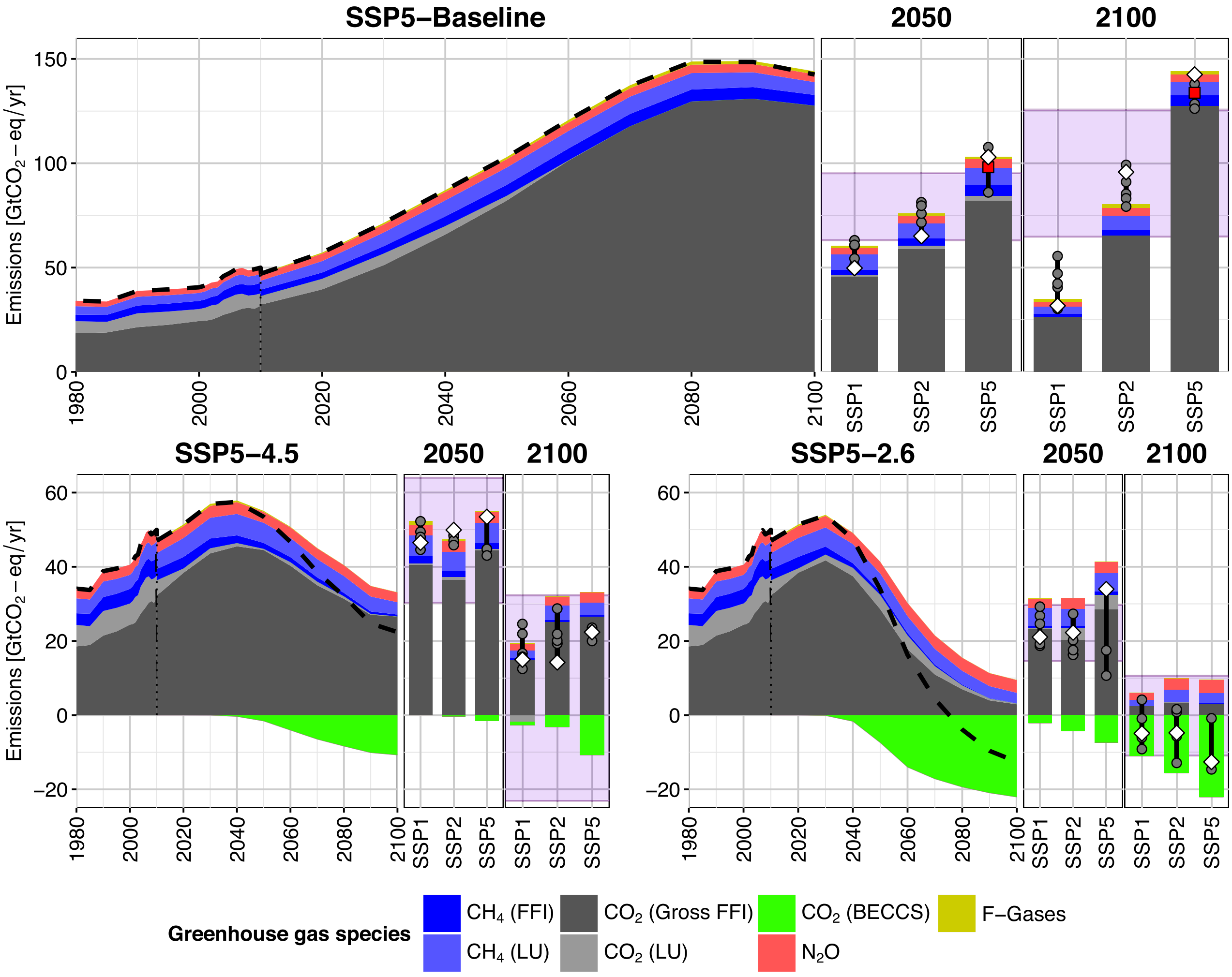

**Fig. 8.** Well-mixed greenhouse gases by source in the SSP5 baseline scenario (top row) and the 4.5 W/m$^2$ (45) and 2.6 W/m$^2$ (26) mitigation cases (bottom row) as derived by REMIND-MAgPIE. Results are compared with SSP1 and SSP2 for the years 2050 and 2100, with RCP8.5 for SSP5-Baseline (red marker), and with the AR5 scenario database (grey bands, see Fig. 3 for details). The dots in the bar plots indicate WMGHG emissions projections across IAMs and the white diamonds represent the SSP marker scenarios. $CH_4$, $N_2O$, and F-gas emissions were converted to $CO_2$-eq emissions using AR4 global warming potentials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(see Section 4.1). SSP5 $CO_2$ emissions are also higher than most of the emissions scenarios collected for AR5 (IPCC, 2014) and the SSP5 scenarios generated by the other IAMs (Figs. 9 , SOM S1.13). In contrast, the marker scenario is highest in $CH_4$ emissions only until 2040 when it peaks due to rapidly increasing livestock productivity (SOM Fig. S3.8) and the peak in natural gas production. Moreover, its $N_2O$ emissions stabilize in the second half of the century and are lowest among SSP5 baseline scenarios. F-Gas emissions come mostly from industry sources and rise even more rapidly than $CO_2$ emissions due to their close coupling with GDP growth. In contrast, air pollutant emissions including sulfate and carbonaceous aerosols (organic and black carbon) are tightly controlled in SSP5 for environmental and health reasons (Sections 2.2 and S3.1).

In the SSP5 mitigation cases, well-mixed GHG emissions are reduced significantly (Figs. 8, 9, SOM S1.13). Emissions are already more than halved in the weakest mitigation scenario SSP5-6.0 with particularly strong reductions in $CH_4$ and F-gases. $CO_2$ emissions are further decreased with decreasing forcing target, and even reach net negative levels by the end of the century in the most stringent mitigation cases SSP5-3.4 and SSP5-2.6. Further reductions also occur for $CH_4$ and particularly F-gases, although they saturate for lower targets indicating a socket of residual emissions that are hard to eliminate even at high marginal mitigation costs. The $N_2O$ emissions exhibit a considerably different response pattern as they are rising with the stringency of forcing targets due to increasing large-scale deployment of bioenergy. The residual $CH_4$ and $N_2O$ emissions give land-use and associated emissions a large significance in the mitigation cases (Figs. 8, SOM S1.13). Air pollutant emissions are not much further reduced in the mitigation cases due to the presence of already tight air pollutant control measures in the baseline case. This implies that the air quality co-benefits of mitigation action are smaller in SSP5 than, e.g., in SSP2 (Rao et al., 2017). The shape of well-mixed GHG emissions in SSP5-2.6 scenarios differs notably between models (SOM Fig. S1.13). While the SSP5-2.6 marker by REMIND-MAgPIE shows smaller emissions reduction until 2050 (reaching 34 $GtCO_2e$ in 2050 compared to 19 $GtCO_2e$ in AIM/CGE), it partly compensates it with larger net negative emissions by the end of century (-11 $GtCO_2e$ compared to 0.3 $GtCO_2e$ in AIM/CGE).

The emissions in the SSP5-Baseline marker scenario increase anthropogenic climate forcing to 8.7 W/m2 by 2100, very close to the forcing development in RCP8.5 (Fig. 10). The well-mixed GHGs are responsible for the largest share of forcing, with the net

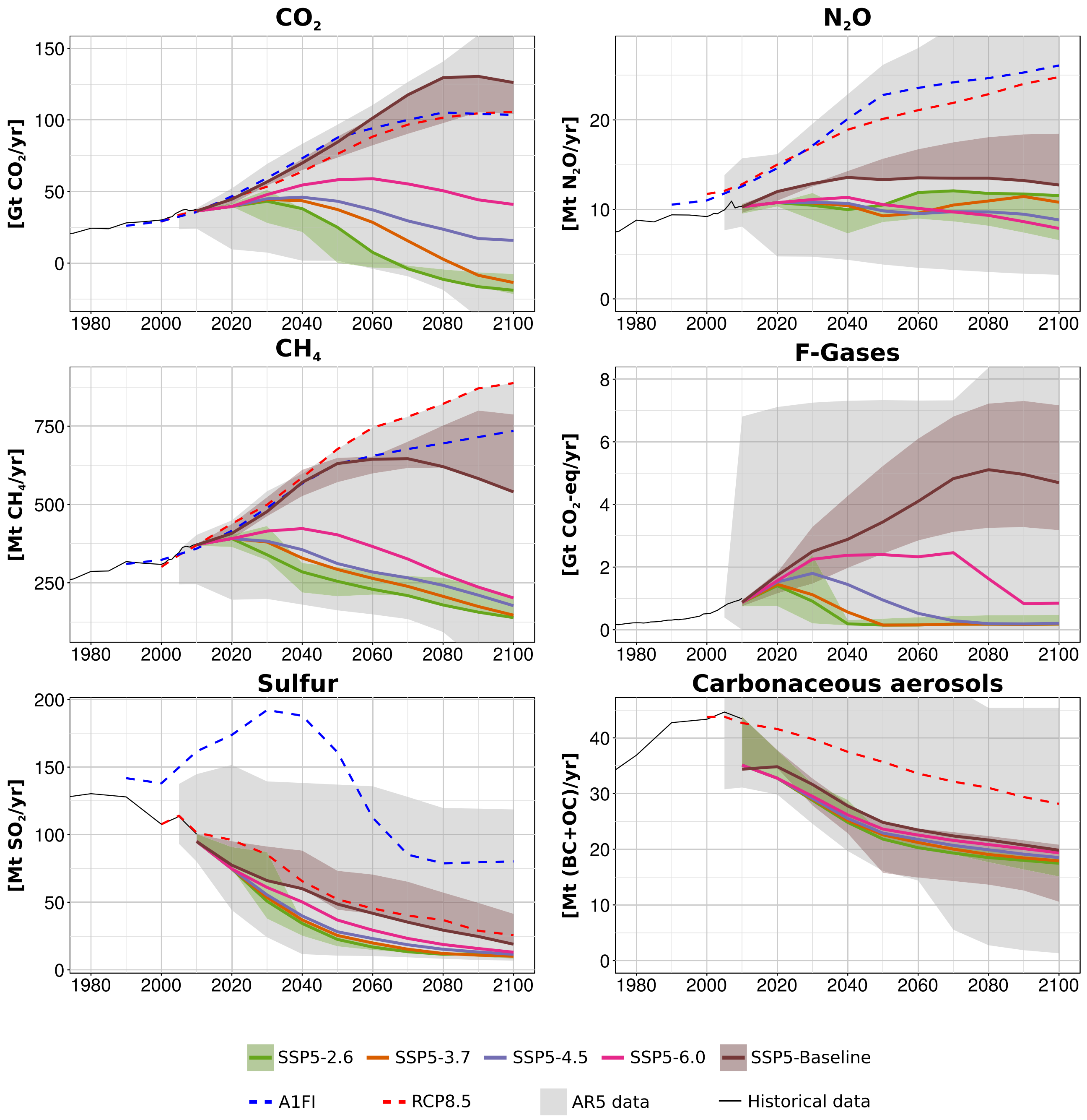

**Fig. 9.** Emissions of $CO_2$, $N_2O$, $CH_4$, F-Gases, Sulfur and carbonaceous aerosols (OC + BC) for the SSP5 baseline and mitigation cases as derived by REMIND-MAgPIE. The SSP5 baseline emissions are compared with the emissions in the RCP8.5 and the A1FI marker scenario from SRES. Also shown are the funnels spanned by all SSP5 IAM interpretations for SSP5-Baseline and SSP5-2.6 (lighter colors) and the 5th to 95th percentile range of emissions scenarios in the AR5 scenario database. Differences in base year emissions are due to calibration to different data sources.

contribution of short-lived climate forcers (SLCFs) being rapidly reduced due to the implementation of air pollution measures (SOM Fig. S1.15). Forcing varies widely in the mitigation cases, ranging from a deceleration of baseline trends (SSP5-6.0) to a peak and decline of the forcing trajectory in the most stringent mitigation cases (SSP5-3.4, SSP5-2.6). The resulting median global mean temperature response (for a climate sensitivity of 3°C) ranges from 5°C warming since preindustrial times in the baseline case to 2°C warming in SSP5-2.6 offering only a median chance to stay below the 2°C target (Fig. 10). Thus, the SSP5-2.6 marker scenario exhibits a higher overshoot than RCP2.6 due to rapid expansion of fossil fuel use and only moderate climate policies in the near term.

## 5. The economics of SSP5 baseline and mitigation scenarios

The economic consequences of the different SSP assumptions are particularly visible in the food and energy markets, which are highly relevant for achieving development goals. Food prices, reflecting the marginal production costs of food commodities, decrease strongly (SSP1) or moderately (SSP5 and SSP2) in the SSP

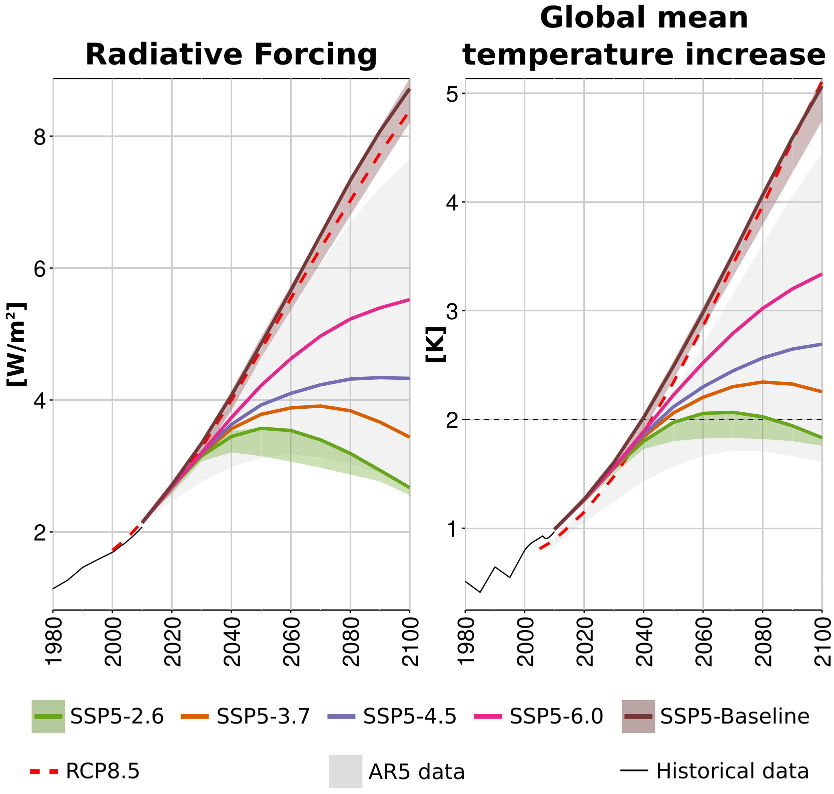

**Fig. 10.** Radiative forcing and temperature in the SSP5 baseline and mitigation marker scenarios. The projections are compared with the RCP8.5 and the A1FI marker scenario from SRES. Also shown are the funnels spanned by all SSP5 IAM interpretations for SSP5-Baseline and SSP5-2.6 (lighter colors) and the 5th to 95th percentile range in the AR5 scenario database.

baseline cases derived by REMIND-MAgPIE (Fig. 11). This is due to the combined effect of increasing agricultural productivity over time (SOM Fig. S1.9) and the peak and decline (SSP1) or stabilization (SSP5 and to a lesser degree SSP2) in food demand (Fig. 1). Combined with significant (SSP1 and SSP2) and very strong (SSP5) growth in global economic output, the income share spent on food (=food expenditure in percent GDP) decreases by an order of magnitude until 2100 in SSP1 and SSP5, and somewhat slower, but still by a factor three, in SSP2 (Fig. 12). Although the risk of undernourishment is not a direct function of overall food availability, the strong emphasis of the SSP1 and SSP5 narratives on lessening inequality suggests that the number of undernourished people will decline rapidly in these worlds.

In contrast, the price of electricity, as a proxy for the availability of modern energy, increases in SSP5-Baseline (Fig. 11), particularly in the second half of the century after gas and oil use have peaked and coal is increasingly used for liquid fuel production (Fig. 3). This compares to rather stable electricity prices in SSP1 and SSP2 as

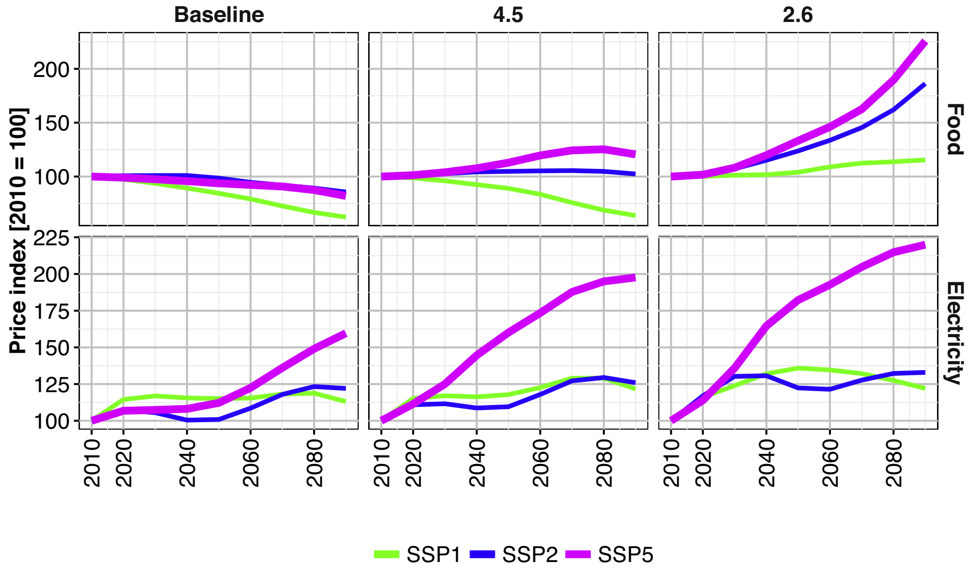

**Fig. 11.** Global electricity and food price developments across SSP1, 2, 5 for the baseline and two mitigation cases as derived by REMIND-MAgPIE.

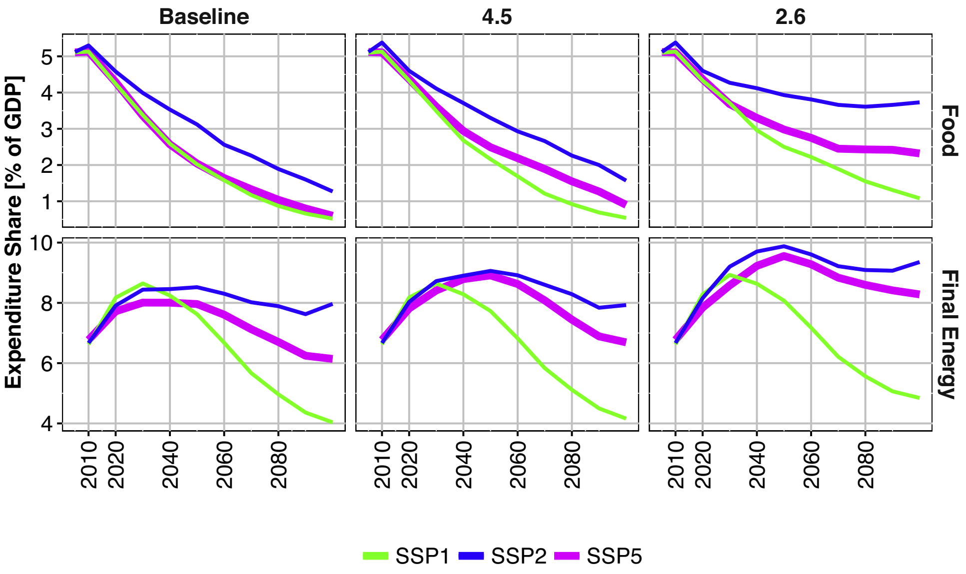

**Fig. 12.** Global expenditure shares for food and final energy across SSP1, 2, 5 for the baseline and two mitigation cases as derived by REMIND-MAgPIE.

projected by REMIND-MAgPIE despite lower fossil fuel resources, but also lower energy demand. However, the simultaneously growing economic output results in a slight decrease in the income share spent on energy (=energy expenditure in percent GDP) in SSP5 despite the increase in energy prices and a strong increase of energy demand. Energy expenditure shares are lower than in SSP2 (which features slower GDP growth), yet higher than in SSP1, where energy expenditure is reduced by a factor of two by the end of the century (Fig. 12). We thus conclude that SSP5-Baseline faces no increase in economic challenges to cover its rapidly growing energy demand due to rapid economic growth.

The economics of energy and land-use are significantly altered in the mitigation cases. Food prices increase due to more limited availability of land for food production and the pricing of residual emissions from agriculture. Energy prices increase as well since fossil fuels are replaced with capital intensive low carbon technologies at the margin. As a result in SSP5-2.6, food expenditure no longer falls below 1% of GDP, but only halves to 2–3% by the end of the century. Energy expenditure increase to a peak at nearly 10% during the main low carbon transition period and then stabilizes at levels above 8% (Fig. 12). The mitigation impacts on food and energy prices and expenditure shares are much smaller in the SSP1 scenario due to its much lower energy and food demand. This shows the important enabling effect of energy efficiency (Riahi et al., 2012; Kriegler et al., 2014b; Luderer et al., 2013) and low-meat diets (Popp et al., 2010) for mitigation policies.

Mitigation measures are reflected in an effective price on greenhouse gas emissions, which in the case of the shared climate policy assumptions for SSP5 is moderate in the near term and adapted towards the long-term forcing target after 2040 (see SOM Section S4 for a detailed discussion). Fig. 13 (upper panel) summarizes the resulting carbon prices in 2050. Carbon prices increase strongly with forcing target, often more than doubling when moving to the next level of stringency. However, the underlying SSP assumptions have a similar large effect on carbon prices, with SSP5 showing significantly higher carbon price levels than SSP1. Thus, much stronger policy intervention is needed in SSP5 to push out abundant fossil fuels and dampen energy demand growth (Kriegler et al., 2016).

The scope of the mitigation challenges can also be measured in terms of the direct macro-economic impacts of mitigation, as for example measured by the reduction in household consumption relative to the baseline case without mitigation policy (Clarke et al., 2014). Importantly, this metric is a measure of gross mitigation costs, and does not include reduced climate impacts nor the co-benefits or adverse side effects of mitigation. As shown in Fig. 13 (lower panel) the mid-century consumption losses in the mitigation scenarios exhibit a similar pattern as the carbon prices, with mostly a doubling of costs when moving to the next stringent mitigation target, and fourfold or even higher mitigation costs in SSP5 than SSP1. This confirms the initial characterization of SSP5 as a world with high socio-economic challenges to mitigation, in contrast to SSP1 with low challenges and SSP2 with intermediate challenges to mitigation.

## 6. Discussion

This paper presents the coupled energy, land-use, emission scenarios associated with SSP5, and compares them with the SSP1 and SSP2 interpretations by the REMIND-MAgPIE integrated assessment modeling framework, the SSP5 interpretations of three other IAMs, and the RCP8.5 and SRES A1FI marker scenarios from the literature. The fossil-fueled development in SSP5 leads to a scenario with very high fossil fuel use, energy demand and $CO_2$ emissions in the baseline. It marks the upper end of the scenario literature in many of these dimensions as shown by a comparison with the AR5 scenario database. The SSP5 emissions developments in the baseline case result in a radiative forcing pathway very close to RCP8.5. Nonetheless, mitigation measures can reduce emissions strongly enough to forcing levels obtained in RCP2.6 in 2100, albeit with a higher overshoot with only a median chance to limit mid-century peak warming to 2°C in the SSP5-2.6 marker scenario. Therefore, SSP5 can be combined with climate model projections based on all RCPs (with some qualification for RCP2.6) within the new scenario framework.

It is shown that the share of GDP spent on energy and food continues to decrease in the SSP5 baseline case despite the rapid increase in energy and food demand. This favorable economic outlook is consistent with the SSP5 narrative of rapidly improving

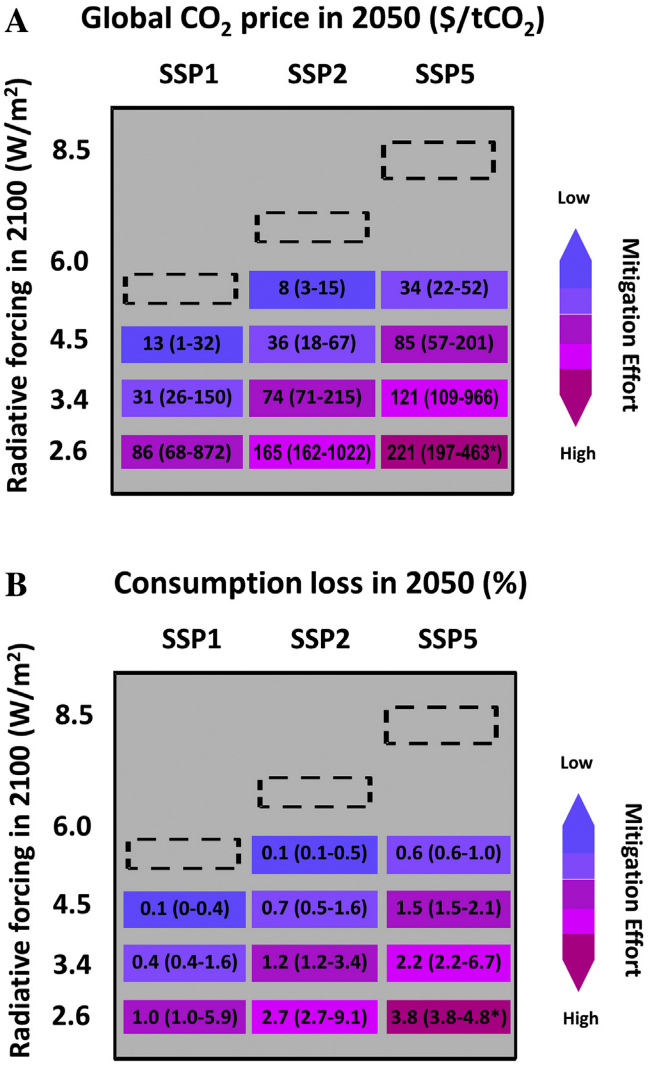

**Fig. 13.** Carbon prices (upper panel) and consumption losses (lower panel; as percent of consumption in the baseline case) for SSP1,2,5 (columns) and the 6.0, 4.5, 3.4, and 2.6 mitigation cases (rows). Results from the REMIND-MAgPIE SSP scenarios are shown before the brackets, and the range across REMIND-MAgPIE, AIM/CGE, WITCH-GLOBIOM, and GCAM (CO$_2$ prices only. GCAM does not model consumption losses) is shown in brackets. The SSP5-2.6 scenario was found infeasible in WITCH-GLOBIOM, thus the upper end of the SSP5-2.6 range (*) cannot be compared to the other matrix cells. Carbon prices and mitigation costs are highly model dependent (Kriegler et al., 2014b, 2016), and therefore the focus is on the relative change of these quantities between cells. IMAGE and MESSAGE-GLOBIOM also derived SSP1 and SSP2 mitigation scenarios, but are not included here to provide a comparison between matrix cells without sampling bias. The full range of mitigation costs across all models and SSPs is presented in Riahi et al. (2017).

human development including better access to modern energy and higher food security. The paper investigates the direct impact of mitigation policies on the physical and economic developments in the energy, land and emissions sectors in SSP5 and confirms the assumption that SSP5 is a world with high socio-economic challenges to mitigation. No analogous statement on the socio-economic challenges to adaptation in SSP5 can yet be made, as both the SSP5 baseline and mitigation scenarios in this study do not yet account for climate change impacts, a subject of future research (see Section 7).

The SSP5 scenarios are contingent on the SSP5 narrative, and therefore should not be understood as a prediction of how the future might evolve. The goal is to provide these scenarios as part of a larger set of plausible SSP-based futures that differ strongly in their baseline assumptions and implications for climate policy. The paper describes the uncertainty in the SSP5 scenario outcomes due to the use of different interpretations of the SSP5 narrative within four different integrated assessment models (AIM/CGE, GCAM, REMIND-MAgPIE, WITCH-GLOBIOM). Generally, the variation of energy-land-emissions outcome across SSPs (due to the different storylines of the SSPs including socio-economic uncertainty) appears to be larger than the model uncertainty. Model uncertainty however is particularly significant for land use changes especially concerning pasture and forest areas, associated land use change emissions, the primary energy mix in the mitigation cases, and the magnitude of resulting carbon prices and mitigation costs. Interestingly, the variation of consumption losses across SSPs in REMIND-MAgPIE is of a similar order of magnitude than the uncertainty in mitigation costs reported in the 5th Assessment Report of the IPCC (Clarke et al., 2014). It will be an important research questions to what extent model uncertainty in energy, land-use, emission and economic outcomes associated with SSP5 will grow as more interpretations of SSP5 by a larger set of models become available over time.

SSP5 combines the highest economic growth among the SSPs with strong reliance on fossil fuels and energy intensive consumption patterns because it was designed to describe a world with very large challenges to mitigation, and not because it hypothesizes high fossil fuel use and resource intensity to be a precondition of high growth. A scenario with high economic growth, but limited fossil fuel availability is also conceivable as for example described by the A1T scenario in the SRES (Nakićenović and Swart, 2000) and the mitigation scenarios in this study. Moreover, the scenario literature has repeatedly highlighted transition scenarios with a focus on broader human well-being rather than rapid economic growth (Raskin et al., 2005). In the SSP family, this is represented by SSP1 with similarly rapid convergence of income levels as in SSP5, but a focus on resource efficiency, healthy diets and lowering environmental impacts.

## 7. Concluding remarks on future uses of SSP5

There are a number of specific research questions that the SSP5 scenario family is particularly suited for. First, it is an obvious question whether strong economic growth, rapid development, and effective institutions can actually materialize in the baseline scenario with its massive greenhouse gas emissions and implied very high climate change impacts. The SSP5 scenario family is ideally suited to investigate this question about the limits to adaptation, in particular since the narrative foresees a large adaptive capacity due to rapid development and technological progress. On the mitigation side, SSP5 is a world with a propensity to engage in carbon dioxide removal (CDR) and other climate engineering practices given its high challenges to mitigation and its emphasis on technological solutions. Thus, SSP5 scenarios offer a consistent context to analyze the impacts and side-effects of deploying such technologies.

With their underlying high economic growth and resource intensive consumption patterns, the SSP5 scenarios exhibit high levels of exploitation of raw materials, high calorie and meat rich diets, and potentially large waste streams raising questions about their environmental sustainability beyond climate change. The extent to which environmental sustainability and human and economic development are interlinked has been a core concern of global futures studies conducted by, e.g., the Global Scenario Group (Raskin et al., 2010), the Global Environmental Outlook (UNEP, 2003) and the Millenium Ecosystem Assessment (Carpenter et al., 2005). To this end, the SSP5 scenario family provides a new generation of energy and resource intensive scenarios that can be used to investigate a range of broader sustainable development questions: to what extent are perceived environmental boundaries beyond climate change transgressed, how much can this impact economic growth and societal development, what mitigation and adaptation measures in these dimensions can be implemented to safeguard economic and human development, and how do these challenges to sustainable development compare with the challenges in an SSP1 world emphasizing resource and energy efficiency? We therefore conclude that the SSP5 scenario family has multiple uses and can be expected to provide a range of new insights on climate mitigation, adaptation and sustainable development.

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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.2016.05.015.

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