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Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives

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A R T I C L E I N F O

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A B S T R A C T

Energy is crucial for supporting basic human needs, development and well-being. The future evolution of the scale and character of the energy system will be fundamentally shaped by socioeconomic conditions and drivers, available energy resources, technologies of energy supply and transformation, and end-use energy demand. However, because energy-related activities are significant sources of greenhouse gas (GHG) emissions and other environmental and social externalities, energy system development will also be influenced by social acceptance and strategic policy choices. All of these uncertainties have important implications for many aspects of economic and environmental sustainability, and climate change in particular. In the Shared-Socioeconomic Pathway (SSP) framework these uncertainties are structured into five narratives, arranged according to the challenges to climate change mitigation and adaptation. In this study we explore future energy sector developments across the five SSPs using Integrated Assessment Models (IAMs), and we also provide summary output and analysis for selected scenarios of global emissions mitigation policies. The mitigation challenge strongly corresponds with global baseline energy sector growth over the 21st century, which varies between 40% and 230% depending on final energy consumer behavior, technological improvements, resource availability and policies. The future baseline CO_2-emission range is even larger, as the most energy-intensive SSP also incorporates a comparatively high share of carbon-intensive fossil fuels, and vice versa. Inter-regional disparities in the SSPs are consistent with the underlying socioeconomic assumptions; these differences are particularly strong in the SSPs with large adaptation challenges, which have little inter-regional convergence in long-term income and final energy demand levels. The scenarios presented do not include feedbacks of climate change on energy sector development. The energy sector SSPs with and without emissions mitigation policies are introduced and analyzed here in order to contribute to future research in climate sciences, mitigation analysis, and studies on impacts, adaptation and vulnerability.

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1. Introduction

The transformation of the energy sector is important in addressing the challenges of both climate change mitigation and adaptation. On the one hand, it is the main contributor to Greenhouse Gas (GHG) emissions and air pollution (Blanco et al., 2014) resulting in much emphasis being put on emission mitigation (Clarke et al., 2014). On the other hand, global energy systems are vulnerable to climate change and can serve as means for adaptation to a changing climate (Bazilian et al., 2011; Chandramowli and Felder, 2014; Ciscar and Dowling, 2014; Fricko et al., 2016, 2017; Isaac and van Vuuren, 2009). The energy sector transformation also has important implications for social and environmental sustainability goals (von Stechow et al., 2015). This study introduces and discusses the energy sector results of the Integrated Assessment Models (IAMs) quantification of the five Shared Socio-economic Pathways (SSPs) for the baselines and two climate change stabilization levels. The SSPs provide a framework for assessing socio-economic challenges to climate change mitigation and adaptation, as well as analyzing broader social and environmental sustainability issues.

Various energy sector challenges and the way they are addressed are crucial in shaping future transformation pathways with important implications for mitigation and adaptation. Five key energy sector challenges, to support basic human needs, development and well-being are (i) energy demand growth and its coupling with demographic and economic drivers, (ii) the phasing out of traditional forms of energy use, improving energy access and modernization of energy use in the context of structural economic change, (iii) the expansion of primary energy supplies, (iv) the future of existing and build-up of new energy infrastructures and technologies, and (v) the GHG and other pollutant emissions and their mitigation. These challenges are related to key scientific debates on global and long-term developments in the energy sector. The coupling between socio-economic development patterns and energy demand has been identified as a fundamental issue for understanding the scale and structure of energy demand (Csereklyei and Stern, 2015; Grübler et al., 2012; Jakob et al., 2012; Schäfer, 2005). Historical trends show that economic development is correlated with modernization of the energy mix towards higher shares of electricity and gases and lower shares of solid and liquid energy carriers (Fouquet and Pearson, 2012; Grübler et al., 1999). These shifts are related to preferences for alternative lifestyles expressed in consumer choices, transportation modes, etc. Dedicated energy access policies are also discussed as means to enhance the modernization process in developing countries (Pachauri et al., 2013). The availability, trade and use of fossil fuels, and energy security concerns, are key energy sector challenges strongly related to mitigation (McCollum et al., 2014; Bauer et al., 2015; McGlade and Ekins, 2015). The lock-in of incumbent technologies and the diffusion of innovative technologies for energy demand and supply, much depend on socio-economic and political factors as well as the development of technology performance and costs (Goldemberg, 1998; Unruh, 2000). Overcoming limitations on up-scaling of innovative technologies and their wide diffusion are key energy sector challenges for policy makers (van Sluisveld et al., 2015; Wilson et al., 2013). The corresponding scientific debates are far from providing final conclusions, but are opening up the perspective on multiple uncertainties that are crucial for climate challenges and broader sustainability issues.

Although the energy sector developments are subject to strong near-term inertias, their fundamental factors and driving forces – such as demographic change, economic growth, and technological change – become fluid and uncertain as the perspective stretches towards the middle, or even the end of the 21st century. Therefore, the shape of future energy sector pathways is deeply uncertain as are the resulting social, economic, political and environmental consequences. A way of addressing the uncertainty is to formulate alternative sets of input assumptions for dynamic drivers, parameters and policy settings that give rise to different energy transformation pathways. To ensure consistency of these assumptions along multiple dimensions, they are often bundled into scenarios derived from broad narratives about socio-economic futures, as in the Special Report on Emission Scenarios (SRES, Nakicenovic et al., 2000). The use of scenarios is a common tool applied to study possible long-term energy futures (Nakicenovic et al., 2000; Riahi et al., 2012; Turkenburg et al., 2000), particularly for those with a focus on climate change stabilization (Bruckner et al., 2014; Clarke et al., 2014).

The SSPs are the next generation of scenarios, succeeding the SRES published in 2000, and they are intended to serve as reference scenarios for various assessments in the area of climate change challenges, as well as broader sustainability issues (van Vuuren et al., 2014). The SSPs complement the Representative Concentration Pathways (RCPs, van Vuuren et al., 2011) by adding the underlying socio-economic narratives and quantitative pathways consistent with the challenges to mitigation and adaptation. The SSPs include five vastly different global futures (SSP1-5) that start at the narrative for alternative development pathways, and vary, depending on how the energy challenges (i-iv) are addressed (O'Neill et al., 2017). The SSP baselines represent pure reference cases that exclude (i) climate change mitigation policies (such as the Paris agreement) and (ii) feedbacks from climate change on socio-economic or natural systems. For example, using the SSPs as a starting point for mitigation policies (Kriegler et al., 2014), enables the differences to the reference baseline to be examined. This will be part of this study. The climate change mitigation cases describe energy system pathways that reach forcing levels consistent with the RCPs. The energy sector pathways presented in this paper are part of broader SSP scenarios that also cover other key dimensions. The overview including overall GHG emissions is given by Riahi et al. (2017), whereas land-use and competition (incl. bio-energy) is analyzed by Popp et al. (2017) and air pollution implications are explored by Rao et al. (2017).

The remainder of this paper is organized as follows. In Section 2 we introduce the energy sector SSPs at a qualitative level and the scenarios that have been computed for each SSP. Section 3 presents the quantitative energy sector pathways. Finally, Section 4 summarizes the energy sector SSPs, discusses the results and indicates directions for future research using the SSPs.

2. Methods

Six leading IAMs have contributed to the quantification of the energy-land-use-emissions outcomes associated with the five SSP narratives (see Table 1 for an overview and the Supplementary material for details on the IAMs). The SSPs have been quantified using IAMs that integrate economy, energy, land-use, and climate, covering all GHGs and air pollutants. For each SSP, the results of one IAM have been selected as the Marker that best illustrates the narrative of the SSP. For the results presented here, we focus our discussion on the Marker scenarios and provide cross-model ranges. For the selection of the Marker scenarios see the Supplementary material and Riahi et al. (2017).

The SSPs have been implemented into the IAMs at various levels. For the SSP driver scenarios of population and economic growth, quantitative projections, that are developed in line with the SSP narratives, have been adopted by all models (Dellink et al., 2017; KC and Lutz, 2017; both in this issue). These projections are complemented by qualitative harmonization on energy sector

Table 1
Overview of SSPs and IAMs.

SSP	Descriptor	Marker team (institution)	Marker paper in this Special Issue	Also computed by
SSP1	Sustainability	IMAGE (PBL)	Van Vuuren et al. (2017)	All
SSP2	Middle-of-the-Road	MESSAGE-GLOBIOM (IIASA)	Fricko et al. (2017)	All
SSP3	Regional Rivalry	AIM/CGE (NIES)	Fujimori et al. (2017)	IMAGE, GCAM, MESSAGE-GLOBIOM, WITCH-GLOBIOM
SSP4	Inequality	GCAM4 (PNNL)	Calvin et al. (2017)	AIM/CGE, WITCH-GLOBIOM
SSP5	Fossil-fueled Development	REMIND-MAgPIE (PIK)	Kriegler et al. (2016)	AIM/CGE, GCAM, WITCH-GLOBIOM

development along the lines of the basic and the extended SSP narratives (Section 2.1). The SSPs have been implemented into the IAMs by systematically varying the assumptions along various dimensions according to the basic and the extended SSPs. The models derived a Baseline scenario and additionally calculate a set of climate policy scenarios to achieve long-term climate change stabilization at various ambition levels (Section 2.2).

2.1. The SSP narratives for the energy sector

The *basic* SSPs narratives (O'Neill et al., 2017) provide the overall scenario framing for the various dimensions that determine the challenges to mitigation and adaptation. The general characteristics of the basic SSPs relevant for the energy sector are summarized in Fig. 1. These also relate to the energy sector challenges mentioned above. The *extended* SSPs are designed to interpret the basic SSPs and serve to qualitatively harmonize the models providing more detail in three domains of the energy sector: (i) final energy demand development, (ii) energy conversion technologies including specific mitigation technologies and (iii) the fossil fuel supply. Detailed information is provided in the Supplementary material. The extended SSPs guided modeling teams to derive assumptions for their model implementations. No attempt was made to prescribe shared quantitative assumptions because the teams follow different modeling approaches and, thus, different parameter definitions apply.

The main points of the *extended* SSPs with a perspective on the energy sector are as

SSP1 sustainability—taking the green road

Economic value creation decouples from material consumption and final energy demand. This is combined with a strong

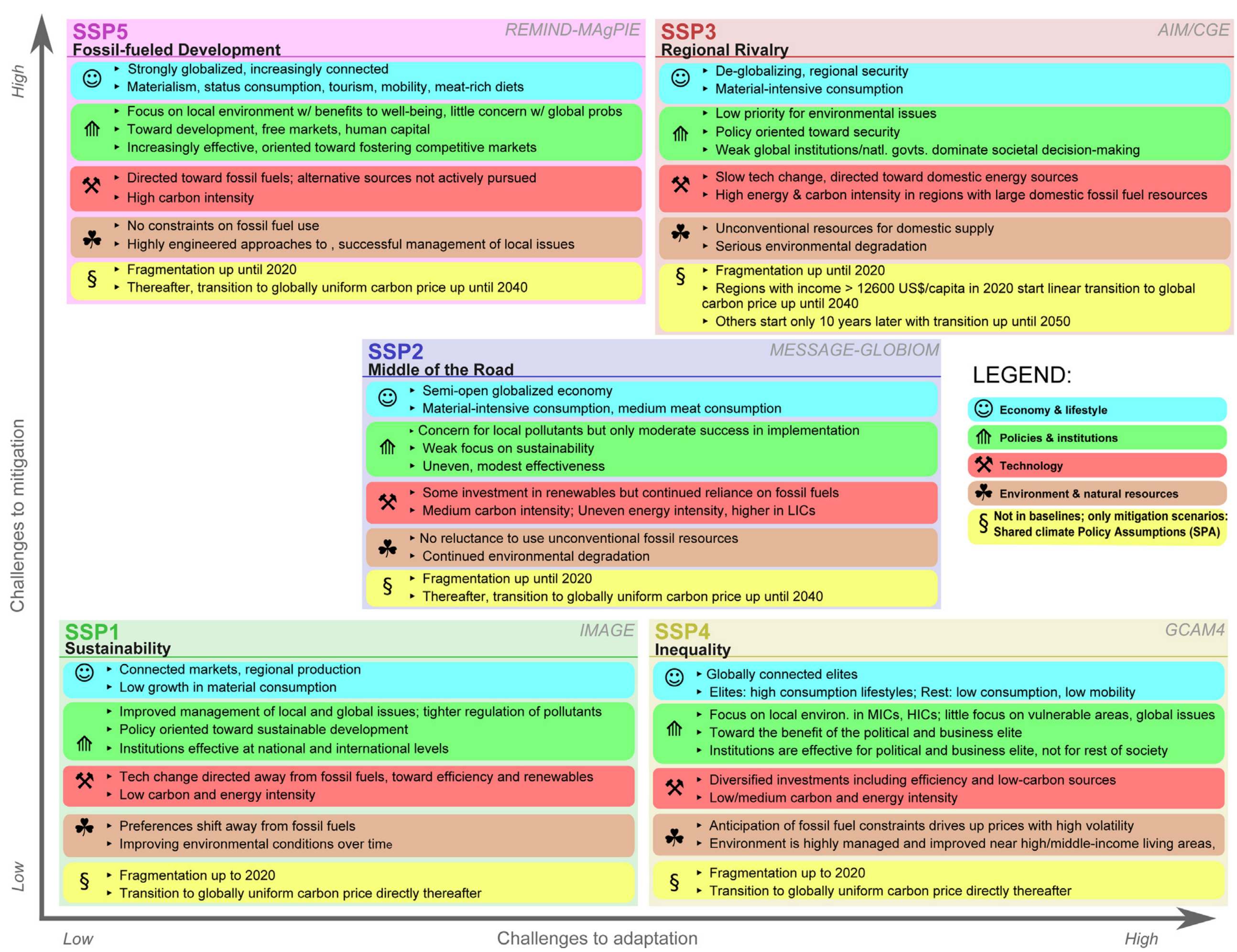

Fig. 1. Overview of *basic* SSPs, the energy sector elements of the narratives and the SPA specifications (O'Neill et al., 2017). HIC and MIC abbreviations for High and Medium Income Countries, respectively. The Shared Climate Policy Assumptions (SPAs), colored in yellow, are not used in the baseline scenarios, but only in the mitigation scenarios introduced in Sec. 2.2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

modernization of energy use due to technological development, lifestyle changes and policies supporting energy efficiency improvements. Social acceptability is generally low for all technologies (particularly nuclear) except non-biomass renewables. The latter is subject to rapid technological improvements, but these are particularly slow in the fossil fuel sector.

SSP2 middle-of-the-road

Energy intensity improvements continue at global historical growth rates with a medium degree of regional convergence. Technological improvements are medium for all technologies and social acceptance does not shift markedly. This results in moderate growth of the energy sector, no remarkable shifts in the primary energy mix and continued modernization of the final energy mix.

SSP3 regional rivalry—a rocky road

Fast population growth in developing countries is combined with slow economic growth and income convergence. Slow technological development, material intensive lifestyles and little environmental awareness maintain the strong link between economic activity and final energy demand. Modernization of final energy use is slow and traditional bio-energy use remains important. Concerns about energy security and national policies support the use of domestic coal and limit trade in energy.

SSP4 inequality—a road divided

Final energy demand is moderately coupled to economic activity, which results in large disparities in energy consumption because of slow income convergence. In poor countries the use of traditional bio-energy remains important. Technological improvements in conventional oil and gas extraction are high, but policies are restrictive in high-income countries because of local pollution problems. There are significant technological improvements in nuclear power. Investments are risky because of generally volatile markets.

SSP5 fossil-fueled development—taking the highway

Energy demand growth is strongly coupled to economic growth, particularly in the transportation sector due to materially intensive lifestyles with a strong preference for intensive material consumption patterns including high transportation demand. Technological development in the fossil fuel sector, including CCS based mitigation technologies, is rapid and social acceptance is high. Non-biomass renewables, however, are subject to low social acceptance.

The five SSPs are similar to earlier scenario frameworks developed for various purposes (van Vuuren et al., 2012). The SRES scenarios produced by the IPCC, being the predecessor of the SSPs, show some similarities with the SSPs (Vuuren and Carter, 2014). The relationship to the broader scenario literature is also discussed by O'Neill et al. (2017).

2.2. Baseline, climate forcing targets and shared climate policy assumptions

By design, the SSP Baselines in this study do not account for any climate policies that aim to reduce emissions and they also do not consider feedbacks of climate change impacts on the economy, the energy sector or the land system (Moss et al., 2010). This approach enables the development of reference scenarios that can then be perturbed by mitigation policies and feedbacks from the climate system resulting in impacts and adaptation measures. Implementation of the SSP narratives required baseline scenarios to consider non-climate change mitigation policies such as bio-fuel mandates that affect energy pathways, but do not vary with the imposition of climate targets (see Table S12).

For climate change stabilization, the scenarios aim to obey specific radiative forcing levels similar to those in the RCPs. In this paper, we focus on a moderate target (similar to RCP4.5) and a stringent target (similar to the RCP2.6). The former case reaches 4.2 W/m^2 by 2100 and increases to 4.5 W/m^2 in the long-run. The latter case is similar to RCP2.6 that reaches 2.6 W/m^2 in 2100, but allows for a peak and decline of forcing during this century. The policy implemented into the IAMs to achieve these targets is explicit GHG pricing that is determined by the long-term target, as well as short-term ambition and regional participation. The explicit GHG prices can also be interpreted as comprehensive policy packages that vary in intensity such that the marginal abatement costs implicitly correspond with the GHG price.

Near-term policies are subject to implementation barriers that limit timing and regional participation as well as the transition to a globally uniform carbon price. These Shared Climate Policy Assumptions (SPAs) are harmonized across modeling teams and consistently defined for each SSP (Kriegler et al., 2014). In the *long-run,* GHG emissions from all countries, sources and sectors are priced at a uniform level determined by the stringency of the long-term forcing target.

The basic specifications of the SPAs for the energy sector are included in Fig. 1. All SPAs assume moderate and regionally fragmented carbon pricing up to 2020, reflecting to a large extent the Cancun pledges (Kriegler et al., 2015). There are three alternative transitions from a regionally fragmented to a globally uniform GHG pricing regime to achieve the long term forcing target. In SSP1 and SSP4 with low mitigation challenges, uniform GHG emission pricing is implemented immediately after 2020. In SSP2 and SSP5 with medium and high mitigation challenges, respectively, all countries transition from their moderate GHG price levels to the global GHG price by 2040 as necessary in order to reach the forcing target. Finally, SSP3, anticipating little international cooperation and significant challenges to mitigation, assumes that it is only countries with per-capita income above world average that will start the transition from 2020 until 2040, whereas the other regions begin after 2030 and converge to the global uniform carbon price by 2050. Thus, the level, shape, and regional fragmentation of the GHG pricing regime vary with SSP and long term forcing target.

The regional results are presented in aggregates of five mega regions: (i) OECD, (ii) Reforming Economies (REF), (iii) Latin America (LAM), (iv) Asia and (v) Middle East and Africa (MAF). The relationship between aggregates and native model regions is not exactly the same for all models and is reported as part of the Supplementary material.

3. Results of energy sector pathways

The transformation of the energy sector is driven by the scale and structure of future final energy demand as described in Section 3.1. This includes regional convergence patterns and the modernization of final energy use. We then discuss the complementary developments of the primary energy supply side (Section 3.2) with a particular focus on the fossil fuel sector. Section 3.3 provides a more detailed analysis of electricity sector pathways. Finally, we discuss the energy-related CO_2 emissions from fossil fuel combustion and industry resulting from the interplay of energy supply and demand (Section 3.4).

3.1. Final energy demand

3.1.1. Total final energy growth

Final energy demand is linked to the fundamental socio-economic drivers of population development, economic growth, technological change and lifestyles. Historically, global final energy

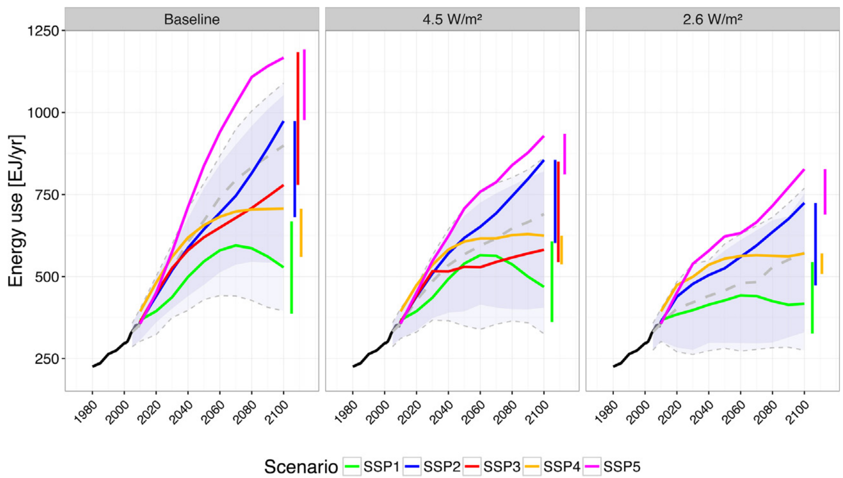

Fig. 2. Global final energy pathways for the marker SSPs and different climate forcing targets. Historical data from IEA (2012). The grey shaded areas show the range of the AR5 database (ranges of the 1/99-percentile in light grey and 5/95-percentile in dark grey); the thick dashed grey line is the median. All AR5 scenarios without climate policies were used for the baseline range; the scenarios from the categories IV&V and category I were used for the 4.5 W/m^2 and 2.6 W/m^2 targets, respectively (as categorized in the IPCC AR5 WG3 Annex II.10.3). The bars on the right hand side of the panels depict the 2100 ranges of all six SSP models for each SSP. Table S13 summarizes the results.

demand from 1980 to 2010 grew annually on average by 1.6%; for the decade 2000–2010 it was even faster (2%/yr), IEA (2012).

The SSP marker scenarios cover a range between 600 and 1200EJ/yr and feature very different time profiles. They mostly lie, however, within the range of baseline AR5 scenarios (Fig. 2). The SSP2 baseline continues a similar trajectory to historical growth rates (1.4%/yr until 2050). This is similar in SSP3 and SSP4, which show a decelerating growth in the second half of the century mainly because economic growth slows down. The high economic growth and material intensive lifestyle in the SSP5 scenario leads to high final energy growth rates (2.1%/yr until 2050) that are similar to the high growth phase between 2000 and 2010. The SSP1 decouples economic growth from final energy demand which leads to a peak in 2070.

A major finding of the mitigation cases is that the 2.6 W/m^2 target is not solvable for SSP3 by any model because of weak near-term policy ambition and insufficient emission mitigation resulting from slow technological progress. For the other cases under climate policies, the demand reductions are greater for SSPs with significant mitigation challenges and tighter stabilization targets. In comparison with the unmitigated cases, the level and the range of final energy demand across the SSPs Is lower. In scenarios with fast growth in final energy use, for instance SSP5, demand is more significantly reduced than in slow energy demand growth scenarios such as SSP1. Final energy consumption, however, does not reduce below the level already achieved in 2010 as can be observed in the SSP1 marker case.

3.1.2. Regional trends in final energy demand

The development of final energy demand is strongly correlated with economic growth and therefore to patterns of income convergence. However, the degree of coupling is uncertain (e.g. Csereklyei and Stern, 2015). The SSPs span a broad range of scenarios for economic growth and regional income convergence (Dellink et al., 2017) as well as very different patterns of coupling to final energy demand. This leads to very diverse regional convergence patterns of per-capita income and per-capita final energy demand. Moreover, based on observed data, annual per-capita final energy consumption below 30GJ/capita is correlated with low levels of development, whereas observations around 100GJ/capita are correlated with very high levels of development (Lamb and Rao, 2015; Steckel et al., 2013 and literature therein). In future, the efficiency of generating human development from final energy could increase through technological improvements.

Panel (A) of Fig. 3 depicts per-capita final energy consumption against per-capita income on a double log-scale of the marker baseline scenarios for the five macro regions. Panel (B) compares final energy per-capita use for developed and developing regions in the baseline and mitigation cases for the marker and also depicts the cross model ranges. In SSP2 the historic coupling between GDP and energy is ongoing, although GDP grows somewhat faster than energy. In OECD countries the per-capita income triples by 2100, while per-capita final energy consumption increases from 140 to 170GJ. Developing and emerging economies follow less energy intensive development pathways, while the coupling with GDP growth is stronger than in developed regions. The convergence in energy use remains incomplete.

In SSP1 and SSP5 global GDP growth is stronger and convergence faster than in SSP2, which also leads to faster convergence of energy use across regions, but at very different levels. In SSP1 global consumption patterns and lifestyles quickly shift to less material intensive modes, while more efficient technologies diffuse quickly and energy demand decouples from economic growth for annual per-capita incomes beyond US $30,000 measured in purchasing power parity (PPP). Developing and emerging economies follow less energy intensive pathways because they are leapfrogging inefficient end-use technologies and, hence, human development is achieved more efficiently. OECD countries show decreasing energy use as more efficient technologies replace obsolete equipment. In SSP5 economic development is quickest; the coupling with energy demand is strong and rapid economic convergence coincides with convergence in energy use leading to a quadrupling in developing and emerging economies. The preference for energy intensive consumption patterns and low energy prices lead to strong income-driven energy-demand growth.

In SSP3 and SSP4 global economic growth is weak and income convergence slow. Consequently, the long-term disparity in final energy use is greater than in SSP2 with energy use being higher in developed countries and lower in emerging and developing countries.

The regional energy demand patterns change with the imposition of policies designed to achieve climate change stabilization (see panel (B)). In all SSPs the coupling between economic and energy demand growth becomes weaker and some

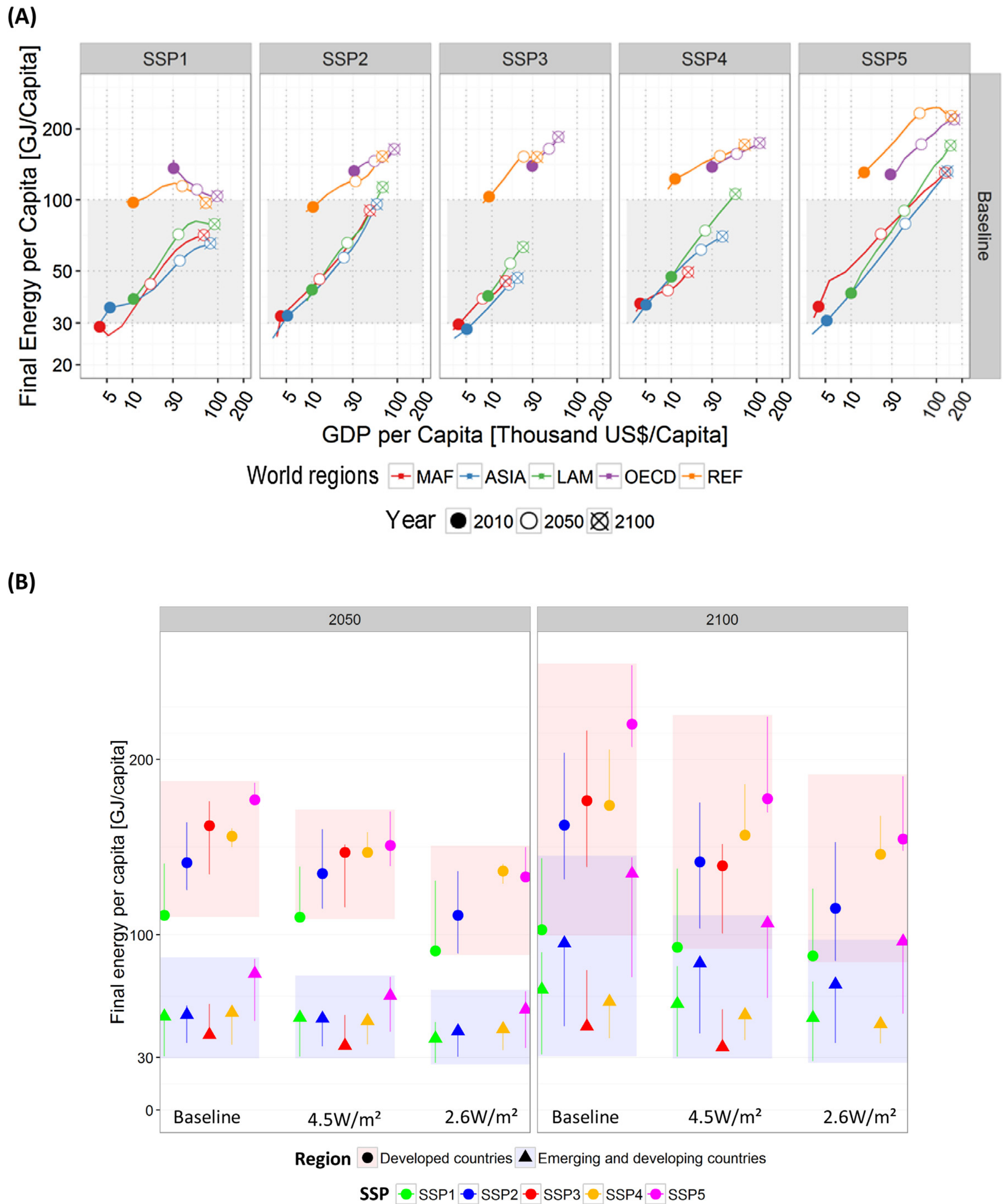

Fig. 3. Development of regional final energy use per capita. The top panel shows the development against per capita GDP (PPP) for the five macro regions across SSP marker baselines. The variations in 2010 values between the regions are due to different definitions of native model regions by the modeling teams. The bottom panel shows the per-capita final energy use in the developing (MAF, ASIA, LAM) and the developed regions (OECD, REF). The vertical lines represent model ranges for each SSP; the colored boxes indicate ranges across all SSPs.

scenarios even feature decoupling. In SSP2 the decoupling results in decreasing final energy per-capita use in the OECD, if the strong stabilization target is achieved. In the SSP3 scenario the moderate stabilization target leads to full decoupling in the low-income regions, and the per-capita energy demand in MAF remains at 30GJ/capita. This leads to an increase in the relative energy gap between high- and low-income countries. In SSP5 the coupling is also dampened in response to climate policy, but a full decoupling is not achieved in any region.

3.1.3. Final energy mix

The share of electricity in the global final energy mix increased from 11% in 1980 to 18% in 2010. This contrasts with a decrease in the share of solids from 14 to 10% and for liquids from 45% to 41% over the same time horizon (IEA, 2012). The future development of the final energy mix across SSPs is shown in Fig. 4.

The SSP2 scenario features a moderate modernization of final energy use. The use of liquids increases by two thirds up to 2050 and remains roughly constant thereafter. The picture is mixed

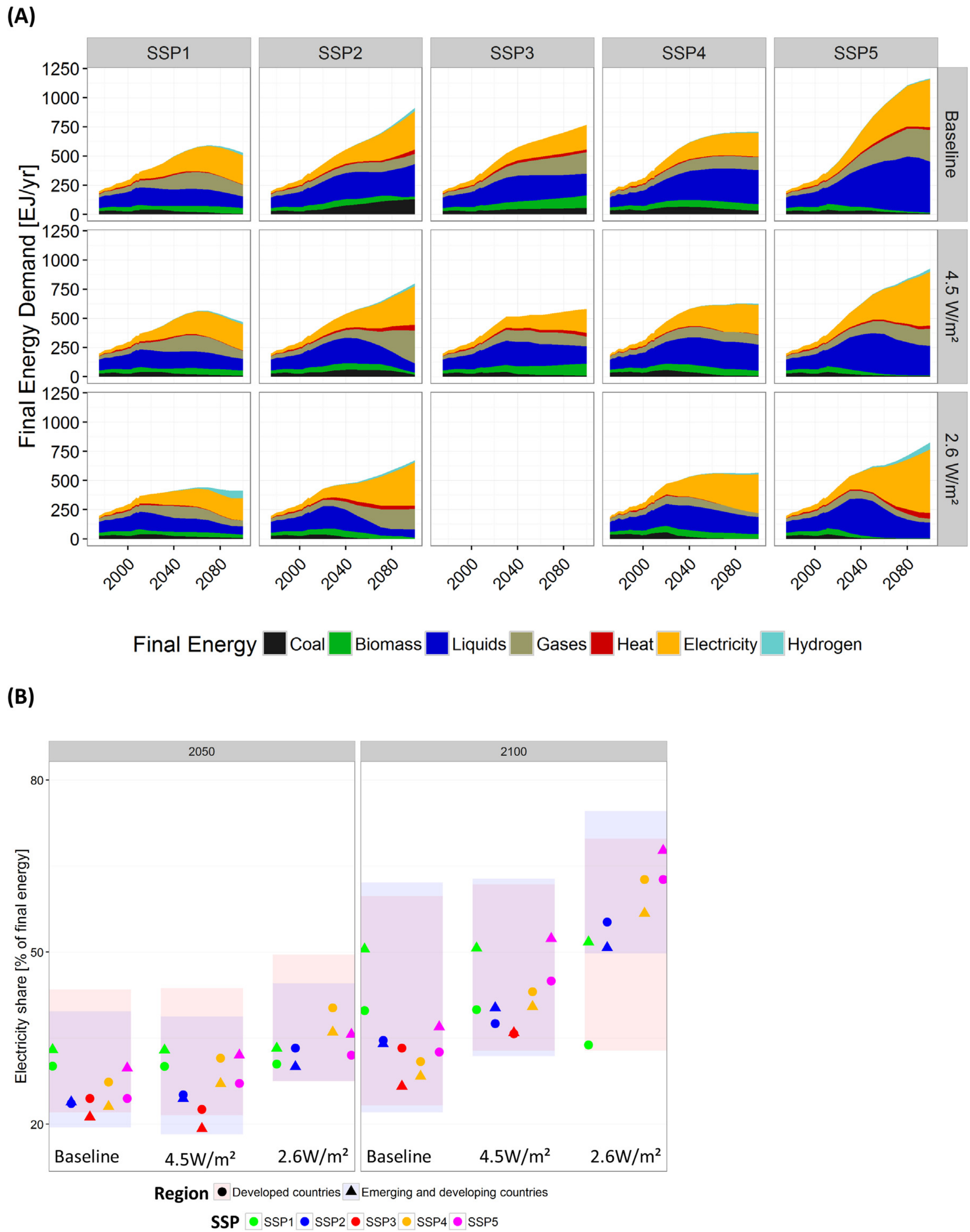

Fig. 4. Panel (A) shows global final energy mixes across SSPs and climate stabilization cases. Electricity accounts for the consumption of final electricity consumers and does not include losses for transmission and distribution. Historic data is taken from IEA (2012). Please note that the SSP4 marker team (GCAM) applies a different aggregation of IEA energy balance data between energy transformation sectors and end-use sectors, to that of other modeling teams. Consequently, the historical data is different, particularly with respect to industrial final energy. Panel (B) shows the electricity shares in Developed countries and Emerging and Developing countries. The boxes indicate the full range across SSPs and models for these regions.

when looking at traditional and modern energy carriers. On the one hand, electricity consumption more than doubles from 2010 to 2050, and quintuples by 2100. On the other hand the direct use of coal doubles (triples) by 2050 (2100) to fuel industrial development in Asia and MAF. In the climate change mitigation scenarios, energy sector modernization accelerates with higher shares of electricity (incl. electrification of transport) and a faster phase out of solid energy carriers.

SSP1 and SSP5 show similarities in the trends in energy modernization, although the scale of total final energy consumption is very different. Electrification is rapid, particularly in developing countries. Demand for gaseous fuels grows substantially up until 2040 in both scenarios, only beginning to deviate from 2040 onwards. The most remarkable difference, however, is in the transportation sector where there is different growth of liquid fuel demand. This reflects alternative pathways of future mobility with a stronger focus on a transformation towards public transport and electric or hydrogen cars in SSP1 compared to a more conventional transport system with high demand for transportation services in SSP5. This is important for the mitigation challenge. In an SSP5 world the decarbonization of the transportation sector is the main bottleneck, which is addressed by decreasing demand and increasing the use of electric and hydrogen vehicles and bio-fuels. In contrast, the low transport energy demand in the SSP1 baseline eases the mitigation challenge significantly and the necessary changes for achieving climate change stabilization remain relatively small (see Figs. S14–S15). Moreover, with increasing stringency of mitigation policies electricity demand decreases in SSP1, whereas it increases in the long-run in SSP5 (see also Fig. S12).

The two scenarios with slow growth and convergence (SSP3 and SSP4) feature slower modernization in the global final energy mix. The electrification in developing regions is slow and does not catch-up with that of developed regions. Additionally, solids continue to play a prominent role in energy use. There is little acceleration of the slow modernization of SSP3 in the climate change mitigation cases because the development of technology is stagnant. To achieve the climate change stabilization targets, in SSP3 non-electric energy demand is reduced; electricity demand is only reduced in Asia and the MAF region. In contrast, there is stronger electrification throughout the century in SSP4, due to the stronger technology development in the end-use sector. This helps reduce non-electric energy use in climate change stabilization scenarios. However, there is no modernization in SSP4 for large parts of the population in poor economies in Asia and the MAF region. These countries continue to rely on traditional biomass use.

3.2. Primary energy supply

3.2.1. Primary energy mix

From 1980–2010, global primary energy supply grew from 300 to 510 EJ/yr. Fossil fuels dominate, supplying around 85% of total primary energy. Over the same period the increase in the shares of natural gas (17%–22%) and coal (25%–29%) have been at the expense of oil (44% to 34%). The increase in coal use was concentrated in Asia, whereas natural gas has increased more evenly around the world. Oil has become more important in developing and emerging economies. Bioenergy (mostly traditional bio-energy) has remained stable at around 10% while the contribution of non-biomass renewables has declined (IEA, 2012).

In Fig. 5 the SSP2 baseline scenario projects a substantial growth in primary energy use with the domination of fossil fuels, whereas renewables, such as wind and solar, increase only slightly. Oil supply peaks in 2050, and grows again at the end of the century with expanding non-conventional oil production. Coal and natural gas increase continuously throughout the century and show 50% and 125% higher production levels, respectively, from 2010 to 2050. Also, in the SSP3 and SSP5 baselines, fossil fuels dominate primary energy supply. In SSP5 this is represented by remarkably high shares of modern and clean natural gas, whereas conventional and dirtier coal expands significantly in SSP3. The small challenges to mitigation are associated with decreasing shares of fossil fuels, which even peak around mid-century in the baseline, with renewables expanding in SSP1 and SSP4 also relying to a significant degree on nuclear power. In both cases bio-energy plays a significant role, but in SSP1 it is used in modern ways, whereas in SSP4 it is used in traditional modes as a result of income inequality and failure of energy access policies.

In the stabilization cases primary energy consumption is reduced and fossil fuels peak before mid-century. By 2050 the fossil fuels share is, however, still significant. The most significant reduction is in the use of coal. Its use in combination with CCS is higher in the moderate stabilization cases. Natural gas still increases in stabilization scenarios and the combination with CCS becomes more significant for the achievement of the 2.6W/m^2 target. Fossil fuels with CCS are important in the SSP2 and SSP5 scenario, but do not play a prominent role in the SSP1 scenario. This is because policies prioritize sustainability and corresponding technological developments. The faster diffusion of renewable energy technologies is also determined by the extended SSP1 narratives regarding political and technological factors. The high share of renewables in SSP5 is due to limitations in nuclear as well as high oil and gas consumption that cannot be combined with CCS, for example in the transportation sector.

Bio-energy is a key option for mitigation in the energy sector. In SSP1 the need for the combination with CCS is moderate, whereas in SSP5 the demand for biofuels as well as for carbon offsets is high due to high energy demand and the abundance of cheap fossil fuels. The demand for bio-energy in SSP5 grows to 480EJ/yr by 2100. The SSP2 shows less deployment of bio-energy with CCS, but in this scenario carbon offsets are also generated by afforestation, which is not available in SSP5 marker because policies support engineering based solutions. The demand for agricultural crop land decreases after global population has peaked in SSP5 (see Popp et al. (2017) for details). There is also significant bio-energy deployment in SSP4, including atmospheric carbon dioxide removal using BECCS, because of strong technological improvements developed by the innovative global elite. In SSP3 the potential for emission reductions as well as the deployment of carbon dioxide removal technologies is strongly limited because of slow technological development and high land demands from a growing population. This means the 2.6W/m^2 target cannot be achieved. It is worth mentioning that bio-energy in combination with CCS is mostly used to produce liquid fuel rather than electricity (Fig. S15), which reconfirms earlier findings (Rose et al., 2013).

3.2.2. Fossil fuel use

Fig. 6 shows the cumulative fossil fuel extraction over the 21st century and compares it with reserves as reported by Rogner et al. (2012). For coal use the intuitive ranking of the SSP baselines is in accordance with the challenge to mitigation. It is worth noting that SSP3 projects very high coal extraction in Asia, but much less so in the OECD and Reforming Economies compared with the SSP5. The energy security concerns assumed in SSP3 establish a significant limit on trade between regions (Note: very high global coal extraction in SSP3 is projected by only one model, which assumes relatively free energy trade). By contrast, in SSP5 the world economy is more globalized and trade is more integrated, which leads to significant exports from coal rich regions in the OECD and the Reforming Economies to fuel development in rapidly growing economies. In SSP1, however, cumulative coal use is less than the reserve that is considered available today. In the stabilization scenario, of all the SSPs, a large portion of the coal reserves are not utilized, even in the moderate 4.5 W/m^2 case.

Oil and gas are not equally ranked across SSP baselines mainly because of differences in availability and trade of fossil fuels across SSP narratives. SSP5 has the highest consumption of gas because it is (i) relatively clean, (ii) technological improvements increase supply, (iii) globalized markets allow for trade, and (iv) social acceptance for gas related infrastructure is high. In SSP3 gas extraction is low because technological progress and demand growth are slow and trade is subject to energy security concerns. In

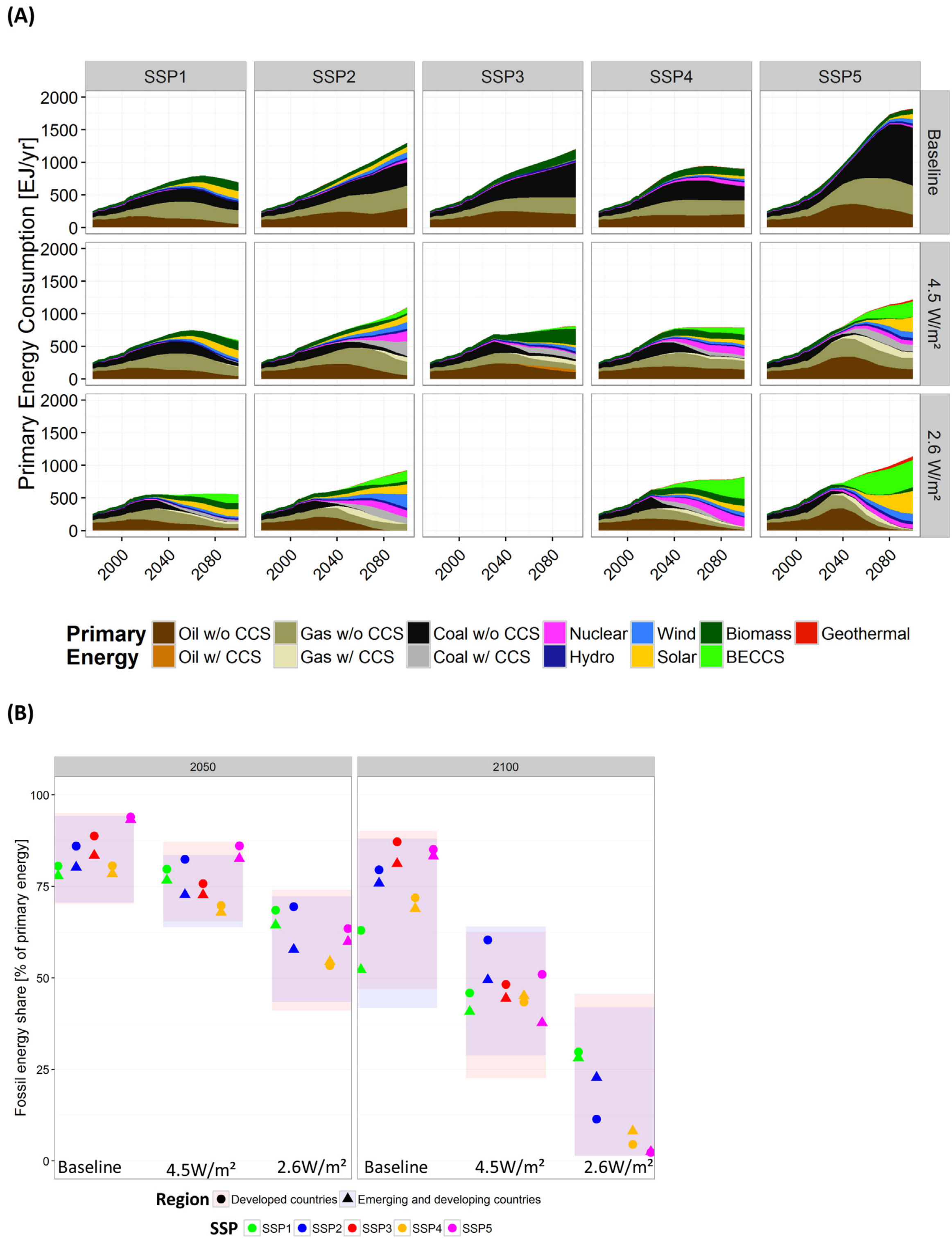

Fig. 5. Panel (A) shows global primary energy mix across SSPs and climate policy cases. Accounting for primary energy follows the direct equivalence approach. Historical data is taken from IEA (2012). Panel (B) shows the fossil fuel shares. The colored boxes indicate the ranges across all SSPs and models for the two regions.

SSP1 gas extraction is relatively high, because clean gas replaces relatively dirty coal in the baseline. In the stabilization cases of all SSPs, gas consumption remains significant and exceeds the conventional reserve estimate.

Oil extraction in the SSP baselines exceeds current estimates of conventional and unconventional reserves and also opens resources. Again, SSP3 ranks low because of slow technological progress. SSP2 is close to SSP5 because SSP2 features less coal-to-liquids production (see Supplementary material). In the 4.5 W/m^2 mitigation case all scenarios, except SSP1, result in cumulative oil consumption that exceeds current reserve estimates of conventional and non-conventional oil. For SSP5, this even holds in the 2.6 W/m^2 case. The sensitivity of oil extraction to climate change mitigation policies is smaller than for gas and coal. It is particularly

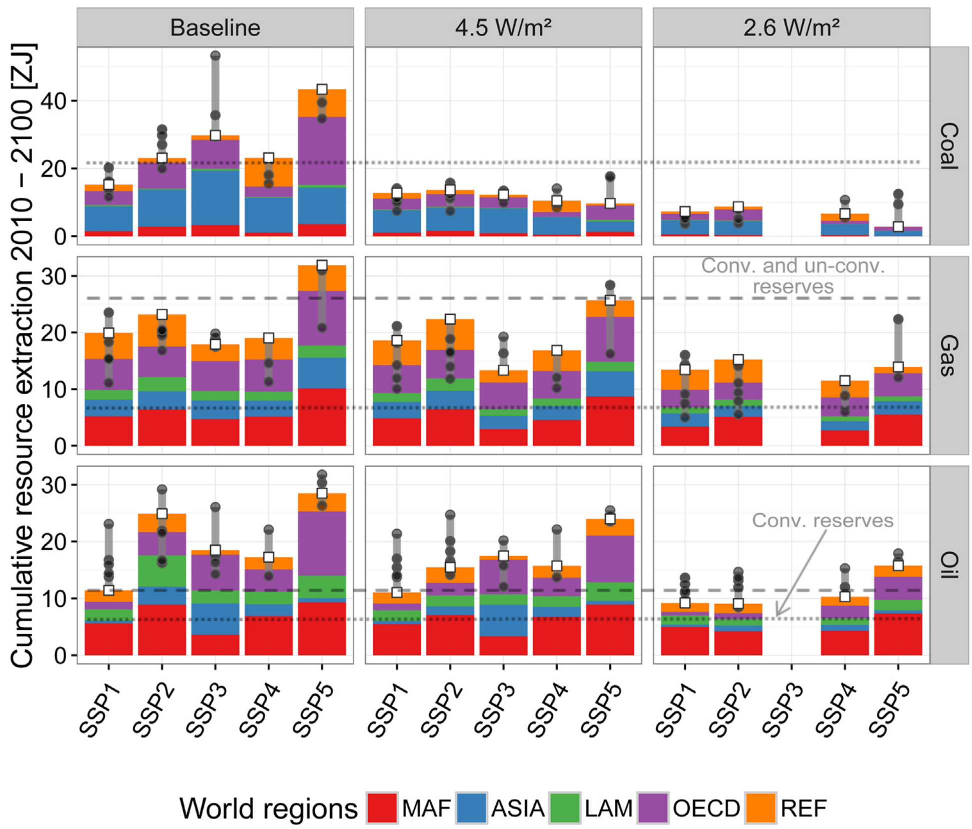

Fig. 6. Cumulative fossil fuel extraction by region. These figures include own-consumption for operating extraction activities. The grey horizontal lines indicate the global ranges across models; white squares represent global values of marker models and grey dots represent non-marker models. For the purpose of orientation the dotted lines depict the level of conventional reserves (proven and economically recoverable) whereas the dashed lines additionally include unconventional recoverable reserves for oil and gas (Rogner et al., 2012). We do not show resources because reported figures are original-in-place quantities, which require additional assumptions on recovery factors. The grey vertical lines indicate the range across models. The white square indicates the SSP marker model, whereas the black dots indicate the non-marker models. Note: the regional allocation pattern is different for non-marker models than for marker models.

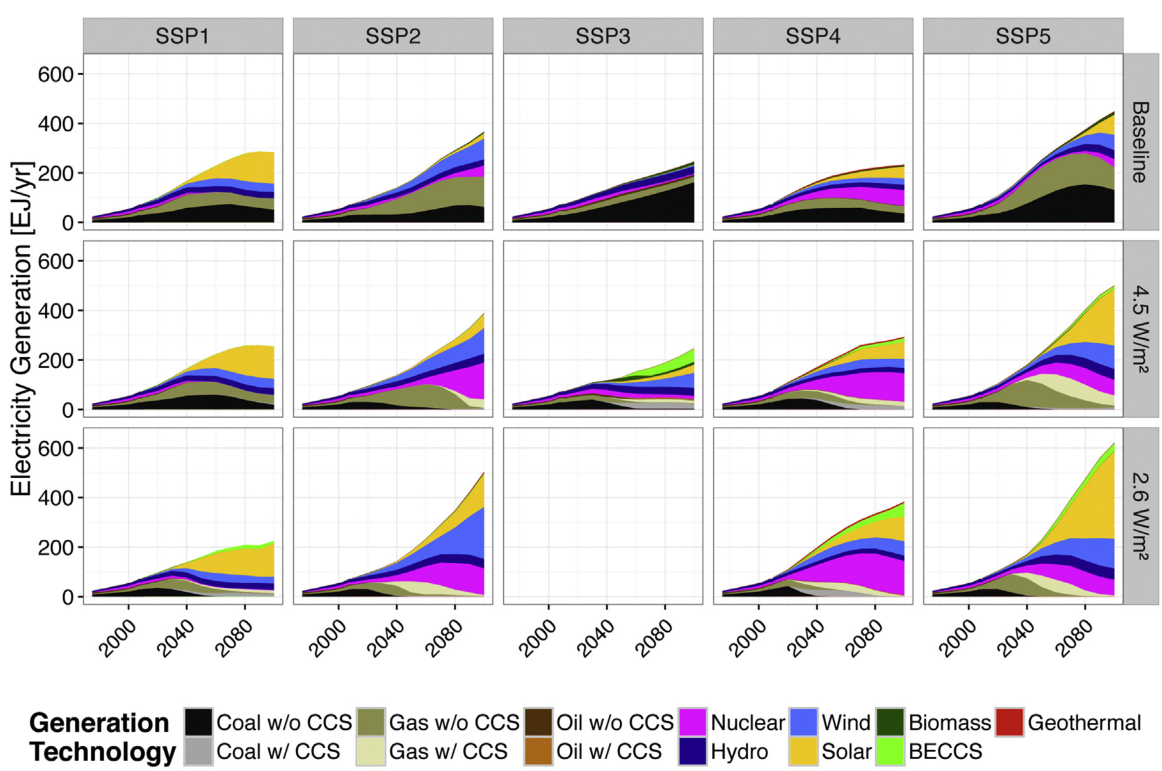

Fig. 7. Global power generation by technology differentiated by SSPs and policy scenario. Historical data 1980–2010 is taken from IEA (2012).

small for the MAF region, which is endowed with most of the low cost oil (McGlade and Ekins, 2015).

3.3. Electricity sector

The electricity sector is critical for mitigating climate change because although its generation causes significant CO_2 emissions, the largest number of decarbonization options are available in this sector (Bruckner et al., 2014). It also has the potential to displace fossil fuel consumption in other sectors through electrification of energy end uses. The electricity sector is important for the challenges to adaptation because thermal generation and hydroelectric capacities served nearly 98% of global power supply in 2010; their sensitivity to ambient temperatures and water availability makes them vulnerable to global warming.

In baseline scenarios, the main uncertainty through the middle of the century relates to the overall size of the electricity sector and the dominant generation technologies in the mix (Fig. 7, see also Fig. S12). SSP2 projects a shift towards gas (80EJ/yr in 2050) that is also featured in SSP5 (160EJ/yr in 2050), but in a faster growing electricity market triggered by abundant gas availability. Towards the end of the century SSP5 shifts to coal (~150EJ/yr) and non-bioenergy renewables (180EJ/yr). Nuclear power is much less widely used due to its unfavorable economics and issues with public acceptance. SSP3 projects electricity sector growth that mainly depends on coal fired power stations (170EJ/yr in 2100) from domestically produced coal. The shift towards gas is limited in SSP1 because renewable technologies, such as wind and solar, improve quickly and are socially more acceptable SSP4 is similar but the role of nuclear power is much more prominent (65EJ/yr in 2100), which reflects the differences with SSP1 in social acceptability and technological development. SSP1 and SSP4 baselines feature significantly increasing shares of non-fossil based power generation technologies, which reduces the challenge to mitigation.

The power sector reacts strongly in scale and structure in the stabilization cases. Across all SSPs, the very significant reduction of coal fired power generation is a robust feature. Besides this, the same stabilization target the SSPs differ very much in scale and structure of the power sector. The use of CCS only slightly counteracts the first-order phase-out of coal from the power sector. The CCS option is more relevant for gas fired power stations, particularly in the moderate stabilization case of SSP5. The large deployment of nuclear power in SSP2 and SSP4 (up to 150EJ/yr) is possible because it is assumed there is high social acceptance for this technology. Limited social acceptance, however, dampens the expansion of nuclear power in SSP1 and also in SSP5. The share of electricity from bio-energy with CCS is small in all SSPs, due to a combination of low conversion efficiency and the demand for bioenergy to produce liquids and/or hydrogen, which can also be combined with CCS (see Fig. S15). The large-scale deployment of non-bioenergy renewables in the stringent stabilization case of SSP5 is due to the extremely high carbon prices that exceed US$300/$tCO_2$ post-2050. This leads to high costs for the residual emissions from fossil fuels with CCS. The high shares of wind and solar lead to very high electricity prices, because the integration of these variable sources requires substantial energy storage.

3.4. Energy sector emissions

This section focuses on energy sector CO_2 emissions from fossil fuels and industry; emissions of CH_4 and F-gases are discussed in the Supplementary material (see Fig. S10–S11). The challenge to mitigation is influenced by the cumulative residual emissions allocated to the energy sector.

CO_2 emissions from the combustion of fossil fuels account for a dominant share of past global anthropogenic greenhouse gases. The IPCC reports that cumulative global CO_2 emissions from fossil fuel combustion and industry from 1750 to 2010 amount to 1350$GtCO_2$, of which coal accounted for 650$GtCO_2$, oil 470$GtCO_2$ and natural gas 180$GtCO_2$ (Blanco et al., 2014). The annual average growth rate was 1.7%/yr between 1970 and 2010 accelerating during the last decade to 2.2%/yr, based on van Vuuren et al. (2011).

The SSP baseline scenarios span a broad range of possible emission futures (Fig. 8) reflecting the large underlying differences in the development of final energy demand and primary energy supply across SSPs. The SSP baselines cover the uncertainty range of IPCC AR5 baseline emissions. The ranking of emissions (incl. marker and cross model ranges) is consistent with the mitigation challenges for the SSPs. SSP2 begins with moderate growth rates (1.2%/yr for the period 2010–50) which accelerates during the second half of the century as more coal is used to fuel economic development. The high mitigation challenge in SSP5 with high final

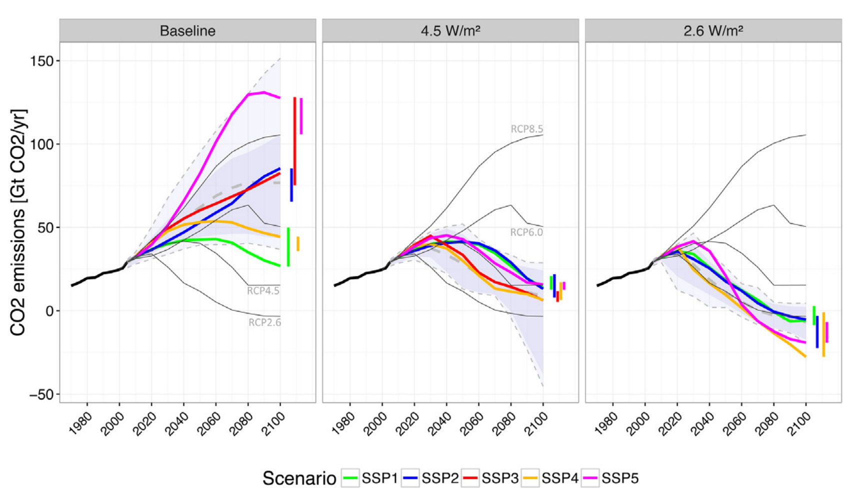

Fig. 8. Global CO_2 emissions from fossil fuels and industry for baseline and stabilization at 4.5 W/m^2 and 2.6 W/m^2. The thin lines show the RCP scenarios (van Vuuren et al., 2011). The grey shaded areas show the range of the AR5 database (ranges of the 1/99-percentile in light grey and 5/95-percentile in dark grey); the thick grey dashed line is the median. All AR5 scenarios without climate policies were used for the baseline range; the scenarios from the categories IV&V and category I were used for the 4.5 W/m^2 and 2.6 W/m^2 targets, respectively (as categorized in the IPCC AR5 WG3 Annex II.10.3). The bars on the right hand side of the panels depict the 2100 ranges of all SSP models for each SSP.

energy demand and abundant fossil fuel supply corresponds with high growth rates (2.3%/yr up to 2050) exceeding the RCP8.5 scenario. The SSP3 scenario is also subject to a substantial mitigation challenge but slow economic growth implies slower emission growth. The low mitigation challenge in SSP1 and SSP4 is associated with peaking baseline emissions resulting from slow energy demand growth and a gradual shift away from fossil fuels.

Stabilizing long-term climate change at a common target level across SSPs narrows the range of emission pathways considerably, but there are still remarkable differences; for the stabilization cases the various SSPs cluster around the original RCPs, but the range in emissions is notable. The moderate forcing target still allows for considerable emissions towards the end of the century. The stringent 2.6 W/m^2 target requires early peaking and net negative emissions in all SSPs. For the SSP3 scenario this target level is not achievable because of the little near-term policy ambition assumed in the corresponding SPA3, the small technological capacity to reduce or offset CO_2 emissions and the high GHG emissions from the land-use sector due to population growth. SSP5 shows a high and late emissions peak due to the difficulty of locking abundant fossil fuels out of the system and a considerable volume of net negative emissions by the end of the century. In contrast, the small mitigation challenge in SSP1 corresponds to a relatively smooth emission profile.

GHG emissions from the land-use sector are very difficult to reduce in the stabilization runs of SSP3 and SSP4 (see Popp et al., 2017). Therefore, stronger CO_2 emission reductions from fossil fuels and industry are required. Moreover, SSP5 does not allow for GHG emission off-sets from afforestation, in contrast with the other SSPs. This puts a larger mitigation burden on the energy sector.

4. Summary, discussion and future research

This study describes the energy sector pathways of the SSPs focussing on the marker scenarios for each SSP, which illustrates the implementation of the varying challenges of climate change mitigation and adaptation. The SSP implementation was based on quantitative assumptions of population and GDP as well as interpretations of the technology, lifestyle and policy elements of the SSP narratives. The SSP quantification applied detailed energy system models that are fully integrated with land-use models and models of the macroeconomy. They fully represent all GHG and air pollutant emissions, and the interrelationship with bio-energy markets that are in competition with other ecosystem services incl. food markets. The SSPs address common energy sector challenges in different ways and resulting energy sector developments span a broad range of possible futures at the global level (see Table 2). These also take account of regional differences. The implementation of SSPs into IAMs delivered scenarios that well reflect the SSP narratives and locate the set of SSP scenarios in the space of climate change mitigation and adaptation challenges. Compared with the bundle of scenarios used in IPCC AR5 the SSPs span a similar range, as a result of differences originating in the SSP narratives and corresponding implementations in the IAMs. Consequently, the quantitative pathways are consistent with the challenges to mitigation and adaptation. This is reflected in the SSP baseline scenarios (e.g. CO_2 emissions, final energy demand, fossil fuel reliance etc.) as well as being a means of reducing emissions in the policy scenarios (e.g. demand reductions, decarbonization of energy supply etc.).

The SSP2 baseline describes a middle-of-the-road scenario with medium challenges to mitigation and adaptation. SSP2 relies on medium assumptions for key input parameters such as population dynamics and economic growth. The implementation into IAMs projects a scenario that continues historic trends observed over recent decades including the dominance of fossil fuels, convergence of per-capita energy consumption, gradual modernization of energy use and greater energy access and therefore increasing GHG emissions.

Table 2
Summary statistics of baseline SSPs at the global level for the year 2100 indexed to 2010 = 100, except for forcing and fossil share, which is given in% of total primary energy consumption.

		Challenge to mitigation				
		Small		Medium	High	
		SSP1	SSP4	SSP2	SSP3	SSP5
	Forcing [W/m^2]	5.0	6.4	6.5	7.2	8.7
	CO_2 Emissions	84	136	262	253	396
Kaya factors	Population	101	135	132	183	107
	Per-capita Income	821	390	607	227	1426
	Energy Intensity	17	34	34	52	21
	Carbon Intensity	59	76	97	117	121
Other Indicators	Fossil Share [%]	55	70	77	83	84
	Electricity	392	313	515	349	654
	Transport	143	228	275	218	450
	Solids[c]	63[a]	89	191[b]	217	16

[a] Include large share of modern solid bio-energy use in industry and households.
[b] Includes large share of direct coal use in industry.
[c] Includes also direct use of coal in the industry sector.

Challenges to mitigation mainly differ in terms of consumption patterns, technological change, fossil fuel availability and efficiency improvements that lead to the highest (SSP5) and lowest (SSP1) emissions in the un-mitigated baseline cases. SSP1 assumes decoupling of economic growth and energy demand that is achieved by increasing energy efficiency and increased use of renewables. Alternatively, SSP5 assumes strong coupling between GDP and energy demand that is supported by abundant fossil fuel supplies. The global decoupling of GDP growth and energy demand assumed in SSP1 has not been observed (Csereklyei and Stern, 2015), but energy efficiency and demand reduction potentials are considerable (e.g. Sims et al., 2014 for transport). The technological lock-in continues in SSP5 (Unruh, 2000), but mobilization of fossil fuels is unprecedented (Aguilera et al., 2009; Bauer et al., 2016). The different energy sector developments, combined with land-use emissions result in radiative forcing in SSP5 exceeding 8.5 W/m^2 in 2100, whereas it increases to 5 W/m^2 in SSP1. Consequently, mitigation policies aimed at forcing levels of 4.5 W/m^2 or even 2.6 W/m^2 differ in strength and imply very different changes in the scale and structure of energy supply and demand, particularly in the power and the transport sectors.

The two scenarios with high adaptation challenges (SSP3 and SSP4) initially differ from SSP1 and SSP5 with respect to socio-economic drivers. High adaptation challenges are consistent with slow income convergence as well as slow technological change (in SSP3) and diffusion (in SSP4). In SSP4 the business elite develops advanced technologies in the energy sector, but broader diffusion is slow and energy access is a pressing, yet unresolved, issue (Pachauri et al., 2013). The technological progress in SSP3, however, is generally slow and energy security is of great concern in a world of political fragmentation (Jewell et al., 2014). Slow regional income convergence translates into slow convergence in per-capita final energy demand and slower modernization of energy use. The growth of total energy demand and CO_2 emissions is less than (SSP4) or similar (SSP3) to SSP2. A key result is that SSP3, despite high population growth and slow energy intensity improvements, does not generate an increase in radiative forcing to 8.5 W/m^2 until 2100, because economic growth is too slow and energy security concerns limit the tradability and, consequently, the use of coal. The high mitigation challenge in SSP3 however, is reflected in slow technological improvements of mitigation options and small near-term climate policy ambition, which makes the long-term forcing target of 2.6 W/m^2 unachievable. This result is robust across all models that addressed the SSP3 scenario. Even though the near-term policy ambition is stronger, only two models (AIM/CGE and MESSAGE-GLOBIOM) could find a solution for the 2.6 W/m^2 target under SSP3 conditions.

On the technology level the SSPs cover a broad range of vastly different pathways that are subject to many uncertainties. Compared with the existing scenario literature three points are worth highlighting. First, the use of bio-energy in the 2.6 W/m^2 scenario varies across SSPs to a greater degree than in the AR5 database, because SSP5 combines very high energy demand with very high yield increases in bio-energy supply. Moreover, as in previous studies (Rose et al., 2013) the allocation of bio-energy is dominated by liquid fuel production rather than power generation. The option to generate electricity from bio-energy in combination with CCS is also applied. This contributes significantly to the carbon dioxide removal because of the higher capture rate of CO_2 compared with the fuel alternative. The share of bio-energy in the electricity mix, however, remains small. This finding is subject to techno-economic uncertainties of these pre-commercial technologies. Second, electrification has been identified as an important component in mitigation pathways. Krey et al. (2014) and Sugiyama (2014) found electricity shares increased in stricter stabilization cases, whereas absolute increases in electricity were only found in the longer run, in few models (Edmonds et al., 2006). The SSPs depict a more diverse picture. SSP2, SSP4 and SSP5 show increasing shares of electricity and, in the long-run, also higher absolute electricity production. SSP1, however, demonstrates decreasing shares of electricity in developed countries as more stringent stabilization targets are achieved. Finally, the use of nuclear energy is generally less than in the high end scenarios of SRES and AR5 scenarios, which is mostly due to the specific SSP narratives. SSP3 and SSP4 are candidates for high nuclear power, but the energy demand growth is relatively small, whereas the SSP5 with high demand assumes less social acceptance for this technology.

The SSPs serve as a framework for systematic future research of climate change mitigation, climate impacts and adaptation as well as broader sustainability issues aiming to integrate studies from a great diversity of research fields. The SSPs are now fully operational and Riahi et al. (2017) provides a general discussion into their use. The energy sector SSPs are useful for future research in the following four directions.

First, the SSPs differ strongly with respect to energy sector challenges, such as technology diffusion and energy sector modernization, that are tightly interlinked with climate change mitigation and adaptation challenges. The SSPs help researchers to guide and classify their scenarios within a broader framework of the challenges space, which helps to communicate results, compare them with other studies and classify their uncertainties (Trutnevyte et al., 2016). Also, assessments of national and sectoral energy systems can benefit from guidance and classification of assumptions on, for example, energy demand development or fossil fuel availability and trade. Regional and sectoral extensions of the SSPs could be formulated to deepen the scenario framework. Coordination of research in this way helps to link global with regional, national and sectorial studies to improve mutual information flow and synthesis of various studies. Analysis of mitigation could also be enriched by building bridges to social sciences focusing on technology transformations (Geels et al., 2016). Moreover, the SSPs can serve as a starting point to discuss climate engineering options such as solar radiation management in vastly different contexts.

Second, the robustness of policies can be tested in various socio-economic contexts. The climate change stabilization scenarios assumed a combination of short-term second best and long-term first best climate policies given the SPAs and the long-term stabilization targets. The long-term uniform carbon price is a highly idealized policy implementation with very strong institutional requirements. It induces relatively synchronous transformation dynamics, which are indicated by the small differences in the fossil fuel shares between regions shown in Fig. 5(B). To better understand second best policies alternative proposals could be implemented into various SSPs, which would imply very different energy sector and market dynamics across regions (Burke et al., 2016).

Third, the SSPs presented here are designed as reference cases that do not – by definition – consider the impacts of climate change on socio-economic development including the energy sector (Kriegler et al., 2012; Moss et al., 2010). The combination of SSPs and RCPs are essential parts of a broader research framework for the assessment of adaptation challenges because physical impacts derived in collaboration with climate modeling teams (Eyring et al., 2015) are superimposed on socio-economic developments. Future studies on climate change impacts, adaptation and vulnerability, in which the energy sector is relevant, can derive different sets of consistent assumptions about total energy demand and fuel mix from the SSPs. For example, if a country study is interested in the vulnerability of the electricity sector to climate change, the SSPs can guide the choice of assumptions about generation mix and electricity demand. This can also be done for mitigation cases considering changes in the scale and structure of the electricity sector combined with the changes in climate variables that correspond to radiative forcing levels. Evaluating the effects of climate change corresponding to, for example, 4.5 W/m^2 under different power sector configurations (see middle row of Fig. 7) establishes the link between SSPs and RCPs in studies on impacts, adaptation and vulnerability studies.

Fourth, studies on broader social and environmental sustainability issues can also be guided by the energy sector SSPs. For example, the use of materials and land are important drivers of global and regional environmental change that are partly determined by energy sector developments and partly by other socio-economic and technological drivers. Similarly, research into energy access, air pollution and energy security can greatly benefit from energy sector SSPs (Jewell et al., 2014; Pachauri et al., 2013).

The energy sector SSPs presented here aim to provide reference cases for future integration, deepening and expanding research into energy transformation pathways. They constitute a major milestone that link the SSP narratives and different levels of forcing stabilization as described by the RCPs with the quantitative developments of the energy sector. As such they can serve as a basis for more integrative assessments in the future.

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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.2016.07.006.

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