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Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm

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ABSTRACT

This paper describes the possible developments in global energy use and production, land use, emissions and climate changes following the SSP1 storyline, a development consistent with the green growth (or sustainable development) paradigm (a more inclusive development respecting environmental boundaries). The results are based on the implementation using the IMAGE 3.0 integrated assessment model and are compared with a) other IMAGE implementations of the SSPs (SSP2 and SSP3) and b) the SSP1 implementation of other integrated assessment models. The results show that a combination of resource efficiency, preferences for sustainable production methods and investment in human development could lead to a strong transition towards a more renewable energy supply, less land use and lower anthropogenic greenhouse gas emissions in 2100 than in 2010, even in the absence of explicit climate policies. At the same time, climate policy would still be needed to reduce emissions further, in order to reduce the projected increase of global mean temperature from 3 °C (SSP1 reference scenario) to 2 or 1.5 °C (in line with current policy targets). The SSP1 storyline could be a basis for further discussions on how climate policy can be combined with achieving other societal goals.

1. Introduction

Model-based scenarios are often used to explore possible environmental trends in relation to uncertain development of driving forces. These driving forces include population and income development, technology development, lifestyle change and evolving production and consumption patterns (see for an overview Van Vuuren et al., 2012). Recently, the Shared Socio-economic Pathways (SSPs) have been proposed as a new set of scenarios to be used as a basis of future climate research (Van Vuuren et al., 2014; O'Neill et al., 2014). The SSPs describes five possible future development trajectories that result in fundamentally different positions of human societies with respect to the ability to mitigate and/or adapt to climate change. The scenarios can be used in combination with additional, climate specific, policy assumptions to explore the costs and benefits of climate policies in different situations or to assess the effects of climate change. The narratives of these scenarios were recently published by O'Neill et al. (2014). The five SSPs include scenarios following a green growth strategy (SSP1), a more middle-of-the-road development pattern (SSP2), further fragmentation between regions (SSP3), an increase in inequality across and within regions (SSP4) and fossil-fuel based economic development (SSP5) (see Section 2).

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Recently, the SSPs have been elaborated using six different integrated assessment models (IAMs) to show possible quantifications of these scenarios for energy, land use, emissions and climate change – and to explore the associated uncertainties (Riahi et al., 2017). These quantified projections facilitate impact analyses of climate change and other environmental or sustainable development problems. They can also assist in analyses of potential climate change mitigation and adaptation strategies (Van Vuuren et al., 2014; O'Neill et al., 2014).

In this paper, we describe the assumptions and results of the work by the IMAGE 3.0 integrated assessment model (Stehfest et al., 2014). We explicitly focus on the SSP1 results, as for this scenario, the IMAGE SSP1 implementation is the marker scenario. The marker scenario is selected from the various quantifications of the storyline by different IAMs as it clearly represents the overall storyline and is recommended for use when a single quantification for a SSP is selected (so for each SSP there is one marker). We will compare the results for SSP1 with the two other SSPs that have been elaborated by the IMAGE model, i.e. the SSP2 and SSP3 scenario. The main research focus of this paper is thus to explore how various trends consistent with a more green growth paradigm – i.e. a more inclusive development respecting environmental boundaries – (SSP1) could evolve in terms of trends for energy use, land use and emissions.

The concept of 'green growth' (and thus the SSP1 storyline) directly relates to the similar concept of 'sustainable development' (Pezzey, 1992). Recently, key global international organizations have embraced these concepts including UNEP, the OECD, the European Commission and the Global Green Growth Institute (OECD, 2011; European Commission, 2011; UNEP, 2011). Moreover, in September 2015 the United Nations adopted the '2030 Agenda for Sustainable Development' (UN, 2015b). Central to this agenda are the Sustainable Development Goals (SDGs) that express the ambition to end poverty and create a sustainable economic growth path and protect the planet from degradation. While the SDGs build on earlier commitments (e.g. the Millennium Development Goals, the Strategic Plan for Biodiversity and Sustainable Energy for All), their adoption signals the interest of countries worldwide to further cooperate on sustainable development issues. It should be noted, however, that, although some improvement with respect to global poverty can be observed, historical development patterns especially for environmental issues have mostly been at odds with this ambition (Van Vuuren et al., 2015; UNEP, 2012). Furthermore, the 2030 Agenda does not state how to deal with the trade-offs and synergies of the various goals. This paper describes a coherent quantification of a sustainable development storyline and compares the outcomes to alternative socio-economic developments (SSP2 and SSP3). It should be noted, however, that in our implementation of SSP1, we have not explicitly addressed the achievement of specific targets, such as defined by the SDGs. Instead, we explored the impact of a set of assumptions derived from the SSP1 storyline regarding 'reasonably ambitious' improvement in resource efficiency, human development and preferences regarding consumption and production patterns within the energy- and land-system. By definition, the "reference" SSP1 does not implement climate policy: greenhouse gas emissions are therefore mitigated on the basis of efficiency assumptions and technology development, but mostly likely not enough to meet ambitious climate targets (see Section 5).

The paper first briefly describes the IMAGE 3.0 model, and the storylines and implementation of the various SSPs (Section 2). Subsequently, we present the results of these scenarios, focusing on the IMAGE implementation of SSP1, but also comparing results to SSP2 and SSP3 and the SSP1 quantification from other IAMs (Section 3). Section 4 discusses the impacts of stringent climate policy. In Section 5 we briefly discuss the consequences of some key assumptions made in the quantification, while finally, in Section 6 conclusions are presented.

2. Methods

2.1. IMAGE 3.0 model

IMAGE is an integrated assessment model framework that simulates global and regional environmental consequences of changes in human activities (Stehfest et al., 2014) (see also Supplementary information). The model is a simulation model, i.e. changes in model variables are calculated on the basis of the information from the previous time-step. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters, depending on the variable, on the basis of a geographical grid of 30 by 30 min or 5 by 5 min (respectively around 50 km and 10 km at the equator). The model has been designed to analyse large-scale and long-term interactions between human development and the natural environment and to identify response strategies to global environmental change based on assessment of options for mitigation and adaption. Earlier, the IMAGE model was used to develop the SRES B1 scenario (De Vries et al., 2000) and the RCP2.6 (Van Vuuren et al., 2011).

IMAGE is a framework with a modular structure, with some components linked directly to the model code of IMAGE, and others connected through soft links (where models run independently with information exchange via data files). The IMAGE framework is structured around to the causal chain of key global sustainability issues and comprises two main systems: 1) the human or socio-economic system that describes the long-term development of human activities relevant for sustainable development; and 2) the earth system that describes changes in natural systems, such as the carbon and hydrological cycle and climate. The two systems are linked through emissions, land-use, climate feedbacks and potential human policy responses.

Important inputs to the model are descriptions of the future development of so-called direct and indirect drivers of global environmental change: Exogenous assumptions on population, economic development, lifestyle, policies and technology change form a key input into the energy system model TIMER and the food and agriculture system model MAGNET (Woltjer et al., 2014). TIMER is a system-dynamics energy system simulation model describing key trends in energy use and supply. MAGNET is a computable general equilibrium (CGE) model (Van Meijl et al., 2006; Woltjer et al., 2014) that is connected via a soft link to the core model of IMAGE. MAGNET uses information from IMAGE on land availability and suitability and on changes in crop yields due to climate change and agricultural expansion into heterogeneous land areas. The results from MAGNET on production and endogenous yield (management factor) are used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity, and climate. In IMAGE, the main interaction with the earth system is by changes in energy, food and biofuel production that induce land-use changes and emissions of carbon dioxide and other greenhouse gases. A key component of the earth system is the LPJmL model (Bondeau et al., 2007) that is included in IMAGE 3.0 (see also Müller et al. (2016) for details). LPJmL covers the terrestrial carbon cycle and vegetation dynamics in IMAGE 3.0. This model is used to determine productivity at grid cell level for natural and cultivated ecosystems on the basis of plant and crop functional types. Based on the regional production levels and the output of LPJmL, a set of allocation rules in IMAGE determine the actual land cover. The calculated emissions of greenhouse gases and air pollutants are used in IMAGE to derive changes in concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale. Climatic change is calculated as global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model (Meinshausen et al., 2011). The changes in temperature and precipitation in each grid cell are derived from the global mean temperature using a pattern-scaling approach. The model accounts for several feedback mechanisms between climate change and dynamics in the energy, land and vegetation systems. For the purpose of the SSP scenarios, nearly all climate impacts have been switched off, with the exception of the impact of climate change and rising CO_2 concentration on natural vegetation (in order to be consistent with how MAGICC is applied for all IAMs and SSPs to derive radiative forcing and climate change).

2.2. Scenario assumptions for the reference scenarios

The SSP framework defines five storylines that strongly differ in the challenges for mitigation and adaptation (O'Neill et al., 2017). Each of these storylines is first implemented under the assumption of an absence of climate policy. This reference scenario functions as a basis for subsequent analysis of the impact of climate policy, implemented in the framework as policies aiming to achieve forcing levels consistent with the Representative Concentration Pathways (Van Vuuren et al., 2014). As briefly indicated in the introduction, the SSP1 scenario depicts a world that aims for green growth (sustainable development). Although climate policy is not implemented in the SSP1 reference scenario, the scenario developments regarding technology and governance imply that adaptation and mitigation to climate change is relatively easy. For instance, the assumed rapid technology development and concerns with respect to environmental impacts lead to high energy efficiency and high shares of renewable energy. The investments into education and development at the same time are assumed to lead to low population levels and as a result relatively low pressure on land. The SSP2 indicates possible development under median assumptions. The SSP3 scenario describes a world of fragmentation. Consequently, the economic growth and technology development are assumed to be slow. Combined with high population growth, in this world, both adaptation and mitigation are relatively difficult. Population (KC and Lutz, 2017) and GDP scenarios (Dellink et al., 2017) consistent with the SSP storylines were developed, and have been used here as input for the IMAGE calculations (Fig. 1). In contrast to SSP1, fragmentation in SSP3 is assumed to lead to high fertility levels and low economic growth. Other input for the IMAGE scenarios have been derived from the storylines (O'Neill et al., 2017) as indicated in Table 1. The small range across models shown for GDP originates from the use of different base year data and differences in regional break down.

2.2.1. SSP1: sustainable development paradigm

In the past, several scenarios have been published that depict possible trends in a world aiming for sustainable development. Key examples include the B1 scenario (De Vries et al., 2000) and the Global Environmental Outlook 'Sustainability First' (UNEP, 2002). Van Vuuren et al. (2012) identified the '*global sustainable development*' scenario group among five other groups that are regularly used in environmental assessment of future global change. Key characteristics include elements of lifestyle change, rapid technology development for sustainable technologies and global cooperation. The same paper identifies a second group of '*local sustainable development*' scenarios that also achieve major progress in reducing environmental pressure and pursuing development goals, based on a stronger focus on local solutions and lifestyle change. The '*Technogarden*' and '*Adapting Mosaic*' scenarios of the Millennium Ecosystem Assessment study illustrate this difference in terms of storyline (Carpenter et al., 2005). This dichotomy is discussed by O'Neill et al. (2017) who indicated that the current version of the SSP1 scenario follows the global storyline, but that alternative (local) interpretations would be interesting to pursue.

The SSP1 storyline thus emphasizes the use of environmentally friendly technologies, a (modest) transition towards less resource intensive lifestyles, and based on global cooperation, still with a relatively high economic growth rate, and a decreasing population in the second half of the century. A key question, therefore, is how this break with current trends can be achieved. One may argue that elements of a SSP1 storyline can already be seen now, mostly in niches that would need to be scaled up to become mainstream (Geels, 2002). These include the adoption of green growth concepts by vanguard organizations, the recent approval of the SDGs but also the rapid decline in costs of key technologies such as PV and electric batteries (IRENA, 2014; Nykvist and Nilsson, 2015), the subsequent use of these technologies also outside OECD countries and the progress with respect to the Millennium Development Goals (UN, 2015a). It is actually more-and-more recognized that it is possible to reduce greenhouse gas emissions

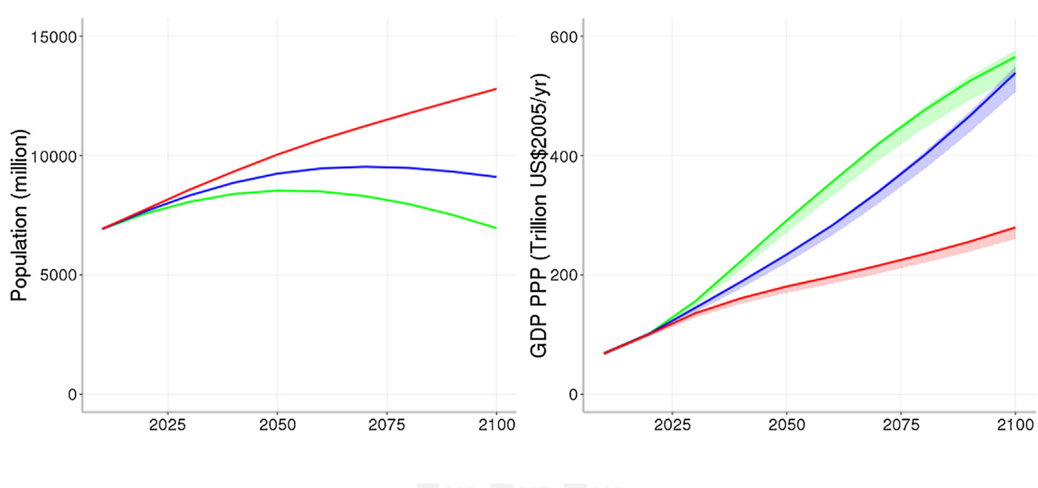

Fig. 1. Global population (left) and economic development (right). The shaded area indicates the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

Table 1
Generic description of the storyline elements and their translation to model assumptions for SSP1, SSP2, and SSP3 in IMAGE (indications high and low are made in comparison to a median development path).

	SSP1	*SSP2*	*SSP3*
Generic elements			
Economic growth	High, based on Dellink et al. (2017)	Medium, based on Dellink et al. (2017)	Low, based on Dellink et al. (2017)
Population growth	Low, based on KC and Lutz (2017)	Medium, based on KC and Lutz (2017)	High in developing countries; low in developed countries, based on KC and Lutz (2017)
Governance and institutions	Effective both nationally and internationally	Uneven	International institutions weak; security policies
Technology	Rapid, translated into for instance in assumptions for efficiency, renewable technologies and yields	Medium	Slow
Consumption/ production preferences	Promotion of sustainable development (lower consumption – see further)	Medium	Relative resource intensive consumption
Energy demand			
Transport	Lower share of income spent on transport leading to less kms travelled. More travel time (0,5 min/day increase each yr) resulting in less shift to faster modes. Preference for public transport, car sharing, and faster increase in efficiency (10% in 2100).	Medium assumptions	Slower reduction of costs and efficiency increase of new technologies. Higher share of income spend on transport and later saturation of transport demand. No increase in travel-time implying a more rapid shift to high speed modes.
Buildings	Behavioural changes lead to overall lower demand for energy services (heating, cooling, appliances). Adoption of more efficient technologies. Faster rural electrification. Rapid phase out of traditional fuels.	Medium assumptions	Slower improvement rates of efficient technologies.Low improvements towards access to modern energy carriers
Industry	Low intensity for cement and steel demand; clinker-cement ratio to 0.7. Preference for efficient technology and natural gas/bio-energy. Penalty for coal. High steel scrap recovery rate.	Medium assumptions	High intensity for cement and steel demand. No convergence in clinker-cement ratio. Preference for standard technologies and fuel preferences based on price only.
Non-energy	Low intensity, following Daioglou et al. (2014)	Medium, following Daioglou et al. (2014)	High intensity, following Daioglou et al. (2014)
Energy supply and conversion			
Fossil fuels	Global trade of fuels; and median technology development for fossil fuel extraction technologies.	Global trade of fuels; Median technology development	Trade barriers; and slow development of technologies.
Bio-energy	Traditional biofuels mostly phased out around 2030; bio-fuels in transport taxed for possible biodiversity damage; less potential based on nature reserves but increased from abandoned lands; high yields; improved efficiencies and costs of biofuel production technologies; residues based on Daioglou et al. (2016).	Traditional biofuels phased out in line with income growth. Default assumptions for modern bio-energy. residues based on Daioglou et al. (2016).	Traditional biofuels phased out at a slower rate; Lack of nature reserves increases potential land; Lower yields; low efficiencies and high costs of biofuel production technologies; residues based on Daioglou et al. (2016).
Renewables	Rapid technology development (high values for learning rates); low integration costs	Medium technology development	Slow technology development (low values for learning rates)
Agriculture and land use			
Land use change regulation	Strong – Protected areas are extended to achieve the Aichi target of 17%. Additional areas are protected making in total 30% of terrestrial area unavailable for agricultural expansion.	Medium – Protected areas are extended to achieve the Aichi target of 17% of the terrestrial area, gradually implemented from 2010–2050.	Low – protected areas at current level.
Agricultural productivity (crops)	Strong – crop yield increase as a function of GDP, increase in irrigation efficiency 20% higher than SSP2	Medium – following largely the projections by FAOs agricultural outlook	Low- crop yield increase as a function of GDP, increase in irrigation efficiency 20% lower than SSP2
Agricultural productivity (livestock)	Efficiency parameters achieve 50% convergence to the levels of the most efficient regions in SSP2	Medium – following largely the projections by FAOs agricultural outlook	Efficiency stagnates at current regional levels
Environmental Impact of Food consumption	Low – Consumption of animal products 30% lower than endogenous outcome in high income countries, reduction of food waste by 1/3.	Medium- Endogenous dynamics	High – Consumption of animal products 30% higher than endogenous outcome, increase of food waste by 1/3.
Trade			
Trade in agricultural commodities	Abolishment of current import tariffs and export subsidies by 2030, preference for regionally produced products.	Current tariffs and subsidies.	Introduction of a 10% import tax for all agricultural products by 2050, for self- sufficiency concerns
Trade in energy carriers	No trade restrictions	No trade restrictions	Stronger reliance on domestic production.
Air pollution			
Emissions factors	Low; rapidly falling in all regions, see Rao et al. (2017)	Medium; falling in low-income regions with some delay see Rao et al. (2017)	High; considerable delay across the regions see Rao et al. (2017)

by implementing a much wider (sustainable) development agenda (LCS.RNET, 2015). The main requirement is the further growth of societal support for such a strategy combined with an actual change in investment patterns (Ocampo, 2011).

In the IMAGE implementation, we assume that the transition towards a SSP1 storyline will slowly be implemented from 2015 onwards. We address several human development issues: 1) it is assumed that full access to modern energy will be achieved in 2030 (consistent with SDG7), 2) it is assumed that global air pollution will be significantly reduced for health reasons (SDG3) by implementing – with some delay – current EU standards for most technologies worldwide (translated in the emission factors used), and 3) it is assumed that significant gains in access to food will be made (SDG2). These trends benefit from a global shift towards societal awareness of sustainable development issues, including a dietary shift towards less meat-intensive diets (Stehfest et al., 2009) and increased use of public transport (Girod et al., 2013). Similar assumptions are made with respect to rapid energy efficiency improvement, yield improvement and implementation of environmentally benign technology (e.g. rapidly decreasing costs for renewable energy), given a different emphasis on consumption and production patterns (see Table 1, and Supplementary Information, consistent with SDG12, 13 and 15).

Crop yields, irrigation efficiency and efficiency of livestock production are improved, reflecting the high level of governance and technology development in order to increase supply for food and protect biodiversity (SDG2 and 13). This is implemented by a convergence towards the values that are projected for the most efficient regions in 2050 by more conventional projections (Alexandratos and Bruinsma, 2012).

2.2.2. Implementation of the other SSPs

The SSP2 and SSP3 storylines entail a very different evolution of trends in human development and global resource use. In the SSP2 storyline, median assumptions have been made for all key model assumptions (see Table 1). This does not necessarily imply a simple extrapolation of current trends, as emphasized by O'Neill et al. (2017), who stated that in several cases median projections of changes might show gradual deviations from past trends. Examples include population growth, for which the SSP2 trajectory shows stabilization at around 9 billion by 2050 and the decreasing costs of renewable energy compared to those of fossil fuels. In the SSP2 scenario, technology is assumed to further improve but no major breakthroughs are expected. Agricultural systems evolve largely following the FAO projections by Alexandratos and Bruinsma (2012).

The SSP3 storyline depicts a very different world in which regions and countries increasingly implement policies that strengthen their own identity and security. In the storyline it is assumed that the lack of global cooperation and the relatively weak institutions result in low global economic growth especially in developing countries. Moreover, the combination of low economic growth and relatively low investments in education are assumed to lead to a slow-down in the demographic transition, and thus to high population growth. The lack of global cooperation is also assumed to slow down technology development, resulting among others in relatively resource-intensive economic growth (e.g. relatively low increase in energy efficiency and crop yields), for instance leading to continuing deforestation trends. Environmental policies get very low priority, also leading to little investment in resource efficiency. The strengthening of trade-barriers implies that regions are assumed to rely more on domestic resources than in other scenarios. The efficiency of agricultural systems stagnates on current levels and the pressure on extensive grasslands and rangelands increases.

2.2.3. Comparison of IMAGE results with other IAMs

In several figures, we compare the IMAGE results with the range of outcomes by the implementation of the other IAMs, i.e. AIM (Fujimori et al., 2017), GCAM (Calvin et al., 2017), MESSAGE-GLOBIOM (Fricko et al., 2017), REMIND-MagPIE (Kriegler et al., 2017), and WITCH (Emmerling et al., 2016). More detailed comparison of the marker scenarios are published for land (Popp et al., 2017), energy (Bauer et al., 2017) and emissions (Rao et al., 2017).

2.3. Introduction of climate policy

In IMAGE, climate policy is usually implemented by introducing a carbon price that induces a transition towards low-greenhouse gas emitting technologies. In order to do so, information on emission reduction options and developments without climate policy is transferred to the FAIR model that forms part of the overall IMAGE framework (Den Elzen et al., 2014). This model is used to derive least-cost scenarios (given assumptions on the timing of climate policys) for different radiative forcing goals. The derived emission reductions are subsequently implemented in the larger IMAGE framework.

Clearly, the formulation of climate policies cannot be seen independent of the overall socio-economic developments (Kriegler et al., 2014a). In the SSP1 scenario, based on the assumed global cooperation, it is assumed that globally a cost-optimal pathway can be implemented from 2020 onwards (after first implementing the Copenhagen pledges). Action is taken in all sectors. In the SSP2 scenario, climate policy is implemented assuming that the current pledges are implemented in 2020. From that year on, all regions follow a linear transition towards a global uniform carbon price with cost-optimal climate policy starting in 2040. In SSP3, higher income regions are assumed to follow a similar trajectory to that of SSP2, with fragmented policy until 2020 and a uniform carbon price in 2040. All other income regions in SSP3 continue with fragmented climate policy until 2030, and start the transition towards unified climate policy 10 years later, between 2030 and 2050.

While the current version of IMAGE is also able to describe possible climate policies in the form of afforestation, reforestation and avoided deforestation (ARD), these are not implemented via a carbon tax. Therefore, for the SSPs an approach was taken that assumes an effort in implementing ARD measures similar to mitigation measures in other sectors at certain radiative forcing goals. This effort is based on two key measures: 1) increasing protection levels for carbon-intensive ecosystems for more ambitious climate targets (representation of REDD-policies, leading to reductions of emissions from deforestation and forest degradation), 2) reforestation of degraded or deforested areas that are not in use for agriculture. Regarding forestry related measures, the lower, medium and higher REDD protection levels were simulated by protecting forests with carbon densities higher than 200, 150 and 100 tC/ha, respectively (see also Table 2). The two reforestation levels imply that either reforestation is implemented on 50% or 100% of the degraded forest land. These values have been roughly calibrated with marginal abatement cost curves derived from the G4M model (Gusti and Kindermann, 2011; Gusti, 2010; Kindermann et al., 2008) to determine the policy response at a certain carbon tax. In SSP1, the stringency of reduction measures for land-use related measures is assumed to be consistent with those in the energy system, while implementation of these measures is assumed to be ineffective in SSP3. In addition, the potential of non-CO_2 emission reductions from agriculture is assumed to be 80% lower than in SSP1 and SSP2.

Table 2
Assumptions on land-use related climate policies implemented in IMAGE.

Climate target (W/m^2)	SSP1	SSP2	SSP3
2.6	High REDD, full reforestation	Medium REDD, full reforestation	No solution
3.4	Medium REDD, full reforestation	Low REDD, half reforestation	No REDD, no reforestation
4.5	Low REDD, half reforestation	No REDD, no reforestation	No REDD, no reforestation
6.0		No REDD, no reforestation	No REDD, no reforestation

3. Socio-economic development and emissions in the absence of climate policy

3.1. Energy system

In the presentation of the results, we focus on global trends (for 2 key graphs, regional information in shown in the Supplementary Information). In the SSP1 storyline, final global energy demand increases only slowly. The increasing demand for energy services resulting from rapid economic growth is almost compensated by simultaneous energy efficiency improvements and changes in lifestyle. Other factors contributing to this are the rapid phase-out of inefficient traditional bioenergy use, and the declining global population after 2050. In 2050 and 2100, the final energy demand is projected to be around 560 EJ and 540 EJ, compared to 370 EJ in 2010. These numbers are significantly lower than those of more 'middle-of-the-road' projections such as SSP2 (620 and 820 EJ in 2050 and 2100, respectively) and SSP3 (around 590 and 780 EJ). The projected growth until 2040 ranges from 36% in SSP1 and 45–49% in SSP2 and SSP3, which can be compared to the 42–54% range in the new and current policies scenarios of the World Energy Outlook (IEA, 2014). The SSP1 findings from IMAGE are representative for other IAM models (Fig. 2). The global average intensity improvement is 2.5% per year in the 2010–2050 period (Fig. 2). This is considerably higher than the historical average rate of around 2%, but is similar to the intensity efficiency in OECD countries during period of high energy prices (IEA/OECD, 2014).

In terms of energy supply, the SSP1 scenario is characterized by a transition from a fossil-fuel dominated system (nearly 90% of energy supply in 2010) towards an energy system in which renewable energy plays a key role. This transition needs time as a result of existing infrastructure and the related competitive position of fossil fuels (Fig. 3). Despite the slow changes, even before 2050 oil use is substantially reduced and coal use increases only slightly. Natural gas use in contrast is projected to grow significantly as a result of relatively low prices and the better environmental performance compared to other fossil fuels. By 2100 in SSP1, total fossil fuel consumption is substantially below today's level of fossil fuel use, while oil use is nearly phased out (see transport system). The SSP2 projection includes considerably more oil and coal use in 2050 (comparable to the IEA reference scenarios (new and current policies) resulting in a fossil fuel share of 75–80% (IEA, 2014)). In the SSP3 scenario, a faster increase in coal use is projected, partly driven by high coal use in Asia, as it is the cheapest available domestic fuel. SSP1 implementations by the other models are more-or-less similar to those of the IMAGE model. As a result of the trends in energy supply, SSP2 and SSP3 are in line with the recent historically observed trend in carbon intensity, while the growth of renewable energy use in SSP1 leads to a clear reduction of the carbon intensity.

The power system is a key factor in the worldwide energy transition. Globally, at the moment, most electricity is produced from coal, followed by natural gas, hydropower and nuclear power. In the SSP1 scenario, electricity use is projected to grow rapidly, which requires a rapid scaling-up of production capacity, mainly based on natural gas and renewables. Interestingly, the 2050 power production in SSP1 exceeds the one in SSP2 and SSP3, given the increasing importance of electricity in SSP1 in energy consumption in transport, industry and buildings sectors. In 2100, the majority of power in SSP1 is projected to be produced by renewable energy (65%). In SSP2, the introduction of renewable energy is much less rapid – leading to a 30% contribution in power production in 2050 and 40% in 2100 (see Fig. 4). Here, the additional costs of implementing intermittent renewables remain a significant barrier. This is even more so in SSP3 as a result of slow technology development. The shares of the SSP2 scenario are comparable to those in the IEA 2014 projection, i.e. 25–30% in 2040 for the current and new policies scenarios (IEA, 2014).

Fig. 5 shows the global trends in transport, residential and industry sector energy use. At the moment, global transport energy consumption is totally dominated by oil. In SSP1, up to 2050, alternative fuels rapidly gain market shares, but oil remains

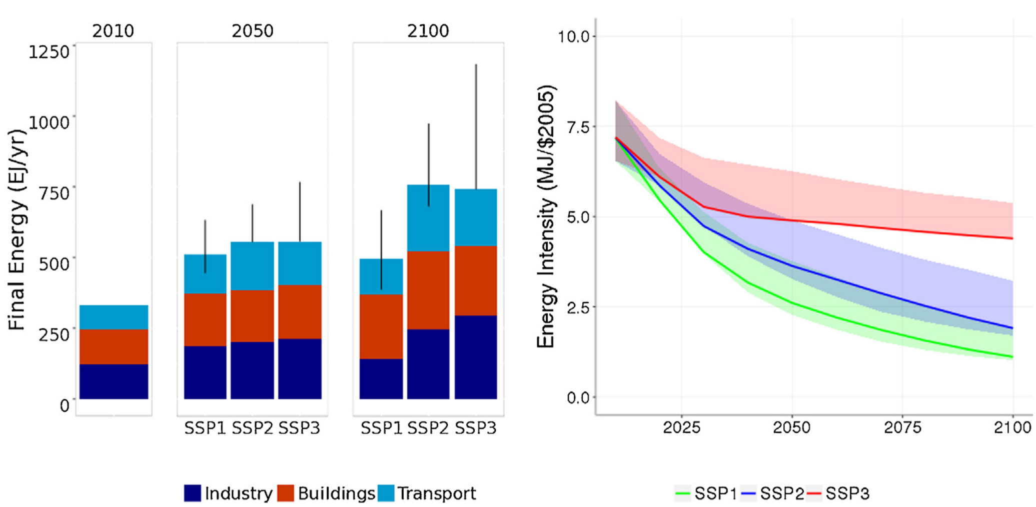

Fig. 2. Global final energy demand per sector (left) and trend in energy intensity (final energy use per unit of GDP) (right). The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

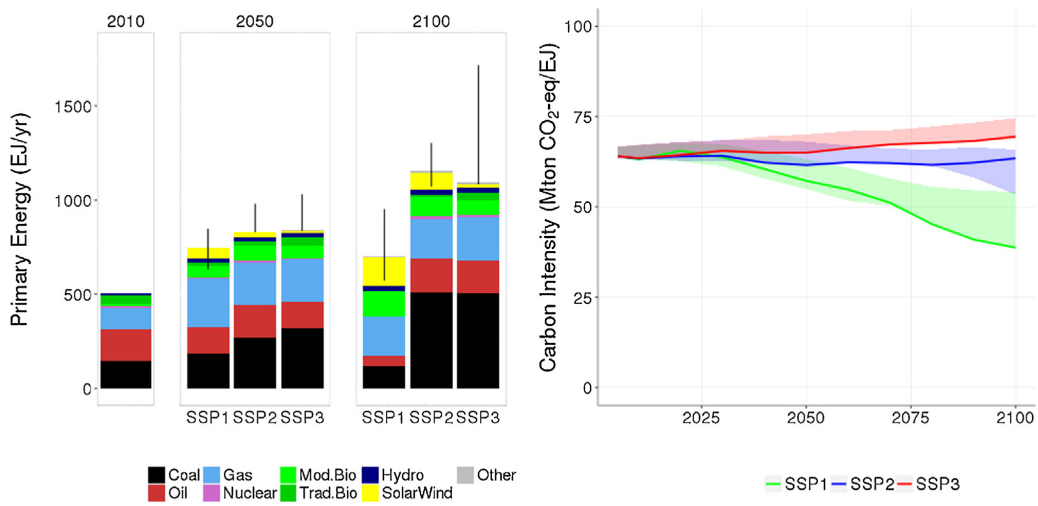

Fig. 3. Global primary energy use per energy carrier and CO_2 emissions per unit of primary energy. The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

important. Key drivers of these trends are: 1) the relatively high shares of public transport in SSP1 compared to other scenarios; 2) the increased electricity consumption driven by rapidly falling costs and increasing preferences for electric vehicles, especially in road and rail passenger transport (as electricity is more efficient than oil, its share in consumption is not indicative of the total contribution in terms of cars); 3) the competitive position of oil in heavy duty freight transport and aviation and finally, 4) existing infrastructure that is expected to slow-down transition rates. By 2100, the transport energy demand has changed much more radically. The projection shows a dominant position of electric and hydrogen-fuelled drive-trains in SSP1 in road transport. For aviation and trucks, biofuels are the most important fuel. While similar trends occur in the SSP2 and SSP3 scenarios, technology development is too slow for electricity, hydrogen and biofuels to really outcompete oil. As a result, new fuels mostly supply additional transport fuel demand while oil use is only slightly higher than today (by the end of the century produced from non-conventional oil sources such as tar sands).

For the residential sector, the different scenarios result in comparable energy demand growth (albeit due to a slightly different combination of drivers) of around 60% between 2010 and 2050. In SSP1, development policies aimed at providing access to modern energy for all lead to a phase out of traditional (biomass) energy use. In contrast, electricity and natural gas use are projected to increase significantly. Electricity is mostly used for appliances and cooling which become the dominant energy services with increasing incomes, especially in warm climates. Fossil fuels (and some electricity) are used for space and water heating. The SSP2 and SSP3 scenarios do not have explicit energy-access policies and therefore the transition away from traditional biomass takes much longer. Besides access to modern energy carriers, the lower long term energy use of SSP1 is due to further improvements in end-use efficiency and behavioural changes.

3.2. Land-use system

Food demand forms a primary driver of land-use trends. In all three SSPs, trends in global population and increasing welfare are expected to lead to an increasing global food demand in the 2010–2050 period. At the same time, other drivers also play a role. In SSP1, policies to reduce poverty and hunger in combination with increased welfare lead to an increase in per capita consumption of food (leading by the end of the century to the highest availability of

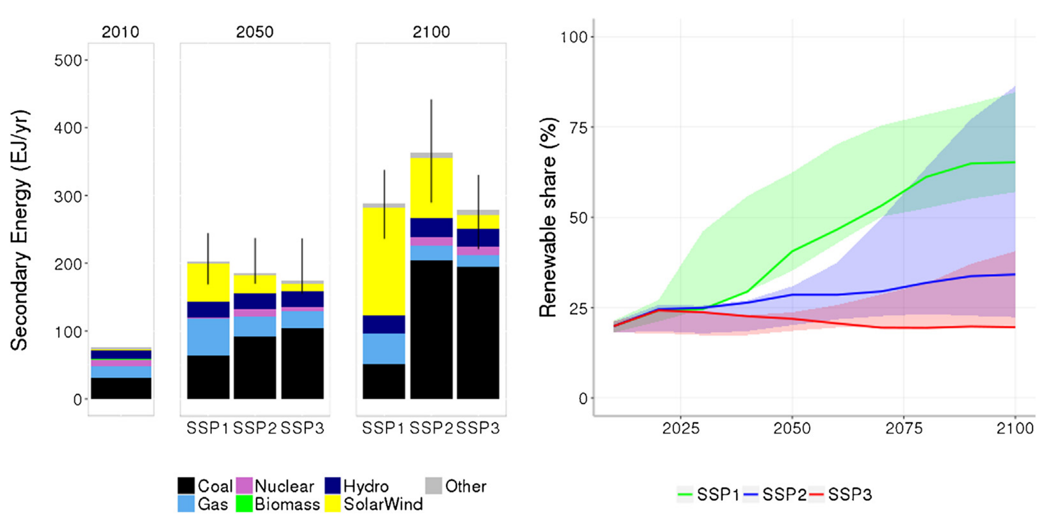

Fig. 4. Power system development and renewable share. The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

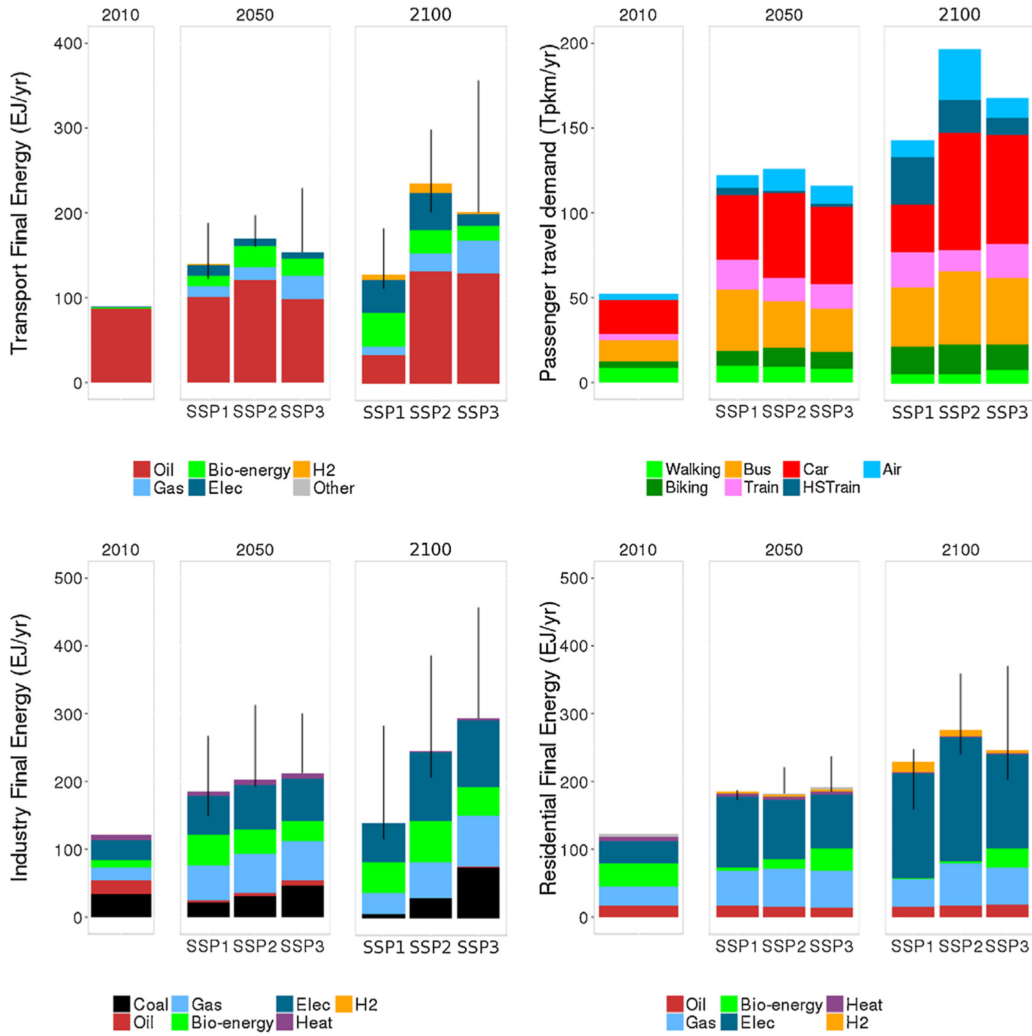

Fig. 5. Development of sectoral energy demand. Transport final energy demand, transport activity levels, industrial and residential final energy use (in the different panels). The vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2). (HSTrain = high-speed train; elec = electricity).

the three storylines). At the same time, a dietary change to less meat-intensive diets in high-income regions is assumed, driven both by environmental and health concerns. As a result, per capita consumption of animal production at the global scale declines. The resulting per capita intake of meat in 2050 in SSP1 is still above the level indicated in the healthy diet of Willett (2005), partly also resulting from reduction in prices as a result of less land-use. Assumptions on reduced food waste also reduce the overall increase in food and meat consumption in SSP1. This, finally, implies that overall consumption levels in SSP1 are just slightly below SSP2 levels. In SSP3, the relative preference for animal products is slightly higher than in SSP2 and SSP1 (Fig. 6). But, as income levels are much lower in this scenario, the resulting per capita food consumption levels are projected to be lower than the other scenarios in the long-term. For total food production in the second half of the century, the diverging population trends drive most of the differences in results.

Clearly, the increasing food demand in all three SSPs implies that more food needs to be produced. This is achieved in different ways. For SSP1, based on the storyline it is assumed that crop yields increase rapidly (illustrated for maize in Fig. 7) on the basis of the rapid technology developed in the storyline and the aim to reduce hunger and protect biodiversity. Obviously, in SSP1 the yield improvement needs to be combined with as much as possible environmentally-friendly production methods. Similarly, it is assumed the livestock systems become more efficient. These two trends combined with the lower share of animal products in the human diet in SSP1 result in the stabilization of the feed demand in 2050 at 2010 level (Fig. 7). In 2100, the demand of feed crops is further reduced. This lead to a reduction of agricultural land. In SSP3 the yield improvement is considerably less given the lower level of technology advancement. However, to understand the relative position of the scenarios it is important to realize that yields are not only influenced by exogenous scenario drivers but also for the autonomous feedbacks, i.e. scarcity of available fertile land. More land expansion leads to higher prices and thus a higher incentive for yield improvement (and the other way around) Therefore, in SSP1, the lower demand for food and feed production stimulates compared to the technology drivers, a lower intensification of agriculture. This means that all-in-all in SSP2, yield improvements are quite similar to those of SSP1, induced by a higher food demand. Similarly, increased in competition also increases yield improvement in SSP3, but here the low technology improvement dominates.

In both SSP2 and SSP3, the demand for feed crops for feeding both monogastric and ruminant systems is much higher compared to SSP1, both in 2050 and 2100 (Fig. 7). In 2100, feed demand in SSP3 is even twice that in SSP1. As a result, the pressure on natural grasslands and rangelands rises in SSP2 and even more in SSP3. All-in-all, in SSP1, there is a significant drop in total agricultural land

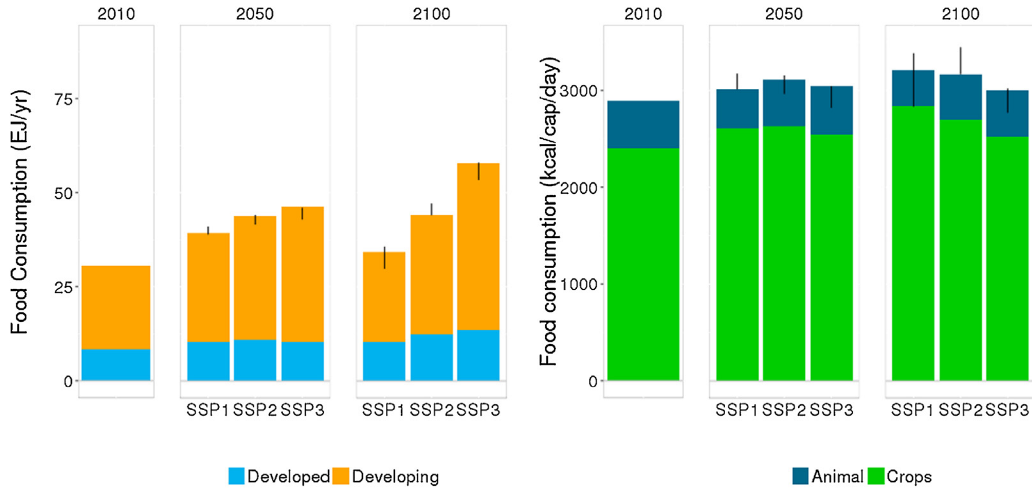

Fig. 6. Total food consumption (left) and per capita food consumption (animal and non-animal intake). The vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

area, both in the 2010–2050 period and the 2050–2100 period, mostly as a result of a decrease in pasture area. Consistent with the SSP1 storyline, this implies that the total natural area can increase (Fig. 8).

3.3. Emissions, forcing, climate change

Trends in the energy system and land use translate into emissions of greenhouse gas and air pollution (Fig. 9). In the literature, reference scenarios usually show a substantial increase in energy-related emissions and a decline in land-use related emissions (Clarke et al., 2014). The SSP1 scenario is indicative of low-end range of scenarios without climate policy in the literature, given very low increase in energy related emissions and the decline of anthropogenic land-use related GHG emissions. The latter is in fact a combination of negative CO_2 emissions from reforestation and the remaining CH_4 and N_2O emissions from agriculture. This trend continues in the 2050–2100 period, resulting in an overall decrease of emissions in 2100 of over 35% compared to today. The SSP2 and SSP3 scenarios follow an opposite trend in which emissions increase throughout the 21st century which is more common for reference scenarios (Van Vuuren et al., 2012). Both SSP2 and SSP3 end up as median emission scenarios compared to the overall literature. The increase in both scenarios is mostly driven by energy-related CO_2 emissions.

The trends in the energy system and land use also affect air pollutant emissions. Here, also air pollution policies play a major role. In SSP1, it is assumed that existing policies in OECD countries are strengthened further and, with some delay, adopted worldwide. This leads to a sharp decline of air pollutant emissions, illustrated in Fig. 10 for SO_2 and NO_x. For all air pollutants the relatively efficient energy system and high share of renewables also play an important role in reducing air pollutants, improving for instance air quality in cities. This can be shown best for NO_x, for which the high share of electric vehicles is an important factor explaining differences between SSP1 and other scenarios. In the SSP2 scenario, a combination of higher fossil fuel use and less stringent air pollution policies leads to a slower decline in air pollutant emissions. In SSP3, today's air pollution policies are assumed to be hardly strengthened: as a result, for nearly all pollutants, emissions are projected to stay at high levels throughout the 21st century (with some improvement in the second half of the century).

The scenarios have been evaluated in terms of their expected impact on climate change. Here, we present the results of the MAGICC 6.8 calculations (Meinshausen et al., 2011) that have been

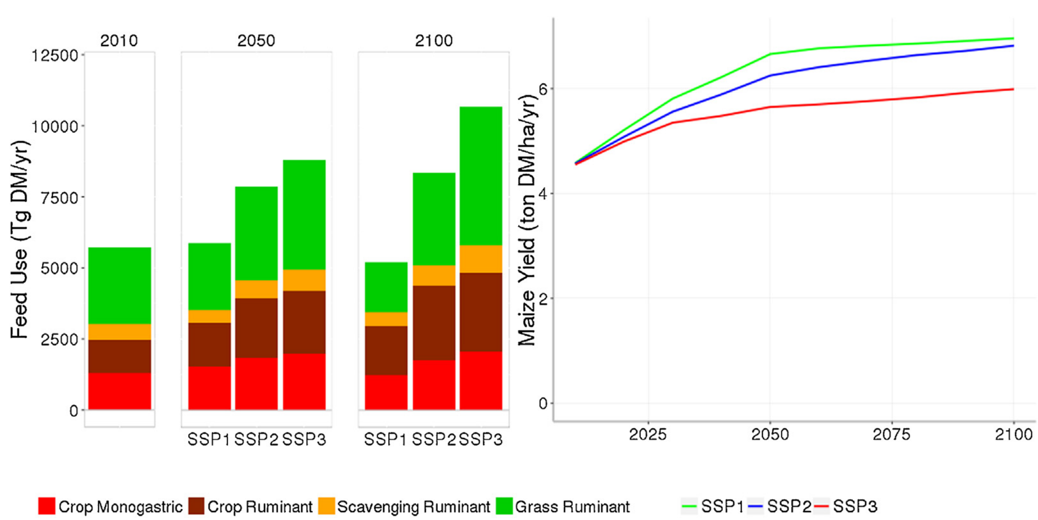

Fig. 7. Global feed requirement for monogastrics and ruminants (left) and global average yield for maize (right).

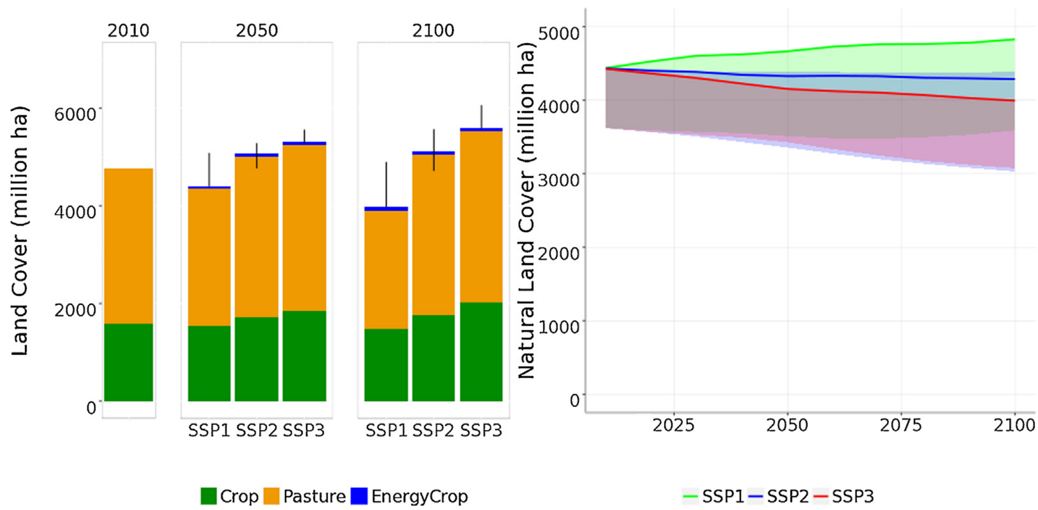

Fig. 8. Development of land use (crop land/pasture land/energy crop) (left) and natural area (right). The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

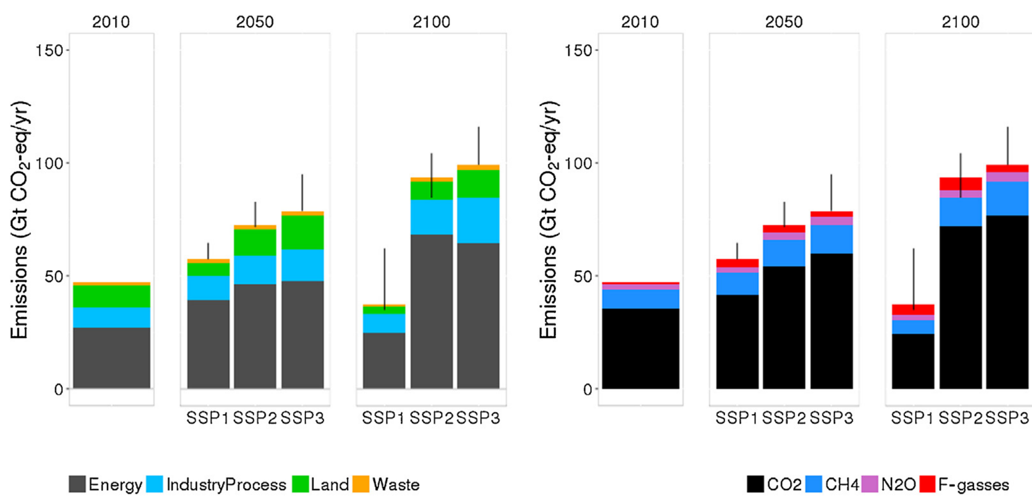

Fig. 9. Global greenhouse gas emissions by main emission category and type of gas. The vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

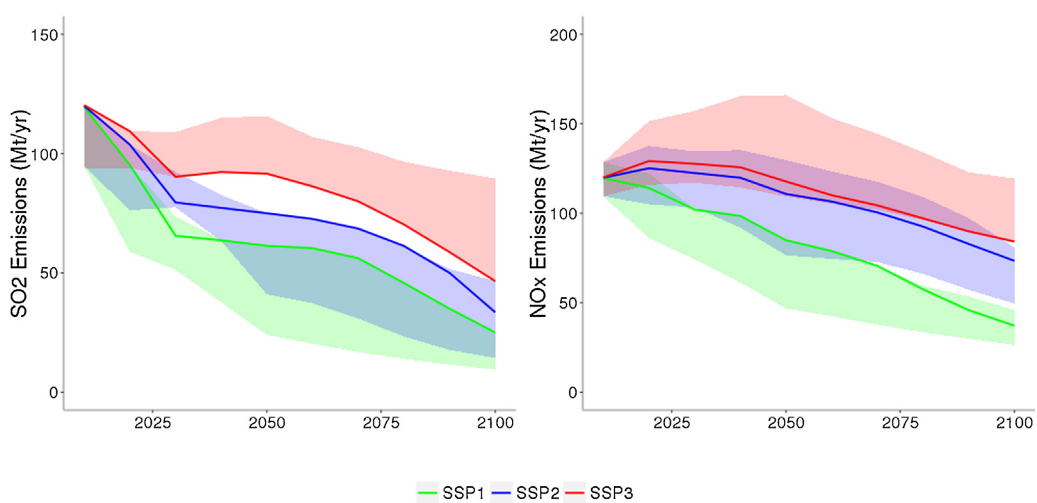

Fig. 10. Air pollutant emissions for SO_2 (left) and NOx (right). The shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2).

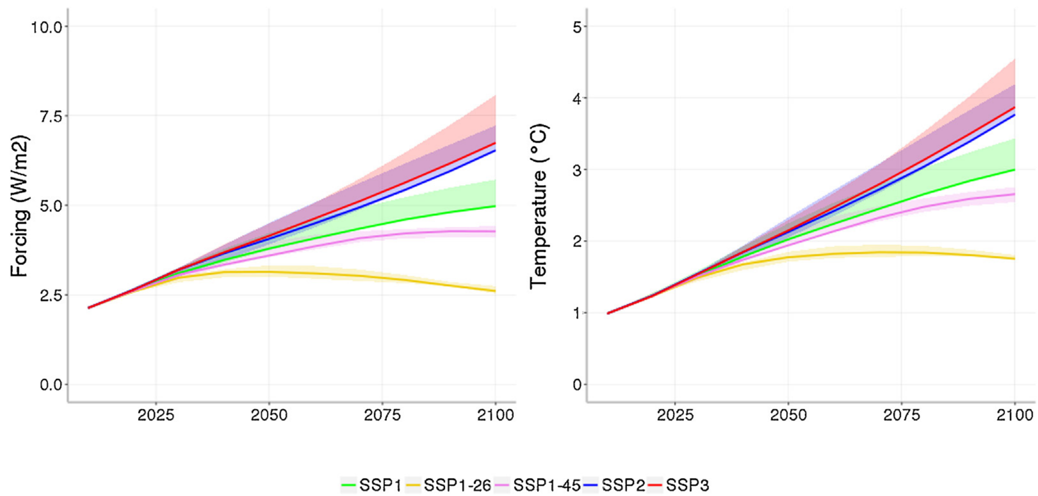

Fig. 11. Radiative forcing (left) and temperature change (right). The area indicates the range of results of the other IAM scenarios for the specific SSP (see references in Section 2).

performed for the output of all models (allowing comparison across the models). Although greenhouse gas emissions actually already peak in the middle of the 21st century, radiative forcing shows a slower transition with a trend leading to a near stabilization of forcing around 5 W/m^2. This is a result of the long life-time of CO_2. The SSP2 and SSP3 follow a considerably higher forcing path. While greenhouse gas emissions of SSP3 are slightly higher, this is compensated by a larger negative forcing by sulphur aerosols.

In terms of temperature, the scenarios follow the trends in forcing with some delay (results are shown in Fig. 11 for the median climate settings of the MAGICC model). The IMAGE SSP1 scenario ends up at around a warming of 3 °C by the end of the century – but temperature is still increasing at that time. The IMAGE SSP2 and SSP3 scenarios, in contrast, lead to around a 4 °C warming in 2100.

4. Results for different climate policy scenarios

In the new Scenario Matrix Framework for climate research (Van Vuuren et al., 2014), the reference scenarios are combined with corresponding mitigation scenarios consistent with the RCP forcing levels. Here, we briefly describe the climate policy scenarios associated with the SSP1 scenario and compare those with similar scenarios derived from SSP2. As the climate policies are implemented via a carbon price, the carbon price can be seen as an indication of the effort of reaching the forcing level. As shown in Fig. 12, reaching a forcing level of 4.5 W/m^2 is relatively easy from the SSP1 reference scenario (without climate policy), requiring only a modest carbon price at the end of the century. Even the 2.6 W/m^2 level can be reached with a relatively low carbon price, given the assumptions on: 1) international cooperation, leading to early globally optimal climate policy and 2) low reference scenario, due to favourable conditions of technology development and lifestyle changes. The corresponding scenarios from the SSP2 scenario require considerably higher carbon prices with a rapid price jump around 2030 related to the transition from the existing policies to the more stringent policies to reach the forcing target.

The carbon prices induce important changes in the energy system, leading to lower greenhouse gas emissions (Fig. 13). Several trends stand out: 1) an increase in energy efficiency, 2) a sharp reduction in unabated use of fossil fuels, 3) an increase in the use of fossil fuel and bio-energy in combination with CCS and finally, 4) a sharp increase in the share of renewable energy. In terms of land use, the impacts of climate policy are less pronounced, but still noticeable. First of all, the increase in the use of modern bio-energy leads to an increase of land for bio-

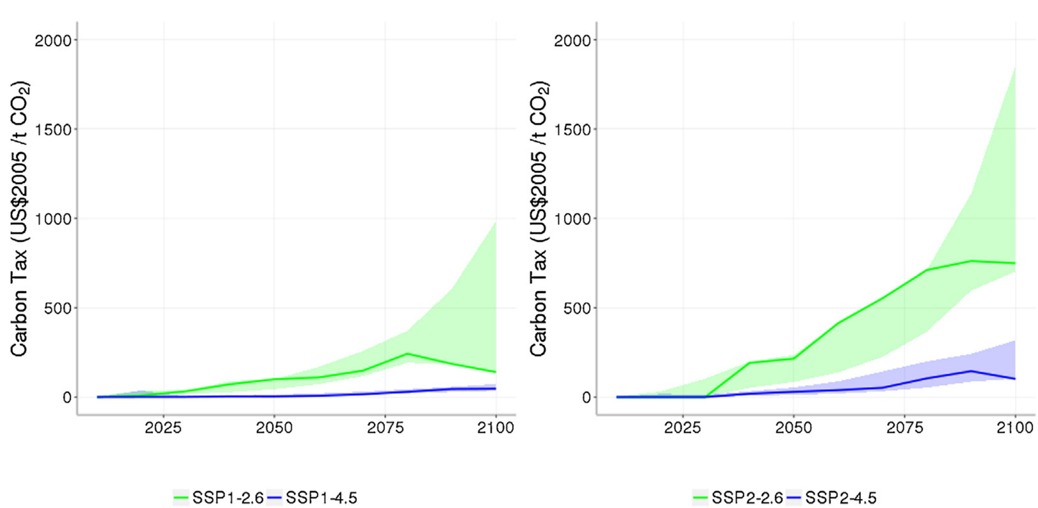

Fig. 12. Carbon price for reaching radiative forcing targets of 4.5 and 2.6 W/m^2 for SSP1 (left) and SSP2 (right). The area indicate the range of results of the other IAM scenarios for the specific SSP (see references in Section 2).

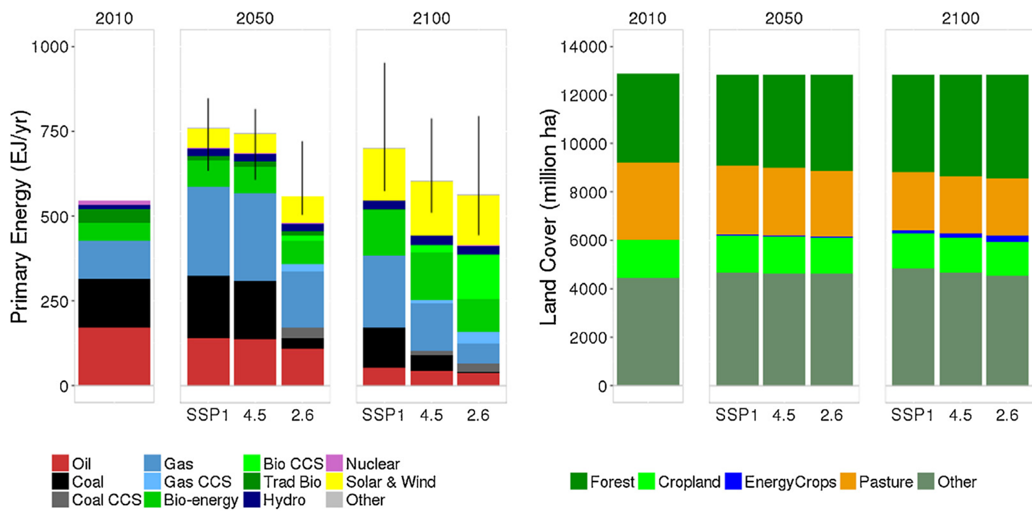

Fig. 13. Primary energy and land-use, 2050 for 4.5/2.6 W/m2. The vertical lines indicate the range of results of the other IAM scenarios for the specific SSP (see references in Section 2).

energy. Secondly, the assumed efforts on ARD lead to a small increase in forest area.

Obviously, the 4.5 and 2.6 W/m^2 stabilization scenarios lead to significantly lower emission levels than the corresponding reference scenarios (Fig. 14). For energy related emissions a very clear emission reduction can be noticed, leading to net negative emissions in case of the 2.6 W/m^2 scenario. For land-use related emissions, several trends happen at the same time. The higher bio-energy use leads to more emissions, but increased ARD activity leads to fewer emissions. The associated forcing and temperature levels are shown in Fig. 11.

5. Discussion and key uncertainties

Obviously, the scenarios shown here are prone to many uncertainties – as several interpretations of the storylines are made in terms of input assumptions for the IMAGE model. Earlier, a full uncertainty analysis was done for the energy system of the IMAGE models in terms of interpretation of reference scenarios (Van Vuuren et al., 2008) and climate mitigation action (Van Vuuren et al., 2007). These studies identified assumptions on energy efficiency, preferences in consumption and production patterns and, overall, technology development assumptions of critical importance for the reference scenarios outcomes, while the bio-energy and CCS assumptions were found to be critically important for the stabilization scenarios. Similar conclusions were derived in model comparison studies (Kriegler et al., 2014b).

The SSP1 scenario is based on relatively environmentally friendly consumption patterns (e.g. for diets and transport patterns), rapid technology development, and good governance without implementing climate policy. In qualitative sense, trends follow many of the SDGs – without necessary meeting the 2030 targets. There are several assumptions in the SSP1 implementation that are open to subjective interpretation. The choice to interpret the SSP1 storyline consistent with the “global sustainability” scenario family is consistent with the storyline described in O’Neill et al. (2017). For instance, the important role for bio-energy, renewables and CCS (in the climate policy case) perfectly fit in this interpretation of the SSP1 storyline, while even stronger lifestyle changes, decentralized energy systems and reducing trade would have fitted a more “local sustainability” version. It would clearly be interesting if alternative SSP1 scenarios are developed – allowing for comparing the trade-offs between these different paths. In the quantification, we have as much as possible followed trends

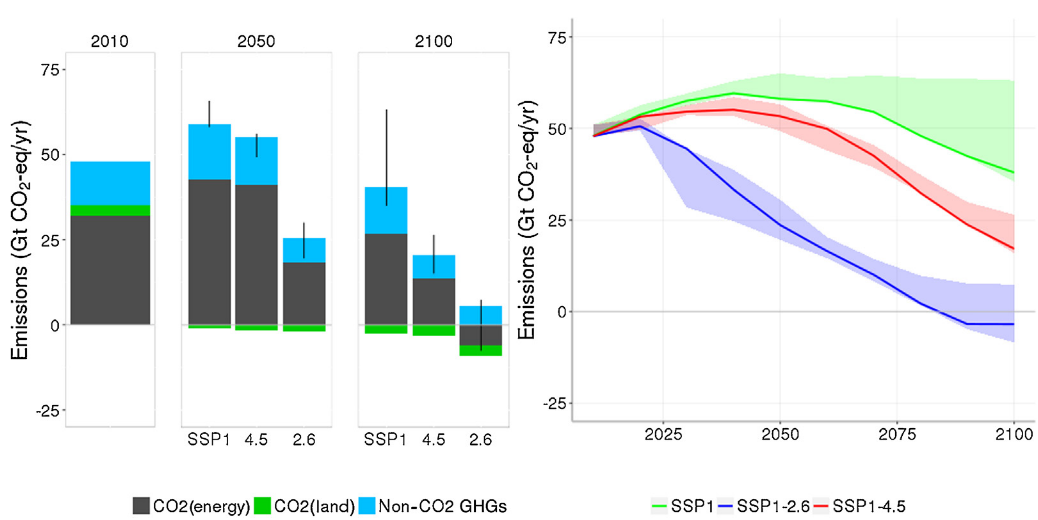

Fig. 14. Emissions over time SSP1 reference scenario, 4.5, 2.6 (by category left and total right). The vertical lines and shaded area indicate the range of results of the other IAM scenarios for the specific SSP (see references in Section 2).

implemented in earlier studies as indicated in the text. In the "family" of global sustainability scenarios developed earlier, several have been implemented by the IMAGE model (B1, Technogarden, Sustainability First – see Van Vuuren et al. (2012)). The current implementation shares several key characteristics of these scenarios. Key differences, however, include the updated base year data and the more detailed description of transitions in different sectors (e.g. transport and land use). Compared to Technogarden and Sustainability First scenarios, the SSP1 reference scenario is different by not including explicit additional climate policies. As a result, the SSP1 reference scenario emissions are higher than these scenarios, and more comparable to the B1 scenario.

Finally, it is clear that the SSP1 scenario world will not emerge automatically. It will require a consistent effort of moving in a certain direction. Important risks of the SSP1 world include non-performance of technology, rebound impact of efficiency, possible tensions associated with free-rider behaviour, and a potential push-back from actors whose interests are not ensured in this storyline. This requires that societal change moves beyond the first-movers and also society-at-large implements the SSP1-related changes. Therefore, interpreting the SSP1 storyline as an *easy way* to achieve climate policy goals is therefore not necessarily correct. At the same time, however, the broad targets in the SSP1 storyline could very well have significantly more societal support (also in developing countries), so if implemented climate policies themselves would be easier to implement.

6. Conclusion

In this paper, we describe three possible pathways of future energy use, land-use, greenhouse gas emissions and air pollution emissions and climate change as implemented in IMAGE 3.0. Most attention is paid to the SSP1 results, for which the IMAGE results form the SSP1 marker scenario, while for comparison also the median assumptions (SSP2) and global fragmentation (SSP3) are presented.

In the SSP1 narrative, an emphasis on resource efficiency, preferences for sustainable production methods and human development can be combined to lead to a 2100 greenhouse gas emission level below 2010 emissions. The assumptions made in the SSP1 quantification have been based on the SSP1 narrative. While we have not targeted the achievement of the SDGs in SSP1, the scenario leads to significant improvement in access to modern energy and food, urban air pollutants, and mitigating climate change. Key aspects include energy efficiency, integration of renewable energy in the overall system, increased access to and use of electricity and hydrogen, dietary change and rapid development of agricultural yields and livestock systems' performances. Moreover, also other factor of the SSP1 storyline such as the high level of education investment and subsequent reduction of fertility play a key role. Together, the trends lead to a pathway with low energy and land-use related greenhouse gas emissions.

The SSP1 reference scenario still leads to a 2100 warming of 3 °C. Mitigation costs for achieving the 2 °C target are relatively low in case explicit climate policies are introduced. It should be acknowledged that the exact implementation of the SSP1 storyline is beset with uncertainty. Still, it can be concluded that, it is not likely that the 2 °C target can be achieved under the SSP1 storyline alone, without introducing additional climate policy. In our calculation, we show the achieving the 2 °C target from the SSP1 storyline would be on the low side of those reported in the literature –and considerably lower than the costs of achieving the same target from a SSP2 scenario. As such, the hypothesis formulated earlier that SSP1 storyline would represent a situation with a relatively low challenge for mitigation is found to be true, also for more ambitious climate targets such as 1.5 °C.

The SSP1 storyline could be a basis for further discussions on how climate policy can be combined with achieving other societal goals. Most model-analysis on achieving low greenhouse gas emission levels look specifically at climate policy. More-and-more, it is emphasized in international climate policy that many countries will only accept costly climate policies if these align with achieving other societal goals. The SSP1 scenario forms an example of a scenario in which climate policy is implemented alongside other goals such as a focus on providing sufficient food, providing modern energy, avoiding deforestation and reducing local air pollution. The resulting emphasis on resource efficiency and more environmentally friendly consumption and production patterns leads also to lower greenhouse gas emissions. Implementing both a sustainable development agenda and climate policy goals might have more support than climate policy alone. As such activities similar to those depicted in the SSP1 scenario could provide a bridge towards a sustainable future that would include climate policy.

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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.2016.05.008.

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