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Global energy system transformations in mitigation scenarios considering climate uncertainties

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HIGHLIGHTS

- Global energy transformations for mitigation evaluated with climate uncertainties.
- Climate uncertainties do not avert decarbonization, CCS, and lower energy use.
- The effect of climate uncertainties was largest for coal without CCS and BECCS.
- Climate uncertainties have smaller effect than those related to IAMs.

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ABSTRACT

This study evaluates the effect of climate uncertainties on the transformations in the global energy system needed for realizing mitigation targets in the long term. Climate uncertainties affect the amount of allowable emissions from human activities that are consistent with a given climate target, and, thus, the range of necessary energy transformations. A range of emission scenarios consistent with intermediate (RCP4.5) and stringent (RCP2.6) mitigation targets are analyzed with an integrated assessment model (IAM). Emission scenarios are generated with an earth system model of intermediate complexity, which evaluated the variability of allowable carbon emissions due to uncertainties in the climate sensitivity, the carbon cycle and its feedbacks. The results showed that even when climate uncertainties are reflected at different scales across energy supply components, achieving mitigation targets needs partial decarbonization of supply, scale up of carbon capture and storage (CCS), and decreased energy consumption. The effect of climate uncertainties was largest for coal without CCS (up to 100% in 2100 compared to the central scenario) and bioenergy with CCS (up to 23% in 2100 compared to the central scenario). Land for bioenergy feedstocks, and the deployment of unmanaged lands for other purposes also had a considerable variation (10–20% in 2100). Compared to the uncertainty in socio-economic factors quantified in IAMs, the variation induced by the climate uncertainties was small. In contrast to previous IAM studies, the results herein explicitly described how climate-related uncertainties affect the global energy system, based on scenarios incorporating a robust approach for covering a wide scope of uncertainties from a climate model.

1. Introduction

Considerable transformations in the global energy system are needed for the realization of climate mitigation targets leading to considerable reductions of greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2), in the long term. Among these transformations, the climate scenario literature based on integrated assessment models (IAMs) in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), indicates the need for decarbonizing the energy supply, increasing the efficiency of both energy supply and end use, and the implementation of carbon dioxide removal technologies such as carbon capture and storage (CCS) [1]. For example, a shift away from fossil fuels and a large contribution of renewables, including modern bioenergy (i.e., energy produced from biomass excluding energy for cooking in traditional cooking stoves) will be needed to decarbonize global energy supply [1,2]. AR5 scenarios targeting GHG concentrations of 430 to 580 ppm CO_2eq by 2100, point out that low carbon primary energy supply in 2050 should be scaled up

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Nomenclature

AMPERE	assessment of climate change mitigation pathways and evaluation of the robustness of mitigation cost estimates
AR5	fifth assessment report
BECSS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
C4MIP	coupled climate-carbon cycle model intercomparison project
EMIC	earth system model of intermediate complexity
ESM	earth system model
FF&I	fossil fuel and industry
GCAM	global change assessment model
GDP	gross domestic product
GHG	greenhouse gas
IAM	integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
MAGICC	model for the assessment of greenhouse-gas induced climate change
RCP	representative concentration pathways
SSP	shared socioeconomic pathways
TPES	total primary energy supply
UNFCCC	United Nations Framework Convention on Climate Change

from two to seven times current levels [3], that bioenergy should take from 10% to 50% of total primary energy supply in 2100, and that considerable penetration of electricity generated from biomass coupled with CCS (BECCS) will be needed [4]. However, the scale of these transformations consistent with a specific mitigation target is unclear, given that the amount of carbon emissions reduction required to achieve a climate target in the long term is subject to uncertainties linked to the carbon cycle and the climate sensitivity [5–7]. This uncertainty affects the balance between sources and sinks of carbon in the land and the ocean, and thus, the trajectory of carbon emissions from human activities that can be allowed under such mitigation target. This, in turn, results in a range of possible pathways for transforming the energy system that would be consistent with a unique climate target (either a GHG concentration or global temperature change target).

Exact quantification of the effect that assuming a different behavior of the climate system may have on the energy system is a challenging matter. The difficulty of this task depends on the level of complexity of the processes under investigation, and the level of integration sought [8]. Integrating the changes in the representation of the climate system into an IAM involves resolving several features mismatching with climate models. On the one hand, the spatial resolution of IAMs is very coarse, usually considering countries aggregated into a few large world regions (e.g., Southeast Asia, South America), while climate models represent variables in a gridded space of some unitary size smaller than the area of most of such aggregated world regions. On the other hand, the temporal resolution of IAMs usually is one or few years per period modeled, while climate models are able to represent seasonal and daily variations within a year. Moreover, the long time needed to obtain the outcomes from a climate model of high complexity, such as an Earth system model (ESM), prevents the assessment of large ensembles of scenarios. To overcome these mismatches, a compromise needs to be undertaken between the level of integration (from soft-linking models to fully coupling models) and the complexity of the models used.

The implications of climate uncertainties on a given global emission scenario are usually evaluated in terms of the possible spectrum of climate outcomes (in particular of the global temperature change) after varying the values of climate parameters in a simple climate model. Examples of these type of studies estimate the range of allowable emissions considering a probability distribution of climate sensitivity [9], the probability of meeting stringent temperature targets for multiple emission scenarios [10], or the mitigation costs considering uncertaintites in both climate and socio-economic parameters [11]. However, in order to describe explicitly the effect of climate uncertainties on the socio-economic system, it is necessary to analyze a range of emission scenarios leading to a given climate target after considering these uncertainties. Assessment of climate targets considering uncertainties in the socio-economic system and across IAMs, has been treated in a comprehensive manner by means of multi-model intercomparisons that study the effect of modeling approach and scenarios assumptions. Representative examples of these studies include analysis on uncertainties related to the role of bioenergy in global energy supply [12], energy technology availability [4], energy technology costs [13], delayed implementation of mitigation actions [14], and economic growth and fossil fuel availability [15]. Other studies analyze uncertainties for a single model, focusing for example on the scenario narratives [16], the role of electrification [17], the learning rates of energy technologies [18], the factors determining wind energy penetration [19], the spread of outcomes for model's sub-optimal solutions [20], the role of storage and hydrogen technologies [21], and on probabilistic analysis of multiple socio-economic/technology parameters by means of Monte-Carlo methodology [22]. In contrast, the existing literature evaluating the effect of climate uncertainties on scenarios using IAMs focuses on few or individual factors related to the climate system. These studies include the effect of assuming different values of climate-related parameters in isolation, such as a stronger/weaker carbon cycle feedback [23], different values of the equilibrium climate sensitivity based on a highly aggregated models [24] and disaggregated models [25], and the use of different emission metrics in addition to global warming potentials [26]. Other IAM studies considering climate uncertainty are based on highly aggregated models focusing on decarbonization of energy supply [27] and social costs [28], but do not represent neither the energy system technologies nor the land use changes in the global system. Other studies assessed the effect of a comprehensive set of climate uncertainties on gross domestic product (GDP) losses and the energy system of uncertain allowable carbon emissions at global scale [29]. However, the assessment considered only an intermediate mitigation target, and the model used lacked any representation of land-use change dynamics.

Addressing these gaps in knowledge related to global energy transformations in mitigation scenarios is important given that: (a) climate uncertainties span over a wide range of parameters describing the climate system; (b) stringent climate targets require more drastic transformations, including large bioenergy deployment, which in turn results in considerable changes in the patterns of land use; (c) clarifying the effect of climate uncertainties has to be viewed in the context of other uncertainties surrounding IAM assessments. The purpose of this study is to assess the effect of climate uncertainties on the global energy transformations for intermediate and stringent mitigation scenarios. For this aim, a set of emission scenarios generated by means of an Earth system model of intermediate complexity (EMIC) were assessed with an IAM including the representation of the land-use sector. The novelty of this study relies on two aspects: (1) the consideration of a comprehensive set of climate uncertainties (including climate sensitivity, the carbon cycle and its feedbacks) in a robust way not possible with simple climate models deployed in other analyses (in contrast to for example Calvin et al. [25] and Marcucci et al. [30]); (2) the identification of the effect of climate uncertainties on individual components of the global energy system, altogether with the implications on land use (in contrast to for example Matsumoto et al. [29].

2. Methodology

The flow of analysis in this study, presented in Fig. 1, considers the input (or "soft-linking") of information on allowable carbon emissions from fossil fuel and industry (FF&I) from a climate model (EMIC) into a socio-economic model (IAM) to analyze the changes in multiple features of the global energy system. The allowable emissions are obtained from EMIC experiments based on carbon concentration scenarios from the Representative Concentration Pathways (RCPs) [31] consistent with two climate targets (in terms of radiative forcing). The EMIC experiments evaluated the climate system uncertainties by considering a range of values for multiple Earth system variables.

2.1. Integrated assessment model

The analysis is conducted with GCAM-SOUSEI[1]. This model is a direct descendant of the Global Change Assessment Model (GCAM), an IAM representing the economy, the energy sector, and the agriculture and land use sector under a partial equilibrium approach [32]). GCAM has been applied for many analyses, including the development and assessment of representative scenarios of global GHG concentration [33] and socio-economic narratives [34], climate change impacts on building energy demand [35], impacts of global biofuel mandates [36], air pollutants projections [37], and co-benefits of air pollution control policies [38]. GCAM analyses have contributed to the development and assessment of emission scenarios contributing to the IPCC, including the special report on emission scenarios [39], and the fourth [40] and fifth [41] assessment reports of the IPCC. Its structure and contents are extensively documented in the literature [42], including technical manuals on the overall features [43], the socio-economic and energy modules [44] and the land use and agriculture modules [45]; thus only the major features are described here to avoid diffuseness. GCAM estimates the supply, demand, and prices of energy resources and agricultural commodities, as well as the resulting emissions for several world aggregated regions under a set of socio-economic (population, GDP), technology (efficiency, cost, and progress of technologies in the energy and agriculture sectors), and mitigation policy assumptions (carbon price by regions and sectors). The model calculates emissions of gases covered by the Kyoto Protocol and aerosols. The energy sector is described into non-renewable and renewable resources, which are used as inputs in conversion technologies, which in turn supply different energy carriers (electricity and fuels) for specific demand sectors. Selection of technologies in the energy sector is based on share functions represented as logistic curves. The agriculture and land-use sectors include the production and demand of crops, livestock, forest products, and bioenergy. Land use is allocated within each world region and agro-ecological zone based on the profit maximization from land-based production. The model provides detailed information on the energy resources and technologies together with land-use changes, by considering interactions between carbon prices, and energy and land prices.

Mitigation of GHGs is implemented by means of a price on emissions (i.e., carbon price) from fossil fuels and industry, and optionally also from land use change, across world regions and sectors. Mitigation of non-CO_2 GHGs (including methane, nitrous oxide and fluorinated gases) is estimated with marginal abatement cost curves, which indicate the rate of emission reduction of a gas in each sector and region for a given carbon price. Carbon prices are adjusted so that emissions match a fixed amount set exogenously (i.e., emission cap), while keeping the balance between supply and demand across markets at the lowest cost.

GCAM-SOUSEI differs from the original GCAM with respect to the process and assumptions to derive the emissions paths considered in the mitigation scenarios (explained in Section 2.3). In GCAM-SOUSEI, the emission pathways consistent with a climate target (e.g., radiative forcing) are obtained from ensemble experiments with an EMIC (which is different to the climate model in the original GCAM model). These experiments estimated the global allowable CO_2 emissions based on the GHGs concentrations indicated by representative concentration pathways, considering the range of values of physical and biogeochemical parameters representing the uncertainty of ESMs. In contrast, in the original GCAM model, emissions pathways are obtained by adjusting exogenously a carbon price pathway in an iterative fashion, until the climate target is met. Climate outcomes are calculated with the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), a simple climate model representing global and hemispheric upwelling-diffusion and energy balances. It includes a range of gas-cycles and climate feedbacks on the carbon cycle [46].

2.2. Climate model

The CO_2 emission trajectories used in this study have been derived from ensemble model simulations with an EMIC [47]. This EMIC model, fully described in Tachiiri et al. [48], consists of a simplified two–dimensional atmosphere, a three-dimensional ocean circulation model, and a "loosely" coupled (i.e., coupled just once a year) terrestrial ecosystem model [48]. In the ensemble experiment, each ensemble member is run with varied physical and biogeochemical parameters, and the ranges of parameter perturbation are tuned to represent the uncertainty of existing ESMs in Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP) [49], in terms of linear transient climate sensitivity and sensitivity of land and carbon storage to change in CO_2 concentration and in temperature. The EMIC experiments varied key parameters affecting transient climate response, CO_2-carbon cycle feedback and climate-carbon cycle feedback. They included parameters related to the atmosphere (climate sensitivity), the ocean (vertical and horizontal diffusivities, thickness, freshwater influx adjustment), marine carbon (wind speed used in marine CO_2 uptake), land (maximum photosynthetic rate, specific leaf area, minimum temperature for photosynthesis, temperature dependencies of plant's and of soil respiration), and forcing (total aerosol forcing) [47].

2.3. Scenarios

2.3.1. Emission scenarios

The scenarios considered in this paper, listed in Table 1, include a reference scenario and a set of mitigation scenarios. The *Reference* scenario considers current policies without any mitigation policy. Mitigation scenarios are defined with respect to two dimensions: (1) a mitigation target (*RCP4.5* and *RCP2.6*), and (2) a range level indicated by the range of climate uncertainties (*Lower*, *Mean*, and *Upper*). These mitigation scenarios assume constraints in terms of CO_2 emissions trajectories, which are obtained from the EMIC (described in the previous subsection).

The mitigation target dimension assumes two trajectories for CO_2 emissions during the 21st century consistent with specific climate targets, and three levels for each target indicating the effect of climate uncertainties (scenarios consider constraints only for CO_2 from FF&I, but considers mitigation of non-CO_2 Kyoto GHGs with marginal abatement cost curves; land use change CO_2 emissions are not constrained, and they are estimated internally from activities in the "agricultural and land use" module of GCAM-SOUSEI). This study assumes emissions consistent with atmospheric concentrations defined by

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[1] GCAM is an open source model with multiple variations generated by different research groups. In order to distinguish the version of the model, the team originally developing the model requires other groups to rename it by appending a name after "GCAM". SOUSEI is the short name of the project "Program for Risk Information on Climate Change" funded by the Ministry of Education, Culture, Sports, Science and Technology of Japan, aiming at the generation of basic information required for managing risks resulting from climate change [64].

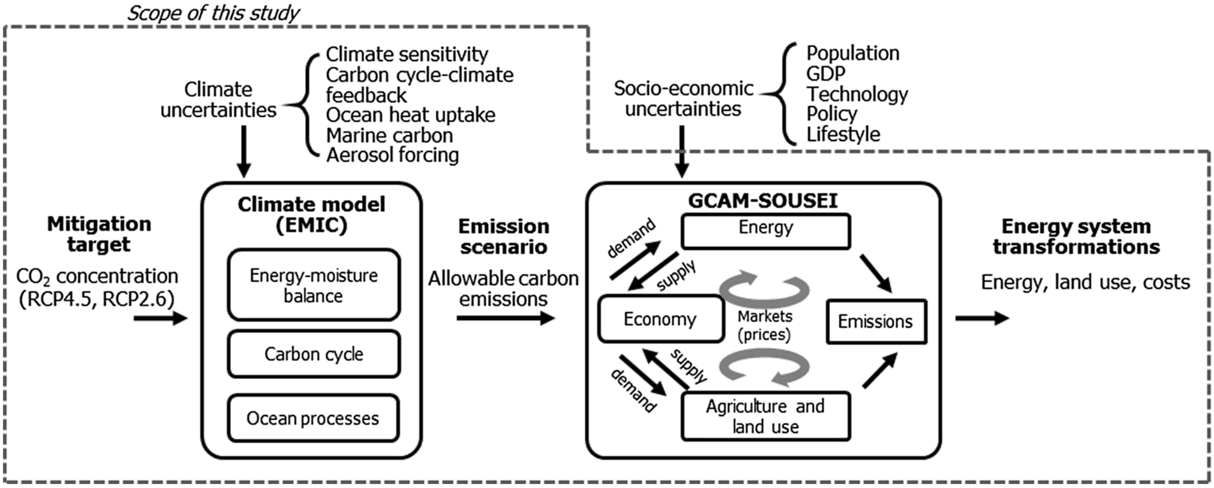

Fig. 1. Modeling framework illustrating the main components and data flows in the climate model (EMIC) and the IAM (GCAM-SOUSEI).

Table 1
Scenarios considered in the study.

Range level of allowable CO_2 emissions	Mitigation target		
	None	RCP4.5 [d]	RCP2.6 [d]
–	*Reference*	–	–
Lower[a]	–	*EMIC-RCP4.5-Lower*	*EMIC-RCP2.6-Lower*
Mean[b]	–	*EMIC-RCP4.5-Mean*	*EMIC-RCP2.6-Mean*
Upper[c]	–	*EMIC-RCP4.5-Upper*	*EMIC-RCP2.6-Upper*

[a] Allowable CO_2 emission 5th percentile of EMIC ensemble.
[b] Allowable CO_2 emission 50th percentile of EMIC ensemble.
[c] Allowable CO_2 emission 95th percentile of EMIC ensemble.
[d] Emission scenarios considering mitigation are for the constrained case from Tachiiri et al. [47]; they assume mitigation of CO_2 from fossil fuel and industry, and non-CO_2 GHGs (i.e., excludes CO_2 from land-use change).

two of the RCPs [31], namely the RCP4.5 [33] and the RCP2.6 [50]. They correspond to concentration pathways keeping global radiative forcing at 4.5 W/m^2 and 2.6 W/m^2 by 2100, respectively. Focusing on these targets helps to compare the importance of climate uncertainties within scenarios that are "not so far" (*RCP4.5*) and "very distant" (*RCP2.6*) from the current socio-economic situation. The intermediate target can be regarded as more feasible than stringent targets, since it involves less drastic changes in energy use and land use, less reliance on uncertain developments in energy technologies and consumption patterns, and lower costs. Nevertheless, we acknowledge that a stringent target may reflect more accurately the perspective of policy making towards climate change mitigation given the status of climate negotiations under the Paris Agreement [51].

The range of carbon emissions for each target derives from the uncertainties in the climate system that affect, among others, the rate of CO_2 uptake by the land and the oceans and the transient climate response. The *Lower*, *Mean*, and *Upper* levels of the emission scenarios (Table 1 and Fig. 2), correspond to the 5th, 50th, and 95th percentiles

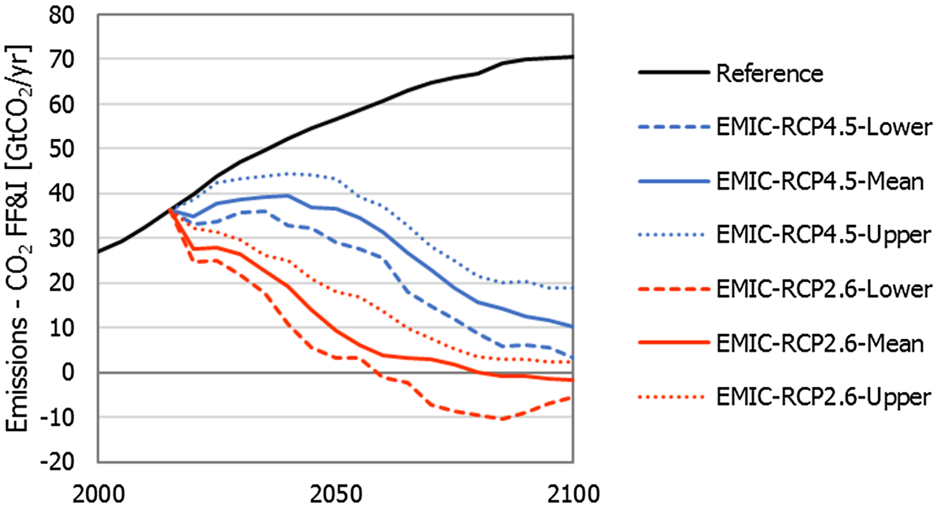

Fig. 2. Emissions paths of CO_2 from fossil fuel and industry (FF&I) based on range of allowable carbon emissions from EMIC (based on [47]).

of the accumulated weight of the ensemble members generated by the EMIC, respectively. These scenarios are generated keeping consistency with the historical observations of several climate indicators. It is worth noting that despite a maximal effort involved in designing and conducting the experiments originating those emission scenarios, it was not possible to capture perfectly the spread of existing ESM values, as outcomes were biased towards the range of low carbon uptake assumptions. Nevertheless, the experiments covered most of the range of ESM's values, and represent valid information based on a probabilistic framework.

The scenarios considering the lower level of the range of allowable emissions for a given climate target (*EMIC-RCP4.5-Lower, EMIC-RCP2.6-Lower*) indicate that the risk of climate change is high. In other words, these scenarios expect larger changes in the climate system for a given amount of carbon emissions, and thus a larger increase in global temperature change [52]. As a result, actions to reduce emissions (e.g., investments in low carbon technologies, and phase-out of carbon and energy intensive activities) need to be implemented earlier and at larger scales, resulting in larger mitigation costs [53]. Therefore, these scenarios assume a perspective for policymaking that aims to avoid climate change risks while accepting the cost of mitigation. On the other hand, the upper level scenarios (*EMIC-RCP4.5-Upper, EMIC-RCP2.6-Upper*), which involve larger amounts of allowable carbon emissions for a given climate target, indicate that the risk of climate change is low, thus the mitigation costs are low. In contrast to the lower level scenarios, mitigation actions can be taken later and at smaller scales. From the policymaking perspective, these scenarios assume a higher acceptability of climate risks while avoiding a large mitigation cost burden.

2.3.2. *Other scenario settings*

All scenarios considered in the assessment are based on the same set of socio-economic assumptions. Population [54] and economic development ([55]) data are from the Shared Socioeconomic Pathways (SSP) [56]). Scenarios are based on the SSP2 storyline, which corresponds to an intermediate scenario within the framework of SSPs. In this scenario, global population peaks at around 9 billion by around year 2070, and global GDP increases steadily to reach around 550 trillion USD in 2100 (see Figs. A1 in the Appendix).

3. Results

This section describes the outcomes of the analysis in three parts, starting with the overall results for the *Reference* and the mitigation scenarios, and followed by the detailed description of the effect of

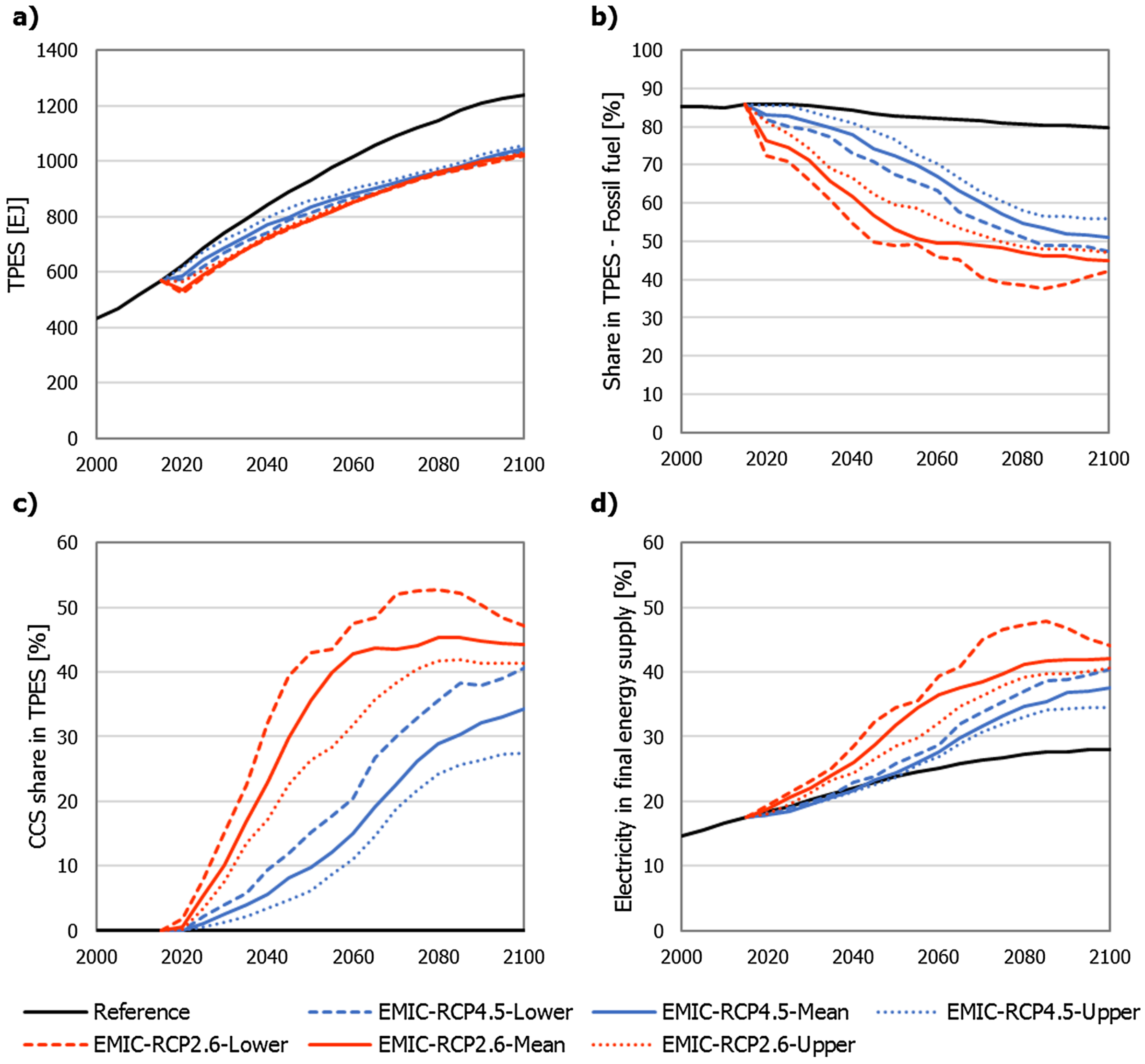

Fig. 3. Major features of the global energy system in scenarios considering the uncertainty in allowable carbon emissions: (a) primary energy supply, (b) share of fossil fuels in TPES, (c) share of primary energy supply with CCS (results for the *Reference* scenario are zero for all periods), and (d) share of electricity in final energy supply.

climate uncertainties on the energy system. In the last part, the effect on land use are presented, given the relevance of biomass energy in the mitigation scenarios.

3.1. Global transformations in the energy system

The trends in major features of the global energy system (total primary energy supply (TPES), the share of fossil fuels and of CCS in TPES, and the share of electricity in final energy supply) for the scenarios assessed are presented in Fig. 3. The breakdown of TPES and final energy supply by sources is presented in Fig. 4.

The absence of policies to mitigate GHGs depicted in the *Reference* scenario, lead CO_2 emissions from fossil fuel and industry to grow from 29 $GtCO_2$ in 2005 to 57 and 71 $GtCO_2$ in 2050 and 2100, respectively (Fig. 2). TPES grew from 471 EJ in 2005 to around 934 and 1239 EJ in 2050 and 2100, respectively (Fig. 3a). The energy supply was dominated by fossil fuels, with a slight decrease in their share from 85% in 2005 to 80% in 2100 (Fig. 3b). Final energy grew steadily from 359 EJ in 2005 to 920 EJ in 2100, and was delivered mostly as liquid fuels (around 40%), electricity (around 25%) and gas (around 15%) (Fig. 4c).

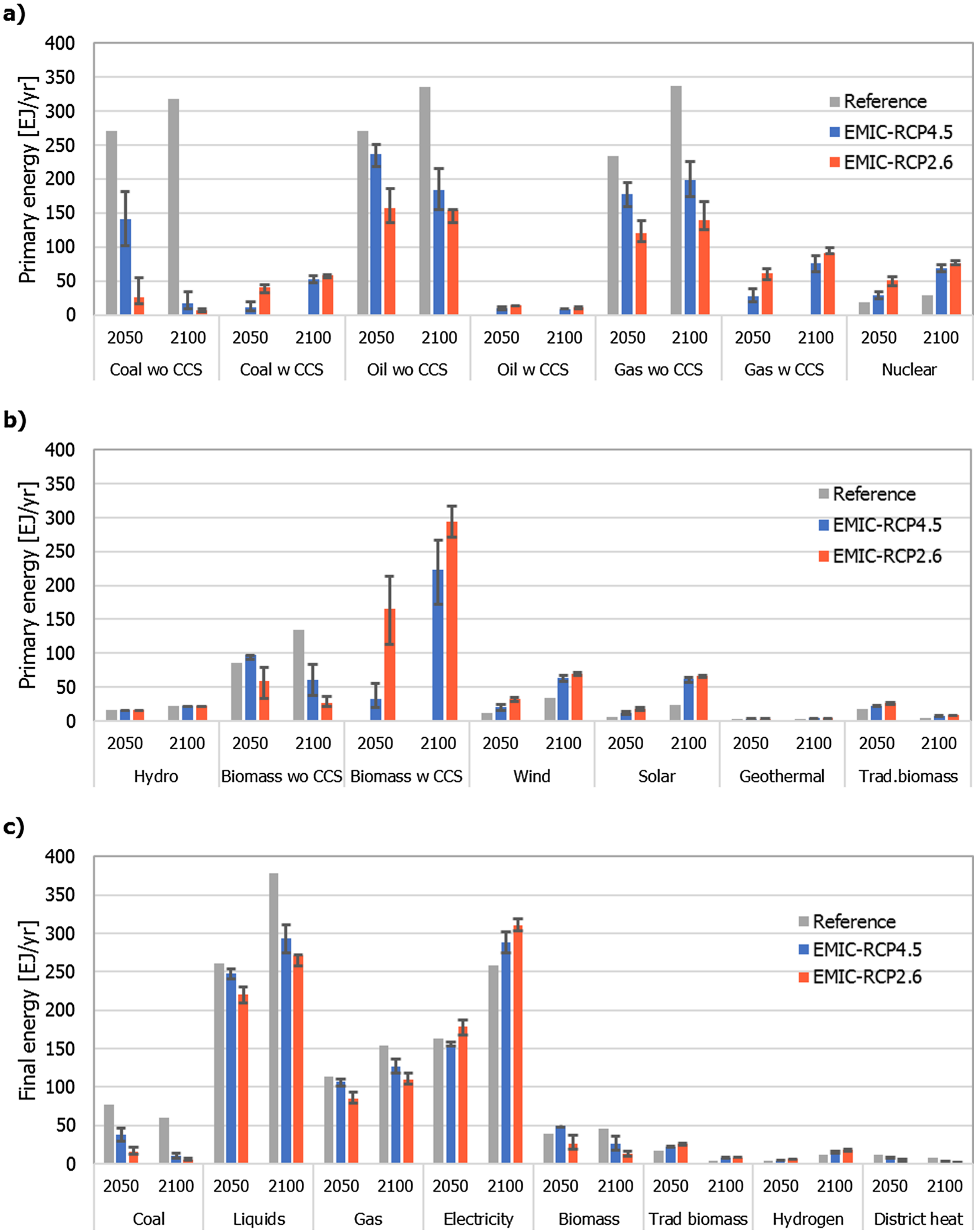

Fig. 4. Structure of the global energy system in scenarios considering the uncertainty in allowable carbon emissions: (a) primary energy supply by sources – Fossil fuels and nuclear; (b) primary energy supply by sources – Renewables; (c) final energy supply by sources. Bars indicate the value of the *Reference* and the *Mean* scenarios, and the whiskers indicate the values of the *Upper/Lower* scenarios.

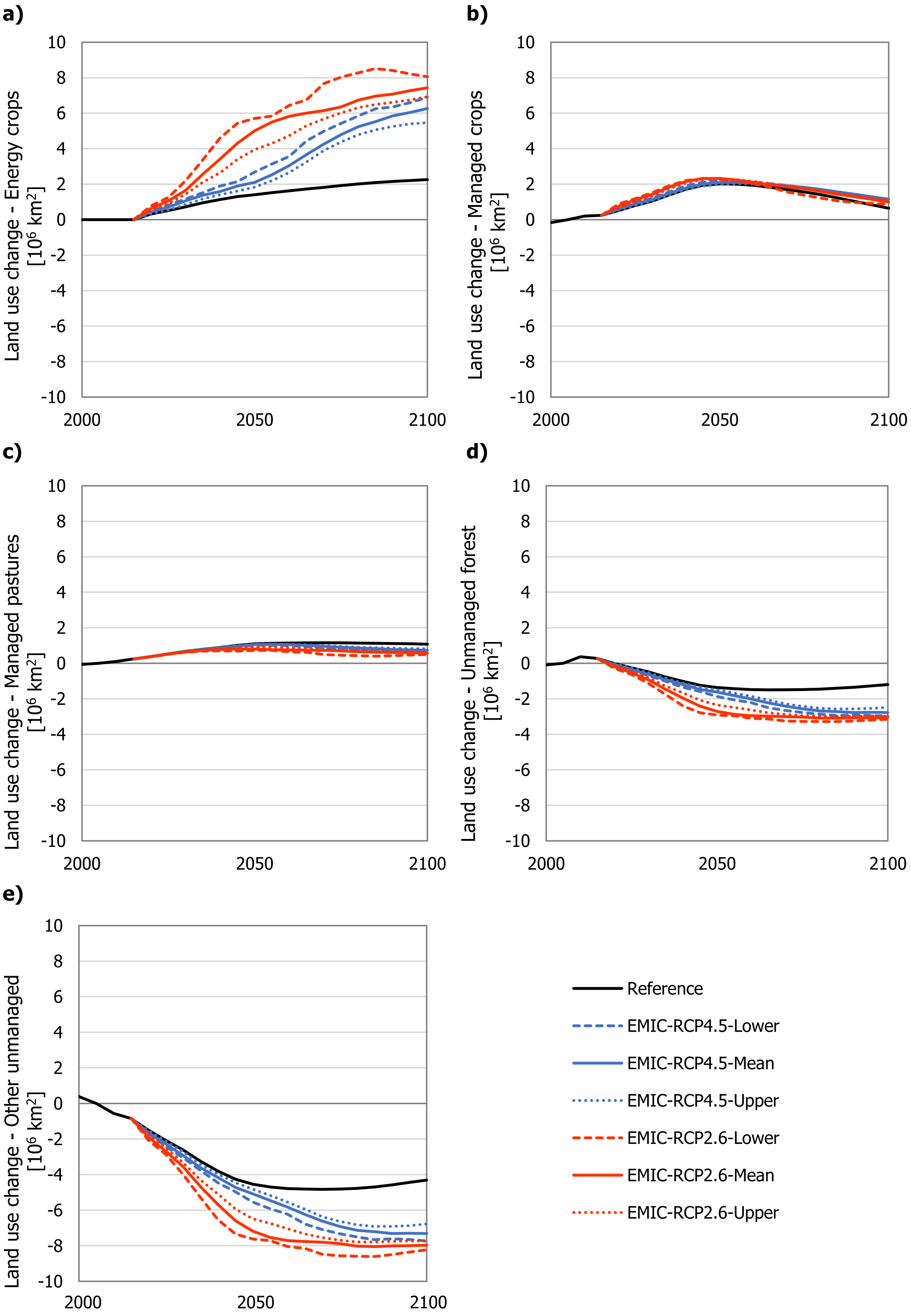

Fig. 5. Effect of uncertainty in allowable carbon emissions on the global land-use change for (a) energy crops, (b) managed crops, (c) managed pastures, (d) unmanaged forests, (e) other unmanaged (arable, pasture, grass, shrub).

Achieving the mitigation targets in both the *RCP4.5* and *RCP2.6* scenarios, required drastic transformations of the global energy system, in terms of decarbonization of energy supply, penetration of CCS technologies and bioenergy, electrification, as well as reduction of energy consumption. The pace of these transformations was faster in scenarios considering a stringent target (*RCP2.6*) than in those aiming at an intermediate target (*RCP4.5*), which resulted in clear diversion in mitigation paths and shifts in energy sources from the early decades of the century. By 2100, the share of fossil-fuel supply in mitigation scenarios fell to between 50% and 40% of TPES, while the share of CCS grew to more than 25%. TPES and final energy consumption decreased by around 20%. The share of non-fossil energy sources in TPES was dominated by biomass (around 30%), followed by other renewables (around 15%) and nuclear (6–7%).

Final energy demand in mitigation scenarios decreased in all sectors, mainly in the industrial sector. In addition to the effect of energy efficiency gains in the energy supply and end-use sectors, larger electrification of the energy supply (and the penetration of hydrogen to a minor extent) displaced the consumption of other fuels, especially of coal and oil. In the electricity supply, the picture was mostly the same with TPES, with a smaller presence of fossil fuels in the energy mix. Among fossil fuels, the more drastic changes were found in coal without CCS. Basically, all fossil fuels without CCS saw a negative growth in supply, except for natural gas, which kept increasing until 2100 yet at lower levels than in the Reference scenario.

3.2. *Effect of climate uncertainties on the global energy system*

The effect of uncertainty in allowable CO_2 emissions presented in Figs. 3 and 4, indicated by the deviation of a mitigation scenario's outcomes with respect to the "*Mean*" scenario, was not uniform across RCP scenarios and periods. In other words, there was not a clear pattern for this effect related to the stringency of the mitigation target, and the timing of the analysis repeating in all the components of the energy system.

The outcomes showed that meeting a climate mitigation target with allowable emissions assuming a high risk of climate change (represented by the *EMIC-RCP4.5-Lower* and the *EMIC-RCP2.6-Lower* scenarios), required considerably larger amounts of low-carbon energy sources, faster and larger penetration of CCS, in particular of BECCS, lower energy consumption, and increased expansion of bioenergy crops in unmanaged arable land, pastures and forests. However, scenarios with allowable emissions that assume a lower mitigation cost (represented by the *EMIC-RCP4.5-Upper* and the *EMIC-RCP2.6-Upper* scenarios), diminished the importance of BECCS in contrast to biomass without CCS, allowed for larger shares of fossil fuel supply and larger energy consumption, and reduced the expansion of land for energy crops over unmanaged forests. Whichever the case was, all mitigation scenarios highlighted the need to reduce considerably the share of fossil fuels in energy supply, to scale up the penetration of CCS (coupled with both fossil fuel and bioenergy), and to lower energy consumption. No matter whether a scenario assumed a high- or low-risk for mitigation, the share of fossil fuels in TPES in the long term remained below 60%. Yet, mitigation targets were feasible without a full decarbonization of the energy supply, thanks to the availability of CCS for fossil fuels, which allowed for a continued use of oil and natural gas without undermining the achievement of mitigation targets.

Another feature highlighted by the outcomes (Figs. 3 and 4) is that the transformations in the global energy system corresponding to the intermediate mitigation target (*RCP4.5*) were clearly differentiated (i.e., do not overlap) from those of the stringent target (*RCP2.6*). This finding confirms the suitability of the RCPs to provide scenarios with unique features even when climate uncertainties are considered. This shows that such uncertainties do not prevent the characterization of a given mitigation target with a unique range of transformations in the global energy system (as long as the settings of the IAM are held constant).

The effect of climate uncertainty was heterogeneous across the components of energy supply. The scale of changes in energy supply was different for primary energy, electricity, and fuels. In particular, coal and bioenergy were the components of energy supply most affected in the long term (48–105% in 2050 and 30–100% in 2100 for coal without CCS; up to 66% and 23% in 2050 and 2100 for BECCS). This was a combined effect of: (1) the growing carbon price (see the Fig. A2 in the Appendix), which increased the cost of fossil fuels (mainly coal); and (2) the improvement in the cost and conversion efficiency of technologies, which increased the market competitiveness of low carbon technologies (such as bioenergy) in the long term. The influence of this "combined effect" was more drastic on coal and bioenergy penetration as they are the technologies with the highest impact on carbon emissions per unit of energy delivered (around 260 gCO_2eq/MJ for coal power based on integrated gasification combined cycle without CCS; around minus 170–220 gCO_2eq/MJ for biomass power with CCS [57]). Different to other technologies, BECCS offers larger impact on emission reduction given it can deliver net negative carbon emissions. This characteristic makes this technology an option with a high impact on mitigation in the long term. In addition, the increase in both the total electricity supply and its share in final energy (see Fig. 4c) in mitigation scenarios, accentuated the importance of climate uncertainties in the role of BECCS for reducing carbon emissions. For most of low carbon energy sources (including fossil fuels with CCS), the relative size of effect of climate uncertainty decreased with the target stringency and in the longer term. For example, the deviation from the *Mean* scenario for natural gas with CCS decreased from 30% in 2050 to 20% in 2100 in the RCP4.5, and from 20% to 10% in the RCP2.6. In contrast, combustion sources (fossil fuels and bioenergy) without CCS showed an increase in the size of the effect with the longer timeframe in the RCP4.5 scenario, while a decrease in the RCP2.6 scenario. Moreover, the effect in 2050 was larger in the RCP2.6 scenario, while the effect in 2100 was larger in the RCP4.5 scenario.

Among the final energy sources, coal and biomass were the most affected by climate uncertainties. The deviation of values from the *Mean* scenario reached up to 20% to 40% for these energy sources, while for other sources, the deviation was less than 10%. When comparing the mid- (2050) and long-term (2100) outcomes, an increase in the relative size of the effect of climate uncertainties was observed for the RCP4.5 scenario, while a decrease was observed for the RCP2.6 scenario. The stringency of the target increased the size of the effect in 2050, while the opposite happened in 2100.

3.3. *Land use transformations*

Land-use changes, presented in Fig. 5, revealed that the variation in the area of unmanaged lands was closely related to changes in bioenergy production, in contrast to the values for cropland and pastures. The expansion of bioenergy without compromising other lands needed for food and fiber production was possible due to the large availability of unmanaged land, such as arable land, grassland, and pastures. Although the outcomes described above suggest that competition of energy crops with other crops was not considerable at global scale, regional outcomes may show a different picture.

The large penetration of bioenergy in supply in the mitigation scenarios, and the large effect of climate uncertainties on this component of the energy system brought along considerable changes in global land use. In the *Reference* scenario, land use for dedicated energy crops increased steadily to 1.4 million km^2 in 2050, and to 2.3 million km^2 in 2100. Expansion of land areas for energy crops, other crops and forest products led to a decrease in unmanaged land (including arable land, pastures and grass, and forests) of 5.9 and 5.5 million km^2 in 2050 and 2100, respectively. The corresponding loss of unmanaged forests was 1.4 and 1.2 million km^2. In all mitigation scenarios, land use for energy crops increased considerably, with only slight changes in croplands and pastures. In 2100, land required for bioenergy production compared to the *Reference* scenario was over two to three times larger. This growth in land use for energy crops, together with a slight growth in cropland, was compensated mainly by decreases in unmanaged lands. The loss in unmanaged forests was up to 3 million km^2, and corresponded to less than 10% of global forest land. The total area of global forests remained almost unchanged in all scenarios (change of less than 3% of total area in 2005) thanks to the expansion of managed forests.

The uncertainty of allowable carbon emissions resulted in a large variation compared to the *Mean* scenario in land for biomass, pastures, and some unmanaged lands (forests and shrubs). For these land categories, land use change compared to the base year deviated between 10% and 20% from the *Mean* scenario. The additional loss of unmanaged forests after considering climate uncertainties, was less than

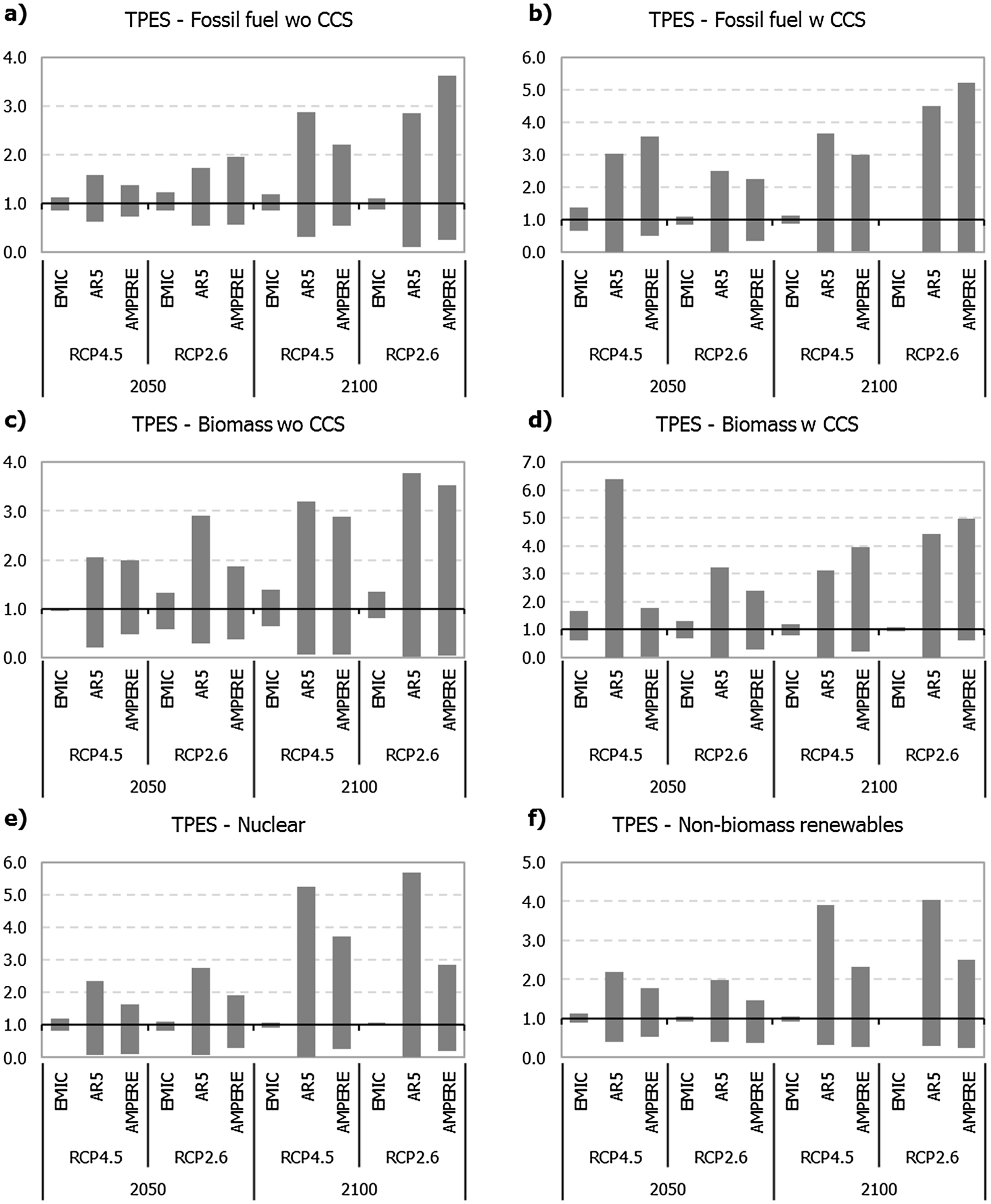

Fig. 6. Range of values of variables describing the primary energy supply for 2050 and 2100, indicated as ratio of the mean scenario: (a) fossil fuel without CCS, (b) fossil fuel with CCS, (c) biomass without CCS, (d) biomass with CCS, (e) nuclear, and (f) non-biomass renewables. Outcomes in this study (“EMIC” in the figure) and a selected set of scenarios from the “AR5” scenario database and the “AMPERE” modeling exercise. AMPERE scenarios correspond to those considering full implementation of technologies (“FullTech”). Mean values for this study correspond to the *EMIC-RCP4.5-Mean* and *EMIC-RCP2.6-Mean* scenarios; for AR5 and AMPERE scenarios, values correspond to the mean of scenarios. Low/high values indicated by the range for this study correspond to the *EMIC-RCP4.5-Upper/Lower* and *EMIC-RCP2.6-Upper/Lower* scenarios; for AR5 and AMPERE scenarios, low/high values correspond to the 5th/95th percentile of values.

1% of the total area of unmanaged forests (around 37 million km^2 in 2005). For other land categories, the deviation from the *Mean* scenario remained below 5%. The stringent scenario did not bring along considerable changes in the effect of climate uncertainties, except for the croplands in 2100, where the relative size of the deviation from the *Mean* scenario jumped from 2% to over 14%. Besides this outcome, the variation in land-use change for croplands was among the smallest values observed for all land use categories. This result indicates that the variation in biomass for energy production due to uncertain allowable carbon emissions has a small impact on cropland, and that other unmanaged land categories (such as shrubs and grass) have a stronger link with biomass land expansion.

4. Discussion

4.1. Implications of the uncertainty analyses

Taking into consideration a range of allowable emissions that reflects climate uncertainty, is an alternative approach to assess energy transformations in mitigation scenarios with IAMs. In general, IAMs analyses cover uncertainties related to the socio-economic projections (i.e., population and income); to the availability, costs and performance of energy resources and technologies; to the emission paths; and to the climate policies (e.g., geographical coverage and timing of emissions cap). Climate uncertainties have been treated indirectly by evaluating the range of possible climate outcomes of a given emission scenario, by considering scenarios that assume the impact of climate change on a certain component within the IAM framework (e.g., energy demand changes due to increased temperatures) [58], or by assessing scenarios with changes in selected climate parameters. In contrast to previous studies, the approach used here allows for: (a) a direct evaluation of the impact that a comprehensive set of climate uncertainties has on the mitigation scenario if other things being equal; (b) the identification of the energy system components most affected by these uncertainties. From the perspective of climate policy making, this analytic capability highlights the existence of a spread of emissions scenarios leading to the same climate target (defined in this study in terms of a global atmospheric carbon concentration by the end of the century consistent with a given radiative forcing), even when the assessment tool (i.e., the IAM), the socio-economic scenario (including the assumptions about the drivers of emissions and the mitigation capacity), and the mitigation policies are the same. For example, compared to the previous study by Matsumoto et al. [29], this study can identify the effect of climate uncertainties for a wider range of variables related to the energy system and the land-use changes, and for multiple mitigation targets (RCP4.5 and RCP2.6). Overall, the features of the transformations needed for mitigation (considerable decarbonization of energy supply and penetration of CCS/renewables, slight decrease in energy demand), and the range of variation induced by the climate uncertainties were similar to those presented by Matsumoto et al. [29].

A question arises on how large climate uncertainties are compared to IAM uncertainties. Fig. 6 shows the values of this research and those of the IPCC's AR5 scenario database [59] corresponding to the same mitigation targets (RCP4.5 and RCP2.6), expressed as the ratio of the central value in each scenario set. In addition, a set of scenarios from the AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates) modeling comparison project is used as a benchmark [14,60]. The AMPERE scenarios are included in the AR5 scenario database, and, different to other scenario sets, were developed with harmonized assumptions (i.e., same or equivalent values across models) on population, income, technology availability, and mitigation policies [14,60]. Therefore, from these data, it is possible to isolate the uncertainty due to the choice of modeling approach for a given mitigation target. Compared to the range of outcomes observed in mitigation scenarios from the AR5, the range due to the uncertainty in allowable emissions found in this study is small. As can be seen in the figure, the range of values for several components of the energy supply obtained in this study is relatively narrow. Also, the changes induced by the uncertainty in allowable emissions are considerably smaller than the effect of the choice of IAM (indicated by the range of values in AMPERE scenarios). For example, focusing on the largest values of BECCS, which was the factor most affected by uncertain allowable emissions, the AMPERE scenarios display values several times larger than the mean in each scenario. For the outcomes of this study, the largest values were at most two times larger than the mean.

For land use, the range of values in this study were compared only to those in the AR5 scenarios (Fig. 7), given that the AMPERE scenarios do not report data on land use. We found that, similar to the outcomes related to the energy system, the effect of climate uncertainties on land for bioenergy crops, other crops and forests, was negligible compared to the effect of IAM uncertainties. The range of values of land for bioenergy crops by 2050 in the RCP2.6 scenarios was of similar scale, but still smaller for this study compared to that of the AR5 scenarios. However, it has to be noted that the spread of land use values in AR5 scenarios may be less representative as the data covers only a few scenarios (around 100) compared to the energy related data (more than 2000).

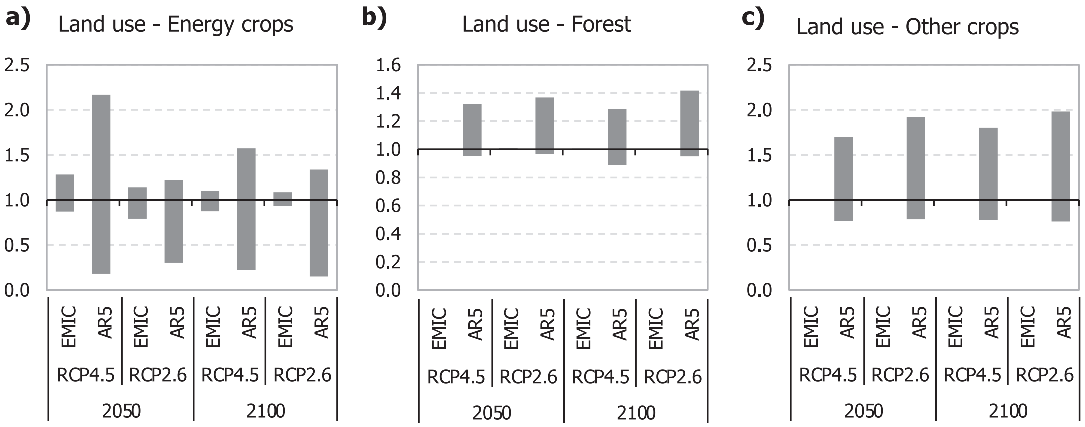

Fig. 7. Range of values of variables describing the land use for 2050 and 2100, indicated as ratio of the mean scenario: a) energy crops, b) forest, c) other crops. Outcomes in this study ("EMIC" in the figure) and a selected set of scenarios from the "AR5" scenario database. Mean values for this study correspond to the *EMIC-RCP4.5-Mean* and *EMIC-RCP2.6-Mean* scenarios; for AR5 scenarios values correspond to the mean of scenarios. Low/high values indicated by the range for this study correspond to the *EMIC-RCP4.5-Upper/Lower* and *EMIC-RCP2.6-Upper/Lower* scenarios; for AR5 scenarios, low/high values correspond to the 5th/95th percentile of values.

This evaluation only shows a limited picture of the significance of the uncertainty in allowable emissions compared to specific uncertainties within IAMs. Firstly, this study only considered two mitigation targets. The choice of the mitigation target changed the scale of climate and IAM-related uncertainties. Moreover, the features of the pathways for a given scenario (climate target stabilization or allowing for overshooting of the target) can have considerable influence on the size of uncertainties.

Secondly, the effect of individual factors within IAMs, such as those related to energy resources and technologies, and socio-economic developments (such as population and GDP), were not treated in isolation. For example, the assumptions on the availability of energy resources and the progress of energy technologies have direct impact on the role of energy transformations in mitigation scenarios. In particular, the assumptions on BECCS are noteworthy, as this component, which is currently an emerging technology without large-scale deployment, was critical to achieve the mitigation targets in this study, and at the same time very sensitive to climate uncertainties. The feasibility of BECCS in the power and refining sectors is affected by uncertainties related to the bioenergy resource supply costs, the performance and costs of CCS technology, and the CO_2 sequestration potential. However, the AR5 scenario database does not provide information on the effect of these assumptions.

Thirdly, the EMIC used to generate the range of emission pathways in this study have limitations in capturing the effect of climate uncertainties. Therefore, there can be potential improvements in this aspect too. Overall, further analyses are required to evaluate the importance of the uncertainty in allowable emissions under other mitigation targets, and against specific IAM assumptions.

Finally, the outcomes of this study were based on quantitative modelling of scenarios comprising a set of assumptions on future developments in socio-economic and technology aspects (including features of the energy system along with other economic activities). As such, the outcomes cannot be validated with “experiments”; instead, the outcomes were supported by the suitability of the models used in the study. The climate model [47–45] and the IAM [34,36]] have been applied for studies published in peer reviewed journals, thus, are regarded suitable for the purpose of this study.

4.2. Integration of climate uncertainties into assessments of energy system transformations

While this study helped to quantify the effect of climate uncertainties on the global energy system, and to identify the components most affected by them, the outcomes only reflected such effect on the paths of allowable emissions for a given mitigation target. The direct effects of climate change and climate uncertainties on energy supply and demand, go beyond those induced by the variability of allowable emissions, and influence the energy system in many ways. Changes in ambient temperatures affect the water cooling requirements of thermal power plants, as well as heating and cooling demands in buildings. Changes in precipitation and humidity affect the feasibility and productivity of bioenergy plantations. In addition, the temporal and spatial pattern of solar and wind energy resources may be affected by climate change, too.

Capturing the direct implications of climate uncertainties on the energy system in connection to climate change impacts, needs further integration of the information between socio-economic analyses with IAMs and climate projections with climate models. In this study we soft-linked the information on emissions from a climate model into an IAM, and neglected any additional linkage with parameters related to the energy system. There are several studies integrating at different levels the effect of climate change in specific aspects of the energy system for selected sectors and regions, such as wind and solar resources [61], buildings [62], and hydropower [63]. While these studies provide useful insights, expanding these efforts to global scale analysis may prove cumbersome and not always result in practical knowledge. The suitability of deep levels of integration is associated to the strength of feedbacks between models, and the size of process and scenario uncertainties [8].

5. Conclusions

This study evaluated the effect of climate-related uncertainties on the global energy system for an intermediate mitigation target (RCP4.5) and a stringent mitigation target (RCP2.6). The assessment was conducted by means of an integrated assessment model of high complexity and a climate model of intermediate complexity. We found that, irrespective of the uncertainty in allowable emissions deriving from a comprehensive set of uncertainties in the climate system, decarbonization of the energy system (i.e., less fossil fuels), scaling up of carbon capture and storage (coupled with both fossil fuel and bioenergy), and lowering energy consumption in the long term were necessary to meet mitigation targets. The effect of these uncertainties reflected in diverse scales among energy system components, and was largest for energy supply from coal without carbon capture and storage and for bioenergy with carbon capture and storage. Moreover, the effect on land-use change was evident for energy crop and unmanaged lands, while very small incidence was observed for croplands and pastures. Compared to the range of values in the IAM scenario literature for variables describing the energy system, the variation induced by climate uncertainties on these variables was small for the same mitigation target. For example, the choice of modeling approach (i.e., IAM) resulted in a considerably larger range of values in energy supply for a given mitigation target.

Understanding of the energy system transformations consistent with the reduction of GHG emissions in the long-term, needs to be challenged against choices related to costs, performance and structure of the energy system, energy security, and the level of GHG mitigation. Our approach introduces climate uncertainties as an additional aspect affecting the energy system by means of scenarios considering a weak, intermediate, and strong response of the climate to anthropogenic emissions. Narrowing down these uncertainties then becomes a matter of concern for researchers and policy makers dealing with global climate targets. Although this issue is outside the scope of this study, its resolution will require a process that recognizes the advances in the understanding of the response of climate to emissions, when considering the implications of climate mitigation in the global energy system.

This study delivered valuable information on the implications of climate uncertainties on mitigation scenarios developed with IAMs, specifically with regard to the global energy system. These outcomes can inform the climate policy process such as the global negotiations hold by the Conference of Parties under the United Nations Framework Convention on Climate Change. In contrast to other IAM studies, the set of emission scenarios in the study incorporated a robust approach to cover a comprehensive scope of climate uncertainties. Further analyses are required to clarify the effect of uncertainty in allowable carbon emissions under other mitigation targets (e.g., 1.5 °C in 2100 as highlighted in the Paris Agreement), and its importance compared to socio-economic uncertainties, including the availability of energy resources and the performance of energy technologies.

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Appendix

Figs. A1 and A2.

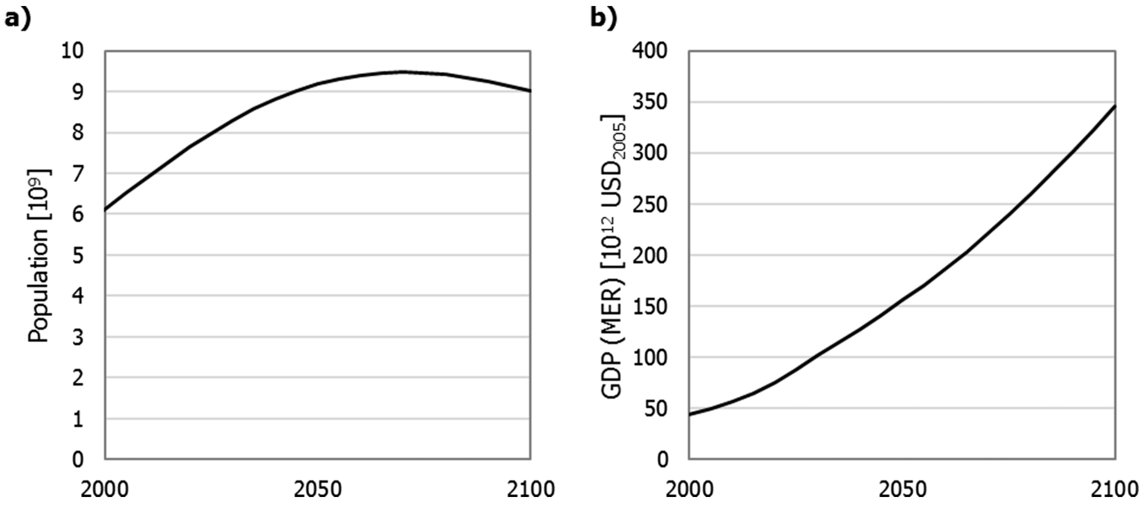

Fig. A1. Trends of population and GDP considered in the scenarios.

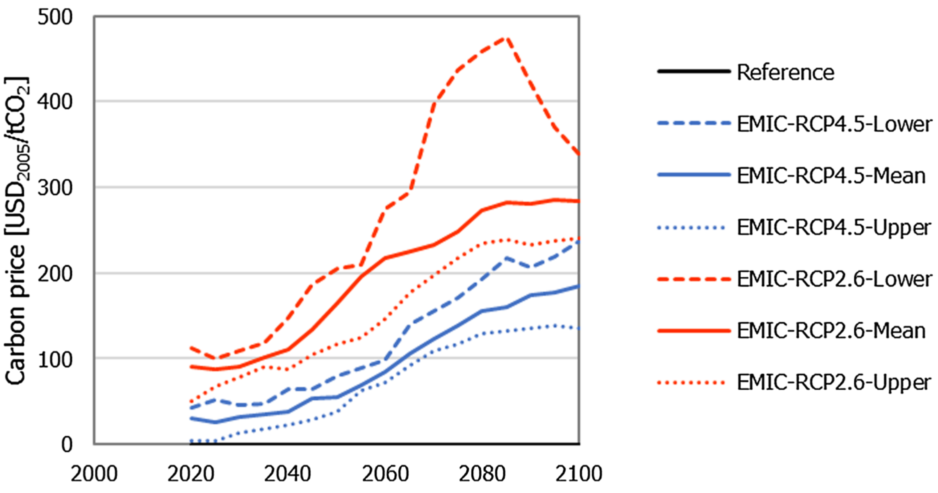

Fig. A2. Carbon price for the emission scenarios in the study (in the *Reference* case carbon price is zero).

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