

# Will economic growth and fossil fuel scarcity help or hinder climate stabilization?

## Overview of the RoSE multi-model study

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**Abstract** We investigate the extent to which future energy transformation pathways meeting ambitious climate change mitigation targets depend on assumptions about economic growth and fossil fuel availability. The analysis synthesizes results from the RoSE multi-model study aiming to identify robust and sensitive features of mitigation pathways under these inherently uncertain drivers of energy and emissions developments. Based on an integrated assessment model comparison exercise, we show that economic growth and fossil resource assumptions substantially affect baseline developments, but in no case they lead to the significant greenhouse gas emission reduction that would be needed to achieve long-term climate targets

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without dedicated climate policy. The influence of economic growth and fossil resource assumptions on climate mitigation pathways is relatively small due to overriding requirements imposed by long-term climate targets. While baseline assumptions can have substantial effects on mitigation costs and carbon prices, we find that the effects of model differences and the stringency of the climate target are larger compared to that of baseline assumptions. We conclude that inherent uncertainties about socio-economic determinants like economic growth and fossil resource availability can be effectively dealt with in the assessment of mitigation pathways.

## 1 Introduction

Climate change is widely recognized as one of the key challenges of the 21st century facing societies around the world. In December 2015, countries agreed to hold global mean temperature to well below 2 °C above preindustrial levels and to pursue efforts to limit warming to 1.5 °C (Article 2, UNFCCC 2015). A large body of research has shown that this requires deep decarbonization by 2050 and a global phase-out of greenhouse gas emissions by the end of the century (see Clarke et al., 2014, for a summary of this literature).

Studies of global mitigation pathways associated with long-term climate policy goals are conducted with global coupled energy-economy-land use-climate models, so called integrated assessment models (IAMs, Weyant et al. 1996). IAMs describe the coupled energy, economy, and in many cases land systems in physical and economic terms. They capture the development of economic output, energy consumption, supply and technologies, and greenhouse gas emissions on the one hand, and the associated development of energy prices, investments, and international trade (e.g. of fossil fuels) on the other hand. Process-based IAMs represent regions, sectors, and technologies in some detail, and as such need to be distinguished from much more aggregated IAMs that aim to provide an integrated assessment of climate mitigation and residual climate damages in a cost-benefit setting (e.g. Nordhaus and Boyer 2000). IAMs make a number of important assumptions about basic socio-economic drivers, such as population and economic growth over the 21st century, fossil fuel availability, and technology learning. Those assumptions can be bundled into scenarios and varied to explore the sensitivity of baseline and mitigation pathways to these major determinants of socio-economic development (Nakicenovic et al. 2000; Riahi et al. 2016).

Although all of these assumptions are highly relevant for the assessment of mitigation pathways, the focus of analysis has mostly been placed on technology and energy demand assumptions (e.g. Clarke et al. 2008; McJeon et al. 2011; Riahi et al. 2012; Luderer et al. 2013; Rogelj et al. 2013a, 2013b; Kriegler et al. 2014, Bosetti et al. 2015), not so much on population, economic growth and fossil fuel availability (but see Morita et al. 2000; Webster et al. 2012; Gillingham et al. 2015; Riahi et al. 2016). The RoSE study “Roadmaps toward Sustainable Energy futures” (RoSE; [www.rose-project.org](http://www.rose-project.org)) is the first to provide an integrated assessment model comparison on harmonized variations in the assumptions of economic growth, population trends and fossil fuel availability, investigating the effects of those input assumptions on energy and emissions pathways with and without climate policy. The aim is to provide new insights into robust and sensitive features of the global energy transformation for reaching ambitious climate targets in the face of inherently uncertain socio-economic developments.

The paper is structured as follows. Section 2 describes the methodology of the RoSE multi-model comparison including participating models and scenario design. Section 3 presents the

results for baseline scenarios without climate policy, while Section 4 focuses on the results for mitigation pathways. Section 5 presents the results in terms of a variance-based sensitivity analysis to identify dominant factors for the spread in key output variables and Section 6 concludes. The underlying RoSE scenarios are published in a database accessible at [www.rose-project.org/database](http://www.rose-project.org/database) and also contributed to the scenario database of the 5th Assessment Report (AR5) of Working Group III of the IPCC (IPCC 2014).

## 2 Methodology

The RoSE model comparison builds on four process-based global integrated assessment models. These are the Global Change Assessment Model (GCAM; Edmonds and Reilly 1985; Edmonds et al. 1997), the Integrated Policy Assessment Model for China (IPAC; Jiang et al. 2000), the Regional Model of Investments and Development (REMIND, Luderer et al. 2015; Bauer et al. 2012; Leimbach et al. 2010), and the World Induced Technical Change Hybrid Model (WITCH, Bosetti et al. 2006; Bosetti et al. 2009).<sup>1</sup> All four models cover the time period until 2100 and include simple climate modules. REMIND and WITCH are hybrid energy-economy-climate models, combining a top-down macro-economic approach and a bottom-up representation of the energy system. Both are general-equilibrium, optimal-growth, intertemporal optimization models assuming perfect foresight. GCAM and IPAC are partial equilibrium models with recursive dynamics and exogenous economic growth assumptions providing a detailed representation of the global energy system and in the case of GCAM also land system. Participating models differ in a variety of structural and input assumptions such as the representation of energy demand and supply sectors. Such differences can have a larger influence on model results than differences in the equilibrium solution approach (Kriegler et al. 2015; see also Section 4). Extensive information on model assumptions regarding the macro-economy, the energy systems and the climate system, are provided in the Electronic Supplementary Material Part 2 (ESM-2) which documents participating models and scenario design.

The scenario specification of RoSE is based on three key dimensions: (1) assumptions on future population and economic growth; (2) assumptions on long-term fossil fuel availability differentiated for coal, oil, and gas; and (3) assumptions on the stringency of climate protection targets and the timing of international climate policy. The variation of the first two dimensions provided 10 baseline assumptions that were adopted by the global models in order to explore the sensitivity of baseline scenarios to the underlying socio-economic and fossil resource assumptions. These baseline assumptions were then combined with climate targets in order to provide insights into the costs and feasibility of mitigation pathways under alternative futures. The resulting RoSE scenario matrix is shown in Table 1. Each column corresponds to a combination of socio-economic and fossil resource drivers, and each row is linked to a climate policy regime.

Regarding population projections, models were harmonized to the medium population projection from the 2008 Revision of the UN World Population Prospects (peaking at 9.4

<sup>1</sup> The RoSE project has been conducted over the period 2010–2013 using model versions as of 2010. Updated versions of each model have been developed since then, and are documented at the following websites. GCAM: <http://wiki.umd.edu/gcam>. REMIND: <http://pik-potsdam.de/research/sustainable-solutions/models/remind> and <https://wiki.ucl.ac.uk/display/ADVIAM/REMIND>. WITCH, <http://doc.witchmodel.org/> and <https://wiki.ucl.ac.uk/display/ADVIAM/WITCH> IPAC: <http://www.ipac-model.org>.

**Table 1** Matrix defining the scenarios of the RoSE multi-model study. Short descriptors for the scenarios as used in the articles of the RoSE special issue are given as well. The models that calculated a given scenario are specified in each matrix cell (All = GCAM (G), IPAC (I), REMIND (R), WITCH (W))

	Socio-economic drivers	DEF	SL Gr	FS Gr	HI Pop	FS Gr SL Conv	DEF	DEF	DEF	DEF	DEF	DEF	DEF
Growth	Med	Med	Slow	Fast	Slow	Fast	Med	Med	Med	Med	Med	Med	Med
	Fast	Fast	Fast	Slow	Slow	Slow	Fast	Fast	Fast	Fast	Fast	Fast	Fast
	Med	Med	Med	Med	High	Med	Med	Med	Med	Med	Med	Med	Med
Population	DEF	DEF	DEF	DEF	DEF	DEF	HI Fos	LO Fos	HI Coal	LO Oil	HI Gas	HI Gas	HI Gas
	Med	Med	Med	Med	Med	Med	High	Low	Low	Low	Med	Med	Med
	Med	Med	Med	Med	Med	Med	High	Low	Low	High	High	High	High
Fossil fuel availability	Med	Med	Med	Med	Med	Med	High	Low	Low	High	High	High	High
	Med	Med	Med	Med	Med	Med	High	Low	Low	High	High	High	High
	Med	Med	Med	Med	Med	Med	High	Low	High	High	High	High	High
Oil	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU	BAU
	DEF	DEF	DEF	DEF	DEF	DEF	HI Fos	LO Fos	HI Coal	LO Oil	HI Gas	HI Gas	HI Gas
	All	All	All	All	All	I, R, W	All	All	All	All	All	All	G, R, W
450 ppm CO2e	450	450	450	450	450	450	450	450	450	450	450	450	450
	DEF	DEF	DEF	DEF	DEF	DEF	HI Fos	LO Fos	HI Coal	LO Oil	HI Gas	HI Gas	HI Gas
	All	All	All	All	All	I, R, W	All	All	All	All	All	All	G
550 ppm CO2e	550	550	550	550	550	550	550	550	550	550	550	550	550
	DEF	DEF	DEF	DEF	DEF	DEF	HI Fos	LO Fos	HI Coal	LO Oil	HI Gas	HI Gas	HI Gas
	All	All	All	All	All	I, R, W	All	All	All	All	All	All	G, R, W

billion in 2070; United Nations 2008).<sup>2</sup> The GDP scenarios build on the population projections and encompass assumptions regarding both the speed of economic growth (slow, medium or fast growth) at the technology frontier in developed countries and the speed of convergence of per capita output across 26 aggregate world regions (slow or fast convergence). Thus, the highest overall growth of gross world output is achieved for the case of fast growth at the frontier and fast convergence across regions, while the lowest growth occurs for the case of slow frontier growth and slow convergence. The development of the GDP projections followed a growth accounting method (Hawksworth 2006) that was later adopted and refined for the development of economic projections for the Shared Socio-economic Pathways (SSPs; Leimbach et al. 2016). Details are provided in ESM-2 Section 3.1. The study also included a slow growth – slow convergence GDP scenario that was based on the high population projection of the UN 2008 Revision (going up to 14 billion in 2100).

Fossil fuel availability was characterized in terms of supply curves describing extraction costs as a function of cumulative extraction (see ESM-2 Tables 14–16). First, data on the estimated total size of the fossil resource base have been assembled from various sources like the US Geological Survey (USGS) and the German Federal Institute for Geosciences and Natural Resources (BGR) (see ESM-2 Section 3.2.1.). Coal and conventional and unconventional oil and gas resources have been treated separately. In a second stage, historical data for recovery rates have been examined and then extrapolated, under varying assumptions about technological progress, toward future resources. Finally, the costs of extraction for different grades of each of the resources have been estimated. The output of this process consists of three extraction cost curves, assuming ‘low’, ‘medium’, and ‘high’ resource availability, for each of the three fossil fuels coal, oil and gas. Details on the specification of the cost curves can be found in the ESM-2 Section 3.2.

Finally, the policy dimension includes different policy cases representing different levels of ambition and timing of climate policy action: i) *Baseline*: the baseline represents a case without climate policy; ii) *450 ppm*: this case corresponds to a 450 ppm CO<sub>2</sub> equivalent concentration target in 2100 allowing for overshoot during the course of the century and with full when-where-what flexibility of emissions reductions after 2010. The forcing target accounts for the radiative forcing of all radiative substances including Non-Kyoto gases and aerosols; iii) *550 ppm*: this case is similar to the previous one, with the exception that the concentration target is set to 550 ppm CO<sub>2</sub> equivalent throughout the century, i.e. no overshoot is allowed. The 450 ppm scenarios result in a likely chance of limiting warming below 2 °C, while the 550 ppm scenarios are more likely than not to exceed the 2 °C threshold (Clarke et al. 2014). In addition, the RoSE study contrasted the case of immediate action on long-term climate goals with weak uncoordinated action until the end of the century and near-term weak action followed by the pursuit of a 450 ppm long-term mitigation target from 2020 or 2030 onwards (Luderer et al. [this issue](#)).

### 3 Impact of economic growth and fossil resource assumptions on baseline scenarios

We discuss the sensitivity of baseline scenarios to economic growth assumptions (Section 3.1) and fossil resource assumptions (Section 3.2) separately. Extended analyses are provided in the

<sup>2</sup> Since then, the UN population projections have increased and no longer project a population peak in the 21st century. The UN 2015 revision gives a medium estimate of 11.2 billion people by 2100.

Electronic Supplementary Material Part 1 (ESM-1) which contains all supplementary figures S1-S12 and Table S1 referenced below.

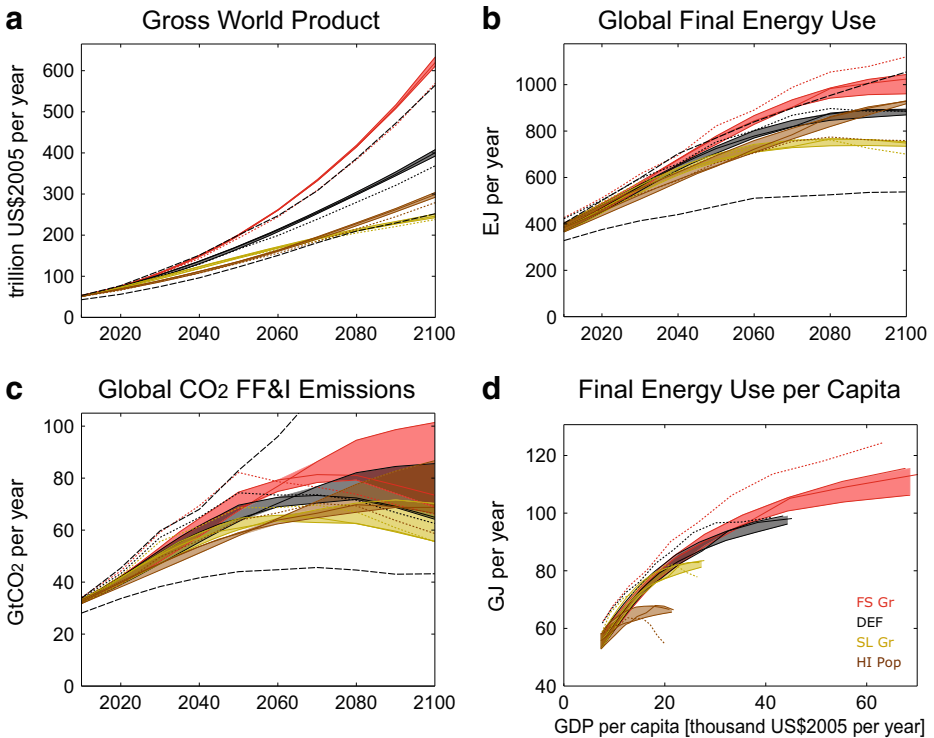
### 3.1 Variation of economic growth and population assumptions

The RoSE scenarios cover a large range of economic growth and population projections (Fig. 1a, S1a). By the end of the century, the Gross World Product (GWP, in Market Exchange Rates (MER)) in the FS Gr scenario is a factor of 2.5 higher than in the SL Gr scenario. The lowest per capita income is reached in the HI Pop scenario with less than a third of the income reached in the FS Gr scenario in 2100 (Fig. S1b). The HI Pop scenario overtakes the SL Gr scenario in absolute GWP terms only due to higher population (Fig. S1a). Figures 1 and S1 compare the RoSE baseline ranges with the IPCC AR5 scenario database (IPCC 2014).<sup>3</sup> It can be seen that RoSE fully covers the 5th–95th percentile range of AR5 baseline scenarios with regard to economic production and population, and even goes above it and for GDP per capita also below. In particular the RoSE HI Pop scenario with its combination of very high population and very slow per capita GDP growth is unique in the AR5 scenario set.

The associated variation in final energy demand is much smaller than that of GWP (between 700 and 1000 EJ in 2100; Fig. 1b), because models capture historical observations of slower growth in energy demand compared to income levels (Grübler et al. 2012). Due to their calibration based on historical trends, the models in the study show close agreement in energy intensity improvements as function of GDP per capita growth (Fig. S2). This results in only small model differences in final energy demand projections for harmonized economic growth and population assumptions. Models account for autonomous improvements in energy intensity over time due to technological progress, but these autonomous improvements lead to only small deviations of per capita energy demand as a function of GDP per capita between different economic growth scenarios, with the exception of IPAC which assumes more aggressive energy efficiency improving technological change in the second half of the century (Fig. 1d). Thus, a robust finding in this study is that energy intensity improvements are not large enough to fully compensate income growth, resulting in a steady increase of per capita final energy use over time. However, the AR5 scenario database includes a number of baseline scenarios with lower final energy demand, which assume a marked increase in energy intensity improvement rates over historical trends (e.g. Kriegler et al. 2014; Krey et al. 2014a, Riahi et al. 2015).

CO<sub>2</sub> emissions from fossil fuel combustion and industry (FF&I) vary between 60 and 100 GtCO<sub>2</sub> in 2100 (Fig. 1c, S10a). Model differences increase considerably after 2050, as models increasingly differ on the primary energy supply response to increasing fossil fuel prices. However, in the absence of fossil resource constraints models agree that primary and final energy mixes are not significantly altered by economic growth variations, but simply scaled in magnitude (Fig. S7a, S9a). To this end, all models show an increase in emissions until 2070 or later. Until then, carbon intensity of energy remains fairly constant over time (Fig. S3a), so that growing energy demand translates into growing emissions. Thus, no autonomous decarbonization is triggered by economic growth unless fossil fuel supply constraints are

<sup>3</sup> The AR5 scenario database contained 228 baseline scenarios to 2100, including the RoSE scenarios of GCAM, REMIND, and WITCH.



**Fig. 1** **a** Gross world product in market exchange rates (MER), **b** final energy, **c** CO<sub>2</sub> emissions from fossil fuels and industry (FFI) over time and **d** per capita final energy use as a function of GDP per capita (MER) across the RoSE baseline scenarios with different assumptions about economic growth and population projections. The FS Gr SL Conv is not shown here because it was not calculated by all models. The funnels are spanned by results from GCAM, REMIND and WITCH, while IPAC results are shown separately by dotted lines because of larger differences in final energy and emissions projections (see ESM-1 Section S1, S2). *Dashed black lines* show the 5th to 95th percentile range of the full century baseline scenarios in the AR5 database

reached (Fig. S1c; see also De Cian et al. [this issue](#)). AR5 baseline scenarios show a much larger CO<sub>2</sub> emissions range than the RoSE scenarios. On the lower end, this is due to scenarios with lower energy demand or fossil fuel availability (see Section 3.2). The upper end is dominated by high growth high coal scenarios which were not considered here (see Table 1).

### 3.2 Variation of fossil resource assumptions

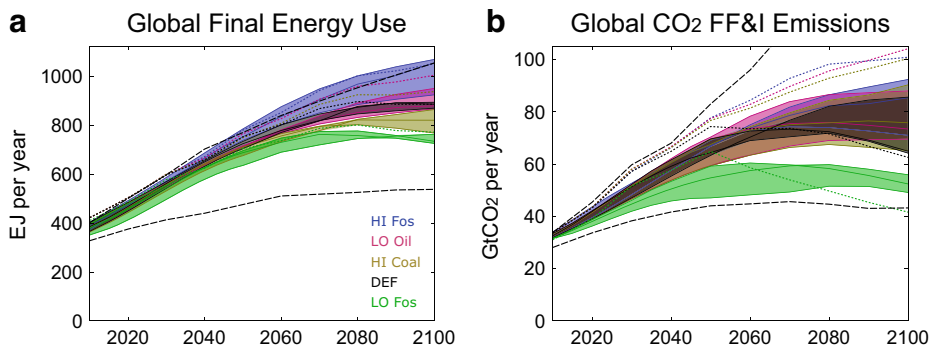
Even though regional fossil fuel supply curves were harmonized across models, global fossil fuel use-price relationships can differ significantly between models due to differences in their energy system and international fossil fuel market representation (Fig. S4). Nevertheless, some robust features can be identified. Oil prices increase by a factor of 5–7 over the 21st century in the low fossil scenario, and only moderately (~two fold) in the high fossil scenario despite significantly higher oil extraction (Fig. S4a). Variation in price increases are slightly smaller for gas (from a factor 1.5–2 in HI Fos to around 4–5 in LO Fos excluding IPAC which assumed smaller economically available gas resources) and coal (from a factor 2.5–4 in HI Fos to 4–7 in LO Fos excluding WITCH with limited representation of coal use in non-electric sectors; see ESM-2 Section 2.3), but show the same pattern (Fig. S4b,c). In general, higher fossil fuel

availability leads to higher fossil fuel extraction at lower prices. Cumulative fossil fuel use (2011–2100) in the baseline varies from 54 to 61 ZJ for low availability (LO Fos) to 72–84 ZJ for high availability (HI Fos) in GCAM, REMIND and WITCH, while IPAC shows lower overall fossil fuel use due to its limited gas use (Table S1). For comparison, ca. 18 ZJ of fossil fuels (7.2 ZJ Oil, 3.5 ZJ Gas, 7.3 ZJ Coal) were used until 2009 (Rogner et al. 2012).

Energy use in the baseline is strongly affected by assumptions about fossil resources availability, as lower fossil fuel prices incentivize more energy intensive production. Final energy demand ranges between ca. 700 EJ/yr. in 2100 in the LO Fos to 900–1100 EJ in the HI Fos scenario (Fig. 2a), associated with significant differences in energy intensity of economic activity (Fig. S3b). The differences predominantly emerge from higher liquids use, and to a lesser extent gases, in the HI Fos compared to the LO Fos case (Fig. S9b).

The highest carbon intensity of energy use is reached in the HI Coal scenario (Fig. S3b), where coal substitutes some of the oil and gas use in the DEF and HI Fos scenarios (Fig. S7b). The only exception is constituted by WITCH, where coal-to-liquid and coal-to-gas conversion technologies are not fully represented in the model version used for the RoSE study. All models obtain the lowest carbon intensity in the LO Fos case, where the limited fossil resource availability leads to a stronger upscaling of non-fossil energy sources such as nuclear and renewable energy particularly in the second half of the century (Fig. S7b, S8b).

As a result of these variations in energy and carbon intensity, CO<sub>2</sub> emissions from fossil fuel combustion and industry vary between 50 and 90 GtCO<sub>2</sub> in 2100 from low to high resource availability (Fig. 2b, S10b). Model differences relating to the substitutability of oil and gas use with coal dominate the emissions outcomes for the DEF, LO Oil, HI Coal, and HI Fos scenarios as can be seen from the largely overlapping emissions ranges. For example, lower energy intensity can be compensated by higher carbon intensity in the HI Coal case compared to the HI Fos case, leading to similar emissions outcomes in both cases. Only the case of low fossil fuel availability is noticeably different, as it is characterized by the lowest energy and carbon intensity and leads to a stabilization or even decline of emission levels after 2050. However, this is by far not enough to prevent the rise of atmospheric CO<sub>2</sub> concentration and anthropogenic climate forcing (Fig. S5) as anthropogenic CO<sub>2</sub> is accumulated in the atmosphere over time scales of centuries.



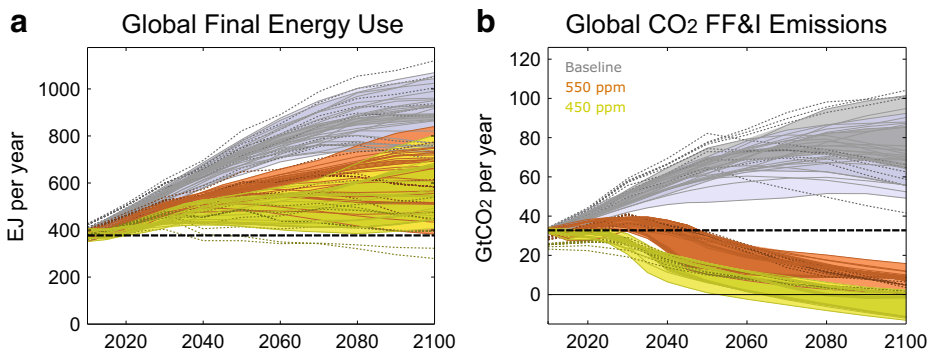
**Fig. 2** a Final energy use and b CO<sub>2</sub> FF&I emissions over time across the RoSE baseline scenarios with different assumptions about fossil fuel availability. See Fig. 1 for further explanation of funnels and lines



## 4 Impact of economic growth and fossil resource assumptions on climate policy scenarios

Limiting anthropogenic climate forcing to levels of 550 CO<sub>eq</sub> throughout the century or 450 ppm CO<sub>eq</sub> by the end of the century (Fig. S5b) requires strong reductions of CO<sub>2</sub> emissions (Fig. 3b) and the wider basket of greenhouse gas emissions (Fig. S5a). As shown in many studies (see Clarke et al. 2014, for an overview), greenhouse gas emissions need to be phased out by the end of the 21st century to reach 450 ppm CO<sub>eq</sub>, which in the majority of cases implies net negative CO<sub>2</sub> emissions via the use of carbon dioxide removal (CDR) technologies such as bioenergy with CCS (BECCS). Emissions reductions requirements are somewhat lower for the not-to-exceed 550 CO<sub>eq</sub> limit, but still significant with bringing CO<sub>2</sub> emissions close to net zero and cutting greenhouse gas emissions by more than half by the end of the century. In both cases, the CO<sub>2</sub> emissions reductions are achieved by a reduction of final energy demand (Fig. 3a) due to higher energy intensity improvements (Fig. S6) combined with a strong decarbonisation of primary energy supply (Fig. S7), initiated by a decarbonization of electricity generation (Fig. S8) and enhanced by a stronger electrification of energy end use (Fig. S9). This leads to strong and rapid reduction of the carbon intensity of energy use (Fig. S6). The reduction of non-CO<sub>2</sub> GHGs also plays a significant role, but models project limits in the mitigation potential of these gases, so that their emissions share increases with tighter emissions targets (Fig. S10).

The focus of the RoSE study is the influence of baseline assumptions about economic growth, population, and fossil fuel availability on climate mitigation strategies and costs. A key finding is that mitigation characteristics are robust across the range of assumptions investigated in RoSE. For reaching the 450 ppm CO<sub>2e</sub> target, carbon intensity is reduced to zero or becomes negative in all cases and all models, and energy intensity is reduced by 10 % to 60 % relative to energy intensity in the baseline (Fig. S6b). In fact, model differences have a larger impact than variation in baseline assumptions. IPAC and WITCH rely more on energy intensity improvements than REMIND and GCAM, while the latter project a more rapid and deeper reduction of carbon intensity. GCAM achieves considerably more net negative CO<sub>2</sub> emissions as it foresees a smaller mitigation potential for non-CO<sub>2</sub> gases (Fig. S10).



**Fig. 3** **a** Final energy and **b** CO<sub>2</sub> FF&I emissions over time for the baseline and the 550 ppm and 450 ppm CO<sub>2e</sub> climate policy cases. Darker colors show the funnel spanned by REMIND, GCAM and WITCH (solid lines) under default assumptions (DEF) while lighter colors the full range across all economic growth and fossil fuel availability assumptions (for the baseline only, the two dimensions are separated into light grey (economic growth) and light blue (fossil resource) funnels). IPAC results are shown separately by dotted lines because of larger differences in final energy and emissions projections. The dashed horizontal lines mark the 2005 values for orientation

Baseline variations introduce only a second order effect in the climate policy scenarios. Climate policy-induced energy intensity (EI) improvements vary with fossil resource availability to compensate differences in EI improvements in the baseline (higher baseline EI improvements and lower climate policy induced EI improvements in the LO Fos scenario than in the HI Fos scenario; Fig. S6). In contrast, differences in energy demand projections between different economic growth scenarios are retained to some extent in the climate policy cases (Fig. 3a).

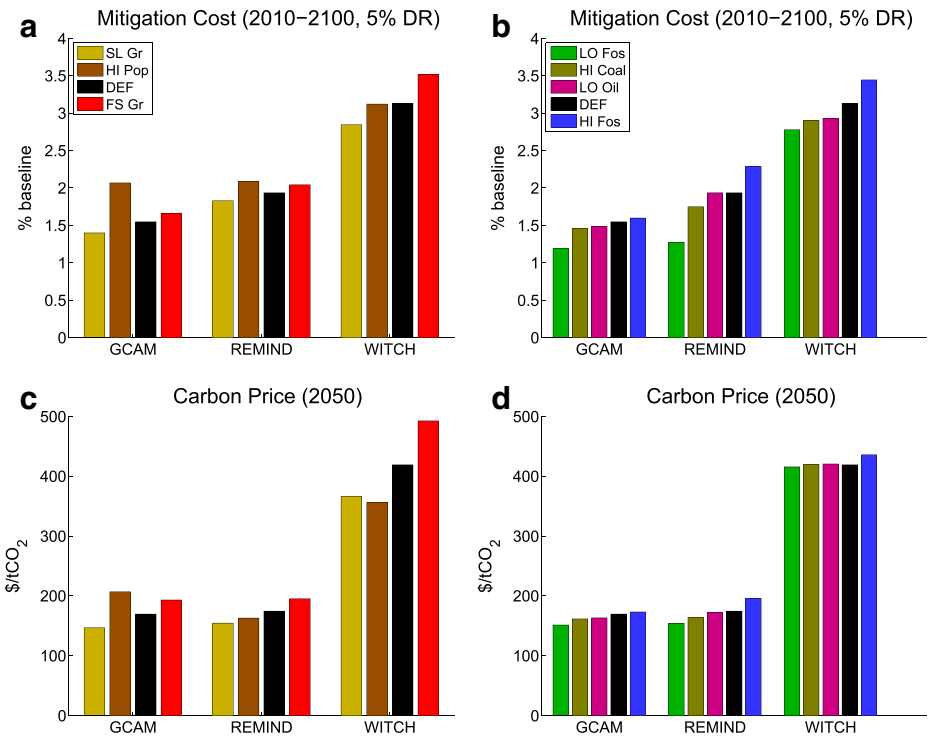
The climate-policy induced reduction of carbon intensity (CI) to near zero or below dominates any variation of CI reductions with baseline assumptions (Fig. S6). As a result, the sensitivity of emissions projections to baseline assumptions is greatly reduced in the climate policy cases (Fig. 3b). Thus, a key finding is that emissions implications of long term climate targets are robust across a range of economic growth, population and fossil resource assumptions – a direct result of the fact that climate targets can be closely associated with carbon budgets. In particular, the amount of fossil fuels that can still be used is significantly constrained (29–46 ZJ in 550 ppm and 19–37 ZJ in 450 ppm case; Table S1). Models also agree that coal use is reduced the earliest and strongest, while oil and gas use continues for some time and does not fall below cumulative 7–8 ZJ each even in the 450 ppm case (Table S1). This result suggests that conventional oil and gas reserves are still exploited under climate policy (cf. Bauer et al. [this issue](#)).

The HI Pop scenario with low growth and high population stands out in terms of timing of emissions reductions. In REMIND and WITCH, this scenario shows higher carbon intensity and higher fossil fuel CO<sub>2</sub> emissions (Fig. S10) by 2100 in the baseline due to higher use of gases and liquids than even in the high growth scenario. This limits the penetration of low carbon energy sources at the end of the century requiring faster decarbonization early on to compensate for higher emissions later. In GCAM, higher population leads to higher emissions from land use due to higher demands for food and food cropland (Fig. S10). These land use emissions need to be compensated by earlier and deeper decarbonization in the energy sector. These dynamics are not reflected in the other models because GCAM is the only model that captures the land use response endogenously in this study. Thus, high population puts pressure on mitigation strategies in two ways, by higher land use emissions and by shifts to energy end uses that are harder to decarbonize, although overall energy use is driven predominantly by economic output.

Another key result is that baseline assumptions have substantial effects on mitigation costs and carbon prices, but that the impact of model differences and the stringency of the climate target are larger (450 ppm: Fig. 4; 550 ppm: Fig. S11). Fig. 4c,d shows carbon prices across scenarios and models<sup>4</sup> for the 450 ppm target and the 2050 midpoint where carbon prices are most comparable between models.<sup>5</sup> Carbon prices are significantly higher in WITCH than in REMIND and GCAM, which is due to the fact that WITCH relies more on energy intensity reductions and assumes a lower substitutability of fossil energy with low carbon energy. Such model differences can have a strong impact on carbon price and mitigation cost estimates (Kriegler et al. 2015). Carbon prices increase by 25–30 % between low and high economic growth, while price increases with fossil fuel availability are smaller. This reflects the fact that smaller price signals are needed to counteract more energy and carbon intensive production

<sup>4</sup> IPAC did not report carbon prices and mitigation costs in the RoSE study.

<sup>5</sup> Near term carbon prices may be affected by additional energy policy assumptions and choice of model time steps, while long term prices can be affected by different ways on how to implement the forcing target (exponentially increasing carbon prices to meet a carbon budget vs. saturating price trajectories once the forcing target is approached).



**Fig. 4** (a + b) Net present value mitigation costs (discounted at 5 % per year) over the period 2010–2100 (consumption losses in percentage net present consumption for ReMIND and WITCH, area under MAC in percentage net present output for GCAM) and (c + d) carbon prices in 2050 for the 450 ppm CO<sub>2</sub>e target. IPAC did not report carbon prices and mitigation costs

due to larger fossil fuel abundance, than to limit increasing energy demand with economic growth. The HI pop scenario is noticeably different in GCAM with higher carbon prices due to the need to compensate for higher land use emissions.

Mitigation costs can be measured in various metrics depending on the model type (Clarke et al. 2014, Paltsev and Capros 2013). Here we measure costs in terms of consumption losses relative to baseline consumption for REMIND and WITCH (general equilibrium models) and energy sector abatement costs relative to baseline GDP in GCAM (partial equilibrium model). Importantly, cost estimates are not including the benefits of avoided climate change or co-benefits and adverse side effects of mitigation on welfare (see Krey et al. 2014b, for a discussion). Relative mitigation cost estimates in GCAM and REMIND vary less than 20 % with economic growth because higher absolute costs are largely compensated by higher economic output and consumption. Only WITCH shows a larger impact of economic growth on costs due to the higher carbon prices and their larger spread. The HI Pop scenario stands out with significantly higher costs in GCAM due to more rapid and stronger decarbonization and a larger amount of carbon dioxide removal needed to compensate the higher land use emissions. In contrast, cost increases with fossil fuel availability are larger, ranging from 25 % to 75 % across models. This shows that the opportunity costs of cheap abundant fossil fuel resources can be high for climate policy. Fig. S12 in ESM-1 shows that the mitigation cost patterns discussed above are robust against the choice of intertemporal aggregation of mitigation costs and associated discount rates.

## 5 Dominant factors of variance in scenario results

Drawing on concepts of variance-based sensitivity analysis (Saltelli et al. 2008) and motivated by its application to uncertainty in climate change projections (Northrop and Chandler 2014), we estimate how much of the variance in results is explained by the model choice (GCAM, IPAC, REMIND, WITCH), the choice of climate policy (Baseline, 550 ppm CO<sub>2</sub>e, 450 ppm CO<sub>2</sub>e), and the assumptions about economic growth (SL Gr, DEF, FS Gr, HI Pop) and fossil fuel availability (LO Fos, DEF, HI Fos, LO Oil, HI Coal),<sup>6</sup> respectively. Although the space of possible combinations of these factors was fully sampled by the RoSE study, the scenario data should not be interpreted as a statistical sample. In particular the policy dimension is a choice to be informed rather than an uncertainty to be accounted for. However, the sample is representative to the extent it captures a variety of structurally different model types (Kriegler et al. 2015) and spans much of the space of plausible economic growth and fossil resource assumptions.

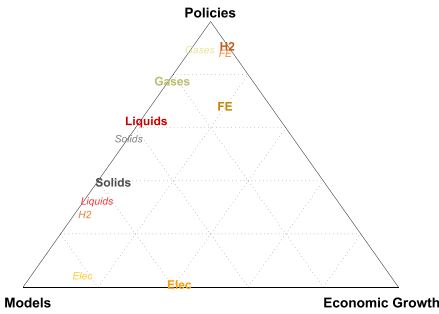
Figure 5 compares the amount of variance explained by model, baseline, and climate policy variations. It shows the first order variances  $V_X$  as shares of total first order effect  $\text{Var}_{FO} = \text{Var}_{\text{Model}} + \text{Var}_{\text{Policy}} + \text{Var}_{\text{Growth/Fossil Fuels}}$  not including second order interaction terms. This is a good approximation, since  $\text{Var}_{FO}$  explains between 75 % to up to 98 % of total variance for 13 of 17 output quantities in Fig. 5. For electricity, solids and oil use, it still explains between 60 % and 75 % of total variance in 2100, and only for bioenergy use the interaction terms dominate by the end of the century. As can be seen from Fig. 5, the policy variation is the most significant factor ( $\text{Var}_{\text{Policy}} > 0.6 \text{Var}_{FO}$ ) for emissions, fossil fuel use, overall final and primary energy use, and gases consumption, and is particularly dominant ( $\text{Var}_{\text{Policy}} > 0.8 \text{Var}_{FO}$ ) for CO<sub>2</sub> emissions from fossil fuel combustion and coal use. In these cases, results are robust against model and baseline uncertainty to the extent they were investigated in the RoSE study, and therefore provide a robust picture on the implications of climate policy choices.

The opposite situation of model uncertainty outrivaling the policy signal ( $\text{Var}_{\text{Model}} > 0.6 \text{Var}_{FO}$ ) can be found for a few variables predominantly relating to the transition of the electricity sector, i.e. overall electricity use and the type of low carbon electricity generation (nuclear vs. renewables). The large model differences in electricity projections are particularly visible in the RoSE model sample, since WITCH and IPAC project a decline of electricity use with climate policy, while REMIND and GCAM show the opposite trend (Fig. S8). In addition there is much higher electrification in the baseline in IPAC. Results from a recent large model comparison study on energy transitions in mitigation pathways (EMF27) suggest that larger model samples will show a more robust electrification signal in climate policy cases (Kriegler et al. 2014; Krey et al. 2014a). But the EMF27 study confirms that the low carbon electricity mix in mitigation pathways varies greatly across models. Recently, there has been progress in consolidating the dominant role of renewable energy for decarbonizing the electricity sector in a multi-model study (Pietzcker et al. 2015).

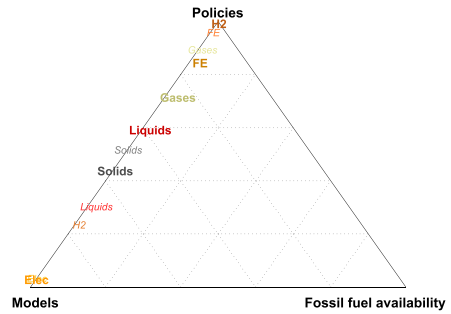
For some output quantities, both policy and model signals play a significant role ( $0.4 \text{Var}_{FO} < \text{Var}_{\text{Model}}, \text{Var}_{\text{Policy}} < 0.6 \text{Var}_{FO}$ ). Within this category, the policy choice still has a larger

<sup>6</sup> The FS Gr SL Conv and the HI Gas scenarios were excluded from the sensitivity analysis since they were not calculated by all models. Since they are intermediate cases, their inclusion is not expected to affect results significantly.

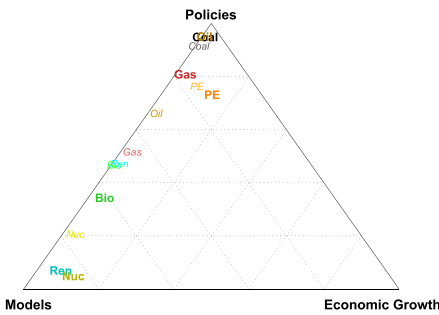
**a** Final Energy – Economic Growth Variation



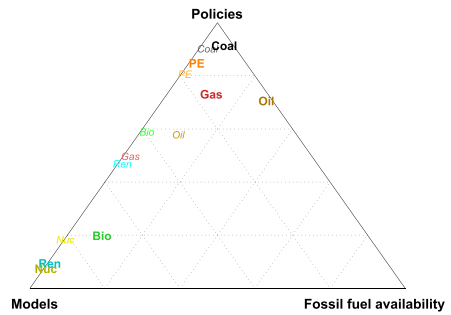
**b** Final Energy – Fossil Resource Variation



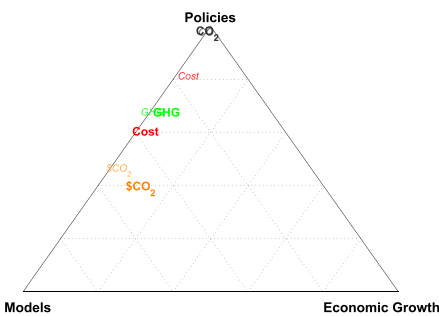
**c** Primary Energy – Economic Growth Variation



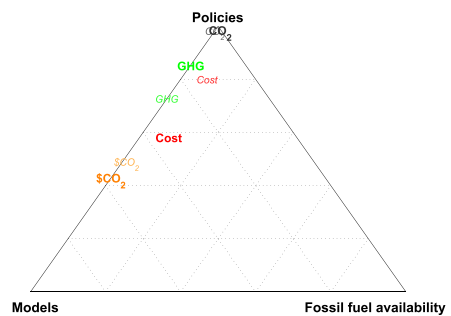
**d** Primary Energy – Fossil Resource Variation



**e** Emissions & Mitigation Costs – Growth Variation



**f** Emissions & Mitigation Costs – Resource Variation



**Fig. 5** First order output variances as shares of total first order effect,  $Var_{FO}$ , due to model (GCAM, IPAC, REMIND, WITCH; bottom left corner =100 %), policy (baseline, 550, 450 ppm CO<sub>2</sub>e; top corner =100 %), economic growth (DEF, SL Gr, FS Gr HI Pop, bottom right corner =100 %; Panels a, c, e), or fossil resource variations (DEF, LO Fos, HI Fos, LO Oil, HI Coal; Panels b, d, f). Variance shares are shown for final energy (Panels a, b), primary energy (Panels c, d) and emissions and mitigation costs (Panels e, f) for 2050 (*smaller light markers*) and 2100 (*larger bold markers*). FE Final energy, Elec Electricity, PE Primary Energy, Ren Non-Biomass Renewables, Nuc Nuclear energy, CO<sub>2</sub> CO<sub>2</sub> FF&I emissions, GHG: CO<sub>2</sub> land use and non-CO<sub>2</sub> emissions; \$CO<sub>2</sub>: carbon price, Cost: NPV mitigation costs over 2010–2050/2010–2100 as in Fig. 4)

impact than model uncertainty on mitigation cost and liquids consumption, while the model signal is stronger for carbon prices and solids consumption. Overall, the results confirm the finding in the IPCC 5th Assessment Report that a clear policy signal is visible in carbon price and mitigation cost estimates but that model uncertainty about these indicators is large (Clarke et al. 2014).

Finally, we observe that variations in economic growth and fossil resource assumption never rise to the level of dominant factor for the variations in model output. The largest effect of fossil resource availability is seen for oil use ( $\text{Var}_{\text{Fossil Fuels}} = 30\%$ ) and to a lesser extent for gas and coal use and mitigation costs. In accordance with the previous discussion, there is no significant effect on final energy mix, emissions, and carbon prices. The largest effect of economic growth assumptions is seen for electricity generation ( $\text{Var}_{\text{Growth}} = 40\%$ ) and to a lesser extent for final and primary energy use and carbon prices. No significant effect is found for primary and final energy mixes, emissions, and mitigation costs. These results do not imply that baseline assumptions as investigated here are irrelevant for the assessment of mitigation pathways. As highlighted in this paper, they affect baseline projections substantially and still influence important aspects of mitigation pathways.

## 6 Conclusions

The RoSE study identified robust and sensitive features of mitigation pathways as projected by integrated assessment models under a range of inherently uncertain socio-economic assumptions. Based on a multi-model ensemble experiment in which climate policy, economic growth and fossil resource assumptions were systematically varied, the study showed that economic growth and fossil resource assumptions substantially affect baseline developments, but that their influence on climate mitigation pathways is smaller due to overriding requirements imposed by the climate target. Since many quantities characterizing mitigation pathways are measured against a baseline without climate policy (e.g. mitigation costs and emissions reductions), baseline uncertainty remains highly relevant for the assessment of mitigation pathways. However, the inherent uncertainty about socio-economic determinants like economic growth and fossil fuel availability can be effectively dealt with in the assessment of mitigation pathways.

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