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RoSE: Roadmaps Towards Sustainable Energy Futures and Climate Protection: A Synthesis of Results from the Rose Project

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RoSE

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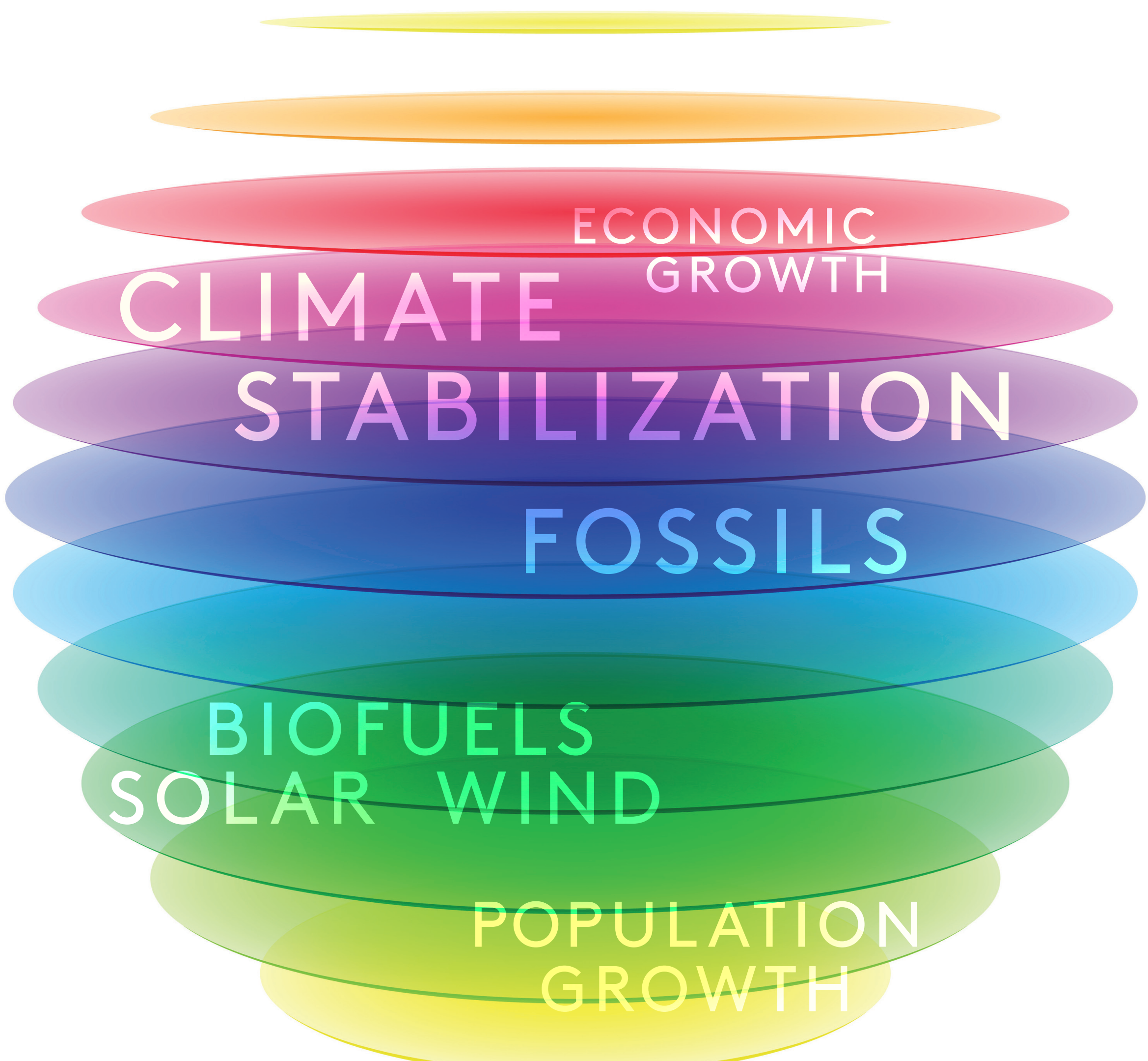

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The Potsdam Institute for Climate Impact Research (PIK) was founded in 1992 and now has a staff of about 300 people. At PIK, researchers in the natural and social sciences work together to study global change and its impacts on ecological, economic and social systems. They examine the Earth system's capacity for withstanding human interventions and devise strategies for a sustainable development of humankind and nature. Through data analysis, computer simulations and models, PIK provides decision makers with sound information and tools for sustainable development.

Centro Euro-Mediterranean Center on Climate Change (CMCC) is a research centre that aims at furthering knowledge in the field of climatic variability, including causes and consequences, through the development of high-resolution simulations and impact models, and with a special emphasis on the Mediterranean Area. The Climate Impacts and Policy Division, led by Fondazione Eni Enrico Mattei, develops the socio-economic research of the Centre and provides support to policy makers involved on the international climate negotiations and dealing with the set-up of mitigation and adaptation policies.

The Pacific Northwest National Laboratory (PNNL) was founded in 1965 and has a staff of approximately 4,700 people. PNNL is one of ten U.S. Department of Energy (DOE) national laboratories and is operated by the Battelle Memorial Institute for DOE's Office of Science. PNNL's research strengthens the U.S. foundation for innovation, and helps find solutions for not only DOE, but for the U.S. Department of Homeland Security, the National Nuclear Security Administration, other government agencies, universities and industry. PNNL's multidisciplinary scientific teams are brought together to address critical U.S. and global problems.

The Energy Research Institute (hereafter, ERI) of the National Development and Reform Commission (NDRC) was established in 1980. It is a national research organization conducting comprehensive studies on China's energy issues. The scope of research conducted by ERI has covered policy assessment for each field of energy production, distribution and consumption, to support relative policy making process as a government think tank. The main focus is on energy economy, energy efficiency, energy & environment, climate change, and renewable energy. ERI is one of the leading research institutes for climate change policy study in China.

The Institute of Energy, Environment and Economy (3E), Tsinghua University has long been on the international and domestic fronts of addressing energy, environment and economic challenges ever since the 1980s, and has come to be recognized with its distinguished academic achievements, as an important policy decision supporting and advising think-tank for government agencies, and a leading research institution in the field of energy system analysis, resource management and sustainable development as well as global climate change mitigation. Over the global climate change issues, 3E has been involved in the national key science and technology programs since the early 1990s, especially focusing on the energy system modeling, global strategy on GHG emission mitigation, GHG emission reduction technology options and corresponding social economic impact assessment.

Stiftung Mercator is one of Germany's largest foundations. It initiates and funds projects that promote better educational opportunities in schools and universities. In the spirit of Gerhard Mercator, it supports initiatives that embody the idea of open-mindedness and tolerance through intercultural encounters, encouraging the sharing of knowledge and culture. The Foundation provides a platform for new ideas to enable people – regardless of their national, cultural or social background – to develop their personality, become involved in society and make the most of the opportunities available to them. In this sense it is committed to inspiring ideas. Stiftung Mercator takes an entrepreneurial, international and professional approach to its work. It has a particular affinity with the Ruhr area, the home of its founding family.

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For more information on RoSE please visit http://www.rose-project.org

Contents

Executive summary

A study on Roadmaps towards Sustainable Energy futures (RoSE)

EXPLORING ENERGY DEMAND AND SUPPLY UNCERTAINTY

An exploration of uncertainty on drivers of energy demand and supply is indispensable for better understanding the prospects of long-tern climate stabilization.

The RoSE study is the first of its kind to systematically explore the impact of economic growth, population and fossil fuel scarcity, in scenarios with and without climate policy, using a model ensemble. A feature of RoSE is the participation of five established integrated assessment modelling teams from three important regions in international climate policy negotiations: the EU, the USA and China.

Economic growth and fossil fuel availability as drivers of CO_2 emissions

ECONOMIC GROWTH

Neither slow nor rapid economic growth solves the climate problem by itself.

In the absence of climate policy and if energy intensity improvements continue along historical trends, higher economic activity implies higher energy demand and greenhouse gas emissions. The increase in energy and carbon intensity improvements with higher economic growth is overcompensated by the larger growth in per capita income. Even under slow economic growth assumptions, GDP will rise significantly above today's level, leading to an increase in greenhouse gas emissions.

FOSSIL FUEL AVAILABILITY

Fossil fuel scarcity is insufficient to slow global warming significantly.

Low fossil fuel availability leads to levels of greenhouse gas emissions that are higher than those under climate change stabilization. Nevertheless, fossil fuel availability significantly influences the energy mix and the CO_2 emissions in scenarios without climate policy.

ENERGY USE

There are robust patterns in projections of energy use in the absence of climate policy.

Higher economic growth increases the scale of the energy system, which continues to be mostly supplied by fossil fuels. Structural differences in the energy supply mix occur for variations in fossil resource availability, particularly coal and oil supply. Models unanimously show an electrification of energy end use independently of economic growth and fossil resource assumptions.

Requirements of climate stabilization

EMISSIONS PHASE OUT

Climate stabilization requires a phase out of global greenhouse gas emissions in the long run.

For a stringent stabilization target compatible with the 2 °C goal (a level of 450 ppm CO_2 equivalent in the atmosphere), net emissions have to be nearly phased out by 2100. For a less ambitious, but still stringent stabilization level of 550 ppm CO_2e, emissions would need to be more than halved by the end of the century, and decline towards zero in the 22nd century.

ENERGY SYSTEMS TRANSFORMATION

Climate stabilization implies a fundamental transformation of global energy systems.

Climate stabilization requires a transformation to a low carbon energy system in the 21st century with historically unprecedented decarbonization rates. Models tell different stories when and what to reduce, but some robust patterns emerge. On the supply side, coal is rapidly replaced with non-fossil energy sources.
On the demand side, models foresee a larger share of electricity and gases coupled with a strong reduction of solids. The structure of the energy transformation is largely unaffected by variations in fossil fuel availability and economic growth. The effect of fossil fuel availability on fossil fuel use is negligible in climate stabilization scenarios. Thus, climate policy effectively limits uncertainty about future fossil fuel use.

CARBON PRICES AND MITIGATION COSTS

Variations in economic growth and fossil fuel availability can alter carbon prices and mitigation costs substantially.

A supply push of fossil energy can be more easily neutralized with a carbon price signal than a demand pull due to higher levels of economic output. Thus, carbon prices vary more strongly with growth projections than with fossil fuel availability. Mitigation cost estimates are sensitive to economic growth and fossil fuel assumptions. Costs increase by approximately 30 to 100 % from low to high economic growth, and from low to high fossil fuel availability.

Fragmented and delayed climate action

WEAK POLICIES

Current climate policies are insufficient for 2°C stabilization

With the currently planned climate policies and pledged emissions reductions the world is not on track towards the 2°C target. If current trends of weak and globally uncoordinated climate policies continue, global mean temperatures are likely to increase by more than 3°C by 2100.

DELAYED ACTION

Delaying action greatly increases the challenge of keeping warming below 2°C.

In case of a further delay in the implementation of comprehensive global emissions reductions the transformation effort needs to be compressed into a shorter period of time. These higher emission reduction rates required in such later-action scenarios imply, inter alia, i) faster decarbonization of the energy system, ii) faster reductions of energy demand, iii) more stranded investments due to prematurely retired fossil capacities, and iv) higher transitory economic losses during the phase-in of climate policies. The implications of delaying action until 2030 are considerably more severe than those of a delay until 2020.

While the models are able to compute low-stabilization scenarios with a prolonged delay of action, the dramatic increase in mitigation challenges in case of policy delay until 2030 make it seem unlikely that such pathways can be implemented in the real world.

Regional perspectives

CHINA

Climate stabilization implies a fundamental energy transformation for China.

Carbon emissions from fossil fuel combustion in China are expected to double from 2005 levels by 2020. Different assumptions on climate policy driven carbon intensity reductions lead to a large range of 6-12 Gt CO_2 emissions by 2050, as calculated with an energy system model of the Chinese economy (China-TIMES model). Climate stabilization scenarios from global models show emissions in China below or at the low end of this range in 2050. The emission trajectories differ across models but all peak during 2020-2025 for the 450 ppm CO_2e target and 2025-2030 for the 550 ppm CO_2e target. This indicates that stringent climate targets would imply ambitious emission reductions in China.

AFRICA

The rates of economic and population growth in Africa have profound implications for energy use and greenhouse gas emissions.

Today Africa accounts for a modest 3% of global energy system CO_2 emissions. The evolution of Africa's emissions over the coming century depends critically on future population and income. Absent any climate policy, Africa could become a major emitter in the second half of the 21st century if economic growth in this part of the world is steady.

In the shorter term, the extent of energy poverty and improvements in access to modern energy in Africa are also driven by assumptions regarding future population and economic growth. Slower economic growth and larger population growth result in a significantly slower transition to modern energy access and use on the continent.

Sectoral perspectives

ENERGY RESOURCE MARKETS

Climate policies have a strong impact on energy resource markets, resource rents and energy security.

Climate policies interfere with fossil fuel markets and reallocate rent incomes from providing scarce goods. The global losses of fossil fuel rents are overcompensated by revenues from carbon pricing. The losses of rents from coal are much smaller than those for oil, though coal is the fossil fuel that needs to be reduced the most. Achieving the 2°C target still allows using conventional and unconventional oil reserves. Large part of the coal reserve needs to be left underground.

Energy security is significantly improved by climate policy under all assumptions about resource availability and GDP growth. That is due to a reduction of risks associated with energy trade and an increase in the resilience of energy systems through higher diversity. Climate policy also makes total energy supply, the energy mix and energy trade more predictable and possibly easier to manage. Climate policies may also entail certain risks for energy security. In particular, deep penetration of solar energy in the electricity sector or biofuels in the liquid fuels sector may reduce the diversity of these energy systems by the end of the century.

LAND USE

Population, economic growth, and fossil fuel scarcity all have implications for land use.

Larger populations require more food, increasing the extent of cropland area. Wealthier populations tend to eat more meat, a land-intensive commodity, increasing cropland and pasture cover. Growing, wealthier populations also demand more energy. Fossil fuel scarcity drives increased consumption of bioenergy and land devoted to its production. All three of these effects lead to reductions in forest cover and increases in land-use change CO_2 emissions.

INVESTMENTS AND INNOVATION

Economic growth and fossil fuel scarcity can both stimulate clean energy innovation and non-fossil-fuel investments.

When economies grow faster energy resources are used more efficiently, but fossil fuels would remain the prevalent source of energy.
In contrast, the expectation of high energy prices could redirect ample financial resources to R&D programs aimed at developing new energy sources.

Although economic growth and fossil fuel prices can create an economic opportunity for more investments in non-fossil energy technologies and clean energy R&D, still they would lag behind the levels observed in stabilization scenarios and would not induce emission reductions compatible with climate stabilization objectives. On average, baseline total R&D investments amount to about 67 billion 2005 US$/yr while they increase to almost twice as much (113 billion 2005 US$/yr) in the 450 ppm CO_2e stabilization scenario. The availability of cheap gas resources would increase gas investments, mostly to substitute coal especially in coal-intensive countries. Yet, it would only marginally displace investments in clean energy innovation.

1

A study on Roadmaps towards Sustainable Energy futures

A broad and systematic exploration of uncertainty on key drivers of energy demand and supply is indispensable for better understanding the prospects of achieving long-tern climate protection targets. The RoSE study is the first of its kind to systematically explore the impact of economic growth, population, and fossil resource scarcity on baseline and climate policy scenarios in a model ensemble. The aim is to provide a robust picture on energy sector transformation scenarios for reaching ambitious climate targets. That is achieved by assessing the feasibility and costs of climate mitigation goals across different reference assumptions, different policy regimes, and different models

The RoSE project has several unique features that distinguish it from past integrated assessment model comparison projects and frame the project objectives:

- Participation of established integrated assessment modeling teams from three important regions for climate policy making: the EU, the USA and China (Box 1–1).
- Exploration of a large scenario space defined by a range of reference assumptions and climate policy stabilization targets.
- Harmonization of key input assumptions in order to provide a better understanding on the effect of input versus model assumptions.
- Analysis of the future development of the Chinese energy system by both global and regional modeling.
- Participation of domain experts in the areas of energy security, transportation, fossil fuel availability, and access to electriity, with the aim to embed scenarios and model results in a larger context beyond model boundaries.

RoSE is in the process of producing a large scenario data base and a series of research papers that can serve as a key input to international climate policy assessments, like the IPCC 5th Assessment Report.

Uncertainty regarding future population growth, economic development and fossil fuel availability, and its implications for climate policy are crucial for the climate debate. This uncertainty is explored and quantified in RoSE by means of baseline and policy scenarios (Box 1–2). The specification of the RoSE scenarios is based on three key dimensions:

- underlying assumptions on future socio-economic development determined by population and economic growth;
- reference assumptions on long-term fossil fuel availability and accompanying extraction costs, with a focus on variations of coal, oil, and gas;
- stringency and timing of climate protection targets and framework of international climate policy.

Box 1-1 Models participating in RoSE

China TIMES: The China TIMES model is a dynamic linear programming energy system optimization model which has been adopted to study China's future energy development strategy. TIMES incorporates the full range of energy processes and it is able to consider existing technologies as well as advanced technologies which may be deployed in the future. The objective function of the model minimizest energy system costs. Five sectors, namely agriculture, industry, commercial, residential (divided into urban and rural) and transportation are considered. The China TIMES energy model is used to determine the least-cost mix of technologies and fuels to meet the predicted energy service demands until 2050.

GCAM: GCAM is a dynamic-recursive model of the coupled global energy-economy-land-climate system. GCAM tracks emissions and concentrations of 15 greenhouse gases and short-lived species. An important feature of the GCAM is that energy, agriculture, forestry, and land markets are integrated with the extent of unmanaged ecosystems and the terrestrial carbon cycle.

IPAC: IPAC is a global multi-model framework that links social and economic development, energy activities and land use activities, and enables a full analysis of emissions. IPAC includes mainly four parts: (1) the society, economy and energy activities module, which mainly analyzes energy demand and supply , and determines energy prices; (2) the energy technology module, which analyzes the short and mid-term energy utilization technologies under different conditions, and determines the energy demand under different technology compositions; (3) the land use module, which analyses the emissions from land use processes; (4) the industrial processes emissions module, which mainly analyzes the emissions from all kinds of industrial production.

REMIND: The global multi-region model REMIND is an inter-temporal energy-economy-environment model which maximizes global welfare based on nested regional macro-economic production functions. REMIND incorporates a detailed description of energy carriers and conversion technologies, and allows for unrestricted inter-temporal trade relations and capital movements between 11 world regions. Mitigation costs estimates are based on technological opportunities and constraints in the development of energy technologies.

WITCH: The WITCH model developed by the climate change modelling and policy group at FEEM is a global integrated assessment model in which the non-cooperative nature of international relationships is explicitly accounted for. The regional and intertemporal dimensions of the model make it possible to differentiate climate policies across regions and over time, and thus consider several policy scenarios. The model includes a wide range of energy technology options, with different assumptions on their future development, which is also related to the level of innovation effort undertaken by countries. Special emphasis is put on the emergence of carbon-free backstop technologies in the electricity and the non-electricity sectors, and on endogenous improvements in energy efficiency triggered by dedicated R&D investments.

Box 1-2 RoSE Scenarios

Population and GDP: Models were harmonized to the medium population projection from the 2008 Revision of the UN World Population Prospects (peaking at 9.4 billion in 2070). The GDP scenarios build on the population projections and encompass assumptions regarding both the speed of economic growth (slow, medium or fast speed) and the convergence characteristics (slow or fast convergence) between 26 aggregate world regions. The study also included a slow growth – slow convergence GDP scenario that was based on the high population projection of the UN 2008 Revisions (increasing to 14 billion in 2100).

Fossil fuel availability: Fossil fuel availability was characterized in terms of supply curves describing extraction costs as a function of cumulative extraction. Oil, gas and coal have been treated separately, with an additional division into conventional and non-conventional resources. Historical data for recovery rates have been examined and then extrapolated, under varying assumptions about technological progress and extraction costs. The output of this process was three extraction cost curves, assuming 'low', 'medium', and 'high' resource availability, for each of the three fossil resources.

Climate Policy: The policy dimension includes different policy cases representing the level of ambition and timing of climate-policy:

- Baseline: no climate-policy;
- 450 ppm CO_2e: adoption of a 450 ppm CO_2 equivalent concentration stabilization target allowing for overshoot, with full when-where-what flexibility of emissions reductions after 2010;
- 550 ppm CO_2e: adoption of a 550ppm CO_2e target, with no overshoot allowed, and full flexibility of emissions reductions;
- Weak Policies: initially world regions take only moderate and uncoordinated action following the lower end of the Copenhagen commitment until 2020. In the different scenarios, either that level of ambition is retained throughout the 21st century, or a 450ppm CO_2e long term stabilization target allowing for overshoot is adopted in 2020 or 2030.

2

Economic growth and fossil fuel availability as drivers of CO_2 emissions

2.1 Neither slow nor rapid economic growth solves the climate problem by itself

In general, higher economic growth leads to higher energy demand and greenhouse gas emissions (Figure 1). Final energy demand in 2100 was projected to range between two to three times of today's level (700–1000 Exajoule [EJ]). These levels correspond to assumptions about global economic output in 2100 ranging between 4 to 12 times of today's level.

Energy demand variations are significantly smaller because models assume progressive energy intensity improvements with GDP per capita growth. Models agree that those energy intensity improvements – in the absence of dedicated policies to improve energy intensity beyond historical trends – are not large enough to fully compensate per capita income growth. Consequently, a steady increase of final energy use both over time (as the economy grows) and from low to high growth scenarios is observed across models.

Carbon intensity of energy production is correlated with economic growth to a much lesser degree than energy intensity. In the absence of climate policies, it remains fairly constant over time so that the growing energy demand is converted into growing emissions for both slow and high growth scenarios. Economic growth thus cannot solve the climate problem by itself as sometimes suggested.

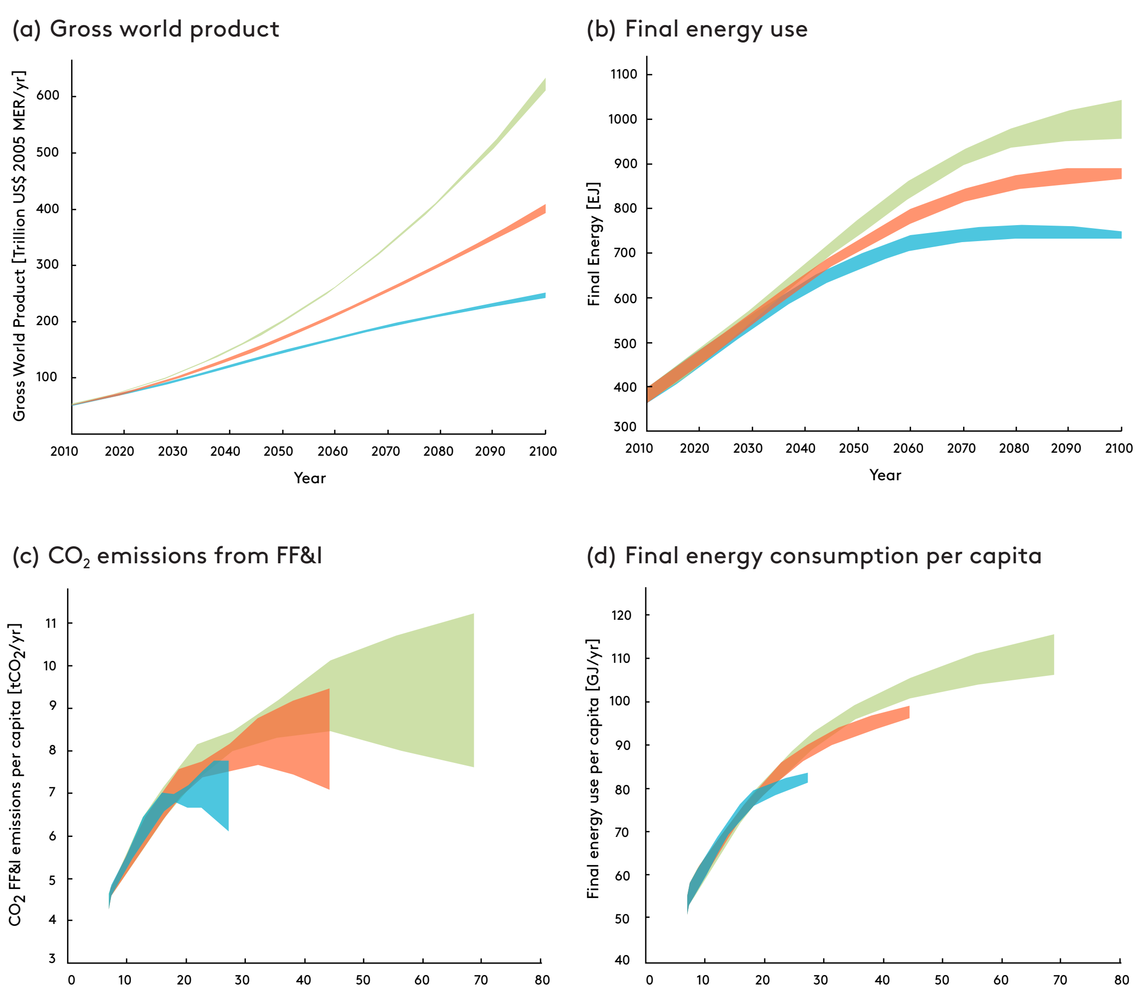


Figure 1*1

(a) Gross world product and (b) final energy use over the 21st century; (c) CO_2 emissions from fossil fuel combustion and industry (FF&I) and (d) per capita final energy consumption as a function of per capita income.

Fast growth
Default
Slow growth

*1 Individual funnels show the range across three different models (GCAM, WITCH, and REMIND) for a given assumption about economic growth (denoted by the color coding).

2.2 Fossil fuel scarcity is insufficient to slow global warming significantly

Cumulative fossil fuel use (2010-2100) in the absence of climate policy was estimated to range from 54-61 Zetajoule [ZJ] for low fossil fuel availability, to 72-84 ZJ for high availability. This can be compared with 18-19 ZJ of fossil fuels used until 2010 and ca. 36 ZJ of proven fossil fuel reserves today. The scenario of low fossil fuel availability leads to a stabilization of emission levels around 2050 (Figure 2). In the other cases, emissions continue to increase in the 2nd half of the century. Even if emission levels are stabilized in the 21st century, atmospheric CO_2 levels will continue to rise. This is incompatible with the goal to stabilize climate change. Thus, fossil resource scarcity alone will not solve the climate problem.

Different assumptions about fossil resource availability translate into differences in estimates about future final energy demand (models project 700-1100 EJ in 2100). This is due to a supply push from lower energy prices. High availability leads to a more energy intensive production, and vice versa, as shown by all models.

Carbon intensity is correlated with fossil fuel availability. It will be lower for limited fossil fuel supply, which requires substituting fossil fuels with non-fossil energy carriers to a larger degree. A higher fossil resource base can lead to lower or higher carbon intensity. It may lower carbon intensity if it allows a more extensive use of gas substituting coal for electricity production and a prolonged use of oil reducing the need for coal to liquid technologies in the long run. However, if the larger fossil fuel supply is dominated by coal, carbon intensity can increase. Models estimate that fossil fuel prices increase by a factor of five to seven over the 21st century in a situation of low fossil fuel availability, and only moderately (~two fold) in the high fossil resource scenario.

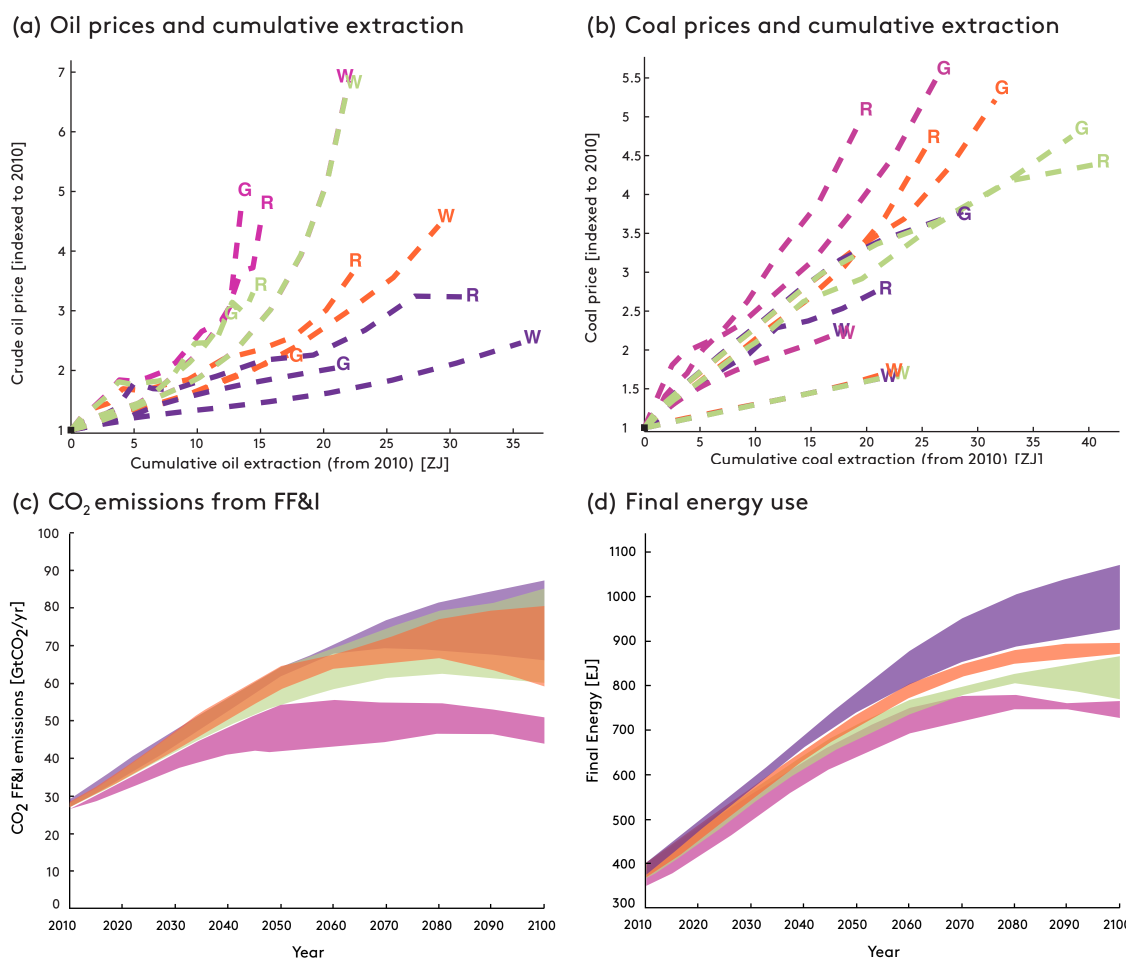


Figure 2
(a) Oil and (b) coal prices as a function of cumulative extraction over the period 2010 (bottom left corner) to 2100 (model letters at the end of the dashed lines); (c) CO_2 emissions from fossil fuel combustion and industry (FF&I) and (d) final energy use over the 21st century. *2

Default — G GCAM
High fossils — R REMIND
Low fossils — W WITCH
Hi coal

*2 Individual funnels show the range across three different models (GCAM, WITCH, and REMIND), while the differences between funnels show the impact of different assumptions about fossil fuel availability (denoted by the color coding).

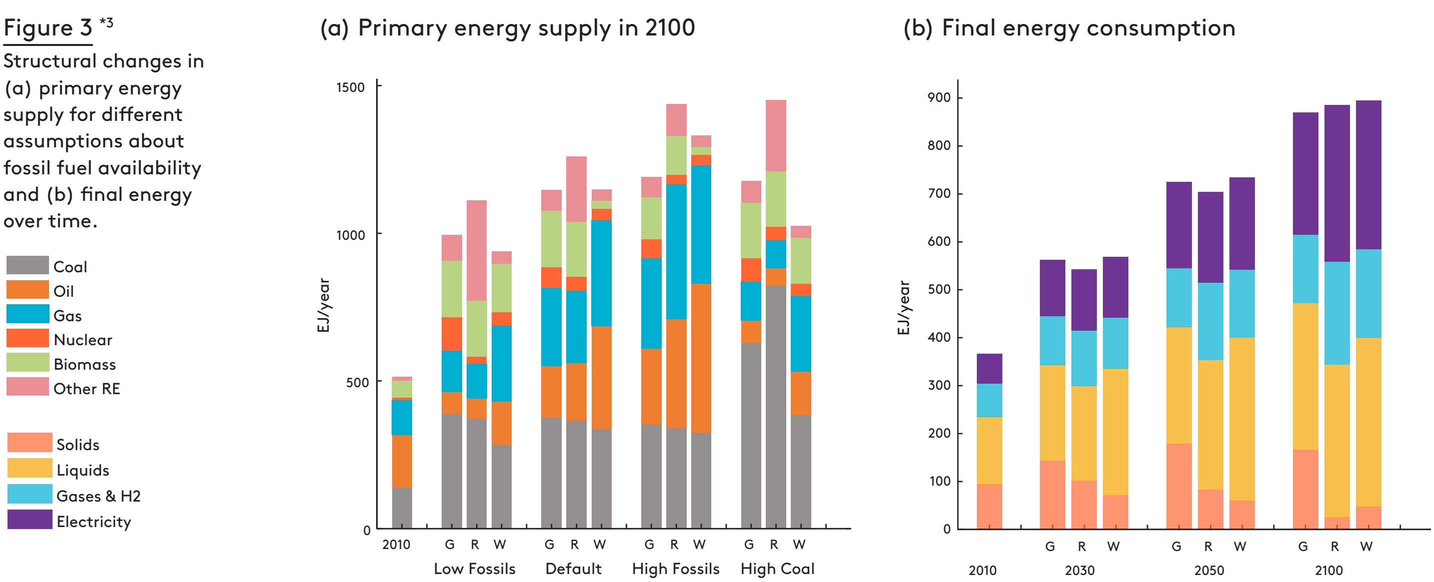
2.3 There are robust patterns in projections of energy use in the absence of climate policy

Higher economic growth increases the scale of the energy system, which continues to be mostly supplied by fossil fuels. Structural differences in the energy supply mix occur for variations in fossil resource availability, particularly coal and oil supply (Figure 3).

Models unanimously show an electrification of energy end use independently of economic growth and fossil resource assumptions. The move towards electrification is amplified if fossil resources are scarce. In contrast, large oil and gas resources allow more extensive use of liquids. Models also show a robust pattern for primary energy supply: a reduction of the share of oil & gas use coupled with an expansion of non-fossils and a modest expansion of coal use. Exceptions are i) the situation of high oil and gas availability, where today's mix of primary energy carriers are basically maintained, ii) low overall fossil fuel availability, where non fossils are expanded much more strongly and iii) high coal but low oil supply, where coal use is increased significantly.

Figure 3 *3

Structural changes in (a) primary energy supply for different assumptions about fossil fuel availability and (b) final energy over time.



*3 Panel (a) depicts primary energy supply in the year 2100 for GCAM (G), REMIND (R), WITCH (W) and four different scenarios of fossil fuel availability.
Panel (b) shows the development of the structure of final energy consumption for the periods 2010, 2030, 2050 and 2100.

3

Requirements of climate stabilization

3.1 Climate stabilization requires a phase out of greenhouse gas emissions

Climate stabilization at levels of 450 ppm or 550 ppm CO_2e in the atmosphere requires massive emissions reductions, in particular in the latter half of the century (Figure 4). In the 450 ppm case, greenhouse gas emissions would need to be nearly phased out by 2100, possibly requiring CO_2 withdrawal from the atmosphere (negative emissions) to compensate for residual emissions in non-energy sectors. In the 550 ppm case, emissions would need to be more than halved by the end of the century, and declining towards zero in the 22nd century

The literature generally regards a stabilization level of 450 ppm CO_2e as being compatible with the 2 degrees target. All RoSE models project global warming around or below 2 degrees in the 450 ppm case. In the 550 ppm case, RoSE models show that temperature rises above 2 degrees around 2050, and reaches ~2.4 degrees in 2100, with a slowly rising trend. If greenhouse gas levels are not lowered in the 2nd half of the century, this would eventually lead to an equilibrium warming of 3 degrees. These estimates are based on the assumption of a climate sensitivity of 3 degrees.

The results hold independently of the assumptions on future fossil resource availability and economic growth.

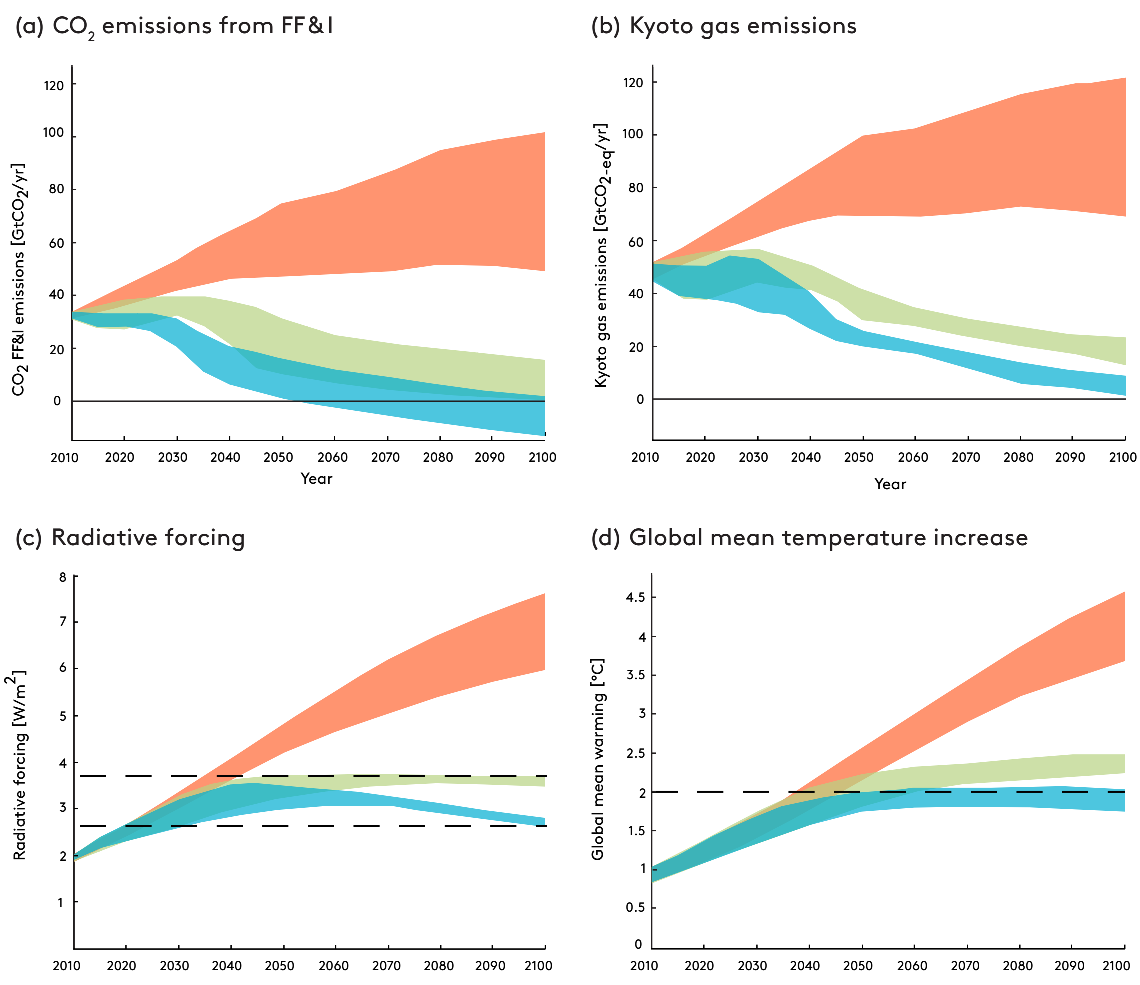


Figure 4
(a) CO_2 emissions from fossil fuel combustion and industry (FF&I), (b) Kyoto gas emissions *4, (c) total anthropogenic radiative forcing and (d) global mean temperature increase since preindustrial.

No climate policy
550 ppm CO_2e
450 ppm CO_2e

*4 These comprise the long-lived greenhouse gases CO_2, CH4, N_2O, HFCs and SF6.

3.2 Climate stabilization requires a massive transformation of the energy system

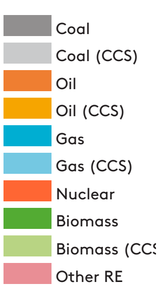
Climate stabilization requires a transformation to a low carbon energy system in the 21st century with historically unprecedented decarbonization rates. This requires climate policy intervention with carbon pricing at its core. Increasing the stabilization target from 550 to 450 ppm CO_2e considerably increases the requirements on the decarbonization of energy supply. Negative emissions due to bioenergy use coupled with CCS are utilized in most model runs to achieve the 450 ppm CO_2e target.

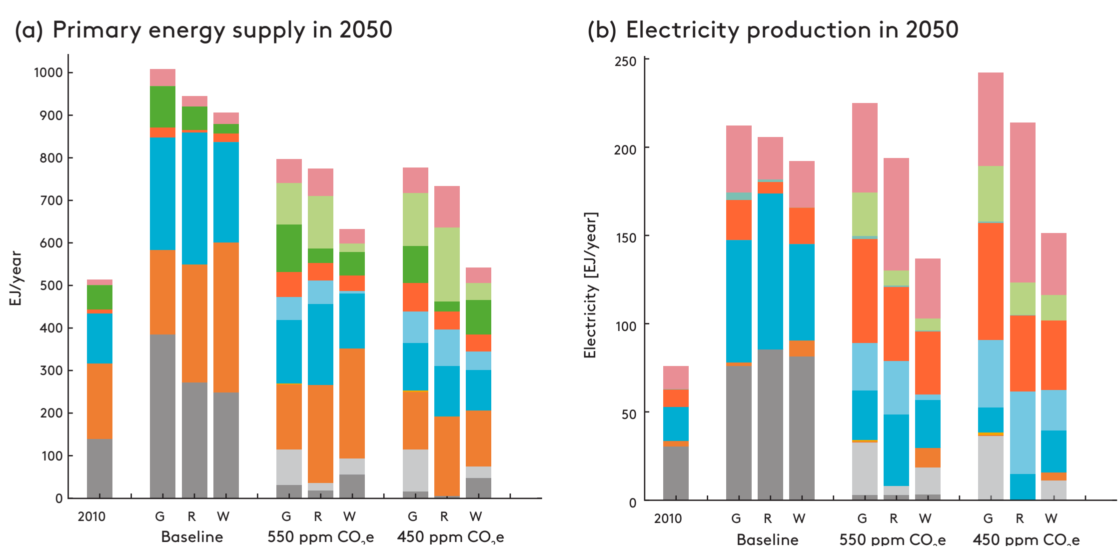
Models can tell very different stories when and what to reduce. While there is broad agreement on Kyoto gas emissions reductions after 2040, large differences on CO_2 fossil fuel and industry emissions reductions are found.

However, some robust patterns in the description of the transformation process emerge (Figure 5). Mitigation leads to a fast phase out of coal and a rapid expansion of non-fossils independently of assumptions on economic growth and fossil fuel availability. All models foresee a larger share of electricity and gases coupled with a strong reduction of solids in the energy demand structure, with the largest share of energy coming from grids in the latter half of the century.

The electricity mix shows the strongest transformation, and the largest differences between models. Models respond to climate targets either with a dominant contribution from nuclear or renewable electricity. Compared to the impact of model differences, the effect of different assumptions about fossil fuel availability and economic growth is small.

Figure 5 *5
Decarbonization of
(a) primary energy supply
and (b) electricity production.





*5 The plot shows values for the 2050 for the default baseline scenario, and the 550 and 450 ppm CO_2e policy scenarios across GCAM (G), REMIND (R), and WITCH (W).

3.3 Climate policy strongly constrains fossil fuel use

Cumulative extraction is significantly reduced in the climate policy cases (38-46 ZJ in the 550 ppm and 26-37 ZJ in the 450 ppm case). Climate policy strongly constrains the variation of fossil fuel use with different assumptions about fossil fuel availability as a large amount of the resources has to remain in the ground. Thus, uncertainty about future fossil fuel use is effectively mitigated by climate policy.

3.4 Variations in economic growth and fossil fuel availability can alter carbon prices and mitigation costs substantially

Mitigation pathways and carbon prices are affected by assumptions on economic growth and fossil fuel availability, as those lead to different levels of final energy demand and greenhouse gas emissions in the absence of climate policy. It matters whether these differences are due to different levels of economic growth (demand pull) or fossil resource availability (supply push). In the former case, carbon prices vary more strongly (Figure 6). A supply push of fossil energy may be more easily neutralized with a carbon price signal than a demand pull due to higher levels of economic output.

In an idealized setting of fully cooperative action, foresight, and functioning energy and land markets, a globally harmonized carbon price will lead to emissions reductions when and where they are most efficient. In this idealized context, global direct mitigation costs are projected to be around or below 1% of economic output (that would have been obtained in the absence of climate policy and climate damages; in net present value terms) for climate stabilization at 550 ppm CO_2e across a range of different assumptions about economic growth and fossil resource availability. This cost measure does not include the benefits from climate protection as well as ancillary benefits from mitigation policies. For achieving the 450 ppm CO_2e target, mitigation costs approximately double compared to the 550 ppm CO_2e target. It is important to note that mitigation costs can be substantially higher in less idealized settings including multiple market externalities and distortions.

Assumptions about economic growth and fossil fuel availability can alter mitigation cost estimates substantially (Figure 6). Mitigation costs increase by approximately 25 to 80% from low to high economic growth, and from low to high fossil fuel availability. Low fossils come in at the lowest cost due to the reduced need of additional transformation under climate policy plus reduction of high fossil fuel expenditures. High growth, high population and high fossil scenarios sit on the high end.

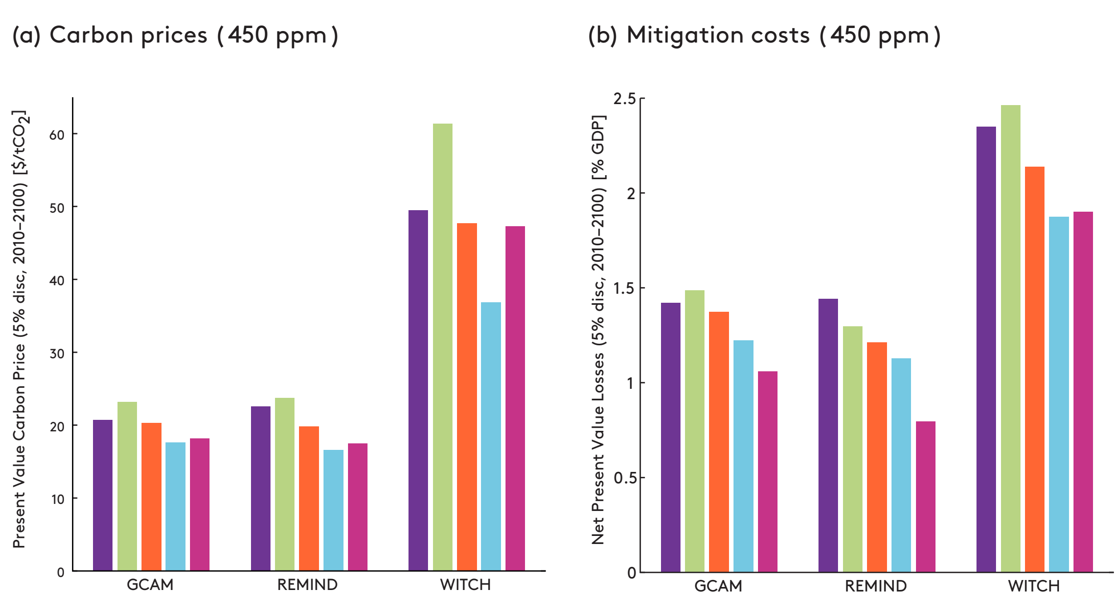


Figure 6
(a) Net present carbon prices and (b) policy costs for the 450 ppm CO_2e stabilization target.

High fossils
Fast growth
Default
Slow growth
Low fossils

4

Fragmented and delayed climate action

The international community set a target of limiting global warming to no more than 2°C above pre-industrial levels. However, as part of the Copenhagen Accord countries have only committed to relatively weak near-term emissions reduction pledges, and so far only few concrete climate policies and measures to reduce greenhouse gas emissions have been implemented.

4.1 Current climate policies are insufficient for 2° C stabilization

By analysing scenarios in which national emission reductions remain comparable in ambition to the level implied by a lenient interpretation of the Copenhagen Pledges, we explored the consequences of a continuation of current climate policy trends. In all models we find that such weak policies fail to prevent a further increase of global GHG emissions at least until mid-century, and are clearly insufficient to meet the 2°C target. Rather, global mean temperature rise by about 3.5°C until 2100, with an increasing trend moving into the 22nd century.

4.2 Later action implies steeper midterm emission reduction requirements for reaching 2°C

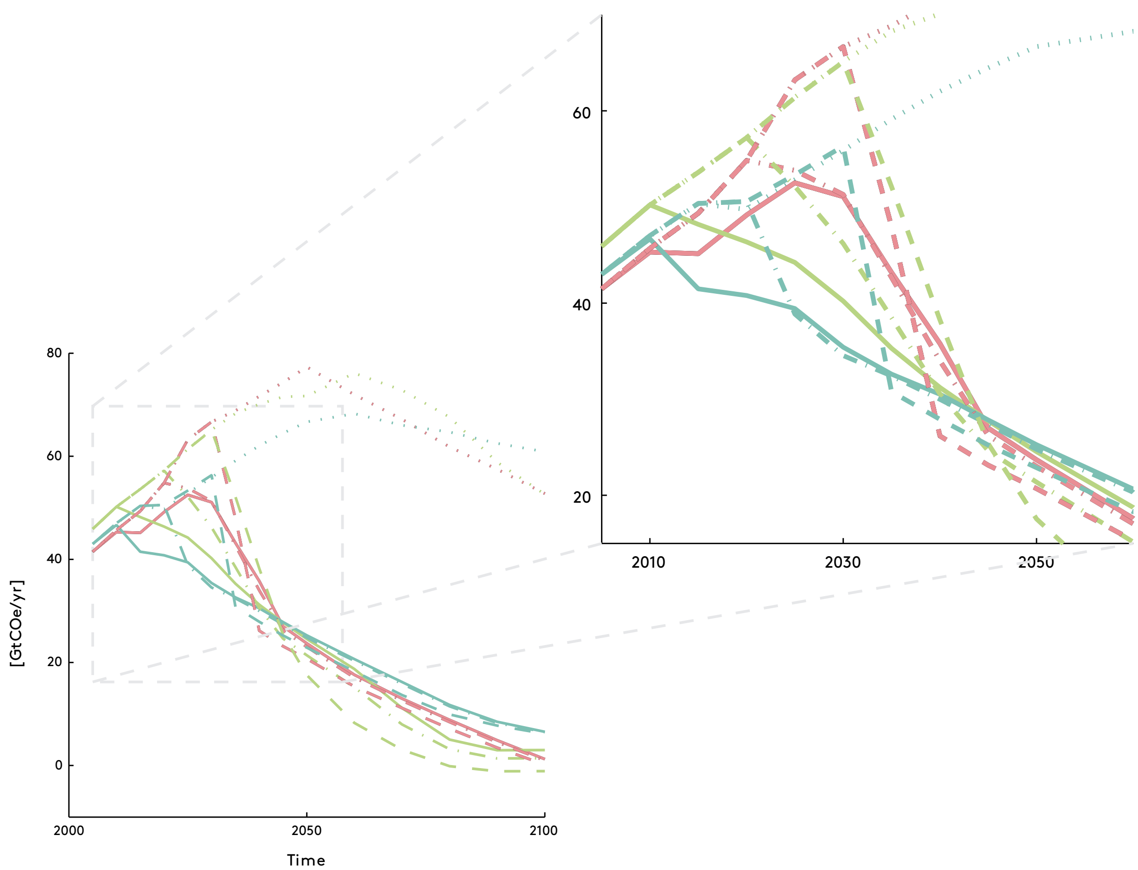
In further scenario experiments, we explored how weak near-term climate policies affect the challenges of reaching long-term climate targets. To this end, we investigated three variants of climate change mitigation scenarios aiming at a stabilization of atmospheric GHG concentrations at 450 ppm CO_2e by 2100. As outlined above, stabilization at 450 ppm CO_2e is roughly consistent with the 2°C target. In the first set of scenarios, we assumed global comprehensive emissions reductions to start immediately (IMMEDIATE). In the second set of scenarios (WEAK-2020), we assumed countries to follow the weak policy scenario until 2020, and to adopt comprehensive, globally coordinated emissions reductions consistent with the long-term target thereafter. Likewise, the WEAK-2030 scenarios assume weak climate policies until 2030, and comprehensive, globally coordinated emissions reductions thereafter.

Comparing the results from these different scenario sets allows us to explore how mitigation pathways and associated socio-economic and technological challenges depend on the start date of comprehensive global emissions reductions. Reaching the 450 ppm target requires a fundamental transformation of global energy systems, even if a global climate agreement were reached immediately. We find that delay of comprehensive global emissions reductions increases the challenge of reaching stabilization levels consistent with the 2°C target in several aspects. While aiming at the same long-term greenhouse gas stabilization levels, later action scenarios result in somewhat higher transitory climate change, and increase the likelihood of temporary overshooting of the 2°C target. Delaying ambitious climate policies results in a compression of the decarbonization effort into a shorter period of time, with higher yearly emissions reduction rates after adoption of the climate policy (Figure 7). The models estimate that GHG emissions have to be reduced by 40 - 60 % within one decade in case of the WEAK-2030 scenario, compared to peak reduction rates of 20-30 % in the IMMEDIATE scenario. Such high emission reduction rates are historically unprecedented. The implications of pathways with prolonged delay for global energy systems are dramatic. In the model scenarios, this is accomplished by a greatly accelerated decarbonization of energy supply, rapid reductions of energy demand, or a combination of both.

Climate policies in line with the 2°C target render a considerable portion of conventional, fossil-based energy supply capacities obsolete. In case of a continuation of weak climate policies, conventional fossil capacities increase further, for instance because of the construction of coal-fired power plants. As a consequence, higher stranded investments due to premature retirement of these capacities occur (Figure 8d).

Figure 7

Total global greenhouse gas emissions for alternative climate policy scenarios.



4.3 Later action implies greater economic challenges for reaching 2°C

The timing of emissions reductions also affects the economics of climate change mitigation (Figure 8). While near-term economic costs in the WEAK-2020 and WEAK-2030 scenarios are small, long-term costs increase by 20-80% compared to the IMMEDIATE scenario. These scenarios are also characterized by higher long-term carbon price levels.

For all mitigation challenges analysed, we find that implications of delaying action until 2030 are considerably more severe than of a delay until 2020. In the WEAK-2030 scenario, the shift from weak policies with low carbon prices to comprehensive global climate regime with high carbon prices and comprehensive emissions pricing is likely to result in considerable economic distortions. All models find a decrease of household income growth of about 0.4 % / yr in this scenario during the decade following the phase-in of ambitious climate policies. This short-term economic distortion is much higher than in the other climate policy scenario. While the models are able to compute low-stabilization scenarios with a prolonged delay of action, the dramatic increase in mitigation challenges in case of policy delay until 2030 make it seem unlikely that such pathways can be implemented in the real world.

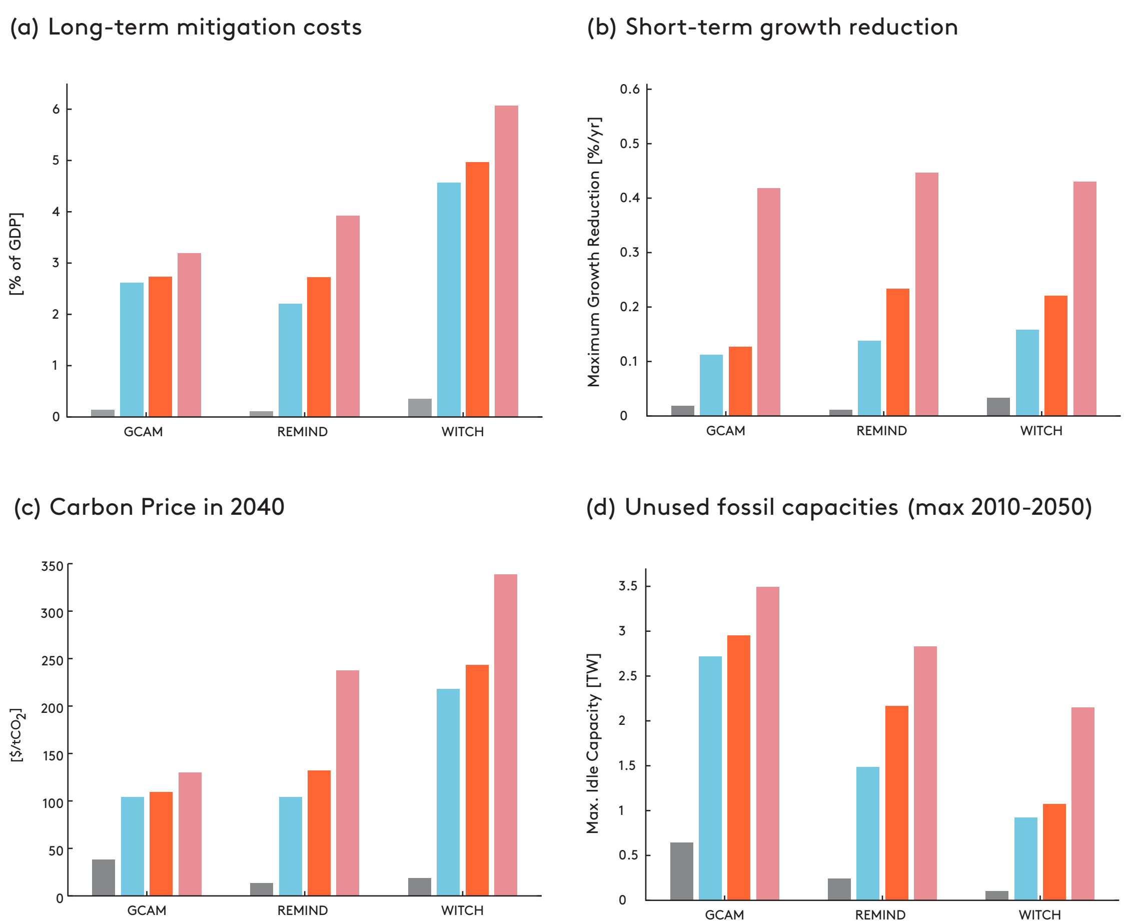


Figure 8
The effect of weak near-term climate policies on (a) long-term mitigation costs (aggregated 2035-2100), (b) economic growth in the decade following the implementation of stringent climate policies, (c) mid-term carbon price levels, and (d) unused fossil capacities.

WEAK–POL
IMMEDIATE
WEAK–2020
WEAK–2030

5

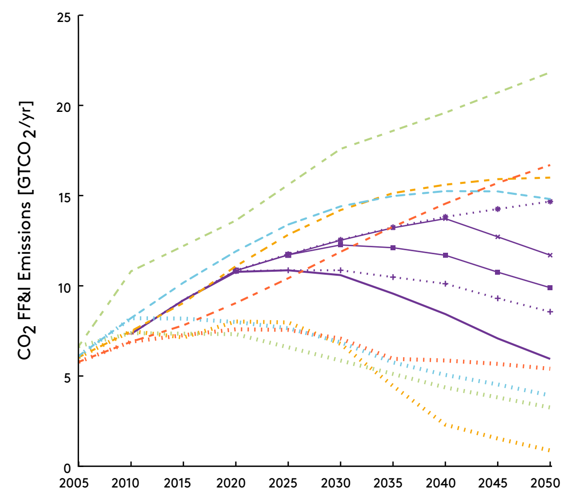
Regional perspectives

5.1 Climate stabilization implies a fundamental energy transformation for China

Figure 9 *6

CO_2 emissions from fossil fuel combustion and industry (FF&I) in China.

TIMES
GCAM
IPAC
REMIND
WITCH
Baseline
Reference
C353040
C354040
C454040
C455050
450 ppm CO_2e



Carbon emissions from fossil fuel combustion in China are expected to increase from 5.5 Gt CO_2 in 2005 to about 11 Gt CO_2 by 2020. Different assumptions on climate policy driven carbon intensity reductions lead to a large range of emissions by 2050 (6-12 Gt CO_2), as calculated with an energy system model of the Chinese economy (China TIMES model) (Figure 9). Climate stabilization scenarios from global models show emission reductions for China below or at the low end of the 6-12 Gt CO_2 range in 2050. The emission trajectories differ across models but all peak during 2020-2025 for the 450 ppm CO_2e target and 2025-2030 for the 550 ppm CO_2e target. This indicates that stringent climate targets would imply ambitious carbon intensity reductions in China. For the 450 ppm CO_2e target, all global models show more reductions during 2010-2050 than the most stringent climate policy scenario in the China TIMES.

Based on results from IPAC, China could make such a contribution to transitioning to a 2°C world. Much focus should be given to the progress on technology. Full effort/collaboration on technology innovation/diffusion is crucial. The mitigation cost could be low if mitigation technologies are a driving force of economic development.

When comparing global model results, including IPAC, with the national model results of China TIMES, the global models illustrate greater carbon mitigation potentials with lower cost. This is mainly due to a substantial decrease of energy demand in the climate policy scenarios, and more rapid expansion of nuclear and renewable energy and CCS until 2050.

The path towards low carbon development for China, a big developing country with high total carbon emissions with still lower per capita carbon emissions compared to industrialized countries, includes challenges and opportunities. Substantial efforts may be required to transform the economic development mode, to speed up innovation, R&D, and deployment of advanced low carbon technologies, to strengthen institutions, to advocate low carbon lifestyles, and to enhance international cooperation.

6* The China Times scenarios C353040, C354040, C454040, and C455050 represent different requirements on carbon intensity improvements.

5.2 Economic and population growth in Africa have profound implications for energy use and emissions

Today Africa accounts for a modest 3% of global energy system CO_2 emissions. The evolution of Africa's emissions over the coming century depends critically on future population and income. Estimates of population in 2100 in Africa vary dramatically, with 2 billion more inhabitants in the UN High population scenario than the UN Low population scenario. Future income growth is also uncertain.

Absent any climate policy, Africa could become a major emitter in the second half of the 21st century if economic growth in this part of the world is steady. 2100 emissions in Africa could be as much as 20% of global CO_2 emissions, with as much as 10% of global emissions in Sub-Saharan Africa (Figure 10).

In the shorter term, the extent of energy poverty and improvements in access to modern energy in Africa are also driven by assumptions regarding future population and economic growth. Slower economic growth and larger population growth result in a significantly slower transition to modern energy access and use on the continent (Figure 11). When climate mitigation is undertaken, Africa shoulders larger emissions reductions relative to baseline levels than the world on average, regardless of future population and income. However, the total cost of climate policy depends critically on assumptions about emissions permit allocations.

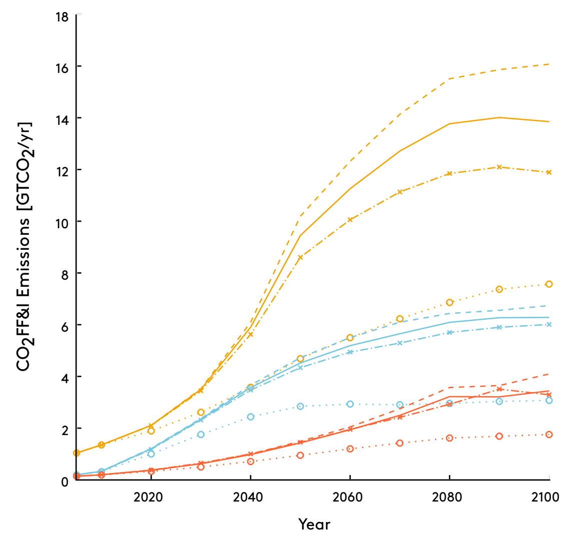


Figure 10 *7
CO_2 emissions from fossil fuel combustion and industry (FF&I) in Africa in baseline scenarios.

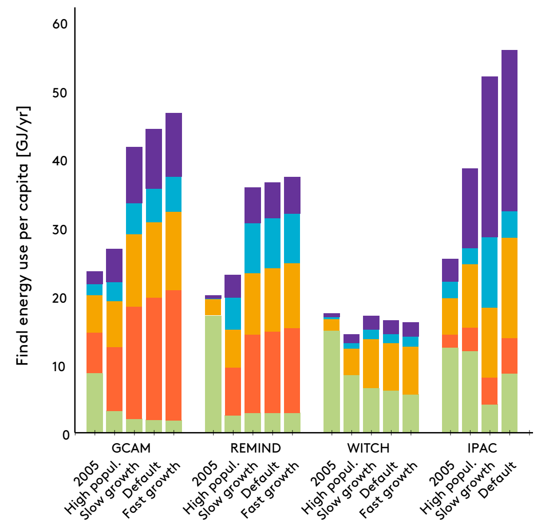


Figure 11
Final energy use per capita in Africa in 2005 and 2050 in baseline scenarios.

7* Africa in GCAM corresponds to continental Africa, while in REMIND and WITCH to Sub-Saharan Africa.

6

Sectoral perspectives

6.1 Climate policies have a strong impact on energy resource markets

6.1.1 Climate policies reallocate fossil rent incomes

Climate policies have a strong impact on fossil fuel markets and rent incomes. Rent incomes refer to the profits of fossil owners caused by the scarcity of exhaustible fossil fuels or by the revenues caused by carbon pricing reflecting the exhaustible carbon budget imposed by climate policy. Since both are expressed in monetary value terms, they can be directly compared and the changes in rents between scenarios indicate the distributive impacts of policies. Under climate policy, the global losses of fossil fuel rents are overcompensated by revenues from carbon pricing (Figure 12). The losses of rents from coal are much smaller than those for oil, though coal is the fossil fuel that needs to be reduced the most. In the 450 and 550 ppm CO_2e scenarios, a large share of coal reserves would be left underground (Figure 13). However, conventional oil and gas reserves and resources are utilized. Also the non-conventional oil reserve would go into production.

According to results from one of the models (REMIND), climate change stabilization at 450 ppm CO_2e decreases fossil fuel rents over the 21st century by 10-15.tril.US$. The loss of fossil fuel rent is highest for the fast growth and the low fossils scenarios. The additional carbon rent exceeds the loss of fossil fuel rents in all cases of economic growth and fossil fuel availability (ca. 20-25tril.US$). The largest over-compensation is resulting in the high fossils scenario, whereas the sensitivity to long-term growth variations is less important.

Figure 12
Net present value of carbon and fossil fuel rents (discounted at 5%).

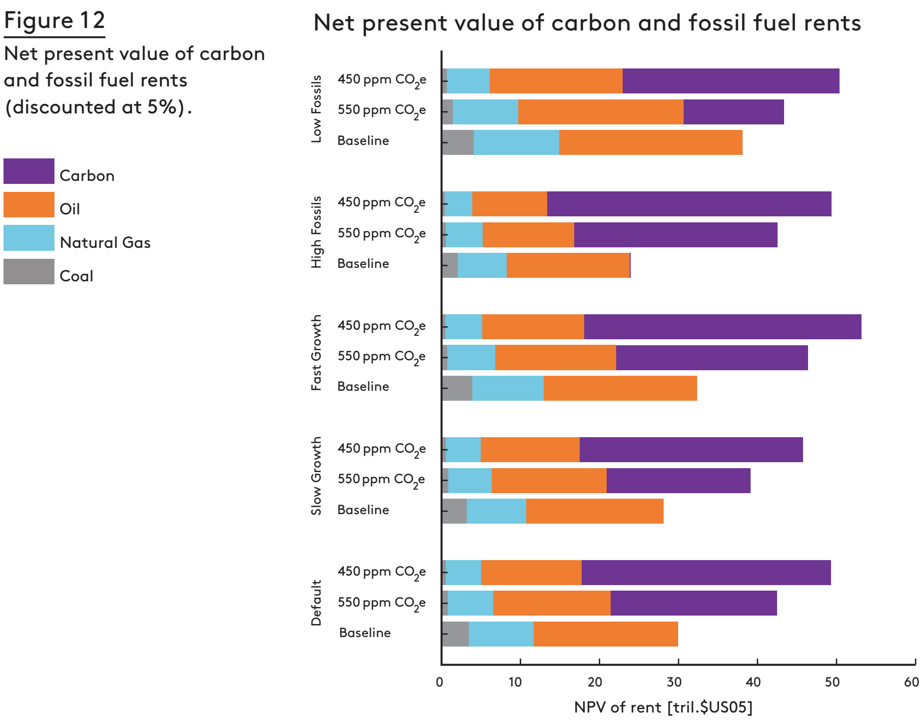
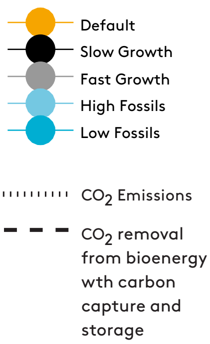
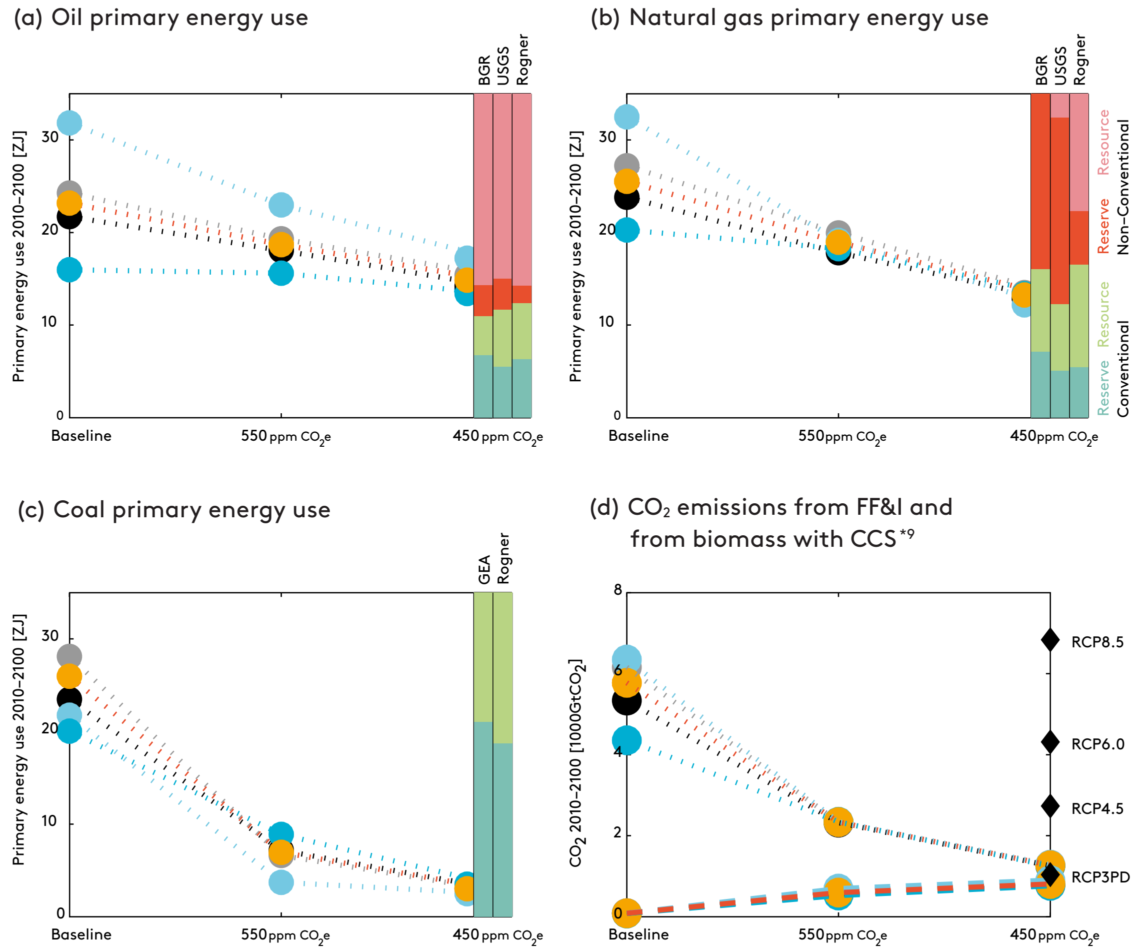


Figure 13 [*8]

(a) Oil primary energy use, (b) natural gas primary energy use, (c) coal primary energy use and (d) CO_2 emissions from fossil fuel combustion and industry (FF&I) and from biomass with CCS.





*8 BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), USGS (US Geological Survey) and GEA (Global Energy Assessment) are taken from Rogner HH, Aguilera R, et al. (2012) Energy Resources and Potentials. In Global Energy Assessment [Johansson TB, Patwardhan A, Nakicenovic N, Gomez-Echeverri L (eds.)], Chapter 7. Cambridge University Press. Cambridge MA. Rogner is Rogner HH (1997) An Assessment of World Hydrocarbon Resources. *Annual Review of Energy and Environment, 22:217-62.*

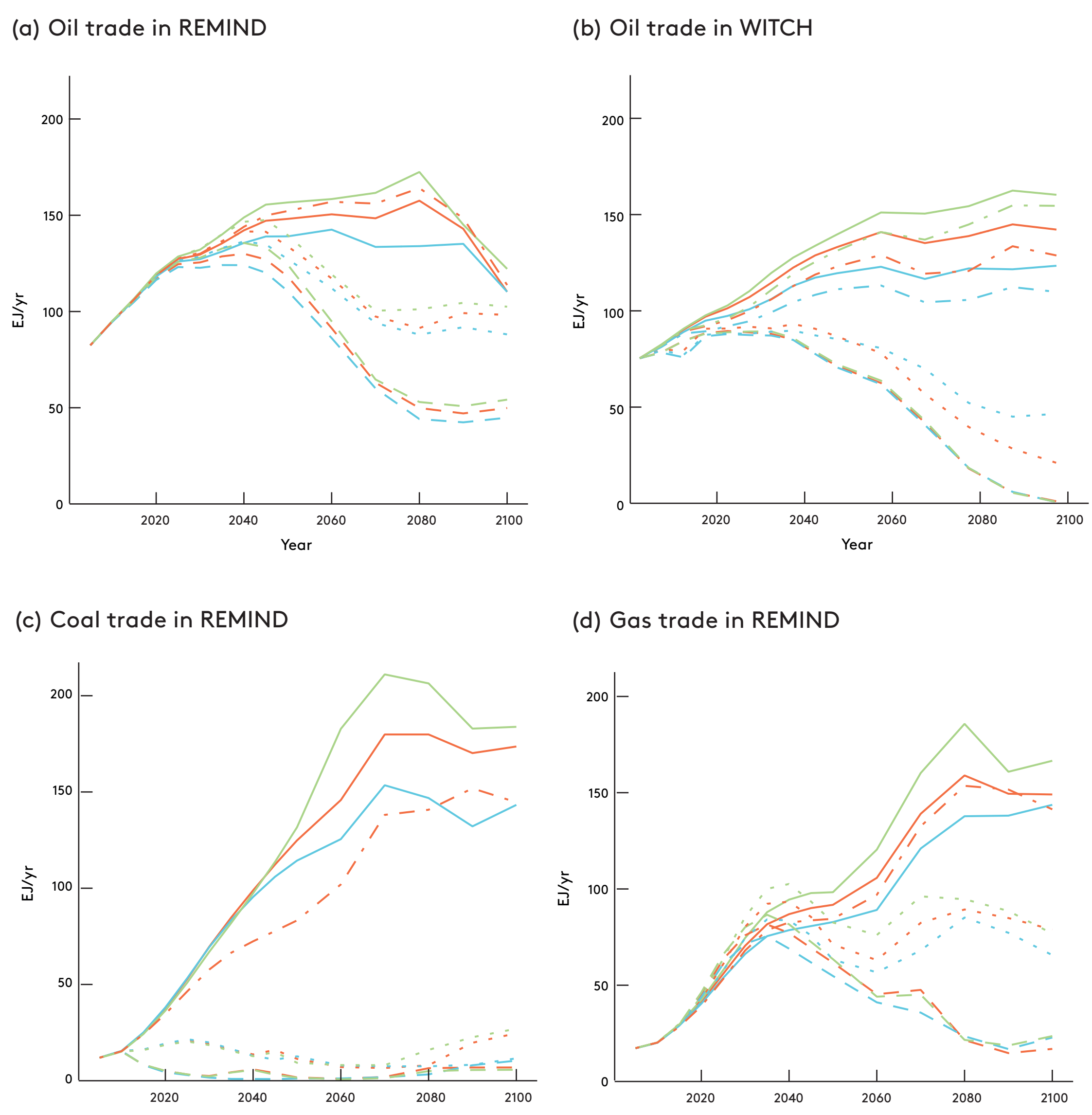
*9 RCP levels are placed here for the purpose of comparison based on the recent "Representative Concentration Pathways". The numbers in the RCP labels indicate total forcing levels in 2100.

6.1.2 Climate policies increase energy security

Under all assumptions about resource availability and GDP growth, climate policies significantly improve energy security by reducing the risks associated with energy trade and increasing the resilience of energy systems through higher diversity. They also make total energy supply, the energy mix and energy trade less dependent upon the variations in economic growth and resource availability, and thus more predictable and possibly easier to manage.

Climate policies may also entail certain risks for energy security. In particular, deep penetration of solar energy in the electricity sector or biofuels in the liquid fuels sector may reduce the diversity of these energy systems by the end of the century (particularly under high economic growth and low fossil fuel assumptions). This may be especially pronounced in regions which will be using their 'competitive' resources rather than relying on the global mix of tradable fuels. Another risk is a moderate increase in trade and import dependency in some fossil fuels in the short- to medium-term when climate policies supress exploration of coal and non-conventional oil. Finally, there is a risk of declining export revenues of energy-exporting regions, but for the main energy-exporting regions this is less pronounced, especially in the medium-term, due to continued demand for conventional oil and gas.

Figure 14
Global energy trade in baseline and climate policy scenarios under different economic growth assumptions.

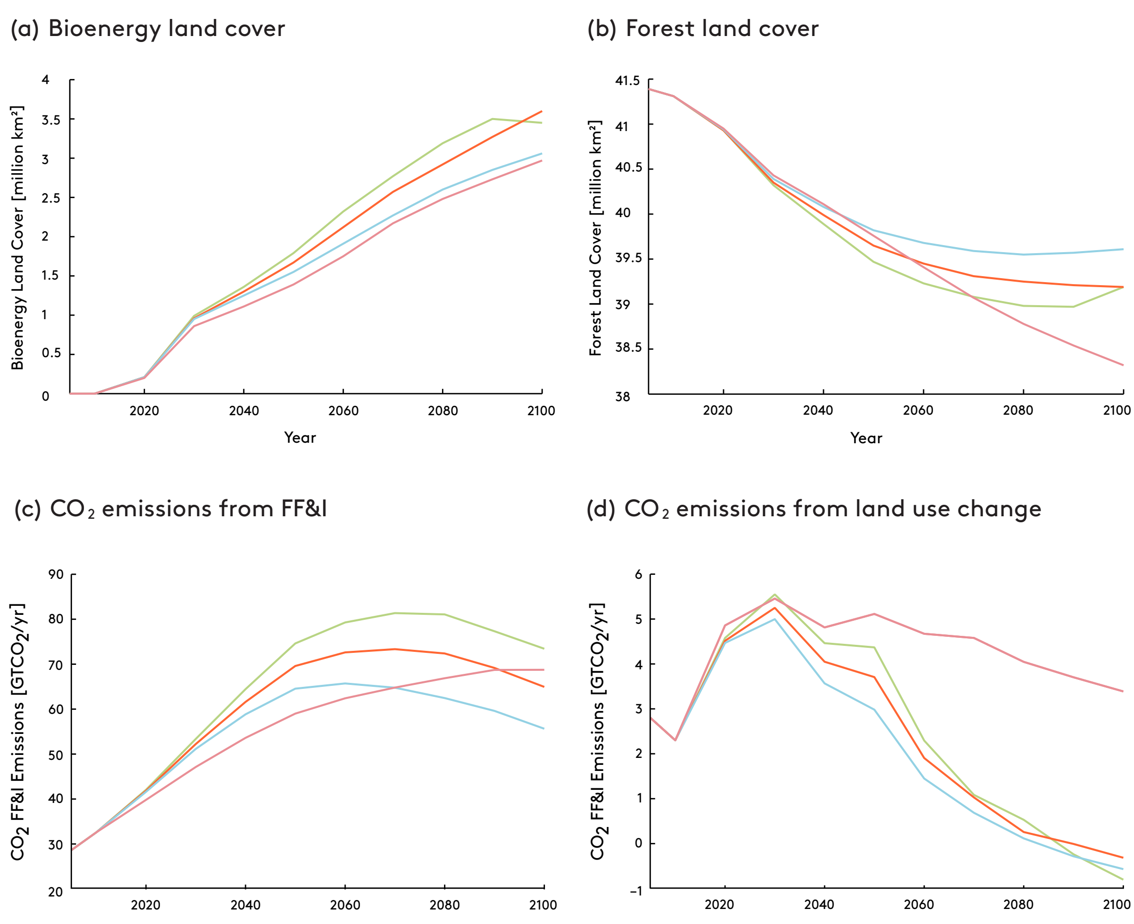


6.2 Population, economic growth and fossil fuel scarcity all have implications for land use

Each of the uncertainties explored in the RoSE project (population, income, and fossil fuel resource availability) has implications for land use, in addition to the implications for energy and mitigation. The availability and cost of extracting fossil fuel resources has an impact on the terrestrial system through the production and use of bioenergy. When fossil fuels are scarce or expensive, bioenergy serves as a substitute for coal and gas in the electricity sector, and for oil in the refinery sector, both with and without climate policy. As a result, more land is devoted to bioenergy production at the expense of forest cover. This results in lower energy system emissions and higher land-use change emissions. Under a climate policy, higher resource prices serve as a complement to carbon prices, leading to lower carbon prices when fossil fuels are scarce.

Increases in population and income can have a significant impact on emissions via increased strain on land and associated land-use emissions. Even if high population scenarios are coupled with low growth of per capita income, such that total economic output is lower than a medium population, medium growth scenario, cumulative land-use change emissions can be more than as 45% higher (Figure 15). The increase in competition for land and land-use change emissions have implications for the cost of mitigation, as more mitigation is required and the potential for land-based mitigation (e.g. afforestation, bioenergy) options are reduced.

Figure 15
(a) Bioenergy land cover, (b) forest land cover, (c) CO_2 emissions from fossil fuel combustion and industry (FF&I) and (d) CO_2 emissions from land use change in baseline scenarios.



6.3 Economic growth and fossil fuel scarcity can both stimulate green investments

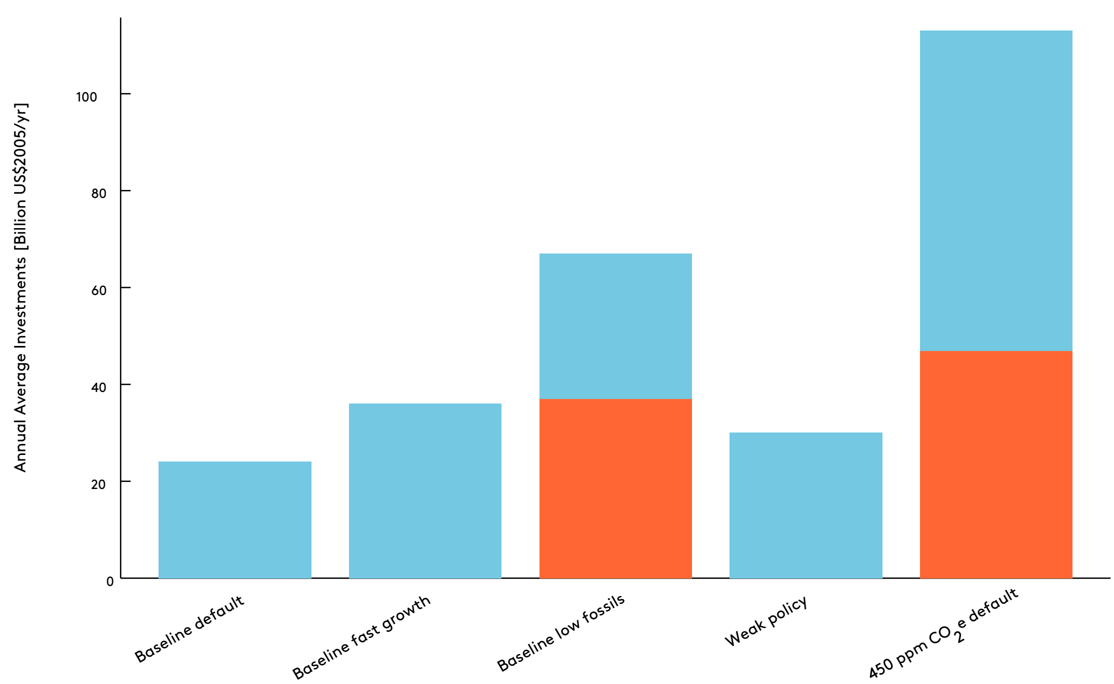
Economic growth stimulates green investments, as more resources become available to invest in clean energy and innovation options (renewables, energy efficiency), but it also increases investment in conventional, fossil technologies. High economic and/or population growth exerts a pressure on energy demand, raising the relative prices of energy to capital. The change in relative prices induces a more efficient use of energy resources, mostly via capital-energy substitution.

Faster convergence across countries also leads to a more efficient use of energy inputs globally. On the one hand, faster convergence increases aggregate energy intensity by raising the weight of energy intensive developing countries. On the other hand, faster convergence improves the use of energy resources via efficiency R&D and capital-energy substitution. This second effect prevails, and overall energy intensity is lower when convergence is faster.

High fossil fuel prices create an economic opportunity for decarbonizing the energy mix even in the absence of a climate policy. In particular, oil scarcity can provide incentives to invest in invention and deployment of a clean substitute to oil on a large scale. When fossil fuel resources are expected to become scarce throughout the century, ample financial resources (in the order of 40 billion USD/yr as estimated in the WITCH model) will be redirected to R&D projects aimed at developing viable new energy sources (Figure 16). Developed countries will provide between half and two third of the global financial flows to R&D programs. The availability of cheap gas resources would increase gas investments, mostly to substitute coal in coal-intensive countries. Yet, it would only marginally displace investments in renewables and clean energy innovation. The R&D sector would continue to attract on the order of 10% of total energy investments.

Although economic growth and fossil fuel prices can create an economic opportunity for more investments in non-fossil energy technologies and clean energy R&D, those investments do not induce emission reductions compatible with climate stabilization objectives. Only the simultaneous expectation of oil, gas, and coal scarcity could set the per capita emission-GDP relationship on a path that mimics a scenario with moderate and fragmented climate policies.

Figure 16
Annual average investments throughout the century.



RoSE

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