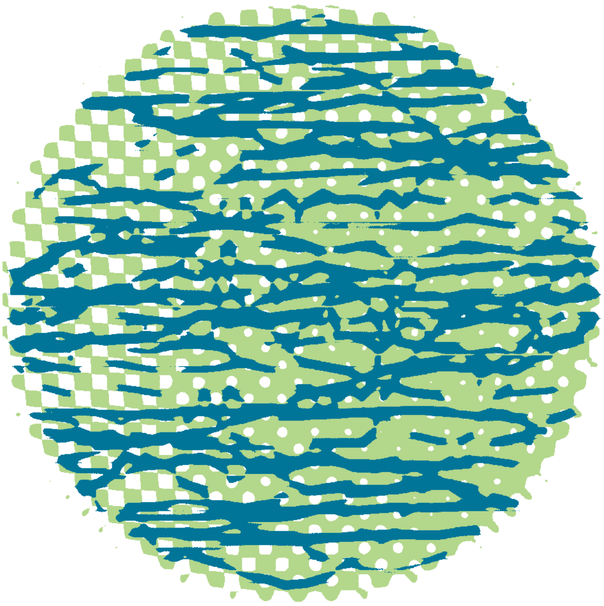

AMPERE

Assessment of Climate Change Mitigation Pathways
and Evaluation of the Robustness of Mitigation Cost Estimates

Assessing Pathways toward Ambitious Climate Targets at the Global and European Levels

A synthesis of results from the AMPERE project

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For more information on AMPERE please visit
http://ampere-project.eu

To access the AMPERE scenario database please visit
https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB

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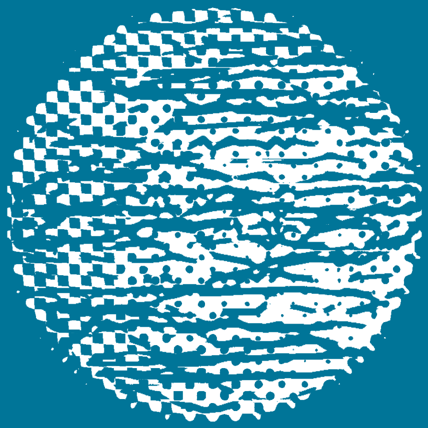


KEY FINDINGS

1) Global progress to reduce greenhouse gas emissions over the next two decades is crucial for achieving ambitious climate targets at low costs

Cumulative CO_2 emissions ('carbon budget') play a dominant role in future climate change. Limiting climate change to levels in the order of 2°C requires restricting future cumulative CO_2 emissions to a tight carbon budget. The likelihood of staying within such a tight budget depends strongly on the stringency of near-term climate policies over the next two decades. According to the AMPERE analysis, the bulk of the overall CO_2 emission budget needed to limit warming to 2°C may already be vented into the atmosphere by 2030 if climate policies remain consistent with current international pledges. Clearly, this lack of early mitigation will need to be compensated by even deeper emission cuts in the long term to stay within the budget.

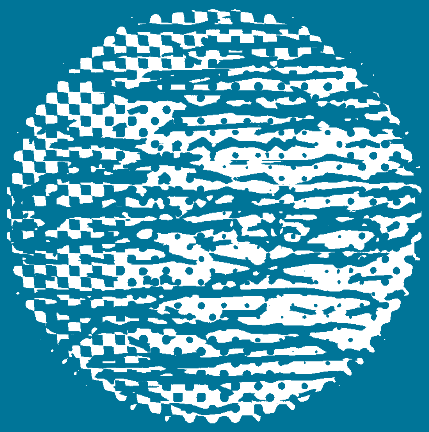
Climate policy over the next two decades has thus fundamental implications for the pace, cost, and attainability of the global energy transformation required to achieve the 2°C target. Even with immediate and strong international action, the global energy system will need to transform extremely rapidly. A lower stringency of climate policy over the next two decades would increase the required speed of the transformation in the following decades even more. Specifically, weak near-term climate policies will entail an unprecedented shift to low-carbon energy technologies, increased reliance on controversial or unproven technologies (e.g., CCS), higher overall mitigation costs, and larger risks of failing to meet climate targets.

2) Europe can signal the will for strong emission reductions – with large climate benefits if others follow

Current climate policies are insufficient for reaching stringent climate targets, and the prospects for an ambitious international climate agreement by 2015 are uncertain. However, the diverse landscape of domestic climate action may be laying the ground from which stronger climate policies could emerge. Countries face a trade-off between higher near-term costs in the case of early action and larger transitional economic impacts if action is delayed. Europe can signal its will to achieve ambitious climate targets by implementing stringent emission reductions domestically without waiting for others to strengthen their climate policy. We find that unilateral action by Europe along the lines of the EU Low Carbon Economy Roadmap is affordable. The roadmap is projected to bring only limited cost mark-ups relative to the EU reference policy, and carbon leakage is estimated to be small as long as other major emitters pursue at least moderate climate policies. Furthermore, significant climate benefits will accrue if other major emitters begin matching the EU ambition in the next two decades.

3) Decarbonisation holds challenges and opportunities for Europe

Strong leadership on climate change mitigation holds challenges as well as opportunities for Europe. Reducing emissions by at least 80% below 1990 levels by 2050 is only feasible if a strong emissions reduction target is set for 2030 in order to provide a clear signal for low-carbon technology investments and to avoid further carbon lock-in. Most importantly, the feasibility of European decarbonisation depends on energy system transformations toward carbon-free electricity, energy efficiency and transport electrification. Policies that promote progress in these areas create opportunities in some economic sectors and increase costs and reduce demand in others. Thus, strong climate action has a mixed impact on output and employment in the various economic sectors. However, if other world regions start decarbonising at a later point, Europe would gain a first mover advantage from being able to export its technological advancements in clean energy technologies induced by decarbonisation.



1.

THE AMPERE PROJECT

Research objectives and scope

The AMPERE project aims to improve our understanding of possible pathways toward medium- and long-term climate targets at the global and European levels. AMPERE is an EU-funded international effort that stands for *Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates*. The project assesses key aspects of the mitigation challenge in a world of delayed and fragmented climate policy:

- What amounts of future emissions are consistent with specific long-term climate targets, taking into account the latest findings on climate feedbacks, the carbon cycle, and the dynamics of energy-land transformations?
- How do short-term climate policies impact the achievability of long-term climate targets?
- What are the economic implications and climate benefits of unilateral mitigation by a first mover followed by delayed global action?
- What are the costs and benefits of potential European Union climate targets for 2030 and 2050, and what are the roles of different technologies?

AMPERE compares and analyses results from a wide range of internationally recognised energy-economy and integrated assessment models with different structures and functions. The diversity of these models can offer particularly robust insights because it allows us to identify areas of uncertainty where model results differ widely as well as areas where models from across the spectrum concur. In addition, AMPERE puts an emphasis on diagnosing model behaviour and assessing model validity to improve our understanding of the differences between models and of how model-based analysis can best be used to inform policy makers.

Establishing a European Modelling Platform

The AMPERE consortium comprises 22 institutions from Europe, Asia and the United States. It combines the capabilities of 17 energy-economy and integrated assessment models. The close collaboration among European and international modelling teams in AMPERE has helped to establish a unique European Modelling platform for coordinated future research efforts.

Achievements

AMPERE has conducted a number of model comparison studies on the implications of short-term climate action for the achievability of long-term targets, the implications of regional climate policies and staged accession to a global climate regime, the climate response to a large range of emissions scenarios, the costs and benefits of the climate policy options faced by the European Union, and model diagnostics. The results have been published in a number of papers in academic journals (see list in the back of this policy brief) among which most are contained in a special issue of the international journal *Technological Forecasting and Social Change*. A database of the scenarios used in the AMPERE studies is available at *https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB*. These scenarios and the AMPERE findings have contributed to the assessment of mitigation pathways in the IPCC 5th Assessment Report.

An important focus of AMPERE has been on model diagnostics and evaluation, and the use of modelling results for policy advice. To this end, AMPERE has conducted several expert and stakeholder workshops on model evaluation, diagnostics, technological learning and the model-policy interface.

AMPERE's contribution to the research on climate mitigation pathways

AMPERE has been among the largest international community projects in the field of integrated assessment in the period 2011-2013, and established close links with concurrent modelling comparison projects such as the Stanford Energy Modeling Forum Studies 27 and 28, the EU funded LIMITS project and the US DOE-funded PIAMDDI project. AMPERE's research agenda has provided important new insights that can be built upon by community platforms such as the Integrated Assessment Modeling Consortium (IAMC) and future research projects.

Brief Overview of AMPERE

Duration: February 2011 – January 2014
Funding: 3,149,490 € from the EU Seventh Framework Program (grant agreement n° 265139)
Project coordinator: Elmar Kriegler, Ottmar Edenhofer (Potsdam Institute for Climate Impact Research)
Steering committee and work package leaders: Valentina Bosetti (FEEM), Pantelis Capros (ICCS), Keywan Riahi (IIASA), Elmar Kriegler (PIK), Detlef P. van Vuuren (UU)
Project Manager: Nils Petermann (PIK)
Consortium: See page 4
Scientific Advisory Panel: Ged Davis (Forescene SA), Karen Fisher-Vanden (Pennsylvania State University), Hans ten Berge (EURELECTRIC), John Weyant (Stanford University)

Models involved in the AMPERE studies

Model name	Institute	Model category	Time horizon	Regional coverage
REMIND	PIK	Energy system – GE growth model	2100	World
MESSAGE-MACRO	IIASA	Energy system – GE growth model	2100	World
WITCH	FEEM	Energy system – GE growth model	2100	World
MERGE-ETL	PSI	Energy system – GE growth model	2100	World
IMACLIM	CIRED	Computable GE model	2100	World
GEM-E3	ICCS, IPTS	Computable GE model	2050	World
WorldScan	CPB	Computable GE model	2050	World
IMAGE/TIMER	UU/PBL	Energy system PE model	2100	World
POLES	EDDEN, IPTS, Enerdata	Energy system PE model	2100	World
TIMES-PanEU	IER	Energy system PE model	2050	EU27
PRIMES	ICCS	Energy system PE model	2050	EU27
Green-X	EEG	Renewable energy system PE model	2050	EU27
GAINS	IIASA	Bottom-up assessment of mitigation potentials, costs and co-benefits	2030	EU27
NEMESIS	ERASME	Econometric model	2030	EU27
AIM-Enduse	NIES	Energy system PE model	2050	World
DNE21+	RITE	Energy system PE model	2050	World
GCAM	JGCRI	Energy system PE model	2050	World

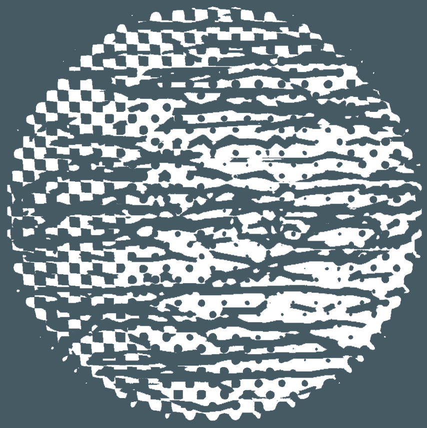
Abbreviations: GE = General equilibrium; PE = Partial Equilibrium. All models calculate carbon dioxide emissions from the combustion of fossil fuels, and most of them include other greenhouse gas emissions from the energy sector. Integrated assessment models that incorporate land use emissions and climate response are highlighted in red.

ENERGY-ECONOMY AND INTEGRATED ASSESSMENT MODELS

What are they? Energy-economy models describe the energy system in physical and economic terms. They include information about the amount and type of energy resources, energy technologies and energy uses, as well as about energy investments and prices. Some of them trace the use and value of energy in the economy (general equilibrium models), others put greater emphasis on a detailed description of the energy sector (partial equilibrium models). Integrated assessment models (IAM) add a description of greenhouse gas emissions, including land-use related emissions, and the associated climate response. The IAMs used in AMPERE focus on the analysis of how energy and land use would need to be transformed to reach long-term climate targets, and need to be distinguished from IAMs which much smaller detail that aim to provide an integrated assessment of climate mitigation and residual climate damages in a cost-benefit setting. The AMPERE models come with different sectoral, regional and temporal coverage (see table on AMPERE models).

What can they tell us? Energy economy and integrated assessment models do not foretell the future. Rather, they are tools to explore consequences of different courses of action in a range of plausible environments. As such they are akin to maps that can be used by policy makers to compare and navigate different paths towards reaching long-term climate targets. They share many features of maps. For one, they are not mirror images of reality, but abstractions of key features that are relevant for navigation. They may be imperfect and in strong need of improvement, but will be useful as long as navigation is served better with than without them. If maps are known to be imperfect, it will help to consult a number of them to identify robust and uncertain features of the landscape ahead. This is the added value of model intercomparison exercises such as those conducted by AMPERE. The multiplicity of results and assumptions can help policy makers to identify potential risks and warn against too much confidence in a single number or set of actions. Finally, maps come at different levels of resolution and coverage, and thus it is important to use the right type of map for the location to be navigated. The domain of application of the AMPERE models is long-term policy targets (2050 or beyond) on a large regional to global level, and their relationship to climate action in the coming two decades.

How much can we trust them? The AMPERE project has recognized the need for a more systematic investigation of how good energy economy and integrated assessment models have become to serve their purpose. To this end, we conducted a number of workshops on model evaluation and diagnostics together with the US DOE-funded PIAMDDI project. In their role as maps about consequences of future actions, models cannot be proven right by reproducing historical patterns or events. However, lessons about needed improvements can be learned from instances where models get it wrong. Such behaviour tests contribute to the continuous process of building trust in models, but are only a part of it. This process also includes proper documentation of model developments, a sound understanding of model behaviour, and continued model applications in policy oriented and diagnostic settings. AMPERE has invested in all of these areas. Particular progress was made on diagnosing model behaviour. A classification of models has been established in terms of moderate vs. strong emissions reductions in response to carbon pricing, and low vs. high economic impact of carbon taxes that serves to better understand model differences in mitigation cost estimates.



2.

GLOBAL PROGRESS TO REDUCE GREENHOUSE GAS EMISSIONS OVER THE NEXT TWO DECADES IS CRUCIAL FOR ACHIEVING AMBITIOUS CLIMATE TARGETS AT LOW COSTS

2.1 Closing the gap between current policies and climate stabilisation requires adherence to a tight emission budget

In the absence of future climate policy, greenhouse gas emissions are expected to rise. The AMPERE models project a global mean warming of 3.5–5.9°C above pre-industrial levels by 2100 depending on the uncertainty in emissions and climate parameters. Following a path based on extrapolation of the current international emission reduction commitments will result in some progress in limiting GHG emissions (Figure 1). Model calculations suggest that emissions would stay above current levels, resulting in a global mean temperature increase of 3.2–3.8°C (Figure 7). Furthermore, temperature would continue to rise over the 22nd century given this emission trajectory. Limiting warming to 2°C would require that global emissions are essentially phased out over the course of the century and, depending on the level of GHG emissions over the next two decades, may even need to become negative by 2100.

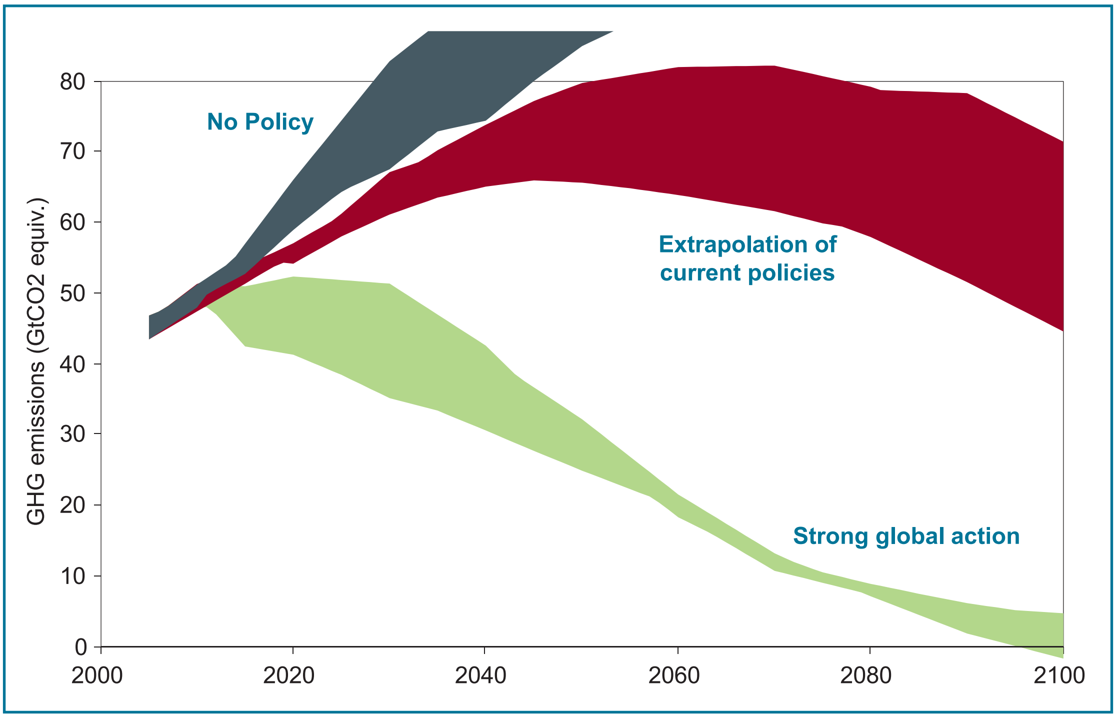


Figure 1: Comparison of GHG emission scenarios simulated by the AMPERE models. "No policy" shows the emission growth in a world without climate policy; "Extrapolation of current policies" indicates possible emission outcomes assuming that current emission reduction targets for 2020 are extrapolated through the century (see Figure 6); "Strong global action" shows possible emission pathways assuming immediate global action to limit warming to 2°C above pre-industrial levels.

Carbon dioxide is by far the most important greenhouse gas. Because of its long lifetime, restricting the increase of global mean temperature to around 2°C requires limiting cumulative emissions to a strict budget. Determining exact budgets is complicated by uncertainties over factors like climate sensitivity and the carbon cycle. Calculations in the AMPERE project and other work indicate that in order to limit global warming to 2°C with high likelihood, the remaining carbon budget for the 21st century is about 1000 Gt CO_2. This is equivalent to fewer than 30 years of current global emissions.

2.2 Delayed action until 2030 requires an unprecedented and more costly transformation of the global energy system in the following decades

Given the limited carbon budget associated with restricting warming to 2°C, any additional emissions resulting from reduced policy stringency until 2030 would need to be compensated by steep emission cuts in the future (Figure 2). We find that the majority of this compensation must occur over a relatively short timeframe (2030 to 2050). Thus, weak near-term policy greatly increases the speed at which emissions must later be reduced. For example, if the world continues its current path of moderate climate action until 2030, staying within an emission budget for 2°C would require global CO_2 emission cuts of 6-8% per year in the decades between 2030 and 2050 (Figure 3). This is in contrast to the 2% *growth* per year in global CO_2 emissions realised over the last decade. Achieving such rapid emission cuts using policy interventions would be historically unprecedented, even at the national scale. It would require the portion of global energy supplied by low-carbon options (renewables, nuclear, and fossil fuels combined with CCS) to quadruple in the two decades between 2030 and 2050 (Figure 3). This means that almost half the global energy supply infrastructure would require replacement over a narrow two decade period.

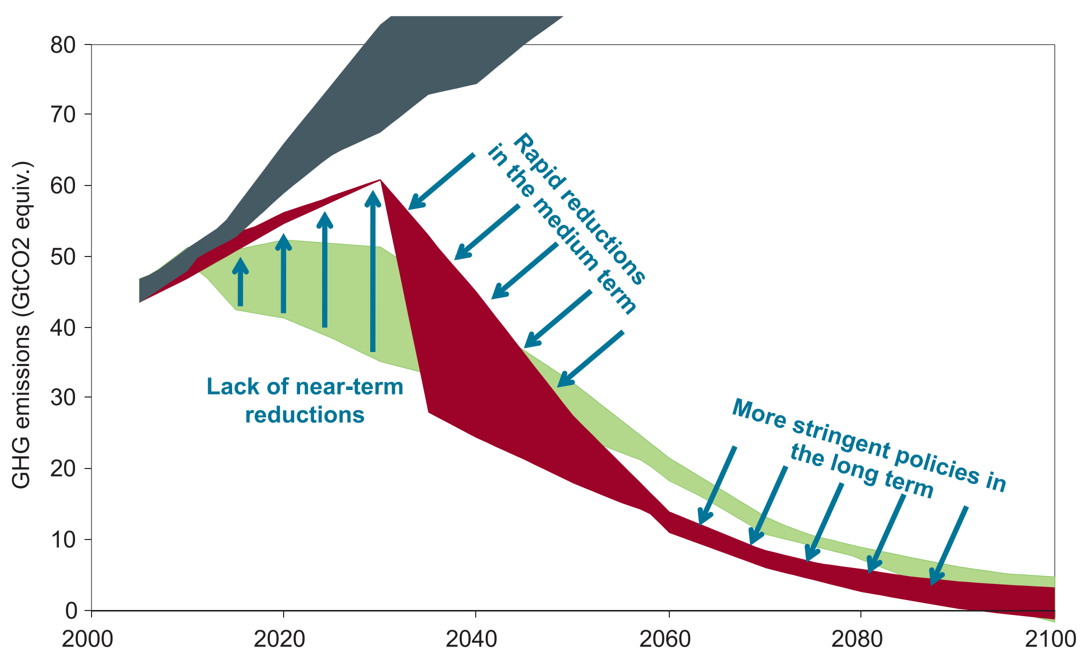


Figure 2: *GHG emission pathways necessary to stay within the budget for limiting warming to 2°C above pre-industrial levels. The optimal emission pathway with immediate action is shown in green and the emission pathway needed if strong international action is delayed until 2030 is shown in red. The emission pathway with no climate policy is shown in grey.*

Such a rapid transformation of the energy system poses a significant challenge to achieving the long-term climate target. Not only would the deployment of low-carbon technologies be unprecedented, but the transformation would also require the early retirement of carbon-intensive infrastructure and lead to larger climate mitigation costs. Delayed policy action is projected to increase mitigation costs by 10-40% relative to a scenario with immediate policy action, and some AMPERE models indicate that the transformation might even get out of reach under delay. However, even with immediate policy action, the energy system transformation between 2030 and 2050 required to limit warming to 2°C will be enormously challenging, requiring a doubling of the portion of energy supplied by low-carbon options and average global CO_2 emission cuts of 3-4% per year (Figure 3).

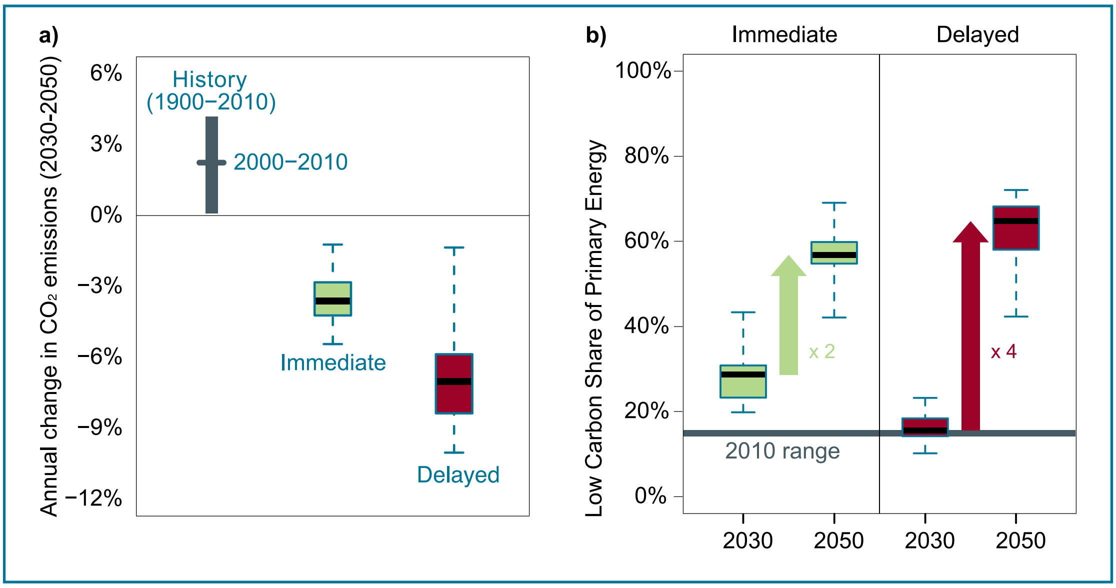


Figure 3: *Comparison of delayed and immediate action scenarios for limiting warming to 2°C. Panel (a) illustrates the required annual CO_2 emission reduction rates and panel (b) indicates the required upscaling of low carbon energy supply. Historical annual CO_2 emission change rates from 1900 to 2010 (sustained over 20-year periods) are shown in grey in panel (a). Boxplots indicate the range and distribution of model results (black line = median).*

ASSESSING THE ROLE OF TECHNOLOGICAL CHANGE

The AMPERE study conducted a systematic sensitivity analysis of the role of technology in achieving long-term climate targets under varying stringency of near-term climate policy and found that technologies and technological change play a crucial role. As the introduction of an emission constraint changes the merit-order of the energy production and conversion technologies to favour those with fewer emissions, it induces new dynamics in terms of the relative deployment of technologies and, therefore, the rate at which these technologies improve through learning effects.

Technological change occurs through two main channels: learning-by-doing and learning-by-searching. Learning-by-doing occurs when experience gained during the deployment and operation of new technologies leads to reductions in their capital and operating costs. By contrast, learning-by-searching occurs through research and development (R&D) activities. The challenge for the assessment models used in AMPERE is to simulate the impacts of such phenomena, in spite of major uncertainties due to the intrinsically stochastic character of invention and innovation.

The AMPERE analysis indicates that learning effects have the potential to decrease the average cost of supplying energy with low-carbon technologies over time. Many of the AMPERE models use learning curves to simulate the impacts of learning on the cost and performance of technologies. To improve the modelling of technological change, AMPERE convened a technology modelling workshop in conjunction with the EU-funded ADVANCE project. The ADVANCE project will continue to direct efforts at advancing the representation of technologies in integrated assessment models.

2.3 Delayed action until 2030 increases reliance on specific mitigation options

If strong international policies are delayed until 2030, our ability to limit warming to 2°C relies increasingly on the availability of specific mitigation technologies. In particular, carbon capture and storage (CCS) and the large-scale deployment of bioenergy appear crucial. Without CCS, for example, the number of models that find the 2°C target feasible decreases substantially if action is delayed until 2030. CCS plays a central role in delay scenarios because, in combination with bioenergy, it allows for negative emissions as CO_2 extracted from the atmosphere by plants used for bioenergy is buried underground. However, the feasibility of applying this option on a large scale is unclear due to uncertainties regarding long-term geologic storage of CO_2 and the competition between bioenergy and food production for arable land. Delays in mitigation thus narrow policy choices and increase technical and economic risks of ambitious climate targets becoming infeasible.

Technological limitations also amplify the impact of delay on mitigation costs. As mentioned in the previous section, if the full range of mitigation technologies is available, a delay of strong international policies leads to mitigation costs across the 21st century that are 10-40% higher than if strong policies are immediately implemented.[1] However, if the potential of solar and wind energy, CCS and/or bioenergy is limited, mitigation costs can significantly increase and the 2°C target becomes unattainable in an increasing number of models (Figure 4). On the other hand, the AMPERE analysis clearly shows the benefits of energy efficiency improvements, which can reduce the cost of mitigation significantly.

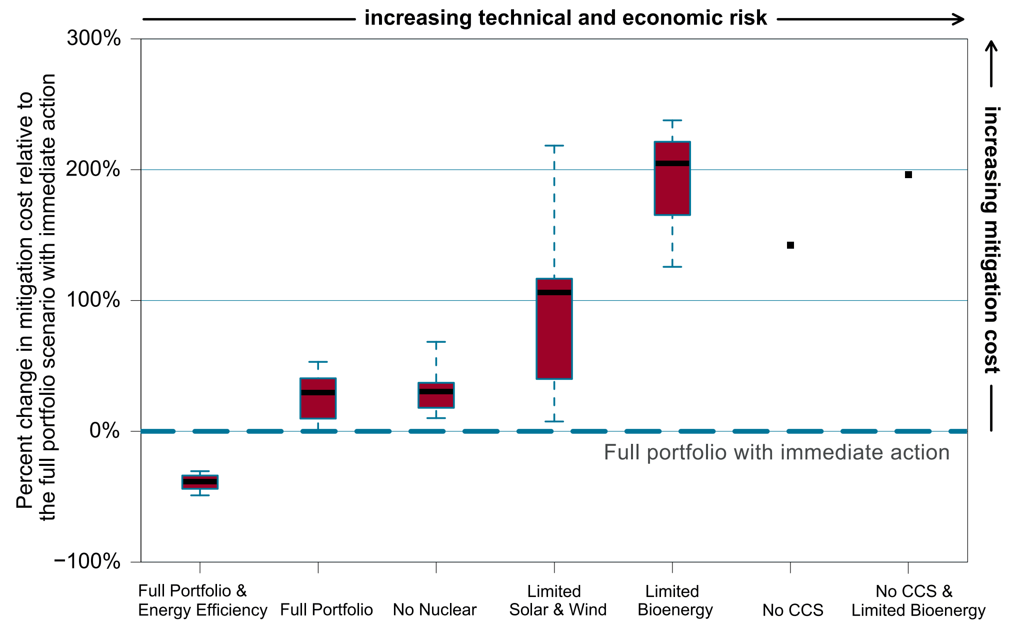


Figure 4: *The impact of technology availability combined with delayed climate action on the mitigation cost associated with a 2°C target. Technical and economic risks increase as a larger number of models are unable to achieve the target under the specific technology assumptions. Boxplots indicate the range and distribution of model results (black line = median). Scenarios without ranges indicate that only one full-century model was able to achieve the 2°C target with both delayed action and the associated technology limitation.*

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[1] We use a discount rate of 5% per year for comparing the net present value of mitigation costs with immediate versus delayed climate action.

2.4 New investments in coal-fired power plants without carbon capture and storage (CCS) should be avoided, if ambitious climate goals are to be achieved.

Today's energy planners are making investment decisions worth hundreds of billions of dollars. Given the long lifetime of energy supply infrastructure, it is important that near-term policies reflect long-term climate objectives to ensure smart investment decisions. Weak near-term climate policies could lead to further expansion of carbon-intensive technologies, such as coal-fired power plants. The AMPERE analysis shows that this expansion would be inconsistent with limiting warming to 2°C, which would entail the rapid phase-out of coal-fired power generation without CCS after 2030. Thus, in a strong mitigation scenario a large fraction of any new coal capacity built over the next two decades would likely need to be shut down prematurely (Figure 5). To prevent hundreds of gigawatts of coal-fired power plants from becoming stranded assets, near-term policies would have to discourage the construction of new coal power plant capacity without CCS.

Preventing stranded coal capacity is especially crucial in emerging economies where most new capacity is added, but also in Europe where the replacement of old capacity is being considered. The best strategy for reducing stranded coal assets is to avoid construction of new coal power plants, either by keeping existing capacity operating or, ideally, replacing old capacity with low-carbon generation. Another strategy is to retrofit plants with CCS once more stringent climate policy is adopted. However, this option would only be effective if retrofits and the associated CCS infrastructure can be deployed extremely rapidly. Given that CCS is technically challenging and politically controversial, it is uncertain whether CCS retrofits will be able to ramp up quickly enough and at sufficient scale to significantly mitigate stranded capacity. To reduce the uncertainty, it is important to ramp up R&D investments and to establish regulatory and legal frameworks that will facilitate rapid CCS deployment as soon as possible.

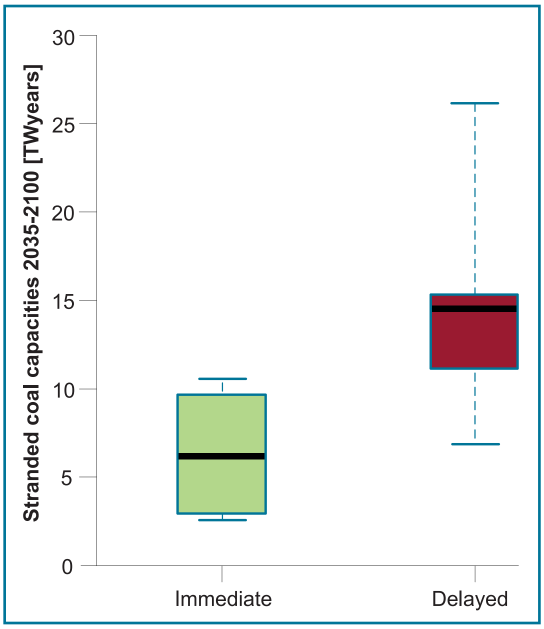
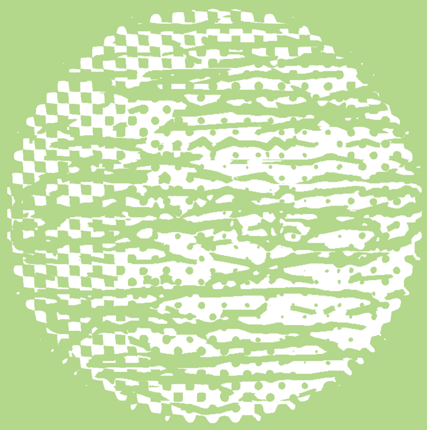


__Figure 5:__ Stranded coal capacity after 2035 in the case of immediate strong international climate action (green box) and in the case of delayed action until 2030 (red box).



3.

EUROPE CAN SIGNAL THE WILL FOR STRONG EMISSION REDUCTIONS – WITH LARGE CLIMATE BENEFITS IF OTHERS FOLLOW

3.1 International climate policy remains uncertain despite some movement by major emitters

Governments have agreed to work towards a comprehensive international climate change agreement by 2015, but due to questions of how to coordinate international efforts, it may prove difficult to overcome the fragmented nature of global climate policy. Despite the slow pace of international negotiations, there has been a significant increase in adoption or discussion of domestic policies for clean energy support and carbon pricing among major emitters. For instance, sub-national carbon pricing mechanisms have emerged in Canada, China, and the USA, while national carbon pricing policies are scheduled for implementation in South Africa and South Korea and have been implemented at least temporarily by Australia. Regulatory measures, such as proposed emission standards for power plants in the USA and clean energy support in many countries, add possible momentum. While current efforts are insufficient for reaching stringent climate targets and political obstacles remain significant, the diverse landscape of domestic policies may be laying the ground on which stronger climate policies could flourish if backed by political will. The European Union is debating its emissions reduction goal for 2030, which depending on the outcome could provide a signal for other countries to strengthen their efforts.

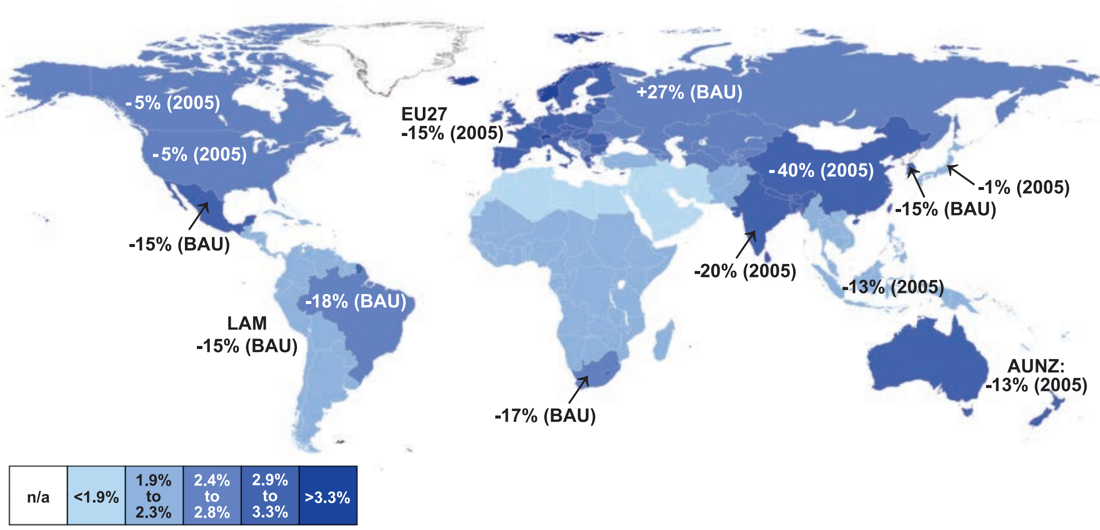


Figure 6: *Climate actions in major world regions assumed for the AMPERE reference policy scenario. The numbers shown are assumed emission reduction targets for 2020 relative to 2005 or to the no policy baseline (BAU). In the case of China and India, the numbers refer to GHG intensity reductions. These 2020 targets are largely based on the pledges made by major emitters at the Copenhagen climate summit in 2009 but are weakened in cases where the implementation of needed policies remains uncertain (such as in the USA and Canada). The regional colouring indicates the assumed annual improvement of the GHG intensity of economic output after 2020.*

WHAT TYPES OF POLICIES ARE ASSUMED IN THE AMPERE MODELLING?

The AMPERE studies are designed to take into account the most important aspects of current national and regional climate policy aspirations, but our modelling assumptions necessarily simplify the implementation of such policies. Most AMPERE models rely on an idealised setting of functioning energy and land markets and full sectoral coverage of policies that lead to emission reductions where they are most efficient. Furthermore, our aggregation of countries into modelling regions – e.g. EU27 or Southeast Asia – does not reflect policy fragmentation within a region. Such simplifications are practical not only because they facilitate the modelling process, but also because it allows us to study future policy scenarios without having to assume the exact choice of policy instruments at the national level.

The AMPERE reference scenario aims to provide a plausible representation of a world that continues to follow the current path of regionally fragmented climate policies (Figure 6). For this, we assume that the EU and several other countries fulfil their emission reduction or emission intensity pledges made at the Copenhagen climate summit, whereas some countries only achieve smaller reductions if their current policies appear to not match their pledges. Independent of the emission reduction targets, the AMPERE studies also reflect ongoing energy technology deployment efforts such as the EU's 20% renewable energy target for 2020 or similar efforts in other world regions. With the exception of such technology policies, AMPERE assumes least cost mitigation strategies, which implies a long-term reliance on carbon pricing coupled with efficient revenue recycling schemes.

Although the AMPERE studies assume a central role for carbon pricing, it is not our intent to specify whether this is implemented through an emissions constraint (as in a cap & trade regime) or as a carbon tax. However, when studying carbon leakage from unilateral EU climate action, we assume that emissions in other world regions are not capped, so that we can observe how emissions outside of Europe respond to EU policies.

The AMPERE scenarios are implemented so that investment decisions do not anticipate policy changes over time. Once mitigation targets and carbon prices are set, however, our modelling assumes that these policies are seen as credible and durable and thus fully impact investments.

3.2 A strong climate policy signal by the European Union reciprocated by other major emitters can effectively limit global warming

A choice of the European Union to continue its ambitious climate policy agenda can have multiple benefits on an international level. It could help with achieving a meaningful global agreement in 2015, which – as discussed in the previous section – may be instrumental in keeping the option of limiting global warming to 2°C on the table. But even if this proves illusive, front-runner action by the European Union could reduce global warming substantially if it succeeds with inducing the other major emitters to accede to an international climate regime by 2030. Our modelling suggests that if between 2030 and 2050, the rest of the world gradually harmonises its climate policy efforts with strong EU carbon pricing, maximum global warming during the 21st century could still be reduced by more than 1°C relative to continuing the current fragmented state of international climate policies (Figure 7). Due to the moderate action in the rest of the world until 2030 and the resulting high global emissions in the near term, global warming is likely to surpass 2°C by less than 0.5°C for a period of time. If the largest emitter China joined the EU with ambitious climate action early on, the likelihood of staying below the 2°C target would be somewhat increased. By contrast, if the rest of the world does not match the EU climate effort at a later point in time, the additional reduction of global warming due to the EU effort would be negligible. Thus, the choice of climate policy action in individual countries or regions should take into account its signalling effect for the international level.

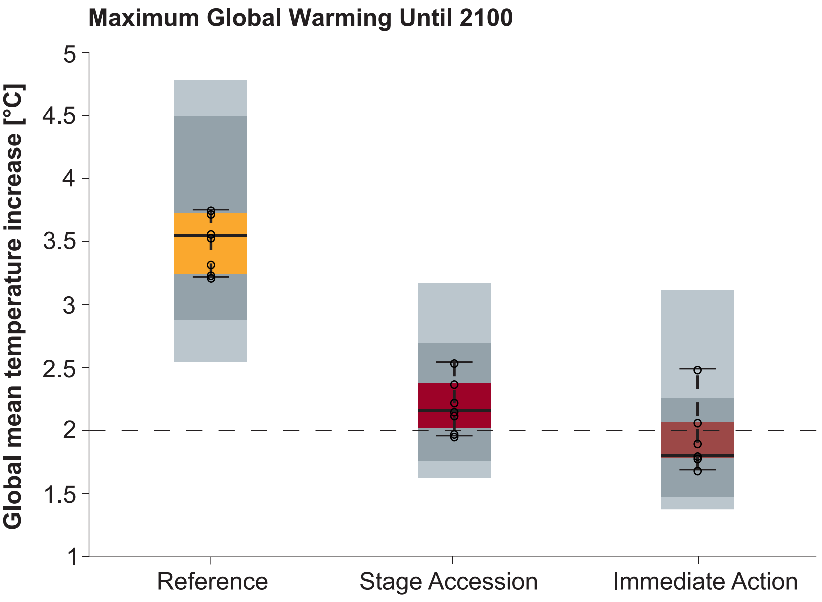


Figure 7: *Maximum global warming until 2100 for the Reference scenario (continuation of current policies) and for the staged accession scenario (Europe as a front runner joined by the rest of the world in 2030) relative to a scenario in which the world undertakes immediate action to adhere to a carbon budget that has a medium to high likelihood of limiting warming to 2°C. The boxplots are based on the projected median warming from the emission scenarios of seven different models, with the median of the seven models shown by the red line, the full range by the whiskers, and the range of the central five models by the box. The grey area shows the range of temperature outcomes including climate uncertainty (two standard deviations) that adds to the variation between emissions scenarios. Dark grey is the range for the central five models, light grey the full range.*

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2 In our scenario, we assume that the global effort over the second half of the century is equal to what it would be if the world immediately implemented a mitigation pathway toward the 2°C target.

3.3 Countries face a trade-off between early costs and later transitional challenges

As discussed in the previous section, early, credible climate policies reduce lock-in into carbon-intensive infrastructure and thus the medium- to long-term challenge of transitioning to a low-carbon economy. On the other hand, near-term costs are obviously higher if stringent climate policies are introduced early. Countries thus face a trade-off when considering the economic rationale for early versus delayed climate action. Our modelling shows that if countries outside of Europe delay strong climate action until 2030, annual consumption growth over the period of 2030 to 2050, i.e. the transition period to a stringent carbon pricing regime in our scenario, is depressed significantly stronger than if ambitious climate action was adopted early on (Figure 8). The transitional challenge due to delay is particularly pronounced in emerging economies like China, where substantial infrastructure investments are yet to be made and where early climate action can prevent very significant carbon lock-ins. On the other hand, the costs of strong near-term mitigation may also be higher for emerging economies due to their higher carbon intensity and rapidly rising baseline emissions. The overall welfare effect is different, though, where substantial co-benefits of climate policies exist. China has an immediate and strong incentive to reduce the use of coal and other fossil fuels as it is suffering from major air pollution problems.

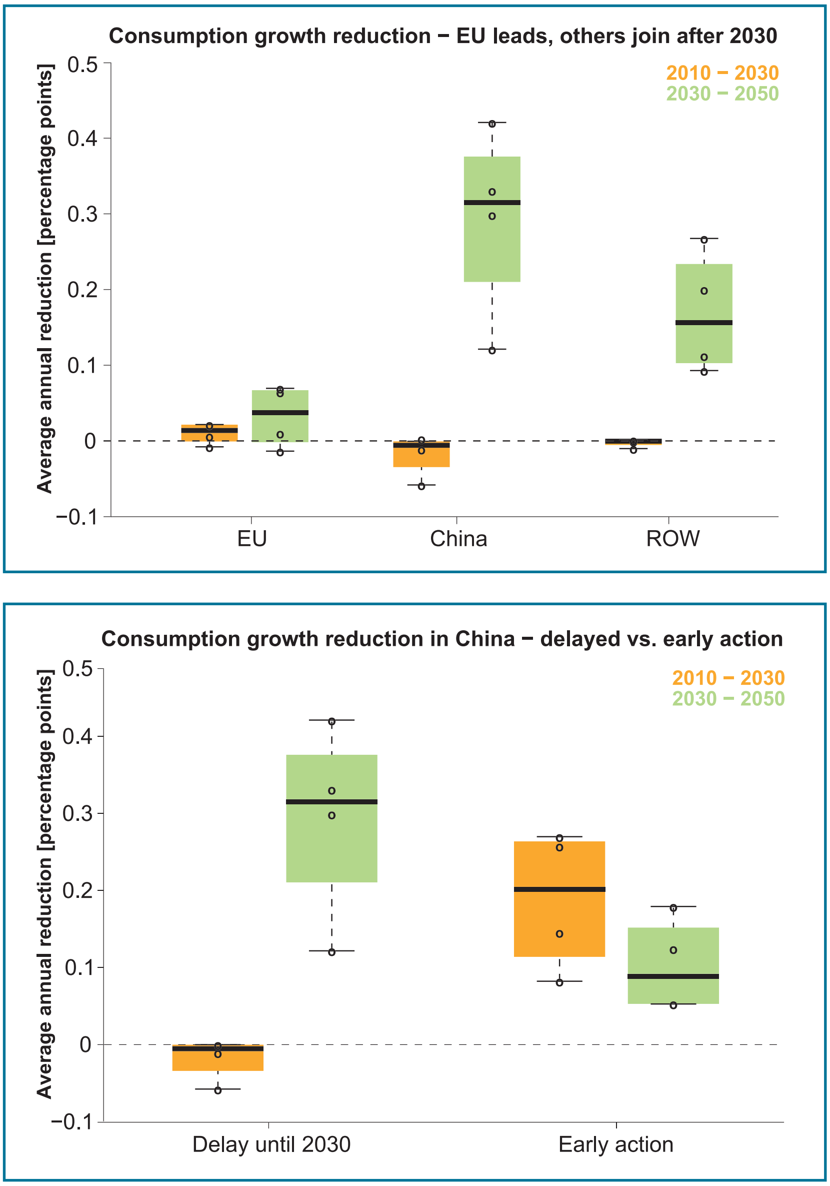

***Figure 8:** Average annual reduction of consumption growth due to stronger climate action relative to the current policies reference scenario over the 2010-2030 and 2030-2050 time frames. The top panel assumes that the EU implements strong climate polices immediately, whereas other world regions start implanting strong policies after 2030. The bottom panel compares the impacts on China of delaying strong climate policy until 2030 with implementing early action. Boxplots indicate the range and distribution of results from four models.*

3.4 Europe can send a strong climate policy signal at manageable economic cost

An outline for credible EU climate action is given by the EU's 2050 Low Carbon Economy Roadmap, which envisions emission reductions compared to 1990 levels of about 40% by 2030 and 80% by 2050. Although Europe would ideally be joined by other major emitters as early as possible, we have studied the European Union's economic costs of strengthening its climate policy unilaterally while the rest of the world does not raise its ambitions from current levels before 2030. Compared to many other regions, Europe's economy relies less on carbon-intensive sectors, and thus the costs of stringent climate policies are projected to be relatively low. According to our modelling, reducing emissions by 40% by 2030 compared to 1990, as outlined in the Roadmap, would reduce cumulative consumption by 0% to 0.8%[3] if compared to a linear continuation of current policies, which would lead to 30% emissions reduction by 2030. Overall, the results of the AMPERE studies suggest that the costs of stringent unilateral EU climate action need not be significantly higher than if the EU acted in concert with other regions.

3.5 Overall carbon leakage from unilateral European climate action is expected to be small

Higher energy prices and lower fuel demand in Europe due to unilateral climate action shifts some carbon-intensive activity to other regions. But this leakage is limited: most of the models in AMPERE find that by 2030, emissions in the rest of the world increase by at most one fifth of the additional emissions reduction by the European Union from implementing the Low Carbon Economy Roadmap instead of the reference policy (Figure 9). For most models, the leakage rate is lower yet in a scenario where China joins the EU in the front runner coalition. One study with a detailed model of the economy (GEM-E3) studied industry re-allocation and did not find a significantly higher overall leakage rate from unilateral European action among energy-intensive industries in Europe. However, more significant emissions leakage of about 30% by 2030 may occur in the chemicals and metals sectors due to their high trade exposure and production shifting outside of Europe, leading to an output reduction in these sectors of 2.5% and 2%, respectively. These findings assume that the EU does not implement policies to directly protect the competitiveness of its trade-exposed industry which can further reduce carbon leakage. Leakage from these sectors was found to be significantly reduced in the scenario of China joining early action by the EU. However, the overall cost of European decarbonisation was found to be comparable regardless of whether the EU acts unilaterally or in concert with China.

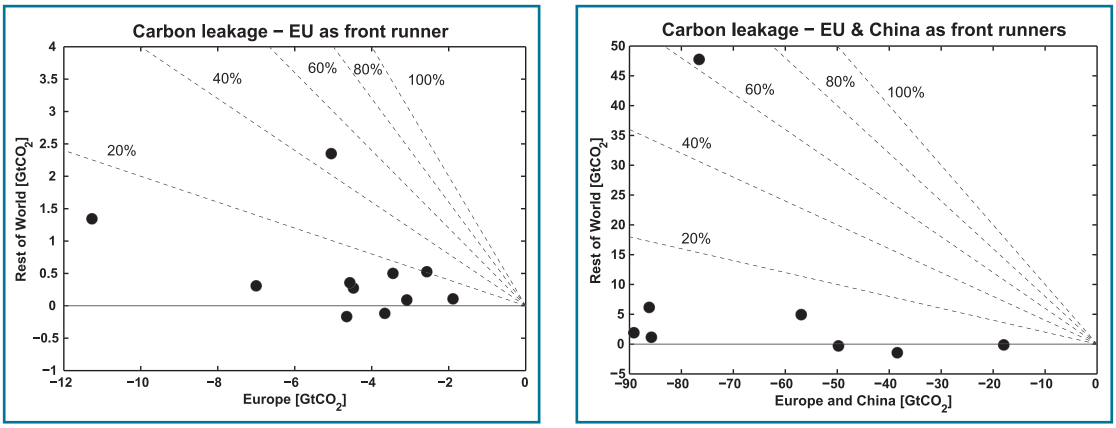

Figure 9: *Cumulative changes in fossil fuel and industry emissions for the period 2010-2030 resulting from front runner action by the EU (left panel) and by a coalition between the EU and China (right panel). The ratio of emission increases in the rest of the world relative to emission reductions in the front runner regions indicates the extent of carbon leakage. The solid line indicates a 0% leakage rate, the dashed lines a 20%-100% leakage rate. Small negative carbon leakage is shown by some models due to factors such as low-carbon technology diffusion or lower European demand for natural gas that makes it cheaper for other regions to substitute gas for coal in power generation.*

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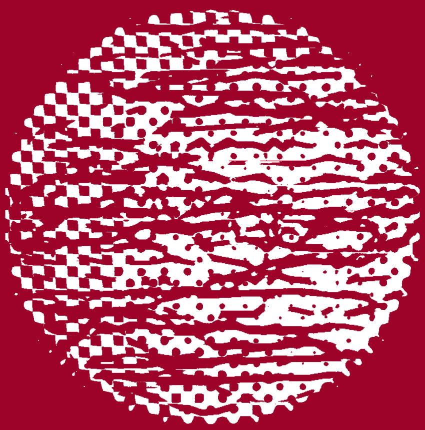
[3] Cost metrics differ between model types. In the AMPERE study, costs are calculated as consumption losses in percent of baseline consumption or GDP losses in percent of baseline GDP for general equilibrium models, and as additional energy system costs or area under the marginal abatement cost curve relative to baseline GDP for partial equilibrium models of the energy sector. Net present value costs presented in this section are calculated using a discount rate of 5% per year.



4.

DECARBONISATION HOLDS CHALLENGES AND OPPORTUNITIES FOR EUROPE

4.1 The European Union's decarbonisation strategy requires strong 2030 targets

Successful implementation of the EU Low Carbon Economy Roadmap, which aims to achieve an 80% reduction in GHG emissions from 1990 levels by 2050, requires a clear signal for clean energy technology investments in order to avoid further carbon lock-in. Over the coming years, substantial infrastructure with a lifetime of several decades needs to be built or replaced in the EU. Thus, giving a clear signal for low-carbon investments now can avoid costly changes in subsequent decades. To this end, the Roadmap and the AMPERE modelling studies suggest GHG emission reductions by 2030 of at least 40% from 1990 levels as a cost-effective milestone, while both renewable energy penetration and energy efficiency progress must accelerate considerably beyond the 2020 commitment. This also implies accelerating the EU emissions trading system cap reduction after 2020 (significantly faster than the current stipulation of 1.74% per year on average).

Increasing the stringency of European climate policy to 40% reductions by 2030 from its current reference policy pathway (which projects about 30% reductions by 2030) can be achieved at moderate additional costs in the period 2010-2030, as discussed in the previous section. If the full range of technological mitigation options is available. Delaying strong climate action until 2030 implies a very steep emissions reduction pathway for the EU after 2030, stresses the system capabilities for decarbonisation and leads to high decarbonisation costs if meeting the carbon budget is supposed to take place in the period 2030-2050. According to the EU energy system models (PRIMES, TIMES-PanEU) used in AMPERE, this increases cumulative 2010-2050 energy system costs by 0.4-0.6 percentage points of GDP compared to the optimal non-delaying decarbonisation scenario as a result of higher abatement efforts after 2030, lock-ins in the energy sector and delays in learning progress for mitigation technologies (Figure 10).

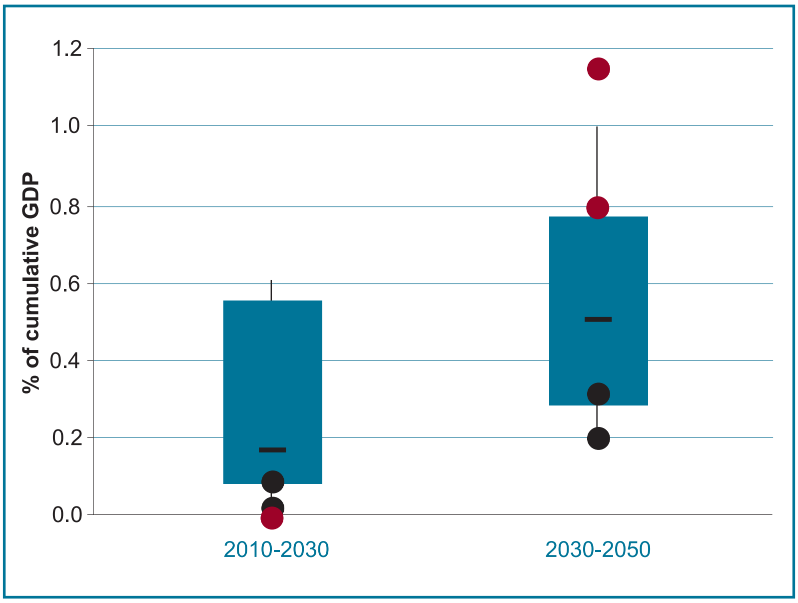


Figure 10: *Mitigation costs for the EU in the full technology availability non-delay decarbonisation scenario relative to the reference (boxplots show the range and distribution of model results, with the black line the median). Results are from regional models of the EU27. Cost estimates of global models are reported in Section 3. No discount rate is assumed. Two of the models (PRIMES and TIMES-PanEU) have run both the EU Roadmap scenario without delay and a scenario in which strong policy is delayed until 2030. The results for these models are indicated by dots: black dots for the scenario without delay and red dots for delay until 2030.*

4.2 Carbon-free electricity, energy efficiency and transport electrification are critical for decarbonisation of the EU energy system

The AMPERE study suggests that the long-term EU decarbonisation target (-80% in GHG emissions by 2050 relative to 1990 levels) is feasible with currently known technologies at relatively low costs. Model results show that decarbonisation of the European energy system can largely be induced by strong carbon pricing as a technology-neutral policy signal that facilitates the efficient distribution of abatement efforts across countries and sectors. However, fully developing the potential for profound structural changes in the energy system would require additional policies such as R&D investments in low carbon technologies, market coordination for timely development of infrastructure (grids, smart metering systems, carbon sequestration, battery recharging infrastructure, energy demand management) and overcoming market and non-market barriers to energy efficiency and renewable energy deployment. The combined results of the AMPERE models suggest key mitigation priorities for Europe in order to achieve the decarbonisation target at limited cost:

- Decarbonisation of power generation and substitution of fossil fuels with electricity in stationary final energy demand
- Transport electrification
- Acceleration of energy efficiency improvements

Carbon-free power generation can be supplied by a range of technological options. Models show that intermittent renewable energy combined with storage and gas-fired capacity (for load balancing and reserve) is likely to be the central option, whereas nuclear power and CCS are critical only if strong climate policy is delayed until 2030. Since low and carbon-free options are limited outside of the electricity generation sector, the electrification of final energy use in households, industrial sectors and transportation is crucial. Energy efficiency improvements are a central factor to contain the costs of decarbonisation, both in the short and long term.

Non-availability of some decarbonisation options implies an increase in marginal abatement costs, as the remaining options have to be used at levels characterised by higher marginal costs and closer to their maximum potential. The models converge to the assessment that technological limitations (nuclear phase-out, low availability of CCS, delays in transport electrification) lead to higher (but manageable) decarbonisation costs for the EU (Figure 11). A large part of the additional costs will be incurred for further grid investment and for power system balancing, storage and reserve services which are increasingly required in case of massive penetration of intermittent renewable sources in the power sector.

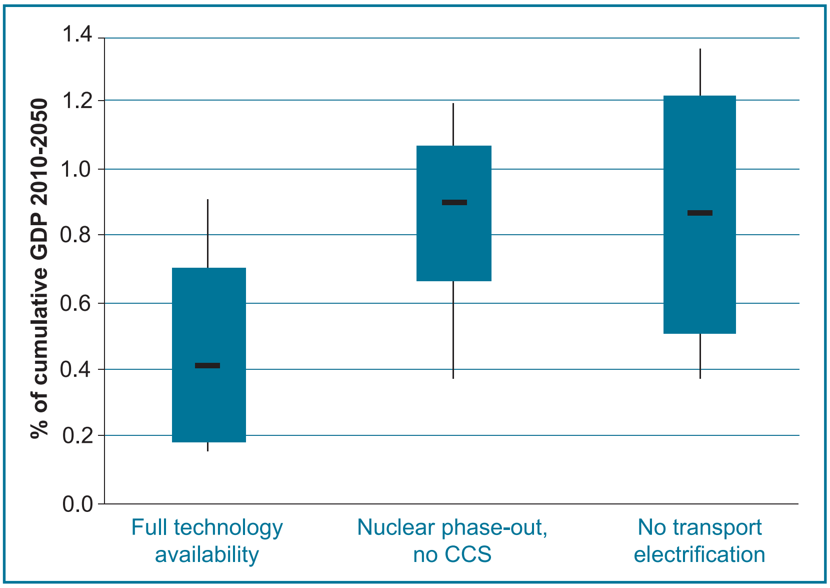


Figure 11: *Decarbonisation costs under technological limitations for the EU relative to the reference in 2010-2050. Ranges and distribution of model results are shown by the boxplots, with black lines indicating the median. No discount rate is assumed.*

4.3 Climate policies create opportunities for some European sectors and challenges for others

Policies that place a price on carbon emissions and promote mitigation technologies and energy efficiency create opportunities in some economic sectors and increase costs and reduce demand in others.

Higher energy costs arising from the imposition of climate policies tend to increase production costs and reduce the overall growth of economic activity. The reduction is more pronounced in sectors that are directly affected by strong climate policy, mainly concerning fossil fuels. Higher energy prices constitute a challenge for trade-exposed energy-intensive industries, despite the fact that the need for investments in capital-intensive renewable energy and transport electrification can increase demand for industrial products like iron and steel. On the other hand, decarbonisation increases output and employment in energy efficiency services and in the agricultural sector due to higher demand for bioenergy. Overall, the AMPERE analysis shows a mixed impact of strong climate action on employment in the various economic sectors identified in the macro-economic models.

For the EU region, decarbonisation generally involves substitution of imported fossil fuels by domestically produced goods and services, which are used to improve energy efficiency and implement renewable energy and other emission reduction technologies. Consequently, strong climate policies lead to a reduction of European dependence on imported oil and natural gas and enhance security of energy supply for Europe.

4.4 If other world regions start decarbonising later, Europe would gain a technological first mover advantage

Using the GEM-E3 and NEMESIS models that explicitly incorporate endogenous technological change mechanisms, we found that not only does an early increase in European mitigation efforts reduce the risk of costly carbon lock-in, it also creates economic opportunities in case of later mitigation efforts in other world regions, which may then demand European clean energy technologies (such as electric vehicles, efficient equipment, CCS, solar and wind).

The European internal market is sufficiently large and unified to allow for achieving significant clean energy technology learning potentials within it. Early climate action sets into motion R&D efforts on low-carbon technologies which combined with economies of scale and learning by doing lead to cost reductions. Such reductions can to a considerable degree be appropriated by European industries leading to competitive advantage in global markets for clean energy technologies. This is particularly important if world markets grow rapidly due to strong climate mitigation policies in non-EU regions. Although in the longer term the European advantage is gradually eroded due to spill-over effects, technology diffusion to non-EU regions yields benefits for Europe by limiting mitigation costs for vital European trading partners.

Electric vehicles are among the most important clean energy technologies, as they tackle emissions reduction in the important road transport sector which is not amenable to many other options. The EU already enjoys a comparative advantage in vehicle construction and is well poised to take advantage of an early start in the construction of electric vehicles (Figure 12). Other decarbonisation options that can generate a large market under appropriate policy conditions include CCS and photovoltaics.

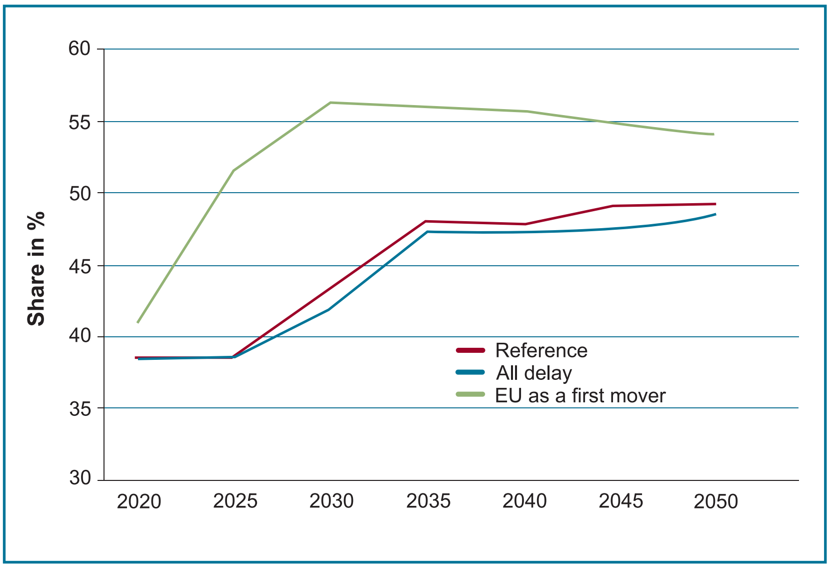


***Figure 12:** Share of EU production in the global market for electric vehicles in alternative scenarios*

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Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates

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