DEEP DECARBONISATION TOWARDS 1.5 °C – 2 °C STABILISATION

Policy findings from the ADVANCE project

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This first edition is partially based on results that are still under review for publication in scientific journals. Once these results are published, an updated second edition of this policy report will be made available.

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For more information on ADVANCE please visit:
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Acronyms and abbreviations

ADVANCE	Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies
AFV	alternative-fuel vehicle
AR5	IPCC Fifth Assessment Report
BECCS	bioenergy with carbon dioxide capture and storage
CCS	carbon dioxide capture and storage
CH_4	methane
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
EJ	exajoule
F-gases	fluorinated gases
g/MJ	gram per megajoule
GDP	gross domestic product
GE	general equilibrium
GHG	greenhouse gas
$GtCO_2$	gigatonnes of carbon dioxide
IAM	Integrated Assessment Model
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LDV	light-duty vehicle
LMDI	logarithmic mean divisia method index
LPG	liquefied petroleum gas
LULUCF	land use, land-use change and forestry
N_2O	nitrous oxide
NO_x	nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
PE	partial equilibrium
ppm	parts per million
PV	photovoltaic
REF	reference scenario
SDG	Sustainable Development Goals
SSP	Shared Socio-Economic Pathways
tCO_2	tonnes of carbon dioxide
UNEP	United Nations Environment Programme
VRE	variable renewable energy

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II. Decarbonisation requirements for the 1.5 °C goal

III. Electricity supply sector decarbonisation and the role of wind and solar power

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VI. Increasing the usefulness of integrated assessment models for decision support

Key findings

Limiting global mean warming to well below 2 °C or even 1.5 °C relative to pre-industrial levels requires a major transformation of the energy system. The ADVANCE project has analysed this mitigation challenge in detail, from the implications of the Intended Nationally Determined Contributions (INDCs) to decarbonisation bottlenecks in energy end-use sectors, taking into account both technological as well as behavioural emission reduction measures. Our key findings are:

The implementation of the Paris Agreement initiates a low-carbon transition for major emitting countries but an intensification of global effort is still required in order to limit global warming to well below 2 °C.
In 2030, the implementation of the INDCs is expected to reduce GHG emissions by around 10 % relative to previous, pre-Paris, policy trends. However, the global emissions gap relative to cost-optimal reduction pathways remains at 14 [4 - 25][1] $GtCO_2eq$ for the 2 °C target and 25 [13 - 30] $GtCO_2eq$ for the 1.5 °C target. The decarbonisation of the power sector accounts for more than half the CO_2 reductions achieved by the INDCs in 2030. It also holds the greatest potential for further near-term reductions which would put the world on track for 1.5 - 2 °C stabilisation. In 2030, the INDCs are expected to generate an increase in the share of zero carbon power supply by 5 % [1-12 %] relative to pre-existing trends, achieving a total share of 48 % [40 - 66 %]. Optimal 2 °C and 1.5 °C scenarios feature 57 % [50 - 90 %] and 73 % [57 - 93 %] zero carbon power supply respectively. In contrast, the INDCs have little effect on near-term emissions from non-electric end-use, even though progress in abating emissions, particularly from industry and transportation, is important for 1.5 - 2 °C-consistent climate stabilisation.

The 1.5 °C temperature target requires reductions in emissions from energy supply and demand as well as removal of CO_2 from the atmosphere.
A warming limit of 1.5 °C requires adherence to a stringent carbon budget of around 400 Gt CO_2 or lower over the 2011 - 2100 period. As the supply-side sector already needs to eliminate nearly all of its emissions by 2050 for 2 °C stabilisation, most of the additional emission reductions need to occur on the demand side. Efficiency improvements, as well as an accelerated electrification, will play a key role in achieving the 1.5 C° target. However our analysis also shows that energy supply and demand will still combine to generate at least 1000 Gt of residual CO_2 emissions over the 2011 - 2100 period. Accordingly, a 1.5 °C-consistent budget will require cumulative carbon dioxide removal of at least 500 Gt CO_2 over the course of the century.

Renewable energy from wind and solar power has great potential to produce environmentally friendly and economical electricity supply.
Reaping the high potential for low-cost emission reduction of the power sector at an early stage is essential for climate change mitigation. We find that the sector could be almost fully decarbonised through wind and solar power alone, without the use of nuclear and carbon capture and storage (CCS). This would require, however, considerable additional investments into grid infrastructure and storage systems. Most previous modelling studies have underestimated the role of wind and solar because of overly conservative assumptions on technology costs and the challenges related to coping with a variable renewable electricity supply. We also find that the low-carbon transformation yields substantial environmental co-benefits, which outweigh adverse environmental side-effects. Among the alternative decarbonisation pathways available, strategies relying heavily on wind and solar are superior to those with substantial CCS and nuclear deployment in terms of minimising environmental impacts.

Technological developments promoting efficiency, electrification and use of low-carbon fuels are the key to demand-side emission reductions.
The demand for energy services is projected to increase substantially over the course of the century. Technology options that promote energy efficiency, electrification and a switch to low-carbon fuels in energy demand sectors (transport, industry and buildings), become increasingly important if a climate target of below 2 °C is to be achieved. In the long-term, conventional fuels will have to be almost completely phased out from transportation energy use. This will largely depend on the development and adoption of new technologies, but also on life-style changes towards low-carbon transport modes.

Policies influencing consumers' attitudes will need to support the energy transformation.
Policies targeting consumers' behaviour and preferences can encourage the adoption of advanced technologies and use of cleaner fuels. These will ultimately speed-up the transition to a low-carbon energy system. For instance, in the transport sector we find that consumers have different attitudes towards vehicle choice, apart from pure financial concerns. This is why a rise of alternative fuel vehicles will critically depend on non-financial measures, such as vehicle efficiency standards and mandates, refuelling infrastructure investments and exclusive access to parking spaces and roadways. Also, with regard to energy access in developing countries, we find that household cooking decisions largely depend on income. Therefore subsidies for cleaner fuels and stoves can speed up the transition to universal clean cooking and even offset the negative effects of rising fuel costs spurred by climate policy.

Structure of the report

In this report, we elaborate on each of these key insights in individual chapters. Chapter 1 characterises the effect of the INDCs compared to the near-term developments of cost-optimal pathways, staying within the 2 °C and 1.5 °C limits. Chapter 2, in contrast, explores the long-term requirements and the 1.5 - 2 °C limits from a cross-sectoral perspective.

Thereafter we look in more detail into the required low-carbon transformation of the energy system. Chapter 3 focuses on emission reduction measures in electricity supply, particularly on the potential of wind and solar power for low-carbon energy supply. Chapters 4 and 5 explore the low-carbon transformation of energy demand. While Chapter 4 looks at technology options in the industry, buildings and transport sectors, Chapter 5 looks at strategies and policies influencing behaviour and individual preferences of energy consumers.

The final Chapter 6 concludes by discussing the role of Integrated Assessment Models (IAMs) for informing climate policy and decision-makers, and describing how ADVANCE contributes to increasing transparency and robustness of IAMs to improve the usefulness of these tools for policy advice.

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[1] Brackets [ ] indicate model ranges.

ADVANCE in a nutshell

ADVANCE objective

International climate policy aims to reduce emissions across all sectors and countries in both the short- and the long-term in order to hold global warming to well below 2 °C. Thus, it needs to bridge geographical scales from national to global and timescales from 10 to 100 years and integrate sectors from power to agriculture. Integrated assessment models (IAMs) of climate change provide cross-scale and cross-sector policy support for efficient and effective emission reductions. These tools explore consistent pathways for the achievement of long-term climate goals, and examine the implications of different courses of action and technological and socio-economic developments for energy use, land use and climate futures. As such, they are an important element of a larger discourse about our collective response to climate change.

With the increasing use and growth in complexity of IAMs, the demand for improved representations, as well as thorough validation of model behaviour, has grown significantly over recent years. The ADVANCE project responds to this demand by facilitating the development of a new generation of advanced energy-economy and integrated assessment modelling tools and, in parallel, making a coordinated effort to improve model transparency, model validation, and data handling.

ADVANCE achievements

[1] Improved science-based policy support

ADVANCE methodological developments contribute to a better representation of the energy-economy-climate system. New insights gained from improved models facilitate the exploration of climate mitigation policy options in the post-Paris framework and provide answers to the following questions:

- What are the requirements for low climate stabilisation?
- What are the bottlenecks for the development of a carbon-free energy supply system?
- What is the potential of energy efficiency improvements for climate change mitigation?
- What is the effect of behavioural change and consumer choices on energy demand?
- How can climate mitigation targets and energy access objectives be reconciled?
- How does uncertainty about technological innovation affect optimal innovation policies?

[2] Transparency of model-based analysis of climate policy strategies

Besides work on model improvement, ADVANCE has developed a systematic documentation of all energy-economy and integrated assessment models participating in the project. This documentation describes the structure and assumptions of each model. In addition, a diagnostic database collects the results of harmonised model experiments and provides quantitative indicators that characterise model behaviour. The model documentation and the diagnostic indicators are crucial for enhancing transparency and enable users from both the scientific and climate policy communities to better interpret results in the light of model assumptions and characteristics.

[3] Transferability of knowledge to the wider scientific community

ADVANCE makes methodological improvements and data available to the broader scientific community in the form of a modelling toolbox.[2] This toolbox includes newly developed model components, mathematical formulae, algorithmic approaches, examples of model code, and generic input datasets. In addition, a database with final scenario results produced by the improved ADVANCE models will be published for further use by the scientific community, for example in the context of future assessment reports by the Intergovernmental Panel on Climate Change (IPCC).

ADVANCE models

Model name	Institute	Model category	Time horizon	Regional coverage
REMIND	PIK	Energy system – GE[3] growth model	2100	World
MESSAGE-MACRO	IIASA	Energy system – GE hybrid model	2100	World
WITCH	FEEM	Energy system – GE growth model	2100	World
IMACLIM	CIRED	Computable GE model	2100	World
GEM-E3-ICCS	ICCS	Computable GE model	2050	World, EU28
IMAGE / TIMER	UU / PBL	Energy-land PE[4] model	2100	World
POLES	EDDEN, DG JRC, Enerdata	Energy system PE model	2100	World
TIAM-UCL	UCL	Energy system PE model	2100	World
REMix	DLR	Electricity system PE model	2050	EU

External partner models

AIM / CGE	NIES	Computable GE model	2100	World
DNE21+	RITE	Energy system PE model	2050	World
GCAM	PNNL	Energy-land PE model	2100	World
iPETS	NCAR	Computable GE model	2100	World

ADVANCE overview

Project coordinator	Potsdam Institute for Climate Impact Research (Gunnar Luderer, Elmar Kriegler)
Duration	January 2013 – December 2016
EU Funding	€ 5,699,168.32 (grant agreement n° 308329)
Steering committee and work package leaders	Potsdam Institute for Climate Impact Research (Gunnar Luderer, Elmar Kriegler) Fondazione Eni Enrico Mattei (Massimo Tavoni) International Institute for Applied Systems Analysis (Keywan Riahi, Volker Krey) Joint Research Centre - European Commission (Bert Saveyn) Netherlands Environmental Assessment Agency (Detlef van Vuuren)
Project Manager	Laura Delsa (Potsdam Institute for Climate Impact Research)
Scientific Advisory Board	Laura Cozzi (International Energy Agency), John Weyant (Stanford University), Ger Klaassen (European Commission), Geoff Blanford (Electric Power Research Institute)

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[2] The ADVANCE modelling toolbox and scenario database will be publicly available from January 2017.

[3] **GE:** general equilibrium

[4] **PE:** partial equilibrium

I.

THE PARIS AGREEMENT AS AN ENTRY POINT FOR 1.5-2 °C STABILISATION

I. The Paris Agreement as an entry point for 1.5 - 2 °C stabilisation

The Paris Agreement is generally considered to be a milestone in international climate policy. Compared to previous climate agreements, such as the Kyoto Protocol, the bottom-up approach to climate change mitigation through the submission of Intended Nationally Determined Contributions (INDC) marked a fundamental shift in the nature of the international climate policy regime. The Paris Agreement strengthens the global long-term target to holding global mean warming to well below 2 °C and pursuing efforts to limit it to 1.5 °C above pre-industrial levels. Based on the methodologically enhanced ADVANCE models, we explored the impacts of the INDCs and their consistency with the 1.5 °C and 2 °C targets.

Additional efforts beyond INDCs are required to put the world on track for global warming below 2 °C

We find that the INDCs result in substantial emission reductions compared to those inferred by pre-existing climate policy commitments, but fall short of reaching reduction levels consistent with cost-optimal 1.5 - 2 °C mitigation. Results from the participating models show that under a combined implementation of conditional[5] INDCs, global emissions will reach 52 [46 - 60][6] GtCO$_2$eq in 2030, around 8 % [4 - 20 %] higher than 2010 levels and 9 % [5 - 19 %] lower than pre-Paris Reference[7] emission levels. When comparing, however, the Paris outcome to an early, cost-optimal and common mitigation action for achieving the 2 °C and 1.5 °C targets starting in 2020, we find an “emissions gap”[8] of 14 [4 - 25] GtCO$_2$eq and 25 [13 - 30] GtCO$_2$eq respectively (Figure 1.1).

Results further indicate that for the INDC scenario in 2030, when compared to the Reference scenario, GHG reductions are comprised of, on average, 83 % from CO$_2$ emission reductions, 11 % from CH$_4$, 4 % from F-gases, and 2 % from N$_2$O emissions.

The power sector accounts for more than half of the CO$_2$ emission reductions in the INDC scenario (51 % [33 - 63 %]), but also holds the greatest potential for further reductions to put the world on track to achieve the 1.5 - 2°C limits (Figure 1.2). In contrast, the INDCs have little effect on near-term emissions from the demand side, even though the industry and transportation sectors are particularly important for 1.5 - 2 °C - consistent climate stabilisation, contributing around 20 % and 15 % of total CO$_2$ reductions respectively.

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[5] The analysis considers the high-end of emission reductions inferred by the INDCs by analysing “conditional” pledges that are subject to financing, capacity transfer etc.

[6] Brackets [ ] indicate model ranges.

[7] In this first Chapter, the term „Reference“ refers to policy trends prior to the adoption of the INDCs.

[8] In line with the UNEP (2015), we define the emissions gap as “the difference between the aggregate effect of the INDCs and the early, cost-optimal 1.5-2°C pathways.”

Fig. 1.1 top: Global GHG emission trajectories until 2050 for Reference, INDC, 2 °C and 1.5 °C scenarios; the lines in the figure represent results from different models.

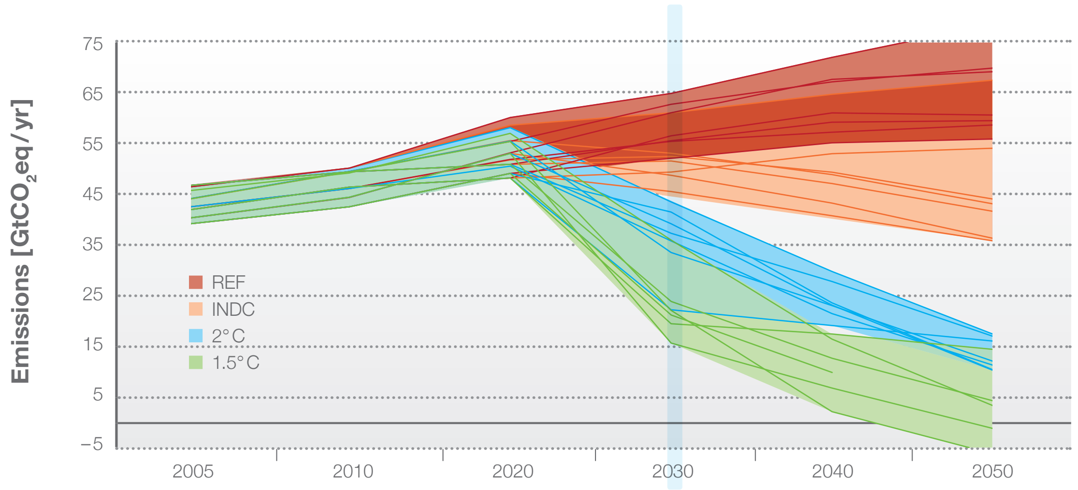


Fig. 1.1 bottom: Zooming into global GHG emissions in 2030; boxplots indicate the range and distribution of model results (line in the rectangle: median, rectangle: interquartile range, whiskers: full range).

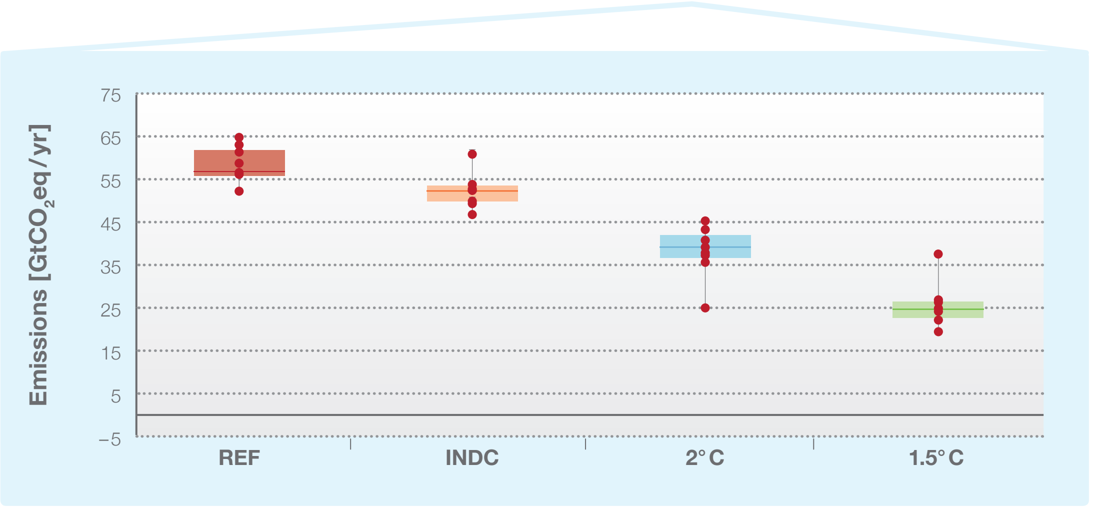
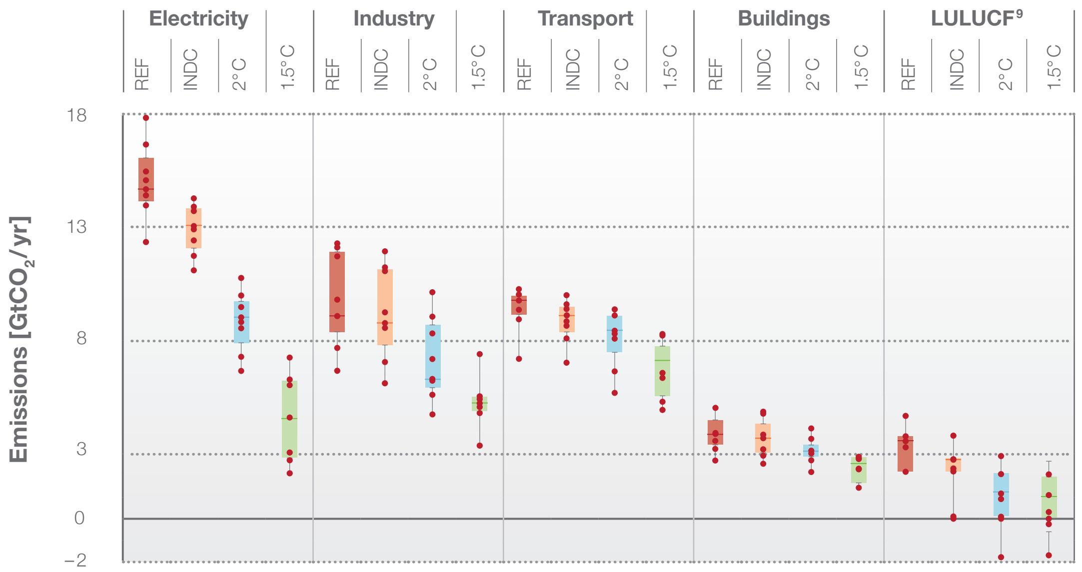


Fig. 1.2: Direct CO$_2$ emissions per sector in 2030. Boxplots indicate the range and distribution of model results (line in the rectangle: median, rectangle: interquartile range, whiskers: full range).



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[9] LULUCF: land use, land-use change and forestry

Accelerating power sector decarbonisation

The abatement effort linked to the INDCs infers a rather moderate change from current trends in the energy system. The transformation of the energy system is limited even when considering the energy-related targets provided by the INDCs. This remains a challenge that needs to be addressed with more ambitious climate policies in order to achieve climate stabilisation. In the INDC scenario, final energy demand is only reduced by 3 % [1 - 5 %] in 2030 compared to the Reference scenario, while cost-optimal global mitigation pathways show much higher efficiency improvements, namely reductions from Reference levels of 13 % [6 - 24 %] and 21 % [9 - 31 %] in the 2 °C and 1.5 °C scenarios respectively.

In 2030, the decarbonisation of the power sector dominates the transformation of the energy system and the mitigation effort of all scenarios. The implementation of the INDCs results in a 48 % [40 - 66 %] share of zero-carbon power supply, 5 % [1 - 12 %] higher than in the Reference. In contrast, the 2 °C and 1.5 °C emission trajectories have respective shares of 57 % [50 - 90 %] and 73 % [57 - 93 %] of zero-carbon supply, as shown in Figure 1.3.

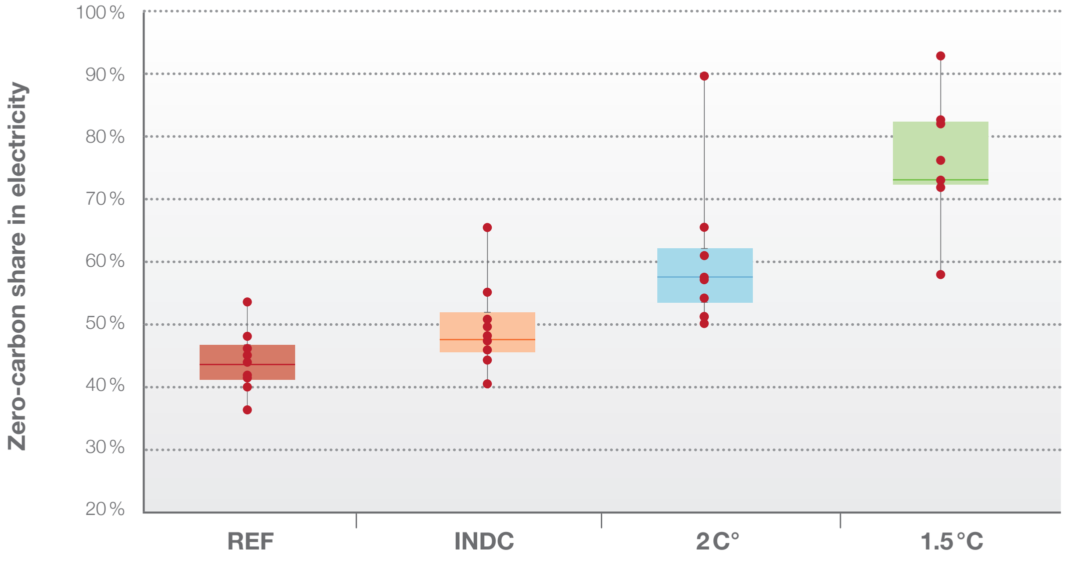


Fig. 1.3: Zero-carbon technologies in 2030 global power mix. Boxplots indicate the range and distribution of model results (line in the rectangle: median, rectangle: interquartile range, whiskers: full range).

1.5°C

II.

DECARBONISATION REQUIREMENTS FOR THE 1.5 °C GOAL

II. Decarbonisation requirements for the 1.5 °C goal

Limiting global mean warming to well below 2 °C or even 1.5 °C demands a very tight budget for future greenhouse gas emissions. Based on the ADVANCE model results, we were able to explore the potential and limitations for deep emissions reductions in individual sectors and relate them to the emissions reduction requirements of the 1.5 °C and 2 °C targets.

The 1.5 °C goal crucially differs from the 2 °C goal in terms of remaining admissible carbon emissions

The existing scientific literature provides us with information on carbon budgets, representing the cumulative amount of carbon dioxide emissions we can still emit while limiting global temperature rise to a given target (see figure 2.1). Climate science shows that there are crucial differences between the 1.5 °C and 2 °C targets in terms of remaining admissible carbon emissions. In order to limit warming to 2 °C with a medium to likely chance, the remaining CO_2 budget up until 2100 has been estimated to be in the range of 960 - 1550 $GtCO_2$ and 630 – 1180 $GtCO_2$, respectively (IPCC AR5, Table TS.1 of WG III report). However, in order to limit warming to 1.5°C with a medium likelihood the estimated remaining CO_2 budget is in the range of a mere 200 – 415 $GtCO_2$ for the same period (Rogelj et al., 2015, Nature Climate Change). To achieve this is a tremendous challenge given that current emission rates are around 40 $GtCO_2$/yr, and a continuation of current policies would yield emissions of 4000 - 5000 $GtCO_2$.

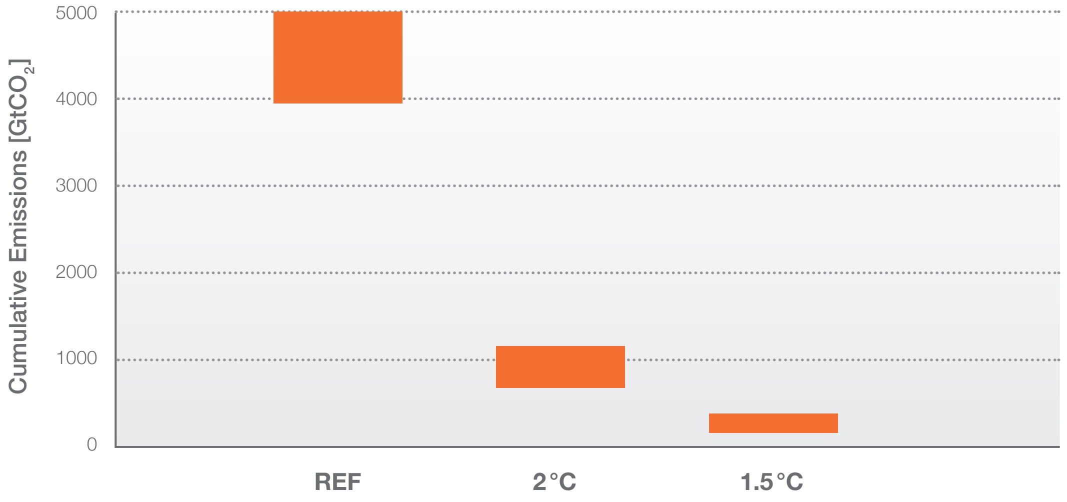


Fig. 2.1: Cumulative global CO_2 emissions for 2011 – 2100 based on the IAM scenario literature and assumed in this study. Scenario categorisation: reference policy scenarios assuming unconditional Cancun-Pledges for 2020 and an extrapolation of the implied ambition levels through 2100, 2 °C-consistent scenarios with likely chance and 1.5 °C-consistent pathways.

Energy demand accounts for most of the additional reductions in 1.5 °C pathways

In view of these tight budgets, we used the improved ADVANCE models to explore the scale and determinants of remaining fossil fuel emissions across the relevant sectors of the energy system, i.e., energy supply (mostly electricity production), industry, transportation, and buildings. Our analysis shows marked differences between supply-side and demand-side decarbonisation patterns. While electricity generation offers the greatest potential for low cost emission reductions in the short term, energy demand sectors account for a dominant share of fossil emissions in the second half of the century (Figure 2.2). However, demand-side emissions also account for most of the additional mitigation efforts for reaching the 1.5 °C limit relative to 2 °C pathways (Figure 2.3). The reason is that, in 2 °C scenarios, freely emitting fossil installations are already almost fully eliminated from the power system by mid-century. Therefore most of the additional emission reductions required for 1.5 °C-consistent stabilisation have to come from further mitigation measures on the demand side. The most important long-term options, enabling these emissions reductions to be achieved, are demand-side efficiency improvements and demand reduction, as well as accelerated electrification.

Fig. 2.2: Fossil-based CO_2 emissions pathways from electricity supply (left), and direct emissions from demand-side fossil fuel use and industrial processes (right) for likely 2 °C stabilization pathways. The lines in the figure represent results from different models.

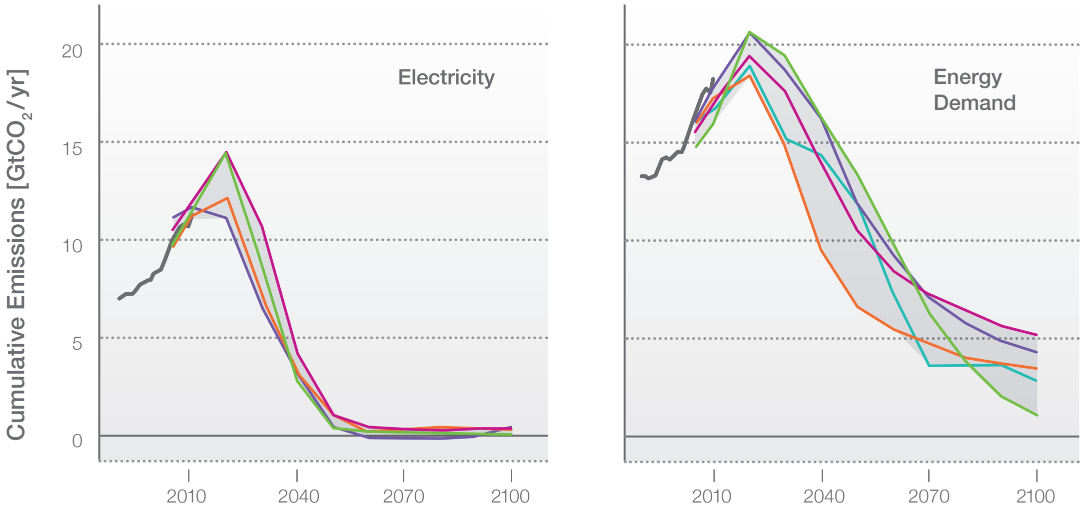
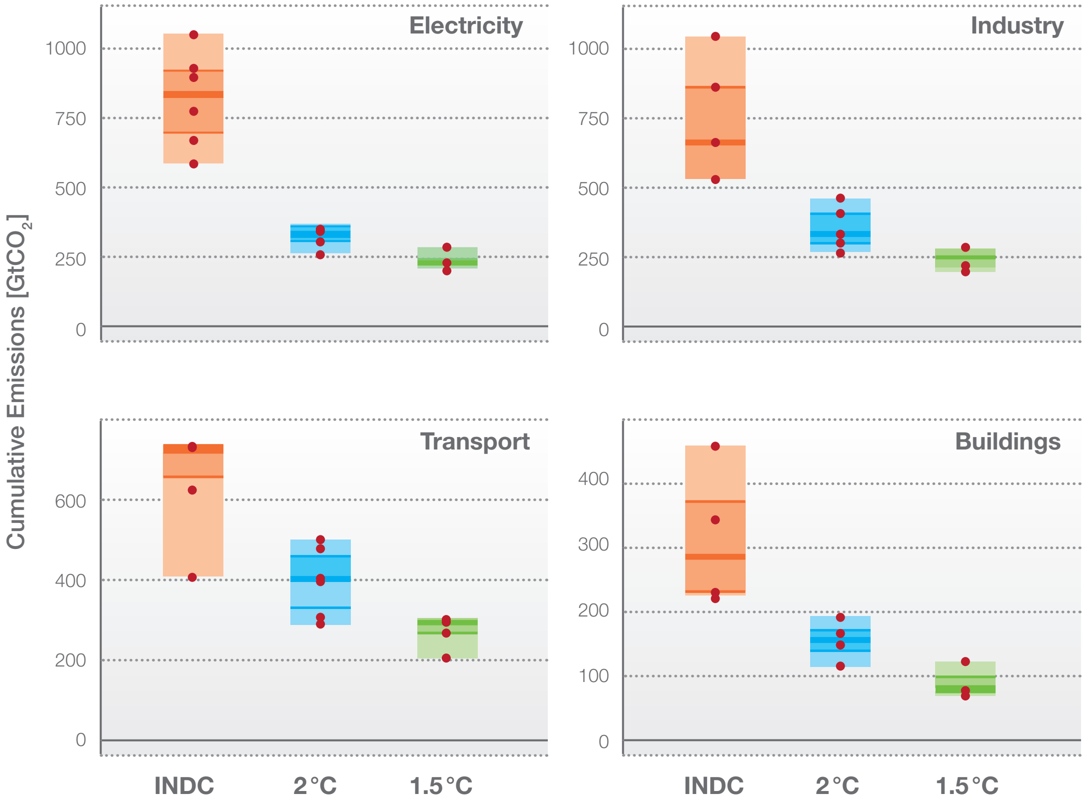


Fig. 2.3: Cumulative (2011 – 2100) fossil CO_2 emissions for the electricity supply, as well as the demand sectors industry, transportation and buildings in three policy scenarios. Scenario categorisation: policy scenarios accounting for the effect of the INDCs, 2 °C-consistent scenarios and 1.5 °C-consistent scenarios. Boxplots indicate the range and distribution of model results (thick line: median, dark shading: interquartile range, light shading: full range).



Carbon dioxide removal technologies will be needed to ensure the 1.5 °C-consistent carbon budget is not exceeded

The substantial magnitude of residual fossil fuel emissions has important implications for climate policy and the feasibility of very low stabilisation targets. In all our scenarios we find that even with an immediate strengthening of near-term mitigation action, and stringent long-term climate policies, energy supply and demand will still combine to generate at least 1000 $GtCO_2$ emissions over the 2011-2100 period. As a direct consequence, a 1.5 °C-consistent budget, of around 400 $GtCO_2$ or lower, requires cumulative carbon dioxide removal, for instance from land-use sinks such as afforestation and from combining bioenergy with CCS (BECCS). Based on these results, we estimate that at least 500 $GtCO_2$ need to be removed from the atmosphere over the course of the century.

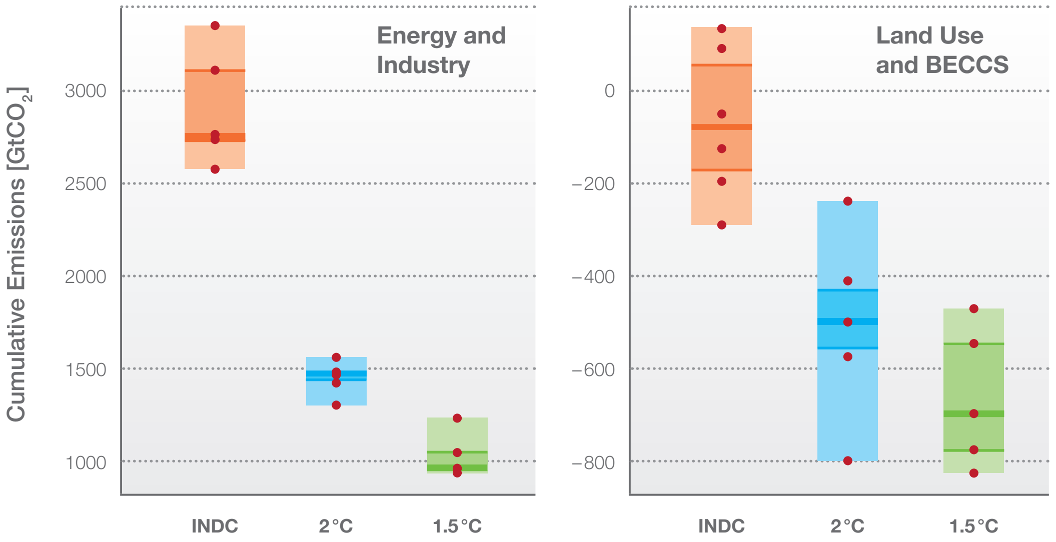


Fig. 2.4: Cumulative (2011 – 2100) total fossil emissions from energy and industry (left), and carbon dioxide removal from land-use sinks and bioenergy combined with CCS (BECCS) (right). Boxplots indicate the range and distribution of model results (thick line: median, dark shading: interquartile range, light shading: full range).

We conclude that mitigation strategies limiting end-of-century warming to 1.5°C have to combine the following crucial elements: (i) rapid restructuring of power supply-side investments so as to avoid further lock-ins into fossil capacities and to achieve rapid upscaling of carbon-free power generation (see Chapter 3), (ii) achievement of accelerated demand-side energy efficiency improvements and electrification of energy end-uses in the industry, transportation and buildings sectors (see Chapter 4), (iii) development and upscaling of carbon dioxide removal technologies to offset residual carbon emissions, which are likely to substantially exceed the CO_2 budget consistent with the 1.5°C limit.

III.

ELECTRICITY SUPPLY SECTOR DECARBONISATION AND THE ROLE OF WIND AND SOLAR POWER

III. Electricity supply sector decarbonisation and the role of wind and solar power

Early and deep decarbonisation of power supply is essential

As discussed in the preceding chapters, early and deep decarbonisation of electricity supply is a core element of effective climate protection strategies. Given the long life-times of power supply infrastructure, achieving these potentials at an early stage is essential to avoid further lock-in into a fossil-intensive system. Moreover, low-carbon electricity supply systems pave the way towards further emission reductions in the buildings, industry and transportation sectors via accelerated electrification.

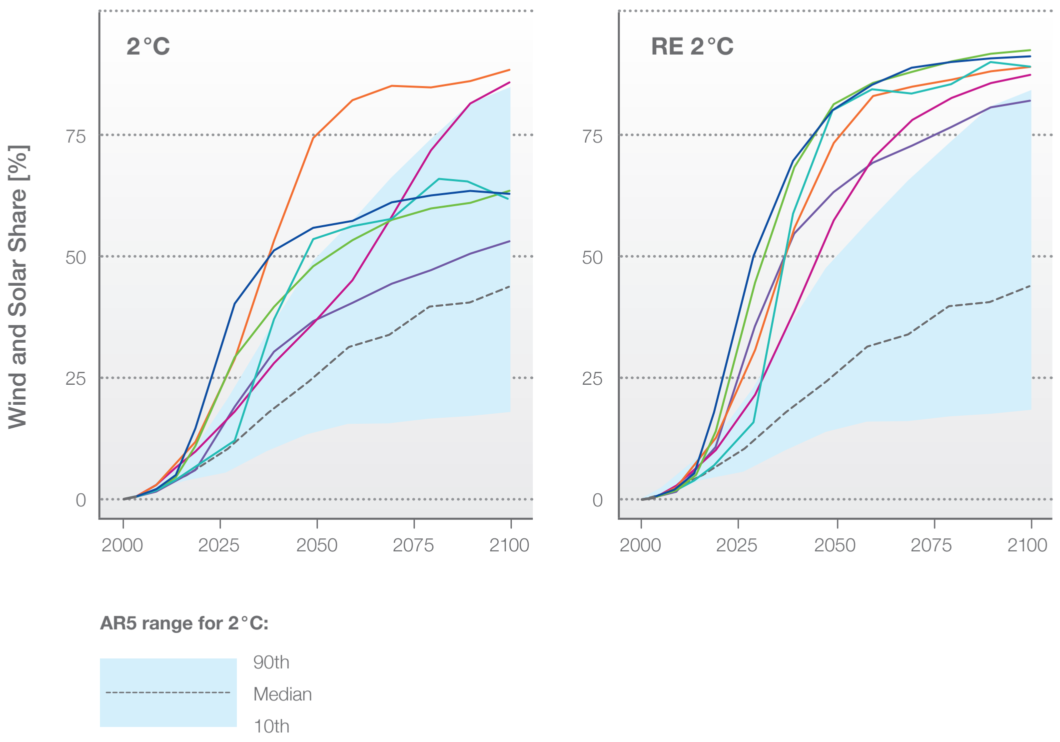
Wind and solar can satisfy most low-carbon power supply

The power supply sector offers a particularly high degree of technology flexibility with renewables, nuclear, and carbon capture and storage (CCS) as alternative mitigation options. With average market growth rates of more than 40 % per year for solar PV, and around 20 % for wind power, over the last decade, these “new renewable” energies are often seen as the most promising technologies for a low-carbon future. Moreover, wind and solar technologies have experienced substantial cost reductions in recent years due to technological progress and economies of scale. As there is still plenty of potential for additional innovation, further cost decreases are expected in the future. Yet many scholars and decision-makers have argued that the prospects of wind and solar power are diminished by the variability and uncertainty of their supply; unlike conventional electricity from fossil or nuclear plants, their electricity output fluctuates with varying wind speed and solar irradiation.

ADVANCE has performed pioneering research to accurately account for the effect of variability on the economics of wind and solar-based power in integrated assessment models. It has developed aggregated IAM modelling approaches based on insights from detailed hourly electricity sector models. ADVANCE has also developed refined datasets on wind and solar resources available for power supply across different world regions. Based on these innovations, we can derive more robust insights into the potential role of variable renewable energy sources for carbon-free electricity supply and climate change mitigation. Specifically, we find that under stringent emission constraints in line with the 2 °C limit, wind and solar will be the main contributors to power sector decarbonisation, and that previous studies based on simpler approaches have tended to underestimate their potential. In these scenarios, carbon prices of $\$50/tCO_2$ and higher by 2030 make fossil-based power generation increasingly unattractive, while the near-term decreases in technology costs of wind and solar make these renewable technologies highly competitive.

We even find that power supply can be almost fully decarbonised without nuclear and CCS. Such scenarios feature shares of combined wind and solar of 60 - 80 % by mid-century. An expansion of grid interconnectors and the provision of additional flexibility, via increasing deployment of electricity storage or demand response, are important factors for enabling such renewable-based power systems, while limiting curtailment of wind and solar electricity to less than 15 % in most regions.

Fig. 3.1: Share of wind and solar in global power supply until 2100 in 2 °C-consistent climate protection scenarios with the full technology portfolio (left panel) and renewable-focused decarbonisation without nuclear and CCS (right panel). Blue shaded areas indicate the 10 – 90 % range of results from 2 °C scenarios assessed in the IPCC's Fifth Assessment Report (AR5). The coloured lines represent ADVANCE results from different models.



Power sector decarbonisation results in environmental co-benefits, especially in terms of reduced air and water pollution

Power sector decarbonisation requires a shift from conventional fossil to alternative sources, including renewables, CCS and nuclear. On the one hand, the phase-out of fossil fuels can be expected to result in environmental co-benefits beyond reduced GHG emissions, such as reduced air pollution from coal power plants. On the other hand, climate policies can also have adverse side-effects, for example land requirements to produce biofuels.

ADVANCE has coupled integrated assessment modelling of the energy-economy system with life-cycle assessment of energy technologies. These were formerly largely separated strands of research. This important innovation has allowed us to comprehensively quantify environmental co-benefits and adverse side-effects of the low-carbon transition, and to quantify alternative power sector decarbonisation strategies in terms of their environmental impacts.

A key finding is that the co-benefits of the low-carbon transformation tend to outweigh adverse side-effects. In particular, climate friendly power systems considerably reduce air pollution, and greatly decrease the release of toxicants to watersheds, while coal mining is responsible for considerable environmental impacts from leaching mine dumps.

Wind and solar based power supply leads to higher environmental co-benefits

In terms of new risks compared to conventional electricity supply, potential areas of concern for low carbon pathways are land requirements (predominantly bioenergy), ionising radiation (due to nuclear power) and mineral resource requirements (for wind, solar and power grids).

To inform decision-makers of the consequences of their choices, ADVANCE compared the risk profiles of renewables-based power sector decarbonisation (with nuclear and CCS excluded from the portfolio of technology options) to a climate protection strategy largely based on nuclear and CCS (with wind and solar limited to a combined share of 10 %). We find that renewables-based strategies are superior in terms of minimising environmental impacts. They greatly decrease air and water pollution as well as total water demand and avoid ionising radiation impacts from the use of nuclear power.

An important drawback of a renewables-based strategy is the substantial use of mineral resources, such as steel, copper and aluminium required for constructing wind turbines, solar panels, grid infrastructure and storage systems. For instance, even if technological progress is accounted for, copper demand for power infrastructure could amount to 5 million tonnes, equivalent to about 25 % of current total copper consumption under global mitigation strategies.

While wind and solar emerge as being comparatively environmentally friendly, biomass is associated with greater environmental impacts than the other renewable supply options. Similarly, hydropower can result in substantial indirect greenhouse gas emissions and upstream energy requirements. Even though it contributes less than 10 % of power supply in either scenario, bioenergy dominates the land footprint of power supply, exceeding land requirements for wind and solar installation, and for grid infrastructure.

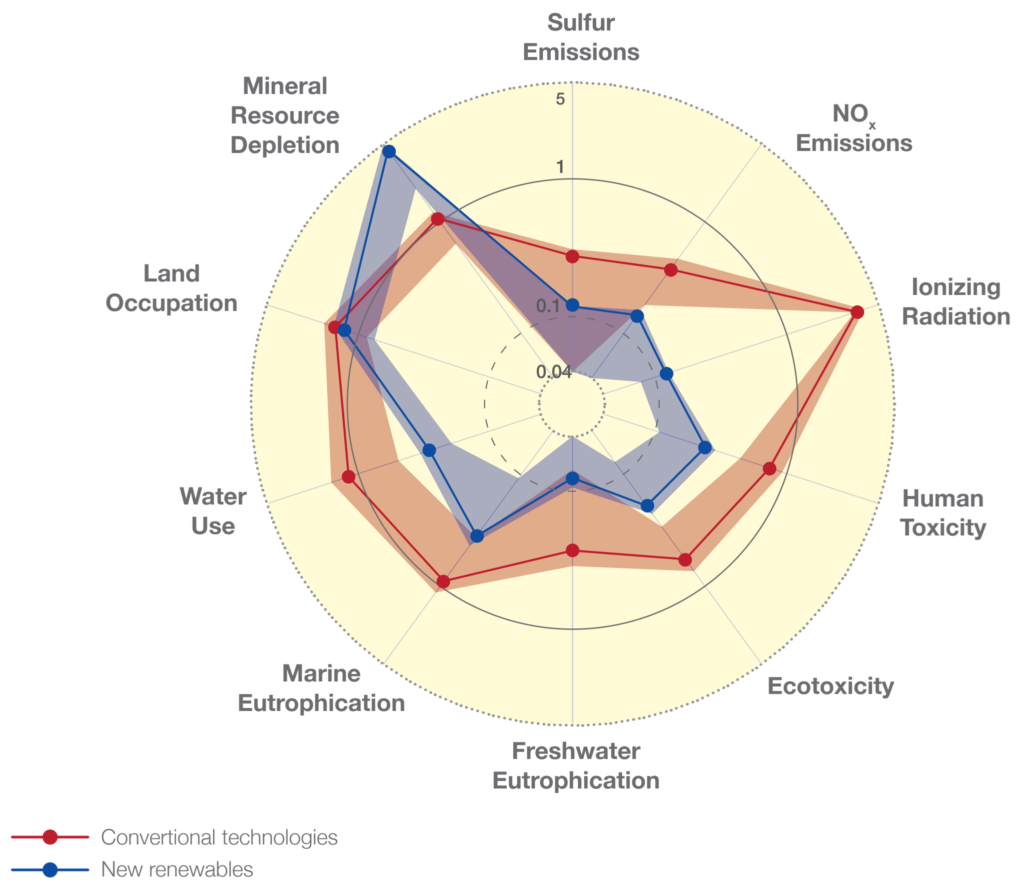


Fig. 3.2: Comparison of non-climate environmental impacts of power sector decarbonisation strategies based on new renewables (high contribution of wind and solar) or conventional technologies (high contribution of CCS and nuclear). Impacts are shown for 2050 and relative to those that would occur in the absence of climate policies, i.e., values smaller than 1 indicate a decrease of impacts due to climate policies. Note that a logarithmic scale is applied.

IV.

TECHNOLOGY DEVELOPMENT FOR DEMAND-SIDE MITIGATION

IV. Technology development for demand-side mitigation

The demand for energy services is projected to increase significantly in all economic sectors

Decarbonising the world's energy end-use sectors (transport, buildings, and industry) is a major challenge for climate change mitigation. The demand for energy services is projected to increase significantly in all three sectors as a result of population and economic growth. For instance, assuming no new climate policies (hereafter referred to as the baseline scenario), energy demand in the transport and industry sectors is projected to more than double (Figure 4.1).

If stringent climate policy consistent with the 2° C target is implemented, all three sectors show strong potential for energy demand reductions (Figure 4.1). Demand-side technology options that increase energy efficiency or boost use of low-carbon fuels are important to fully exploit this potential.

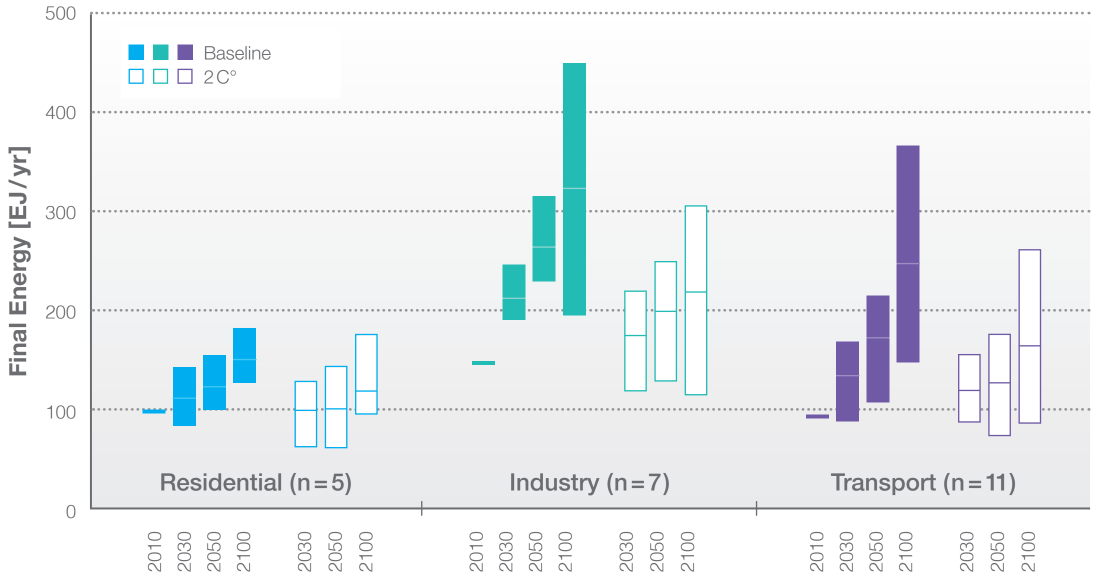


Fig. 4.1: Ranges of final energy demand in the residential, industrial and transport sectors for baseline and 2 °C scenarios. The line in the middle of the range indicates the average development across models. N indicates the number of models participating in the comparison.

A climate target of below 2 °C requires efficiency, electrification and fuel switching

Carbon dioxide emissions in energy end-use sectors can be reduced through a lower demand for energy services, energy efficiency improvements, electrification and a switch to less carbon intensive fuels, such as biomass (see Figure 4.2).

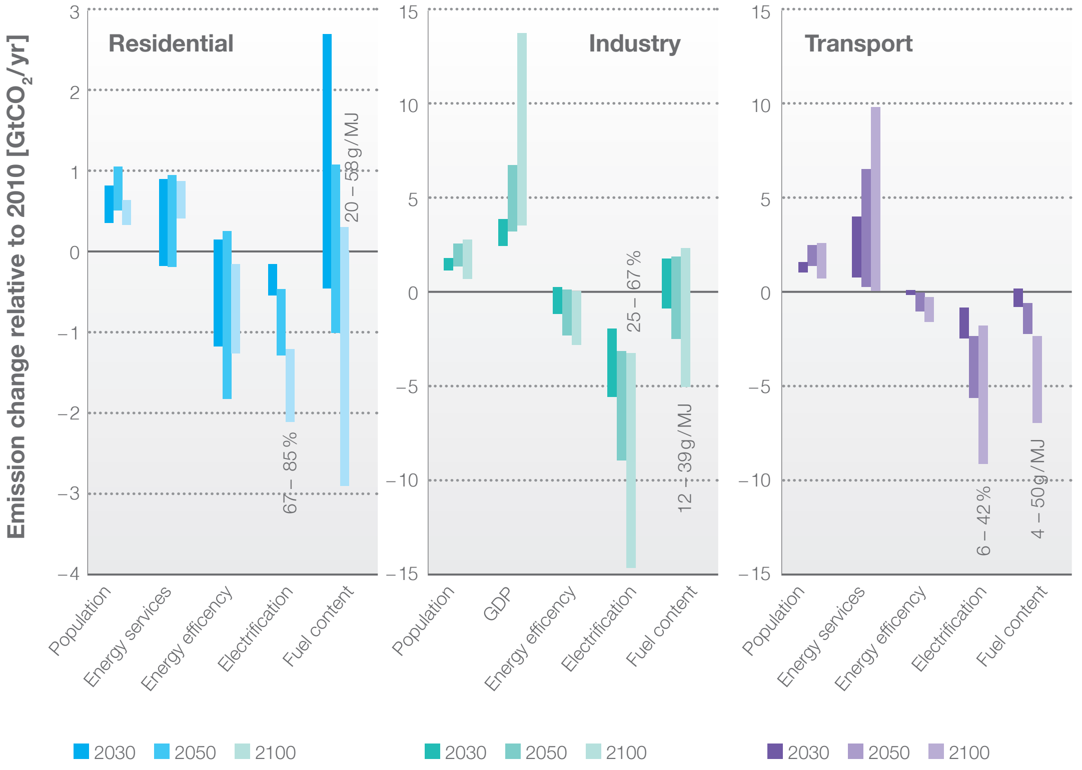
Even in the absence of new climate policies, energy efficiency is projected to increase in all three sectors in line with historic trends. For instance, efficiency is projected to increase annually by 0.5 % in the buildings sector and by 0.7 % in the transport sector between 2010 and 2050. However energy efficiency improvements are substantially higher in the climate policy scenario. In 2 °C consistent model scenarios, yearly average efficiency improvements for 2010 - 2050 reach 1.0 % in the buildings sector and 1.3 % in the transport sector.

A large shift from the use of fossil fuels to electricity is projected in the residential baseline scenario. This is in line with current trends of increased use of electrical appliances and equipment, and less use of oil and coal boilers for heating. Electrification is also projected to take place in non-OECD countries, where biomass and waste are currently the largest sources of energy used. As a result the residential electricity share is projected to reach an average level of around 40 % in 2050. If climate policies are implemented to stabilise warming below 2 °C, electricity use in the residential sector is projected to increase to 67-85 % of total final energy demand by the end of the century.

In the transport and industry sectors, electrification has only a small impact on emission trends in the baseline scenario. Oil currently represents 94 % of the energy mix in the transport sector and, in absence of climate policies, this share is projected to decrease only slightly. The projections also suggest a limited increase in alternative fuel use in the industrial sector. However, in response to climate policy, alternative fuel use, both in the form of electricity and low carbon fuels, increases significantly, especially during the second half of the century. Conventional oil-fuelled vehicles can be substituted by electric vehicles in passenger transport, while biofuels are an important abatement option for freight transport.

By 2050, the average electricity share is 7 % in transport, 38 % in industry and 46 % in buildings for the 2 °C-consistent scenarios. Moreover, across models, carbon intensity of non-electric fuel will have decreased from an average of 69 g / MJ to 49 g / MJ in transport and 92 g / MJ to 74 g / MJ in industry, indicating a substantial shift to low carbon fuels. In the residential sector, by contrast, carbon intensity increases from to 37 to 50 g / MJ due to decreased use of traditional biomass in developing countries.

Fig. 4.2: Decomposition[10] of carbon emissions per end-use sector in the 2 °C-consistent climate policy scenario. This figure shows, for each sector, how population and activity growth[11] (e.g. passenger kilometre growth for the transport sector) contributes to increasing emissions (positive values), while energy efficiency (i.e. the energy used per activity), electrification, or shift to less carbon intensive fuels for the remaining non-electric final energy shares contribute to decreasing emissions (negative values).



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[10] Additive logarithmic mean divisia method index I (LMDI) is used to decompose sectoral emissions.

[11] For those models that do not model physical sectoral energy service data (for example kilometres travelled or floor space of residential buildings) we explicitly used GDP per capita values. For industry, we used GDP as the activity indicator.

The mitigation potential of the transport sector is highly dependent on technological innovations

Alternative fuels and technologies have significant potential to mitigate emissions, particularly in the transport sector in the 2nd half of the century. As an example, several ADVANCE models project a complete phase-out of conventional fuels in transportation in 2100. They also project that activity reduction (i.e., less travel) and a shift towards less carbon intensive modes of travelling (e.g., public transport instead of cars) will only play a minor role in reducing emissions.

Do these technological changes imply a radical break in the trend? The global efficiency improvements required are similar to the maximum value of efficiency improvements measured in the OECD regions between 1973 and 2007. In contrast however, switching fuels (towards electricity, hydrogen and biofuels) marks a strong break in the trend, as the transport sector has been historically dominated by oil use. Clearly, this transition would not only depend on the development of alternative technologies, but also on the propensity of consumers to adopt them, as discussed in the following Chapter 5.

V.

BEHAVIOUR AND POVERTY AS DETERMINANTS OF CONSUMERS' ENERGY CHOICES

V. Behaviour and poverty as determinants of consumers' energy choices

As global incomes have risen in recent years, transport emissions have grown quickly – faster, in fact, than those from other sectors. Meanwhile, among the world's poor, the grossly inefficient and polluting use of traditional fuels in the buildings sector (firewood, charcoal, animal dung) hinders socio-economic development. Although advanced technologies and cleaner fuels are available to transform the transport and buildings sectors over the next few decades, the behaviour and preferences of different types of consumers – whether in developed or developing countries – will determine how quickly those technologies and fuels are adopted and, thus, the speed with which the transformation takes place.

Strategies and policies influencing consumer preferences are critical to ensuring transport sector decarbonisation

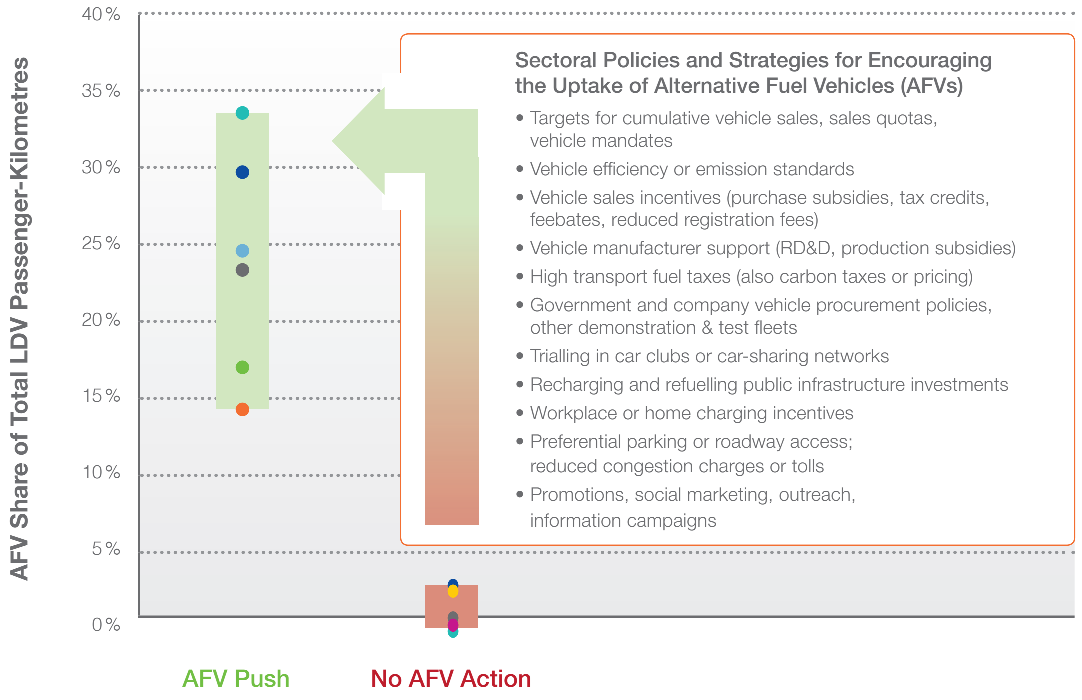
Although growing quickly in number, alternative fuel vehicles (AFVs) still comprise far less than 1 % of the global private vehicle fleet. Widespread adoption of AFVs (including biofuel, electric and fuel cell vehicles) suggests that consumers are actively choosing to purchase them over conventional (fossil fuel) vehicles, which at the moment remain the more cost-competitive option.

Yet, consumer behaviour is not narrowly financial: in a major review of over 80 empirical studies, we found strong evidence that heterogeneous consumers have measurably different attitudes toward vehicle choice, outside of pure financial concerns. Consumers can be differentiated, for example, according to their propensity to adopt new technologies (e.g., early vs. late adopters), their location (e.g., urban vs. rural), and their vehicle usage intensity (e.g., modest vs. frequent). Across these different consumer segments, preferences may vary and relate to risk aversion, range anxiety, the availability (or lack thereof) of refuelling stations, and the variety of vehicle makes and models on offer. Moreover, according to our analysis, preferences within different consumer segments vary from country to country. Nationally-specific cultural characteristics can help predict this variation.

Based on these empirical findings, ADVANCE models have, for the first time, ventured beyond an exclusive focus on technology-related costs (see Chapter 4), in order to capture the intangible considerations of consumers when making vehicle purchase decisions. Representation of these heterogeneous behavioural features allows the models to simulate the effects of a wide-range of sectoral policies and strategies to encourage the uptake of AFVs. Such actions include (i) financial incentives (e.g., fuel taxes, subsidies, feebates), and (ii) non-financial levers (e.g., efficiency standards, vehicle mandates, refuelling infrastructure investments, exclusive access to parking spaces or roads). In addition, a wider range of strategies involving not just policymakers but also businesses and civil society, can effectively support the adoption and use of AFVs: examples include car clubs or car-sharing networks and social marketing campaigns using celebrity endorsements.

We find that concerted near-to-mid-term actions that explicitly address the non-financial dimension of consumer preferences are critical to, if not absolutely necessary for, the ultimate success of AFVs. Financial incentives, such as vehicle subsidies and fuel taxes (including carbon pricing), can certainly help; but without investments in recharging/refuelling infrastructure, heightened efficiency standards, stricter vehicle mandates and other levers, the early market for AFVs may not take off on the timescales necessary for rapid decarbonisation (Figure 5.1). If the market never takes off, then the task of mitigating carbon in the transport sector – indeed throughout the rest of the energy system – will be far more challenging. For a list of important sectoral policies that can encourage the uptake of AVs, see the box in Figure 5.1. ADVANCE focused primarily on the aggregated effect of these policies on consumer preferences rather than the explicit representation of each of the measures.

Fig. 5.1: Global shares of electric and fuel cell vehicles in 2050, assuming strong sectoral strategies ('AFV Push') or no sectoral strategies ('No AFV Action'), across six global integrated assessment models (each coloured point is a separate model). Global, economy-wide carbon pricing is assumed as climate policy in both scenarios from 2020 onward (100 US$ 2010/tCO$_2$ held constant over time), which raises fuel costs of conventional vehicles and induces a shift away from upstream fossil energy production.



Simultaneously achieving both universal clean cooking and climate mitigation goals is possible

A lack of access to clean fuels and stoves is a major global policy concern, especially in South Asia where, even today, over 70 % of the population relies primarily on solid fuels for cooking. This has far reaching effects on health and wellbeing, particularly for the most marginalised, including women and young children. Recent estimates suggest that exposure to household air pollution from solid fuels burnt in inefficient stoves is responsible for over 4 million premature deaths globally, with over 1.3 million deaths in India alone.

Without new policies and additional efforts, clean cooking fuels and stoves could remain unaffordable and inaccessible to over a third of the South Asian population, even in 2030. Expanding clean cooking may become more challenging if climate policies increase the cost of cleaner cooking fuels such as liquid petroleum gas (LPG), electricity or piped natural gas. To further investigate the interactions between climate mitigation and energy access objectives, the ADVANCE project carried out a study with a focus on South Asia to answer the following questions: Do climate mitigation policies slow down the transition to modern cooking energy services? What are the distributional impacts of these policies, particularly on the energy poor? Can effective policy design help to simultaneously achieve both access to clean cooking and climate mitigation goals?

To analyse the effect of climate policy on energy poverty we developed a model of the drivers of household fuel choice and demand - the "MESSAGE-Access" model. In contrast with traditional energy models, this model represents cooking demand for four heterogeneous population groups, covering the rich and poor in rural and urban areas. The model is used to test the implications of increasing the stringency of climate policy, and the resulting price impacts, on household cooking decisions.

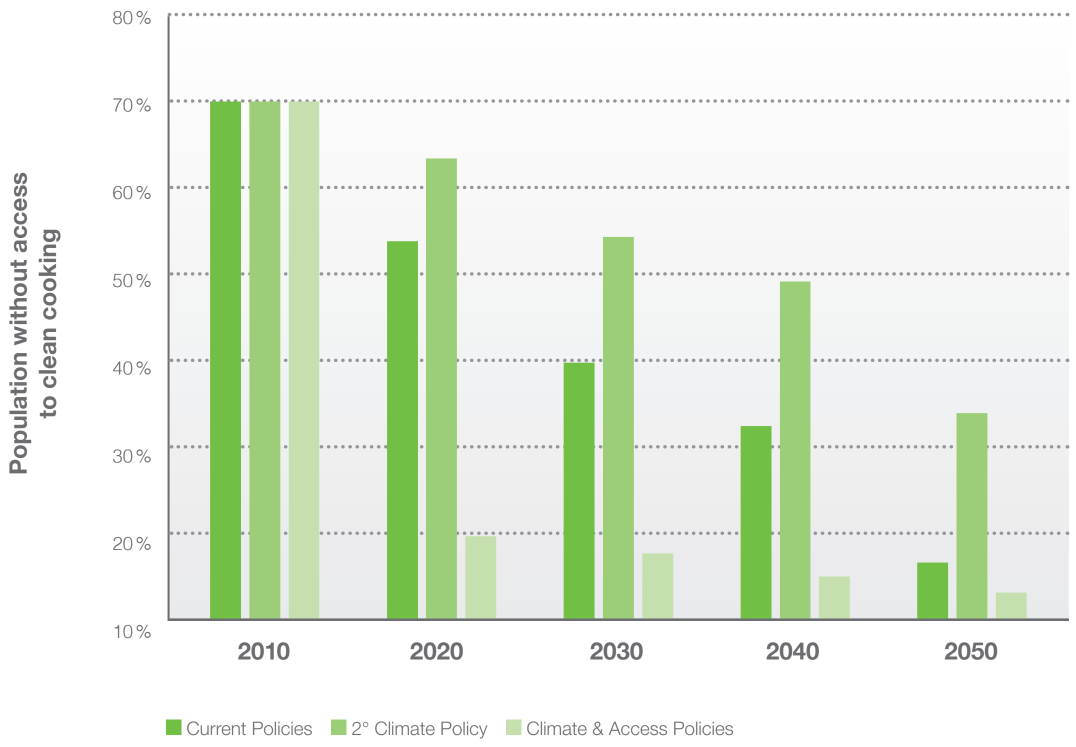
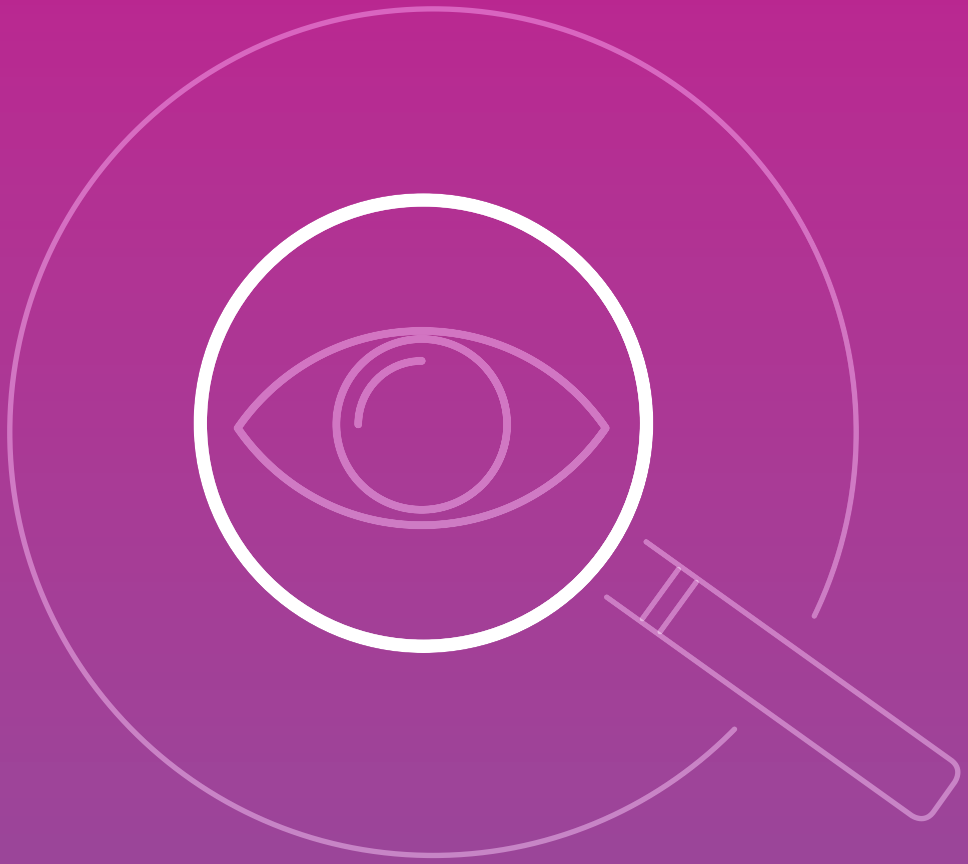


Fig. 5.2: South Asian Population dependent on solid unclean cooking over time (i) under a current policy baseline, (ii) under stringent climate mitigation policy, and (iii) when climate and access policies are implemented simultaneously to shield the poor.

We find that global climate policy can achieve a reduction in regional GHG emissions, but, as an adverse side-effect, could also slow the transition to clean cooking fuels. Under stringent mitigation (2 °C climate policy scenario), there could be up to 20 % additional solid fuel users in South Asia in 2030 compared to the Current Policies Scenario without stringent mitigation (Figure 5.2). The impacts of climate policies on those reliant on solid fuels also varies significantly between different population groups. Wealthier rural and poorer urban households are most impacted by any fuel price rises because these groups are the most likely to be able to afford transitioning to cleaner cooking as their incomes rise, if prices remain stable and infrastructure improves. Among the rural poor, income growth till 2030 is likely to be insufficient to make cleaner cooking affordable even in the absence of fuel price changes. On the other hand, the urban rich are already able to afford cleaner cooking.

The analysis carried out in ADVANCE shows that subsidies for cleaner fuels and stoves could more than offset the negative effects of rising fuel costs spurred by climate policy. Among the subsidy policies examined, the most efficient are those that support cook-stove purchases along with the lowering of fuel bills. The reason for this is that, for many people, the initial investment in a stove is the biggest hurdle to switching to clean-burning fuels.

To achieve the Sustainable Development Goals (SDG) target of universal clean cooking by 2030, more policy intervention and support than is currently available are needed, even if no climate policy is imposed. With carbon pricing in place the minimum policy support required to achieve universal access will increase, as more of the population becomes unable to afford cleaner fuels. However, the additional policy cost of achieving universal clean cooking access with climate policy is still less than the financial transfers to South Asia that may result from international effort sharing climate regimes, for example, in a per capita emissions allocation regime. Thus, climate policy might potentially act as a means to finance energy access policy costs.



VI.

INCREASING THE USEFULNESS OF INTEGRATED ASSESSMENT MODELS FOR DECISION SUPPORT

VI. Increasing the usefulness of integrated assessment models for decision support

As climate change is a long-term global problem, climate policy needs to cover all sectors and regions with a time horizon of at least a century. It therefore needs cross-scale and cross-sector policy advice which is the domain of integrated assessment models (IAMs) of climate change. As a result of this inevitable complexity, there needs to be a clear understanding of the role, purpose and limitations of IAMs as tools to inform climate policy makers.

Integrated assessment models provide maps of plausible futures between which to choose

As with every model used for policy advice, IAMs need to be fit for purpose. Climate policy makers will only consult IAMs, if they can trust them. The basis for establishing this trust is a clear communication and understanding of the use and purpose of IAMs – namely, to explore pathways for international climate policy and their determining factors in a broader “path-finding” discussion. To this end, IAMs may be seen as map-making tools – used, for example, to generate a carefully crafted set of scenarios – to navigate the space of plausible futures between which we can choose. Maps abstract from reality, and, as the history of cartography has shown, can be incomplete in many aspects and still be useful. Consulting an IAM is like consulting a map-making tool. It is useful if it produces the right kind of maps for the policy question and the user knows how to read these maps with all their limitations. ADVANCE has worked under this paradigm from the start. It has aimed to improve critical components of IAMs to enable them to make better maps for international climate policy.

Transparency is key for maintaining trust in integrated assessment models

One important element of maintaining trust in the usefulness of IAMs is transparency on how they work. A user’s willingness to consult a map will be greatly aided by a basic understanding of how the maps are produced and what they do and do not show. This does not mean the user has to become a cartographer herself. Simplified spreadsheet models that offer an interactive map-making capability are very useful for tutorial purposes, but not for drawing the maps as best as possible. Given the cross-scale and cross-sector scope of IAMs, nothing very simple should be expected – much in the same way as state-of-the-art Earth System Models are not expected to be simple. Transparency does not mean simplicity; it involves a careful documentation of IAM structure and assumptions enabling users to grasp their key characteristics and experts to evaluate their validity.

ADVANCE has heavily invested in this transparency by developing a standardised format for model documentation combining a headline summary of model features with a detailed wiki-description of model structure and assumptions (see ADVANCE model documentation under “Open-access products”). The standardisation is an important feature because IAMs are not a monolithic block of a single type of model; they come in different forms. Some focus on the energy-land-climate interactions and trade reduced information on macro-economic effects for greater detail in these sectors (partial equilibrium models). Others demonstrate a detailed representation of the economy at the expense of less detail in the energy and land sectors (computable general equilibrium models). Some take long-term planning horizons into account, while others focus on the myopic nature of human decision-making. This diversity is not a weakness, but a strength when considering policy advice. There are many maps available from different types of IAMs, and it is their combination that helps to improve the sense of their robust and sensitive features. The standardised model documentation provides a means to more easily compare the characteristics of different models. ADVANCE included IAMs of very different kinds – partial and general equilibrium, foresight and myopic – and they are now all documented using the same standard.

Model diagnostics greatly enhances the transparency of IAM characteristics

Standardised model documentation is a cornerstone of information for the comparative use of maps from multiple IAMs. What is needed, in addition, is an understanding of how different model characteristics result in different model behaviour and thus lead to differences in the maps drawn by individual IAMs. Model diagnostics aims to draw this link. In earlier projects, standardised generic climate policy runs were performed by IAMs to diagnose the differences in their policy response. ADVANCE has heavily invested in taking this a step further by generating a more detailed picture of IAM response patterns and by linking them to underlying model characteristics. For this, it has established an IAM community diagnostics database and experimental setup, allowing IAMs to compare their policy response to each other (see ADVANCE diagnostic database under "Open-access products"). The analysis has highlighted the fact that the connections between model features and model response patterns are not as simple as often claimed – for example techno-economic cost assumptions are rarely the main driver of technology deployment. In particular, it has provided important insights into the fundamental differences between model response patterns enhancing the ability of policy makers to read and use maps from multiple IAMs in context.

Structured sensitivity analysis helps understand key uncertainty dimensions

IAMs help to elucidate the dependency of mitigation strategies on a host of assumptions, for instance future socio-economic developments. The uncertainty in these assumptions results in a high degree of uncertainty in model results. To better quantify the sensitivity of results to specific assumptions, ADVANCE engaged in a structured uncertainty analysis drawing on the framework of the Shared Socio-economic Pathways (SSPs).

These SSPs have been developed to describe alternative narratives regarding socio-economic developments, spanning a wide range of plausible futures. So, for instance, while SSP1 assumes a future that is moving towards a more sustainable path, SSP2 describes a future in which development trends are not extreme, but rather follow middle-of-the-road pathways. In ADVANCE we have used this new scenario platform to improve the understanding of how future CO_2 emissions from fossil fuels are influenced by the key drivers characterising the SSPs. We used six state of the art climate-economy-energy integrated models to explore the impact of five key factors: population, income, energy efficiency, fossil fuel availability, and low-carbon energy technology development.

Uncertainty analysis of this kind has rarely been done in the past due to the computational complexities of assessing all the interdependencies. To overcome this problem, we used a newly developed decomposition algorithm which has allowed us to compute both the direct effect of each of the underlying drivers of emissions, as well as the interaction between the different drivers.

The results of this multi model, global sensitivity analysis has revealed that the assumptions about energy intensity and economic growth are the most important determinants of future emissions. This is depicted in Figure 6.1. Interaction terms between parameters have been shown to be important determinants of the total sensitivities. The results suggest that improving the understanding of energy efficiency should be a crucial priority for future research, as it has substantial potential for reducing uncertainty in IAM projections.

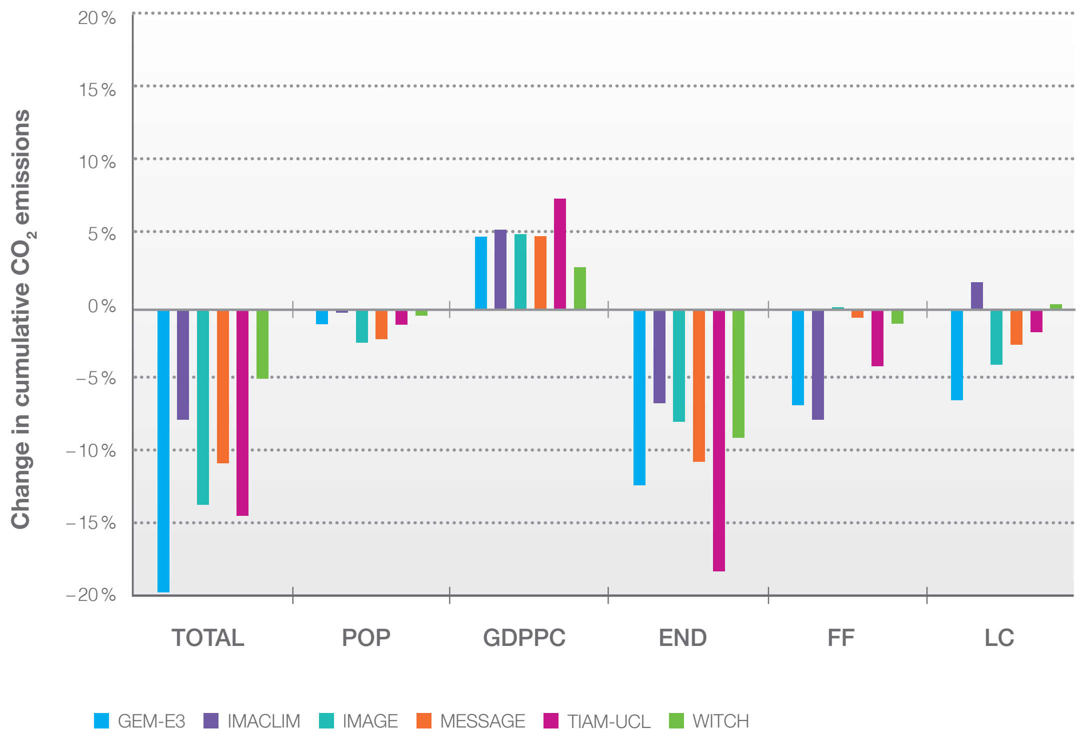


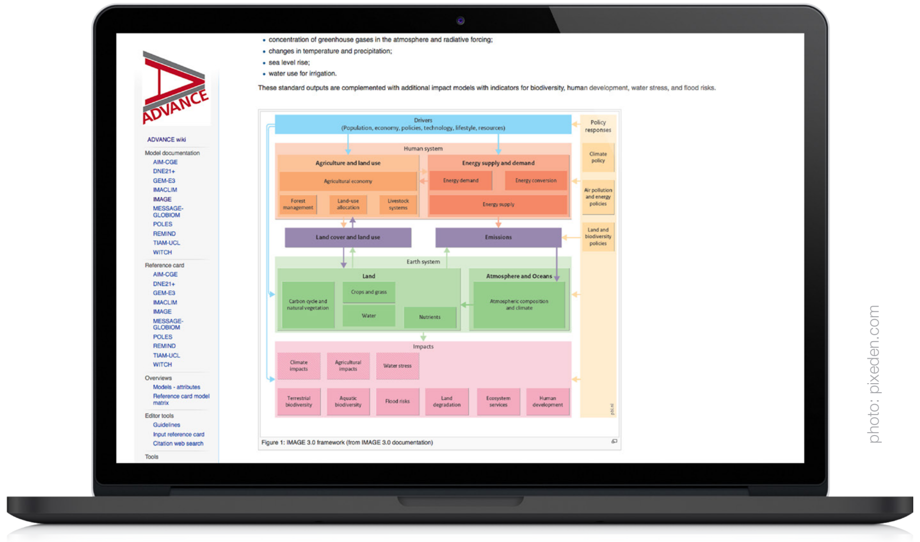
Fig. 6.1: Projected change in cumulative CO_2 emissions from fossil fuels up to mid-century when passing from the SSP2 "Middle of the road" to the SSP1 "Sustainability" narrative. The biggest emission changes are attributed to income (GDPPC) and energy efficiency (END), while population (POP), fossil fuel availability (FF) and low-carbon energy technology development (LC) are less influential.

OPEN-ACCESS PRODUCTS
PUBLICATIONS

Open-access products

ADVANCE model documentation

The ADVANCE model documentation elucidates structure and assumptions of energy-economy and integrated assessment models. The aim is to better understand key differences between modelling approaches and enhance comparability and interpretability of model results. The documentation is composed of two target-group specific components: (i) the 2-page reference cards describe main features across models and are primarily targeted to decision makers (ii) the comprehensive model documentation describes the model structure, including mathematical formulae as well as reference to relevant input datasets, and is primarily targeted towards energy-land-climate modellers, technical staff in government and firms, PhD students and postdoctoral researchers.
Web: themasites.pbl.nl/models/advance/index.php



- concentration of greenhouse gases in the atmosphere and radiative forcing;
- changes in temperature and precipitation;
- sea level rise;
- water use for irrigation.

These standard outputs are complemented with additional impact models with indicators for biodiversity, human development, water stress, and flood risks.

Figure 1: IMAGE 3.0 framework (from IMAGE 3.0 documentation)

photo: pixeden.com

Fig. 7 : Screenshot: ADVANCE model documentation hosted by the Netherlands Environmental Assessment Agency (PBL) at http://themasites.pbl.nl/models/advance/index.php

ADVANCE diagnostic database

The ADVANCE diagnostic database collects the results from individual energy-economy and integrated assessment modelling teams in a single platform. It offers modellers easy access to diagnostic indicators that allow differences in model behaviour to be better understood, enable fingerprinting of model responses as well as classification of models along their fingerprints.
Web: tntcat.iiasa.ac.at/ADVANCEWP1DB

ADVANCE modelling toolbox and scenario database

The ADVANCE modelling toolbox collects detailed descriptions of the methodologies developed in the project to ensure they are easily transferable. The toolbox includes new model components, mathematical formulae, algorithmic approaches, examples of model code, and generic input datasets. Each methodology is accompanied by a manual providing instruction for implementation. In addition, a database with final scenario results produced by the improved ADVANCE models is published for further use by the scientific community, for example in the context of future assessment reports by the Intergovernmental Panel on Climate Change (IPCC). **Web: fp7-advance.eu**

Journal publications

As of October 2016, ADVANCE has already resulted in more than twenty publications in scientific journals. Additional papers, e.g. on the effect of the Paris Agreement and 1.5 °C pathways, are currently in preparation. An updated list of ADVANCE publications can be found at http://fp7-advance.eu/content/publications.

Baker E, Olaleye O, Aleluia Reis L (2015). **Decision frameworks and the investment in R&D.** Energy Policy 80:275–285. doi: 10.1016 / j.enpol.2015.01.027

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Bertram C, Luderer G, Pietzcker RC, Schmid E, Kriegler E, Edenhofer O (2015). **Complementing carbon prices with technology policies to keep climate targets within reach.** Nature Climate Change 5:235–239. doi: 10.1038/nclimate2514.

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