2 °C and SDGs: united they stand, divided they fall?

Supplementary Information

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The supplementary information (SI) is structured as follows: SI section 1 provides a brief introduction into energy-economy-climate models, their differences and the rationale for model inter-comparison projects. SI section 2 gives an overview of important limitations of integrated models to address implications for some non-climate sustainability objectives. SI section 3 explains the link between a set of energy-related SDGs and other sustainable energy objectives, SD risks and associated indicators used in the analysis. SI section 4 lays out the main advantages of the model inter-comparison project AMPERE for such analysis. Supplementary figures and data are shown in SI section 5.

1 Integrated energy-economy-climate models

Integrated energy-economy-climate models, also often referred to as Integrated Assessment Models (IAMs), are computer-based tools to better understand the interactions between the economy, energy (in physical and economic terms) and often land-use systems as well as their effects on climate change. To explore the implications of alternative pathways in a range of plausible environments, they integrate insights from different disciplines and draw on models of both biogeophysical and human processes over long time horizons (Hourcade *et al* 2006, van Vuuren *et al* 2009, Edenhofer *et al* 2014). For example, they use information about energy resources, technologies, and investments as well as (land-use) emissions. The scenario results on which this letter's analysis is based are derived from seven different integrated energy-economy-climate models that took part in the AMPERE project (see SI section 4). They span a diversity of modelling approaches with respect to functional structures and parametric assumptions (Riahi *et al* 2015). Table S1 summarizes some of the main differences across the different models to the extent that they are relevant for our analysis. Please refer to Riahi *et al* (2015), the AMPERE website (http://ampere-project.eu) and the AMPERE scenario database for further information on the individual models and the scenario results they supplied.

The IAM community regularly organizes model inter-comparison projects in which efforts are made to harmonize key input parameters and to make model outputs comparable (Kriegler *et al* 2015b, Weyant *et al* 2006). As differences persist, a range of outcomes is plausible (Kriegler *et al* 2015a). To understand which results are robust across different models, we follow the approach of comparing results from multiple models in this letter. To circumvent climate system uncertainties with respect to the temperature response due to a given GHG emission scenario, the integrated models considered here usually calculate mitigation scenarios whose emission pathways meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. The uncertainty reflected in their results (represented by the ranges in figures 1-4 and S3-S11) is hence distinct from the uncertainty of the change in the global temperature due to different emission scenarios (see Section 6.3.2.6 in Clarke *et al* 2014). The models analyzed here belong to a type of IAM that is based on cost-effectiveness analysis (CEA) and has to be differentiated from cost-benefit analysis (CBA)-based IAMs which are more controversial, e.g., in their attempt to determine optimal climate goals (Edenhofer *et al* 2014).

Also due to this coordinated research effort, the scenario results have been an important contribution to the IPCC WGIII (e.g., Fisher *et al* 2007, Fischedick *et al* 2011, Clarke *et al* 2014) and other global environmental science assessments (GEA 2012, UNEP 2014). Many of the widely held views about the requirements to meet the 2°C target stem from their insights, e.g. the GHG emissions reductions goals of 80-95% in developed countries below 1990 levels by 2050 (Knopf and Geden 2014).

Table S1. Key characteristics and representation of multiple sustainability objectives for the global integrated model frameworks used in the analysis (partly derived from Krey *et al* 2014, and von Stechow *et al* 2015).

Model name	Model type	Metric for climate change mitigation costs	System boundaries	Non-climate sustainability objectives covered	References for model documentation
DNE21+	Energy system partial equilibrium model – intertemporal optimization	Energy system cost mark-up	Energy, climate	Air pollution, energy security	(Akimoto *et al* 2012, Sano *et al* 2015, 2012, Wada *et al* 2012)
GCAM	Energy system partial equilibrium model – recursive dynamic simulation	Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, forestry, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, energy security	(Calvin *et al* 2014, 2013, 2009, Clarke *et al* 2007)
IMAGE		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land-use change, agriculture, climate, hydrology, some adaptation (not comprehensive)	Energy access, food, water, air pollution, biodiversity loss, energy security	(Bouwman *et al* 2006, Lucas *et al* 2013, van Ruijven *et al* 2012, Vliet *et al* 2013)
POLES		Area under marginal abatement cost curve, energy system cost mark-up	Energy, land use change	Air pollution, energy security	(Dowling and Russ 2012, Griffin *et al* 2013, IPTS 2010)
MESSAGE-MACRO	Systems engineering energy system model coupled with macroeconomic generable equilibrium model – perfect foresight, optimization	GDP & consumption loss, energy system cost mark-up, area under marginal abatement cost curve	Energy, aggregated representation of land-use GHG emissions, climate, water for energy	Energy access, water, air pollution/health, energy security	(McCollum *et al* 2013, Messner and Schrattenholzer 2000, Pachauri *et al* 2013, Rao and Riahi 2006, Riahi *et al* 2007)
REMIND	Optimal growth general equilibrium model – perfect foresight, optimization	Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate,	Air pollution, energy security	(Bauer *et al* 2011, Leimbach *et al* 2010, 2009, Luderer *et al* 2013b, 2011)
WITCH		Welfare change, GDP & consumption loss, energy system cost mark-up	Energy, aggregated representation of land-use GHG emissions, climate, climate damages and adaptation	Air pollution, energy security, adaptation	(Bosetti *et al* 2009b, 2006, De Cian *et al* 2011, Tavoni *et al* 2013)

2 Limitations of integrated models to address implications for non-climate sustainability objectives

In the WGIII AR5, alternative mitigation scenarios based on integrated models were mainly used to analyze (i) the technological and energy-system requirements of staying below a pre-determined GHG concentration threshold (such as decarbonization rates in a given period) and their regional interactions, (ii) the probability of exceeding that threshold, and (iii) the associated aggregate macroeconomic costs on global or regional levels (Bruckner *et al* 2014, Clarke *et al* 2014). Only a fraction of the studies that were assessed have also analyzed (i) the potential co-benefits for non-climate sustainability objectives (such as energy access, energy security and air quality) and (ii) the risks for non-climate sustainability objectives (such as land and water availability and biodiversity). But these studies either focused on specific co-benefits and SD risks or build on individual models (von Stechow *et al* 2015).

Similar to the challenges of aggregating local co-benefits on a global scale (von Stechow *et al* 2015), mitigation risks are challenging to quantify, let alone monetize, on a global level. Recently published literature hence focuses on technology-specific indicators for global mitigation risks, such as those associated with bioenergy (see, e.g., Bonsch *et al* 2016, Humpenöder *et al* 2014, Creutzig *et al* 2012b, 2012a), comparing scenario results with empirical evidence of energy technology transition processes in the past (e.g., Guivarch and Hallegatte 2013, Wilson *et al* 2013); or outlining the socioeconomic challenges of meeting international agreements given the discrepancy between current trends and long-term requirements (Luderer *et al* 2013c, Rogelj *et al* 2013a, 2013b, 2010, UNEP 2014, Luderer *et al* 2013a, Kriegler *et al* 2015b, Rogelj *et al* 2015, Kriegler *et al* 2013).

Fully understanding the implications of alternative 2°C pathways for non-climate sustainability objectives would require modelling frameworks that can simultaneously optimize multiple objectives across sectors, regions and generations taking into account institutional settings. There are thus far, however, no modelling frameworks available that can optimize development pathways across that many objectives – also because the determination of damage functions is also highly value-laden (Ackerman and Heinzerling 2002, Lackey 2001, Pindyck 2013). This is why we draw on results from integrated models whose strength it is to analyze long-term mitigation pathways across sectors and regions in a consistent way although integrated models do neither optimize over other objectives nor measure the levels of sustainability objectives directly (for exceptions, see section 4 in von Stechow *et al* 2015). Hence, the interpretation of integrated model results as risk indicators for non-climate sustainability objectives provides, at best, a reasonable approximation of the interrelation between mitigation and multiple other objectives at the global level. Given the current little previous research on the impacts of climate change mitigation on non-climate sustainability objectives, this exercise already yields interesting new results.

Due to their global scope and coverage of the economy, energy, climate as well as land-use systems, integrated models inevitably are limited in the level of detail they can represent in other dimensions. For example, there is some critical literature on the implications of the structural set-up of and assumptions in integrated models for SD more broadly, such as for human development and inequality (e.g., Lamb and Rao 2015, Steckel *et al* 2013, Sathaye *et al* 2011, Stanton 2010). In the following paragraphs, we address some of these limitations to the extent they pertain to the models' ability to analyze the implications for non-climate sustainability objectives. Some of these limitations are briefly mentioned in the discussion of the main text while others are discussed in SI section 3. But rather than pointing to new insights, this section aims at providing an overview by structuring existing model critique into issues around (i) economic aggregation, (i) spatial aggregation, as well as (iii) institutional settings.

Like other economic models, integrated assessment models often assume homogeneity across economic agents by relying on a representative household rather than differentiating income groups or along other socio-economic criteria. This makes any analysis of distributional consequences within countries very challenging. Many climate policies have been identified as increasing equality challenges through, e.g., higher energy prices (see SI section 3.1.3), higher food prices (Wise *et al* 2014, Tadesse *et al* 2014, von Braun *et al* 2008) or indirectly through higher consumer prices (Fullerton and Metcalf 2001, Bovenberg and van der Ploeg 1994). However, integrated models can only take this into account if coupled to other models that consider, e.g., different income groups and/or rural and urban populations (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012) and skill levels (Guivarch *et al* 2011). Unless a model study is specifically designed to consider such distribution effects, multi-model results, such as those of AMPERE, are not suitable to analyze effects on SDG 1, 5 or 10.

Analyzing distributional effect among countries (SDG 10) is challenging due to the coarse spatial disaggregation of integrated models. The models only represent broad major economies, such as USA, China, Brazil and Japan as individual countries, while aggregating others to up to continental-scale macro-regions (Krey *et al* 2014). Analysis of distributional effects hence focuses on an inter-regional perspective and is only meaningful for alternative assumptions on international effort sharing regimes (Ekholm *et al* 2010, Elzen *et al* 2008, Elzen and Höhne 2008, Tavoni *et al* 2013, 2015, Aboumahboub *et al* 2014, Luderer *et al* 2012). In addition, models vary in their sectoral resolution, and only represent a limited number of sectors explicitly. This makes any analysis of technological issues related to spatial heterogeneity, such as infrastructure build-up and urban transformation (SDGs 9 and 11), highly challenging or even impossible.

With their focus on the technological and macroeconomic aspects of energy transitions, integrated models have very limited abilities to capture social phenomena and structural changes (Sathaye *et al* 2011). At the same time, there are many sustainability objectives for which institutional and social developments are much more decisive than the structure of the energy system, such as for the provision of basic services health, education and justice (SDGs 3, 4 and 16). This makes integrated models poorly equipped to address these SD dimensions.

Considering the models' limited ability to consider different income groups for different geographical characteristics and institutional settings, "an explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output" (Sathaye *et al* 2011, p 752). From the literature, we know, however, that there is a minimum energy requirement to satiate basic human needs (Pachauri and Spreng 2004, Steinberger and Roberts 2010, Lamb and Rao 2015) unless economic growth is assumed to break with historical trends (Steckel *et al* 2013). According to Lamb and Rao (2015), this threshold is approximately 30 GJ/year per capita. While the models typically do not explicitly take into account energy demands for basic needs related to cooking, heating, health and other infrastructure and services, their final energy pathways in mitigation scenarios still largely respect the 30 GJ/yr threshold. For instance, only two out of the seven models project final energy supply levels in mitigation pathways for India in 2050 that are below this level for reference assumptions on final energy (see figure S1). At the same time, as highlighted in the main text, the assumptions for lower energy demand growth need not additionally affect development outcomes but assume lower energy intensity (lowEI) through higher energy efficiency and, e.g., the viability of more compact, public transit-friendly urban areas (Riahi *et al* 2015).

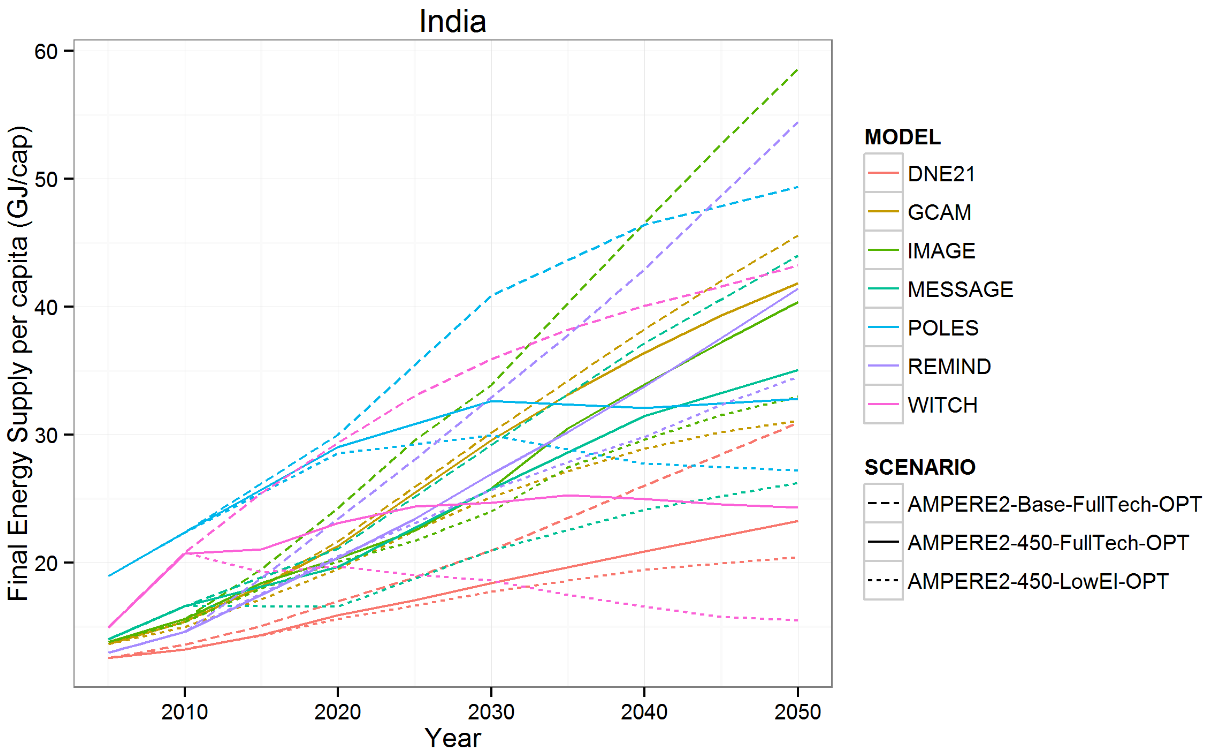

Figure S1. Final Energy Supply (in GJ) per capita for baseline scenarios and 2°C pathways with conventional and low energy demand growth assumptions

4 Linking energy-related SDGs and other sustainable energy objectives to SD risks and associated indicators based on integrated model results

This section gives some background on the choice of indicators calculated from model variables (column 1 in table 2) that approximate SD risks (column 2) for energy-related SDGs and other sustainable energy objectives (column 3), used for the analysis of alternative 2°C pathways in the main text. The choice of SD risk dimensions discussed in this letter was guided by three criteria:

1. Discussion of risk dimensions and related quantitative indicators in the literature (see table 1);
2. Possibility to link to energy-related SDGs (or other sustainable energy objectives) covering all three SD dimensions: economic, environmental and social (see SI section 3.1).
3. Public availability of model variables (from which suitable indicators can be calculated, see SI section 3.2) in the AMPERE database to serve transparency purposes (see SI section 4);

SI section 3.1 lays out in some detail the avenues by which mitigation can lead to increased or decreased risks for non-climate sustainability objectives and how the different SD risks can be linked to a set of energy-related SDGs and other sustainable energy objectives. It should be noted that many risk dimensions in fact have an impact on several SDGs – both in negative and in positive ways (see figure S2 for an overview) and choosing a single SDG to represent one risk dimension means simplifying these complex interlinkages. SI section 3.2 then explains how the chosen indicators for these risk dimensions can be calculated from integrated model variables reported in the AMPERE scenario database.

4.1 Linking SD risks to energy-related SDGs and other sustainable energy objectives

This section discusses the second criterion and reviews literature on the basis of which the link between SD risk dimensions and SDGs and other sustainable energy objectives can be established. This section is partly based on the Supplemental Material from von Stechow *et al* (2015) which reviews recent literature on the co-effects of mitigation measures in the energy supply as well as different energy demand sectors. As in von Stechow *et al* (2015), the discussion of co-effects in the agriculture, forestry and other land-use (AFOLU) sector is limited to the co-effects of increasing bioenergy supply – mainly because this was not a focus of the AMPERE project.

As discussed in SI section 2, integrated models have some limitations in their ability to address some non-climate sustainability objectives, such as distributional effects. This is why this section does not discuss links to some important SDGs, such as SDG1 ("end poverty in all its forms everywhere") and SDG 10 ("reduce inequality within and among countries"). To some extent, however, the chosen set of indicators implicitly speaks to the aims of poverty and inequality reduction, because:

i) food security concerns are most problematic for the urban poor (Ahmed *et al* 2009);
ii) air pollution disproportionally impacts the poor in dense urban areas (Frumkin 2002);
iii) not achieving energy access goals threatens the associated benefits in terms of local economic development, educational benefits, and income generation (SI section 3.1.6);
iv) economic growth reduction makes poverty reduction more challenging (SI section 3.1.4);
v) jobs at risk in the fossil fuel industry affect the unskilled most (Fankhauser *et al* 2008).

4.1.1 *Bioenergy expansion and food security (SDG 2)*

Achieving food security is an important aspect of SDG 2 but may be challenging to achieve in the light of climate change. On the one hand, stringent mitigation is likely to avoid the worst impacts of climate change which endangers sustainable food production systems (Porter *et al* 2014). On the other hand, an increased amount of biomass demand for energy purposes required in many mitigation scenarios may induce competition on arable land (except for bioenergy derived from residues, wastes or by-products) (Haberl *et al* 2014) with resulting impacts on food production and security (Ewing and Msangi 2009, Finco and Doppler 2010, Tilman *et al* 2009).[1] In a study that compares the effect of 100 EJ of lignocellulosic bioenergy to the potential climate impacts of a high-emission scenario on crop yields, the benefits of bioenergy for mitigation outweigh the adverse impacts in terms of food prices increases (Lotze-Campen *et al* 2014). But with higher amounts of bioenergy demand, the risks are likely to increase: Bioenergy production and the resulting land competition have implications for many non-climate sustainability objectives, such as reducing water availability (SDG 6.4), displacing communities and economic activities (SDG 8), driving deforestation (SDG 15.2), reducing soil quality (SDG 15.3), and impacting biodiversity (SDG 15.5) (Amigun *et al* 2011, Borzoni 2011, Chum *et al* 2011, Creutzig *et al* 2013, German and Schoneveld 2012, Hall *et al* 2009). Most integrated models are not yet well equipped to study these effects, but preliminary research exists, e.g., on water and biodiversity impacts (Bonsch *et al* 2016, De Fraiture *et al* 2008, PBL 2012, van Vuuren *et al* 2015). The main potential co-benefits seem to be related to improved access to energy services (SDG 7), job creation (SDG 8.3), and energy security (Amigun *et al* 2011, Arndt *et al* 2012, Duvenage *et al* 2012, Finco and Doppler 2010, Huang *et al* 2012, Leiby and Rubin 2013, Tilman *et al* 2009). More generally, due to the different bioenergy sources as well as to the specificities of the areas where bioenergy is produced, SD impacts from bioenergy are context-, pace- and size-specific (Bustamante *et al* 2014, Creutzig *et al* 2013, Popp *et al* 2011, Smith *et al* 2014b).

4.1.2 *Air pollutant concentration and health via air quality (SDG 3.9)*

One important aspect to ensure healthy lives is to substantially "reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination" (SDG 3.9). SO_2 and NOx, for instance, contribute to the acidification of water bodies (SDG 6.3) and soil (SDG 15.3) and NOx to eutrophication – a threat to biodiversity (SDG 15.5) (Hertwich *et al* 2010, Rockström *et al* 2009). Exposure to particulate matter (PM), emitted directly as BC and OC or formed from SO_2 and NOx, leads to premature deaths of more than 3.5 million people per year (Lim *et al* 2012, Smith *et al* 2014a). More than 80% of the global population is still exposed to PM concentrations that exceed the WHO recommendations of 10 µg/m3 $PM_{2.5}$ (Rao *et al* 2013). But the local health effects can differ substantially depending, for example, on the efficiency of the combustion process, the place of the emission source, the scrubber technology, the downwind population concentration as well as the background pollution from other sources (Bell *et al* 2008, Smith and Haigler 2008, Sathaye *et al* 2011).

In addition to the reduced health effects of less air pollution and resulting water and soil pollution, reducing air pollutant emissions arising from energy supply also helps protecting and restoring the

[1] Some agroforestry plantation can contribute to food security while producing biomass resources (Smith *et al* 2014b).

sustainable use of marine and terrestrial ecosystems (SDGs 14 and 15). Even though some individual low-carbon energy technologies such as concentrated solar power tower technologies, some hydropower plants and CCS technologies show considerable pollution-related health and ecological effects – taking into account life-cycle emissions and thus accounting for emissions from material and fuel production, manufacturing, operation and decommissioning – Hertwich *et al* (2015) generally found significantly lower pollution-related indicators for renewable energy (RE) technologies (see discussion in SI section 3.1.6 on wind energy and PV). This co-benefit is mainly due to the reduction of co-emitted pollutants associated with the decarbonization of energy supply, which is nearly complete in 2050 for stringent 2°C pathways (Bruckner *et al* 2014, Clarke *et al* 2014, Riahi *et al* 2015). Integrated model studies indicate that there are significant co-benefits for a number of pollutants – up to 50/35/30/22% reductions by 2030 globally of SO_2, NOx, $PM_{2.5}$, and Hg emissions or concentrations relative to baseline scenarios (see von Stechow *et al* 2015 for a review).

Finally, methane emissions that contribute to the formation of tropospheric ozone with negative impact on crop yields (van Dingenen *et al* 2009) can be reduced in coal mining and gas and oil production (Bruckner *et al* 2014). Reducing fossil fuel use, particularly coal, and methane leakage reduction can mitigate near-term climate change and improve health and food security (Anenberg *et al* 2012, Shindell *et al* 2012).

4.1.3 Energy price growth and energy access (SDG 7)

SDG 7 aims at ensuring “universal access to affordable, reliable, and modern energy for all”. This is a huge challenge since more than 1.3 billion people worldwide, especially in sub-Saharan Africa and developing Asia, lack access to electricity and over 2.5 to 3 million people are estimated to lack modern fuels for heating and cooking (IEA 2012, Pachauri *et al* 2013). Whilst improvements in energy access do not need to entail significant changes in GHG emissions (Pachauri *et al* 2013), climate policies are likely to increase energy prices, at least in the short term, due to carbon pricing, fuel switching and higher energy production costs from low-carbon energy technologies (Bertram *et al* 2015b, Bruckner *et al* 2014, Fischedick *et al* 2011, Jakob and Steckel 2014) which can result in higher challenges for achieving energy access objectives (van Ruijven *et al* 2012, Cameron *et al* 2016, Pachauri *et al* 2013, Daioglou *et al* 2012, Krey *et al* 2012, van Vuuren *et al* 2015).

Even though the global energy price index that was used for this letter (see SI section 3.2.2) is generally set to increase in mitigation scenarios with conventional energy demand growth assumptions, the effect on those without energy access today depends importantly on locally specific circumstances, such as the type of fuel used by different income groups, the distribution of the revenues from climate policy and the effectiveness of pro-poor policies that are in place today or could be implemented to complement climate policies (Casillas and Kammen 2010). In fact, a recent study shows that the costs of achieving energy access change with the stringency of climate policy but are even more sensitive to the way energy access policies are implemented (Cameron *et al* 2016).

The effects of energy prices on economic growth are not explicitly analyzed here because the macroeconomic effects of mitigation, including general equilibrium effects of changing energy prices, are captured to some extent by the integrated models (see below in SI section 3.1.4). To what extent higher energy prices are a concern from an inequality perspective depends on the distributional consequences, which cannot be derived from the AMPERE scenario database (see SI section 2). Since poorer households spend a higher proportion of their disposable income on energy needs, higher energy prices are a problem not just for those without sufficient energy access today (Moore 2012). While there is a regressive impact of higher energy prices in developed countries (Grainger and Kolstad 2010, Romero-Jordán *et al* 2016, Frondel *et al* 2015, Nelson *et al* 2011), the empirical evidence is mixed for developing countries (Jakob and Steckel 2014). Fuel taxes, for example, seem to be generally progressive in poor countries (Somanathan *et al* 2014).

In addition, higher energy prices are not only a concern for energy access goals, but also for health (SDG 3): Higher energy prices could adversely affect the ability of households to guarantee a certain level of consumption of domestic energy services (especially heating) or may place disproportionate expenditure burdens to meet these needs. Fuel poverty has a range of negative effects on the health and welfare of fuel poor households, such as an increase in excess winter mortality rates, excess morbidity effects, depression and anxiety (Clinch and Healy 2001). But these effects can be greatly reduced by mitigation measures in the buildings sector (Ürge-Vorsatz and Tirado Herrero 2012).

4.1.4 Consumption growth reduction and economic growth (SDG 8.1)

Sustaining economic growth is one of the core requirements to achieve a number of non-climate sustainability objectives, such as poverty reduction (Ravallion and Chen 1997, Rodrik 2008) and higher employment levels (Blanchard and Wolfers 2000, Crivelli *et al* 2012, McMillan *et al* 2014), and are reflected in SDGs 1 and 8. While the negative impact of stringent climate policy on aggregate measures of consumption growth is limited (see SI section 3.2.1), integrated models project higher transitional economic growth reductions in the decade after implementation of the climate policy (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013a, 2013c). Because the effects in the short to medium term are of particular interest for achieving SDG 8.1, this letter's focus is on transitional rather than aggregate long-term metrics of economic growth reductions as mitigation risk indicator.

4.1.5 Stranded fossil investment and full employment (SDG 8.3)

Achieving full and productive employment features as another sub-goal of SDG 8. While many mitigation measures potentially have a positive effect on gross job creation (such as energy efficiency measures in the housing and industry sectors as well as upscaling of RE, see below in SI section 3.1.6), the net effect of mitigation pathways on employment in the medium to long term remains disputed, considering all aspects of mitigation technologies (e.g., labor intensity and implications for job quality and skills) as well as trade, investment, innovation and general equilibrium effects (Babiker and Eckaus 2007, Böhringer *et al* 2013, Clarke *et al* 2014, Fankhauser *et al* 2008, Guivarch *et al* 2011). Yet, it is clear that many jobs in the fossil fuel industry (and the associated value chains) will be lost in the short term due to the energy system transition from carbon-intensive industries towards more low-carbon sectors (Fankhauser *et al* 2008).

Since it is difficult for policy makers to credibly commit to a climate policy trajectory, investors will find it challenging to make investment decisions consistent with long-term climate goals in a changing policy environment dominated by uncertainties about the possibility and extent of global cooperation on climate change mitigation (Brunner *et al* 2012). Accordingly, from 2005 through 2013, approximately 722 GW of new capacity was added to the global coal fleet and over 1,000 GW of coal power plant capacity is still proposed globally – despite a drop of 23% from 2012 numbers (Shearer *et* *al* 2015). Some experts speak about a 'renaissance of coal' (Steckel *et al* 2015). To avoid excess job losses (and the associated negative effects on overall economic output) when choosing climate policies, decision makers should be interested in minimizing the additional build-up of long-lived carbon-intensive infrastructure (such as coal power, see SI section 3.2) (Rozenberg *et al* 2014). This is because a large share of any new coal capacity built over the next decades would likely need to retire early to comply with the carbon budget consistent with the 2°C target – with the associated employment implications.[2] This is particularly important in emerging economies where most new capacity would be built (Bertram *et al* 2015a, Johnson *et al* 2015). Early retirement of thermal power plants also impacts power grid stability (Holttinen 2012) that is discussed in the next sub-section.

4.1.6 Wind & PV grid integration and resilient infrastructure (SDG 9)

Building resilient infrastructure features as SDG 9 to support economic development and human well-being. As described in SI section 3.2.7, adding large amounts of partially dispatchable and predictable RE capacity (e.g., wind energy and PV) in a short time is a challenge for power grids. The resulting technical and economic risks may even put public acceptance of RE at risk as can be observed in the public debate on the German 'Energiewende' (Frondel *et al* 2015, 2012). This is a concern from the perspective of many other SDGs on which higher RE deployment would have positive impacts:

- Replacing coal with wind and PV would be associated with a wide range of co-benefits as their pollution-related indicators are generally significantly lower (Hertwich *et al* 2015).[3] This would reduce the number of deaths and illnesses from air pollution (SDG 3.9), improve the water quality by reducing pollution (SDG 6.3) and contribute to "conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services" (SDG 15.1). This is also helped by the fact that the consumptive water use of wind energy and PV is small (Meldrum *et al* 2013).
- Higher deployment of wind energy and PV links directly to a sub-goal of SDG 7 (7.2: "increase substantially the share of RE in the global energy mix by 2030") because they can help promote off-grid access to energy services in countries with little central grid access. This is because research indicates that improved energy access by means of RE also stimulated local economic development in a number of developing countries (Goldemberg *et al* 2008, Walter *et al* 2011) and led to educational benefits and enhanced support for income generation in large parts of the developing world (Bazilian *et al* 2012, Kanagawa and Nakata 2007, Sokona *et al* 2012).
- Studies from China, Germany, Spain and the US found net job gains due to an increased share of RE with higher labour intensity (Cai *et al* 2011, Lehr *et al* 2012, Ruiz Romero *et al* 2012, Wei *et al* 2010). Similar results have been found for RE in the buildings sector (Lucon *et al* 2014). On the one hand, this may help achieving SDG 8, namely "higher levels of productivity of economies…through a focus on high value added and labour-intensive sectors" (SDG 8.3). On the other hand, RE, particularly PV, still relies on substantial public support, implying that some of the above adverse effects apply with respect to opportunity costs of using public funds and skilled

[2] As witnessed in Germany, even the prospect of climate regulation that would necessitate the retirement of rather old coal power plants led to a public debate and subsequent withdrawal of the initial proposal, based on (mainly unsubstantiated) arguments around potentially substantial job losses in particular regions and supplying industry (Oei *et al* 2015).

[3] It should be noted, however, that collisions of birds and bats with wind power plants are an important concern (Giavi *et al* 2014, Lehnert *et al* 2014, Marques *et al* 2014).

workers as well as trade and general equilibrium effects (see SI section 3.1.5) (Böhringer *et al* 2013, Frondel *et al* 2010, Lambert and Silva 2012).

- Finally, higher RE deployment in mitigation scenarios generally leads to lower energy imports (Criqui and Mima 2012, Jewell *et al* 2014, Kruyt *et al* 2009), a co-benefit for energy security.

4.1.7 Energy security

Energy security vulnerabilities can be characterized by three different perspectives: sovereignty (risks primarily arise from foreign actors), robustness (risks can be calculated and avoided) and resilience (risks are uncertain and systems must be designed to be able to recover from disruptions) (Cherp and Jewell 2014, 2011). For the purposes of this letter, we focus on oil security since it is the most vulnerable fuel globally with most countries dependent on imported oil from a limited number of exporting countries, the most acute scarcity concerns (both real and perceived) and it faces virtually no substitutes in the transport sector (Cherp *et al* 2012). In fact, the inflexibility of the oil system is one of the reasons it has been one of the main foci of energy security strategies, in particular with the creation of the International Energy Agency (IEA) after the 1970s oil crises.

For our analysis, we consider one indicator for each perspective on oil security: cumulative oil trade to represent sovereignty risks (see SI section 3.2.10); cumulative oil extraction to represent robustness concerns (see SI section 3.2.11); and non-oil use in the transport sector to represent the resilience perspective (see SI section 3.2.12). This admittedly neglects energy security risks arising from critical infrastructure vulnerabilities (Farrell *et al* 2004) – except short-term reliability concerns from variable renewables (see SI section 3.2.7) (Johansson 2013) – but infrastructure is not very well depicted in integrated models so is not the best tool to explore these types of risks (see SI section 2).

4.1.8 Peaceful use of nuclear power

Many mitigation scenarios depict tremendous growth in nuclear energy – up to four times current levels by mid-century (Kim *et al* 2014). The risks associated with nuclear energy include accidents, physical security – nuclear materials falling into the wrong hands – and proliferation – the spread of nuclear weapons and fissile material to new countries (von Hippel *et al* 2012).[4] Similar to the relationship with energy intensity (EI), the less energy produced from nuclear, the lower each of these risks is. The accident risk is calculated in terms of incidents per reactor years; thus all else being equal, increasing the nuclear power fleet increases the risk of accidents. Yet, many integrated models do not distinguish between types of nuclear power plants, let alone which safety mechanisms are implemented where so the only way to analyze this would be assume the same accident risk for the full nuclear fleet. Thus for the purposes of our analysis we focus on physical security and proliferation risks related to nuclear power (see SI section 3.2.5).

[4] Some epidemiological studies on the health effect of radioactive material handling find a higher childhood leukemia of populations living within 5 km of nuclear power plants (Heinävaara *et al* 2010, Kaatsch *et al* 2008, Sermage-Faure *et al* 2012). Nuclear energy also reduces pollution-related indicators compared to coal with positive health effects (Hertwich *et al* 2015) making the net effect on health very challenging to assess.

4.1.9 Environmental risks of CCS chain and sustainable production (SDG 12.4)

Achieving environmentally sound management of chemicals and reducing their release to air and water to minimize their adverse impacts on human health and the environment features prominently in SDG 12. While CCS is an important mitigation technology, particularly because it can be coupled with bioenergy to produce negative emissions and thus increases the flexibility to reach stringent climate goals (Clarke *et al* 2014, Fuss *et al* 2014), high deployment of CCS increase the environmental concerns of fossil-fuel based power supply. On the one hand, the CCS process requires 16-44% of additional energy (Corsten *et al* 2013), thereby increasing the fuel requirements and associated environmental impacts, such as ecological damage (SDG 15), higher mudslides risks, and water contamination (SDG 6.3) (Adibee *et al* 2013, Palmer *et al* 2010, Smith *et al* 2013). On the other hand, CO_2 capture requires a pure gas stream, reducing some air pollution from the power plant, such as SO_2 (Koornneef *et al* 2008). Investigating different CCS technologies for relevant life-cycle indicators, Hertwich *et al* (2015) find that, on balance, CCS leads to increases in PM, toxicity and eutrophication by 5-60% compared to modern coal and gas power plants. Many of these additional air pollutant emissions would also negatively impact health (SDG 3.9, see SI section 3.1.2) and marine ecosystems (SDG 14). If coal is substituted by biomass (to enable net negative GHG emissions via BECCS), Schakel *et al* (2014) find that the biomass supply chain and the combustion-related pollution are comparable to that of coal with respect to environmental and health impacts.

Most CCS technologies also significantly increase water withdrawal and consumption (up to 100%) due to efficiency penalties and additional process demands (Zhai *et al* 2011, Meldrum *et al* 2013) – with the latter causing ecological impacts (Verones *et al* 2010). There are also concerns about groundwater contamination due to CO_2 leakage (Apps *et al* 2010, Atchley *et al* 2013, Siirila *et al* 2012). As much as additional wind energy and PV helps alleviating concerns about water availability and quality, CCS may hence add to these (SDG 6.3). As discussed in SI section 3.2.4, there are substantial uncertainties attached to the hydrogeological characteristics and volumes of the geological reservoirs. For example, concerns about induced seismicity could potentially affect surface structures or simply alarm the population (Mazzoldi *et al* 2012). With open questions about the resilience of existing reservoirs (White *et al* 2014), higher CCS deployment may increase concerns about the resilience of the installed infrastructure (SDG 9).

On the positive side, retrofitting CCS can potentially alleviate the extent of stranded investment of coal-power plants (Johnson *et al* 2015). Successful deployment of CCS technologies could potentially preserve many jobs in the fossil-fuel industry (Fankhauser *et al* 2008, Wei *et al* 2010) – a contribution to achieving SDG 8.3 in the short term.

4.1.10 Peak atmospheric CO_2 concentration and minimization of ocean acidification (SDG 14.3)

Ocean acidification is an important global change problem and hence features as one sub-goal of SDG 14. While it is often analyzed together with impacts of climate change (IPCC 2014), future changes in ocean acidification are largely independent of the amounts of climate change but are mainly driven by CO_2 emissions (Cao *et al* 2007). As such, reductions in ocean acidification and associated aragonite saturation states (Ω_a) can also be regarded as a co-benefit of CO_2 emissions reductions primarily targeted at climate change mitigation (Joos *et al* 2011). High changes in pH and Ω_a adversely affect vulnerable marine organisms that build shells and other structures from aragonite (Orr *et al* 2005). For example, if atmospheric CO_2 is stabilized at 450 ppm, only 8% of existing coral reefs will be surrounded by water with pre-industrial saturation levels down from 98% (Cao and Caldeira 2008). These concentrations are surpassed by 2050 in some delayed 2°C pathways due to high concentration overshoot whereas pathways without negative emissions stay below that threshold. Whereas global mean temperature change mainly depends on cumulative CO_2 emissions (IPCC 2014), the response of pH and Ω_a is delayed in the ocean interior – highlighting the importance of 2°C pathways with low concentration overshoot to avoid irreversible damage (Mathesius *et al* 2015).

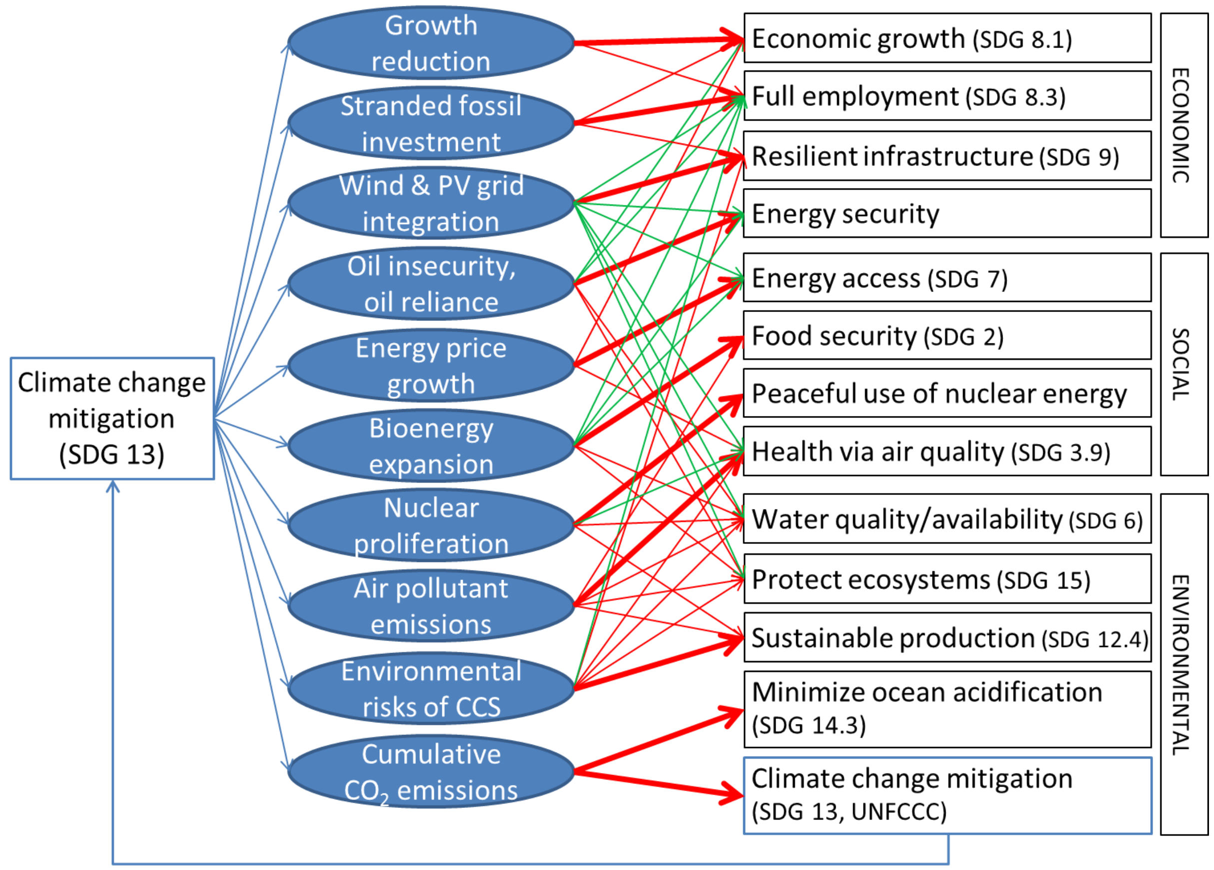

Figure S2. The SD risks were chosen (i) based on existing literature and such that (ii) associated indicators can be calculated from integrated model variables that are readily available from scenario results in the AMPERE scenario database to serve transparency purposes; and (iii) link directly to a set of energy-related SDGs and other multilaterally agreed sustainable energy objectives covering all three SD dimensions: economic, environmental and social.

4.2 Linking indicators calculated from integrated model variables to SD risks

All indicators for SD risks that are described in detail below – following the order of the indicators as they appear in figure 5 – show the difference between the value for each mitigation scenario and that for the baseline as a percentage of the baseline value (except for Figure 5 which compares alternative 2°C pathways to each other, see Table S.4 for the underlying data). The baseline is derived from the values of the "AMPERE2-Base-FullTech-OPT" scenario in the same model, unless otherwise stated. For the indicator for which baseline scenarios show values of or near zero (and hence does not lend itself to an analysis of relative changes), the following paragraphs introduce a reference value against which the values from mitigation scenarios are compared (see SI section 3.2.4).

4.2.1 Maximum decadal consumption growth reduction

While cost-benefit analyses (CBA) of climate change mitigation has been prominently discussed in climate economics (Stern, 2008), the approach has many drawbacks (as discussed, e.g., in Edenhofer *et al* 2014, Kunreuther *et al* 2014, Pindyck 2013). Most studies with integrated models rather analyze the macroeconomic costs of not exceeding a specific mitigation goal in the most cost-effective way (CEA, see SI section 1).

Since in this mode of operation mitigation scenarios do not account for avoided damages or co-benefits, the climate constraint to the respective optimization models leads to lower economic activity and hence a reduction of available consumption compared to baseline developments (Paltsev and Capros 2013). Depending on the modeling framework, these effects are measured in different metrics, such as the area under the marginal abatement curve, the aggregated and discounted increase in energy system costs, or aggregated and discounted GDP or consumption losses relative to GDP (see table S1). While many studies have analysed aggregate economic indicators for the mitigation costs, the analysis of delayed scenarios highlights that such cumulative metrics are not reflecting the full economic costs borne by societies: due to the discounting usually applied when calculating aggregated costs, sharp increases of costs in later decades (due to delayed climate policy scenarios) are not fully reflected in cumulative metrics. Metrics that measure transitional costs, such as the maximum transitional costs to be born within a decade, expressed as reduction of consumption growth, have been used to illustrate the economic challenges beyond the cumulative, discounted approach (Bertram *et al* 2015b, Kriegler *et al* 2013, Luderer *et al* 2013c) and can be calculated based on reported data from MESSAGE, GCAM and WITCH.

For the purpose of this letter, the indicator is defined as the maximum difference (in percentage change) in the consumption (C) growth rate (g) over a decade between mitigation and baseline scenarios in the same model – compared to a 1% change in the growth rate in the same period.

$$\max_{2010<t<2050} \left(g^{\mathrm{Baseline}}(t) - g^{\mathrm{Mitigation}}(t)\right)/1\%$$

where for each scenario

$$g(t) = \frac{C(t) - C(t-10)}{C(t-10)} \cdot 100\%$$

is the decadal rate of growth (in percentage change) for each scenario.

4.2.2 Maximum decadal energy price growth

Measuring the macroeconomic costs of mitigation for societies implicitly or explicitly takes into account inter-generational distributions by means of choosing a specific discount factor. But adjustment costs and intra-generational distribution issues are often neglected (Fleurbaey *et al* 2014, Fleurbaey and Zuber 2012). While direct analysis of the distributional impacts of climate policy is not possible with such global models with only coarse geographical scales and assumptions on homogeneity of economic agents (see SI section 2), some recent studies identified economic indicators that could be indirectly related to distributional issues. One example for such an indicator is the maximum growth of an energy price index to be born within a decade, calculated similarly to a consumer price index, due to climate policies (Bertram *et al* 2015b, Luderer *et al* 2013c). Although such an indicator is only an approximation for the actual increase of household expenditure for energy services (see SI section 3.1.3), it is an interesting alternative, given that energy services are not explicitly modelled in the majority of integrated models. Since the models that report secondary energy prices (MESSAGE and REMIND) include carbon price mark-ups, the indicator is set to increase for climate policy.

For the purpose of this letter, the indicator is defined as the maximum decadal increase in the Energy Price Index (*EPX*) in the given time period, where *EPX* is the weighted average of the price (*p*) of the secondary energy demand basket (*SE*) relative to the price of the same basket 10 years previously.

$$EPX(t) = \sum_i p_i(t) SE_i(t) \, / \sum_i p_i(t-10) SE_i(t),$$

such that maximum decadal energy price growth (in percentage change) is

$$\max_{2010<t<2050} \frac{EPX_{\mathrm{Mitigation}}(t) - EPX_{\mathrm{Baseline}}(t)}{EPX_{\mathrm{Baseline}}(t)} \cdot 100\%$$

4.2.3 Idle coal capacity per year

Due to the high GHG emissions of the current, mainly fossil-based, energy system, stringent mitigation goals necessarily lead to a significant energy system transition (Bruckner *et al* 2014). Should the global community or individual countries ramp up climate policies, some existing and even newly built fossil capacities may turn out to be unprofitable since they are not able to recover their short-term costs, ending up as stranded investments (Bosetti *et al* 2009a) (see SI section 3.1.5).

Since integrated models project more carbon-intensive coal power plant build-up for the next decades in delayed mitigation pathways (assuming myopic investment behavior), these are the plants that would – under normal market conditions – still operate in 2050 but may have to be prematurely retired for suddenly high carbon prices after the period of delay (Bertram *et al* 2015a, Johnson *et al* 2015). This is approximated by the amount of 'idle coal capacity' in the models which depends on the carbon intensity reduction rates necessary to stay within the carbon budget which is more challenging the later emissions peak and the higher this peak level will be (Johnson *et al* 2015). Here, we build on the metric used by Bertram *et al* (2015a), who calculate the average load factor of the global coal capacity, albeit looking at the share lying idle in mitigation scenarios.

For the purpose of this letter, the indicator measures the percentage change in the share of coal power plant capacity – "Capacity|Electricity|Coal|w/o CCS" (*Capacity_Coal* in GW) – in 2050 that is not being used to generate electricity – "Secondary Energy|Electricity|Coal|w/o CCS" (*SE_Coal* in EJ/a) – i.e. is lying idle:

$$\frac{\left(1 - \frac{Capacity\_Coal^{\mathrm{Mitigation}}(2050)}{SE\_Coal^{\mathrm{Mitigation}}(2050) \cdot \mathrm{s/a}}\right) - \left(1 - \frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050) \cdot \mathrm{s/a}}\right)}{\left(1 - \frac{Capacity\_Coal^{\mathrm{Baseline}}(2050)}{SE\_Coal^{\mathrm{Baseline}}(2050) \cdot 0.031536}\right)} \cdot 100\%$$

4.2.4 *CO_2 captured and stored per year*

In addition to other concerns (see SI section 3.1.9), one major uncertainty in the process chain of CCS are the hydrogeological characteristics and volumes of the geological reservoirs in which the CO_2 is supposed to be stored (Humpenöder *et al* 2014). Since the global storage potential of deep saline aquifers is large compared to alternative storage types (1000 up to 10000 Gt, see Benson *et al* 2005), the uncertainty about hydrogeological data leads to high ranges of estimates. The IEA qualifies the storage in depleted oil and gas fields for which reliable data already available as well as the usage of CO_2 for 'Enhance Oil Recovery (EOR)' as 'early opportunities' (IEA 2009). Since point sources of CO_2 do not necessarily arise in places with the largest storage sites, source-sink matching leads to lower storage potential estimates. If global CO_2 storage demand exceeds these estimates, more risky reservoir types have to be tapped.

Drawing on the regionally differentiated estimates of Hendriks *et al* (2004), the global CO_2 storage potential for depleted oil and gas fields stands at 250 Gt CO_2 (best estimate). Assuming an injection duration of 50 years (to avoid pressure build-up, see Szulczewski *et al* 2012), the storage potential per year amounts to 5 Gt. Although more storage volume is available from other reservoir types (deep saline aquifers, coalbed methane recovery), all values above 5 Gt are judged as more risky.

For the purpose of this letter, the indicator measures the percentage increase of CO_2 emissions stored – "Emissions|CO2|Carbon Capture and Storage" (*Emi_CCS*) – in geological storage facilities in 2050 relative to a reference value of 5000 Mt that can presumably be stored at low technical risks.

$$\frac{Emi_{\mathrm{CCS}^{\mathrm{Mitigation}}(2050)} - 5000\ \mathrm{Mt\ CO_2}}{5000\ \mathrm{Mt\ CO_2}} \cdot 100\%$$

4.2.5 *Nuclear capacity expansion in Newcomer countries*

Today, only thirty countries have nuclear energy but much of the development of nuclear power in low-carbon scenarios happens in regions where nuclear power has played a very small role. The question then becomes, does a spread of nuclear power increase the risk of proliferation and physical security concerns? The relationship between proliferation and civilian nuclear power programs is contentious to say the least. However, there is generally consensus that civilian nuclear power programs shorten the time it would take a country to develop the bomb (Sagan 2011). There's also empirical evidence that 'client' countries that have nuclear cooperation agreements with 'supplier' countries are more likely to develop nuclear weapons (Fuhrmann 2009). Since few 'Nuclear Newcomers' would be able to introduce nuclear power without significant international support (Jewell 2011), the growth of nuclear proliferation would increase with the spread of the technology to new countries.

To measure this risk, we developed an indicator for the (percentage) change in the capacity of nuclear power in countries which today do not currently have nuclear power. In the absence of country-by-country values, this is approximated as the sum of nuclear capacity – "Capacity|Electricity|Nuclear" (*Capacity_Nuc*) – in 2050 in regions (*r*) that largely do not have nuclear power (Asia, the Middle East and Africa and Latin America) less the sum of the projected nuclear capacity (i) in those countries which do (China, India and Brazil) and for which the AMPERE database supplies data.[5]

$$\frac{NewNuclear^{\text{Migitation}} - NewNuclear^{\text{Baseline}}}{NewNuclear^{\text{Baseline}}} \cdot 100\%,$$

where

$$NewNuclear = \sum_{r} Capacity\_Nuc(2050) - \sum_{i} Capacity\_Nuc(2050)$$

4.2.6 Biomass supply for energy per year

Biomass is a basic resource for food, fodder and fiber and is hence crucial to many peoples' well-being, particularly for those that have to rely on subsistence agriculture and on traditional biomass for cooking and heating. Since it is also a versatile form of RE, potentially being able to be converted to liquid and gaseous fuels, electricity and heat, it also plays an important role in integrated model projections of energy systems moving away from fossil-based fuels (Chum *et al* 2011, Smith *et al* 2014b). For many technological routes, this implies that bioenergy may compete with other biomass demand for arable land (Haberl *et al* 2014). Since land is a finite resource, this could lead to a range of effects for SD (see SI section 3.1.1).

Since there are many uncertainties involved in calculating the land use impact of bioenergy, including the (induced) yield changes through agricultural technology innovation and diffusion processes and the interactions with dietary patterns and non-climate policies (Creutzig *et al* 2012a, PBL 2012, Popp *et al* 2014, Rose *et al* 2012, Sathaye *et al* 2011, Smith *et al* 2014b, Wise *et al* 2009), we simply use the total amount of bioenergy as an imperfect but available indicator for this range of potential risks.

For the purpose of this letter, the indicator refers to the percentage change in the primary energy supply of biomass – "Primary Energy|Biomass" (*Bioenergy*) – in 2050 relative to the baseline scenario.

$$\frac{Bioenergy^{\text{Mitigation}}(2050) - Bioenergy^{\text{Baseline}}(2050)}{Bioenergy^{\text{Baseline}}(2050)} \cdot 100\%$$

4.2.7 Maximum decadal PV and wind capacity upscaling

Modern electrical power systems widely differ in terms of their development and reliability across countries. But the balancing of electricity supply and demand requires complex operational planning from the management of instantaneous changes in demand to the longer-term investment decisions in generation capacity and transmission grids. Because the generators, interconnectors and loads are designed to operate within certain frequency limits, large amounts of only partially dispatchable and predictable power capacity are potentially a threat to the security and reliability of the system. This entails the need to build new grid infrastructure (e.g. grid reinforcements and new lines) both inside the region as well as interconnection to neighbouring regions. But because the construction of networks involves long lead times, "… major investments will be needed and will need to be

[5] Although South Korea (21.6GW) and South Africa (1.8GW) already have nuclear capacity (whose lifetime ends, however, before 2050), the AMPERE database does not report country-specific data in these cases. This likely implies a slight overestimation of the nuclear newcomers capacity – in baseline and mitigation scenarios.

undertaken in such a way, and far enough in advance, so as to not jeopardize the reliability and security of electricity supply (Sims *et al* 2011, p 627)."

With timing conflicts (PV and wind plants can be constructed in less than 2 years, while planning, permitting and constructing a transmission line takes 5 to 10 years) and cost recovery uncertainties, very fast upscaling of PV and wind power plants is a risk – both technically and economically (Sims *et al* 2011). Possible other solutions (such as curtailment, provision of ancillary services, demand-side measures and additional reserve capacity and storage facilities) may have to be relied on for higher penetration rates but also requires additional time and/or investments (Hirth 2013, Hirth and Ueckerdt 2013, Holttinen *et al* 2011, Söder *et al* 2007, Ueckerdt *et al* 2013). Because the majority of integrated models only report the various variables in 10-year time steps, we have to rely on decadal values for upscaling that we use as a mitigation risk indicator reflecting both technical and economic risks.

For the purpose of this letter the indicator refers to the maximum decadal increase (in percentage change) in the combined capacity of PV and wind power – "Capacity|Electricity|Solar|PV" (*Capacity_PV*) and "Capacity|Electricity|Wind" (*Capacity_Wind*) – between 2010 and 2050 relative to the maximum decadal increase in capacity in baseline scenarios.

$$\frac{CapacityUpscaling^{\text{Migitation}}(t) - CapacityUpscaling^{\text{Baseline}}(t)}{CapacityUpscaling^{\text{Baseline}}(\text{t})} \cdot 100\%,$$

where

$$CapacityUpscaling = \max_{2010<t<2050} Capacity\_PV(t) + Capacity\_Wind(t)$$

4.2.8 Cumulative CO_2 emissions

As described in SI section 1, the emission pathways in integrated model mitigation scenarios are designed to meet different atmospheric CO_2eq concentrations or carbon budgets by 2100. They are, however, given the flexibility to overshoot the constraint over the course of the century. Otherwise, many models would not find a solution for mitigation scenarios with very low concentration targets. This implies that CO_2 emission trajectories and concentrations can differ substantially across alternative 2°C pathways – mainly depending on the deployment levels of negative emission technologies in the second half of the century (Clarke *et al* 2014, Fuss *et al* 2014). As described in SI section 3.1.10, this can have very different implications for the marine environment, because past CO_2 emissions can leave a substantial legacy in the marine environment due to delayed responses in the ocean interior and irreversibility of some of the impacts of ocean acidification, such as calcification (Boucher *et al* 2012, Zickfeld *et al* 2012). We hence look at differences in cumulative CO_2 emissions by 2050 in alternative 2°C pathways to approximate the changes is risks due to ocean acidification and its implication for marine ecosystems.

For the purpose of this letter, the indicator refers to the percentage change in cumulative CO_2 emissions – "Emissions|CO2" (*Emi_CO2*) – from 2020-2050.

$$\frac{Emi\_CO2^{\text{Mitigation}} - Emi\_CO2^{\text{Baseline}}}{Emi\_CO2^{\text{Baseline}}} \cdot 100\%$$

Cumulative values are calculated by multiplying the value in each timestep (*t*) by half the difference between that timestep's year (*Y*) and the previous timestep's year plus half the difference between its year and the next timestep's year, for all timesteps included in the period under consideration.

4.2.9 Cumulative SO_2 and BC emissions

The emissions arising from the combustion of fossil fuels, such as soot (black carbon, BC), sulfur dioxide (SO_2), nitrogen oxides (NOx) and mercury (Hg), cause significant and widespread human health impacts as well as ecological impacts as described in SI section 3.1.2. Although the negative environmental and health impacts primarily arise from the (regionally very different) concentration of these pollutants, the scenario databases merely report the amount of global emissions that serve here as indicator. There are, however, individual studies that establish a clear link between emissions, concentrations and the negative impacts of the pollutants in question (Rao *et al* 2013, Shindell *et al* 2012, Smith and Mizrahi 2013).

For the purpose of this letter, the indicator for cumulative BC Emissions (2020-2050) refers to the percentage change in the cumulative value of BC emissions – "Emissions|BC" (*Emi_BC*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_BC^{\text{Mitigation}} - Emi\_BC^{\text{Baseline}}}{Emi\_BC^{\text{Baseline}}} \cdot 100\%$$

For the purpose of this letter, the indicator for cumulative SO_2 Emissions (2020-2050) refers to the percentage change in the cumulative value of sulfur emissions – "Emissions|Sulfur" (*Emi_SO2*) – from 2020 to 2050 relative to the baseline scenario.

$$\frac{Emi\_SO2^{\text{Mitigation}} - \text{Emi}\_SO2^{\text{Baseline}}}{Emi\_SO2^{\text{Baseline}}} \cdot 100\%$$

4.2.10 Cumulative global oil trade

For oil trade, we measure interregional oil trade as an indicator for the concerns around the sovereignty perspective that sees the origin of risks in deliberate actions of foreign actors (Jewell *et al* 2014). While this indicator does capture lower risks from decreasing oil imports, it also measures lost oil export revenues for oil exporters, which is most likely a loss rather than a benefit for major oil exporting countries which would lose oil export revenues from a fall of oil trade (Clarke *et al* 2014).

With increasing ambition of mitigation, however, global oil trade is projected to significantly decrease. One important aspect is that development pathways characterized by lower energy intensity (EI) are often likely to rely more heavily on oil than mitigation scenarios with conventional EI assumptions (see figure S5) because the mitigation options in the transport sectors are among those with the highest costs (Kriegler *et al* 2014b). Theoretically, the mitigation costs saved from lower EI could be used to lower the energy security risks around the reliance of the transport sector on oil.

For the purpose of this letter, the indicator refers to the percentage change in global oil imports, i.e. the sum of positive "Trade|Primary Energy|Oil|Volume" in each region *r* between 2020 and 2050 (*Trade_Oil*) relative to the baseline scenario.

$$\frac{\sum_r Trade\_Oil_r^{\text{Mitigation}} - \sum_r Trade\_Oil_r^{\text{Baseline}}}{\sum_r Trade\_Oil_r^{\text{Baseline}}} \cdot 100\%$$

4.2.11 Cumulative oil extraction

For the robustness perspective related to oil security, we measure the cumulative extraction of oil resources as a relevant indicator for judging scarcity concerns (Jewell *et al* 2014). While the 'peak-oil' theory is still debated, even the perception of resource scarcity can lead to price volatility (McCollum *et al* 2013). Although global conventional oil reserves are limited, oil demand projections often exceed these already by 2050 in baseline scenarios (Rogner *et al* 2012). An alternative to conventional oil reserves would be to draw on so-called unconventional oil reserves. This alternative is, however, problematic, as there is considerable evidence that unconventional oil production involves bigger environmental and health risks as well as an increased carbon intensity of production, relative to conventional oil production (Bruckner *et al* 2014, Rogner *et al* 2012). For instance, Canada's oil sands production appears to generate three times as many GHG emissions as its conventional oil production. Moreover, it is plausible that part of the water used in oil sands production pollutes the ground water. There is also evidence of it altering ecosystems (Engemann and Owyang 2010, Woynillowicz *et al* 2005).

Analogously, the production of oil shale has also been found to emit more GHGs than conventional oil production, decrease water quality, and permanently change ecosystems (Bartis *et al* 2005, Engemann and Owyang 2010). As a final example, Rogner *et al* (2012, p. 437) note that "severe soil and water contamination by chlorinated hydrocarbons and heavy metals" is likely to result from the processing of raw unconventional oil into sellable oil.

For the purpose of this letter, the indicator refers to the percentage change in the cumulative extraction of crude oil – "Resource|Cumulative Extraction|Oil" (*Oil*) – between 2020 and 2050 relative to the baseline scenario.

$$\frac{Oil^{\text{Mitigation}} - Oil^{\text{Baseline}}}{Oil^{\text{Baseline}}} \cdot 100\%$$

4.2.12 Fuel diversity of transport sector

For the resilience perspective, we measure the fuel diversity of the transport sector which currently is very low in most countries of the world due to high reliance on oil (Cherp *et al* 2012). For countries that are net importers of oil, the exposure to volatile and unpredictable oil prices affects the terms of trade and their economic stability (Sathaye *et al* 2011). Electrification of the transport sector and switching to biofuels would decrease the oil dependency by diversifying the energy supply, thus increasing resilience (Jewell *et al* 2014). Although mitigation scenarios often project less oil demand by 2050 relative to baseline developments, cost-effective technological options in the transport sector to substitute oil are still limited (Sims *et al* 2014). Global roll-out of alternative propulsion technology, particularly in the individual mobility sector, is likely to require clear price signals in many countries (either through global cooperation on carbon pricing or transport sector innovation) to spread the enormous investment costs in R&D, early deployment and diffusion (Bosetti *et al* 2011).

For the purpose of this letter, the indicator refers to the percentage change in the Shannon Wiener Diversity Index (SWDI) – multiplied by -1 to measure transport sector oil reliance, a SD risk, rather than fuel diversity of the transport sector, a policy objective – of the five most widely used final energy carriers in the transport sector – oil (‘Final Energy|Transportation|Liquids|Oil’), biofuels (‘Final Energy|Transportation|Liquids|Biomass’), gases (‘Final Energy|Transportation|Gases’), electricity (‘Final Energy|Transportation|Electricity’), and hydrogen (‘Final Energy|Transportation|Hydrogen’). The SWDI is the sum of the share of each final energy carrier (*f*) in total final transport energy (‘Final Energy|Transportation’) (*t*) multiplied by its natural logarithm.

$$\frac{\sum_f(\frac{f}{t}\cdot\ln(\frac{f}{t}))^{\text{Mitigation}}-\sum_f(\frac{f}{t}\cdot\ln(\frac{f}{t}))^{\text{Baseline}}}{\sum_f(\frac{f}{t}\cdot\ln(\frac{f}{t}))^{\text{Baseline}}}\cdot 100\%$$

5 AMPERE model inter-comparison project

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'. This inter-comparison project of integrated models focused on the mitigation challenge of delayed and fragmented climate policy. AMPERE compares results from a wide range of internationally recognized energy-economy-climate models with different functional structures, parametric assumptions, and sectoral coverage (see table S1). The model diversity allowed identifying model uncertainty (i.e., where model results differed widely) and robust insights (i.e., where model results were similar).

AMPERE covered several key aspects not assessed in previous inter-comparison projects:

- Impact of short-term climate policies on the achievability of long-term mitigation goals;
- Role of individual technologies within the mitigation technology portfolio;
- Harmonization of key socioeconomic drivers (GDP, population and energy demand growth);
- Economic effects and climate benefits of early unilateral followed by delayed global action;
- Costs and benefits of alternative European Union climate policy choices;
- Diagnosing model behavior and assessing model validity to better understand differences.

The first two aspects are particularly important for this letter's analysis which is why the respective scenario specifications are described in more detail in table S3. The third point is also of importance for this analysis (see discussion) since harmonized key socioeconomic drivers allow a better mapping of the changes in the model variables to climate policy signals across models. The main finding of AMPERE is that any emissions resulting from low-ambitious short-term climate policies (until 2030) would need to be compensated over a relatively short timeframe (2030-2050) to stay within the limited carbon budget associated with restricting warming to 2°C (see figure S3).

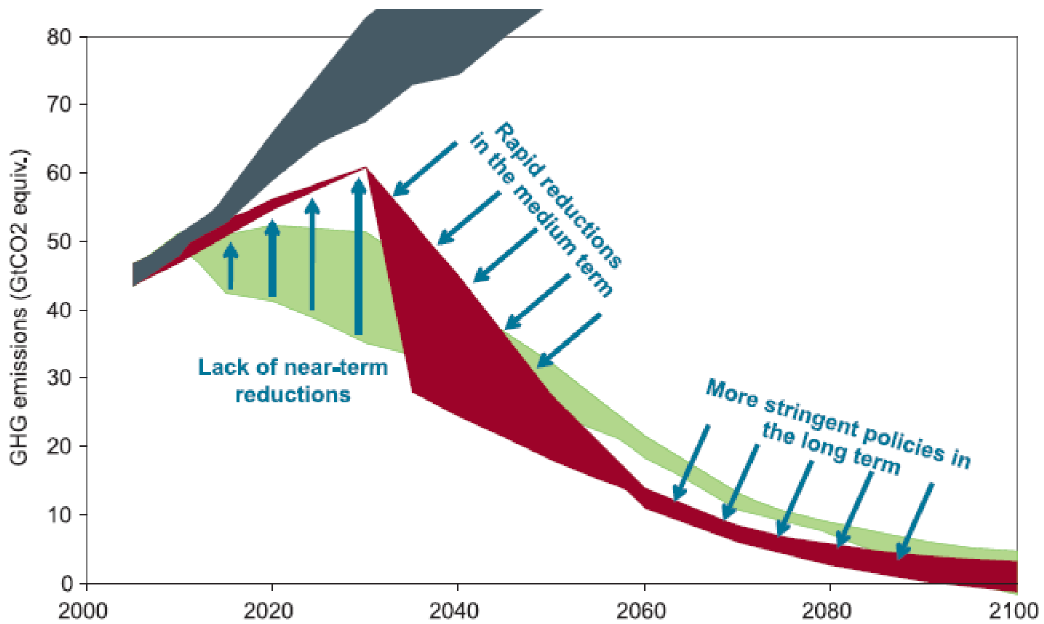

Figure S3. GHG emission pathways of AMPERE models necessary to stay within the carbon budget consistent with the 2°C target. The optimal pathway with immediate mitigation is shown in green while the red emission pathway represents delayed 2°C pathways. The grey emission pathway denotes baseline development without climate policy. Source: Kriegler *et al* (2014a).

Mitigation scenarios with low-ambitious short-term climate policies ("HST") would require quadrupling the low-carbon energy share and global CO_2 emission cuts of 6-8% per year in the two decades between 2030 and 2050. This means that almost half the global energy supply infrastructure would require replacement over a narrow two decade period. In optimal immediate climate policy scenarios ("OPT"), the energy system transition between 2030 and 2050 required to limit warming to 2°C would still be highly challenging, requiring a doubling of the low-carbon energy share and carbon intensity reductions of 3-4% per year (see figure S4).

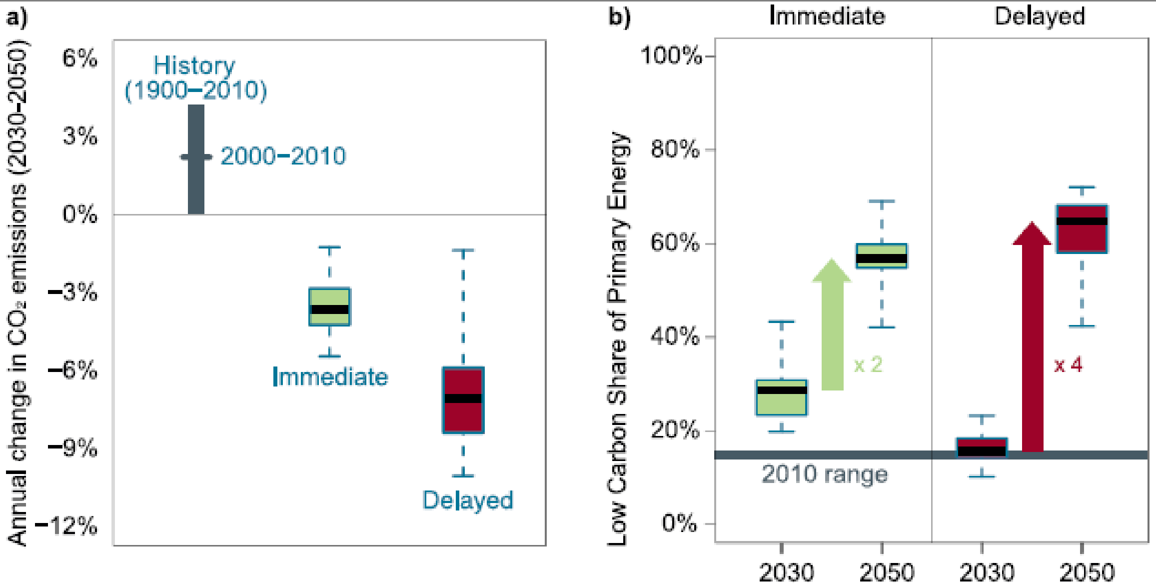

Figure S4. Comparison of delayed and immediate mitigation pathways consistent with 2°C. Panel (a) illustrates the required carbon intensity reduction rates and panel (b) the required upscaling of low-carbon energy supply. Historical annual carbon intensity change rates from 1900 to 2010 (sustained over 20-year periods) are shown in grey in panel (a). Boxplots indicate median, interquartile and full ranges of model results. Source: Kriegler *et al* (2014a).

The AMPERE models project a global mean warming of 3.5 – 5.9°C above pre-industrial levels by 2100 for the baseline scenarios, depending on the uncertainty in emissions and climate parameters (table S2). By contrast, all mitigation scenarios that are analyzed in this letter are scenarios designed to stay within the cumulative emission budget of 1500 $GtCO_2$ (2000–2100) – which largely corresponds to the mitigation scenarios with 450 ppm CO_2-equivalent concentrations at the end of the century (Clarke *et al* 2014, Riahi *et al* 2015, Schaeffer *et al* 2015). For median assumptions, this implies a 42-47% probability of not exceeding the 2°C target for all 450-FullTech scenarios which corresponds to maximum temperature changes of 2.5°C (see table S3).

Table S2. GHG emissions, atmospheric concentrations, and temperature consequences in the "FullTech" scenarios. Numbers correspond to the median and the full range across the scenarios. Note that for the climate simulations, emissions were harmonized to the same base year using inventories from Granier *et al* (2011) and Lamarque *et al* (2010) (adapted from Riahi *et al* 2015).

	CO_2 Emission (2030) $GtCO_2$	CO_2eq Emissions (2030) $GtCO_2$e	Cumulative CO_2 emissions (2000-2100) $GtCO_2$	CO_2eq concentrations (2100) ppm	Temperature change (max) °C	Probability of exceeding 2°C (max) %
Baseline	53 (50-67)	71 (68-83)	6,268 (5,670-8,755)	1,143 (1,023-1,338)	4.6 (3.5-5.9)	100 (100-100)
450 optimal	31 (24-45)	46 (35-60)	1,330 (1,242-1,350)	485 (453-522)	1.9 (1.5-2.4)	42 (26-84)
450 LST	39 (37-42)	53 (53-53)	1,335 (1,263-1,379)	488 (455-524)	2.0 (1.5-2.5)	45 (28-84)
450 HST	46 (44-49)	61 (60-61)	1,344 (1,274-1,382)	484 (452-520)	2.0 (1.6-2.5)	47 (28-84)

Table S3. Mitigation technology choices and short-term climate policy stringencies assumed in the AMPERE scenarios (adapted from Riahi *et al* 2015).

Short-term targets (2030)	Description	Scenario name
Low short-term target	Global emissions follow a high ambition pledge pathway reaching 53 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"LST"
High short-term target	Global emissions follow a low ambition pledge pathway reaching 61 $GtCO_2$eq by 2030. Thereafter ambitions are adjusted to meet the long-term target (450 CO_2eq)	"HST"
Optimal policy	Global emissions follow an optimal pathway assuming immediate introduction of climate policies to meet the long-term target (450 ppm CO_2eq). No explicit short-term target for 2030 is assumed.	"OPT"
Technology cases	**Description**	**Scenario name**
Full technology	The full portfolio of technologies is available and may scale up successfully to meet the respective climate targets	"FullTech"
Low Demand and Energy Intensity	A combination of stringent efficiency measures and behavioural changes radically limits energy demand, leading to a doubling of the rate energy intensity improvements compared to the past. The full portfolio of technologies is available on the supply side.	"LowEI"
No new nuclear	No new investments into nuclear power after 2020; existing plants are fully phased out over their life time.	"NucOff"
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate "negative emissions" when combined with bioenergy.	"NoCCS"
Limited Solar and Wind	Limited contribution of solar and wind to 20% of total power generation, reflecting potential implementation barriers of variable renewable energy at high penetration rates	"LimSW"
Limited Biomass	Limited potential for biomass (maximum of 100 EJ/yr), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fibre	"LimBio"

6 Supplementary figures

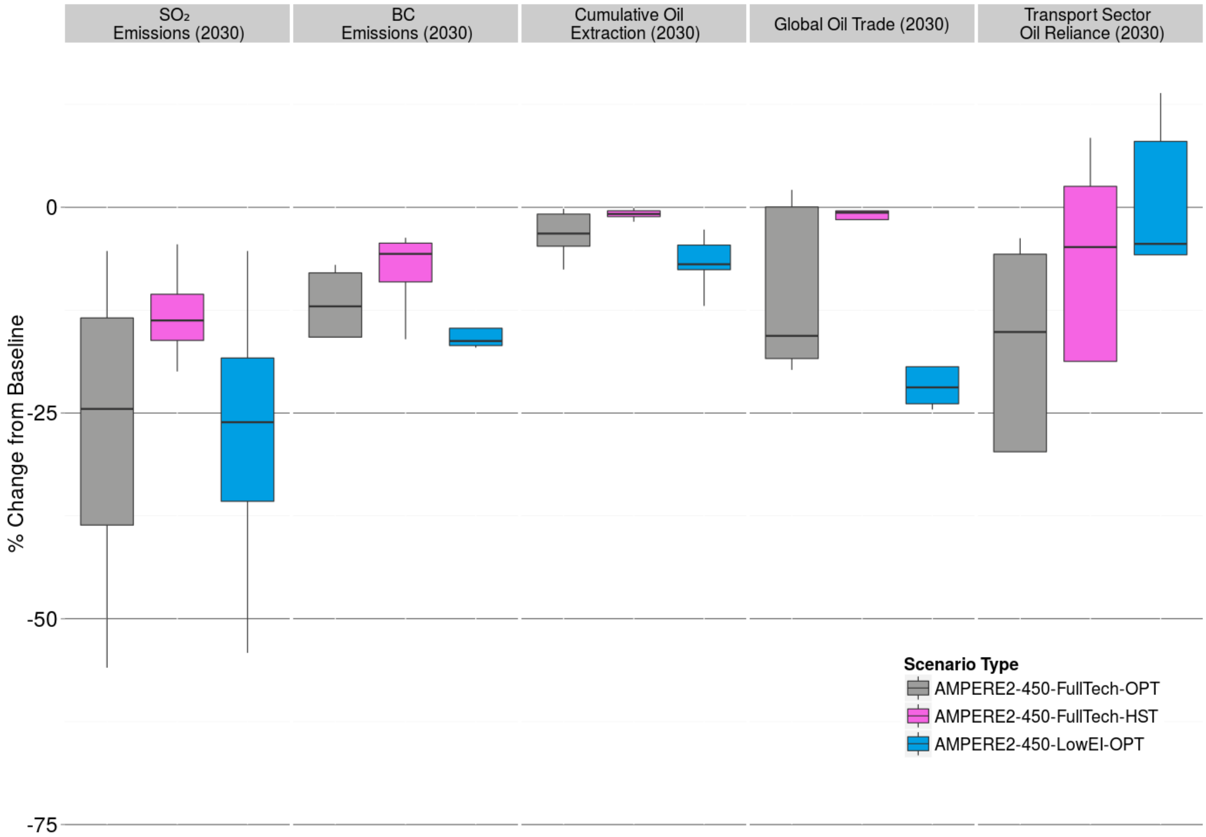

Figure S5. Percentage changes in indicators for co-benefits for air quality, oil security and fuel diversity in the transport sector in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios in 2030, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). The thick coloured lines show median results, coloured ranges show interquartile ranges and whiskers show the minimum and maximum results.

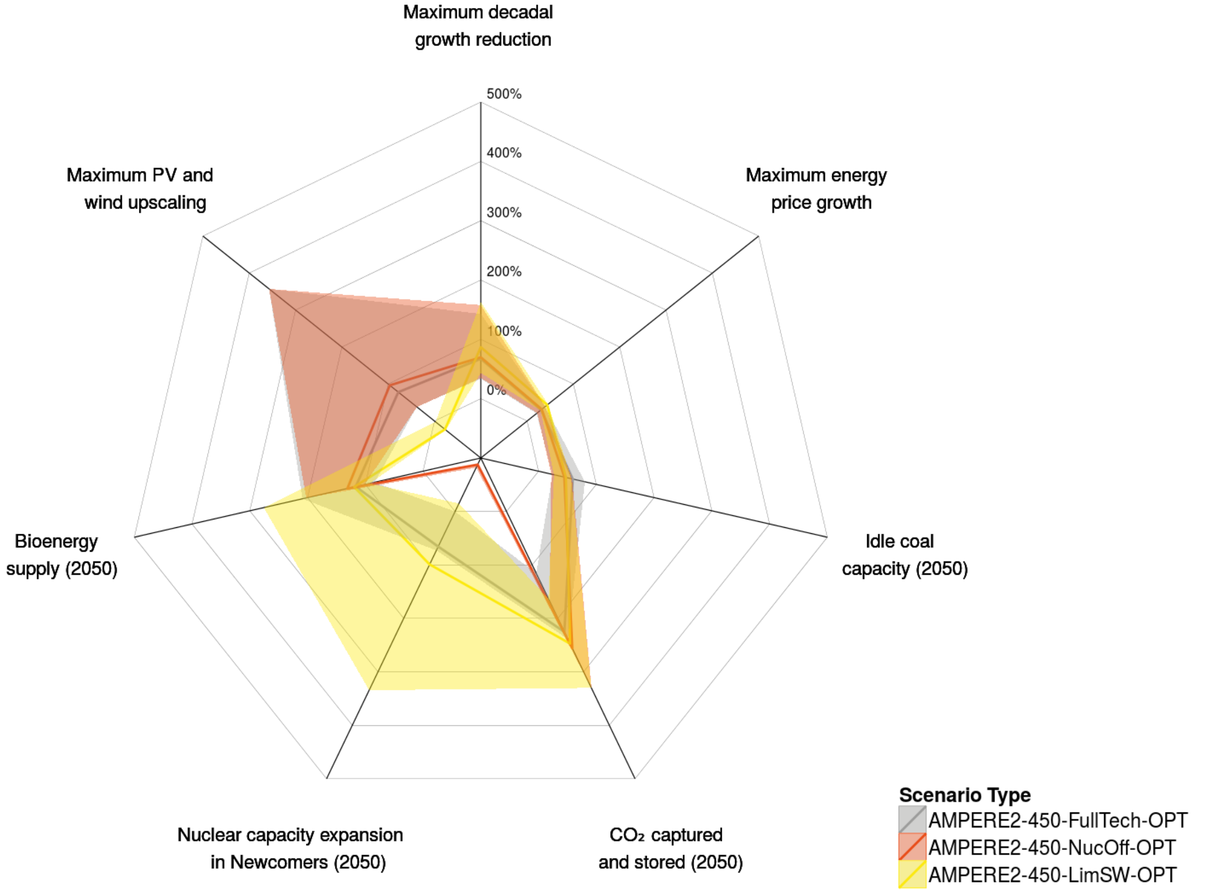

Figure S6. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for five integrated models (GCAM, IMAGE, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with mitigation scenarios assuming no new nuclear capacity (red) or limited potential for solar and wind energy (yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

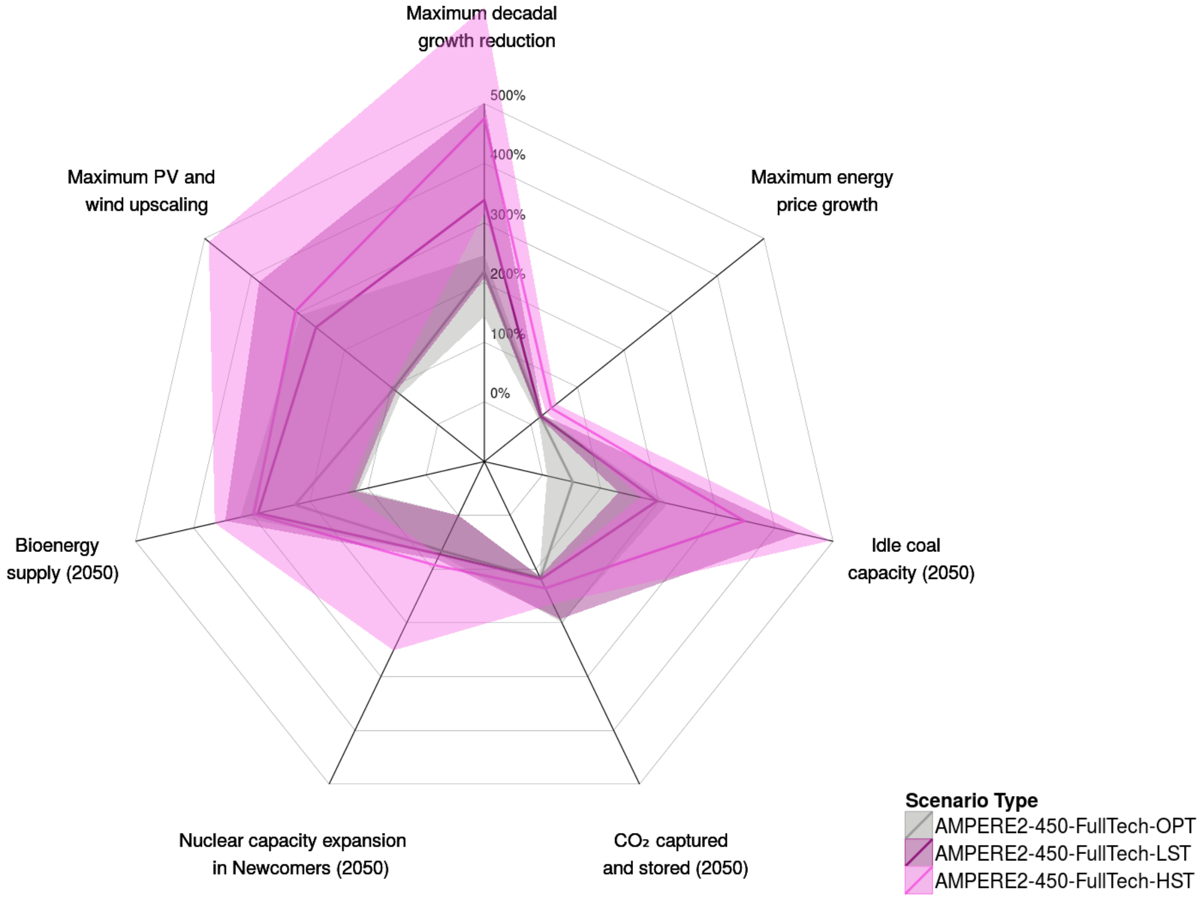

Figure S7. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing immediate mitigation scenarios (grey) with delayed mitigation scenarios with high short-term targets (pink) or low short-term targets (purple). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

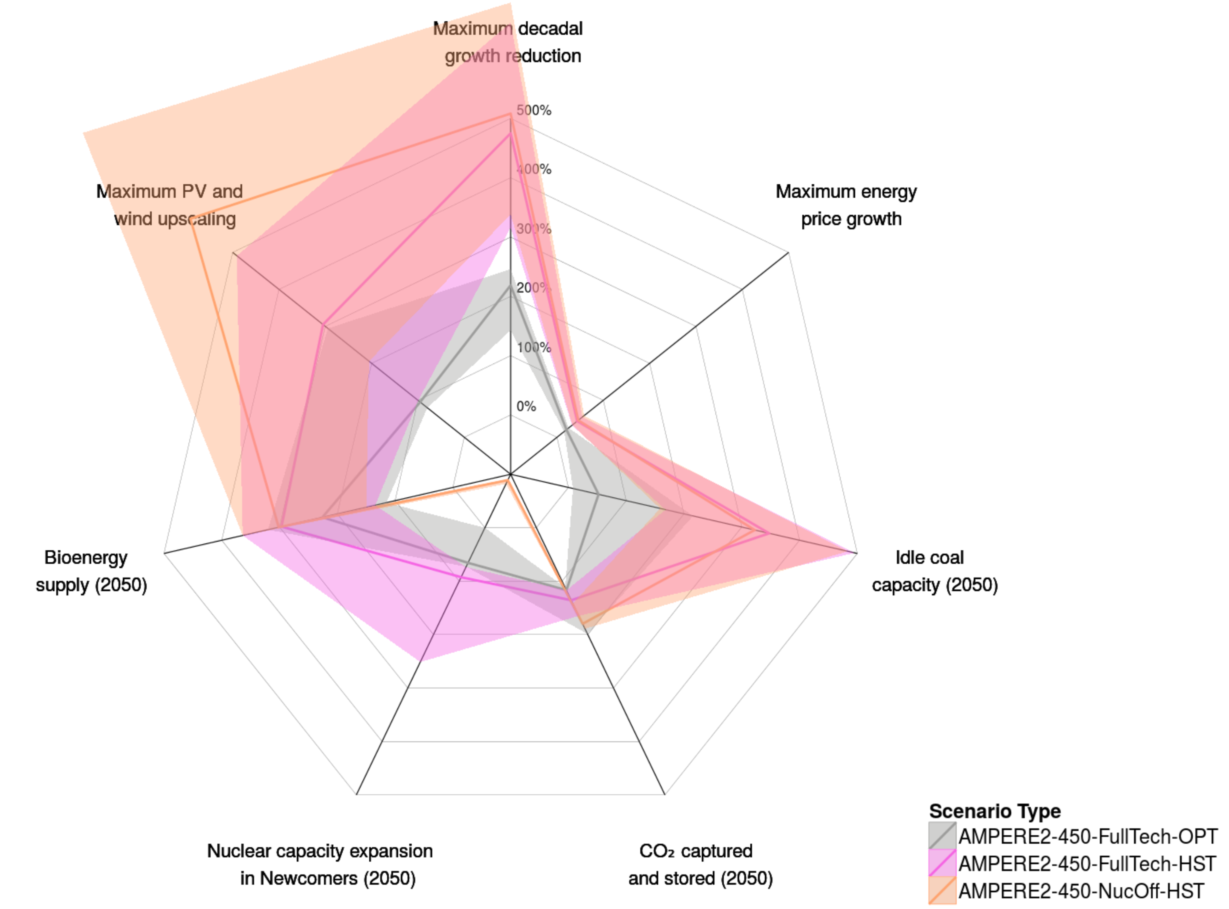

Figure S8. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or no new nuclear capacity (red). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

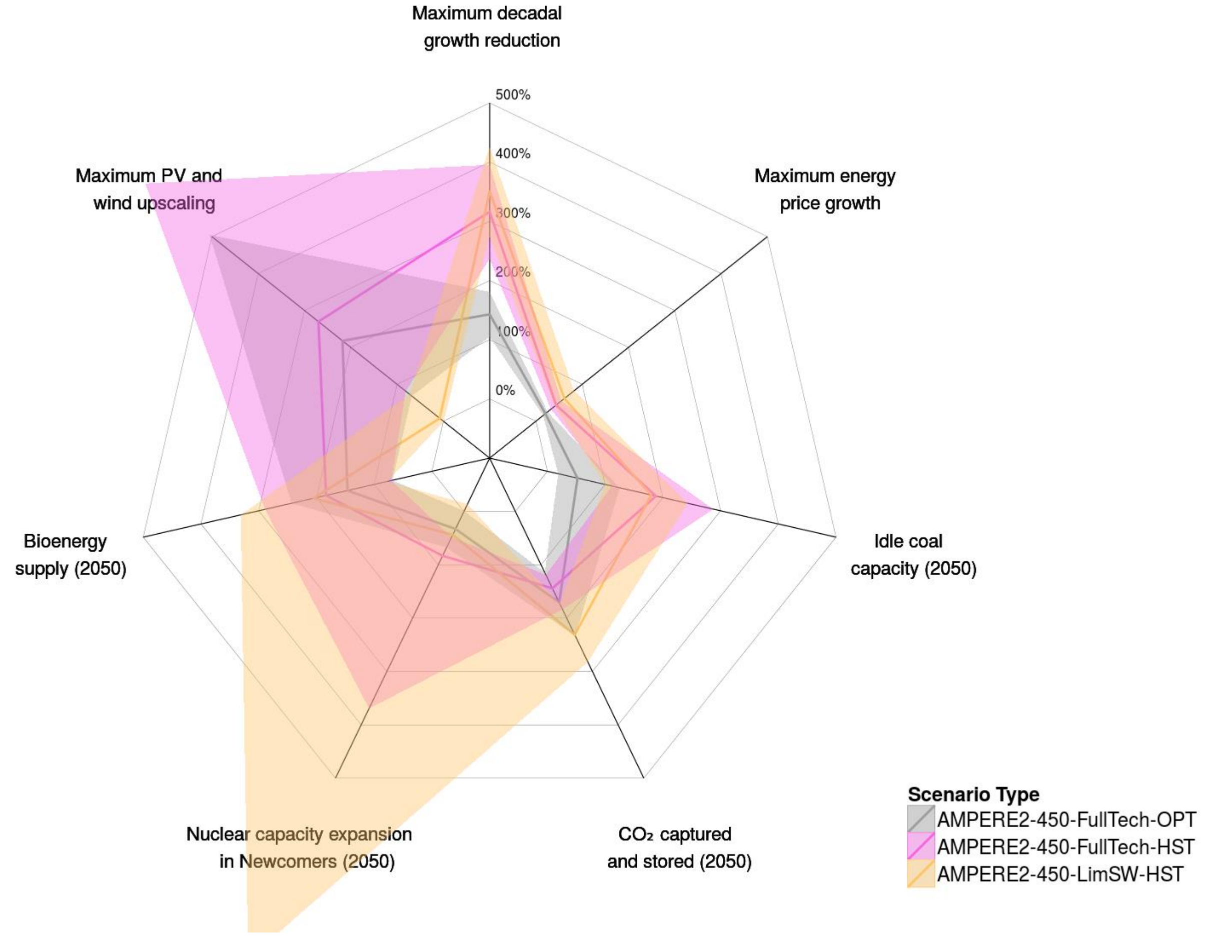

Figure S9. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to reference values or values from baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios assuming full availability of mitigation technologies (pink) or limited potential for solar and wind energy (warm yellow). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

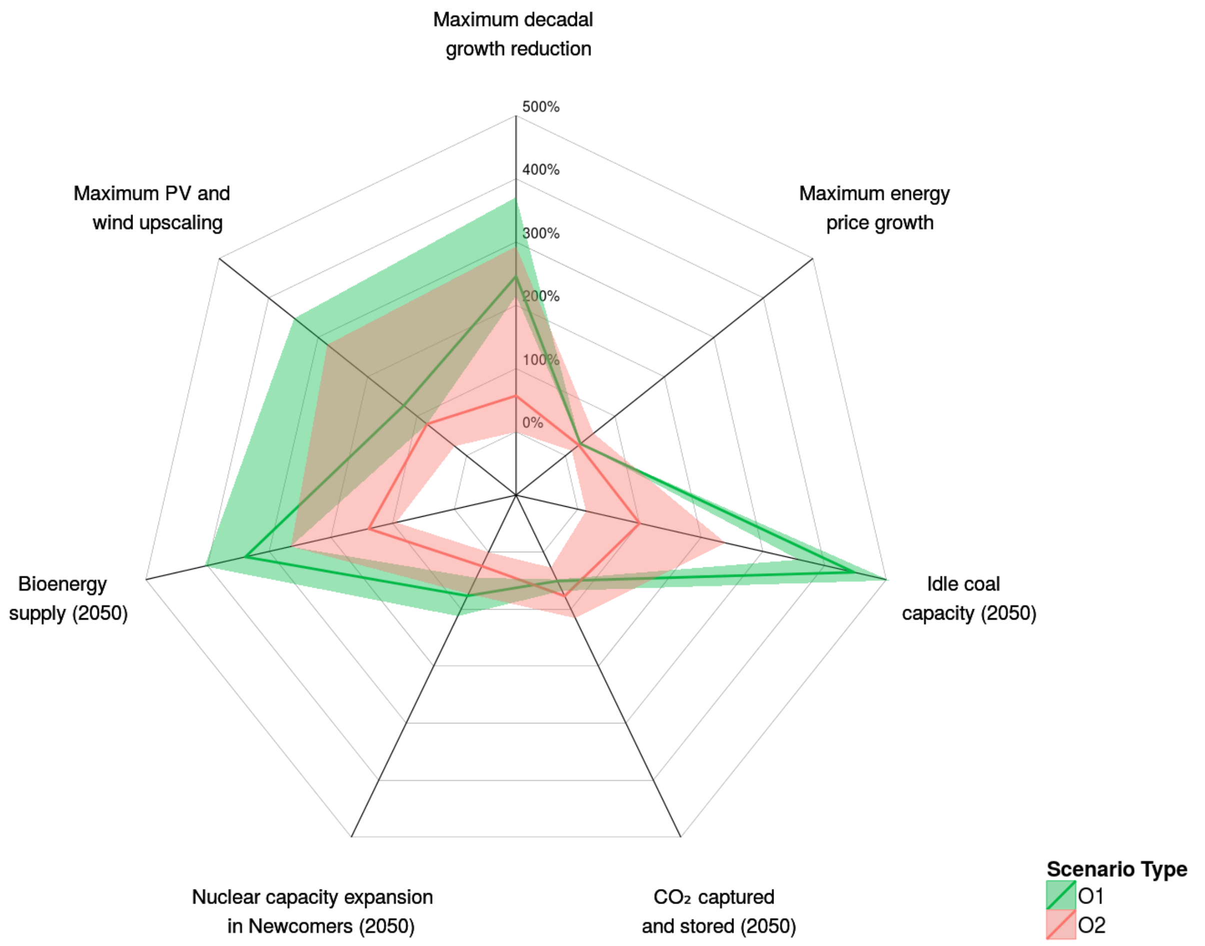

Figure S10. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2050 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

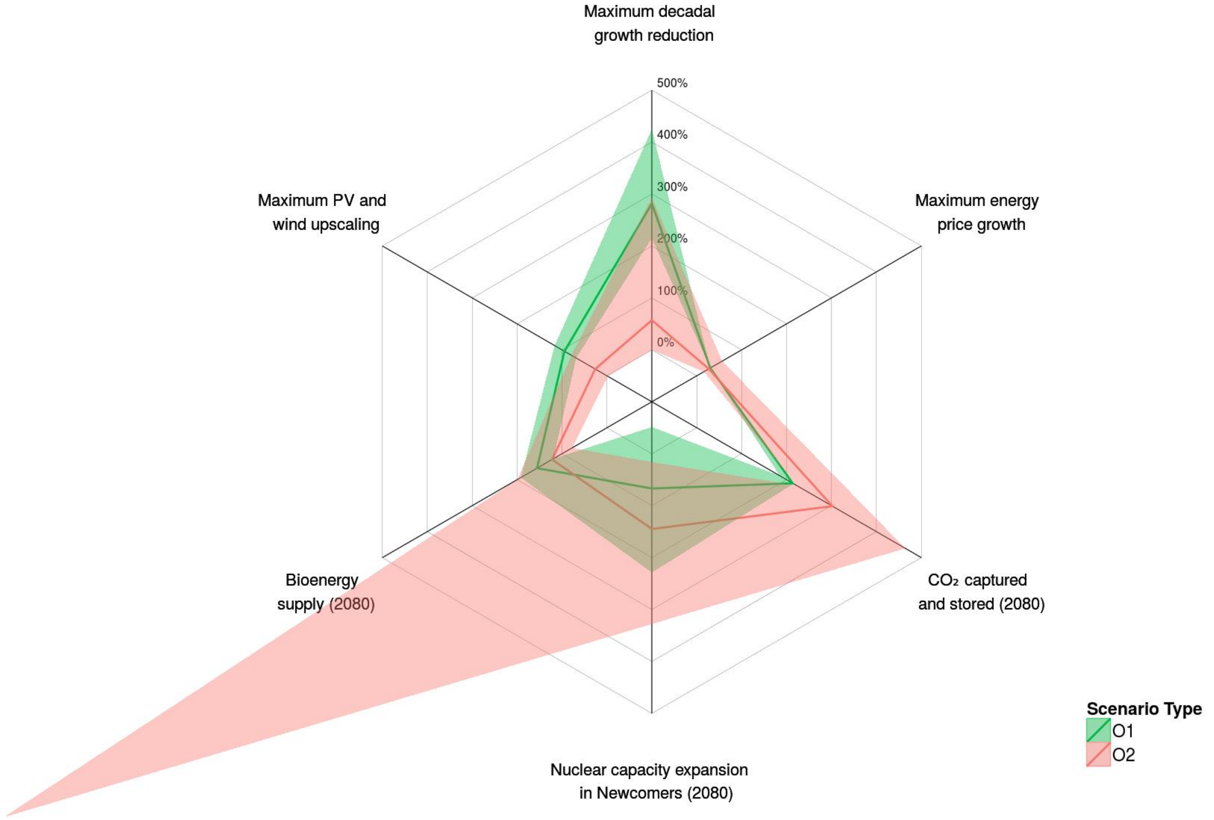

Figure S11. Percentage changes in mitigation risk dimensions in alternative 2°C pathways for the year 2080 and the preceding decades for seven integrated models (DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios, comparing mitigation scenarios assuming full availability of mitigation technologies with low overshoot 'O1' (< 0.4 W/m^2) and high (> 0.4 W/m^2) overshoot 'O2' (see Clarke *et al* 2014 for details). The thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance of individual data points to the 0%-line nor the total area covered by the shaded area are good guidance for the overall mitigation risk of particular scenarios. Instead, the evaluation differs for locally specific contexts with varying priority settings and risk perceptions.

Table S4. Data underlying Figure 5. Percentage changes in median values of indicators for SD risk dimensions in different constrained 2°C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth).

Mitigation scenario	Indicator	Median value of indicator…	Median value of 'optimal' 2°C scenario…	Percentage change [%]	Year(s)		DNE21 V.12	GCAM 3.0	MESSAGE V.4	POLES AMPERE	REMIND 1.5	WITCH_ AMPERE
		…of the respective models										
AMPERE2-450-FullTech-OPT	Cumulative CO_2 Emissions [Gt]	812896,90	812896,90	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative CO_2 Emissions [Gt]	813594,96	812896,90	**0,1**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative CO_2 Emissions [Gt]	805455,62	873256,50	**-1,6**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative CO_2 Emissions [Gt]	676945,25	873256,50	**-24,2**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative CO_2 Emissions [Gt]	721414,77	873256,50	**-27,9**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative CO_2 Emissions [Gt]	821073,44	812896,90	**0,2**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative CO_2 Emissions [Gt]	843678,04	812896,90	**7,6**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative CO_2 Emissions [Gt]	842362,81	812896,90	**7,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative CO_2 Emissions [Gt]	901729,82	873256,50	**3,4**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative CO_2 Emissions [Gt]	781099,87	873256,50	**-6,7**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative CO_2 Emissions [Gt]	812376,62	1026093,61	**-17,2**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative CO_2 Emissions [Gt]	864305,32	812896,90	**11,7**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative SO_2 Emissions [Gt]	1748,35	1748,35	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative SO_2 Emissions [Gt]	1738,58	1748,35	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative SO_2 Emissions [Gt]	1509,10	1560,63	**-3,3**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative SO_2 Emissions [Gt]	1324,99	1560,63	**-16,1**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative SO_2 Emissions [Gt]	1248,98	1748,35	**-22,2**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative SO_2 Emissions [Gt]	1698,26	1748,35	**1,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative SO_2 Emissions [Gt]	1724,12	1748,35	**2,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative SO_2 Emissions [Gt]	1727,50	1748,35	**2,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative SO_2 Emissions [Gt]	1594,31	1560,63	**2,2**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative SO_2 Emissions [Gt]	1495,05	1560,63	**-2,7**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative SO_2 Emissions [Gt]	1782,04	2021,98	**-12,5**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative SO_2 Emissions [Gt]	1753,20	1748,35	**7,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative BC Emissions [Gt]	186,11	186,11	**0,0**	2020-50		x	x	x		x	
AMPERE2-450-NucOff-OPT	Cumulative BC Emissions [Gt]	186,95	186,11	**0,0**	2020-50		x	x	x		x	
AMPERE2-450-LimSW-OPT	Cumulative BC Emissions [Gt]	172,44	176,57	**-2,3**	2020-50			x	x		x	
AMPERE2-450-LimBio-OPT	Cumulative BC Emissions [Gt]	167,65	176,57	**-8,9**	2020-50			x	x		x	
AMPERE2-450-NoCCS-OPT	Cumulative BC Emissions [Gt]	172,89	186,11	**-7,1**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative BC Emissions [Gt]	166,20	168,89	**-1,6**	2020-50		x	x	x		x	
AMPERE2-450-FullTech-LST	Cumulative BC Emissions [Gt]	178,17	186,11	**-1,6**	2020-50		x	x	x		x	
AMPERE2-450-NucOff-LST	Cumulative BC Emissions [Gt]	178,99	186,11	**-1,1**	2020-50		x	x	x		x	
AMPERE2-450-LimSW-LST	Cumulative BC Emissions [Gt]	161,61	176,57	**-1,7**	2020-50			x	x		x	
AMPERE2-450-LimBio-LST	Cumulative BC Emissions [Gt]	159,42	176,57	**-9,7**	2020-50			x	x		x	
AMPERE2-450-NoCCS-LST	Cumulative BC Emissions [Gt]	203,10	212,57	**-4,7**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative BC Emissions [Gt]	166,19	186,11	**-5,4**	2020-50		x	x	x		x	
AMPERE2-450-FullTech-OPT	Cumlative global oil trade [EJ]	3338,07	3338,07	**0,0**	2020-50			x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumlative global oil trade [EJ]	3369,41	3338,07	**-0,2**	2020-50			x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumlative global oil trade [EJ]	3294,56	3307,93	**-0,4**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumlative global oil trade [EJ]	3094,82	3307,93	**-8,1**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumlative global oil trade [EJ]	2881,66	3338,07	**-13,7**	2020-50			x	x		x	
AMPERE2-450-LowEI-OPT	Cumlative global oil trade [EJ]	3014,26	3338,07	**-8,0**	2020-50			x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumlative global oil trade [EJ]	3378,56	3338,07	**-0,5**	2020-50			x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumlative global oil trade [EJ]	3375,27	3338,07	**1,1**	2020-50			x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumlative global oil trade [EJ]	3307,45	3307,93	**-0,6**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumlative global oil trade [EJ]	3082,99	3307,93	**-6,8**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumlative global oil trade [EJ]	2875,70	3338,07	**-13,9**	2020-50			x				
AMPERE2-450-LowEI-LST	Cumlative global oil trade [EJ]	3087,27	3338,07	**-5,8**	2020-50			x	x	x	x	x
AMPERE2-450-FullTech-OPT	Cumulative oil extraction [EJ]	6149,59	6149,59	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Cumulative oil extraction [EJ]	6144,59	6149,59	**-0,4**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Cumulative oil extraction [EJ]	6039,16	6149,59	**-1,7**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Cumulative oil extraction [EJ]	5142,31	6149,59	**-10,5**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Cumulative oil extraction [EJ]	5362,68	6451,85	**-17,1**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Cumulative oil extraction [EJ]	5729,45	6149,59	**-7,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Cumulative oil extraction [EJ]	6016,11	6149,59	**0,6**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Cumulative oil extraction [EJ]	6020,79	6149,59	**0,9**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Cumulative oil extraction [EJ]	6082,86	6149,59	**-1,1**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Cumulative oil extraction [EJ]	5134,03	6149,59	**-9,9**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Cumulative oil extraction [EJ]	5560,36	6451,85	**-13,9**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Cumulative oil extraction [EJ]	5683,63	6149,59	**-6,7**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Fuel diversity of transport [SWDI]	-0,82	-0,82	**0,0**	2050		x	x	x	x	x	
AMPERE2-450-NucOff-OPT	Fuel diversity of transport [SWDI]	-0,78	-0,82	**-0,1**	2050		x	x	x	x	x	
AMPERE2-450-LimSW-OPT	Fuel diversity of transport [SWDI]	-0,91	-0,90	**-1,3**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Fuel diversity of transport [SWDI]	-1,03	-0,90	**-11,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Fuel diversity of transport [SWDI]	-1,16	-0,88	**-31,2**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Fuel diversity of transport [SWDI]	-0,63	-0,82	**22,9**	2050		x	x	x	x	x	
AMPERE2-450-FullTech-LST	Fuel diversity of transport [SWDI]	-0,98	-0,82	**-2,8**	2050		x	x	x	x	x	
AMPERE2-450-NucOff-LST	Fuel diversity of transport [SWDI]	-0,99	-0,82	**-1,8**	2050		x	x	x	x	x	
AMPERE2-450-LimSW-LST	Fuel diversity of transport [SWDI]	-0,94	-0,90	**-4,8**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Fuel diversity of transport [SWDI]	-1,09	-0,90	**-14,5**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Fuel diversity of transport [SWDI]	-1,38	-0,88	**-60,6**	2050		x	x				
AMPERE2-450-LowEI-LST	Fuel diversity of transport [SWDI]	-0,93	-0,82	**16,3**	2050		x	x	x	x	x	

AMPERE2-450-FullTech-OPT	Maximum transitional growth reduction	41,09	41,09	**0,0**	2020-50				x		x	x
AMPERE2-450-NucOff-OPT	Maximum transitional growth reduction	45,11	45,15	**33,8**	2020-50				x		x	x
AMPERE2-450-LimSW-OPT	Maximum transitional growth reduction	35,01	35,33	**32,3**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maximum transitional growth reduction	42,59	43,66	**107,5**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maximum transitional growth reduction	42,23	43,75	**152,0**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maximum transitional growth reduction	41,28	41,02	**-25,7**	2020-50				x		x	x
AMPERE2-450-FullTech-LST	Maximum transitional growth reduction	28,65	30,02	**119,4**	2020-50				x		x	x
AMPERE2-450-NucOff-LST	Maximum transitional growth reduction	28,62	30,07	**144,4**	2020-50				x		x	x
AMPERE2-450-LimSW-LST	Maximum transitional growth reduction	28,35	29,47	**112,5**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maximum transitional growth reduction	29,83	32,88	**304,3**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maximum transitional growth reduction	n/a	n/a	**n/a**	2020-50				x		x	
AMPERE2-450-LowEI-LST	Maximum transitional growth reduction	29,40	28,25	**-3,0**	2020-50				x		x	x
AMPERE2-450-FullTech-OPT	Maxium decadal energy price growth	1,33	1,33	**0,0**	2020-50				x		x	
AMPERE2-450-NucOff-OPT	Maxium decadal energy price growth	1,21	1,19	**1,8**	2020-50				x		x	
AMPERE2-450-LimSW-OPT	Maxium decadal energy price growth	1,40	1,30	**6,8**	2020-50				x		x	
AMPERE2-450-LimBio-OPT	Maxium decadal energy price growth	1,46	1,30	**11,6**	2020-50				x		x	
AMPERE2-450-NoCCS-OPT	Maxium decadal energy price growth	1,62	1,30	**23,4**	2020-50				x		x	
AMPERE2-450-LowEI-OPT	Maxium decadal energy price growth	1,21	1,21	**0,6**	2020-50				x		x	
AMPERE2-450-FullTech-LST	Maxium decadal energy price growth	1,38	1,23	**12,3**	2020-50				x		x	
AMPERE2-450-NucOff-LST	Maxium decadal energy price growth	1,40	1,23	**13,9**	2020-50				x		x	
AMPERE2-450-LimSW-LST	Maxium decadal energy price growth	1,52	1,23	**23,2**	2020-50				x		x	
AMPERE2-450-LimBio-LST	Maxium decadal energy price growth	2,24	1,28	**76,6**	2020-50				x		x	
AMPERE2-450-NoCCS-LST	Maxium decadal energy price growth	n/a	n/a	**n/a**	2020-50							
AMPERE2-450-LowEI-LST	Maxium decadal energy price growth	1,40	1,28	**9,8**	2020-50				x		x	
AMPERE2-450-FullTech-OPT	Share of idle coal capacity	0,41	0,41	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Share of idle coal capacity	0,56	0,41	**-1,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Share of idle coal capacity	0,35	0,41	**1,1**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Share of idle coal capacity	0,77	0,41	**7,0**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Share of idle coal capacity	0,45	0,21	**7,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Share of idle coal capacity	0,43	0,41	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Share of idle coal capacity	0,85	0,41	**24,9**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Share of idle coal capacity	0,81	0,41	**17,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Share of idle coal capacity	0,81	0,41	**9,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Share of idle coal capacity	0,89	0,41	**19,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Share of idle coal capacity	0,59	0,17	**276,1**	2050		x	x				
AMPERE2-450-LowEI-LST	Share of idle coal capacity	0,83	0,41	**27,1**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	CO_2 captured & stored [Gt]	10844,76	10844,76	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	CO_2 captured & stored [Gt]	13638,38	10844,76	**22,4**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	CO_2 captured & stored [Gt]	17328,08	13521,52	**22,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	CO_2 captured & stored [Gt]	15836,94	13521,52	**-6,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	CO_2 captured & stored [Gt]	6807,59	10844,76	**-36,8**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	CO_2 captured & stored [Gt]	10925,85	10844,76	**-0,2**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	CO_2 captured & stored [Gt]	13307,78	10844,76	**14,5**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	CO_2 captured & stored [Gt]	16728,00	13521,52	**20,0**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	CO_2 captured & stored [Gt]	13920,23	13521,52	**-17,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	CO_2 captured & stored [Gt]	0,00	10844,76	**-100,0**	2050		x	x				
AMPERE2-450-LowEI-LST	CO_2 captured & stored [Gt]	6764,11	10844,76	**-34,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Nuclear capacity expansion in Newcomers [in GW]	166,94	166,94	**0,0**	2050			x	x	x	x	x
AMPERE2-450-NucOff-OPT	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-OPT	Nuclear capacity expansion in Newcomers [in GW]	141,73	210,52	**1,9**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Nuclear capacity expansion in Newcomers [in GW]	206,69	210,52	**45,1**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Nuclear capacity expansion in Newcomers [in GW]	600,81	254,10	**153,3**	2050			x	x		x	
AMPERE2-450-LowEI-OPT	Nuclear capacity expansion in Newcomers [in GW]	86,64	166,94	**-32,4**	2050			x	x	x	x	x
AMPERE2-450-FullTech-LST	Nuclear capacity expansion in Newcomers [in GW]	172,77	166,94	**3,5**	2050			x	x	x	x	x
AMPERE2-450-NucOff-LST	Nuclear capacity expansion in Newcomers [in GW]	6,70	166,94	**-93,7**	2050			x	x	x	x	x
AMPERE2-450-LimSW-LST	Nuclear capacity expansion in Newcomers [in GW]	180,83	210,52	**18,3**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Nuclear capacity expansion in Newcomers [in GW]	255,71	210,52	**56,8**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Nuclear capacity expansion in Newcomers [in GW]	715,12	254,10	**181,4**	2050			x				
AMPERE2-450-LowEI-LST	Nuclear capacity expansion in Newcomers [in GW]	82,56	166,94	**-32,0**	2050			x	x	x	x	x
AMPERE2-450-FullTech-OPT	Bioenergy supply [EJ]	146,83	146,83	**0,0**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Bioenergy supply [EJ]	150,44	146,83	**3,3**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Bioenergy supply [EJ]	168,30	162,96	**3,6**	2050			x	x	x	x	
AMPERE2-450-LimBio-OPT	Bioenergy supply [EJ]	108,54	162,96	**-35,3**	2050			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Bioenergy supply [EJ]	170,05	146,83	**11,6**	2050		x	x	x		x	
AMPERE2-450-LowEI-OPT	Bioenergy supply [EJ]	96,88	146,83	**-30,6**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Bioenergy supply [EJ]	148,49	146,83	**0,3**	2050		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Bioenergy supply [EJ]	157,42	146,83	**6,8**	2050		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Bioenergy supply [EJ]	168,62	162,96	**3,4**	2050			x	x	x	x	
AMPERE2-450-LimBio-LST	Bioenergy supply [EJ]	110,83	162,96	**-33,9**	2050			x	x	x	x	
AMPERE2-450-NoCCS-LST	Bioenergy supply [EJ]	216,14	132,83	**56,5**	2050		x	x				
AMPERE2-450-LowEI-LST	Bioenergy supply [EJ]	113,84	146,83	**-30,0**	2050		x	x	x	x	x	x
AMPERE2-450-FullTech-OPT	Maximum PV and wind upscaling	2637,39	2637,39	**0,0**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-OPT	Maximum PV and wind upscaling	2631,82	2637,39	**23,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-OPT	Maximum PV and wind upscaling	933,03	2637,39	**-66,3**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-OPT	Maximum PV and wind upscaling	2737,18	2637,39	**8,8**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-OPT	Maximum PV and wind upscaling	6079,59	3185,02	**57,3**	2020-50		x	x	x		x	
AMPERE2-450-LowEI-OPT	Maximum PV and wind upscaling	1033,60	2637,39	**-55,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-FullTech-LST	Maximum PV and wind upscaling	2828,07	2637,39	**11,5**	2020-50		x	x	x	x	x	x
AMPERE2-450-NucOff-LST	Maximum PV and wind upscaling	2971,95	2637,39	**35,3**	2020-50		x	x	x	x	x	x
AMPERE2-450-LimSW-LST	Maximum PV and wind upscaling	1134,66	2637,39	**-57,0**	2020-50			x	x	x	x	
AMPERE2-450-LimBio-LST	Maximum PV and wind upscaling	3574,35	2637,39	**49,3**	2020-50			x	x	x	x	
AMPERE2-450-NoCCS-LST	Maximum PV and wind upscaling	11495,02	2281,02	**268,8**	2020-50		x	x				
AMPERE2-450-LowEI-LST	Maximum PV and wind upscaling	1591,21	2637,39	**-38,6**	2020-50		x	x	x	x	x	x

7 Acronyms and definitions

All acronym and definitions are adapted from Allwood *et al* (2014), mostly following von Stechow *et al* (2015). Blue words indicate that the term is defined in the following:

Adverse side-effects: the potential negative effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications.

Aerosol: a suspension of airborne solid [primary particulate matter (PM)] or liquid particles (secondary PM from gaseous precursors) that may influence climate in several ways.

AFOLU: Agriculture, Forestry and Other Land Use plays a central role for food security and sustainable development (SD).

Black carbon (BC): an aerosol species mostly formed by incomplete fuel combustion, causing a warming effect by absorbing heat into the atmosphere.

Carbon dioxide (CO_2): A naturally occurring gas and by-product of burning fossil fuels and biomass, of land use changes and of industrial processes – the principal anthropogenic greenhouse gas (GHG).

CO_2-equivalent concentration (CO_2eq): The concentration of carbon dioxide (CO_2) that would cause the same radiative forcing as a given mixture of GHGs, aerosols, and surface albedo changes.

Co-benefits: the potential positive effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications.

Conference of Parties (COP): The supreme body of the United Nations Framework Convention on Climate Change (UNFCCC).

Cost-effectiveness analysis (CEA): a tool based on constrained optimization for comparing policies designed to meet a pre-specified target.

Cost-benefit analysis (CBA): monetary measurement of all negative and positive effects associated with a given policy.

Carbon dioxide capture and storage (CCS): Carbon dioxide (CO_2) from industrial and energy-related sources, which is captured, conditioned, compressed, and transported to a long-term storage location.

> Bioenergy and CCS (BECCS): the application of CCS technology to bioenergy conversion processes. Depending on the total lifecycle emissions, BECCS has the potential for net carbon dioxide (CO_2) removal from the atmosphere.

Energy intensity (EI): the ratio of energy use to economic or physical output.

EJ: exajoule

Greenhouse gas (GHG): gaseous constituents of the atmosphere (natural and anthropogenic), which absorb and emit radiation at specific wavelengths emitted, e.g., by Earth's surface.

Gross domestic product (GDP): the sum of gross value added by all producers in an economy for a given period, normally one year.

Hg: mercury

Integrated assessment model (IAM): integrated (assessment) models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. In this letter, we refer to these models as 'integrated models'.

Mitigation (of climate change): reducing the sources or enhancing the sinks of greenhouse gases (GHGs); or reducing other substances that contribute directly or indirectly to limiting climate change.

Mitigation measures: technologies, processes or practices that contribute to mitigation.

Mitigation pathway: The trajectory taken over time to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological, and behavioural changes.

Nitrogen oxides (NO_x): Any of several oxides of nitrogen.

Particulate matter (PM): very small solid particles from solid fuel combustion, which cause adverse health effects and can directly alter the radiation balance.

$PM_{2.5}$: particulate matter 2.5 micrometers in diameter or smaller.

Precursors: atmospheric compounds that have an effect on greenhouse gas (GHG) or aerosol concentrations regulating their production or destruction rates.

Radiative forcing: the change in the net radiative flux at the tropopause due to a change in an external driver of climate change.

Renewable energy (RE): Any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use.

Sink: any process, activity, or mechanism that removes a greenhouse gas (GHG), an aerosol, or a precursor of a GHG or aerosol from the atmosphere.

SO_2: sulfur dioxide.

Sustainable development (SD): development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Traditional biomass: fuelwood, charcoal, agricultural residues, and animal dung used with traditional technologies, e.g., open fires for cooking, rustic kilns, and ovens for small industries.

WGIII AR5: Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

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