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

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Abstract

The adoption of the Sustainable Development Goals (SDGs) and the new international climate treaty could put 2015 into the history books as a defining year for setting human development on a more sustainable pathway. The global climate policy and SDG agendas are highly interconnected: the way that the climate problem is addressed strongly affects the prospects of meeting numerous other SDGs and vice versa. Drawing on existing scenario results from a recent energy-economy-climate model inter-comparison project, this letter analyses these synergies and (risk) trade-offs of alternative 2 °C pathways across indicators relevant for energy-related SDGs and sustainable energy objectives. We find that limiting the availability of key mitigation technologies yields some co-benefits and decreases risks specific to these technologies but greatly increases many others. Fewer synergies and substantial trade-offs across SDGs are locked into the system for weak short-term climate policies that are broadly in line with current Intended Nationally Determined Contributions (INDCs), particularly when combined with constraints on technologies. Lowering energy demand growth is key to managing these trade-offs and creating synergies across multiple energy-related SD dimensions. We argue that SD considerations are central for choosing socially acceptable 2 °C pathways: the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Progress on the climate policy and SDG agendas should therefore be tracked within a unified framework.

1. Introduction

There is hope that 2015 will be remembered as a defining year for setting human development on a more sustainable pathway. Two important milestones were reached. On 25 September, a new development agenda was adopted in New York aimed at eradicating poverty and facilitating inclusive development within ever tighter planetary boundaries. Economic, social and environmental progress will be tracked across a set of agreed sustainable development goals (SDGs). The SDG framework is intended to manage trade-offs and maximize synergies across the 17 different goals and associated 169 targets (Griggs *et al* 2013).

On 12 December, countries agreed upon a new international climate treaty, the Paris Agreement, at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP21) in Paris. It 'aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by holding the increase in the global average temperature to well below 2 °C above pre-industrial levels' (UNFCCC 2015a).

Both processes are highly interrelated: SD is an explicit part of the Paris Agreement, while avoiding dangerous climate change features as one of the SDGs (#13). In fact, failure in one process would undermine the success of the other. Stringent and sustained mitigation is a *necessary* condition for SD, because unabated climate change will exacerbate many of today's development issues and negate future improvements (see Fleurbaey *et al* 2014). However, it is an *insufficient* condition for SD, because some 2 °C pathways could, if not designed properly, undermine SD in non-climate dimensions. For example, pathways with a limited short-term ambition like the current INDCs may have higher SD risks than more ambitious ones. Such broader SD implications could delegitimize some 2 °C pathways or even the 2 °C target itself (Edenhofer and Kowarsch 2015). SD further hinges on the successful implementation of non-climate policies that complement or support climate policies in other dimensions. Thus, identifying socially acceptable 2 °C pathways requires framing climate policy in a broader SD context.

Assessments of alternative mitigation pathways so far have mainly focused on characterizing the underlying technological and economic challenges (Clarke *et al* 2014), but less is known about the wider social, economic and environmental implications. For example, many 2 °C pathways project large amounts of bioenergy demand in the second half of this century. It is highly debated in the literature whether these can be provided sustainably: food security, place-specific livelihoods, water availability and biodiversity are amongst the critical issues being discussed (Creutzig *et al* 2012, Smith *et al* 2014). At the same time, many 2 °C pathways project potential health gains and co-benefits for other sustainability objectives. The balance of these co-effects is poorly understood, particularly on the supply side, because risks of alternative 2 °C pathways for non-climate sustainability objectives have not yet been systematically analyzed (von Stechow *et al* 2015).

In this letter, we analyze the implications of alternative 2 °C pathways for SD risk dimensions by drawing on existing, publicly available inter-model comparison results from integrated energy-economy-climate models—henceforth referred to as integrated models (see SI section 1, available at stacks.iop.org/ERL/11/034022/mmedia). We demonstrate how broadening the analytical framework can allow both for a more informed public debate about alternative 2 °C pathways and how achieving the climate SDG may affect the prospects of meeting other energy-related SDGs. This is important both for critically discussing the relationship between the international climate policy and SDG agendas as well as for identifying stringent mitigation pathways that are socially acceptable.

2. Methods

Choosing appropriate climate policies is an exercise in risk management for which it is key to understand and evaluate relevant uncertainties (Kunreuther *et al* 2013). We focus on uncertainties related to different model structures and assumptions, i.e. 'model uncertainty' (Drouet *et al* 2015) and draw on results from a structured inter-comparison exercise of integrated energy-economy-climate models, AMPERE (Kriegler *et al* 2015, Riahi *et al* 2015). To complement existing literature, this data is used to assess relevant SD implications of alternative clusters of mitigation pathways that are consistent with the 2 °C target (see table S2) to initiate a public debate on their wider sustainability implications.

2.1. Choice of indicators for SD risks

The analysis builds on recent literature that explores a growing number of mitigation challenges with implications for non-climate sustainability objectives. Comprehensive discussions can be found in Clarke *et al* (2014, section 6.6) and von Stechow *et al* (2015, section 4). Table 1 summarizes the indicators that can be calculated from integrated model variables. Our choice of indicators is further constrained by the model structures, scenario runs, and reported variables as aggregated in the publicly available AMPERE database (https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB). For example, the coarse regional disaggregation of reported data in AMPERE impedes the analysis of indicators that are most relevant for inequality and poverty outcomes, such as energy supply per capita to satiate basic human needs (see Steckel *et al* 2013, Lamb and Rao 2015 and SI section 2 for a discussion of further model limitations). By systematically linking the chosen set of indicators to global SD risks, we can present a first, rough approximation of how alternative clusters of 2 °C pathways perform with respect to energy-related SDGs and other multilaterally agreed sustainable energy objectives (see table 2 and SI section 3 for a discussion on the indicator choice).

Due to the limited data availability, the analysis cannot address all relevant SDGs explicitly. But it enables us to provide an early contribution to public and scientific debates on the relationship between the international climate policy and SDG agendas and contribute to important early learning processes. To simplify the complex relationship between indicators, energy-related SDGs and other sustainable energy objectives (see figure S2), table 2 focuses on the strongest links between them. However, many indicators are also relevant for some cross-cutting SDGs, such as poverty and inequality, which are not addressed in the analysis (see SI section 3.1). The resulting set of indicators is relevant for judging both co-benefits of mitigation (air quality, oil security) and mitigation risks (upscaling of

Table 1. Integrated model literature on mitigation challenges with implications for non-climate sustainability objectives, with a focus on indicators that can be calculated from model variables. The different categories largely follow table 4.1 in Fleurbaey *et al* (2014). Due to strengths and weaknesses of the models, some mitigation challenges were only analyzed by individual models while others were covered by multiple models—mostly in the context of model inter-comparison projects. A comprehensive review on co-benefits and risks of mitigation is provided in von Stechow *et al* (2015).

Mitigation challenges	Indicators used	Selected literature
Economic/affordability challenges		
Aggregate economic costs of mitigation	Aggregated and discounted GDP/consumption losses	Kriegler *et al* 2013, Paltsev and Capros 2013, Clarke *et al* 2014, Kriegler *et al* 2014, Rogelj *et al* 2015
Transitional economic costs of mitigation	Consumption growth reduction	Kriegler *et al* 2013, Luderer *et al* 2013a, 2013b, Bertram *et al* 2015b
Carbon price growth	Carbon price jump over a decade	Rogelj *et al* 2013a, 2015
	Global energy price index	Luderer *et al* 2013b, Bertram *et al* 2015b
Energy price growth	Electricity price growth rate	Kriegler *et al* 2013, Rogelj *et al* 2015
Stranded fossil investment	Idle power plant capacity per year	Luderer *et al* 2013a, Rogelj *et al* 2013a, Bertram *et al* 2015a, Johnson *et al* 2015
Energy dependence	Trade flows between regions	Cherp *et al* 2013, Jewell *et al* 2013, 2014, Riahi *et al* 2012
Resilience of energy systems	Diversity of energy carriers in individual sectors (SWDI, HHI)	Cherp *et al* 2013, Jewell *et al* 2013, 2014
Depletion of oil reserves	Cumulative oil extraction	Sathaye *et al* 2011, Jewell *et al* 2013
Technological/innovation challenges		
Integration challenges of low-carbon technologies	Technological upscaling (rates)	Wilson *et al* 2013, Kim *et al* 2014, Eom *et al* 2015, Riahi *et al* 2015, van Sluisveld *et al* 2015, Bertram *et al* 2015a
Carbon intensity improvement	Carbon intensity reduction rates	Luderer *et al* 2013a, Edenhofer *et al* 2014a, Kriegler *et al* 2014, Riahi *et al* 2015
Social/institutional challenges		
Food price increase	World and regional market prices	von Braun *et al* 2008, PBL 2012, Lotze-Campen *et al* 2014, Wise *et al* 2014, van Vuuren *et al* 2015
Energy supply per capita/energy access	Final energy supply per year/access to modern fuels	van Ruijven *et al* 2012, Daioglou *et al* 2012, Krey *et al* 2012, Steckel *et al* 2013, Riahi *et al* 2012, Pachauri *et al* 2013, Lamb and Rao 2015, van Vuuren *et al* 2015
Nuclear proliferation	Enrichment/reprocessing facilities	Lehtveer and Hedenus 2015
Carbon market value	Value of cumulative emissions	Luderer *et al* 2013b, Bertram *et al* 2015b
Environmental challenges		
Resource extraction/use	Cumulative coal/uranium extraction	Rogner *et al* 2012, Bauer *et al* 2013, McCollum *et al* 2014
Bioenergy expansion	Biomass supply for energy	Creutzig *et al* 2012, Smith *et al* 2014
Air pollutant concentration	SO_2, BC, OC and NO_x emissions/concentrations	Riahi *et al* 2012, McCollum *et al* 2013a, Rogelj *et al* 2014, Rose *et al* 2014, Strefler *et al* 2014, van Vuuren *et al* 2015
Environmental risks of CO_2 capture and storage	CO_2 (fossil/biomass) captured and stored underground	Kriegler *et al* 2013, Eom *et al* 2015, Rogelj *et al* 2015, Smith *et al* 2016
Land use change	Global area changes for cropland, pasture, biomass, unmanaged land	Wise *et al* 2009, Reilly *et al* 2012, Lotze-Campen *et al* 2014, Popp *et al* 2014, Calvin *et al* 2014
Water shortage	Water use (mainly for bioenergy supply)	De Fraiture *et al* 2008, Arnell *et al* 2011, PBL 2012, Hejazi *et al* 2013, Bonsch *et al* 2016
Biodiversity loss	Mean species abundance (MSA)	PBL 2012, van Vuuren *et al* 2015
Peak atmospheric CO_2 concentration	Cumulative CO_2 emissions until mid-century	Joos *et al* 2011, Zickfeld *et al* 2012
Exceedance likelihood/overshoot risk	Likelihood of exceeding specific temperature/concentration target	Kriegler *et al* 2013, Luderer *et al* 2013b, Rogelj *et al* 2013a, 2013b

bioenergy and low-carbon electricity technologies) and has been shown to have substantial sustainability implications in many integrated models (Jewell *et al* 2013, McCollum *et al* 2013a, von Stechow *et al* 2015). It also includes an indicator for ocean acidification (Joos *et al* 2011, Zickfeld *et al* 2012) as well as three indicators that relate to transitional socioeconomic mitigation risks (growth in mitigation costs and energy prices as well as early retirement of coal capacity).

Our analysis presents SD risk profiles for alternative clusters of 2 °C pathways (see figures 2–4). The figures plot percentage changes over baseline projections in each dimension rather than comparing different metrics to each other and/or identifying critical thresholds because of the difficulty of incommensurability across different SD dimensions (von Stechow *et al* 2015). Care needs to be taken in the interpretation, because the different risks analyzed cannot be

Table 2. The link between relevant and available indicators calculated from integrated model variables, SD risk dimensions, and SDGs and other sustainable energy objectives. See figure S2 and SI section 3 for more details.

Indicators calculated from integrated model variables	SD risk dimensions affected by mitigation	SDGs and other sustainable energy objectives
Biomass supply for energy per year	Bioenergy expansion	Food security (SDG 2)
Cumulative BC and SO_2 emissions	Air pollutant concentration	Health via air quality (SDG 3.9)
Maximum decadal energy price growth	Energy price growth	Energy access (SDG 7)
Maximum decadal growth reduction	Consumption growth reduction	Economic growth (SDG 8.1)
Idle coal capacity per year	Stranded fossil investment	Full employment (SDG 8.3)
Maximum decadal PV and Wind upscaling	Wind & PV grid integration	Resilient infrastructure (SDG 9)
Cumulative global oil trade, cumulative oil extraction, fuel diversity of transport sector	Oil insecurity, transport sector reliance on oil	Ensure energy security[a]
Nuclear capacity expansion in Newcomers[b]	Nuclear proliferation	Peaceful use of nuclear power
Cumulative CO_2 emissions until mid-century	Peak atmospheric CO_2 concentration	Minimize ocean acidification (SDG 14.3)
CO_2 captured and stored per year	Environmental risks of CCS	Sustainable production (SDG 12.4)

[a] Due to the focus on global risks, the analysis is limited to oil security—the fuel with the highest scarcity concerns and high import dependence in most countries, lacking substitutes in transport (see SI section 3.1.7).

[b] We designed a new indicator that can draw on existing model variables (see SI section 3.2).

directly compared to each other, i.e. a larger increase in one risk is not necessarily more important than a smaller increase in another risk. Any interpretation of these risk profiles and any trade-off across risk dimensions requires evaluation and weighting—and this depends on the locally specific policy contexts and differ depending on individual priorities and risk perceptions (Slovic 1987, Jakob and Edenhofer 2014, Kunreuther *et al* 2014). The provided risk profiles therefore allow readers to make their own judgement about the relevance of changes in risk levels across SD dimensions. In this sense our analysis provides a starting point for a more informed public debate about the interaction between the mitigation and other energy-related SDGs that will put the normative aspects of such evaluation centre stage (see Edenhofer *et al* 2014b).

2.2. Choice of scenario data

Using model inter-comparison results from AMPERE allows us to take advantage of an internally consistent set of scenario specifications and harmonized input assumptions (Kriegler *et al* 2015, Riahi *et al* 2015). AMPERE work package 2 was chosen because (i) the data is publicly available, (ii) it consistently defines alternative short-term climate policy pathways across models until 2030, which is particularly relevant from an SDG perspective with a focus on short/medium-term developments, and (iii) it is the only model inter-comparison project that combines different types of constraints with respect to the stringency of short-term climate policies and the availability of mitigation technologies or energy demand growth assumptions (see table 3 and SI section S4). This is a key requirement for comprehensively exploring the SD risk dimensions of alternative 2 °C pathways. Yet the reported data does not shed light on all relevant dimensions. One shortcoming is the simplifying assumption of regionally homogeneous carbon prices without consideration of burden sharing regimes. This impedes an analysis of regional mitigation cost distributions (see den Elzen *et al* 2008, Luderer *et al* 2012, Tavoni *et al* 2013, Aboumahboub *et al* 2014, Tavoni *et al* 2015) and related SD implications.

The analysis draws on more than 20 scenario specifications from seven models: DNE21+, GCAM, IMAGE, MESSAGE, POLES, REMIND, and WITCH (for further information, see Riahi *et al* (2015) and SI section 4). To avoid comparisons of scenario results from different sets of models, most figures only draw on a subset of models as (i) not all models ran or found a solution for all mitigation scenario specifications, and (ii) not all models report results for all indicators due to model type, assumptions on parameters and constraints, or respective system boundaries (see table S1). The results are presented similarly to the scenario ranges in the Working Group III contribution to the IPCC Fifth Assessment Report (WGIII AR5) because this shows variability across models. However, given that the sample size is small and no systematic variation of all relevant model input assumptions was performed this variability does not represent full model uncertainty.

3. Results

The analysis is divided into two parts: we assess co-benefits of alternative 2 °C pathways before turning to their mitigation risk profiles. In each part, we systematically analyze different clusters of 2 °C pathways to understand the implications for SD outcomes of variations in (i) short-term climate policy stringency, (ii) availability of mitigation technologies or (iii) a combination of the two. Analyzing these clusters is highly relevant, because the current and projected INDC emission trajectories are not consistent with

Table 3. Naming of AMPERE mitigation scenarios (see table S3 and Riahi *et al* 2015 for details).

Model constraints	Description	Scenario name
Short-term targets (2030)		
Optimal policy	Emissions follow optimal 2 °C pathway	'OPT'
Low short-term target	High-ambition pathway (low short-term target): 53 Gt CO_2eq	'LST'
High short-term target	Low-ambition pathway (high short-term target): 61 Gt CO_2eq	'HST'
Technology cases		
Full portfolio of technologies	Full portfolio of mitigation technologies	'Full-Tech'
Low energy intensity[a]	Energy intensity improvements rate doubles	'LowEI'
Limited biomass	Limited global potential for bioenergy (<100 EJ/yr)	'LimBio'
No CCS available	CO_2 capture and storage never becomes available	'NoCCS'
Limited solar/wind potential	Limited potential (<20% of regional electricity supply)	'LimSW'
No new nuclear plants	No new nuclear capacity is added; older plants are retired	'NucOff'

[a] LowEI scenarios assume lower final energy demand due to improvements in energy efficiency and behavioral changes so that equivalent levels of overall energy service are supplied with lower final energy. Due to the limited representation of end-use technologies in some models, many models represent this in a stylized way.

optimal 2 °C pathways (UNFCCC 2015b) and the standard assumption of full technological flexibility is inhibited as significant upscaling of low-carbon technologies faces many different hurdles in practice[8]. Our analysis here focuses on the first half of the 21st century in which the interaction of short-term climate policies and the long-term climate target is strongest (Kriegler *et al* 2013, Luderer *et al* 2013a, 2013b, Riahi *et al* 2015, Eom *et al* 2015, Bertram *et al* 2015a).

3.1. Synergies across mitigation and sustainable energy objectives

Figure 1 uses cumulative indicators for (i) CO_2 emissions (Zickfeld *et al* 2012), (ii) the co-emitted air pollutants black carbon (BC) and sulphur dioxide (SO_2) and (iii) global oil extraction and trade as well as transport sector reliance on oil to present reduced SD risks, i.e. co-benefits of mitigation scenarios compared to baseline developments. Figure 1 shows that co-benefits in terms of lower ocean acidification, health and oil security increase relative to optimal 2 °C pathways by limiting the availability of key mitigation technologies, though considerable differences exist for different technologies and different sustainable energy objectives. This is for three main reasons:

(i) The unavailability of low-carbon technologies limits long-term mitigation potential, resulting in greater near-term emissions reduction requirements to meet a particular long-term climate goal. This leads to a decrease in fossil fuel use in the medium term (with lower cumulative global oil trade, oil extraction as well as transport sector reliance on oil) and the associated CO_2 emissions and co-emitted air pollutants. Limiting technologies that play a smaller role in reaching the long-term goal results in less dramatic transition requirements and fewer additional co-benefits.

(ii) When relying less on bioenergy and/or CO_2 capture and storage (CCS) technologies, the models are forced to switch more rapidly from fossil fuels to solar, wind and nuclear energy, which have higher co-benefits for air quality and oil security (Bruckner *et al* 2014, Hertwich *et al* 2015).

(iii) Limiting the deployment of bioenergy or CCS technologies that are associated with co-emitted air pollutants themselves (see SI section 3.1.9) additionally reduces air pollutant emission levels —which is not the case for limiting the availability of non-combustible RE or new nuclear capacity.

Admittedly, these results only cover a small subset of potential co-benefits from mitigation. However, the literature suggests that this finding may apply more broadly (see von Stechow *et al* 2015 for a review and synthesis): climate policy that leads to less fossil fuel use and energy demand growth in the near term drives a broad range of co-benefits beyond air quality and oil security, such as reduced water use and pollution, reduced ecosystem impacts, reduced health impacts (also due to more physical activity under changed mobility patterns and less fuel poverty in insulated housing) as well as more local employment opportunities.

[8] For example, CCS technology demonstration lags behind early IEA technology roadmaps (IEA 2009); nuclear power plant investments face high public acceptance challenges and even renewable energy (RE) investments are often opposed (Bruckner *et al* 2014). Unforeseen events or accidents (e.g., Fukushima) change risk perceptions of technologies (Rogers 1997, Patt and Weber 2014) making the analysis of limited mitigation technology portfolios interesting and relevant. To avoid unavailability of specific technologies, complementary technology policies (Somanathan *et al* 2014) could reduce additional costs (Kalkuhl *et al* 2013, Bertram *et al* 2015b) and ensure innovation activity, such as for CCS (von Stechow *et al* 2011) or PV (Peters *et al* 2012).

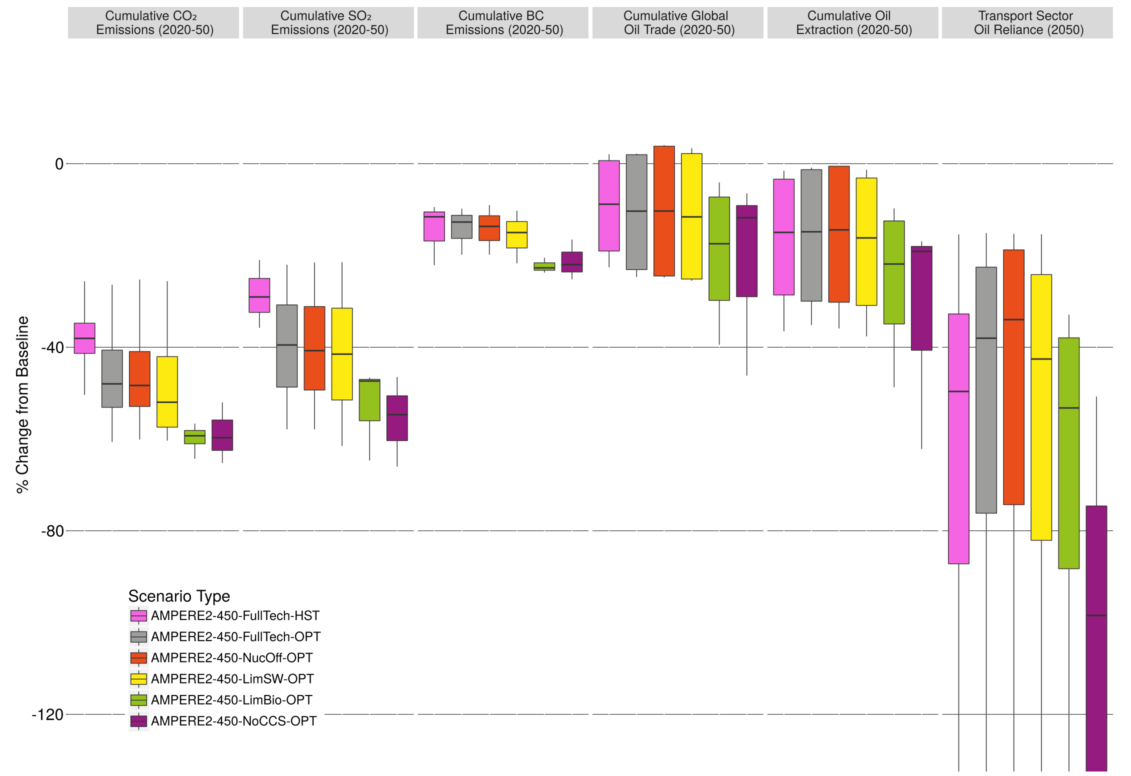

Figure 1. Percentage changes in indicators for co-benefits for reduced ocean acidification, air quality, oil security, and transport sector fuel diversity in alternative 2 °C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios assuming no new nuclear capacity (red), limited potential for solar and wind energy (yellow) limited global bioenergy potential (green) or unavailability of CCS (purple). The thick black lines show the median of results, the coloured ranges show the interquartile ranges and whiskers show the minimum and maximum results.

Comparing optimal 2 °C pathways with scenarios assuming weak short-term climate policies confirms the positive effect of stringent mitigation in the near term on the magnitude of co-benefits (see figure S5 for the year 2030): weak short-term climate policies imply a reduction in co-benefits relative to those that could materialize in optimal 2 °C pathways. This effect is, however, not as obvious for cumulative 2050 values (see figure 1) because some of the additional mitigation efforts in the period 2030–2050 partially compensate for weak climate policies until 2030. Since the transport sector is characterized by faster capital turnover rates (at least with regard to the vehicle fleet) (Bertram *et al* 2015a), it can react more quickly to carbon price changes, compensating for higher emissions from sectors that are less flexible. This may lead, for example, to a higher fuel diversity in the transport sector in the year 2050 in delayed mitigation scenarios compared to optimal 2 °C pathways albeit at high uncertainty.

3.2. Trade-offs between mitigation and sustainable energy objectives

While constraining a particular mitigation technology may minimize the mitigation risks specific to that technology, it usually implies an increase in the deployment of other low-carbon technologies, which may incur other mitigation risks. Figure 2 shows that limiting the availability of specific technologies in 2 °C pathways with immediate global climate policies substantially increases the risk of not meeting other sustainable energy objectives. While the unavailability of CCS and limitation of bioenergy potential lead to the largest co-benefits (see figure 1), they also entail significantly higher SD risks. This can be explained by the promise of greater flexibility in near-term emission pathways that are still able to meet the long-term climate goal through the presence of carbon dioxide removal technologies, such as bioenergy with CCS (BECCS). Constraining BECCS deployment by limiting the global bioenergy potential or ruling out CCS deployment results in substantially higher deployment of other mitigation technologies in the medium term. The increase is much less pronounced for limiting the potential for solar and wind energy or assuming no new nuclear capacity (see figure S6).

Due to the different nature of the mitigation risks, it is unclear how decreasing risks in one dimension (e.g. bioenergy expansion or environmental risks associated with CCS deployment), can be traded off with risk increases in others (e.g. transitional growth reduction, energy price growth, nuclear proliferation or the technological challenges of integrating high amounts of fluctuating RE into existing power grids in a very

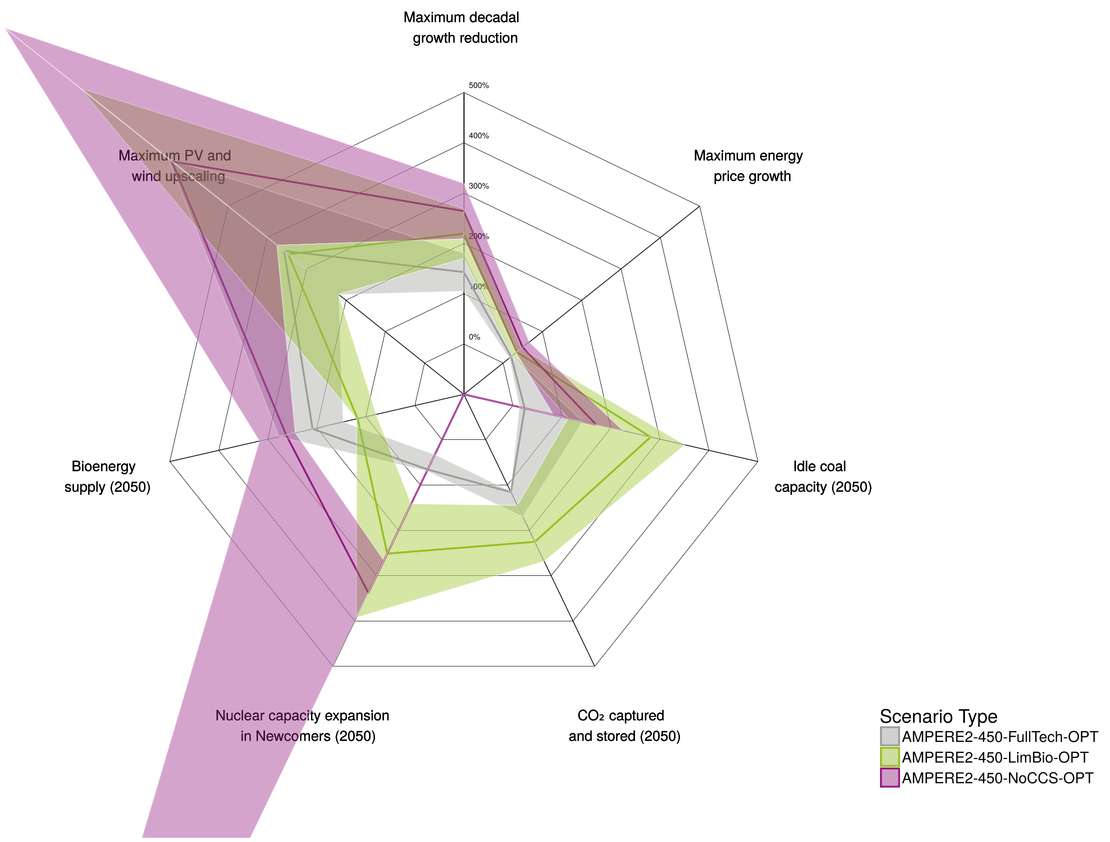

Figure 2. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for three integrated models (GCAM, MESSAGE, REMIND) relative to baseline scenarios and a CCS reference value, comparing immediate mitigation scenarios assuming full availability of mitigation technologies (grey), with scenarios assuming limited global bioenergy potential (green) and unavailability of CCS (purple). Thick coloured lines show median results; coloured ranges show interquartile ranges. Neither the distance to the 0%-line nor the total area covered by the shaded areas 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 (see discussion in section 2.2).

short time frame). For example, a 20%–30% increase in energy prices may have a much more immediate, adverse effect on the poor in many countries than a 4-7-fold increase in maximum decadal upscaling of variable renewable energy sources, which is primarily a technological and institutional challenge for infrastructure provision. Rather than aggregating effects across different risk dimensions, the purpose of this analysis is to make the trade-offs across alternative clusters of mitigation pathways transparent. Hence, the way the climate SDG is met can substantially alter the risks of not meeting other SDGs and sustainable energy objectives.

This is confirmed by figure 3: delaying stringent mitigation in the near term leads to a significant increase in mitigation risk levels in the medium term compared to optimal 2 °C pathways. With more GHG emissions before 2030, subsequent reductions are more expensive (Luderer *et al* 2013b) and need to be faster to stay below 2 °C (Eom *et al* 2015)—with implications for the grid integration of fluctuating RE (see SI section 3.1.6) and for stranded investments in coal capacity (Johnson *et al* 2015) and the associated job losses (Rozenberg *et al* 2014). The carbon lock-in effect hence manifests itself particularly in technological and economic risk dimensions. To a lesser degree, these effects can also be seen for delayed mitigation scenarios with more optimistic assumptions about short-term climate policies (see figure S7). Hence, delaying stringent mitigation implies forgoing potential paths with lower risks along multiple SD dimensions.

In contrast, assuming lower energy demand growth entails mitigation risk reductions relative to optimal 2 °C pathways (see figure 3). As each unit of energy not produced is free of pervasive supply-side risks, reducing energy demand by promoting energy efficiency in end-use sectors (e.g., consumer appliances), lifestyle changes (e.g., people living in higher-density areas and eating less dairy and meat) and structural changes in the economy (e.g., shifting to more service-oriented economies) is an important strategy both for mitigation and other sustainable energy objectives (von Stechow *et al* 2015).

Note that these reductions in energy demand growth are assumed to happen in the baseline scenarios, i.e. independent of the mitigation efforts and hence without a cost mark-up; it is unclear how future energy demand levels would develop under real-world conditions where clean energy and energy efficiency

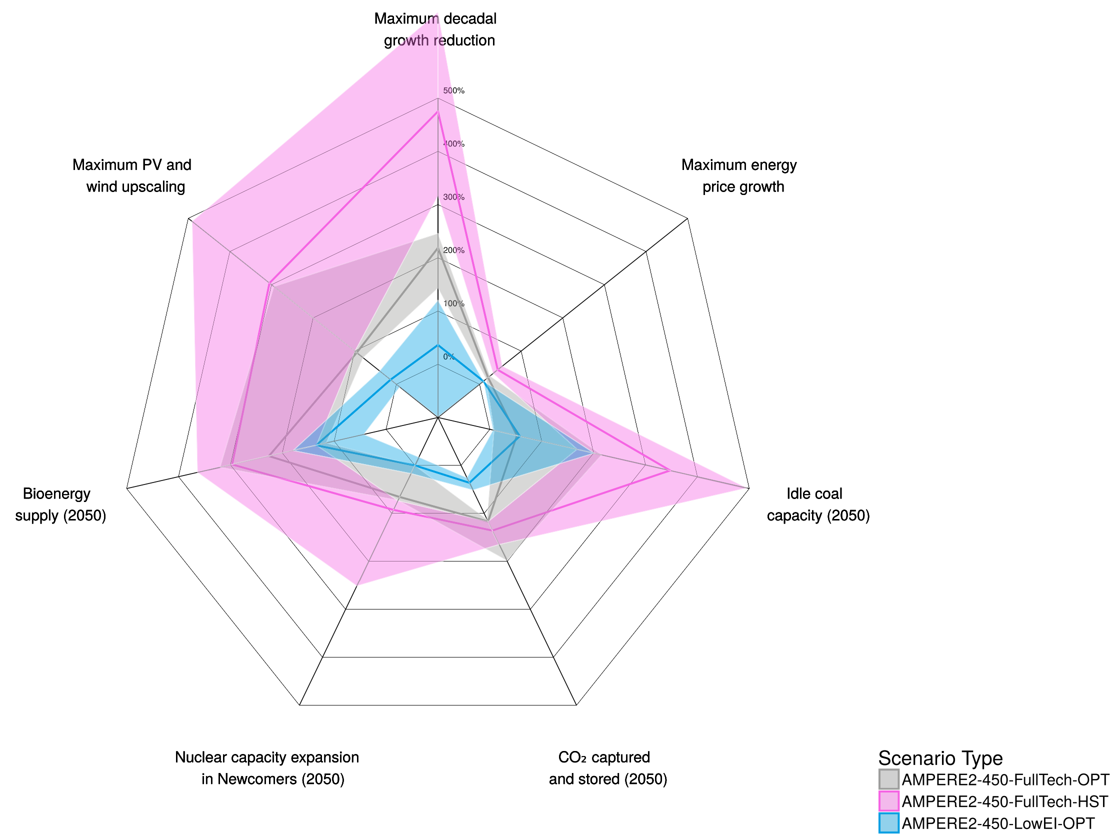

Figure 3. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for six integrated models (DNE21+, GCAM, MESSAGE, POLES, REMIND, WITCH) relative to baseline scenarios and a CCS reference value, comparing immediate (grey) with delayed mitigation scenarios (pink) and immediate mitigation scenarios with lower energy demand growth (blue). Neither the distance to the 0%-line nor the total area covered by the shaded areas 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 (see discussion in section 2.2).

projects may compete for limited funds (McCollum *et al* 2013b). Furthermore, the models do not simply prescribe lower energy supply at the expense of energy service supply, but alter assumptions on the average energy intensity improvement rates and, e.g., on the viability of more compact, public transit-friendly urban areas (Riahi *et al* 2015). This does not imply, however, that all integrated models project final energy supplies in mitigation scenarios that are consistent with minimum thresholds of energy consumption to satiate basic needs related to cooking, heating, health and other infrastructure (Steckel *et al* 2013, Lamb and Rao 2015). Hence, projections of energy demand from individual models need to be interpreted with care (see discussion in SI section 2).

3.3. Trade-offs between mitigation and sustainable energy objectives for combined model constraints

As current GHG emission trends keep tracking along business-as-usual (Edenhofer *et al* 2014a) and societal concerns grow with regard to upscaling of many low-carbon technologies (see footnote 8), 2 °C pathways with multiple constraints seem to mirror most closely developments observed in the real world. In fact, delaying stringent mitigation in combination with technological constraints risks no longer meeting the climate goal (Riahi *et al* 2015), substantially increases mitigation risks (see figure 4) and increasingly jeopardizes our ability to manage risk trade-offs. For CCS and bioenergy whose unavailability/limitations already show substantial risk trade-offs in immediate mitigation scenarios, most models can no longer find a solution (for CCS unavailability only DNE21+ and GCAM; for limited global bioenergy potential only GCAM, POLES, and REMIND) implying a high risk of not meeting the 2 °C target.

Figure 4 draws on AMPERE scenarios with multiple constraints but shows results for more optimistic —albeit not optimal — short-term climate policies[9], with and without limited global bioenergy potential. As models work close to their feasibility frontier, the additional constraint results in large mitigation risk increases. Even for non-biomass RE and nuclear energy, whose limitation/phase-out has rather small effects in immediate 2 °C pathways, risk trade-offs

[9] Figure 4 shows 'LST' scenarios (i.e. with more optimistic assumptions about near-term climate policies relative to 'HST' scenarios but still less stringent than optimal, see table 1) because only three models (GCAM, POLES, and REMIND) were able to find a solution for the 'HST-LimBio' scenarios.

Figure 4. Percentage changes in mitigation risk dimensions in alternative 2 °C pathways for four integrated models (GCAM, MESSAGE, POLES, REMIND) relative to baseline scenarios and a CCS reference value, comparing delayed mitigation scenarios assuming full availability of mitigation technologies and weak short-term climate policies (purple) with delayed mitigation scenarios assuming limited global availability of bioenergy (green). Neither the distance to the 0%-line nor the total area covered by the shaded areas 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 (see discussion in section 2.2).

increase strongly for delayed mitigation scenarios in some dimensions (see figures S7 and S8).

4. Discussion

This letter presents a first attempt to shed light on the question of how alternative 2 °C pathways perform in non-climate SD dimensions and to draw conclusions about important interactions between stringent mitigation and other sustainable energy objectives. Figure 5 shows an overview of the different clusters of constrained 2 °C pathways relative to (each model's) optimal pathways (i.e., those with immediate mitigation, full technology portfolios, and conventional energy demand growth). We use 'optimal' scenarios as benchmarks because they show comparatively balanced risk profiles relative to baseline developments (see figures 2–4) and because they are commonly used as reference point for policy analysis, e.g. in the WGIII AR5 (Edenhofer *et al* 2014a). This enables the comparison of the various SD implications of one cluster of 2 °C pathways to those of all others and therefore facilitates an informed public debate on socially acceptable SD risks and thus the interaction between the international climate policy and the broader SDG agendas.

Note that 'optimal' pathways are not necessarily the most socially desirable because they may already involve unacceptable risks. Scientific analysis alone cannot judge whether a particular 2 °C pathway poses acceptable or unacceptable risks to society (Edenhofer and Minx 2014). Science can, however, explore alternative mitigation pathways and inform an enlightened public debate across SD risk dimensions in an iterative learning process (Edenhofer and Kowarsch 2015). For example, annual bioenergy supply is projected to reach up to 168 EJ (median: 158 EJ) in 2050 in optimal scenarios. These levels of biomass extraction may already be associated with fundamental challenges with respect to food security, place-specific livelihoods, water availability and biodiversity (Creutzig *et al* 2012, Smith *et al* 2014). These numbers further increase substantially over the second half of the century, reaching up to 862 EJ (median: 268 EJ) with growing requirements for removing CO_2 from the atmosphere via bioenergy with CCS (BECCS) technologies in many available scenarios (Clarke *et al* 2014). Many 'optimal' 2 °C pathways have therefore been

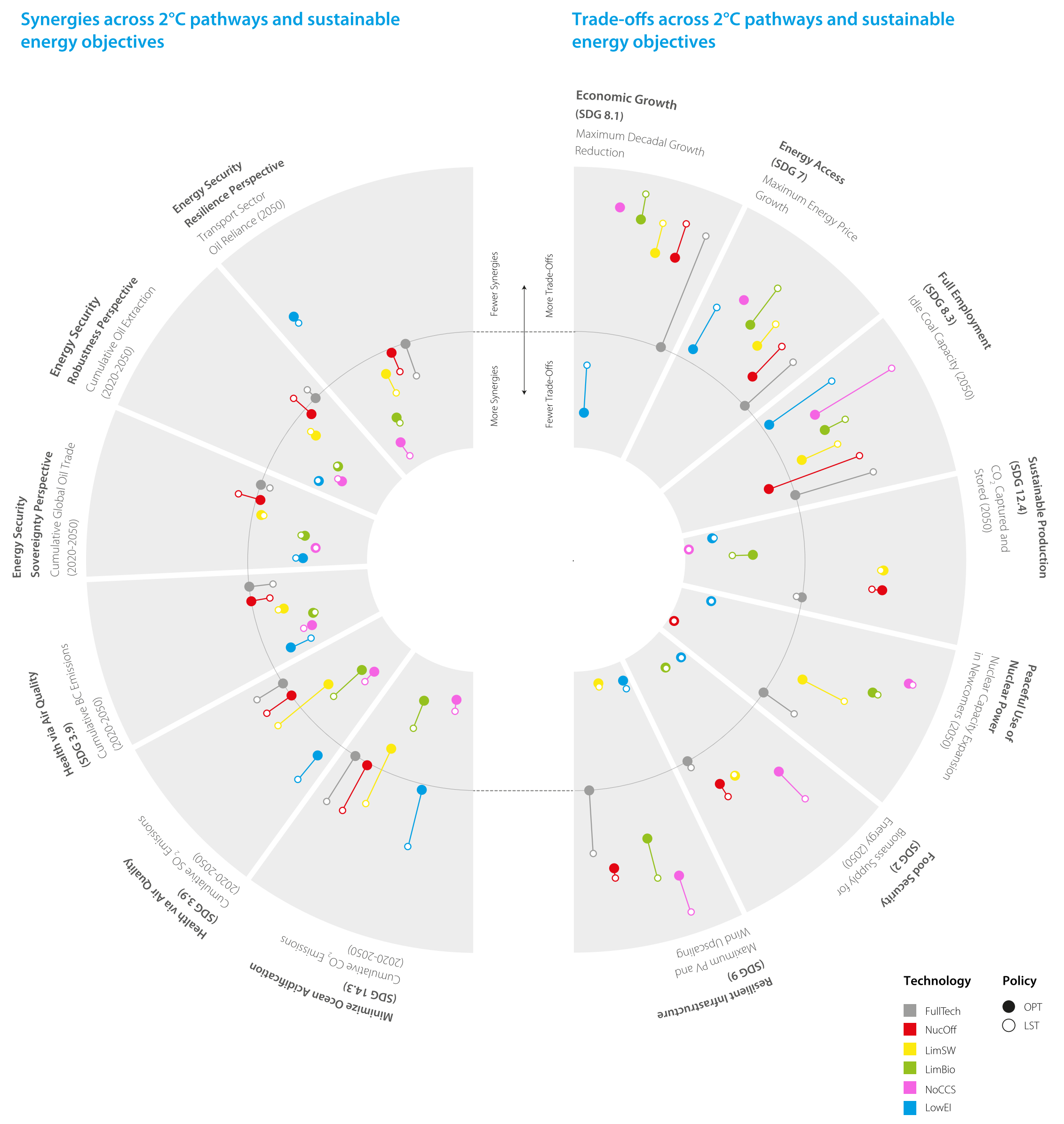

Figure 5. Percentage changes in SD risk dimensions that can be linked to a set of SDGs and other sustainable energy objectives in constrained 2 °C pathways relative to optimal pathways (assuming immediate mitigation with full availability of mitigation technologies and conventional energy demand growth). The different shapes denote different short-term climate policy stringencies while the different colours denote different technology cases (see table 3). As the figure aims at showing trends in synergies and risk trade-offs of alternative clusters of 2 °C pathways rather than an exact quantitative analysis, results are plotted in logarithmic scale (see table S4 for the underlying data).

challenged on these grounds (Fuss *et al* 2014, Smith *et al* 2016).

In a world which is increasingly unlikely to develop along 'optimal' scenario trajectories, an informed public debate about synergies and risk trade-offs implied by alternative clusters of constrained 2 °C pathways is key for identifying those which are socially acceptable. For example, current INDCs at best add up to emission trajectories similar to those 2 °C pathways with low short-term ambition ('LST' scenarios, see table 3)[10]. According to figure 5, these pathways (presented as circles) not only lead to fewer co-benefits compared to optimal 2 °C pathways (except for cumulative BC emissions and transport sector oil reliance) but also to significantly higher mitigation risk levels, particularly in socioeconomic dimensions—with higher risks of not meeting those SDGs related to economic growth, energy access, job preservation, food security and resilient grid infrastructure (see also figure S7).

When a technology constraint is added, only the risks specific to that technology can be lowered (e.g. reduced nuclear proliferation risks for scenarios with no new nuclear capacity or fewer grid integration challenges for scenarios with limited potential for solar and wind energy, see also figures S8 and S9). The other risk levels are exacerbated, particularly for those SDGs

[10] See http://infographics.pbl.nl/indc and http://climateactiontracker.org/global.

that relate to economic growth, job preservation, resilient infrastructure, and ocean acidification. This is particularly obvious for scenarios with limited global potential of bioenergy in which the risks related to bioenergy expansion are lower (including environmental effects related to BECCS deployment) but the risks of not meeting socioeconomic SDGs are significantly higher (see green circles in figure 5). Limiting the global use of bioenergy to 100 EJ per year by 2050—widely believed to be more sustainable (Creutzig *et al* 2014)—hence introduces a trade-off with socioeconomic objectives for weak short-term climate policies (see green circles in figure 5).

While there are uncertainties around acceptable levels of bioenergy deployment, the development and deployment of CCS technology is lagging behind expectations (IEA 2009), despite its important role in keeping mitigation costs at relatively low levels (Edenhofer *et al* 2014a). Our results highlight two things: first, those models that are flexible enough to compensate for the unavailability of CCS can only do so with increased upscaling requirements for other low-carbon technologies and related SD risks (see pink circles in figure 5). This also implies high near-term mitigation requirements with associated co-benefits. Second, the absence of CCS seriously questions the achievability of the 2 °C target in a world with delayed climate action and therefore threatens the climate SDG itself—only two models can report results for the combination with weak short-term climate policies.

In contrast, 2 °C pathways with lower energy demand growth generally entail a substantial reduction in SD risk levels (blue shapes in figure 5). This confirms results from a bottom-up assessment of the wider SD implications of technology-specific studies from a cross-sectoral perspective (von Stechow *et al* 2015). While these scenarios typically do not feature many additional co-benefits due to lower supply-side transition requirements, achieving lower energy demand growth has considerable synergies with the SDG agenda related to economic growth, food security, resilient grid infrastructure as well as with the peaceful use of nuclear energy. Delaying mitigation in scenarios with low energy demand growth only entails moderate risk increases—although some co-benefits are reduced and more coal capacity is likely to be retired early. Pursuing aggressive energy efficiency improvements across all sectors and rethinking high-energy lifestyles therefore seems essential to increase synergies and keep the trade-offs across SDGs manageable in a world that is characterized by multiple constraints. Unfortunately, model inter-comparison projects have not yet analyzed the combination of technology constraints and low energy demand growth pathways, which is a promising research area to better understand synergies between SDGs. Future research should also ensure that mitigation scenarios are consistent with minimum thresholds of energy demand necessary to satiate basic human needs (see discussion in SI section 2).

This letter has analyzed the changes in SD risks across alternative 2 °C pathways. These effects depend to a great extent on the development context, i.e., assumptions about baseline developments (Moss *et al* 2010, O'Neill *et al* 2014). To circumvent this potential caveat, the analysis used AMPERE data that stands out in its comprehensive effort to harmonize future socio-economic drivers of SD across models in the baseline scenarios: e.g., regional-level gross domestic product (GDP), population, and energy demand growth. This makes the results more comparable across models but begs the question of how the results would have changed for alternative assumptions beyond changes in energy demand growth. Research can and should build on alternative baseline developments as expressed by the 'shared socio-economic pathways' (O'Neill *et al* 2014) that will soon be published even though important, non-trivial discussions remain on how SDGs can be adequately built into these baselines (O'Neill *et al* 2015).

Indicators that were used to track the changes in SD risks are only rough and sometimes very rough approximations of individual SDGs. There is no doubt that individual models—particularly those coupled to a detailed agro-economic and land-use model—could already provide better indicators, such as for water availability and ecosystem impacts which are important concerns in stringent mitigation pathways (see SI section 3.1.1). However, these have not yet been analyzed in a multi-model study (von Stechow *et al* 2015). We believe that such inter-model comparison results are crucial for a meaningful public debate about SD risks.

Another important caveat of the analysis is that we focus on 2050 and the preceding decades when looking at the implications of alternative 2 °C pathways for SD risk dimensions. The risks of some 2 °C pathways, however, only unfold later in that century when some particularly risky negative emissions technologies, such as BECCS, are being deployed at large scale to compensate for lower mitigation efforts in the first decades and residual GHG emissions in other sectors (Fuss *et al* 2014, Smith *et al* 2016). For illustrative purposes, figures S10 and S11 show how mitigation risks change from 2050 to 2080 for scenarios with substantially different amounts of negative emission requirements. Since the AMPERE scenario specifications do not allow for a meaningful comparison across scenarios with low or high amounts of negative emissions, we use the amount of radiative forcing overshoot to cluster scenarios with respect to their dependence on negative emissions (also used in the WGIII AR5 scenario database, see Krey *et al* 2014). It shows that the magnitude of the mitigation risk levels can change substantially over time for those dimensions that are related to negative emission technologies such as CCS and bioenergy deployment.

Our analysis points to important future challenges: first, the chosen indicators do not represent all SDGs as some touch on socio-cultural and institutional aspects which are challenging—if not impossible—to represent in an economic model framework (see SI section 2). Second, the changes in the indicators across scenarios are merely indicative for the change in risks to meet the related SDGs and sustainable energy objectives because there are many more relevant drivers that cannot be analyzed based on the available scenario data. Third, many relevant issues play out at lower geographic and time scales which are difficult to represent adequately in global-scale integrated models. For example, food security is driven by many socioeconomic drivers both on global and local scales and bioenergy expansion represents but one of those (Tscharntke *et al* 2012). And according to Creutzig *et al* (2012), the models are not (yet) suitable for operationalizing important global SD dimensions of bioenergy supply such as the socioeconomic convergence across different countries. Nevertheless, we argue that the indicators used in this letter are relevant for evaluating additional pressure on the energy-economy-climate system from additional constraints as represented in the models. As such, they supply important information from internally consistent model frameworks taking into account inter-sectoral and inter-regional interactions (von Stechow *et al* 2015 and SI section 1).

We provide this early contribution to a public debate on the relationship between the international climate policy and the SDG agendas based on existing multi-model scenario data that was not specifically developed for this particular purpose. This stimulus seems important because results from model inter-comparisons that are tailored towards the SDG-climate nexus will not be published for some years. Only by working with the available data can we start discussing relevant (risk) trade-offs and synergies. Based on our analysis, we argue that SD considerations are central for determining socially acceptable climate policies and that the prospects of meeting other SDGs need not dwindle and can even be enhanced for some goals if appropriate climate policy choices are made. Moreover, experiences and caveats of this analysis can help guide future research efforts at a relevant moment in time when new model comparison exercises are being designed. For example, to remain policy-relevant, SDG-focused multi-model comparisons will need to address inequality, poverty, and basic human needs as major drivers of the policy process much more adequately. This requires a serious discussion, e.g., on how to deal with the coarse regional disaggregation in the integrated modelling frameworks. Equally, successful efforts to address SDG-relevant issues in one model, e.g., for the analysis of water availability or ecosystem impacts (see SI section 2), will need to be lifted into a multi-model context.

5. Conclusion

Until now, no multi-model study has been used to systematically analyze the changes in SD risks implied by stringent mitigation scenarios and evaluate them across a set of SDGs. This letter addresses this research gap by analyzing a comprehensive set of alternative clusters of 2 °C pathways consistently formulated across many integrated models from the AMPERE model inter-comparison study, drawing on publicly available scenario results to calculate indicators for global SD risks. We shed light on the implications of alternative clusters of 2 °C pathways for meeting a set of energy-related SDGs and other sustainable energy objectives and to inform the public debate about the synergies and trade-offs across the international climate policy and the SDG agendas.

Our analysis shows that the near-term choice of 2 °C pathways has implications for the extent of synergies and trade-offs across energy-related SDGs in the medium term. Given current trends in emissions and technology deployment, we argue that mitigation pathways are likely to be characterized by multiple constraints. But adding limits on the availability of specific mitigation technologies on top of weak short-term climate policies decreases synergies and locks in substantial trade-offs across environmental and socioeconomic objectives. From an SDG perspective, the challenges of meeting other sustainable energy objectives substantially change with the way the climate SDG will be met. In some cases, meeting the 2 °C target is even threatened itself. Achieving low-energy demand growth, e.g., through aggressive energy efficiency improvements, helps to manage these trade-offs and attain multiple energy-related SDGs together. We find the greater the constraints on flexibility in meeting the 2 °C target, the higher the risks of not meeting other SDGs and the flexibility to manage these risks. Governments at all levels need to be informed about such implications of their collective decision for the attainability of global SDGs. This could avoid additional pressures on the sustainability of each region's development pathway.

After COP21, decision makers need to rethink their commitment to the SDG agenda, given that the short-term ambition for mitigation action falls short of the mitigation efforts consistent with staying below 2 °C in a cost-effective way. According to our results, this is likely to decrease co-benefits and increase the risks for attaining energy-related SDGs and other sustainable energy objectives. Since many of these SD risks are best dealt with at the global level, however, they might be good entry points into additional incentives for international cooperation. We suggest that the review of INDCs should provide for an assessment of policies at all scales to monitor global risks for non-climate sustainability objectives that arise from specific global mitigation pathways. Monitoring these risks could avoid unintended consequences (which might even delegitimize the 2 °C target), finding new entry points for global cooperation and providing rationales for ramping up mitigation ambition in the short to medium term.

Future research should extend the current system boundaries and, based on a comprehensive review of model literature on the climate-SDG nexus, establish indicators that help evaluate integrated policies addressing multiple SDGs in a unified framework. This would be a prerequisite for model inter-comparison projects with a focus on the interactions across multiple SDGs that could result in meaningful and robust results for better decision making. Climate policy will not be successful unless it seriously considers other policy objectives and therefore wider SD implications. Dividing the huge effort of achieving more sustainable development pathways into isolated policy problems will fall short of reaping synergies and successfully managing trade-offs across the many SDGs.

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References

Aboumahboub T, Luderer G, Kriegler E, Leimbach M, Bauer N, Pehl M and Baumstark L 2014 On the regional distribution of climate mitigation costs: the impact of delayed cooperative action *Clim. Change Econ.* **05** 1440002

Arnell N W, van Vuuren D P and Isaac M 2011 The implications of climate policy for the impacts of climate change on global water resources *Global Environmental Change* **21** 592–603

Bauer N, Mouratiadou I, Luderer G, Baumstark L, Brecha R J, Edenhofer O and Kriegler E 2013 Global fossil energy markets and climate change mitigation—an analysis with REMIND *Clim. Change* 1–14

Bertram C, Johnson N, Luderer G, Riahi K, Isaac M and Eom J 2015a Carbon lock-in through capital stock inertia associated with weak near-term climate policies *Technol. Forecast. Soc. Change* A **90** 62–72

Bertram C, Luderer G, Pietzcker R C, Schmid E, Kriegler E and Edenhofer O 2015b Complementing carbon prices with technology policies to keep climate targets within reach *Nat. Clim. Change* **5** 235–9

Bonsch M *et al* 2016 Trade-offs between land and water requirements for large-scale bioenergy production *Glob. Change Biol. Bioenergy* **8** 11–24

von Braun J *et al* 2008 *High Food Prices: The What, Who, and How of Proposed Policy Actions* (Washington, DC: International Food Policy Research Institute)

Bruckner T *et al* 2014 Energy systems *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 511–97

Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J 2014 Trade-offs of different land and bioenergy policies on the path to achieving climate targets *Clim. Change* **123** 691–704

Cherp A, Jewell J, Vinichenko V, Bauer N and Cian E D 2013 Global energy security under different climate policies, GDP growth rates and fossil resource availabilities *Clim. Change* 1–12

Clarke L *et al* 2014 Assessing transformation pathways *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 413–506

Creutzig F *et al* 2014 Bioenergy and climate change mitigation: an assessment GCB *Bioenergy* **7** 916–44

Creutzig F, von Stechow C, Klein D, Hunsberger C, Bauer N, Popp A and Edenhofer O 2012 Can bioenergy assessments deliver? *Economics of Energy & Environmental Policy* **1** 65–82

Daioglou V, van Ruijven B J and van Vuuren D P 2012 Model projections for household energy use in developing countries *Energy* **37** 601–15

De Fraiture C, Giordano M and Liao Y 2008 Biofuels and implications for agricultural water use: blue impacts of green energy *Water Policy* **10** 67–81

den Elzen M G J, Lucas P L and van Vuuren D P 2008 Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations *Clim. Change* **90** 243–68

Drouet L, Bosetti V and Tavoni M 2015 Selection of climate policies under the uncertainties in the fifth assessment report of the IPCC *Nat. Clim. Change* **5** 937–40

Edenhofer O and Kowarsch M 2015 Cartography of pathways: a new model for environmental policy assessments *Environ. Sci. Policy* **51** 56–64

Edenhofer O and Minx J 2014 Mapmakers and navigators, facts and values *Science* **345** 37–8

Edenhofer O *et al* 2014a Technical summary *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 31–107

Edenhofer O, Kadner S, von Stechow C, Schwerhoff G and Luderer G 2014b Linking climate change mitigation research to sustainable development *Handbook of Sustainable Development* 2nd edn ed G Atkinson, S Dietz, E Neumayer and M Agarwala (Cheltenham, UK: Edward Elgar) pp 476–99

Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, Riahi K and Van Vuuren D P 2015 The impact of near-term climate policy choices on technology and emission transition pathways *Technological Forecasting and Social Change* **90** 73–88

Fleurbaey M *et al* 2014 Sustainable development and equity *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 283–350

Fuss S *et al* 2014 Betting on negative emissions *Nature Clim. Change* **4** 850–3

Griggs D, Stafford-Smith M, Gaffney O, Rockström J, Öhman M C, Shyamsundar P, Steffen W, Glaser G, Kanie N and Noble I

2013 Policy: sustainable development goals for people and planet *Nature* **495** 305–7
Hejazi M I, Edmonds J, Clarke L, Kyle P, Davies E, Chaturvedi V, Eom J, Wise M, Patel P and Calvin K 2013 Integrated assessment of global water scarcity over the 21st century: 2. Climate change mitigation policies *Hydrology and Earth System Sciences Discussions* **10** 3383–425
Hertwich E G, Gibon T, Bouman E A, Arvesen A, Suh S, Heath G A, Bergesen J D, Ramirez A, Vega M I and Shi L 2015 Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies *Proc. Natl Acad. Sci. USA* **112** 6260–4
IEA 2009 *Technology Roadmap: Carbon Capture and Storage* (Paris, France: Organisation for Economic Co-operation and Development/International Energy Agency (IEA)) (https://iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2009.html)
Jakob M and Edenhofer O 2014 Green growth, degrowth, and the commons *Oxford Review of Economic Policy* **30** 447–68
Jewell J, Cherp A and Riahi K 2014 Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices *Energy Policy* **65** 743–60
Jewell J, Cherp A, Vinichenko V, Bauer N, Kober T, McCollum D L, van Vuuren D P and van der Zwaan B 2013 Energy security of China, India, the EU and the US under long-term scenarios: results from six IAMs *Clim. Change Econ.* **4** 1340011
Johnson N, Krey V, McCollum D L, Rao S, Riahi K and Rogelj J 2015 Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants *Technol. Forecast. Soc. Change* A **90** 89–102
Joos F, Fröhlicher T L, Steinacher M and Plattner G-K 2011 Impact of climate change mitigation on ocean acidification projections *Ocean Acidification* ed J-P Gattuso and L Hansson (Oxford: Oxford University Press) pp 272–90
Kalkuhl M, Edenhofer O and Lessmann K 2013 Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? *Resour. Energy Econ.* **35** 217–34
Kim S H, Wada K, Kurosawa A and Roberts M 2014 Nuclear energy response in the EMF27 study *Clim. Change* **123** 443–60
Krey V *et al* 2014 Annex II: metrics & methodology *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 1281–328
Krey V, O'Neill B C, van Ruijven B, Chaturvedi V, Daioglou V, Eom J, Jiang L, Nagai Y, Pachauri S and Ren X 2012 Urban and rural energy use and carbon dioxide emissions in *Asia Energy Economics* **34** S272–83
Kriegler E *et al* 2015 Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy *Technol. Forecast. Soc. Change* A **90** 24–44
Kriegler E *et al* 2013 What does the 2 °C target imply for a global climate agreement in 2020? The limits study on Durban Platform scenarios *Clim. Change Econ.* **04** 1340008
Kriegler E *et al* 2014 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies *Clim. Change* **123** 353–67
Kunreuther H *et al* 2014 Integrated risk and uncertainty assessment of climate change response policies *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 151–205
Kunreuther H, Heal G, Allen M, Edenhofer O, Field C B and Yohe G 2013 Risk management and climate change *Nature Clim. Change* **3** 447–50
Lamb W F and Rao N D 2015 Human development in a climate-constrained world: what the past says about the future *Glob. Environ. Change* **33** 14–22
Lehtveer M and Hedenus F 2015 Nuclear power as a climate mitigation strategy—technology and proliferation risk *J. Risk Res.* **18** 273–90
Lotze-Campen H *et al* 2014 Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison *Agricultural Economics* **45** 103–16
Luderer G, Bertram C, Calvin K, Cian E D and Kriegler E 2013a Implications of weak near-term climate policies on long-term mitigation pathways *Clim. Change* 1–14
Luderer G, De Cian E, Hourcade J-C, Leimbach M, Waisman H and Edenhofer O 2012 On the regional distribution of mitigation costs in a global cap-and-trade regime *Clim. Change* **114** 59–78
Luderer G, Pietzcker R C, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013b Economic mitigation challenges: How further delay closes the door for achieving climate targets *Environ. Res. Lett.* **8** 034033
McCollum D, Bauer N, Calvin K, Kitous A and Riahi K 2014 Fossil resource and energy security dynamics in conventional and carbon-constrained worlds *Clim. Change* **123** 413–26
McCollum D L, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013a Climate policies can help resolve energy security and air pollution challenges *Clim. Change* **119** 479–94
McCollum D, Nagai Y, Riahi K, Marangoni G, Calvin K, Pietzcker R, van Vliet J and van der Zwaan B 2013b Energy investments under climate policy: a comparison of global models *Clim. Change Econ.* **04** 1340010
Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56
O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400
O'Neill B C *et al* 2015 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* (doi:10.1016/j.gloenvcha.2015.01.004)
Pachauri S, Ruijven B J van, Nagai Y, Riahi K, Vuuren D P van, Brew-Hammond A and Nakicenovic N 2013 Pathways to achieve universal household access to modern energy by 2030 *Environ. Res. Lett.* **8** 024015
Paltsev S and Capros P 2013 Cost concepts for climate change mitigation *Clim. Change Econ.* **04** 1340003
Patt A G and Weber E U 2014 Perceptions and communication strategies for the many uncertainties relevant for climate policy *WIREs Clim Change* **5** 219–32
PBL 2012 Roads from Rio+20 Pathways to achieve global sustainability goals by 2050 (The Hague, The Netherlands: Netherlands 3 Environmental Assessment Agency (PBL)) (http://pbl.nl/en/publications/2012/roads-from-rio20)
Peters M, Schneider M, Griesshaber T and Hoffmann V H 2012 The impact of technology-push and demand-pull policies on technical change—does the locus of policies matter? *Research Policy* **41** 1296–308
Popp A *et al* 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options *Clim. Change* **123** 495–509
Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A and Schlosser A 2012 Using land to mitigate climate change: hitting the target, recognizing the trade-offs *Environ. Sci. Technol.* **46** 5672–9
Riahi K *et al* 2015 Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals *Technol. Forecast. Soc. Change* A **90** 8–23
Riahi K *et al* 2012 Energy pathways for sustainable development *Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press, and Laxenburg, Austria: International Institute for Applied Systems Analysis) ch 17, pp 1203–306 (www.globalenergyassessment.org)
Rogelj J, Luderer G, Pietzcker R C, Kriegler E, Schaeffer M, Krey V and Riahi K 2015 Energy system transformations for

limiting end-of-century warming to below 1.5 °C *Nature Clim. Change* **5** 519–27

Rogelj J, McCollum D L, O'Neill B C and Riahi K 2013a 2020 emissions levels required to limit warming to below 2 °C *Nature Clim. Change* **3** 405–12

Rogelj J, McCollum D L, Reisinger A, Meinshausen M and Riahi K 2013b Probabilistic cost estimates for climate change mitigation *Nature* **493** 79–83

Rogelj J, Schaeffer M, Meinshausen M, Shindell D T, Hare W, Klimont Z, Velders G J M, Amann M and Schellnhuber H J 2014 Disentangling the effects of CO2 and short-lived climate forcer mitigation *Proc. Natl Acad. Sci. USA* **111** 16325–30

Rogers G O 1997 The dynamics of risk perception: how does perceived risk respond to risk events? *Risk Anal.* **17** 745–57

Rogner H-H *et al* 2012 *Energy Resources and Potentials Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press, and Laxenburg, Austria: International Institute for Applied Systems) ch 7, pp 423–512 (www.globalenergyassessment.org)

Rose S K, Richels R, Smith S, Riahi K, Strefler J and van Vuuren D P 2014 Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios *Clim. Change* **123** 511–25

Rozenberg J, Vogt-Schilb A and Hallegatte S 2014 Transition to clean capital, irreversible investment and stranded assets *World Bank Policy Research Working Paper 6859* (http://papers.ssrn.com/abstract=2 433 812)

van Ruijven B J, Schers J and van Vuuren D P 2012 Model-based scenarios for rural electrification in developing countries *Energy* **38** 386–97

Sathaye J *et al* 2011 Renewable energy in the context of sustainable development *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 707–89

Slovic P 1987 Perception of risk *Science* **236** 280–5

van Sluisveld M A E, Harmsen J H M, Bauer N, McCollum D L, Riahi K, Tavoni M, Vuuren D P, van, Wilson C and Zwaan B van der 2015 Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change *Global Environmental Change* **35** 436–49

Smith P *et al* 2014 Agriculture, forestry and other land use (AFOLU) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 811–922

Smith P *et al* 2016 Biophysical and economic limits to negative CO_2 emissions *Nature Clim. Change* **6** 42–50

Somanathan E *et al* 2014 National and sub-national policies and institutions *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press) pp 1141–205

von Stechow C *et al* 2015 Integrating global climate change mitigation goals with other sustainability objectives: a synthesis *Ann. Rev. Environ. Res.* **40** 363–94

von Stechow C, Watson J and Praetorius B 2011 Policy incentives for carbon capture and storage technologies in Europe: a qualitative multi-criteria analysis *Glob. Environ. Change* **21** 346–57

Steckel J C, Brecha R J, Jakob M, Strefler J and Luderer G 2013 Development without energy? Assessing future scenarios of energy consumption in developing countries *Ecological Economics* **90** 53–67

Strefler J, Luderer G, Kriegler E and Meinshausen M 2014 Can air pollutant controls change global warming? *Environ. Sci. Policy* **41** 33–43

Tavoni M *et al* 2013 The distribution of the major economies' effort in the Durban Platform scenarios *Clim. Change Econ.* **04** 1340009

Tavoni M *et al* 2015 Post-2020 climate agreements in the major economies assessed in the light of global models *Nature Clim. Change* **5** 119–26

Tscharntke T, Clough Y, Wanger T C, Jackson L, Motzke I, Perfecto I, Vandermeer J and Whitbread A 2012 Global food security, biodiversity conservation and the future of agricultural intensification *Biological Conservation* **151** 53–9

UNFCCC 2015a *Adoption of the Paris Agreement Proposal by the President* (Paris: United Nations Framework Convention on Climate Change (UNFCCC)) (http://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008831)

UNFCCC 2015b Synthesis report on the aggregate effect of the intended nationally determined contributions. Note by the secretariat. Report of the Ad Hoc Working Group on the Durban Platform for Enhanced Action (Paris: United Nations Framework Convention on Climate Change (UNFCCC)) (http://unfccc.int/resource/docs/2015/cop21/eng/07.pdf)

van Vuuren D P *et al* 2015 Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model *Technol. Forecast. Soc. Change* **98** 303–23

Wilson C, Grubler A, Bauer N, Krey V and Riahi K 2013 Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change* **118** 381–95

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S J, Janetos A and Edmonds J 2009 Implications of limiting CO_2 concentrations for land use and energy *Science* **324** 1183–6

Wise M, Dooley J, Luckow P, Calvin K and Kyle P 2014 Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century *Appl. Energy* **114** 763–73

Zickfeld K, Arora V K and Gillett N P 2012 Is the climate response to CO_2 emissions path dependent? *Geophys. Res. Lett.* **39** L05703