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LETTER

Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios

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Abstract

Meeting the 1.5 °C goal will require a rapid scale-up of zero-carbon energy supply, fuel switching to electricity, efficiency and demand-reduction in all sectors, and the replenishment of natural carbon sinks. These transformations will have immediate impacts on various of the sustainable development goals. As goals such as affordable and clean energy and zero hunger are more immediate to great parts of global population, these impacts are central for societal acceptability of climate policies. Yet, little is known about how the achievement of other social and environmental sustainability objectives can be directly managed through emission reduction policies. In addition, the integrated assessment literature has so far emphasized a single, global (cost-minimizing) carbon price as the optimal mechanism to achieve emissions reductions. In this paper we introduce a broader suite of policies—including direct sector-level regulation, early mitigation action, and lifestyle changes—into the integrated energy-economy-land-use modeling system REMIND-MAgPIE. We examine their impact on non-climate sustainability issues when mean warming is to be kept well below 2 °C or 1.5 °C. We find that a combination of these policies can alleviate air pollution, water extraction, uranium extraction, food and energy price hikes, and dependence on negative emissions technologies, thus resulting in substantially reduced sustainability risks associated with mitigating climate change. Importantly, we find that these targeted policies can more than compensate for most sustainability risks of increasing climate ambition from 2 °C to 1.5 °C.

Background

Climate change and sustainable development have a long history in international diplomacy, and recent developments have attempted to merge the two agendas into a common discourse. Climate change has been enshrined in the sustainable development goals, as goal 13, whereas the Paris Agreement in turn has been strongly framed in the context of sustainable development (United Nations General Assembly 2015, UNFCCC 2015).

At the heart of this common discourse is a growing appreciation that both agendas directly depend on the success of the other (Stechow *et al* 2016). Arguably, sustainable development cannot be achieved unless the most severe, pervasive and potentially irreversible climate impacts of business-as-usual development to people and natural systems can be avoided—requiring limiting warming to well below 2 °C or possibly even 1.5 °C (Edenhofer *et al* 2014, IPCC 2014a). However, the means by which such emissions reductions would be achieved are highly consequential for future human development. For instance, a large-scale dependence on bioenergy and negative emissions deployments could threaten long-term food security and biodiversity objectives (Creutzig *et al* 2015, Fuss *et al* 2018, Minx *et al* 2018).

Conversely, it is becoming increasingly apparent that sustainable development is a key enabler for climate change mitigation. For instance, energy access

(SDG 7) and adequate food supply (SDG 2) are fundamental for livelihoods and poverty reduction (SDG 1), but they must be provisioned via low-carbon and sustainable infrastructures to avoid locking-in future emissions (Lamb and Rao 2015). Emissions reductions also require strong institutions (SDG 16), international partnerships (SDG 17), innovation (SDG 9), as well as healthy ecosystems (SDGs 13 and 14).

Many studies have explored the linkages between climate change mitigation and individual sustainability objectives. In the integrated assessment model (IAM) literature, streams of work have focused on climate policy in the context of household energy access (Riahi *et al* 2012, Pachauri *et al* 2013, Cameron *et al* 2016). Another series of studies have explored the economic implications of climate change mitigation, including policy costs in the short and long term, technological progress, carbon and energy price development, energy security aspects, and innovation and upscaling (Wilson *et al* 2013, Jewell *et al* 2014, Bertram *et al* 2015, Rogelj *et al* 2015). The wider impacts of climate change policies for other environmental problems such as local air pollution (West *et al* 2013, Strefler *et al* 2014), water scarcity (Bonsch *et al* 2016), deforestation, land-use change, and biodiversity have also been studied quite intensively (van Vuuren *et al* 2015), while social aspects have only been scarcely addressed (Stevanović *et al* 2017). Literature from a development angle has explored climate policy pathways that protect and enhance low-income livelihoods (Hallegatte *et al* 2016), potentially through targeted policies on high emitters and global reductions in inequality (Piketty and Chancel 2015, Rao and Min 2018), or by recycling carbon tax revenues into public goods (Jakob *et al* 2016).

Yet there have been few attempts so far to study synergies and trade-offs of mitigation policies across multiple sustainability objectives quantitatively (McCollum *et al* 2018). These studies typically include either a systematic assessment of existing research on individual SDG dimensions, within a matrix of potential policy measures (Weitz *et al* 2017), or integrated analysis examining the trade-offs between climate change mitigation, food security, biodiversity (van Vuuren *et al* 2015), food consumption and the land system (Obersteiner *et al* 2016). Research efforts from the sustainable development disciplines are also driving a 'energy-water-food nexus' framing, which has attracted both integrated modeling studies (Kyle *et al* 2013, Bonsch *et al* 2016) and bottom-up case studies (Biggs *et al* 2015, Keairns *et al* 2016). Still, a comprehensive assessment of sustainability implications associated with the 1.5 °C limit is so far unavailable. Such evidence is critical because stringent mitigation policy involves very aggressive efforts, including those that remove carbon dioxide from the atmosphere at a very large-scale (Luderer *et al* 2013, Rogelj *et al* 2015, Rogelj *et al* 2017). Furthermore, while increasing attention is given to the wider sustainability implications of mitigation policies, there is little analysis so far regarding how these can be directly managed through the choice of alternative mitigation policies.

Against this background, the goals of our study are to: (a) quantify the potential benefits and adverse side-effects of climate change mitigation on sustainability indicators, both for 2 °C and 1.5 °C; (b) evaluate the effectiveness of different policies in fostering sustainable development; and (c) understand the trade-offs implied by single instruments and their complementarity.

Methods

In this study, we provide an integrated analysis of sustainability impacts of 1.5 °C and 2 °C scenarios, across a comparatively large number of sustainability dimensions, and analyze how policy packages addressing climate and non-climate objectives can help to manage wider sustainability impacts.

We use the integrated energy-economy-climate model REMIND (Leimbach *et al* 2010, Luderer *et al* 2015) coupled to the land-use model MAgPIE (Lotze-Campen *et al* 2008, Popp *et al* 2014). Further details on the two models and their coupling can be found in supplementary section 1 available at stacks.iop.org/ERL/13/064038/mmedia. Within this modeling framework, we construct various transformation pathways that lead to two different long-term climate targets and are differentiated by five different policy paradigms. In terms of the socio-economic development of population, GDP, trade, and development of technology cost and availability, middle-of-the road assumptions as in the SSP2 scenario (Fricko *et al* 2017) are underlying all scenarios. Scenarios are differentiated along the two dimensions of climate stabilization target and policy paradigm.

Stabilization target: For the long-term climate target, we investigate both a 'well-below 2 °C' scenario and a '1.5 °C by 2100' scenario (table 1). As in Luderer *et al* (2018) the climate targets are defined via a bound on cumulative total CO_2 emissions (including emissions from fossil fuel combustion, industrial processes and land-use and land-use change). The bound is adhered by iteratively adjusting the emissions price on CO_2, N_2O and CH_4, using 100 year global warming potentials, with reduced prices for emissions from the land-use system (cf. table 2). Emission pricing starts in 2020 and prices increase exponentially until 2060 with 5% p.a. in the default policy setting and linearly thereafter. For the well-below 2 °C target, cumulative 2011–2100 net emissions are limited to 1000 Gt CO_2, whereas the 1.5 °C scenario has a budget of 400 $GtCO_2$. These budget values represent a likelihood of 66% of staying below 2 °C throughout the 21st century in the 'well below 2 °C' scenarios, as well as 66% of staying below 1.5 °C after 2100 in the 1.5 °C scenario (Clarke *et al* 2014, Luderer *et al* 2018).

Table 1. Overview of scenarios. For a complete list of policies included in each of the policy paradigm cases and further explanations, see table 2.

		Policy paradigm				
		Default	Regulation	Early action	Lifestyle	Sustainable
		Carbon price increasing at 5% p.a.	Water and forest protection; Nuclear phase-out; Fossil subsidy phase-out	Higher initial carbon price increase at 3% p.a.	Healthier diets; Lower energy use	***Regulation, early action, lifestyle*** policy approaches combined
Stabilization target	**Reference** (no mitigation)	**REF_Def**				**REF_Sust**
	Well below 2 °C limit	**2 °C_Def**	2 °C_regul	2 °C_early	2 °C_lifesty	**2 °C_Sust**
	1.5 °C limit	**1.5 °C_Def**	1.5 °C_regul	1.5 °C_early	1.5 °C_lifesty	**1.5 °C_Sust**

Policy paradigm: As a reference case for the analysis of stabilization scenarios, we design a default climate-only policy scenario following cost-effective achievement of climate targets via a globally and sectorally harmonized carbon price increasing exponentially at 5% p.a. in real terms. In a second step we add combined policy packages deviating from the least-cost paradigm by imposing dedicated technology and management *regulations* in the land and energy sectors, increased *early action* mitigation and *lifestyle* changes towards less material, energy, and land intensive-lifestyles (table 2), on top of the carbon price. Criteria for the choice of policy elements are that they have an intuitive linkage to identified sustainability risks of mitigation, and that they can be represented in our modeling framework in a meaningful way. The list is therefore not necessarily exhaustive, and the purpose of grouping elements into the three distinct policy paradigms serves to illustrate crucial characteristics and interactions. Since these additional policies influence the portfolio of mitigation options, they typically also change the carbon price required to achieve the same climate target (supplementary figure S7). The additional policy elements are either implemented by adding bounds to the solution space (for example requiring a certain share of new vehicle sales to be electric), by assuming a different value for a certain input parameter (food and baseline energy demand, for example, are input parameters to the model), or by adjusting the temporal profile of carbon price trajectories (early action scenario).

Table 2 lists the elements of the policy strategies that are analyzed in this study, and how they are combined for the three individual policy paradigm cases 'Regulation', 'Early action', and 'Lifestyle'. Further description on the implementation of policies can be found in supplementary section 3.

Indicator selection: We develop customized indicators that capture global stressors for individual SDGs in our global modeling framework. In case of an increase of the stressor level due to mitigation, we speak of a sustainability risk of mitigation, using the broad IPCC usage of the term 'risk' (IPCC 2014b). Table 3 lists the 12 indicators used in this study and indicates relevant links to SDGs. We took the freedom of mapping indicators to SDGs based on the underlying transformation requirements of SDGs, abstracting from the official sub-targets and related indicators of them. While no indicator alone is able to fully capture any of the SDGs, and the time-frame of the analysis is mostly for 2030–2050, 10 of the 17 SDGs receive at least some coverage in this analysis.

The indicator selection is constrained by the scope of the REMIND and MAgPIE models. For instance, food prices do not fully address nutritional and calorific needs; aggregate water withdrawal does not reflect region specific limits; while cost indicators may not capture distributional burdens. The divergence between a pragmatic and ideal indicator selection is, however, a feature of all sustainability studies (Jones *et al* 2016).

While acknowledging the regional heterogeneity of sustainability impacts and the political importance of evaluating SDGs on the country level, we here deliberately focus on impact indicators aggregated to the global level. This approach offers greatest conceptual clarity in quantifying crucial synergies and tradeoffs between climate change mitigation and other sustainability objectives. Importantly, we do not attempt to monetarize all sustainability risks in order to minimize an aggregate overall risk indicator. We also refrain from defining thresholds for intolerable risk levels in the various sustainability dimensions, given that this involves value judgments and that for many indicators it is impossible to derive meaningful global-level thresholds. Regarding the temporal scope of the analyzed indicators, we have chosen the time frame until which most of the impacts of policy choices have materialized. Therefore, the analysis goes beyond the target year of SDGs (2030), as many of these are only milestones on a longer transformation that we capture in our analysis. Further explanations on the choice, limitation, and definition of the used indicators can be found in supplementary section 4.

Table 2. Overview of settings in the different policy paradigms scenarios.

Policy element			Policy setting active in scenario....			
	Setting in default scenarios	Policy setting	Regulation	Early action	Lifestyle	Sustainability
Trade in agricultural products (Schmitz *et al* 2012)	Agricultural trade barriers (i.e. the amount of the trade pool with trade according to historic patterns) decline by 0.5% per year	Agricultural trade barriers decline by 1% per year ('Policy scenario' in Schmitz *et al* 2012)	X			X
1st generation biofuels (Lotze-Campen *et al* 2010)	Constant at 2020 levels	Phase-out	X			X
Water protection (Bonsch *et al* 2015)	No dedicated measure	Protection of water resources based on environmental flow requirements resulting in around 40% lower agricultural water withdrawals in 2050 globally	X			X
Forest protection (Popp *et al* 2017)	Linear increase of protected forest areas by factor 1.5 between 2010 and 2100	Linear increase of protected forest areas by factor 4 between 2010 and 2100	X			X
Nitrogen efficiency (Bodirsky *et al* 2014)	Soil nitrogen uptake efficiency converges to 60% globally by 2050; constant thereafter	Soil nitrogen uptake efficiency converges to 75% globally by 2050, and rises to 85% by 2100	X			X
Agri. waste management systems (Bodirsky *et al* 2014)	30% adoption rate for anaerobic digesters by 2050.	60% adoption rate for anaerobic digesters by 2050.	X			X
Feeding convergence (Popp *et al* 2017)	Faster increase of productivity in low income countries; continuing increase in high income countries.	20% more efficient	X			X
Nuclear power (Bauer *et al* 2012)	No constraint	No new plants after 2020	X			X
CCS injection	Flow constraint of 1% of total reservoir capacity per year	Flow constraint of 0.5% of total reservoir capacity per year	X			
Electric vehicles (IEA 2016)	No dedicated support	Dedicated support, mandating 8, 5 and 2% LDV market share in different regions in 2020, each rising by 2% points per year afterwards (capped at 80%, reached around 2060)	X			X
Carbon pricing	Exponential increase at 5% p.a. from 2020–2060, linear increase thereafter	Exponential increase at 3% p.a. from 2020–2060, linear increase thereafter		X		X
Pricing of land-use emissions	50% of price level in the energy system	25% of price level in the energy system		X		X
Early retirement of coal power plants	Max 6% linearly per year (full phase-out earliest in 2035)	Max 10% linearly per year (full phase-out earliest in 2030)		X		X
Fossil fuel subsidies (Schwanitz *et al* 2014, Bertram *et al* 2015)	Phase-out until 2050	Phase-out until 2030		X		X

Table 2. *Contined.*

Policy element	Setting in default scenarios	Policy setting	Policy setting active in scenario.... Regulation	Early action	Lifestyle	Sustainability
Final energy demand	SSP2 (∼700 EJ in 2050, 900 EJ in 2100)	SSP1 per capita demand with SSP2 population assumptions: −25% at the end of the century (∼600 EJ in 2050, 700 in 2100)			X	X
Agricultural demand (Bodirsky *et al* 2014, Stevanović *et al* 2017)	Continuation of current trends, with doubling of total food demand by the end of the century, caused by the increase in population and income.	−20% below reference overall at the end of the century, 50% for livestock products			X	X

Table 3. Analyzed indicators and relevant SDGs. Please note that the cost indicators do not take into account avoided damages due to lower warming, as the modeling framework does not yet include climate feedbacks and damages. For further explanations on the indicators, see the list in supplementary section 4.

Indicator	Relevant SDG
Food price index in 2030	SDG 2 (Zero hunger)
Water withdrawal for irrigation and power generation in 2030	SDG 6 (Clean water and sanitation)
Short-term costs (cumulative consumption losses from 2015–2050)	SDG 1 (No poverty)
Long-term costs (cumulative consumption losses from 2050–2100)	SDG 8 (Decent work and economic growth)
SO_2 emissions from power generation in 2030	SDG 3 (Good health and well-being)
Temperature increase in 2050 relative to 2015	SDG 13 (Climate Change)
Cumulative uranium extraction 2015–2100	SDG 12 (Responsible consumption and production)
Cumulative extraction of fossil fuels	SDG 12 (Responsible consumption and production)
Cumulative sequestered CO_2 2015–2100	SDG 12 (Responsible consumption and production)
Energy price index in 2030	SDG 7 (Affordable and clean energy)
Cropland for bioenergy crops (average 2050–2100)	SDG 15 (Life on Land)
Fertilizer use in 2030 (Nitrogen)	SDG 14 (Life below water)

Results

The 2 °C and 1.5 °C scenarios in this study broadly share general transformation characteristics with comparable scenarios of the literature (Rogelj *et al* 2013, 2015, Luderer *et al* 2013) (figure 1). 2 °C pathways are characterized by a peaking of CO_2 emissions by 2020, steep emission reductions through mid-century, and CO_2 neutrality or net-negative emissions in the second half of the 21st century. For 1.5 °C pathways, near-term emissions reductions are even faster, and CO_2 neutrality is achieved around mid-century. Decarbonization is achieved by a fast ramp-up of various low-carbon energy types, electrification of end-use (supplementary figures S1 and S4), as well as a strong transformation of land-use (supplementary figures S5 and S6).

The choice of policy approach alters the scale and timing of decarbonization, so that the scenarios with the complete set of additional policy packages ('_Sust') show an earlier and faster decarbonization process than in the existing literature. Therefore emissions during the second half of the century remain higher in comparison to the default mitigation policy scenarios, although there are more negative emissions from afforestation throughout the century, with a peak around mid-century (figures 1(*a*),(*c*)). The 1.5 °C_Sust scenario therefore reaches net-negative emissions already before 2050, but maximum total net negative emissions are at around 7 Gt CO_2 yr^{-1} compared to 13 Gt CO_2 yr^{-1} in the 1.5 °C_Def scenario. The share of low-carbon technologies (renewables, nuclear and fossils with carbon capture and storage (CCS), figure 1(*b*)) shows, compared to existing scenarios, relatively low values for the sustainable scenarios at the end of the century. The reason is that the faster decarbonization in the first half leaves more room for the later use of oil in sectors that are projected to remain dependent on non-electric fuels, which are mostly provided by biofuels in default policy scenarios. Electrification is higher throughout the century in scenarios with additional sustainability policies, and due to the dedicated policies on electric mobility shows a faster near-term increase than the scenarios from previous studies (supplementary figure S1).

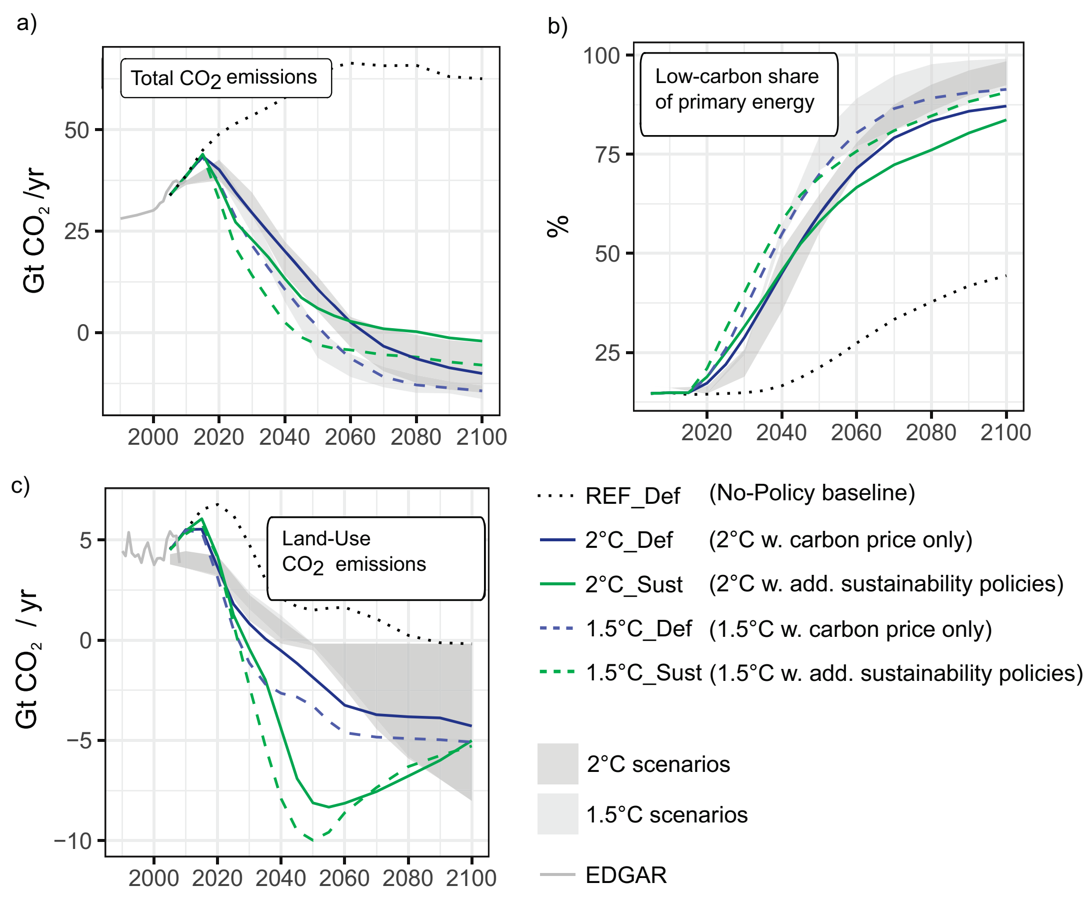

Figure 1. General transformation characteristics in the five main scenarios. (*a*) Total CO_2 emissions, (*b*) share of low-carbon technologies in total primary energy supply (using direct equivalent accounting method and considering renewables, nuclear and fossils with CCS as low-carbon) and (*c*) land-use CO_2 emissions. Historic emission data is from EDGAR (EDGAR 2011) and the grey funnels in the background show the scenarios from previous studies on 1.5 °C and 2 °C scenarios (Rogelj *et al* 2013, 2015, Luderer *et al* 2013), selecting those scenarios with a start of ambitious climate policies in 2015 or 2020. Supplementary figure S1 additionally shows CO_2 emissions from fossil fuel and industry, food price developments over time and the share of electricity in total final energy.

Benefits and risks of 2 °C mitigations pathways

Our default mitigation-only policy scenarios toward 2 °C (2 °C_Def) highlights benefits and risks associated with mitigation in non-climate dimensions (called 'sustainability benefits/risks of mitigation' from now on) (figure 2(*b*)) (Jakob and Steckel 2016, Stechow *et al* 2016). Reduced air pollution from fossil fuel use, and the reduction of temperature increase until 2050 by more than 0.5 °C compared to the no-policy reference scenario (REF_Def) feature as important benefits of mitigation. Furthermore, near-term water withdrawal for irrigation and power generation is slightly reduced due to a lower deployment of thermal power generation technologies.

Uranium and fertilizer use increase slightly in the 2 °C scenario compared to the baseline, as higher carbon prices lead to a further increase of nuclear power and bioenergy. The demand for biomass, together with carbon pricing for land-conversion emissions, limit land available for food production, such that the 2 °C scenario with default pricing-only climate policies leads to a pronounced increase of 35% in food prices in 15 years, roughly double the projected increase in the no-policy reference scenario.

Clear sustainability risks of mitigation emerge for energy price increases, short and long-term mitigation costs, as well as land requirements for bioenergy and geological CO_2 sequestration. The 2 °C scenario with default policies results in an increase of energy prices of around 45%, more than double the increase without climate policy. A crucial technology option in our scenarios is the combination of bio-energy with carbon capture and geological sequestration (BECCS). This combination leads to removal of carbon dioxide from the atmosphere and thus can offset some of the residual emissions that are difficult to avoid (such as fossil fuel use for freight transport, aviation and shipping, as well as certain industrial processes and non-CO_2 greenhouse gas emissions from agriculture (Gernaat *et al* 2015)). Our analysis distinguishes two important sustainability risks of BECCS, illustrated by the requirement for land and geological reservoirs. In the default pricing-only 2 °C scenario, close to 300 million ha of crop-land are dedicated for growing energy crops on average between 2050 and 2100, and a cumulative total of more than 700 Gt CO_2 is sequestered in geological formations in this century, 65% of which originate from BECCS. Finally, economic risks

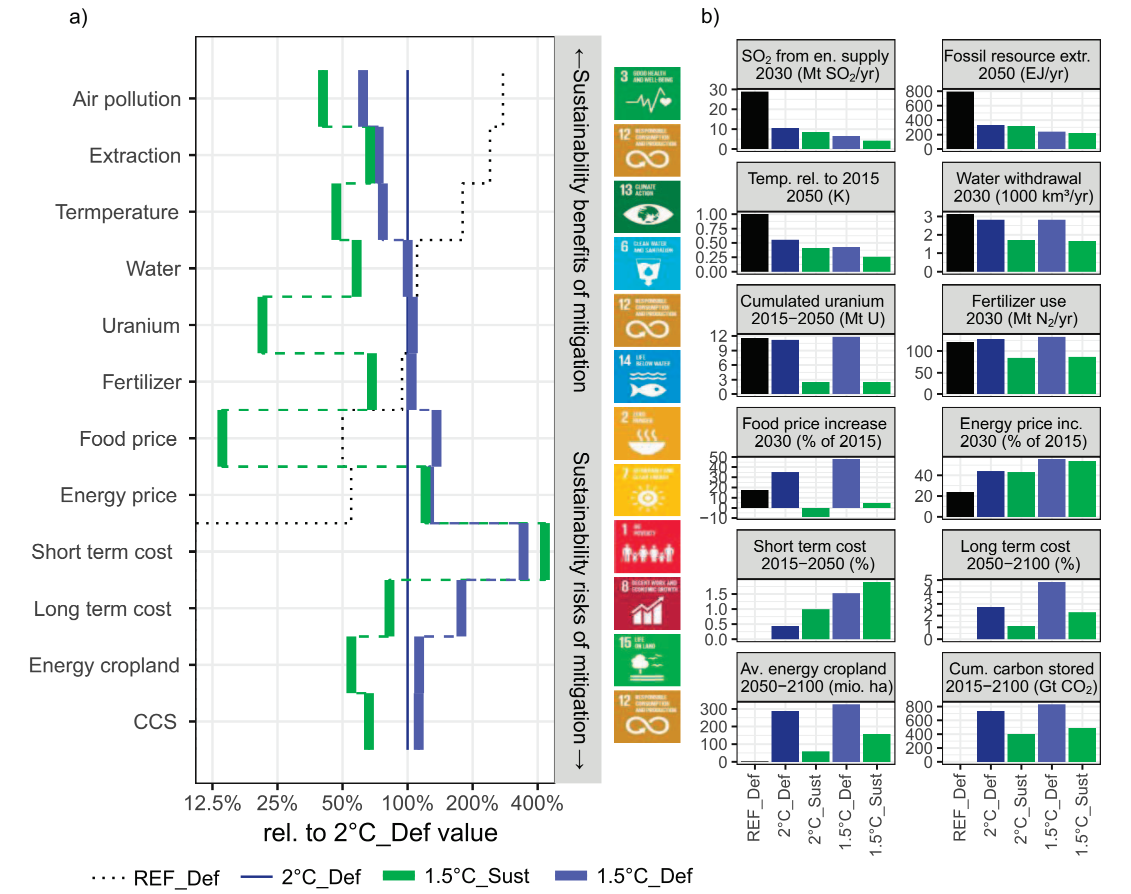

Figure 2. Comparative analysis of both policy approaches and long-term targets. Sustainability indicators for 2 °C and 1.5 °C scenarios with mitigation-only policy (Def) and combined sustainability policy package (Sust). Panel (*a*) shows values relative to the 2 °C_Def scenario in logarithmic scale, panel (*b*) shows the absolute values for all five main scenarios and additionally indicates the time/time-span shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations. Please note that the 2 °C_Sust scenario is only shown in panel (*b*), in order to provide a clear overview in panel (*a*). A version of panel a including 2 °C_Sust is provided as supplementary figure S2.

associated with mitigation are limited in the default 2 °C scenario with less than 0.5% of consumption losses on average during the first 35 years and about 3% during the second half of the 21st century.

1.5 °C shows higher benefits but also increased risks than 2 °C

Both sustainability benefits and risks of mitigation increase further when the long-term mitigation target is strengthened from 2 °C (2 °C_Def) to 1.5 °C scenarios (1.5 °C_Def) with default policies. In the mid-century warming indicator, there is only limited improvement possible (0.13 °C), as the inertia of both capital stocks and the climate system has already locked-in a certain amount of warming until mid-century. Yet this reduced warming could still imply substantial cost savings due to avoided monetary and physical damages not represented in this study. For example, small temperature differentials could help securing the future of coral reefs that provide crucial ecosystem services (Schleussner *et al* 2016).

We observe most substantial risk increases for economic costs: a doubling of long-term costs and a tripling of short-term costs. This is due to the much smaller CO_2 budget for the 1.5 °C target that requires even deeper reductions in residudal fossil fuel emissions and a much greater reliance on carbon dioxide removal (supplementary figure S6) to pull temperatures back to 1.5 °C by 2100 after a brief period of overshoot (Rogelj *et al* 2015). For indicators related to fertilizer use, food and energy prices, CCS and nuclear, risks increase only incrementally. This is partly due to assumed maximum deployment levels that are already reached under the 2 °C scenario. For example, yearly carbon sequestration of carbon dioxide into geological reservoirs is constrained by a certain fraction of total reservoir capacity, and this constraint is already binding in later decades in the 2 °C scenario. Therefore, total CCS storage can only be increased by accelerating the ramp-up of this technology.

Dedicated sustainabilty policies can reduce impacts along many dimensions, and compensate incremental risks of 1.5 °C

Given the widespread concerns with regard to particular sustainability risks of mitigation (Jakob and Steckel 2016, Stechow *et al* 2016), the key question is whether and how risks (reductions) and benefits (amplification) can be directly managed through dedicated policies. This is particularly important as risks and opportunities are more significant under 1.5 °C than 2 °C scenarios (figure 2). Hence, can the additional sustainability risks of 1.5 °C scenarios be reduced or offset through the combined package of dedicated policies?

The combined additional policies we consider here (the impact of individual policy components are discussed below) have a substantially positive impact in all sustainability indicators with the exception of short term costs, strongly boosting the benefits, and alleviating most risks considerably. In all four indicators where default mitigation policies already result in a benefit, the additional benefit from the sustainability policies is higher than the improvement from moving from 2 °C to 1.5 °C. For fertilizer use and food prices, the additional policies even fully offset the sustainability risks of mitigation implied by pricing policies, resulting in a benefit of reducing fertilizer use by one quarter and food price increases even by three quarters compared to the baseline.

For some policy risk indicators, a certain risk level remains even with the targeted sustainability policies. For four of these indicators, however, energy prices, bioenergy cropland, long-term costs and geological storage requirement, the additional sustainability policies more than offset the risk difference between the 2 °C and the 1.5 °C scenario, leading to considerably lower risks in 1.5 °C_Sust relative to the 2 °C_Def.

Our analysis nevertheless shows that the better attainment of a broad set of sustainability targets comes at the price of increased short-term costs. Yet the interpretation of this trade-off is complicated by the set of underlying value judgements. First, stakeholders place differing value weights on each dimension, rendering their comparison problematic outside of a procedural setting (Edenhofer and Minx 2014, Edenhofer and Kowarsch 2015, Kowarsch *et al* 2017). In this sense, strengthened (and costly) mitigation ambition may be judged as appropriate—particularly once the costs of inaction (and the potential range of additional benefits) are credited.

It is important to note again that these costs do not take into account any avoided damages due to lower temperature increase nor monetary benefits from reduction in other externalities like air pollution. Second, there is a trade-off between costs incurred in the first half of the century vs. costs later on. Underlying the optimization that leads to the temporal profile of mitigation costs in the default scenarios (with higher relative costs in later decades) is a pure rate of time preference of 3%. There is a lively debate around whether or not lower rates at least for later periods would be called for from an intergenerational justice point of view (which would favour more balanced profiles like in the Sustainable scenarios). From a sustainability perspective, it would be important to explore to what extent higher consumption losses in the near-term will impact on poverty reduction. However, since our modeling system does not differentiate within-region income classes, such an examination is outside the scope of our analysis.

Complementarity of individual sustainability policy approaches due to different risk profiles

An analysis of the individual effects of the components of the sustainable policy package (table 1) shows that they have significant complementarity, such that their combination performs best in terms of alleviating sustainability risks of mitigation and enhancing benefits (figure 3).

The first policy package ('_regul') consists of direct regulation of a range of controversial technologies and management practices in both the energy and land-use systems, as well as standards supporting more sustainable alternatives. Figure 3(*a*) shows how this package of policies impacts the overall sustainability assessment under 1.5 °C policies.

Five of the indicators, water withdrawal, uranium and CCS deployment, nitrogen use and land for bioenergy crops directly show the desired effect of the regulation. In the temperature and SO_2 indicators, this policy package also shows a slight benefit, which is mainly due to the reduced reliance on CCS, which in turn leads to somewhat higher carbon prices and thus slighty faster decarbonization. In the socio-economic indicators, however, clear trade-offs emerge. While the adverse effect on food prices and long-term costs is very small, short term economy-wide costs increase by more than 50% due to the regulation.

The second policy package ('_early'), increased early action, shifts the mitigation burden in time, by introducing a higher initial carbon price increasing exponentially at a rate of 3% p.a. compared to the 5% p.a. increase in the default policy scenarios. Therefore, short-term costs are higher, but long-term costs lower than in the default case. Additionally, faster retirement of existing capacity is allowed, and the carbon price applied in the land-use system is halved, which leads to less afforestation (supplementary figure S6) and negative emissions in the long run and thus further reduces near-term emissions.

The primary impact of this policy package is a faster phase-out of fossil fuels in many sectors, which is mirrored in lower 2050 temperatures and the SO_2 indicator which is nearly halved in comparison to the default 1.5 °C scenario. Nuclear use is expanded faster in the near-term to make up for the faster phase-out of fossil fuels, giving rise to increased proliferation related risks. Enhanced early action limits long-term mitigation pressures, and therefore results in a reduction of

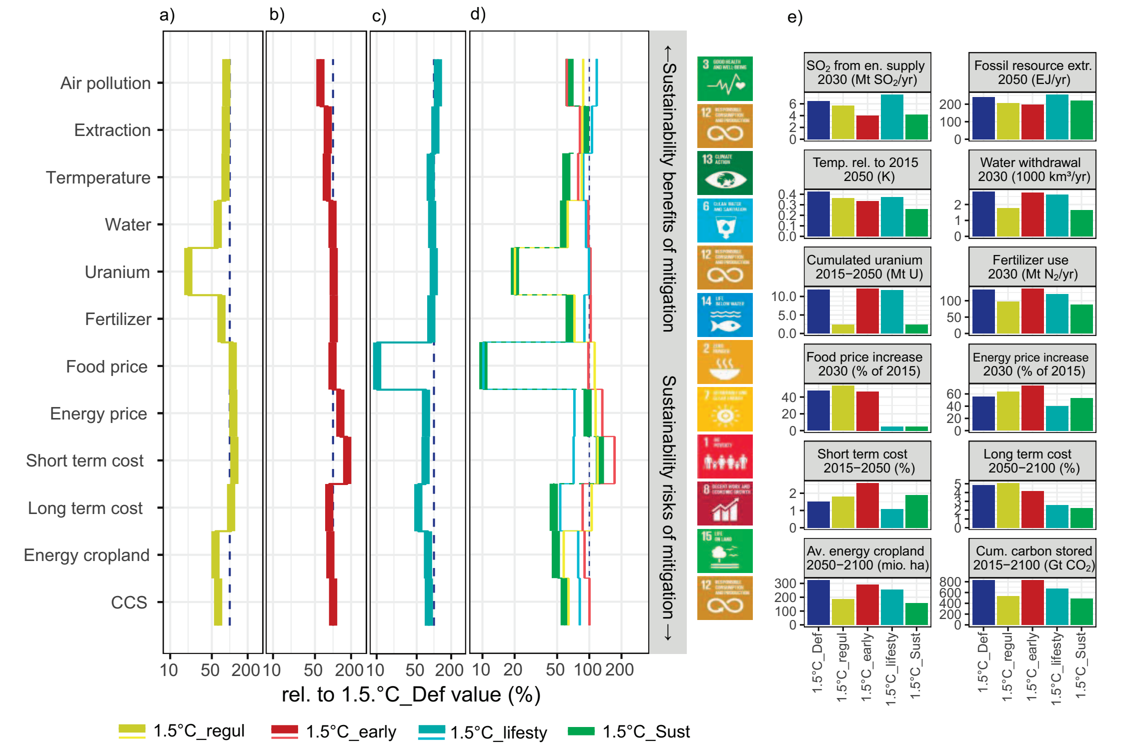

Figure 3. Detailed comparison of individual policy approaches. Sustainability indicators for five different 1.5 °C scenarios, differentiated by policy approach. Panels (*a*)–(*d*) show relative values normalized to the 1.5°C_Ref scenario on a logarithmic scale, panel (*e*) shows absolute values and additionally indicates the time/time-span shown. All values are global totals or averages. Indicators are arranged such that the most pronounced sustainability benefits of mitigation sit on top, and the most severe sustainability risks at the bottom. This ranking is based on the relative values, and does not imply a normative weighting of the different dimensions which can only emerge from broad public deliberations.

cropland required for bioenergy in the 2nd half of the century. The main trade-off resulting from early action policy package, as with the regulation, is the much increased short-term cost stemming from higher initial carbon prices (supplementary figure S7).

The third policy package ('_lifesty') consists of a promotion of less material- and energy-intensive lifestyles and healthier diets relying on fewer animal products. Such a policy reduces pressures both in the energy and land-use system, which are mutually linked via bioenergy. This leads to considerable reductions in long-term costs and food security risks. Through lower demand for fuels, mid-century temperatures and CCS requirements for negative emissions are also reduced. In contrast to the other two policy types, no stark trade-offs can be observed (with the sole exception of a 25% increase in SO_2 emissions steming from the a slower phase-out of coal power generation due to lower carbon prices). This finding suggests that lifestyle changes have a no-cost character in the climate change mitigation effort, under the assumption that welfare effects of such behavioural policies cancel out.

The previous sections have shown that individually, each of the three considered policy approaches is effective in reducing risks in some dimensions, but none manages to bring down risks across the full set of indicators considered. Furthermore, the regulation and early action packages exhibit substantial trade-offs, with especially the short-term cost indicator increasing considerably. Therefore, a combination of all three policy packages ('Sust') might be considered as a means to complement individual policies and soften their risks. Indeed, this results in the lowest risk levels in 8 out of the 12 indicators considered in figures 2 and 3. This not only applies to the 1.5 °C scenarios, but equally is valid for the 2 °C scenarios shown in figure 2 and supplementary figure S3.

Furthermore, short-term costs are, as discussed above, the only indicator in which the combined sustainability policies lead to a higher risk value than the default 1.5 °C scenario with carbon pricing alone.

Policy implications and outlook

Our results highlight the importance of synergies and trade-offs that exist between climate and non-climate sustainability dimensions. Given the inherent requirement for value judgments when it comes to weighing the different dimensions against each other, our results reinforce the call for an as broad as possible public deliberation on the exact mix of policies to take within each country (Jakob and Steckel 2016).

Crucial but unavoidable limitations of our study comprise deep uncertainties in the framing condition of the scenario analysis, both with respect to the future development of some crucial input parameters of the analysis (socio-economics, technology availability, costs and performance, etc.), as well as the structural relationship within and between the analysed systems (investments and demand for energy services, demand for agricultural products, working fundamentals of both energy and other markets, etc.). Our way of generating useful insights under these circumstances is to concentrate on the qualitative effects of analyzed policy interventions, and exploring underlying system effects.

The results highlight that the default policy scenario in the academic literature, in which mitigation is achieved by the single instrument of carbon pricing, exhibits much higher risk values in a range of sustainability indicators in comparison to other scenarios that include further sustainability measures. Yet we do not claim that in our analysis such risks remain within safe limits or sustainability thresholds even with further measures. Such an assessment would require much more fine-grained and locally-specific analysis, which we have to leave to further research. One economic standard argument for implementing climate policies via pricing only is cost-effectiveness. Accordingly the core trade-off in scenarios where sustainability risks are reduced by additional policies is higher near-term mitigation costs. To what extent avoided monetary damages associated with the sustainability risks would compensate for the higher mitigation costs is an important but challenging avenue for future research. As shown in this paper, the SDGs also provide a lens to assess climate policy, hence we see further work to design and articulate mitigation pathways in the context of human well-being, in particular focusing on food, energy and mobility provisioning—issues at the heart of an energy transformation (Lamb and Steinberger 2017).

A central insight of our study is that the benefit of dedicated sustainability policy in the considered indicators (except short-term costs and energy price) is higher than the incremental effect of moving from a 2 °C to a more stringent 1.5 °C target. Even frequently mentioned sustainability risks of mitigation like land requirement for energy crops (Fuss *et al* 2014), food prices, and nuclear and CCS deployment are much lower in a scenario reaching 1.5 °C with a sustainability policy package than reaching 2 °C with the single instrument of a global carbon price.

The analysis of different types of sustainability policies identifies their relative strengths and weaknesses. Dedicated regulation on specific risks fares best in reducing each risk individually, but typically increases pressures in other parts of the system. An increase of early action in comparison to cost-optimal policies brings down a range of risks and leads to lower mitigation costs in the long run, but results in considerably increased near-term costs. Arguments related to inter-generational equity and hedging against higher climate sensitivity values or less effective long-term mitigation might still call for such approaches. In light of complementary work on inter- and intra-national inequalities in emissions (Piketty and Chancel 2015, Rao and Min 2018) it would be an important extension to explicitly consider the impact of distributional policies which could further ease the sustainability trade-offs we discuss. Finally, we find that lifestyle changes that immediately bring down end-use energy consumption, allow for more flexibility, offsetting partially the higher short-term costs of early action.

Shifting towards healthier diets and less energy- and material-intensive consumption patterns appears to have greatest potential for reducing sustainability risks along a wide range of dimensions, although it is unclear to what extent policy-makers have a direct handle to bring about the assumed lifestyle changes and what welfare effects those would have. Certainly, shifting lifestyles would require confronting prevailing social habits, as well as the constellation of private interests that sustain, reproduce, and benefit from existing consumption patterns (Fuchs *et al* 2016). Yet such issues are also fundamental to realizing the ‘regulation’ and ‘early action’ policies directed at the fossil fuel and energy system sectors. Thus while a combination of diverse policy approaches emerges as the most promising way to balance climate and other sustainability risks, the political challenge of doing so should not be understated. A key task going forward is to explore how such policies can be adapted for local needs and circumstances, and whether they can build momentum towards a more encompassing global engagement in climate and sustainability issues.

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