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Implications of climate change mitigation for sustainable development

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Abstract

Evaluating the trade-offs between the risks related to climate change, climate change mitigation as well as co-benefits requires an integrated scenarios approach to sustainable development. We outline a conceptual multi-objective framework to assess climate policies that takes into account climate impacts, mitigation costs, water and food availability, technological risks of nuclear energy and carbon capture and sequestration as well as co-benefits of reducing local air pollution and increasing energy security. This framework is then employed as an example to different climate change mitigation scenarios generated with integrated assessment models. Even though some scenarios encompass considerable challenges for sustainability, no scenario performs better or worse than others in all dimensions, pointing to trade-offs between different dimensions of sustainable development. For this reason, we argue that these trade-offs need to be evaluated in a process of public deliberation that includes all relevant social actors.

1. Introduction

Recent research confirms the potentially serious impacts of unabated climate change on issues that are central to human well-being, including e.g. human health, food security and water availability [1, 2]. In this context, policy makers have widely acknowledged the need to limit greenhouse gas emissions to a level appropriate to avoid 'dangerous anthropogenic climate change' [3]. One metric to operationalize this target could be to ensure stabilization of global mean temperature increase, for instance requiring that a rise of more than 2 °C is avoided [4, 5].

However, reducing the risks of climate change could also entail considerable risks in additional dimensions relevant for sustainable development, including risks related to mitigation technologies such as nuclear power and carbon capture and sequestration (CCS), as well as water scarcity and rising food prices as a result of increased use of bio-energy [6].

To be able to decide on a mitigation target and a suitable course of action to achieve it, policy makers need information on climate impacts for different temperatures as well as costs and adverse side-effects of mitigation measures. This need has become especially pronounced since the Paris Agreement [7], which '[i]nvites the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways' (Art. 21).

Our paper is not the first to apply a multi-objective perspective to assess the effect of climate policy. Recent research has investigated trade-offs and synergies between different policy objectives. For instance, Hezaji *et al* [8] examine the relationship between climate impacts, mitigation policies, and water scarcity. Biewald *et al* [9] also focus on the importance of climate change for water policy, focusing on ethical questions to evaluate trade-offs between different policy objectives. Lotze-Campen *et al* [6] present a detailed analysis of increased bioenergy demand and its implications for global food prices. McCollum *et al* [10] analyze the co-benefits of mitigation policies for energy security and local air pollution. Von Stechow *et al* [11] present the yet most comprehensive assessment of different pathways that have a high probability of limiting global warming to below 2 °C.

In this paper, we discuss how the kind of analysis discussed above could be extended in order to be able to compare sustainability indicators across different mitigation targets. Examining existing scenario data, we take stock of the currently available information and identify gaps that will need to be addressed by future research. Finally, we also highlight the importance of a well-designed science-policy interface to address questions that are not of a purely technical nature, but imply normative evaluations.

2. Motivation

Climate science has clearly laid out the dangers of unabated climate change, including rising sea levels, more frequent extreme events, and reduced agricultural productivity. For this reason, it is straightforward to call for measures to mitigate these impacts. Yet, climate change mitigation also entails costs and risks. Mitigation costs—i.e. the additional costs of low-carbon technologies compared to conventional, fossil fuel based forms of energy—have occupied a central point in the debate on 'dangerous climate change versus dangerous mitigation' [12]. Results from integrated climate-energy-economy models suggest that in optimistic scenarios, in which a globally coordinated effort to reduce GHG emissions is started immediately, and all technological options are available, mitigation costs could be rather modest. For instance, the IPCC's Fifth Assessment Report of Working Group III [5] points out that in this case, model scenarios arrive at a reduction of the annual growth rate of 0.06% (compared to average economic growth rates of 1.6%–3%). In addition to these monetary costs, a number of technological risks have to be taken into account when comparing the risks of climate change with those of mitigation. Increased uptake of nuclear power increases the likelihood of accidents, proliferation, and poses problems with regard to storage and disposal of waste [13]. Scaling up biomass use (especially as a low-carbon transport fuel, or as an option to achieve negative emissions if used in combination with CCS) raises pressure on land, such that it may adversely affect food security [14, 15] and biodiversity [16, 17]. Biomass use is also related to higher water use, which could exacerbate existing water scarcity, with already almost 30% of the global population being affected by severe water stress in the year 2005 [18]. Finally, use of CCS inter alia carries the danger of poisoning ground-water reserves (see also SI for a more detailed discussion of risks). Even though policy makers may opt to exclude any of the above options or limit its use, the reduction of associated risks needs to be weighed against the higher financial costs resulting from a restricted technology portfolio [19, 20].

On the other hand it has also been argued that climate change mitigation achieves benefits in areas not directly related to climate impacts (so-called 'co-benefits') [21]. Health benefits accruing as a result of improved ambient air quality due to reduced fossil fuel combustion are a prominent example, and some authors point out that these could exceed the benefits of avoided climate damages [21]. Further, as low-carbon sources of energy are often produced locally and reduce import dependence, they contribute to increased energy security. Even though the concept of energy security is contested in the literature, it is frequently stated as one of the most important objectives of energy policy [22, 23]. Although this is only a subset of co-effects of mitigation, air quality and energy security co-benefits are relatively well quantified in the scenario literature [24].

As a consequence, climate policies need to be assessed in a multi-objective framework that takes into account climate impacts, adverse effect of mitigation technologies as well as co-benefits of mitigation. For this reason, Hallegatte *et al* [25] emphasize the importance of including the above dimensions of sustainable development in a summary framework similar to the 'reasons for concerns' used by the IPCC [1] to provide a qualitative assessment of the severity of climate impacts.

3. Scenarios, indicators and risk classification

Calling for evaluation of climate policy in a broader framework, our approach is closely related to current proposals to establish 'sustainable development goals' (SDGs). The SDG agenda aims at ensuring human well-being extending traditional development targets, such as poverty or health, by conditions necessary to assure the stability of the Earth systems [26]. Based on availability of scenario data we compile eight indicators to illustrate how different policy objectives relevant for the attainment of the SDGs can be assessed within an integrated framework (table 1). These indicators include climate impacts, mitigation costs [27], water scarcity [8], food security [28], risks of nuclear power and CCS [27], as well as co-benefits of local air quality and energy security [29]. Data sources and definitions of these indicators are described in detail in the supplementary information.

Due to the fact that these indicators were derived with different assumptions and modeling frameworks, the analysis should first and foremost be regarded as a conceptual exercise providing an outlook on how to derive methodologies to identify synergies and trade-offs between individual policy objectives.

For the analysis, we consider 11 scenarios from integrated energy-climate-economy models that

Table 1. Description of the indicators used to assess multiple dimensions of sustainability relevant for climate policy. See SI for data sources and detailed description of the indicators.

Indicator	Direct Climate Impacts	Severe Water Stress	Food Insecurity	Nuclear Risks
				
Description	Rise of the global mean temperature in the year 2100	Increase in the percentage of the global population affected by severe water stress in the year 2100	Sum of the percentage of arable land used for the production of bioenergy and the projected share of additional global land area affected by a substantial temperature increase	Cumulative production of nuclear power until the year 2100
Indicator	**CCS Risks**	**Mitigation Costs**	**Local Air Pollution**	**Energy Insecurity**
				
Description	Cumulative sequestration of emissions until the year 2100	Net present value of consumption losses over the 21st century	Cumulative SO_2 emissions until the year 2100	Cumulative net oil imports until the year 2100

Table 2. Classification of indicators into risk categories. For description of indicators, see table 1.

	Very low	Low	Medium	High	Very high
Temperature increase (°C)		2 °C	3 °C		BAU
CCS Risks (Gt CO_2)	<332	332–665	666–997	998–1330	>1330
Nuclear risks (EJ)	<1501	1501–2716	2717–3931	3932–5145	>5145
Food supply (%)	<7	7–15	16–22	23–30	>30
Water scarcity (%)	<10	10–19	20–29	30–38	>38
Mitigation costs (USD bln)	<2360	2360–4721	4722–7081	7082–9442	>9442
Energy insecurity (EJ)	<3504	3504–3967	3968–4430	4431–4892	>4892
Air pollution (Mt SO_2)	<3889	3889–4992	4993–6095	6096–7199	>7199

result in atmospheric concentrations of 450 ppm CO_2-eq., 550 ppm CO_2-eq., as well as business-as-usual projections. As no single model can provide information on all dimensions analyzed in this study, we combine data from different models that depict comparable climate scenarios (see SI).

These scenarios can roughly be equated with increases of the global mean temperature in the year 2100 of 2 °C, 3 °C, and 4 °C, respectively. For all scenarios, we consider the case in which all technologies are available (FullTech), as well as limited availability of biomass (LimBio), a nuclear phase-out (NoNuc) and unavailability of CCS (NoCCS); the latter only applies for the stabilization scenarios (as this technology is not used if one does not aim at climate change mitigation). As our analysis is mainly concerned with the restriction of technologies due to important risks, we did not include restrictions on the deployment of energy efficiency and renewable energy technologies, because the literature has to date produced only scant evidence related to large-scale risks of these technologies (see von Stechow *et al* [24] for a review). Likewise, we did not consider scenarios in which climate policy is only conducted from a later date. As IAMs depict optimal transformation pathways, any delay would result in a decrease in social welfare. For this reason, delaying mitigation is not desirable within the scope of this paper, which aims to provide information for optimal policy decisions. However, there may be political motives to postpone mitigation, which makes the sustainability impacts of delayed climate action an interesting topic for future research.

Table 2 presents one example of classifying indicators into risk categories based on the scenario data. For each policy objective the indicators are assigned to a category ranging from 'very low' to 'very high'. In this example, informed by IPCC AR5 (1), we take 2 °C as a 'low' risk, 3 °C as a 'moderate risk', and the BAU as a 'very high'. For food insecurity and severe water stress, we divide the future increase (i.e. the projected minus the current level) into five intervals of equal size ranging from zero to the maximum value. For all remaining indicators, we divide the range of scenario data (i.e. from minimum to maximum) into intervals of equal size (see SI for more detail and a discussion of alternative classifications). Hence, the minima will be classified as 'very low', whereas the maxima are regarded to be 'very high' and central values tend to fall in the 'medium' category. Of course, these categories would be chosen differently by different groups in different places reflecting varying values and priorities. Hence, this methodology could be called into question, as one could argue that even values at the upper end of the scenario range can be considered as safe, or, vice versa, those at the lower end as dangerous. An unambiguous definition of such thresholds would require data on social preferences that are hardly available in practice, particularly aggregated for the entire globe. In addition, it would hampered by methodological shortcomings (the SI for details). The debates on the 2 °C temperature target [30] and 'planetary boundaries' [31] have highlighted the challenges to define what constitutes a high or a low risk. Nevertheless, we argue that the conceptual argument that put forward here can be upheld.

4. Identification of trade-offs and synergies between objectives

The main results of this analysis are shown in figure 1 (the numerical values for each indicator are listed in table 3, which also explores the models uncertainties discussed in more detail below). In spite of the stylized nature of our approach, several trade-offs become readily apparent. Whereas the business-as-usual scenarios have zero mitigation costs, no CCS risks, and low or very low nuclear risks, climate change risks are very high. In addition, these scenarios also display high water scarcity, high risks for food supply and perform poorly in terms of local air quality and energy security co-benefits. More ambitious mitigation targets, by contrast, reduce climate change risks but may even exacerbate water availability compared to the business-as-usual—that is, unless the use of biomass for energy production (which takes up a considerable fraction of available water) is limited. The most ambitious mitigation scenarios (namely 450 ppm) may in addition not only entail high mitigation costs, but also high nuclear risks, namely if CCS is unavailable.

It should be noted that figure 1 only illustrates a first estimate how various risk in principle could be evaluated, but comes with several caveats and future research needs. One example is how societies are prepared to deal with negative outcomes or—related—how well societies are prepared to manage specific risks, e.g. regarding their institutional quality. For example, democracies are generally found to better manage food shortages or price spikes [32]. In contrast, developing countries are often not only highly vulnerable to food price increases due to low institutional failures and high poverty rates, but are also vulnerable to tele-connected food supply shocks, which are difficult to address on a domestic level [33]. A second issue is the perception of risks in different societies: for example, risks of nuclear accidents are very differently assessed in (neighboring) France and Germany [34], even though institutional capacities in both countries to deal with them are arguably comparable. Finally, different risks are interlinked. For example, the risk of nuclear proliferation does not only depend on the absolute amount of nuclear power stations, but also on the geographical distribution of plants [35].

This analysis points to the fact that societies may face tough choices: reducing costs or risk in one dimension can only be achieved by increasing costs and risks in at least one other. For instance, in the scenarios under consideration, aiming for stabilization at 450 ppm without CCS more than triples mitigation costs and doubles use of nuclear energy compared to the case with full technological flexibility, and foregoing nuclear energy implies risks for food supply and water availability that exceed those of unmitigated climate change. Even though some scenarios turn out to encompass considerable challenges for sustainability, e.g. water scarcity for mitigation scenarios with unrestricted biomass use, there are no scenarios which perform better or worse than others in *all* dimensions considered. That is, a lower risk in any one-dimension can only be achieved by increased risk in another one. Assessing the trade-offs between different dimensions on the basis of which policy decisions are taken depends on social preferences as well as a country's or region's ability (e.g. in terms of institutional capacity) to deal with specific risks [36].

5. Further issues

In addition to the stylized analysis presented above, policy makers would need to take into account several other dimensions in their decision on what constitutes a feasible course of action to deal with climate change. First, uncertainty plays a major role. For instance, as shown in table 3, estimates of mitigation costs can differ by an order of magnitude across different models. Likewise, for some scenarios there is a more than six-fold difference between the highest and the lowest model output for use of nuclear power, and a more than four-fold difference for emissions stored with CCS. Model uncertainty for local air quality and energy security are less pronounced. Any analysis to be used as a basis for policy making will need to explore the full range of these uncertainties.

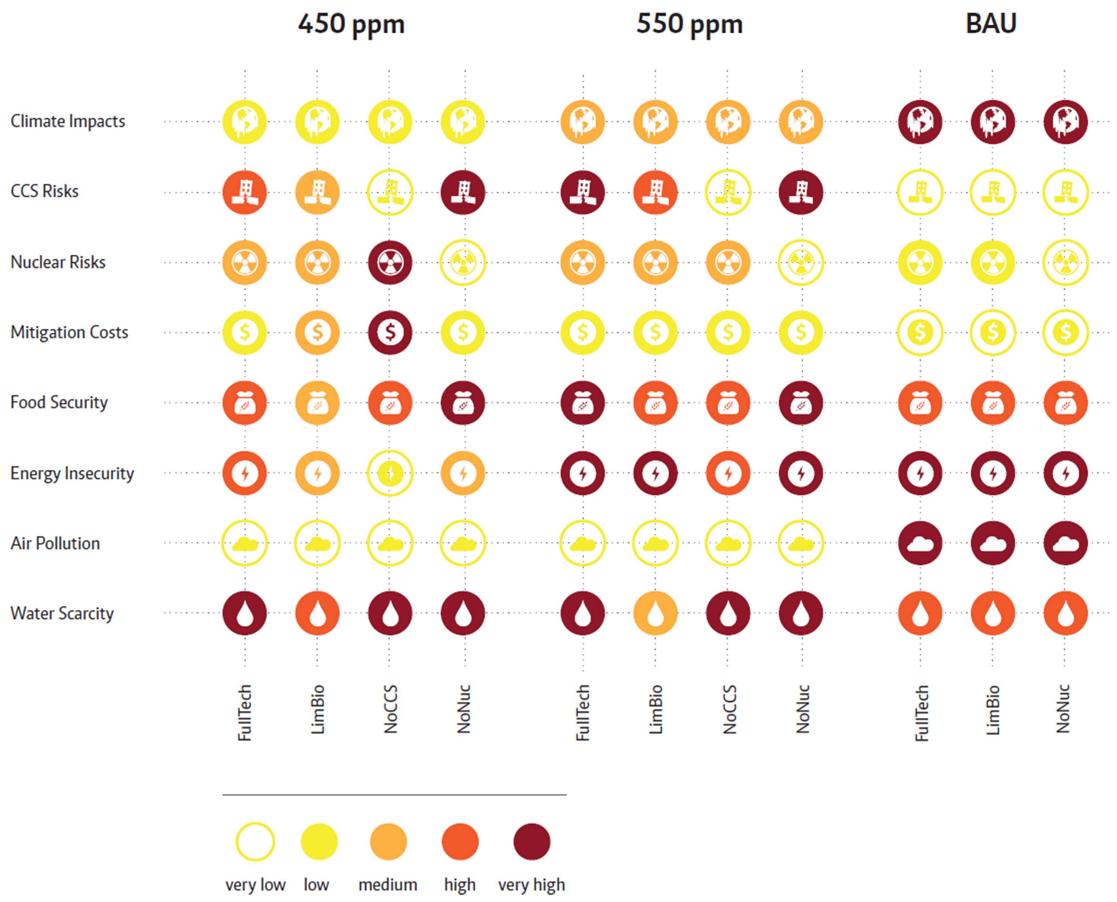

Figure 1. The option space for climate policy is determined by implications for sustainable development in multiple dimensions. Policy formulation will depend on an assessment of trade-offs and synergies between these dimensions.

Second, policy decisions and evaluation of different pathways are not necessarily taken on the global level. Rather, particular communities, regions or countries will need to evaluate their particular risks and trade-offs. They are by far not distributed evenly across the globe. In the case of climate impacts it is long highlighted that the Southern hemisphere and tropical countries might be hit most severely [1]. Regarding regional mitigation costs the IPCC [5] (p 457) reports lower than global average costs for OECD countries in low stabilization scenarios, while mitigation costs in Middle East and Africa (MAF) and economies in transition (EIT) are more than twice as high than the global average. However, regional mitigation costs can of course be altered by transfers and depend on the chosen allocation scheme [37].

Tables S2 in the SI indicates that large regional differences are also relevant for other indicators. For example, the cumulative energy production by nuclear energy in the 21st century differs by factor 14 between Asia (highest) and Latin America (lowest) in a low stabilization scenario. Asia is also the region with the highest deployment of CCS, which is by factor 5 larger than in the region with lowest deployment, i.e. EIT. Yet, the fact that the former has a considerably larger population than the latter region, also needs to be taken into account for risk assessment (see also discussion in the SI).

Energy security (based on cumulative oil imports as a share of oil consumption) is mainly an issue for Asia and OECD countries, while it does not play a role in the other regions. Comparing oil imports to oil consumption for Asia models foresee an increase from 75% in baseline to 81% in mitigation scenarios while OECD countries show a dependence of 37% in baseline and 54% in mitigation scenarios. Remarkably, though, in both regions the share of oil imports relative to total PE consumption remains nearly unchanged in baseline and mitigation scenarios at around 10%. Regarding food security, land used for energy crops plays a different role across various regions. While it increases by 23% points in Latin America in 2100 comparing baseline and policy scenario there are only small differences (lower 5% points) in Asia, MAF and OECD countries. In mitigation scenarios land for energy crops becomes an important issue already prior 2100. For example, in 2050 large difference between baseline and low stabilization scenario can be observed in all regions, with the largest difference (20% points) in the EIT region (results based on [38]). Regional differences are also prominent when comparing the production of major stable crops over the 21st century

Table 3. Ranges of sustainability indicators for different climate scenarios and model uncertainty (see SI for details). 'None' means that only a single model run has been available.

Scenario			Climate Impacts	Mitig. Costs	Food Insecurity	Water Stress	Nuc. Risks	CCS Risks	Energy Insecurity	Air Pollution
			ΔT	USD bln	Land Area (%)	Severe Stress (%)	EJ	$GtCO_2$	EJ	Mt SO_2
		Min.		1252	27%		2006	661		2942
450	FullTech	**Median**	**2°C**	**3762**	**28%**	**48%**	**3288**	**1291**	**4587**	**3700**
		Max		14276	48%		8079	2410	4981	4247
		Min		2252	17%		1746	503	2427	2666
450	LimBio	**Median**	**2°C**	6710	**19%**	**32%**	**3611**	**828**	**4171**	**3187**
		Max		20528	35%		9761	2229	4950	3786
		Min		1337	27%		65	853	3153	2941
450	NoNuc	**Median**	**2°C**	4066	**37%**	**48%**	**318**	**1346**	**4317**	**3180**
		Max		14108	48%		464	2733	5192	4250
		Min			23%		2995		2182	2054
450	NoCCS	**Median**	**2°C**	11802	**25%**	**48%**	**6360**	**0**	**3041**	**2785**
		Max			48%		13261		4265	3516
		Min		992	30%		1098	659	4185	3248
550	FullTech	**Median**	**3°C**	2471	**30%**	**47%**	**3125**	**1348**	**5301**	**3888**
		Max		9667	53%		6872	1746	6191	4853
		Min		1185	21%		1861	605	3919	3017
550	LimBio	**Median**	**3°C**	2832	**24%**	**28%**	**3108**	**1209**	**5251**	**3768**
		Max		9629	40%		7674	1480	5464	4766
		Min		1009	30%		69	726	4167	3223
550	NoNuc	**Median**	**3°C**	2629	**31%**	**47%**	**287**	**1662**	**5206**	**3864**
		Max		9490	53%		464	1998	5293	4857
		Min		1374	28%		3075		3909	2915
550	NoCCS	**Median**	**3°C**	3395	**29%**	**47%**	**3707**	**0**	**4562**	**3639**
		Max		11372	53%		10665		4992	4318
		Min			22%		349		4996	6761
BAU	FullTech	**Median**	4°C	**0**	**29%**	**35%**	**2250**	**0**	**5324**	**8242**
		Max			41%		2921		8240	9723
		Min			20%		349		4651	6774
BAU	LimBio	**Median**	**4°C**	**0**	**27%**	**35%**	**2273**	**0**	**5355**	**8248**
		Max			41%		2946		6592	9723
		Min			22%		75		4975	6881
BAU	NoNuc	**Median**	**4°C**	**0**	29%	**35%**	**287**	**0**	**5337**	**8302**
		Max			54%		464		8186	9723

Colors indicate model uncertainty:

very high | high | medium | low | none

between a baseline and a low-stabilization scenario [39, 40]. While generally climate impacts reduce yields, for some regions, production is expected to be higher in baseline than in low stabilization scenarios. This effect seems to be particular salient for wheat (see also table S2 in the SI).

Third, the classification of indicators into risk categories is necessarily arbitrary and should hence only be regarded as an example. People with different world-views might come to very different evaluations. For instance, opponents of nuclear energy might maintain that the capacity already installed to date constitutes a very high risk, while technology optimists might argue that even large quantities of nuclear power and CCS can be handled safely. In a similar vein, people skeptic of the contributions of economic growth for human welfare might uphold that high mitigation costs are not a major issue. Any real world policy will need to take into account this diversity of normative positions when evaluating different outcomes.

6. Evaluating trade-offs

To provide guidance for policy makers and societies with regard to the question which stabilization target and which technology portfolio they should opt for requires a measure of how one policy objective is valued relative to all other objectives.

For instance, whether for a 450 ppm stabilization target the scenario with limited biomass use is preferred over the one with full technological availability depends on how food insecurity, water scarcity, energy insecurity and air pollution are valuated in contrast to nuclear risks. Likewise, for the 550 ppm scenario, whether foregoing nuclear power is worthwhile depends on how the risks of the additional 300 $GtCO_2$ that are stored underground over the 21st century by means of CCS are valued against the reduction of more than 2800 EJ of nuclear power generation (the NoNuc and FullTech scenarios are very similar in all other aspects).

How should policy makers decide on how to rank outcomes? In theory, one could calculate the 'equivalent income', which adjusts mitigation costs by a monetary valuation of all other dimensions, for each scenario [41]. The outcome with the highest equivalent income would then be the most desirable one. Such an approach would, of course, require a valuation of risks that are not traded on markets and for which prices are not readily available. One conceivable way to answer these questions would be to employ methodologies that measure what people are willing to pay to arrive at a specified outcome, or how much compensation they require to accept a certain outcome [42], as has been done e.g. for the case of nuclear power [43, 44]. Such an undertaking would, however, be plagued by serious methodological problems. For instance, it has been noted that contingent valuation produces results are inconsistent with human behavior observed in other areas, which raises doubts that these studies indeed measure what they claim to [45]. In addition, one would need to take into account considerable differences across various regions and income groups. For example, Roe *et al* [46] find severe difference in the willingness to pay for green electricity and avoided air pollution across different US regions. It can be expected that numbers differ significantly when comparing countries with different income levels. Finally, as climate change is a long-term issue and valuations are subject to change, it is unclear how future valuations should be taken into account.

A more modest (but still effective) approach could lie in identifying the range of relative prices that would make one scenario be preferred to another. In the above example for stabilization at 550 ppm, foregoing the use of nuclear power would then be worthwhile if the social costs of sequestrating one $GtCO_2$ exceed the social costs related to the production of 9.3 EJ (i.e. 2.800 EJ/300 $GtCO_2$) of nuclear power. This kind of analysis could identify research questions that could be addressed by techniques designed for the revelation of otherwise unobservable preferences, such as conjoint analysis [47]. Finally, even if such valuations are unavailable, critical threshold or minimum requirements can be used as a basis to exclude the scenarios that perform most poorly, i.e. have the most adverse implications for sustainability [36]. That is, one could for instance ask which scenarios would be compatible with the achievement of the SDGs.

For this reason, the evaluation of trade-offs between individual policy objectives is not simply a question of data and models [9]. Rather, it requires embedding model-based analysis in the framework of innovative forms of public deliberation [48]. Stakeholders need to be consulted before the modeling in order to determine which indicators should be assessed, as well as afterward to assess the relative desirability of different outcomes [39].

7. Discussion

The analysis presented in this article provides a conceptual framework to combine analyses of climate change mitigation with the literature on climate change impacts and co-benefits of mitigation policies as a basis for the formulation of policies that meet criteria of sustainable development. One reason why climate policy has made comparatively slow progress in recent years is related to the complexity of choices that goes beyond a mere analysis of the costs of climate impacts versus the costs of climate change mitigation and the fact that policy objectives affected by climate measures are located on different levels of governance, ranging from the local to the global. For this reason, we believe that it is crucial to make the trade-offs between different policy objectives explicit as a basis for sound decision-making.

Arguably, doing so is a tremendously difficult task. Hence, our selection of scenarios provides only a rough assessment of the solution space with a strong focus on the climate dimension, for which these scenarios were designed. For this reason, the analysis does not consider that some risks could be alleviated more easily than others by means of accompanying policies. Furthermore, it also does not appropriately take into account that once action is delayed to a point in which the most ambitious mitigation targets become infeasible, the risk of irreversible climate damages increases considerably. In contrast risks associated to certain technologies can to at least some part be reversed by limiting or discontinuing the use of these technologies [25]. Hence, our analysis should primarily be regarded as a first step aiming to give an impression of the trade-offs relevant to climate policy formulation. It motivates a holistic approach to integrated assessment that is based on the notion of sustainable development and acknowledges the multiplicity of policy objectives involved in the design of climate policies. Future research will need to obtain a more comprehensive picture of the risks in the different dimensions outlined above. In addition, it should go beyond this study by considering additional policy objectives and developing more sophisticated methods to quantify and compare the respective indicators.

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