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Assessing stakeholder preferences on low-carbon energy transitions

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ABSTRACT

Low carbon transition pathways entail diverse uncertainties and risks in the underlying environmental, social, political, economic and technological factors. Inadequate information about such risks could affect the achievement of climate change mitigation targets negatively. This paper provides a novel experiment in which quantitative tools and stakeholder engagement are combined in order to identify the barriers between stakeholders and scientists concerning climate change mitigation aspects. Technological risks are captured by simulating different low carbon scenarios with limited technology options. Stakeholders are asked about their preferences on technology options regarding a low carbon future. After providing them with the simulation results, they are asked again in order to see whether those initial preferences had changed. Results prove the necessity for better communication between modelers and stakeholders. Closing the gaps between both communities is essential to remove barriers for more ambitious action against climate change.

KEYWORDS

Climate policy; GCAM model; risk analysis; stakeholder engagement; transition pathways

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has already stated that human influence on the climate system is clear. Observed impacts of climate change are “widespread and consequential”, but future effects still largely depend on current actions worldwide to reduce emissions (IPCC 2014b). Defining feasible and cost-effective low-emission pathways therefore becomes crucial in order to avoid the most severe impacts of global warming. In this context, scenario-based model projections play an important role in evaluating different mitigation options.

Scenarios are commonly used to facilitate short and long-term policy decisions associated with climate change, given the uncertainty in the underlying environmental, social, political, economic and technological factors. According to the IPCC definition, “a scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold” (IPCC 2013a). Models (purely quantitative tools) are widely used as an instrument to develop climate scenarios, thereby optimizing aspects that can be quantified, such as economic variables and CO_2 emissions (reduction). However, policy making based on quantified information only implies the risk of aspects that cannot be quantified and thus not be modeled, but which are nevertheless important for the successful implementation of the scenario, are not considered. We consider the use of interactive and participatory methods with stakeholder engagement to overcome that limitation of quantitative tools (Doukas and Nikas 2020; Geels, Berkhout, and van Vuuren 2016; Mietzner and Reger 2005; van den Berg et al. 2019; Verdolini, Anadon, and Laura 2016). In fact, model simulation results could be attractive from a theoretical standpoint (e.g. large-scale diffusion of wind turbines can strongly contribute to

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achieving the 1.5-degree Celsius target), but unfeasible from a more practical angle (e.g. there can be social resistance against large-scale application of wind energy in the landscape), leading to important risks in the transition toward a low carbon economy. In this sense, the role of stakeholders is important to provide information for a more (socially) realistic scenario analysis and, if possible, greater engagement throughout the research process.[1]

Other papers have already explored this connection between stakeholders and models aimed at implementing climate change policy. In particular, Bell, Hobbs, and Elliott (2000) work under the hypothesis that models are most useful to policy makers if they are explicitly linked to decision-making by providing information on trade-offs. They conclude that combining model results and stakeholder consultation can test the validity of the models and help to assess trade-offs and risks of different climate change scenarios. Shackley and Deanwood (2003) go one step further and highlight the role of stakeholder engagement to facilitate decision making in model-based climate change pathways by reconciling those long-term scenarios applied in models with short-term policy requirements for stakeholders. Cairns et al. (2013) share this dichotomy between short and long term decisions and, focusing on a local case study for climate change impacts in Australia, conclude that this integration may not work when multiple agencies, interests and agendas are present. When climate change is treated at a global level, consensus becomes even more complicated.

More recently, Eker et al. (2018) perform a comprehensive review on model validation with stakeholders, where validation is understood as the evaluation of a model's performance and suitability for its intended use). They conclude that the three key dimensions on model validation are (i) the dichotomy between representativeness and usefulness, (ii) the role of empirical data in validation, and (iii) the view of decision-makers on validity. The mainstream literature exploring the modeling-policymaking interface concludes that if models and stakeholders do not work together, it is much more difficult to support climate policy effectively (Doukas et al. 2018). Therefore, the interaction between different agents is now "moving from a knowledge-supply driven model towards a knowledge-demand driven model", in order to meet the specific social, political and economic needs of a much larger number of heterogeneous agents (Tàbara, Clair, and Hermansen 2017).

We developed a two-step survey in which respondents from public agencies, private and public-sector industries, scientists and researchers, international associations, NGOs and the finance community participated in order to demonstrate our approach to the above problem. In the first step, respondents were asked about their preferences regarding climate change mitigation in the 21st century. The objective of the survey was to collect information on how they perceive and assess the risks related to a changing climate, and which low-emission pathways (i.e. which technology options for mitigation) they prefer to mitigate these risks.

As the next step, respondents were provided with a summary of simulation results concerning emission reductions, energy system changes and mitigation costs consistent with keeping the increase in global mean temperature below 2ºC and 1.5ºC above pre-industrial levels. Simulations were performed in advance using the Global Change Assessment Model (GCAM), which is one of the models used by the IPCC (IPCC 2014a). Respondents were thus confronted with several consequential risks of pursuing different pathways to reach the Paris Agreement goals, in terms of, e.g., costs, welfare levels, energy security. These risks were presented to them under different assumptions, such as assumed delay of technology development and deployment of Carbon Capture and Storage (CCS), and the ensuing impact on the use and costs of alternative mitigation options.

Based on that information, respondents were asked to answer the same set of questions as in the first step (but now with knowledge of consequential risks of low-emission transition paths). This second round of consultation aimed at observing whether respondents changed their initial preferences about mitigation technology options after having been confronted with possible consequential risks. For instance, a respondent who may have initially indicated a strong preference for globally expanding renewables and a low preference for CCS, may change this opinion when

[1]See Lieu et al. (2020) for additional contribution on this research line.

confronted with the risk that economic costs of a renewables-dominated scenario without CCS, may become high. Finally, the ultimate outputs of this paper are the underlying policy implications for each scenario and the risks associated to them.

Therefore, this paper seeks to contribute in this research area involving participatory modeling (see Voinov et al. 2016, 2018; Gray et al. 2018; and references therein) by combining traditional modeling tools with stakeholder consultation methods in order to identify the gap between what quantitative tools can handle and what policy makers need to know about people's preferences, as well as the associated risks. This research is particularly relevant, since sustainable transitions involve technical, institutional and social alignments (Turnheim et al. 2015). The key feature of this trans-methodological approach is the involvement of stakeholders throughout the scenario-based decision-making process in order to better understand how they perceive this information and how the risk of public resistance could be reduced.

The remaining of the paper is structured as follows. Section 2 describes the methods used to develop this analysis, including a quantitative approach based on an integrated assessment model and a stakeholder engagement approach. Section 3 presents the socio-demographic characteristics of the respondents involved in our survey. Section 4 details the changes in stakeholder preferences as a result of model inputs. Section 5 discusses the risks associated to the limited technology options. Finally, conclusions and policy implications are presented in Section 6.

2. Material and methods

The trans-methodological methodology used in this paper combines modeled scenarios (Section 2.1) and stakeholder engagement tools (Section 2.2) in order to evaluate whether stakeholder initial preferences change when they are provided with quantitative information and which the perceived risks associated to these preferences are.

2.1. The GCAM model

This section describes the model used to simulate climate scenarios (Section 2.2.1), as well as the specifications for each scenario (Section 2.2.2).

2.1.1. Model description

The model used in this paper is the Global Change Assessment Model (GCAM), developed by the University of Maryland and the Pacific Northwest National Laboratory (PNNL) and implemented by the Basque Center of Climate Change (BC3). GCAM is an integrated assessment model that links economic, energy, land use and climate systems which has the advantage of being able to explore connections of climate measures on different systems and impacts of measures and developments within these systems on climate systems. It was one of the four models chosen to develop the Representative Concentration Pathways (RCPs) of the IPCC's 5th Assessment Report (IPCC 2014a). The model is available under the terms of the ECL open source license version 2.0. In this study, the standard release of GCAM 4.2 is used (see GCAM documentation 2017).

GCAM is a global dynamic-recursive partial equilibrium disaggregated in 32 geopolitical regions and operating in 5-year time steps from 1990 to 2100. The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services. The model distinguishes between two different types of resources: depletable and renewable. Depletable resources include oil, unconventional oil, natural gas, coal, and uranium; renewable resources include hydropower, biomass, wind, solar, geothermal energy, municipal and industrial waste (for waste-to-energy). All resources are characterized by supply curves and the competition between technologies is based on discrete choice modeling (Clarke and Edmonds 1993) in a way that allows for a smooth transition of technologies in the energy system (logit probabilistic model). Complete documentation on all the technologies in the energy system is provided in Clarke et al. (2009).

GCAM tracks all greenhouse gas (GHG) emissions from the energy and the land-use systems. GCAM provides the mitigation cost of different energy and climate policies for each specific region. The mitigation costs are calculated as the area below the marginal abatement cost curve for a technology, assuming implementation at a certain scale (Kyle 2015). GCAM also reports the emissions of main air pollutants (including NO_x, VOCs, CO or SO_2) and can be used to analyze the co-benefits/trade-offs of mitigation in terms of whether air pollution emissions reduce or increase. Emissions of air pollutants depend on activity levels in each region, such as fuel consumption, and the level of pollution controls, which are assumed to increase over time (Smith, Pitcher, and Wigley 2005; Smith and Wigley 2006).

Another important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded within the agriculture-land-use system model. Thus, all land uses and land covers, including the noncommercial lands, are fully integrated into the economic modeling in GCAM. This coverage gives GCAM the capability to model policies that jointly sequester or reduce carbon across all activities in the energy, agriculture, forest, and other land uses.

The model allows calibration and can be run with any combination of climate and non-climate policies.[2] At each time step, GCAM searches for a vector of prices that cause all markets to be cleared and all consistency conditions to be satisfied (GCAM documentation 2017). As output, simulations provide an energy mix, carbon price and mitigation costs, among other relevant variables for this paper.

2.1.2. Scenario implementation

A summary of the six scenarios that we developed in GCAM is presented in Table 1. Scenario 0 is modeled with all the technologies available and no climate policy; in this case, global average temperature increase reaches 3.8ºC by 2100, according to the GCAM model. This scenario is used as an upper bound of temperature and emissions, when no mitigation measures beyond those currently in place are adopted. Concerning scenarios with climate policy, Scenario 1 represents the reference scenario with all low-emission technologies available, whereas Scenarios 2–5 are the restrictive scenarios including the limited technology options resulting from the interaction with stakeholders. The 'all technologies available' scenario is the most cost-effective scenario, since the least costly technology portfolio is selected by the model in order to achieve the climate target. It is used as a benchmark for emissions and costs. However, the mitigation-optimal share of technologies is limited and thus costs increase in the restrictive scenario.

The scenario where no climate policy is implemented is not realistic, since most countries have already implemented policy measures or will implement them in the future, in accordance with the Nationally Determined Contributions (NDCs) already submitted. Similarly, the scenario with all technologies available could also pose some doubts, since there is uncertainty about the commercial readiness of some technologies (e.g. CCS). The most likely scenarios are therefore those with limited technology options. In any case, the most pessimistic and optimistic scenarios set the boundaries to allow comparison.

Additional assumptions for all technologies available scenarios (with and without climate policy) include high renewable energy participation (particularly for wind, solar and geothermal) and restrict the commercial availability of CCS to the year 2030 (i.e. CCS is available from 2030 onwards). The rest of the technologies keep the original GCAM specifications.

This scenario selection is in line with the scenario reporting from IPCC (2014b, 60) (and it is used by other authors modeling low carbon transitions, such as Edenhofer et al. 2010; Kriegler et al. 2014). Our contribution is that in this paper the focus is not on a model inter-comparison, but in the trade-offs of the different climate policy and technology options for a single model.

Another highlight of this scenario selection is the level of detail for the 1.5ºC temperature target analysis. This more ambitious goal has been less explored in the scientific literature than the 2°C goal,

[2]For instance, temperature target policies are climate policies, whereas shared socioeconomic pathways are non-climate policies.

Table 1. Scenario implementation in GCAM and technology characteristics.

Scenario Nr.	Technology options	Characteristics	Temperature target 2ºC	Temperature target 1.5ºC
0.	No climate policy	All technologies available in GCAM are included.	N/A	N/A
1.	All technologies available	All technologies available in GCAM are included. CCS is available from 2030 onwards.	✓	✓
2.	No CCS	All technologies available except for CCS, which is unavailable in the whole century.	✓	✓
3.	Nuclear phase-out	All technologies available but assuming a nuclear energy phase out consisting of no addition of new nuclear plants beyond those under construction and existing plants operating until the end of their lifetime.	✓	✓
4.	Limited solar/wind	All technologies available except for solar/wind, which are limited to a maximum of 20% annual global electricity generation.	✓	✓
5.	Limited Biomass	All technologies available except for biomass, biogas and biofuels, which are limited to a maximum of 100 EJ per year.	✓	✓

Note: Options marked with ✓ indicate feasible scenarios with GCAM. Temperature target is not applicable (N/A) when there is no climate policy.

although the interest in it has increased since the Paris Agreement (see IPCC 2018 and references therein). The 0.5ºC reduction in anticipated peak global mean temperature could mark the boundary for decreasing climate impacts, including the prevention of extreme weather events, changes in water availability, crop yield projections, sea-level rise and coral reef degradation (Schleussner, Lissner, and Fischer et al. 2016). Deeper analysis on mitigation pathways toward a 1.5ºC stabilization target are thus needed, including both model and stakeholder perspectives. In particular, Ranger et al. (2012) analyzed different global emission paths and suggested that emissions should peak by around 2015 to limit global warming below 1.5ºC at the end of the century. However, they did not explore the technological feasibility, an issue that was further developed in Rogelj et al. (2015). They suggested that the global energy system should be decarbonized by 2050 in order to achieve the 1.5ºC target and highlighted the role of the technologies able to achieve negative emissions in the second half of the century (e.g. CCS and biomass with CCS). Nevertheless, they assumed a default mitigation portfolio and did not explore the trade-offs between the different technology options.

More recently, the IPCC published a special report on the impacts of global warming of 1.5°C (IPCC 2018), where they model a range of potential mitigation approaches toward the 1.5°C target with different assumptions on the projected energy and land use, as well as future socio-economic developments (i.e. economic and population growth, equity and sustainability). In this report they also explore pathways with no or little overshoot, showing system changes that are more rapid and pronounced over the next two decades than in 2°C pathways. These analyses conclude that shares of nuclear and fossil fuels with CCS are modeled to increase in most 1.5°C pathways with no or limited overshoot and that renewables are projected to supply 70–85% of electricity in 2050. While acknowledging the challenges and differences between the options and national circumstances, limited technology options are not modeled in this report. Therefore, further analysis is needed of different technology portfolios toward a 1.5ºC target and the comparison with the 2ºC target.

According to the literature, there is controversy regarding reliance on negative emissions. For instance, Anderson and Peters (2016) consider that integrated assessment models assume large-scale use of negative-emission technologies, which would reduce the chances of controlling global temperatures if they are not deployed. Smith et al. (2016) explore the biophysical and economic limitations on the implementation of negative emissions technologies and point out that social, educational and institutional barriers could also limit their implementation. Some other authors, such as van Vuuren et al. (2018), also acknowledge the limitations of carbon dioxide removal technologies and they thus explore transition pathways with a reduced need for negative emissions, though they do not fully eliminate them. This increases the motivation toward a no CCS scenario and adds relevance to the stakeholder consultation.

Finally, socioeconomic variables have not been changed with respect to the model baseline assumptions based on Edmonds and Reilly (1983). The default scenario of the GCAM model assumes a global population peak in 2065 at roughly 9 billion people and a long-term labor productivity growth of approximately 1.5% per year in the developed world. Moreover, it is assumed that economic growth rates are generally higher in developing countries, with countries undergoing initially rapid growth, which then gradually slows toward the growth levels of developed countries (Calvin et al. 2015).

2.2. Stakeholder engagement

The innovative aspect of this work is the stakeholder engagement approach that was carried out through a two-step survey via an online questionnaire aimed at experts in energy and climate change.[3] As compared to other methods such as direct observation, experimentation, focus-groups, etc., surveys are effective to provide a broader range of information on opinions and socio-demographic characteristics, since questions are simple to administer and produce a larger database to work with. Additionally, the online survey approach (compared to phone or face-to-face surveys) has the advantage of approaching a wider and broader number of respondents at a global level, which was the aim of this study. Other authors have also employed online surveys with the aim of interrelating models and stakeholders from a theoretical perspective. In particular, Eker et al. (2018) checked the perceived validity of models in terms of representativeness and usefulness. The main difference is that this research presents model results to the respondents in order to observe if respondents's preferences change when they are confronted with model results.

The design of the final set of questions took three steps. First, we developed an initial version of the questionnaire and circulated it internally among European researchers on climate change. Second, we designed an improved version of the survey and discussed it in a workshop with 12 international experts on climate policy from Spain, Austria, Switzerland, United Kingdom, Kenya, Chile, Mexico and Canada. Third, we sent the final version to the online global database (see Section 3).

In the first step (Section 2.2.1), survey respondents were asked about their preferences for mitigation pathways. No additional information of any kind was provided, so their initial opinion was captured. It is also worth noting that, in this analysis, we refer to respondents when we refer to the persons who took part in the survey in order to avoid that survey respondents are considered a fair representation of global stakeholders for climate policies (see Sections 3 and 5.1). In fact, while the approach developed has been instrumental to show how people can change their preferences regarding climate policy once clearly confronted with the consequential risks of these preferences, it was based on a consultation among an online community of climate professionals and people otherwise interested in the topic, and therefore not targeted at a carefully selected stakeholder group. Hence, our preference is to refer to respondents instead of stakeholders.

In the second step (Section 2.2.2), stakeholders were asked the same technical questions again, but extra information related to their initial answers was provided alongside the questionnaire (via a set of statements), such as impacts of preferences, as well as control questions. The two questionnaires and the statements can be found in Appendix A.

2.2.1. First step: stating initial preferences

A first step was used to analyze respondent initial mitigation preferences at a global level. The survey consisted of 4 technical questions reflecting key themes in the international debate on climate change. These were categorized in two content blocks: (Q1) target to limit global temperature increase, and (Q2-Q4) technology options and preferences. Table 2 summarizes the four questions.

The motivation for this classification is further explained below.

[3]One of the main limitations of this study, which is further described in Sections 3, 5 and 6, is the selected database, which mainly consists of climate experts, potentially including representatives interested or engaged in climate science and policy except for citizens.

Table 2. Technical questions Q1-Q4.

Question Nr.	Question text (possible answers)
Q1	What is the optimal temperature target that we should aim for to limit global warming by 2100? (<3ºC, <2.5ºC, <2ºC or <1.5ºC)
Q2	Which technologies will be most important in the next 50 years? (CCS, Nuclear, Renewable Energy, Biomass Coal, Oil, Natural Gas, Others)
Q3	Which should receive more public support? (CCS, Nuclear, Renewable Energy, Biomass Coal, Oil, Natural Gas, Others)
Q4	What is the future for each technology in the next 50 years? (Expansion, Hold, Phase-Out)

2.2.1.1. Temperature target (Q1). There are multiple mitigation pathways that could limit global warming to below 2°C and avoid the worst consequences of climate change. This temperature target is consistent with RCP2.6, where RCP stands for Representative Concentration Pathways, which are scenarios that describe the development of greenhouse gas emissions under different policy ambition level assumptions (IPCC 2013b). These pathways would require substantial emissions reductions over the coming decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century. Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and also if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges, but on different timescales and with different intensities.

2.2.1.2. Technology options and preferences (Q2-Q4). The IPCC has stressed in its reports that there is no "magic bullet" or technology that can deliver all the mitigation that is needed. Portfolios of technologies and measures will instead need to be compiled and it is very likely that these portfolios depend on the context of each country and sector (IPCC 2007). The choice of these technologies will be determined, for example, by their cost (which can be different for each country), their public acceptability (which can also change due to its perceived negative or positive side effects related to socioeconomic factors), and how the technologies may contribute to achieving socio-economic goals. The focus in the survey was on the following wide range of technologies: Carbon capture and storage (CCS), nuclear energy, renewables (excluding biomass), biomass, natural gas, coal and oil.

2.2.2. Second step: observing changes in preferences

The technical questions included in the second step were the same as those in the first consultation step (see Table 2). The second part of the survey also included some control questions to evaluate the effect of the information provided (if any) on the new stated preference. These questions read as follows: "Do you think that the results provided in the statements are insightful?", "What is your opinion about the 'interface' between stakeholders and scientists concerning climate change mitigation aspects?" and "Who should make a greater effort to align positions?". Those questions included open ended sentences with no direct numerical value, as well as a free text field to collect qualitative information. Socio-demographic questions, such as age, gender, country, institutional affiliation and sector, were also included in the survey for the statistical analysis.

Additionally, consequential risks resulting from the GCAM-simulations were incorporated in the survey via seven statements, which are further explained below. The full set of statements can be found in Appendix A and the detailed explanation (including figures and tables) of the trade-offs resulting from the model results is included in Appendix B.

2.2.2.1. Statements 1-3. These statements are related to the global temperature target that should be aimed at according to the stakeholders. Therefore, data on emissions, primary energy consumption and mitigation costs (with respect to the GDP) are presented, comparing the below 1.5ºC, below 2ºC and below 3ºC temperature targets.

2.2.2.2. Statement 4-7. These statements refer to the results of the simulations for the technology options toward a low-emission future that were reported by the respondents in the first step of surveys. The focus here lies on the description of the trade-offs between the different technology portfolios that have been explored. For instance, if technologies needed for achieving negative emissions (e.g. carbon capture) are not available or economically deployable, emission reductions in order to achieve the target under 2°C should start no later than 2020. Similarly, a scenario below 1.5°C would be unfeasible without a carbon capture technology option.

Statements were used as a way to show the environmental and economic consequences of technology limitations. Models usually rely on technologies that are not currently ready or are available at a very high cost. However, if these technologies were not available on a large scale in the near future, due to economic, social, political or even technological risks, many climate targets could not be reached (e.g. temperature limitation targets). Therefore, presenting these effects to stakeholders might lead to changes in their initial preferences and those changes would be directly linked to risk perception.

3. Data

The survey was sent via the Climate-L list server, which includes worldwide climate professionals from the quadruple helix (research, policy, civil organizations, NGOs) on climate change issues. The survey was posted to this community in 2016 and three reminders were sent during a six-month period. 106 responses were collected, which represents a 3% response rate. Answers by respondents who had not completed the full survey were excluded and therefore a sample of 80 members was finally processed (i.e. we excluded 25% of the sample because of missing values).

Climate-L seemed a good option as the target of the survey was climate professionals, such as researchers, policy makers, or other stakeholders. This is a global, and widely used list server managed by the International Institute for Sustainable Development for peer-to-peer exchange of information on climate change publication, workshops and conferences, job listing and other types, such as surveys. An unknown aspect of using Climate-L is the composition of the subscriber group, such as their professional background and region. The assumption when distributing the survey via Climate-L was that this would not lead to a strong bias, as the service is free of charge and very easy to use, with the only condition being internet access. A disadvantage of using Climate-L is that invitations are not personal and can be overlooked by subscribers. At the same time, this disadvantage did not affect one of the main goals of the survey, namely to check respondents' change in opinion when provided with more information on impacts of low-emission pathways. In future research, and assuming more resources were available, a specific database could be established with 'climate peers' to be targeted, with a checked balanced representation in terms of profession, background, region, etc. Such a database would also allow for personalized invitations, reminders and follow-up interviews.

Participants came from the categories presented in Table 3. Due to the large share of European respondents in the survey (61%), the resulting views may differ from non-European views. While this has been a limitation of the geographical scope of the analysis, the approach remains useful to illustrate how views on socioeconomic factors and climate change can be incorporated in modeled scenarios. Further research could expand the set of participants outside Europe in an attempt to capture wider viewpoints.

4. Results

This section presents the main findings of the paper, related to the combined use of models and participatory methods for a low-emission future. The focus is placed on analyzing the change in preferences of the second part of the survey with respect to the initial responses (Section 4.1). Additionally, control responses show how stakeholders and scientists perceive each other (Section 4.2). Finally, we conduct a statistical analysis (Section 4.3).

Table 3. Socio-demographic information of the engaged participants [%].

Affiliation	
Academics	36%
Research and consulting	35%
International organizations	8%
Government	6%
Civil society	3%
Others (media, NGOs, utilities, finance community, coal/gas/oil companies)	12%
Region	
Europe	61%
Asia	14%
America	13%
Africa	9%
Oceania	1%
Age	
<30	14%
30–49	53%
≥50	31%
Gender	
Males	66%
Females	34%

4.1. Change in preferences

4.1.1. Temperature target

79% of the participants did not change their opinion regarding what is the desired maximum global average temperature increase, whereas 15% increased their targeted temperature limit in the second step and only 6% decreased it. After the survey 41% still believed that the target should be 1.5ºC (although 8% less than in the first step) and 48% considered that the target should be 2ºC (9% more than in the first step). This contributes to the current debate about the temperature target (1.5ºC vs. 2ºC): 15% of the respondents preferred a less ambitious climate target, in light of the economic costs related to a stringent target as presented to them via the statements.

4.1.2. Technology options and preferences

Table 4 ranks the most preferred technologies by respondents for the next 50 years with a view to climate change mitigation investments. With respect to technology, 58% of the participants did not change their preference and renewable energy (excluding biomass) and CCS remained the most preferred combination to limit global warming in the next 50 years. These two technologies were selected by 67% of the participants in the first step, increasing to 72% in the second step. The rise is especially noticeable for CCS, which was selected by 18% in the first step and by 28% in the second one, probably due to the potential role of "negative emissions" in future scenarios and the communicated impact on costs should CCS not be included in future climate mitigation mixes. If there is no CCS, more expensive options will be needed to achieve the same climate goals. It is also notable that, in the second step, no one reported oil among the first two preferred options, and only 1% named coal (but conditional on the presence of CCS). This may also be striking to some extent, as one could expect that coal could become more popular with greater CCS popularity. The results seem to indicate that survey respondents may have considered CCS an important option for mitigating industry-based emissions and less for those in the energy sector. An alternative explanation is that they considered coal as part of CCS.

Furthermore, natural gas was selected by 9% of the respondents in the first step and only 4% in the second one (combined with renewable sources in 67% of responses and nuclear in 33%), being considered the most important fossil technology. This means that increased CCS popularity is at the expense of renewable energy and gas. A possible interpretation is that while gas has long been considered a transition technology, this role is envisaged for CCS in the longer term (to cover the

Table 4. Mitigation technology options preferred [%] for investments in the next 50 years.

	First Round	Second Round
Renewable Energy*	(1) 49%	(1) 44%
CCS	(2) 18%	(2) 28%
Biomass	(3) 9%	(3) 10%
Natural gas	(4) 9%	(5) 4%
Others**	(5) 8%	(4) 9%
Nuclear	(6) 7%	(6) 5%
Oil	(7) 1%	(8) 0%
Coal	(8) 0%	(7) 1%

*Renewable energy excludes biomass. **Others include energy efficiency, storage, grid balancing and hydrogen.

time between coal and zero emission technologies). Finally, there is almost no change in the nuclear and biomass preferences between the surveys.

Concerning the level of governmental support that technologies should receive (see Table 5), renewable energy (excluding biomass) and CCS continue to be the two most preferred technologies with 40% of the respondents, while the combination of renewable energy and biomass is the second most preferred combination, with 16% of the participants. The role of other technologies (including energy efficiency, storage, grid balancing and hydrogen) increases in the second step of the survey, particularly if they are combined with renewable energy. The largest change, however, is for the CCS with biomass combinations – some respondents even claim that this should be considered as a single technology – which is a negative-emission technology option, while CCS is zero emissions. CCS plus biomass is in '4th place' with 10% of the respondents in the second step, up from only 4% in the first survey.

Figure 1 presents, for the second step, the preferences when stakeholders were asked how the different technology options would develop globally in the next 50 years Figure 1a shows preferences for expansion, whereas Figure 1b shows preferences for phase-out and hold.

4.1.3. Biomass

64% of the respondents reported in the second step that they prefer biomass expansion, 30% that current levels will hold and 4% that there will be a phase-out (2 respondents did not provide any information). With respect to the first survey, 19% changed their responses, mostly (10%) from hold to expansion.

4.1.4. Renewables (excluding biomass)

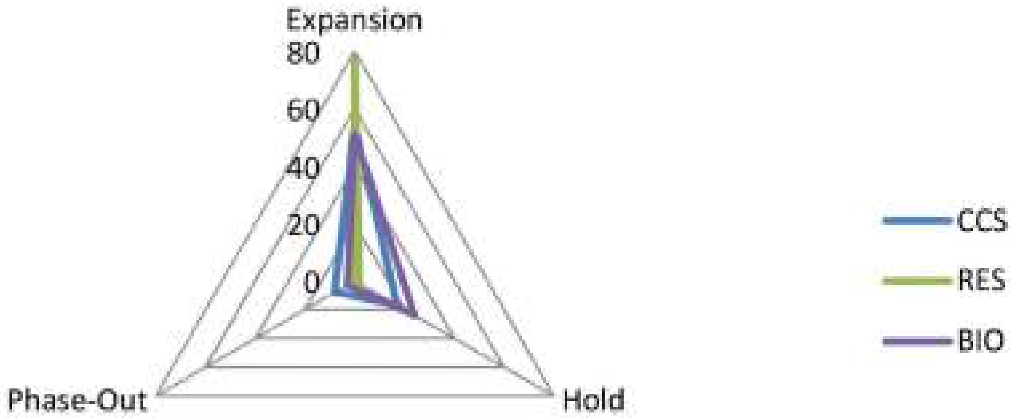
96% of the respondents reported in the second step that renewable energy will expand (the highest consensus), 3% that current levels will hold and none that there will be a phase-out (1 respondent did not provide any information). With respect to the first survey, only 3% changed their responses.

CCS: 68% of the respondents reported in the second step that CCS will expand, 21% that current levels will hold and 10% that there will be a phase-out (1 respondent did not provide any information).

Table 5. Mitigation technology options preferred [%] for governmental support in the next 50 years.

	First Round	Second Round
Renewable energy + CCS	(1) 43%	(1) 40%
Renewable energy + Biomass	(2) 18%	(2) 16%
Renewable energy + Others	(3) 10%	(3) 13%
CCS + Nuclear	(4) 8%	(5) 9%
CCS + Biomass	(5) 4%	(4) 10%

Note: Renewable energy excludes biomass. Others include energy efficiency, storage, grid balancing and hydrogen.



1b. Preferences for phase-out and hold

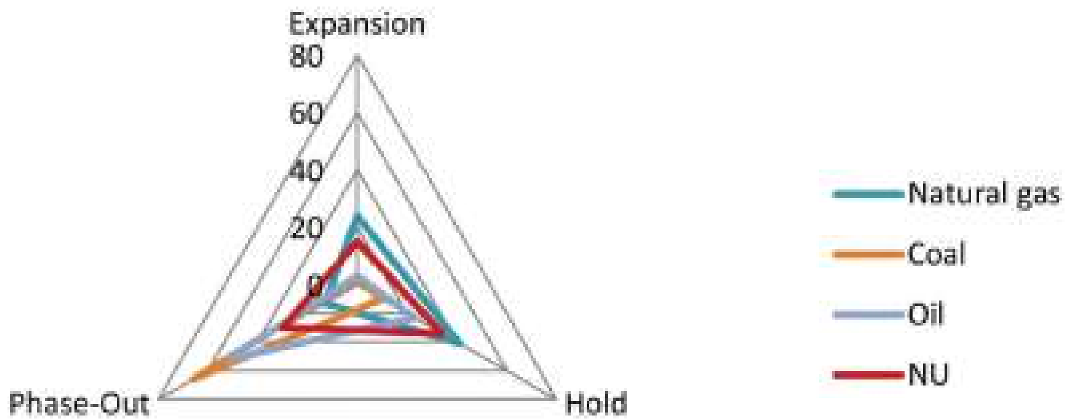


Figure 1. Preferences for future technology development in the next 50 years [number of participants] in the second step.

With respect to the first survey, 11% changed their responses. Almost half of these (5%) were from hold to expansion and 3.8% from expansion to hold. Only two respondents turned to a CCS phase-out.

4.1.5. Nuclear power

19% of the respondents reported in the second step that nuclear will expand, 43% that current levels will hold and 38% that there will be a phase-out (1 respondent did not provide any information). With respect to the first survey, 20% changed their responses, 6% from expansion to hold, 5% from hold to expansion, 5% from hold to expansion and 4% from phase-out to hold. In this sense, the model results could have had a double effect. On the one hand, some respondents could have perceived that mitigation targets could be reached in the absence of nuclear power, and therefore switched from expansion to hold or even phase-out. On the other hand, other respondents could have considered that other mitigating technology options may not be ready on a large scale in the near future, and therefore they improved their view of nuclear power.

4.1.6. Natural gas

30% of the respondents reported in the second step that natural gas will expand, 51% that current levels will hold and 16% that there will be a phase-out (2 respondents did not provide any information). With respect to the first survey, 25% changed their responses. This is the highest switch rate and there is little consensus among the future of this technology: 11% switched from expansion to hold, 5% from hold to phase-out, 5% from hold to expansion and 4% from phase-out to hold. In any case, the majority of new preferences are in the direction of a lower use of this technology in the next 50 years.

4.1.7. Coal

3% of the respondents reported in the second step that coal will expand, 13% that current levels will hold and 83% that there will be a phase-out (2 respondents did not provide any information). This technology presents the greatest consensus on future phase-out. With respect to the first survey, 9% changed their responses, most of them from hold to phase-out.

Oil: 4% of the respondents reported in the second step that oil will expand, 29% that current levels will hold and 65% that there will be a phase-out (2 respondents did not provide any information). With respect to the first survey, 15% changed their responses. Most of them from hold to phase-out.

4.2. Control responses

As regard respondents' opinion regarding the utility of the information provided in the survey (resulting from the model simulations based on their initial preferences), 74% found the results provided useful (45% results not new, but useful and 29% results new). 10% reported that, although results could be useful, the gap between research and policy making is still too large, 3% had a different expectation of the results and 1% did not rely on the model outcomes for decision making.

Participants were also asked about the 'interface' between stakeholders and scientists concerning climate change mitigation aspects (bringing stakeholders' knowledge needs and scientific research together) in the second questionnaire. 73% answered that there are barriers between stakeholders and scientists, but they can be reduced, 10% considered that the understanding between stakeholders and scientists is very difficult (25% of them had previously reported that there is a gap between stakeholders and scientists, but 50% had reported that results were not new but useful; the remaining respondents had reported other reasons, such as the high uncertainty regarding mitigation cost estimates and GDP growth) and only 5% that there is a good understanding between stakeholders and scientists. Other options were also raised by 13% of the respondents, such as scientists underestimating the dimension of the climate change problem, or government contribution to create these barriers, or about the cost of inaction.

Figure 2 shows the breakdown of the different institutional affiliations of the representatives taking part in the survey (blue), together with the proportion that reported that the results of the model simulations were not new to them (green) and the share of them that claimed that the results of the model simulations were new to them (red). For instance, 36% of the respondents were academics (blue), 43% of the people who said that the results were new to them were academics (red) and 30% of the people claiming the novelty of the results were academics (green). In relation to their participation share in the survey, the participants involved in research and consulting were more familiar with technical issues, whereas most academics acknowledged that the results were new. In terms of civil society, NGOs, utilities, coal/gas/oil companies and financial institutions the results were new, whereas governments did know the results in advance.

Finally, 65% of the respondents stated that both scientists and stakeholders should make a greater effort to understand each other, 13% considered that the effort should be greater by stakeholders and 9% that scientists should make a greater effort to understand stakeholders. Some other participants also highlighted the role of governments and clear climate policy to improve the understanding between scientists and stakeholders.

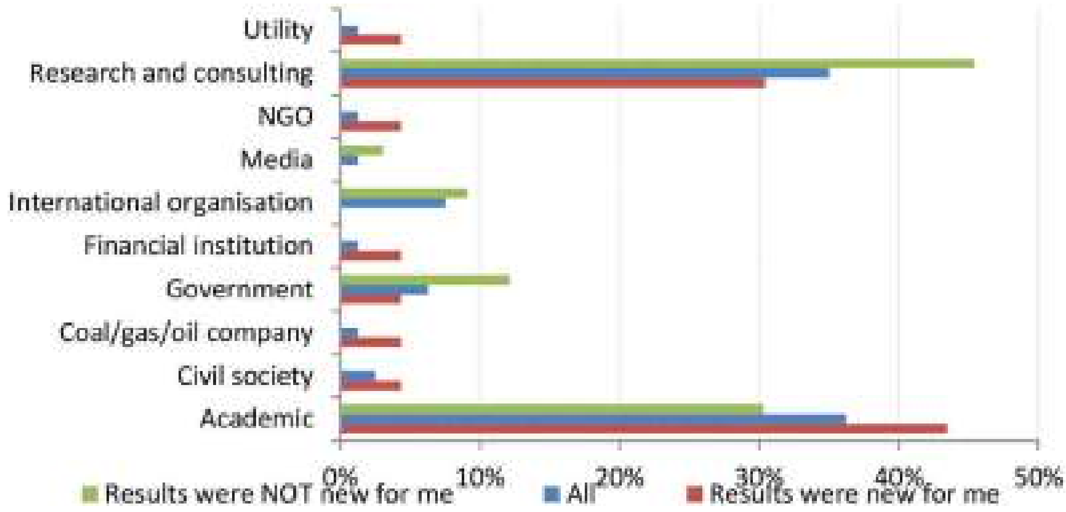


Figure 2. Relationship between the institutional affiliation of the stakeholders and their perception of the model results [%].

4.3. Statistical analysis

Since one or more of our cells have an expected frequency of five or less, we run a Fisher's exact test to see if there is a relationship between responses by institutional affiliation, age, gender or region. We conducted this statistical analysis for the questions related with temperature targets, mitigation costs and technologies, as well as for the control questions. We found the same results using the Kruskal Wallis H test in all cases (given that our variables in the survey are categorical and we have more than three independent groups). For all the statistically significant results, we run the Dunn's post-hoc test to see where these differences are. One limitation of this statistical analysis is our sample size. We could have obtained more statistically significant differences with a higher number of observations, particularly for some institutional affiliations (such as ONG, civil society, etc.) for which we obtained lower participation rates (recall the participation rates by affiliation presented in Table 3 and see Section 5.1 for a more detailed discussion on this limitation). Nevertheless, we obtained statistical significance in some relevant results.

4.3.1. Temperature

We analyzed if there was any statistically significant relationship between participant responses concerning temperature targets by institutional affiliation, age, gender and region. We tested initial responses, final responses (after providing model results) and the interaction between initial and final responses. We did not find any statistically significant relationship by affiliation, age, gender or region. However, we found statistically significance at the 1% level between initial and final responses concerning temperature targets, which supports that respondents react to model results. In particular, we found statistically significant differences between those who answered that their preferred target was "below 1.5ºC" in the second part of the questionnaire (after being confronted with consequential risks) and the rest of the targets.

4.3.2. Mitigation costs

Results suggest that there is not a statistically significant relationship between respondents' expectations for mitigation costs and institutional affiliation, age, gender and region; but there is a statistically significant relationship at the 5% level between expectations and age. After running Dunn's post-hoc test, we observe that the difference exists between the 30–39 and 40–49 groups and between the 30–39 and 50–59 groups. In particular, respondents in the 30–39 age group thought that actual mitigation costs were higher than the presented estimates, whereas participants in the 40–49 and 50–59 groups confirmed that their expectations were in line with the provided results. Those differences are statistically significant.

4.3.3. Technologies

Concerning the questions involving technologies, we find statistically significant differences at the 1% level between the initial responses and the responses after the model results. However, we do not find any statistical difference by affiliation, age, gender or region.

4.3.4. Control questions

Testing again by affiliation, age, gender and region, we did not find any statistically significant difference between the opinions of the respondents concerning our three control questions: (i) whether they found the results new, (ii) their opinion concerning the understanding between scientists and stakeholders, and (iii) who they think should make a greater effort to align positions (stakeholders and/or scientists). However, analyzing the differences between respondents' expectations concerning mitigation costs and who should make a greater effort, we found statistically significant differences at the 10% level between the group that answered that scientists should make a greater effort and the group that answered that both scientists and stakeholder should make an effort. In particular, those who responded that scientists should make a greater effort claimed that actual mitigation costs are higher than the provided model estimates. On the contrary, for those who reported that mitigation cost estimates were line with their expectations, both scientists and stakeholders should make an effort to align positions. Those differences are statistically significant and support the necessity of a better communication between modelers/scientists and stakeholders.

5. Discussion

The analysis made in this paper consisted first of a public consultation to establish respondents' initial preferences, then a model was run to identify consequential risks, and finally a confrontation with these in the second part of the survey. Accordingly, three types of risks are discussed in this section: methodological (Section 5.1), consequential (Section 5.2) and implementation risks, the latter which could be reduced with better informed stakeholders (Section 5.3).

5.1. Methodological risks

Since this paper combines two different methodologies (model simulations and a participatory process), different types of methodological risks arise.

On the one hand, while the analysis enlightens participants about the consequences of scaling up mitigation actions over a longer time, models are only indications based upon best available current knowledge. Indeed, models have limited value over 50+ year horizons. They do not capture technological change over such a time period well and assume technology breakthroughs. In effect, nuclear energy and CCS are usually default mitigation options because the models cannot incorporate future technologies (which do not exist yet). This technological risk was identified by participants and they therefore showed better informed opinions toward other technologies that were not included in the simulations, such as energy efficiency, storage, grid access or hydrogen.

Furthermore, the annual rate of decarbonization needed to achieve the 1.5°C target and how fast it could take should be agreed, in order to be able to implement immediate actions to tackle climate change. This would strongly depend on technology availability, since emission pathways are subject to the technology portfolio. Therefore, there is an environmental risk if technologies able to reduce emissions (or even capture them) are not ready in the near future.

On the other hand, concerning the participatory process, one of the greatest challenges lies in the ability to attract diversity when engaging representatives regarding climate change issues. The main objective of the analysis is to integrate models with different individual visions in order to define feasible low carbon trajectories. However, if some interest groups do not participate in the survey (or their participation is low), the conclusions could be incomplete or even biased. Finding balance between stakeholder groups is thus key, but extremely difficult; particularly when completing the survey takes time. And this is precisely where another important risk arises. If a short survey is provided, in order to avoid the previous limitation and capture a greater number of agents, the risk of losing relevant information increases. If, on the other hand, an in-depth survey is proposed, many stakeholder groups will be less inclined to participate and will not take part in the process. In this paper, the survey consisted of two steps and both of them were needed to capture participants' views toward model results (the first part captures initial preferences and the second part evaluates how respondents react to model results). However, 25% of the initial sample did not complete the second part of the survey, reducing the number of valid responses.

In our particular sample, most of the participants were experts on climate change issues engaged in an existing online community (Climate-L), and therefore not targeted at a carefully selected stakeholder group. Representativeness was achieved in the sense that all institutional affiliations responded the questionnaire. However, academics plus research and consulting groups accounted for more than 70% of the participation, and civil participation was still very low (3%); which could lead to some bias in the results. Other authors, such as Eker et al. (2018) also claim that the majority of their respondents are scientists. We observed the same representativeness problem when looking at the geographical distribution of the participants, since more than 60% came from Europe. One way to solve this issue could be to reduce the number of representatives in the sample and make more targeted invitations. However, in this first approach we were interested in having a high number of responses at a global level, so we decided to use an existing database such as Climate-L. In further research we would also like to focus on civil society, which tends to be passively supportive about energy transitions, but with a "not in my backyard" attitude. We will also introduce just transition factors in the survey, in order to assess the exposure to the social dimension of the transition.

5.2. Consequential risks

The simulations in GCAM provided the survey participants with interesting examples of consequential risks of 1.5–2°C pathways with limited technology options. In particular, when CCS and biomass were the restricted technologies, the emission reduction path necessarily began earlier, because there were fewer possibilities for negative emissions at the end of the century, which is in line with the results provided in IPCC (2018). This would lead to the use of more expensive mitigation technologies in order to reduce emissions to the desired level. When the limited technologies were solar/wind and nuclear (and also when all technologies were available), emissions peaked later, however, but reductions were faster from then onwards. This consequential risk was acknowledged by the respondents who, when confronted with these results, expressed a stronger preference for CCS and biomass, agreeing that the mitigation process should start earlier than initially expected. The special relevance of biomass for feasible low-emission pathways has been underscored in the literature (IPCC 2014a; Vergragt, Markusson, and Karlsson 2011). For instance, Vergragt, Markusson, and Karlsson (2011) claim that bioenergy with carbon capture and storage (BECCS) has enormous potential to achieve net negative emissions, since the CO2 capture from biomass can effectively remove CO2 from the atmosphere, avoiding the fossil fuel technological lock-in of conventional CCS. In this sense, literature also supports the fact that CCS is still unknown to a large part of the population, and that better informed stakeholders have a higher regard for CCS usage (Poumadère, Bertoldo, and Samadi 2011), which could have been the case here, when respondents were confronted with the risks of CCS not being available. On the contrary, according to Selma et al. (2014), if participants had been presented with unfavorable views of CCS (CO2 leakage, problems with CCS storage), CCS support would have decreased. One way to avoid this and to increase CCS approval is to engage stakeholders from the first stages of the project. Moreover, small-scale projects tend to give rise to less concern than big-scale projects (Dütschke 2011).

Given these results, it can be interpreted that respondents' preferences change according to the emission reduction potential of each technology option, their current state of maturity (including also the technological development perspectives) and their costs. Furthermore, participants' initial knowledge of each technology option also affects their new preferences. So, after seeing the results of the model, participants prioritized the development of renewables and have shown themselves to be more favorable to technologies that are currently in a more preliminary phase, but that if not developed in a few years, they would increase the mitigation costs considerably. In line with this result, Saygin et al. (2019) point out that the global transformation of the power sector based on accelerated deployment of renewables would result in stranded assets that could double their value if action is delayed until 2030. They also suggest that countries should consider assets' age profile characteristics in their decision making, since early action and avoidance of investments in new carbon-intensive assets can minimize stranded asset risks. The transformation of the energy sector is thus key, in order to avoid delayed action to mitigate climate change.

Information on pathways and mitigation costs also changed participants' views concerning the temperature target we should set. As a consequence of higher costs (and even some technically unfeasible scenarios), 15% of the respondents preferred a less ambitious climate target. If decision-makers trust models and model results lead them to be more pessimistic, efforts to reduce global warming could be reduced. Nevertheless, this interaction between models and agents could also be used positively to enhance mitigation policies and investments.

5.3. Reduced implementation risk through better informed stakeholders

The type of analysis as applied in this paper of integrating modeled scenarios and individual preferences could in general contribute to reducing the risk of public resistance to mitigation option portfolios. The literature recognizes the importance of including stakeholders in dealing with environmental problems, since solutions are dynamic and interactive processes help necessary adjustments to environmental decisions to be made (Burger 2011). In this paper, engagement in the two-step survey proved that the quantitative information provided was generally perceived as useful. Based on the trade-off between emission reduction and higher economic costs, participants could evaluate different pathways with assumptions about limited availability or applicability of technologies for mitigation and indicate their preferences. From the findings in the survey, it can be concluded that considering participant preferences, certainly when it is about costs and economic impacts, results in different compositions of climate change mitigation technology mixes for low-emission transition pathways.

Therefore, asking for feedback about quantified portfolios of technically feasible mitigation options, and using this feedback in future modeling scenarios, would increase the likelihood of public acceptance of portfolios of climate technology options. Therefore, such an integration of quantitative and qualitative data can be an effective way of reducing the implementation risk of public resistance to 1.5° – 2°C packages. It is noted that, while the integrated analysis in this paper had a global focus, both in terms of modeling and public consultation, the analysis needs to have national or regional focus for enhanced likelihood of implementation of low-emission climate portfolios.

The survey also proved the need for better communication among participants. Many of them were not previously aware of the technical results presented in the simulations, which could be the reason for a change in their preferences in the second round. This was particularly the case for stakeholders from civil society, NGOs, utilities, coal/gas/oil companies and financial institutions. This could be identified as a social risk, since society as a whole needs to be aware of the consequences of bad technology investments, both public and private. Otherwise the effect of past decisions could not be reversed. This result is in line with IPCC (2018), where they highlight the need for cooperation on strengthened accountable multilevel governance including non-state actors such as industry, civil society and scientific institutions, in order to ensure participation, transparency, capacity building and learning among different players.

Other authors have already theorized that there is "a gap between what scientists understand as useful information and what users recognize as usable in their decision making", concluding that "potentially useful climate information often goes unused" (Lemos, Kirchhoff, and Ramprasad 2012) and that a closer look at the science-policy interface in future research is needed (Eker et al. 2018). This is precisely what our survey results empirically suggest: if stakeholders are not aware of technical results, or they do not rely on them, the implementation of the necessary measures to tackle climate change (investments, policies, social resistance) will be delayed. Therefore, this gap due to the differences between what stakeholders require and what scientists can realistically achieve should be reduced. One way to do so is to make scientific results accessible to the nonspecialist, and involving stakeholders in relevant projects from the design stage (Hanson et al. 2006). Other interesting approach to tackle this issue, as Flamos (2015) suggests, involves creating networks of academic-research and business (commercial, industrial, etc.) entities that may catalyze clean energy developments. This would be achieved through (i) the reinforcement of cooperation (at the level of research, technology, and industry), (ii) dissemination of information, and advice on clean energy policies, capacity building, and exchange of know-how, and (iii) exploration of possibilities for joint projects (both technological research and pilot industrial scale projects).

Finally, the fact that the model can solve a scenario does not necessarily mean that it could be easily transposed into the real world. Political, economic and social concerns, other than the economic trade-off effects that were the focus of the analysis in this paper, could complicate the implementation of theoretically feasible scenarios and this is precisely what triggers the relevance of stakeholder participation in the decision-making process.

6. Conclusions

This paper combines modeled scenarios and individual preferences to identify the barriers between stakeholders and models concerning climate change mitigation aspects, as well as the associated risks. First, stakeholders are asked about their preferences on low carbon transitions with limited technology options. Then, they are presented with low carbon pathways resulting from a model simulation that was made in advance. Finally, after seeing the model results, they are asked again about their preferences. The aim of analyzing different mitigation portfolios was twofold. First, to observe if initial individual preferences about mitigation transition pathways change when participants are provided with more information on trade-offs in terms of environmental benefits (global temperature increment limit) against economic costs (mitigation costs). Second, to identify risks associated with this transition to low carbon technologies. A two-step survey was conducted, where respondents were confronted with the consequential risks of their preferences in the first round of the survey.

After the second step of the survey, most participants commented that the information provided in the statements was useful for them (in several cases even new to them) and claimed that it had influenced their responses. Additionally, 10% of the respondents reacted to the simulation results by relaxing the temperature target they had favored in the first survey, which leaves open the debate about the temperature target we should aim (1.5°C vs. 2°C). The iterative process with an open community also resulted in improved opinions toward future combined development of bioenergy and CCS, and increased concerns regarding the future of the most emitting fossil-fuel technologies. There was consensus on the relevance of renewable energy; however, there were still divergences concerning the role of nuclear power and natural gas in this energy transition.

Consequential risks arise from the technical feasibility of the different mitigation portfolios. The model could not find a solution given the particular conditions of certain scenarios (i.e. the 1.5°C temperature target when CCS is not available or renewable energy is limited). This could be due to technical reasons, i.e. the remaining technology options could not meet the demand and keep emissions at the necessary level (technological risk) or economic concerns, i.e. prices of certain markets would be disproportionate to ensure the required emissions cap (economic risk). At the same time, when the model can solve a scenario, this does not necessarily mean that it could be easily transposed into the real world. Political and social concerns could complicate the implementation of theoretically feasible scenarios and this is precisely what triggers the relevance of stakeholder participation in the decision-making process. Additionally, another drawback of model-based approaches is at what extent are the results conditioned by the model parametrization/assumptions.

Stakeholders also confirmed that the status of the technology portfolio, which is heavily founded on public/private support, determines the timing and speed of the emission reductions, and thus the costs, given a desired end goal −1.5 or 2 degree temperature limitation- (methodological risks). For instance, in case negative-emission technologies, such as the combined option of biomass and CCS, are not or limitedly available, then the 1.5ºC target can only be reached without additional economic costs if other climate change mitigation options are pursued early. When dealing with mitigation options, multiple options will be needed, but policy makers should consider that different combinations and delayed implementation of options implies risks of higher costs in the longer term (and uncertainties in the discounting). Additionally, a single technology approach will not work for all countries (it could perhaps work for a few or may not work at all), since, for example, the resources, technologies or public acceptability of different options vary by geographical scales and will change with time (implementation risks).

Concerning the methodological limitations of the paper, the way we implemented the online survey could lead to some bias in the results. In particular, we used an existing database such as Climate-L to engage participants. This could lead to representativeness issues, since not all participatory groups are equally represented (e.g. large proportion of academics compared to civil society). One way to solve this issue and target more citizens in the study could be to include a different stakeholder engagement medium, such as more targeted invitations, which could be done in further research. Furthermore, another prospect for future research, coupled with the expansion of the stakeholder pool to include a large number of citizens, could be the expansion of the questions to topics/metrics outside the strict economic perspective (like GDP, costs, etc.) but social aspects and just transition factors, which, although they cannot directly translate into an integrated assessment model, might alter the socio-economic assumptions employed and the associated storylines framing them.

Finally, and more importantly, the results show the need for better communication between modelers/scientists and stakeholders, since 23% of the respondents were not previously aware of the technical results presented in the simulations and, at the same time, modelers are not always in direct contact with the limitation and barriers of decision-makers. This figure could also indicate a gap between policy (particular group of stakeholders) and research, in addition to the gap between (other) stakeholders and scientists. This was particularly the case for stakeholders from civil society, NGOs, utilities, coal/gas/oil companies and financial institutions. If these sectors lack information on the mitigation technology portfolio (social risk), action against climate change will be much harder (environmental risk). In fact, 73% of the participants answered that there are important barriers between stakeholders and scientists, but fortunately most of them agree that understanding between stakeholders and scientists is possible if both communities make an effort. The paper concludes that implementation risks could be reduced with better informed stakeholders. This is an important result that could lead to further research: what else would be needed? If providing information about costs and GDP impacts of climate ambitions is not enough, what additional information is needed, or is it about communication? Therefore, approaches such as the one used in this study will be crucial in the future in order to reduce barriers for a more ambitious action against climate change and to make quantitative tools more useful in the decision-making process.

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Appendices

A. **Online survey for stakeholders**

This appendix presents the online survey that was conducted. It includes the presentation, the first-round questions, the statements providing information from the simulations and the second-round questions, also including the control and socio-demographic questions. Detail on the answers is also provided.

a. **Presentation**

The EU-funded project **TRANSrisk** aims to explore pathways for low-emission development and, eventually, reaching the goal of the Paris Agreement (limiting temperature increase to 2°C, or, if possible, 1.5°C). While such pathways contribute to greenhouse gas emission reduction, they may have impacts on different aspects of society, some of which may be positive and others negative. Understanding these impacts will enable policy makers to take appropriate actions so that a pathway will also become acceptable from a societal perspective.

In order to understand the impacts of low-emission pathways for society and how this may have an influence on public acceptance of the pathways, TRANSrisk uses modeled analysis in combination with stakeholder consultation. This is done at the level of individual countries – models generate possible low-emission futures with their costs, benefits, uncertainties and consequent risks, which are subsequently assessed by stakeholder groups in each country, in terms of what they prefer and find acceptable.

This approach – stakeholder consultation in combination with modeled analysis – is also carried out from an **international perspective**, for which we have set up this survey. It contains two steps:

1. **General stakeholder consultation: information is collected on how a wide group of stakeholders (incl. policy makers, private sector decision makers, researchers, policy advisers, NGO representatives) perceive and assess climate change and possible measures (such as technology options) to reduce emissions.**
2. **Specific stakeholder consultation based on a set of low-emission pathways, which are based on model simulations.**

The focus of the survey is on mitigation measures in the energy sector at a global level.

As a stakeholder, you are cordially invited to participate in this survey in your personal capacity. Your views will be treated anonymously and will not be used for any other purpose than for this study. The whole survey will take approximately 20 minutes of your time.

Your feedback is extremely valuable therefore we would like to thank you for participating in our survey.

b. **First round**

Q1. In your opinion, what is the optimal temperature target that we SHOULD aim for by the end of the century to limit global warming? Please select one of the following options:

Answer Options	Response Percent	Response Count
Below 1.5°C	45.71%	48
Below 2°C	43.81%	46
Below 2.5°C	4.76%	5
Below 3°C	0.95%	1
Others	4.76%	5
answered question		105
skipped question		1

Q2. With a view to climate change mitigation investments in the global energy sector, which technologies, do you think, WILL be the two most important during the next 50 years? Please select the TWO most important options:

Answer Options	Response Percent	Response Count
CCS (Carbon capture and storage)	33.96%	36
Nuclear	15.09%	16
Renewables (excluding biomass)	92.45%	98
Biomass	14.15%	15
Natural gas	14.15%	15
Coal	0.94%	1
Oil	1.89%	2
Others*	16.04%	17
answered question		106
skipped question		0

* The following technologies were mentioned: Energy Efficiency, Storage, Grid Balancing, and Hydrogen.

Q3. The technologies listed in Question 2 are in different stages of development in terms of market readiness: some are close to or in the stage of commercial application, while others require governmental support to successfully conclude the research, development and demonstration stage. Which of the following options, do you think, require more governmental support in the next 50 years for successful deployment and diffusion in the global energy sector? Please select the TWO most important options:

Answer Options	Response Percent	Response Count
CCS (Carbon capture and storage)	55.66%	59
Nuclear	11.32%	12
Renewables (excluding biomass)	75.47%	80
Biomass	17.92%	19
Natural gas	3.77%	4
Coal	0.94%	1
Oil	0.94%	1
Others*	19.81%	21
answered question		106
skipped question		0

* The following technologies were mentioned: Energy Efficiency, Storage, Grid Balancing, and Hydrogen.

Q4. In your personal/professional opinion, how will the different technology options develop in the next 50 years at a global scale? Please select the options (technology will phase-out, hold or expand) from the dropdown menu:

Answer Options	PHASE-OUT	HOLD	EXPANSION	TOTAL
CCS (Carbon capture and storage)	7.62%	26.67%	65.71%	105
	8	28	69	
Nuclear	31.07%	45.63%	23.30%	103
	32	47	24	
Renewables (excluding biomass)	0.96%	0.96%	98.08%	104
	1	1	102	
Biomass	4.85%	33.98%	61.17%	103
	5	35	63	
Natural gas	16.67%	49.02%	34.31%	102
	17	50	35	
Coal	81.37%	15.69%	2.94%	102
	83	16	3	
Oil	63.73%	32.35%	3.92%	102
	65	33	4	

c. **Statements**

In this second part of the survey, we present you with a set of low-emission pathways and see whether these statements change your preferences.

To determine the pathways, we have modeled the following set of scenarios, which are in line with those presented in the IPCC Fifth Assessment Report with the goal of limiting global average temperature increase by 1.5ºC or 2ºC by 2100: 880

- **no climate policy**
- **climate policy and all technologies available: “all technologies available”**
- **climate policy with all technologies available, but with limited use of biomass: “limited biomass”**
- **climate policy with all technologies available, but with limited use of solar/wind: “limited solar/wind availability”**
- **climate policy with all technologies available except Carbon Capture and Storage (CCS): “no CCS”**
- **climate policy with all technologies available but assuming a nuclear energy phase out: “nuclear phase out”**

To obtain a set of low-emission pathways, we used the GCAM model (version 4.2, and one of the models used by IPCC) which is an integrated assessment tool for exploring consequences and responses to global change. Further information on this model can be found at http://jgcri.github.io/gcam-doc/v4.2/toc.html.

In this second part of the survey, we would like to present to you the low-emission pathways in the form of seven statements. These are followed by a set of questions about the impacts of the pathways and how you perceive these.

Please read the statements carefully and answer the next questions.

Statement 1: In a 2ºC scenario, global emissions would be 65% higher than in a 1.5ºC scenario, but less than half of the emissions in a 3ºC scenario.

Statement 2: In a 1.5ºC scenario, global mitigation costs account for 6% of global GDP by 2100; in a 2ºC scenario, costs are 3% of GDP and 0.3% in a 3ºC scenario. For each target, this represents a reduction in annual economic growth of less than 0.05 percentage points.

Statement 3: In a 2ºC/1.5º scenario, any limitation of technological availability will increase mitigation costs (see Figure A1**). The scenarios with the highest mitigation costs are those without CCS and with limited biomass. Other, but lower increases in mitigation costs can be found in scenarios which assume restricted use of intermittent renewables and nuclear energy phase out**.

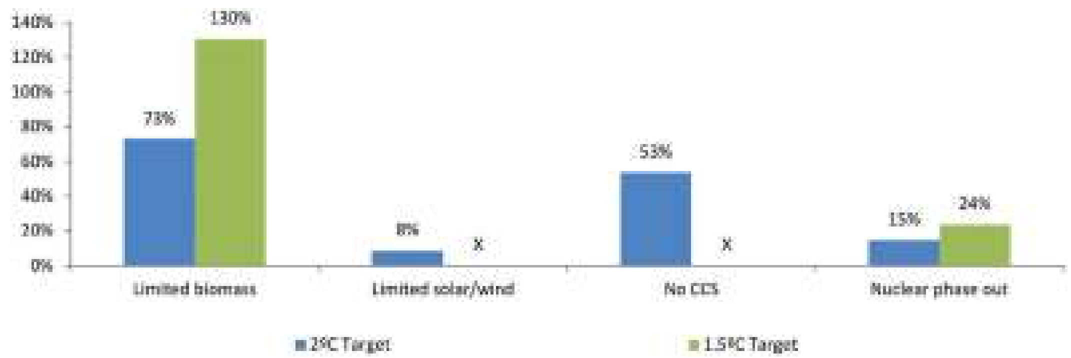

Figure A1. Mitigation cost increment compared to the all technologies available policy scenario for both target scenarios 1.5ºC vs 2ºC by 2100.
Note: Limited solar/wind and No CCS are not feasible for a 1.5ºC temperature target. In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible for a 1.5ºC temperature target. Mitigation costs for the period 2020–2100, discounted at 5% per year.

Statement 4: All scenarios require negative emissions (carbon removal from the atmosphere) to reach the 2 or 1.5oC goals. The scenarios “all technologies available”, “limited solar/wind availability” and “nuclear phase out” require negative emissions from 2080 onwards while the scenarios “no CCS” and “limited biomass” require negative emissions from 2095 and 2100 onwards, respectively. However, policy costs increase when emission reductions are lower than expected and negative emissions delayed, since other more expensive options need to be used to fulfill the climate goals. In fact, if negative emission options are not readily available, emission reductions should start earlier. In particular, if the technology options achieving negative emissions are limited, emission reductions should start in 2020 (otherwise in 2030).

Statement 5: In the absence of a climate policy (scenario ‘no climate policy’), coal and natural gas remain the main components of the global energy mix with more than 60% of the total energy consumption. In all the other scenarios, their share in the global mix is considerably reduced (see Figure A2**).**

Statement 6: In the absence of CCS, fossil-fuel-based technologies are completely eliminated (i.e. oil and coal) or marginalized (i.e. natural gas) by the end of the century, whereas renewable energy and nuclear power increase their share in the mix (see Figure A2).

Statement 7: Without CCS and only limited availability of solar and wind technologies on a global scale the model was not able to find a suitable technology mix to achieve 1.5ºC target in 2100. However, the model shows that the 1.5ºC target is feasible without using nuclear energy (see Figure A2).

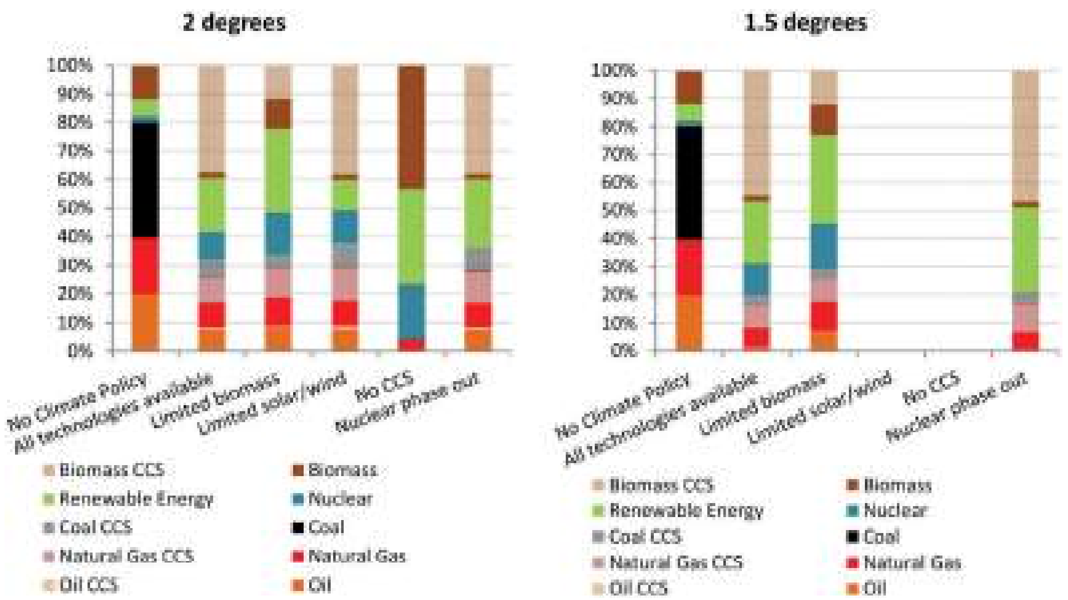

Figure A2. Energy mix in 2100 for both target scenarios.
Note: Limited solar/wind and No CCS are not feasible for a 1.5ºC temperature target. In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added.

c. **Second round**

Main questions

Q5. Consider the information provided in the statements. What is the optimal temperature target that we SHOULD aim for by the end of the century to limit global warming? Please select one of the following options:

Answer Options	Response Percent	Response Count
Below 1.5°C	40.74%	33
Below 2°C	48.15%	39
Below 2.5°C	4.94%	4
Below 3°C	2.47%	2
Others	3.70%	3
answered question		81
skipped question		25

Q6. Statement 2 contains estimates of mitigation costs expressed as percentage of GDP for each of the three temperature limitation targets explored (6% for 1.5ºC, 3% for 2ºC and 0.3% for 3ºC). For your preferred target (your answer to Q1), is the estimated share of mitigation per GDP lower or higher than you expected, or in line with your initial expectations?

Answer Options	Response Percent	Response Count
Lower	24.69%	20
Higher	20.99%	17
In line with my expectations	54.32%	44
answered question		81
skipped question		25

Q7. Consider the information provided in the statements and your answers to Q1-2. With a view to climate change mitigation investments in the global energy sector, which technologies, do you think, WILL be the two most important during the next 50 years? Please select the TWO most important options:

Answer Options	Response Percent	Response Count
CCS (Carbon capture and storage)	51.85%	42
Nuclear	9.88%	8
Renewables (excluding biomass)	83.95%	68
Biomass	18.52%	15
Natural gas	7.41%	6
Coal	1.23%	1
Oil	0.00%	0
Others*	19.75%	16
answered question		81
skipped question		25

* The following technologies were mentioned: Energy Efficiency, Storage, Grid Balancing, and Hydrogen.

Q8. Consider the information provided in the statements. The technologies listed in Question 7 are in different stages of development in terms of market readiness: some are close to or in the stage of commercial application, while others require governmental support to successfully conclude the research, development and demonstration stage. Which of the following options, do you think, require more governmental support in the next 50 years for successful deployment and diffusion in the global energy sector? Please select the TWO most important options:

Answer Options	Response Percent	Response Count
CCS (Carbon capture and storage)	59.26%	48
Nuclear	12.35%	10
Renewables (excluding biomass)	76.54%	62
Biomass	25.93%	21
Natural gas	1.23%	1
Coal	0.00%	0
Oil	0.00%	0
Others*	17.28%	14
answered question		81
skipped question		25

* The following technologies were mentioned: Energy Efficiency, Storage, Grid Balancing, and Hydrogen.

Q9. Consider the information provided in the statements. In your personal/professional opinion, how will the different technology options develop in the next 50 years at a global scale? Please select the options (technology will phase-out, hold or expand) from the dropdown menu:

Answer Options	PHASE-OUT	HOLD	EXPANSION	TOTAL
CCS (Carbon capture and storage)	10.00% 8	21.25% 17	68.75% 55	80
Nuclear	37.50% 30	43.75% 35	18.75% 15	80
Renewables (excluding biomass)	0.00% 0	2.50% 2	97.50% 78	80
Biomass	3.85% 3	30.77% 24	65.38% 51	78
Natural gas	16.67% 13	52.56% 41	30.77% 24	78
Coal	84.62% 66	12.82% 10	2.56% 2	78
Oil	66.67% 52	29.49% 23	3.85% 3	78

Control questions:

Q10. Do you think that the results provided in the statements are insightful? Please select one of the following options:

Answer Options	Response Percent	Response Count
Yes, the results provided were useful and new for me	28.75%	23
Yes, the results provided were not new for me, but I find them useful	45.00%	36
No, my expectations of the results where different	2.50%	2
No, although results from models could be useful, the gap between developers/scientists and policy makers is still too big	10.26%	8
No, I do not rely much on the results from models for decision making	1.25%	1
Others	12.50%	10
answered question		80
skipped question		26

Q11. What is your opinion about the 'interface' between stakeholders and scientists concerning climate change mitigation aspects (bringing stakeholders' knowledge needs and scientific research together)? Please select one of the following options:

Answer Options	Response Percent	Response Count
There is a good understanding between stakeholders and scientists	5.00%	4
There are barriers between stakeholders and scientists, but they can be reduced	71.25%	57
Understanding between stakeholders and scientists is very difficult	10.00%	8
Others	13.75%	11
answered question		80
skipped question		26

Q12. Considering your answer to Q7, who should make a greater effort to align positions, if required? Please select one of the following options:

Answer Options	Response Percent	Response Count
Stakeholders should make a greater effort to understand scientists	12.50%	10
Scientists should make a greater effort to understand stakeholders	8.75%	7
Both stakeholders and scientists should make a greater effort to understand each other	65.00%	52
Neither stakeholders nor scientists need to make a greater effort to understand each other	1.25%	1
Others	12.50%	10
answered question		80
skipped question		26

Socio-demographic questions:

Q13. In what country do you live?		
Answer Options	Response Percent	Response Count
Albania	1%	1
Australia	1%	1
Austria	5%	4
Bangladesh	1%	1
Belgium	3%	2
Brazil	1%	1
Cameroon	3%	2
Canada	3%	2
Egypt	1%	1
France	4%	3
Germany	4%	3
Greece	6%	5
Guatemala	1%	1
Iceland	1%	1
India	4%	3
Indonesia	1%	1
Ireland	3%	2
Italy	3%	2
Japan	3%	2
Kenya	1%	1
Mexico	1%	1
Montenegro	1%	1
Netherlands	1%	1
Nigeria	3%	2
Norway	1%	1
Pakistan	1%	1
Peru	1%	1
Philippines	1%	1
Portugal	1%	1
Republic of Korea	1%	1
Romania	1%	1
Rwanda	1%	1
Spain	21%	17
Uganda	1%	1
UK	5%	4
USA	5%	4
N/A	3%	2
answered question		80
skipped question		26

Q14. What is your institutional affiliation?		
Answer Options	Response Percent	Response Count
Academic	36.25%	29
Civil society	2.50%	2
Coal/gas/oil company	1.25%	1
Government	6.25%	5
Financial institution	1.25%	1
International organization	7.50%	6
Media	1.25%	1
ONG	1.25%	1
Research and consulting	35.00%	28
Utility	1.25%	1
Others*	1.25%	1
N/A	5.00%	4
answered question		80
skipped question		26

* Climate change was mentioned as others.

Q15. Which sector do you work in?		
Answer Options	Response Percent	Response Count
Renewable energy	18.75%	15
Agriculture/waste/forestry	17.50%	14
Coal/gas/oil company	1.25%	1
Others	60.00%	48
N/A	2.50%	2
answered question		80
skipped question		26

Note: Others include academia or research institution, civil society, climate policy, environment, government, trade, water, energy planning and regulation.

Q16. What is your gender?		
Answer Options	Response Percent	Response Count
Male	66.25%	53
Female	33.00%	24
N/A	3.75%	3
answered question		80
skipped question		26

Q17. What is your age?		
Answer Options	Response Percent	Response Count
20–29	13.75%	11
30–39	25.00%	20
40–49	27.5%	22
50–59	11.25%	9
60–69	12.50%	10
70 or older	7.50%	6
N/A	2.50%	2
answered question		80
skipped question		26

Appendices

B. **Model results**

This appendix explores the trade-offs in the different mitigation portfolios described in Section 2. Climate policy has been modeled in this paper by means of different temperature targets, i.e. below 1.5°C versus below 2°C, and considering diverse technology portfolios (recall Table 1 in the paper). The focus lies on the implications of those temperature targets on the energy mix, CO_2 emissions and mitigation costs. The following subsections provide a detailed discussion of these issues.

a. **Energy Mix**

Figure B1 compares the share of each technology in global energy consumption in 2050 and in 2100 for both the 2°C and 1.5°C temperature targets. In the absence of climate policies, coal and natural gas remain the main components of the mix, representing more than 60% of total energy consumption. In all the mitigation portfolios, the share of those with assumed climate policies, however, in the global mix is considerably reduced. This is especially apparent in the future use of coal, since the model shows that the share of coal reduces over time and at the end of the century it is only present in combination with CCS. Moreover, without CCS, fossil-fuel-based technologies are completely eliminated (i.e. oil and coal) or marginalized (i.e. natural gas) by the end of the century, although they still play an important role in 2050. In this no-CCS scenario, biomass becomes the most relevant mitigation technology in 2100, with roughly 40% share of the global energy mix.

The special relevance of biomass is due to the bioenergy with carbon capture and storage (BECCS), since it has an enormous potential to achieve negative emissions, since the CO_2 capture from biomass can effectively remove CO_2 from the atmosphere, avoiding the fossil fuel technological lock-in of conventional CCS (Vergragt, Markusson, and Karlsson 2011).

Finally, renewable energy and nuclear power increase their share in the mix when technologies with negative emissions potential are limited or not available (i.e. scenarios with no CCS and limited bioenergy). If emissions cannot be captured, the low emitting technologies become particularly important in early stages.

b. **Electricity mix**

Figure A2 presents the global electricity mix picture for 2050 and 2100 under the 2°C and 1.5°C temperature targets. As observed in the global energy mix in Figure B2, fossil technologies are only present if CCS is available. Additionally, renewable energy becomes a critical technology in 2100, overtaking the 40% in the nuclear phase out scenario for both stabilization targets (41% for a 2°C target and 45% for a 1.5°C target). Concerning the global electricity mix, renewable energy and CCS are the key technologies to limit global warming, both in the 1.5°C and 2°C scenarios.

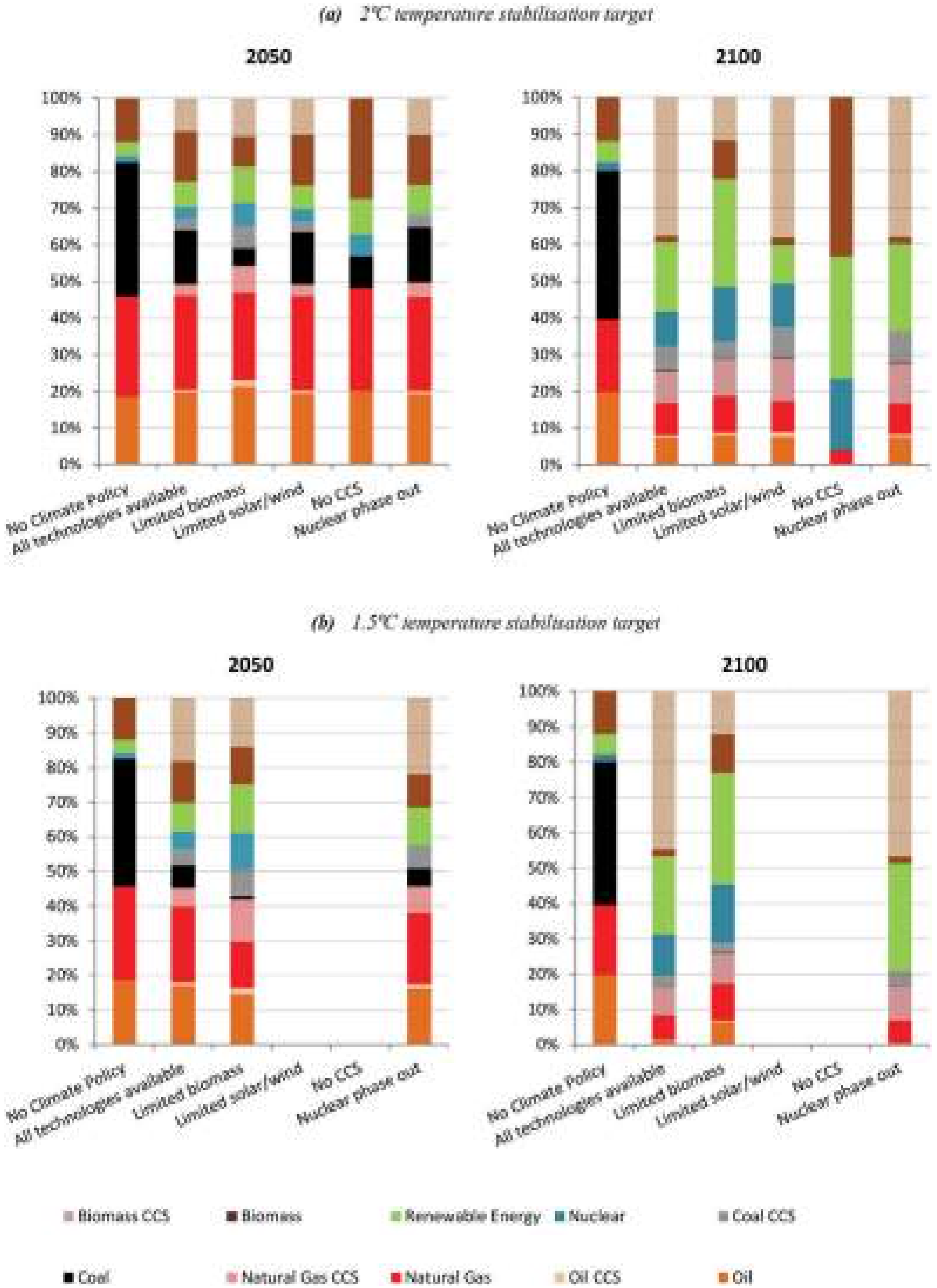

Figure B1. Energy mix [%] for different global temperature targets.

Note: Renewable energy includes intermittent renewables (solar/wind/geothermal) and hydro-power. In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target.

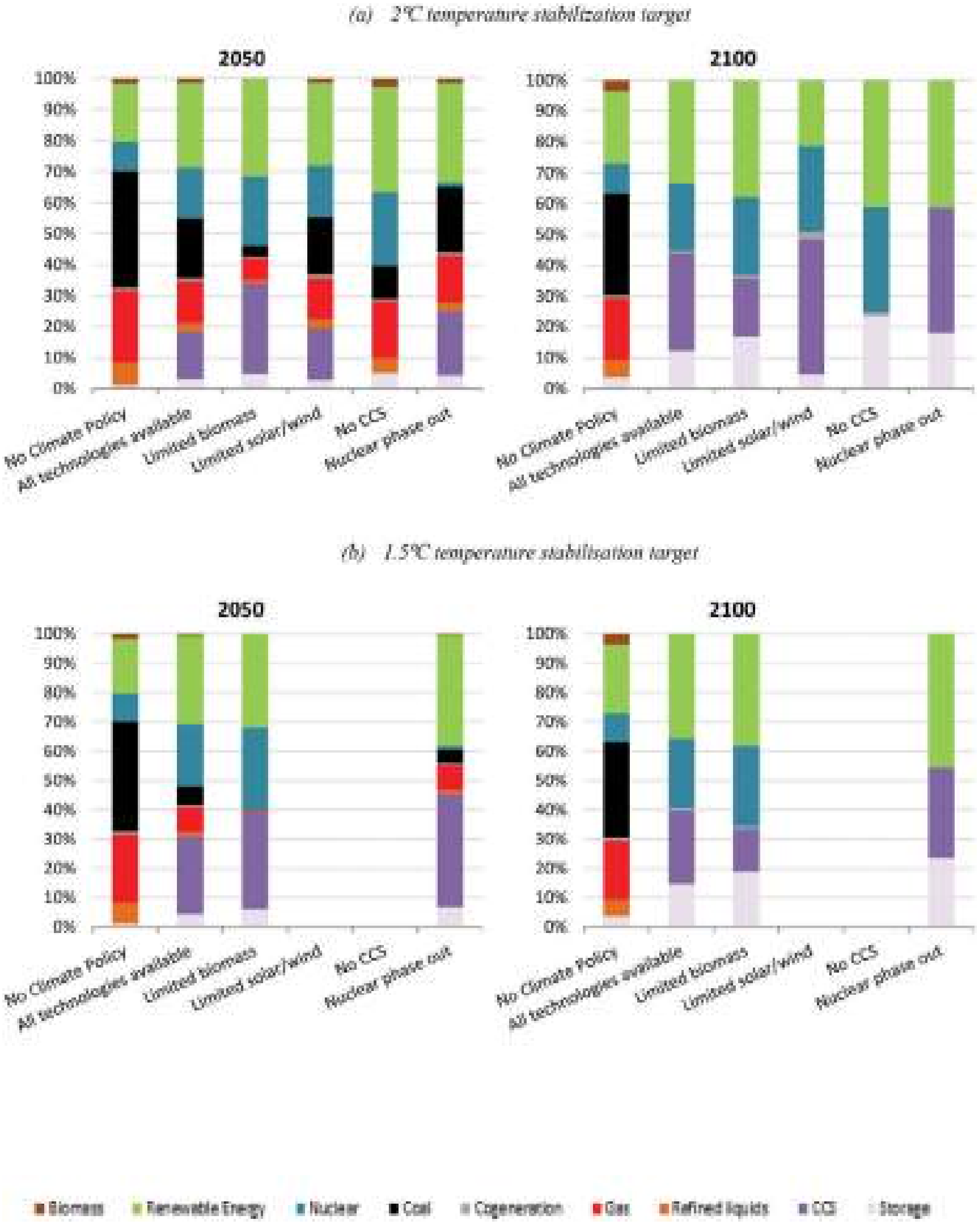

Figure B2. Electricity mix [%] for different global temperature targets.

Note: Storage includes CSP storage, PV storage and wind power storage. In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target.

c. **CO2 Emissions**

The two climate policies evaluated in this paper (1.5 and 2°C targets) are aimed at reducing GHG emissions. According to the IPCC, anthropogenic GHG emissions are extremely likely to have been the dominant cause of the global warming observed since the mid-20th century. Among them, CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions from 1970 to 2010 (IPCC 2014b). Therefore, CO_2 emissions became a key indicator for comparing the different mitigation portfolios (although there are additional sources of emissions that have not been considered in this analysis).

i. **CO2 emissions in the energy system**

Figure B3 represents the evolution of CO_2 emissions for atemperature increase target of below 2ºC (Figure B3a) and a temperature increase target of below 1.5ºC (Figure B3b) for the energy-use sectors (i.e. AFOLU emissions are not considered). As the figure shows, without a climate policy target (dashed black line), annual emissions are above 10 GtC/yr from 2015 onwards, surpassing the 20 GtC/yr in 2065 and peaking at 25 GtC/yr by the end of the century. Considering that, according to the IPCC, the remainder of the carbon budget likely to keep global mean temperatures below 2ºC is estimated to be 275 GtC in 2011 (IPCC 2013a), the absence of climate policies would increase the likelihood of missing the 2ºC temperature limit (i.e. within 15 to 20 years). Achieving a temperature target below 1.5ºC would depend even more on climate policies, given that there is a very tight budget for remaining carbon emissions.[4]

In this context, negative emissions are a key element to achieving these challenging climate policy targets. The concept of "negative emissions", which is widely used in this paper, implies carbon removal from the atmosphere. One important technology able to achieve these negative emissions is CCS,[5] either combined with fossil fuels (e.g. coal with CCS, natural gas with CCS, oil with CCS) or with biomass (i.e. BECCS). Figure B3 shows that producing negative emissions is optimal in all the scenarios to achieve both the 2ºC and the 1.5ºC scenarios, but the optimal level varies depending on the technology that is limited.

In particular, when CCS and biomass are the restricted technologies, the emissions reduction path must necessarily begin earlier, because there are fewer possibilities for negative emissions at the end of the century. However, when the limited technologies are solar/wind and nuclear (and also when all technologies are available), emissions are higher until 2060 in both temperature targets, but reductions are faster from then onwards. For the 2ºC temperature target, negative emissions begin in 2080 for the scenarios where all technologies are available, when solar/wind is limited and also when biomass is restricted.

When there is no CCS, negative emissions are needed from 2095, and when biomass is limited from 2100. Emissions are much more restrictive for the 1.5ºC scenario, for which negative values are required from 2065 for the nuclear phase out scenario and from 2070 for the all technologies available scenario and for the limited biomass scenario. As is shown in Figure B6, the fact that some scenarios required additional efforts to start mitigation earlier imposes extra costs in the mitigation process, since higher cost technologies need to be employed to fulfil the climate policy target. This effect is particularly important when biomass is limited (because in that case BECCS is limited), especially in the 1.5ºC scenario.

A caveat is needed. The limited intermittent renewables scenario and the no CCS scenario are not feasible under a 1.5ºC temperature stabilization target. This means that the model cannot find a solution, because of technical or economic constraints. This proves that renewable energy and CCS are crucial technologies for achieving demanding mitigation targets.

[4]The carbon budget available for limiting temperature increases to less than 1.5°C (with a likelihood of 66%) is estimated to be 109 GtC from 2011 onwards. Emissions from 2011 to 2015 totaled 48 GtC and, therefore, the carbon budget currently available is 61 GtC for the goal of 1.5°C.

[5]Other ways to achieve negative emissions include afforestation, Carbon Dioxide Removal (CDR) technologies or other geo-engineering options.

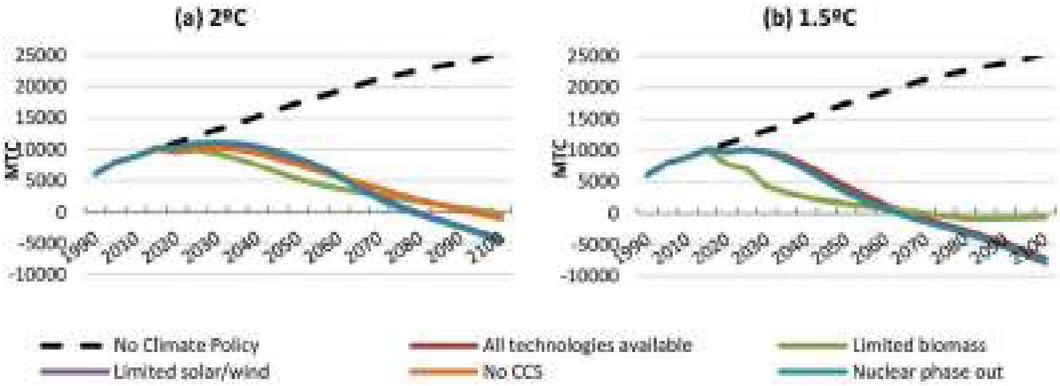

Figure B3. Evolution of global CO2 emissions in the energy sector [MtC] for different global temperature targets.
Note: In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target. Emissions only include the energy sector.

ii. **CO2 emissions by region**

Figure B4 details the evolution of CO_2 emissions toward a 2ºC temperature target by region, where USA, EU27, Canada, Japan and the BRICS countries are considered. The model seeks the global minimum cost at a global CO_2 price, which determines the reduction by country. The main message of this figure is that, in the optimal case, only the BRICS countries are allowed to continue increasing their emissions until 2035 (if all technologies are available, with limited technology options reductions should start earlier), given that they need energy to meet their growing demand. However, the rest of the regions analyzed should start before 2020. Concerning the effect of each technology, there are no differences among regions: a situation with limited biomass requires higher efforts in the first half of the century, in order to compensate for the limited availability of BECCS in the last years.

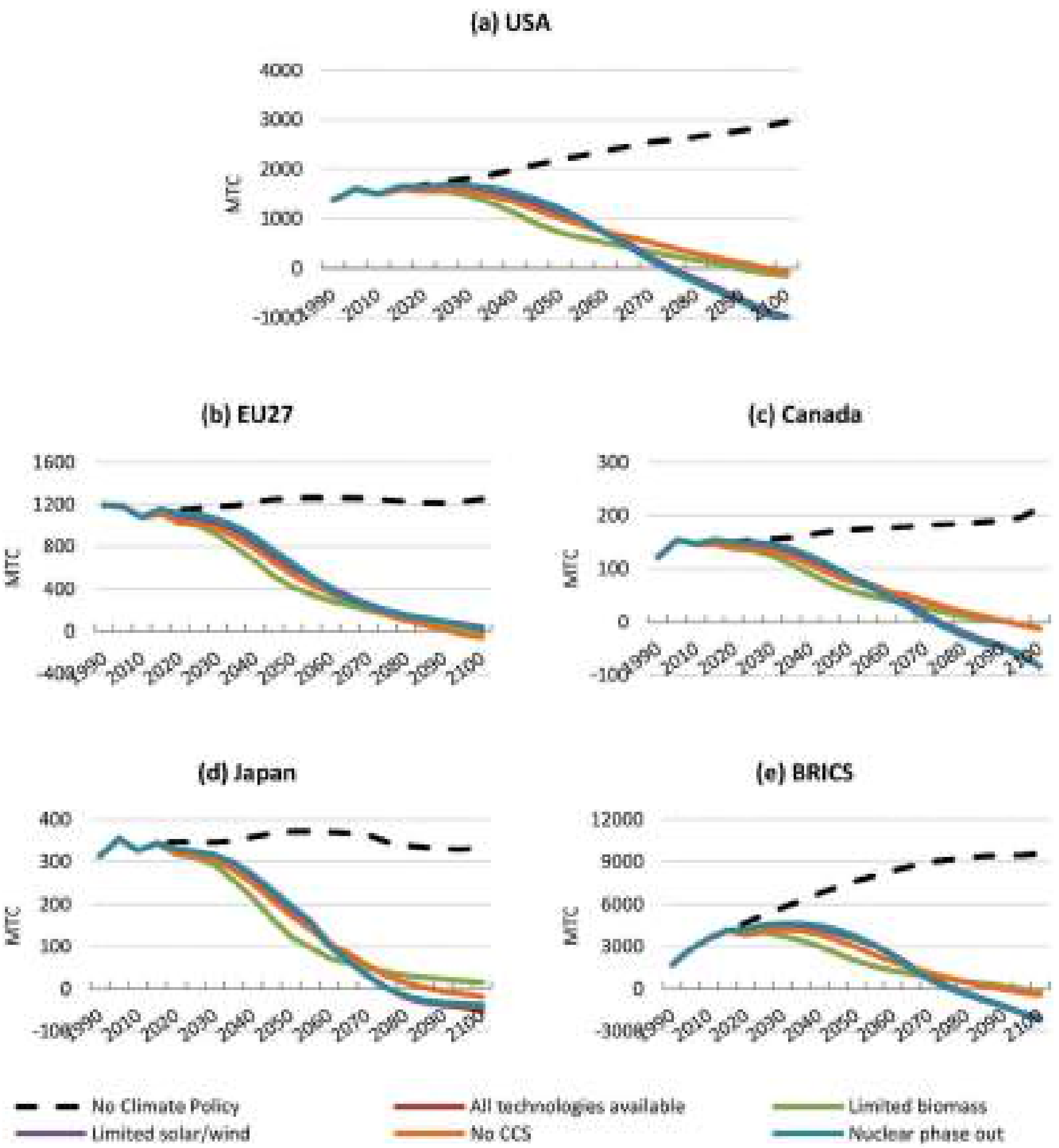

Figure B4. Evolution of CO2 emissions in the energy sector [MtC] by region under a 2ºC global temperature target.
Note: In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Emissions only include the energy sector.

d. **Mitigation costs**

This subsection presents an analysis of the mitigation costs of the different technology options explored in this paper. Mitigation costs refer to the policy costs necessary to achieve the climate targets, i.e. below 2ºC and below 1.5ºC. This calculation strongly depends on the model that is used. In the case of GCAM, mitigation costs are computed in terms of the area under the marginal abatement cost (MAC) curve and are expressed as the net present value (NPV) over the course of the full century, discounted at a 5% rate.

Figure B5 compares the mitigation costs increase for the limited technologies scenarios to the situation where all the technology options are available. Results are presented for the 2ºC (Figure B5a) and 1.5º (Figure B5b) temperature stabilization targets. In a 2ºC temperature stabilization scenario by the end of the century, the scenarios with the highest mitigation costs are the limited biomass (by 73%) and the no-CCS scenario (by 53%). Moreover, these costs increase considerably if the temperature limit is 1.5ºC, particularly when biomass is restricted (by 130%). This is caused by the fact that a bioenergy limitation scenario reduces the amount of available BECCS in latter periods (remember Figure B1), which would lead to the use of more expensive mitigation technologies in order to reduce emissions to the desired level (recall Figure B3).

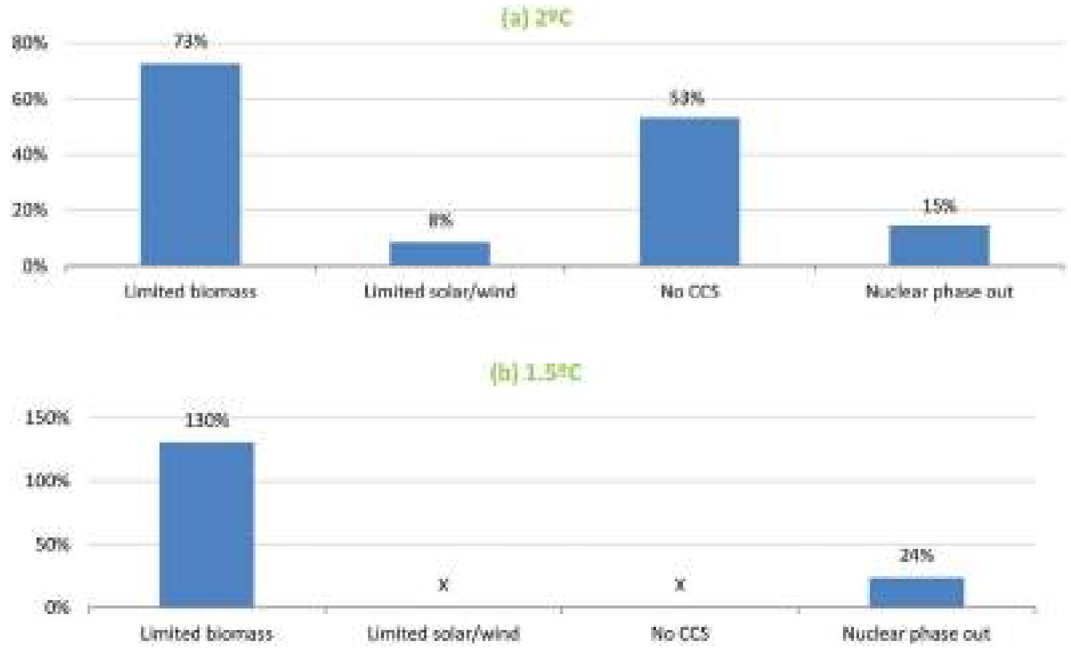

Figure B5. Mitigation costs for different global temperature targets.
Note: In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target. Mitigation costs for the period 2020–2100, discounted at 5% per year.

An indicator that reports the relative magnitude of mitigation costs in the economy are the global mitigation costs in 2100 expressed as percentage of GDP, presented in Table B1. If all the technologies are available, mitigation costs account for 3% of GDP when the temperature target is 2ºC and 6% for a 1.5ºC target. Under the assumptions of limited technology options, however, results tell a different story, especially for the 1.5ºC target. Limited solar/wind for the 2ºC target does not increase the ratio, a nuclear phase-out raises it up to4% and the limited biomass and the no CCS scenarios achieve 5%. The most expensive scenario is the one with restricted biomass under a 1.5ºC target: global mitigation costs can account for up to 14% of GDP.

Table B1. Share of global mitigation costs over GDP [%].

	GDP share	
Technology options	2ºC	1.5ºC
All technologies available	3%	6%
Limited biomass	5%	14%
Limited solar/wind	3%	-
No CCS	5%	-
Nuclear phase-out	4%	7%

Note: In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target. Mitigation costs for the period 2020–2100, discounted at 5% per year.

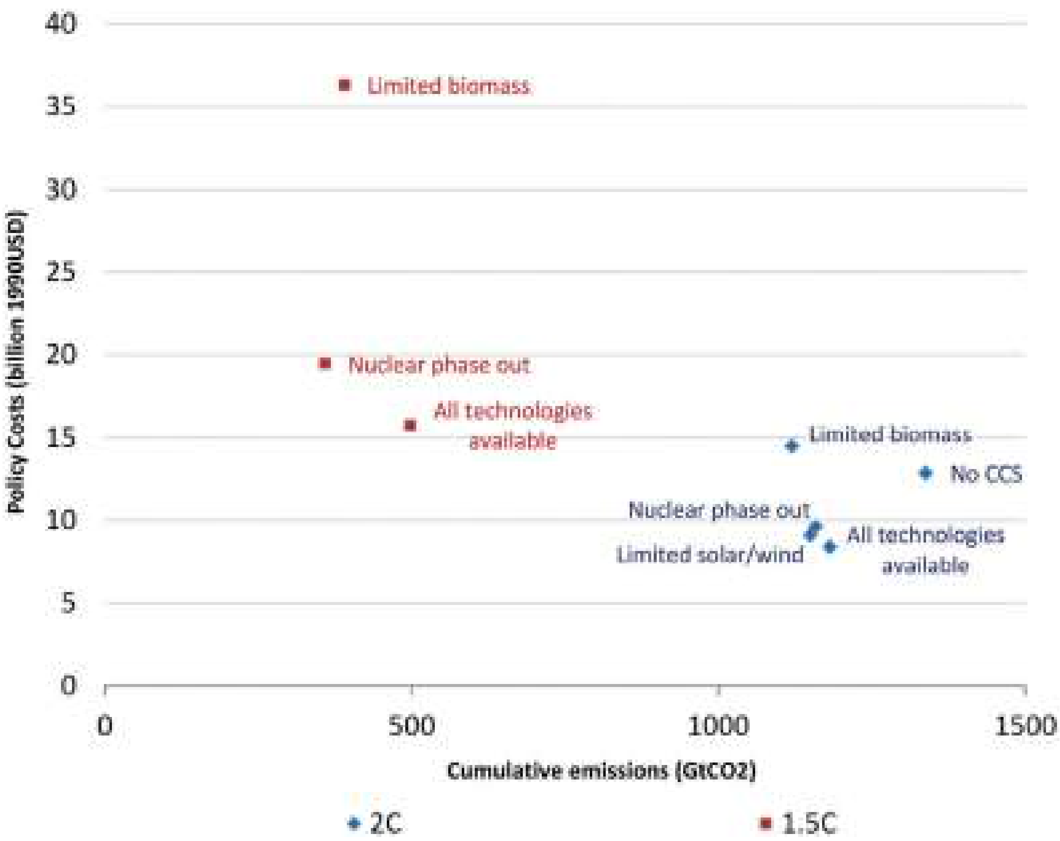

Figure B6. Mitigation costs [billion 1990USD] and cumulative CO2 emissions [GtCO2] for different global temperature targets. Note: In the Limited biomass scenario, biomass is constrained to a maximum of 100EJ/yr. In the Limited solar/wind scenario, solar and wind technologies are constrained to a maximum electricity share of 20% for any year. In the No CCS scenario, there is no CCS. In the Nuclear phase out scenario, existing plants operate until the end of their lifetime and no new nuclear plants are added. Limited solar/wind and No CCS are not feasible under a 1.5ºC global temperature increase target. Mitigation costs for the period 2020–2100, discounted at 5% per year. Cumulative emissions for the period 2020–2100.

The relationship between mitigation costs and cumulative emissions for the period 2020–2100 is presented in Figure B6. Red symbols represent feasible scenarios for a 1.5ºC temperature target, whereas blue marks stand for the 2ºC temperature target. The main conclusion of this figure is that it is possible to achieve the climate targets even if some technologies are absent or limited, but this increases the mitigation costs considerably. However, the highest costs do not necessarily lead to the lowest emissions.

According to Figure B6, compared to a 2ºC target, mitigation costs are always higher for the 1.5ºC climate policy, given that the entailed emissions reduction is also much higher. In particular, the highest cost corresponds to the limited biomass scenario toward a 1.5ºC limit. This almost double the cost of the second highest cost layout – the nuclear phase out scenario for 1.5ºC. This can be explained by the steeper emission reductions needed to compensate for the reduction of negative emissions, since in this scenario the potential for carbon capture is reduced. It is also remarkable that despite the costs, the limited biomass scenario is not the lowest emission scenario, which once again highlights the relevance of biomass in mitigation, particularly biomass with CCS. In fact, the lowest emissions are achieved in the nuclear phase out scenario toward 1.5ºC, but mitigation costs increase. Finally, the lowest mitigation costs in Figure B6 are associated to a situation with all technologies available and a 2ºC target.

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