D1.1
Summary report on policy evaluation and the role of social and economic heterogeneity for policy effectiveness and acceptability

June 2024

Programme Call:	Cross-sectoral solutions for the climate transition (HORIZON-CL5-2021-D1-01)
Grant agreement ID:	101056891
Project Title:	ClimAte Policy AcceptaBiLity Economic framework
Project Acronym	CAPABLE
Partners:	CMCC (Project Coordinator), EUI, IESEG, CNRS, PIK, MCC, UAB, CUNI, RUG, E6, ETH Zurich.
Work-Package:	WP1
Deliverable #:	D1.1

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Deliverable Type:	R — Document, report/DEC —Websites, patent filings, videos, etc
Contractual Date of Delivery:	30 June 2024
Actual Date of Delivery:	28 June 2024
Title of Document:	Summary report on policy evaluation and the role of social and economic heterogeneity for policy effectiveness and acceptability
Responsible partner:	UAB
Author(s):	Jeroen van den Bergh, Johannes Emmerling and Kai Lessman
Content of this report:	Three sub-contributions
Dissemination Level:	PU – Public

Document revisions		
Author	*Revision content*	*Date*
Jeroen, Johannes & Kai	Initial draft	14/6/2024
Johannes Emmerling	First revision and review	26/06/2024
Jeroen van den Bergh	Final Document	28/06/2024

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Table of Contents

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Executive summary

This report presents the results of three related investigations of how to improve approaches and frameworks to evaluate climate policy.

The first examination, in Section 1, offers a discussion of two features of studies on climate policy that have not yet received much attention even though they potentially have considerable impact on insights obtained. These features are ex-ante versus ex-post approaches, and heterogeneity of socio-economic characteristics of individuals. A conceptual discussion of these issues, proposing a more detailed classification and initial conjectures, is followed by a systematic literature review and some initial mapping. We identify 85 studies addressing the role of heterogeneity of socio-economic characteristics of individuals on the assessment of climate policy. We examine if and how this role differs between ex-ante and ex-post studies, giving attention to policy support, emissions reduction, and perception and behaviour.

The second examination, in Section 2, develops a policy evaluation of the key IPCC scenario categorised, based on multidimensional welfare indices that also allow to capture heterogeneity. Here, we apply recent advances in the theoretical multidimensional measurement of welfare, like the Human Development Index, to the AR6 database. The welfare metric is based on a welfare function approach, simple to apply, and intuitive. We apply a range of specifications of the welfare metric, aiming to derive robust rankings of climate policy targets that perform best in terms of the multidimensional welfare index. Across a large range of weights on welfare-relevant variables, we find that lower temperature is associated with higher welfare in 2100 unless there is a high weight on food supply.

The final examination, in Section 3, develops an analytical framework for evaluating climate policies to inform policy-makers. Our approach allows considering (i) various policy instruments like carbon pricing, taxes, subsidies, standards or bans, (ii) multiple market failures and externalities, related to market as well as non-market good consumption and (iii) the social cost of distributional effects of policies. Our approach is a generalisation of cost-benefit analysis to facilitate the comparability of climate policy measures within a consistent welfare-economic perspective. It can be substantiated by synthesising ex-post and ex-ante works on policy instruments. We outline the information needed to apply the framework. We illustrate the approach by evaluating a tax reform on meat products and a price on greenhouse gas emissions on food products.

These are initial results, and they will be further developed and refined in the course of the CAPABLE project.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

1. Ex-ante vs ex-post assessment and attention for socio-economic diversity in climate-policy studies

Introduction

With so many studies on climate policy appearing, an important task of science is to clarify what overall lessons can be derived from these. For this purpose, one needs to compare and aggregate policy findings, which is not always easy because of multiple and sometimes fundamental differences in study approaches. Here we zoom in on two features of studies that have received scattered attention, despite potentially having considerable impact on policy insights. The first is what we call socio-economic diversity, covering the heterogeneity of social, economic and attitudinal characteristics of individuals or households. The second is the distinction between ex-ante and ex-post approaches to analyse impacts of, and support for, climate policy. This can be seen as modelling versus empirical studies – but a more precise description will follow in the next section. Addressing the combination of both study features, as we do here, is motivated by the fact that socio-economic characteristics and heterogeneities in these tend seem to differ systematically between ex-ante and ex-post studies. This might translate in systematic differences between the two types of studies.

A better understanding of this can help to inform policy makers about relevant insights and their aggregation. For instance, according to Tol (2022), in reviewing the literature on climate policy assessment, the IPCC so far did not address in a balanced way the ex-ante and ex-post approaches. Others suggest that systematic and living reviews may help out here (Elliot et al., 2021; Callaghan et al., 2024). Since that itself does not solve the issue of fundamental differences between the approaches, the current paper is a modest effort to add more clarity about this.

Given the lack of attention for these issues, we first offer a conceptual discussion of definitions, classifications, basic considerations and conjectures. This is followed by a literature review to provide some illustration and initial testing of these. To this end we undertook a systematic literature review and applied topic modelling, a special technique of computational linguistics. Our discussion and review cover both studies of the effectiveness of emissions reduction and the socio-political support of policies.

As indicated, this topic has not received much and certainly not systematic attention. Next to the study of Tol mentioned, we found two other studies discussing the relationship explicitly. One is Qiu et al. (2020) who compare the two approaches to find that ex-ante studies overestimate the effectiveness of China's energy intensity and SO_2 policies due to baseline assumptions and ignoring firm-level heterogeneity. In addition, Wang et al. (2022) conclude that an ex-ante study underestimates emission reduction in urban rail compared to an ex-post study.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Since these studies arrive at distinct conclusions, it is worthwhile to examine the difference between ex-ante and ex-post studies for a larger sample of studies, as we do here.

The organisation of the remainder of this paper is as follows. Since we did not come across any study that offers a basic discussion of the connection between ex-ante/post and socio-economic heterogeneities, Section 2 provides such a conceptual discussion. Section 3 describes the search and selection of studies in the systematic review, while Section 4 discussed the results of this. Section 5 concludes.

Key concepts

As a start, it is relevant to clarify the distinction between ex-ante and ex-post studies of climate policy. Generally, an ex-ante or prospective approach develops or uses a model of the economy and emissions to simulate one or more hypothetical futures (scenarios) where the policy is implemented and then assesses its impact, notably on carbon emissions or public support. Alternatively, ex-ante study uses a survey suggesting participants to evaluate a hypothetical policy scenario. An ex-post or retrospective approach evaluates the measured impacts of, or support for, implemented policies using observed empirical data. Now while this seems a clear-cut division, there are some complications in classifying studies as one or the other type. One reason is that there is considerable diversity within each category. For example, ex-ante studies cover approaches that border on pure theory whereas others have a strong basis in empirical data, in terms of setting, calibrating or statistical estimation of parameter values, through scenario formulation, or as regards validation of results. Among ex-post studies there are approaches that use only objective data while others use some subjective data, such as opinions of citizens in the context of evaluation of implemented policy.

Now given such differences, one may wonder if there is a possibility of bias – i.e. over- or underestimation of effects – in the results of ex-ante versus ex-post studies. One could test this by comparing averages of the two types (or possibly even for sub-types as mentioned). This resembles past exercises undertaken for a similar distinction, between stated and revealed preference methods, in monetary valuation of environmental change and policy (Carson et al., 1992; Alberini, 2019). If the comparison suggests that insights are similar, then this could be seen as a kind of robustness check. Such an approach considers the different types of studies as substitutes. Of course, one can also consider them as complements, given that the ex-ante can in principle test a wider range of policies, beyond those already implemented, which restrict the scope of ex-post studies (again, one can compare with lessons drawn comparing stated and revealed preferences in valuation studies).

This raises the question whether policy instruments used in ex-ante studies tend to be different from those in ex-post studies. One would expect relatively ambitious instruments (in terms of emissions coverage and stringency) to be more common in ex-ante than in ex-post studies, simply because there is little experience with these in reality and hence limited empirical data to

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

work with. Moreover, while ex-ante studies can typically focus on one policy instrument of interest, ex-post research faces the complication that in reality climate policies tend to be implemented in a form of a policy mix (van den Bergh et al., 2021). This creates the problem that it is not easy to attribute policy impacts to an instrument of interest. Finally, for completeness it is good to note there is a third category next to substitute and complement relation, namely when results of ex-post studies serve as inputs (e.g., to set parameter values) in ex-ante studies. In that case one must be careful to compare for robustness purposes, as the studies will not be independent.

Regarding the second aspect of socio-economic heterogeneities, this is relevant as one can imagine that the amount of attention given to these – notably explicitly describing certain heterogeneities – will affect the results of associated policy analysis. This holds true for various socio-economic and attitudinal dimensions: age, education, gender, health, household size, income, political views, religion and settlement (e.g., urban vs countryside). This is illustrated for the context of integrated assessment modelling of climate change by Emmerling and Tavoni (2021). Some of these heterogeneities have received more attention than others, notably income.

We contend that the ex-ante and ex-post approaches tend to differ in their treatment of socio-economic heterogeneities. One reason is that ex-ante approaches may use modelling types – such as traditional equilibrium analysis – that tend to focus on aggregates or averages through assuming representative agents, in turn assumes away many socio-economic diversities. There is a huge literature in behavioural economics criticising this (Kirman, 1992; Farmer et al., 2015), arguing that associated ex-ante models often offer a highly aggregate and oversimplified representation of a complex socio-economic reality. More recent modelling approaches, notably agent-based modelling, facilitate addressing heterogeneities and associated distributional (equity) performance of policies (Safarzynska and van den Bergh, 2022). One might then conclude that ex-ante will generally be poorer in accounting for socio-economic heterogeneities. However, it is also true that the ex-post approach is often limited by data availability, meaning that certain features of individuals, households, firms or other stakeholders are not elicited and hence not part of the empirical data.

Search and selection process

Search and selection of studies

To illustrate and where possible test some of the statements in the previous section, we undertake a systematic literature review. On 1 March 2024, we retrieved relevant studies on socio-economic heterogeneity and climate policy from the publication database Scopus.[1] To this end, we applied the following search query on titles, abstracts, and keywords of publications:

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

(income OR wealth OR education OR gender OR age OR health OR race OR "family size" OR "household size" OR "political view" OR religion OR profession OR urban OR rural OR "town size" OR "city size") AND (inequality OR heterogeneity OR diversity OR disparity OR distribution) AND ("climate policy" OR "carbon pric" OR "carbon tax*" OR "cap and trade" OR "cap-and-trade" OR "carbon market*" OR "emissions trading system" OR ets OR quota* OR subsid* OR nudge*) AND (climate OR carbon).*

The query consists of four parts: (1) socio-economic characteristics; (2) inequality synonyms; (3) instruments of climate policy; and (4) other terms relating to climate. The search yielded a total number of 1098 documents published in the period from 2008 to 2024. We carried out the systematic review in accordance with the established PRISMA protocols. It excluded non-English studies (n=52). Since our interest is in peer-reviewed journal articles, we omitted all books, book chapters, reviews, editorials, conference papers, short surveys, letters, notes and errata (n=206). In addition, one duplicate article was removed. This reduced the sample to 839 articles.

Next, we reviewed these articles to identify the relevant ones given our study's objective as described in Section 2. The process of screening involved checking paper titles and abstracts. If abstracts were insufficiently informative, the full text of the paper was consulted. We removed papers that did not include an abstract (n=2) or whose full text was inaccessible (n= 7). Additional exclusion criteria used were the following:

1. Studies lacking a quantitative analysis of some type (n= 63). This includes opinions, literature reviews and qualitative studies.
2. Studies exploring the impact of climate policy instruments on socio-economic heterogeneities rather than the reverse (n= 250). The dominant category here is formed by studies assessing the influence of climate policy on income inequality.
3. Studies that do not focus on climate policy but instead address climate change impacts or damages (n=244). An example is Harkness et al. (2023) studying the impact of climate change on agricultural productivity.
4. Studies that investigate environmental issues distinct from climate change (n=188).

Applying these exclusion criteria, we end up with 85 papers that align with our research objectives.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Selective results

To reveal hidden structure in our textual data, we use topic modelling, a technique of computation linguistics. It clusters words into topics based on how often any pair of words appears in the same texts (Blei, 2012; Savin, 2023). For example, if we see the words "policy", "support" and "opinion" in one of the topics presented in the next section, it means that these words appear relatively often in combination. Compared to simple count of keywords, topic modelling considers words not as isolated, but based on other words they appear with, which can influence the meaning of the text. An advantage of structural topic modelling over classical is that it can include additional information about the publications (Savin and van den Bergh, 2021), such as year of publication, number of citations per year, and whether we classified the study as an ex-ante or an ex-post policy evaluation. We apply the method using the associated R package by Roberts et al. (2019). This results in the identification of nine topics.

We tested if certain topics are systematically more or less related to ex-ante vs ex-post studies. To this end, we statistically regress prevalence of each topic (bounded between 0 and 1) in the sample of our studies on the type of study (1 if it is ex-post and 0 if it is ex-ante). Results of the regression are presented in Figure 1. Studies addressing T1 on carbon emissions and T9 on gender (in)equality tend to be predominantly ex-post in nature, while studies focusing on T8 about consumer preferences are using more ex-ante approaches. This finding makes sense since evaluating emissions requires factual data, while assessing consumer preferences of (hypothetical) policies is commonly done using surveys or experiments.

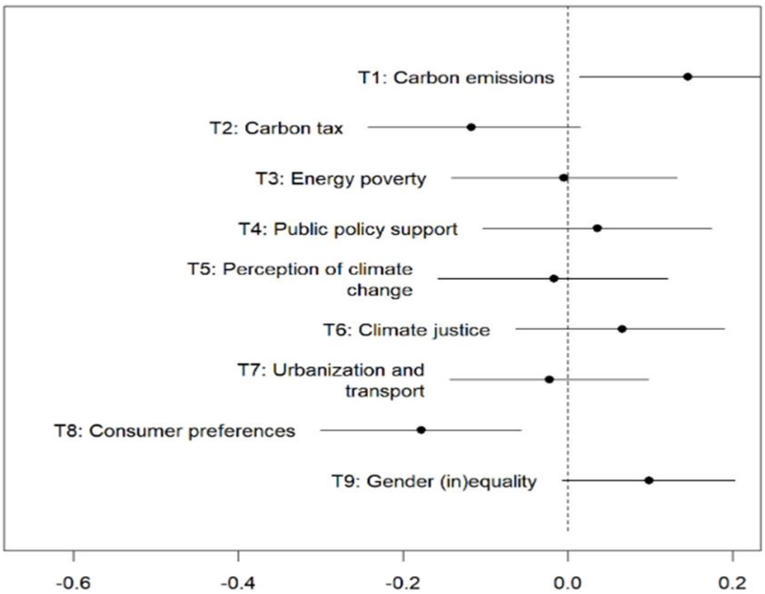

Figure 1. Statistical association between ex-ante vs. ex-post type of study and topic prevalence

Note: a positive value on the X-axis indicates a larger prevalence of that topic among ex-post studies, while a negative value – among ex-ante studies. The error bars represent mean +/- 2 standard errors.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Figure 2 displays the heterogeneities addressed in the studies in the sample along with their respective frequencies. The larger number of heterogeneities than studies is because several studies address more than one type of heterogeneity. The most frequent category is income, followed by education, region and age.

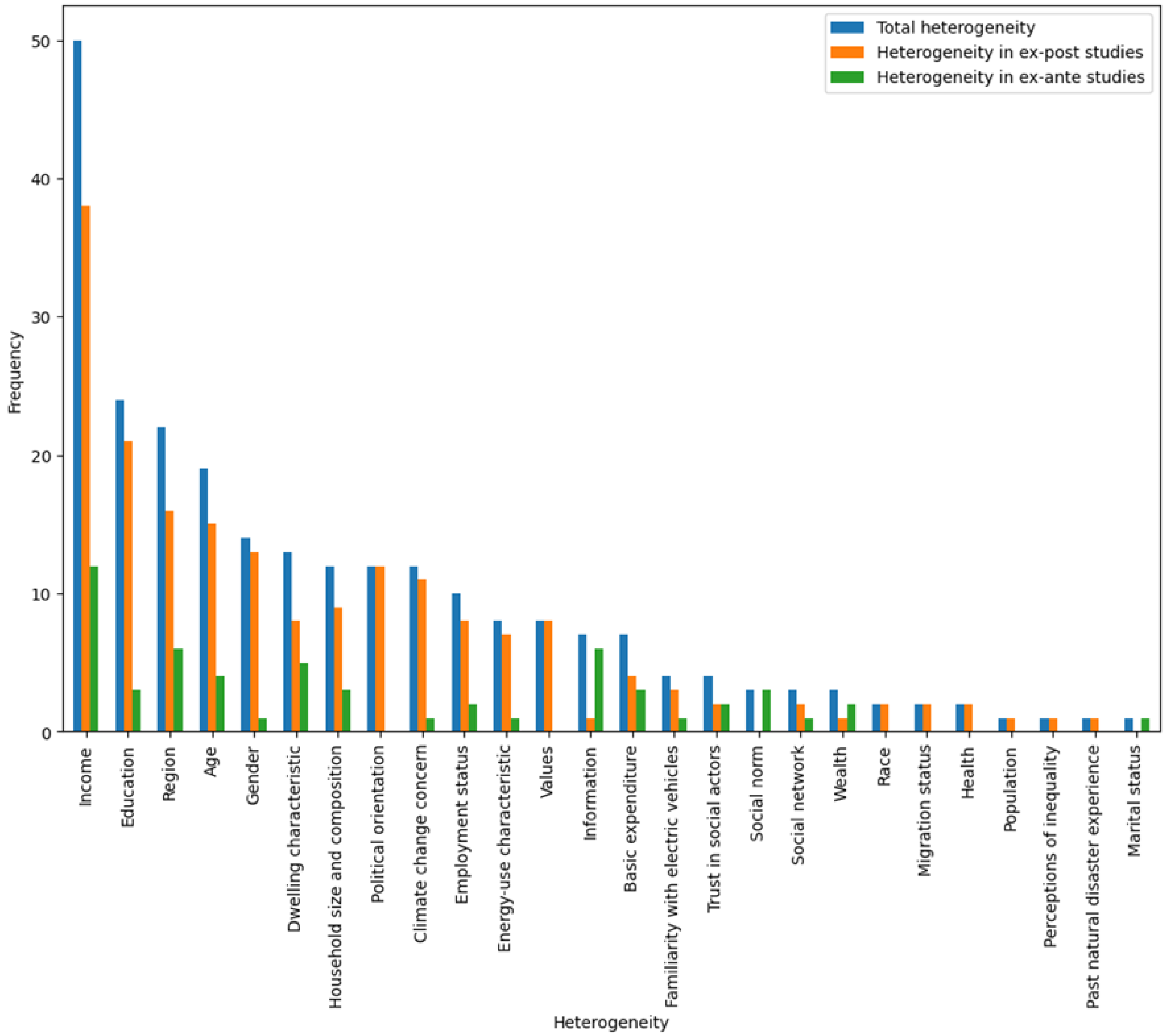

Figure 2. Frequency of socio-economic and attitudinal heterogeneities in all, ex-post, and ex-ante studies

Initial insights

Heterogeneity in socio-economic and attitudinal characteristics plays a crucial role in how individuals perceive climate risks, judge strategies, and respond to policies in terms of political support and behavioural change. We have focused on how this plays out in the context of the distinction between ex-ante and ex-post approaches to assessing climate policy.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Through a systematic literature review, we collected 85 studies giving explicit attention to the socioeconomic heterogeneities in the setting of climate policy analysis. Using computational linguistic methods, we classified them into 9 main topics ranging from energy poverty and policy support to consumer preferences and gender (in)equality. Topics on carbon emissions and on gender (in)equality tend to be accentuated by ex-post studies. On the other hand, ex-ante studies focus on consumer preferences. Overall, 23 distinct types of socio-economic heterogeneity were identified: dominant is income (n=37), followed by education (n=19), region (n=18), and age (n=18). Several studies address more than one heterogeneity.

We next investigated the extent to which heterogeneity in socio-economic characteristics influences climate policy by directly impacting policy support, affecting the carbon emissions of individuals and households, and modifying climate-relevant perceptions and behaviours. The results indicate that in some instances, both approaches yield similar outcomes. For example, both ex-post and ex-ante studies highlight the contrasting effect of income. However, in most cases, the overall evaluation from ex-post studies diverges from ex-ante estimations. An example of this divergence is the impact of age on policy support, which is assessed negatively by ex-post studies but estimated positively by ex-ante studies. Additionally, we observe that certain dimensions of heterogeneity have been neglected in ex-ante studies. For instance, gender, which plays a significantly positive role in the evaluation of policy support and effectiveness in ex-post studies, has not been examined in ex-ante analyses. That ex-ante studies pay less attention to heterogeneities than ex-post studies may be related to equilibrium models receiving more attention in the sampled studies than agent-based models.

Overall, our study highlights the complexity of how socio-economic and attitudinal characteristics such as income, region, education, gender, and personal values are associated with climate policy support and behaviour. While ex-post studies provide valuable insights into real-world behaviours and outcomes, they often reveal the dual nature of these heterogeneities, showing both positive and negative association. Conversely, ex-ante studies, which aim to predict future scenarios, frequently yield less definitive conclusions and sometimes even contradict real-world findings. This discrepancy underscores the need for more comprehensive and integrative approaches in climate policy research, achieving more coherence between prospective and retrospective studies. Future research could expand the scope of ex-ante studies to include a wider range of factors and refine their predictive capabilities, possibly making more use of agent-based modelling.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

2. Climate policy evaluation under multidimensional welfare evaluation

Human development in the 21st century faces significant challenges. The Sustainable Development Goals call for human progress in a wide range of economic, social and ecological dimensions, where there may be synergies in achieving some goals but where progress in other dimensions may compete for limited resources. The Sustainable Development Goals are thus broadening our understanding of what is important for human development for the next decades. While economic growth has been an engine of development in the 20th century, though not universally the Human Development Index (HDI) introduced in 1990 adds education and health to economic development as important determinants of human wellbeing (UNDP 2010). The HDI allows ranking different development pathways across space and time to identify strategies that further human wellbeing. Considering the Sustainable Development Goals, multidimensional welfare metrics such as the HDI need to be amended to include more dimensions, most importantly those pertaining to environmental issues such as climate change and biodiversity.

We apply a class of multidimensional welfare metrics based on the HDI to rank alternative scenarios of climate change mitigation. The welfare metric aggregates indicators for economic development, education, health, climate change and biodiversity. By ranking alternative scenarios of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), we test in which cases meeting more stringent climate targets improves welfare. We find that in many scenarios, welfare improves with lower global temperature. There are, however, important exceptions. First, strong climate policy is associated with lower welfare in the short-term especially if there is low substitutability between different dimensions. In the short term, costly climate action hinders economic development and adversely affects food supply that cannot be offset by progress in other indicators if substitutability is low. Second, welfare improves if less stringent climate targets are met when there is a relatively high weight on food supply, because stringent climate change mitigation competes with higher global food supply.

Our welfare metrics extend concepts such as the Planetary pressures adjusted HDI (PHDI) by incorporating environmental indicators for human wellbeing but allowing for flexible assumptions about normative parameters, such as the OECD's Better Life Index. The normative parameters allow varying the importance that certain dimensions play in aggregate welfare and allow varying in how far a low score in one dimension may be offset by a high score in another dimension. The welfare metric thus quantifies trade-offs between reaching multiple dimensions of human development. Indeed, assessing environmental dimensions or sustainability in a broad

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

sense using a unique index has many conceptual and practical issues. While our approach is based on a conceptually founded welfare function approach, notably weighting exhibits still a great degree of arbitrariness, which we address by performing a large sensitivity analysis on the vector of weights applied. Our indices also satisfies the conditions of being "meaningful" environmental indices. Our welfare metrics allow ranking alternative strategies and explicitly stating normative preferences about the importance of different dimensions, and their trade-offs, for human wellbeing.

We apply our welfare framework to the question of climate change mitigation. Limiting climate change is one of the key societal goals over the next decades as unmitigated climate change leads to significant impacts on human wellbeing.

Taken together, for our central specification, Figure 3 shows the multivariate welfare index across the seven scenario categories of the IPCC in 2100. It shows the secular decline in average welfare as the temperature target becomes less stringent, while also for low temperature targets, the model uncertainty is larger indicating that the Paris Agreement compatible scenarios exhibit significant model differences and uncertainty. Only for the most stringent 1.5-degree target without or with overshoot (C1 and C2) the ranking is reversed, in that the scenarios without overshoot show a slightly lower level of welfare on average, albeit also a higher degree of uncertainty.

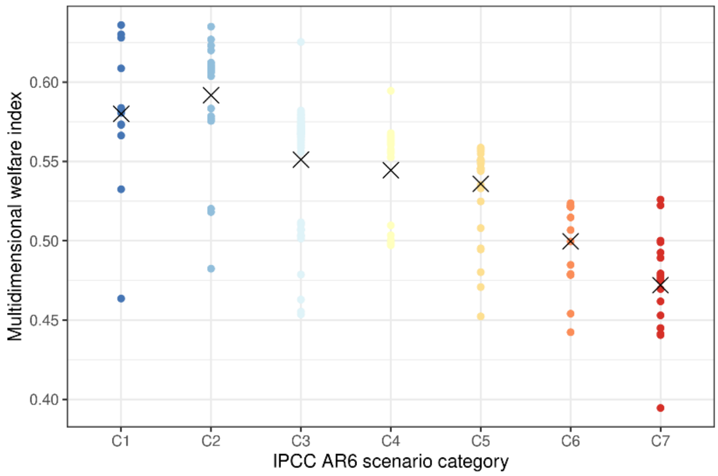

*Figure 3. SEQ Figure * ARABIC 1: Central case, welfare across climate categories (equal weights, ϱ=1) in 2100; black crosses indicate mean across models.*

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

3. A welfare analytic approach to climate policy

With the Green Deal, the EU has set broad and ambitious goals for its environmental policies. The Green Deal covers a broad range of areas, including resource use, pollution, biodiversity and climate neutrality, to name but a few. To implement this agenda, the EU needs to define specific policies. However, agreeing on policies is challenging because different policies differ not only in their intended direct effects, such as reducing emissions, but also in the costs they impose on consumers and industries, in their distributional effects on consumer income and wealth, or in their effects on other policy areas (so-called co-benefits).

We propose a conceptual framework for assessing and comparing the welfare costs of different policies, normalised to an outcome variable (such as emission reductions), that is, for a specific policy we consider implication for social welfare per ton of emissions reduced. Our framework is flexible enough to consider both consumption and non-market effects; it can include co-benefits of policies and the effects of tax and transfer rules as part of a policy package. In particular, welfare effects are approximated by consumption-equivalent variations, which allow the effects of a policy on consumption, income and other externalities to be converted into a common metric. Furthermore, the distributional effects of policies can be considered within the framework. To achieve this, the effects of a policy are differentiated along income groups and aggregated using "welfare weights" that reflect the greater sensitivity of low-income consumers to changes in consumption and income.

Its key strength is to aggregate various information and evidence on multi-dimensional outcomes of policies into a one-dimensional metric. This constitutes a great step in reducing complexity in evaluating trade-offs of policies to a simple ranking. However, the framework also allows to decompose aggregate effects into its components to shed light on the relevance of specific welfare dimensions for the overall assessment. This latter property makes it valuable for researchers and analysts with an interest in a consistent overall welfare assessment or policy makers that with a specific interest in a particular welfare-related aspects.

With increasing evidence on the impacts of policies on environmental outcomes but also on relevant welfare dimensions, this approach can be put into practice. We illustrate this for the case of policies in the food sector to reduce greenhouse gas emissions but also other environmental footprints. Our framework stresses that, for a comprehensive welfare evaluation, the distributional effects with respect to costs but also benefits of a policy should be considered. While a growing literature focuses on the distribution of the costs of climate policy, more evidence is needed regarding the distribution of the benefits.

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Application: Tax policies in the food sector to reduce GHG emissions

We demonstrate the usefulness of our methodological approach by comparing two distinct policy instruments and their respective welfare costs and benefits analysed by Plinke, Sureth, and Kalkuhl (2024).[1] The main objective of the policies under investigation is the reduction of greenhouse gas emissions induced by food consumption in the European Union (EU27). We compare the removal of existing value-added tax (VAT) reductions on meat products to a greenhouse gas (GHG) emission price on all food products, which is endogenously determined to achieve the same GHG emission reductions as the former policy.

Figure 4 compares the two policy instruments in a decomposition of the effects. As benefits of the policy, reductions of pollutants (GHG and others) and recycling of tax revenues are stacked up, and (partially offset) by the reduction of consumer surplus. The remained ("net change") indicates the welfare improvement. In comparison with the VAT reform, the GHG emission price policy yields additional global co-benefits of 16,818 t nitrogen, 894 t phosphorus, 486 Mm^3 water consumption, 0.688 Mha land use reductions. Only for biodiversity loss, the associated co-benefits of the VAT reform are marginally higher (0.0001 global potentially disappeared fraction of species, i.e. the committed share of global loss of species richness as a direct consequence of anthropogenic impacts on ecosystem quality) than those achieved under the GHG emission price policy. To allow for an overall evaluation to what extent the policies increase global aggregate well-being, we monetize the changes in environmental footprints using the global social cost of greenhouse gases (CO_2, CH_4, N_2O), the domestic social cost of nitrogen and the domestic social cost of phosphorus. Changes in biodiversity loss, land occupation and water consumption are not monetized due to a lack of social cost estimates.

[1] Plinke, Charlotte, Michael Sureth, and Matthias Kalkuhl. 2024. "Assessing the Potential of Tax Policies in Reducing Environmental Impacts from European Food Consumption."

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

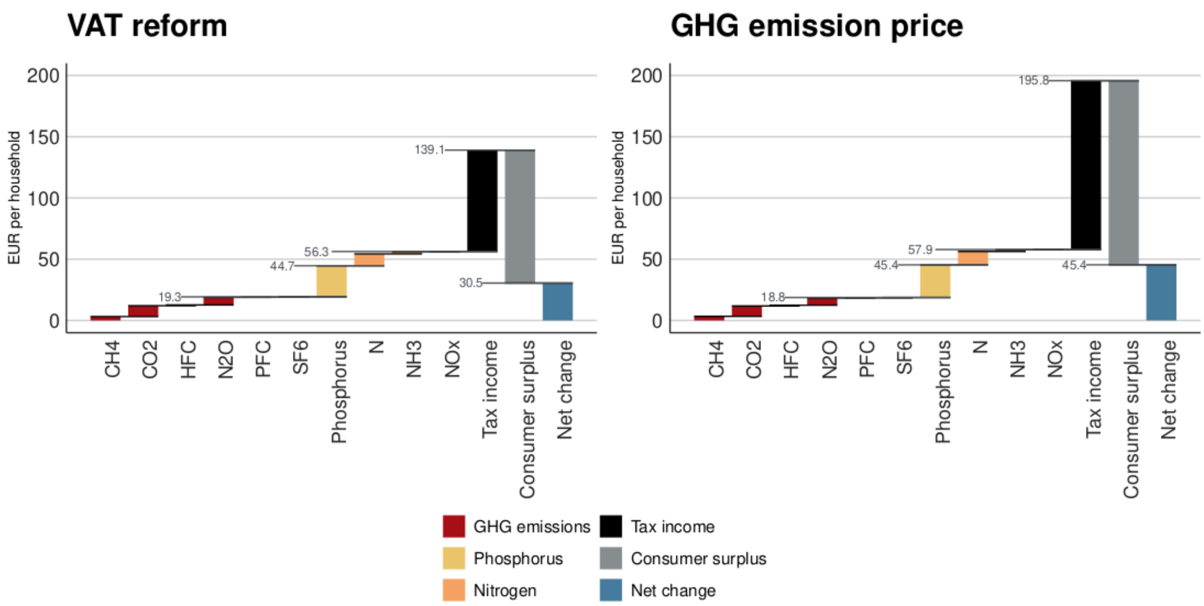

Figure 4. Changes in welfare resulting from removing value-added tax reductions for meat products (VAT reform) and implementing a GHG emission emission price of 51.62 EUR/tCO2eq on all food products (GHG emission price), measured in EUR per household. GHG emissi

In addition to the environmental co-benefits, the two policy options generate tax revenue. We thus contrast the monetarized environmental co-benefits and the increase in tax revenue with the reduction in consumer surplus for the two policies. While both policies improve overall welfare, the GHG emission price policy results in a higher overall net welfare increase driven by slightly higher environmental co-benefits in nitrogen and phosphorus reductions and a smaller difference in welfare losses to increased tax revenue. The net aggregate welfare benefit of the two policies amounts to 45.4 EUR per household for the removal of VAT reductions for meat products, and 30.5 EUR per household for the introduction of a GHG emission price of approximately 52 EUR/tCO_2eq on all food products. Noteworthy, both policies result in positive aggregate welfare changes as the environmental benefits exceed the costs for consumers. This is even true when 'global' benefits from reduced climate change are disregarded and only 'local' benefits from reducing nitrogen and phosphorus emissions are considered.

APPENDIX

Detailed information about each section is available in the following papers:

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

1. Salekpay, Savin and van den Bergh (2024)

Working paper: Foroogh Salekpay, Ivan Savin and Jeroen van den Bergh (2024). Ex-ante vs ex-post assessment and attention for socio-economic diversity in climate-policy studies

2. Emmerling, Kornek, and Zuber (2024)

Published paper: Emmerling, Johannes, Ulrike Kornek, and Stéphane Zuber. "Multidimensional Welfare Indices and the IPCC 6th Assessment Report Scenarios." *Ecological Economics* 220 (June 1, 2024): 108182. https://doi.org/10.1016/j.ecolecon.2024.108182.

3. Kalkuhl, Lessmann, Plinke, Stern and Sureth (2024)

Working paper: Kalkuhl, Lessmann, Plinke, Stern and Sureth: "A Welfare Analytic Approach to Climate Policy".

This publication was funded by the European Union. Its contents are the sole responsibility of the author(s) and do not necessarily reflect the views of the European Union.

Ex-ante vs ex-post assessment and attention for socio-economic diversity in climate-policy studies

Foroogh Salekpay[a,*] and Ivan Savin[b,a,c] and Jeroen van den Bergh[a,d,e]

[a] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Spain; & ICREA, Barcelona, Spain

[b] ESCP Business School, Madrid Campus. C. de Arroyofresno, 1, Madrid 28035, Spain

[c] Graduate School of Economics and Management, Ural Federal University, Yekaterinburg, Russian Federation

[d] ICREA, Barcelona, Spain

[e] School of Business and Economics & Institute for Environmental Studies, VU University Amsterdam, The Netherlands

[*] Corresponding author; contact: ICTA, Edifici Z, UAB Campus, 08192 Bellaterra, Spain, +34 93 586 8773, Foroogh.Salekpay@uab.cat

June 2024, draft working paper, please do not cite or diffuse

Acknowledgements: We are grateful to Jan Minx and Max Callaghan for extracting study characteristics for the studies we sampled using their machine learning algorithm, which helped us to check our data. This work was funded by the European Union's Horizon Europe research and innovation program under project CAPABLE (grant agreement 101056891).

Abstract

We offer a discussion of two features of studies on climate policy that have not yet received much attention even though they potentially have considerable impact on insights obtained. These features are ex-ante versus ex-post approaches, and heterogeneity of socio-economic and attitudinal characteristics of individuals. A conceptual discussion of these issues, proposing a more detailed classification and initial conjectures, is followed by a systematic literature review and some initial mapping. We identify 85 studies addressing the role of heterogeneity of socio-economic characteristics of individuals on the assessment of climate policy. We examine if and how this role differs between ex-ante and ex-post studies, distinguishing between assessments of policy support and emissions reduction.

Keywords: heterogeneity, effectiveness, feasibility, policy support, topic modelling.

1. Introduction

With so many studies on climate policy appearing, an important task of science is to clarify what overall lessons can be derived from these. For this purpose, one needs to compare and aggregate policy findings, which is not always easy because of multiple and sometimes fundamental differences in study approaches. Here we zoom in on two features of studies that have received scattered attention, despite potentially having considerable impact on policy insights. The first is what we call socio-economic diversity, covering the heterogeneity of social, economic and attitudinal characteristics of individuals or households. The second is the distinction between ex-ante and ex-post approaches to analyse impacts of, and support for, climate policy. This can be seen as modelling versus empirical studies – but a more precise description will follow in the next section. Addressing the combination of both study features, as we do here, is motivated by the fact that socio-economic characteristics and heterogeneities in these tend to differ systematically between ex-ante and ex-post studies. This might translate in systematic differences between the two types of studies.

A better understanding of this can help to inform policy makers about relevant insights and their aggregation. For instance, according to Tol (2022), in reviewing the literature on climate policy assessment, the IPCC so far did not address in a balanced way the ex-ante and ex-post approaches. Others suggest that systematic and living reviews may help out here (Elliot et al., 2021; Callaghan et al., 2024). Since that itself does not solve the issue of fundamental differences between the approaches, the current paper is a modest effort to add more clarity about this.

Given the lack of attention for these issues, we first offer a conceptual discussion of definitions, classifications, basic considerations and conjectures. This is followed by a literature review to provide some illustration and initial testing of these. To this end we undertook a systematic literature review and applied topic modelling, a special technique of computational linguistics. Our discussion and review cover both studies of the effectiveness of emissions reduction and the socio-political support of policies.

As indicated, this topic has not received much and certainly not systematic attention. Next to the study of Tol mentioned, we found two other studies discussing the relationship explicitly. One is Qiu et al. (2020) who compare the two approaches to find that ex-ante studies overestimate the effectiveness of China's energy intensity and SO_2 policies due to baseline assumptions and ignoring firm-level heterogeneity. In addition, Wang et al. (2022) conclude that an ex-ante study underestimates emission reduction in urban rail compared to an ex-post study. Since these studies arrive at distinct conclusions, it is worthwhile to examine the difference between ex-ante and ex-post studies for a larger sample of studies, as we do here.

The organization of the remainder of this paper is as follows. Since we did not come across any study that offers a basic discussion of the connection between ex-ante/post and socio-economic heterogeneities, Section 2 provides such a conceptual discussion. Section 3 describes the search and selection of studies in the systematic review, while Section 4 discussed the results of this. Section 5 concludes.

2. Key concepts

As a start, it is relevant to clarify the distinction between ex-ante and ex-post studies of climate policy. Generally, an ex-ante or prospective approach develops or uses a model of the economy and emissions to simulate one or more hypothetical futures (scenarios) where the policy is implemented and then assesses its impact, notably on carbon emissions or public support. Alternatively, ex-ante study uses a survey suggesting participants to evaluate a hypothetical policy scenario. An ex-post or retrospective approach evaluates the measured impacts of, or support for, implemented policies using observed empirical data. Now while this seems a clear-cut division, there are some complications in classifying studies as one or the other type. One reason is that there is considerable diversity within each category. For example, ex-ante studies cover approaches that border on pure theory whereas others have a strong basis in empirical data, in terms of setting, calibrating or statistical estimation of parameter values, through scenario formulation, or as regards validation of results. Among ex-post studies there are approaches that use only objective data while others use some subjective data, such as opinions of citizens in the context of evaluation of implemented policy.

Now given such differences, one may wonder if there is a possibility of bias – i.e. over- or underestimation of effects – in the results of ex-ante versus ex-post studies. One could test this by comparing averages of the two types (or possibly even for sub-types as mentioned). This resembles past exercises undertaken for a similar distinction, between stated and revealed preference methods, in monetary valuation of environmental change and policy (Carson et al., 1992; Alberini, 2019). If the comparison suggests that insights are similar, then this could be seen as a kind of robustness check. Such an approach considers the different types of studies as substitutes. Of course, one can also consider them as complements, given that the ex-ante can in principle test a wider range of policies, beyond those already implemented, which restrict the scope of ex-post studies (again, one can compare with lessons drawn comparing stated and revealed preferences in valuation studies).

This raises the question whether policy instruments used in ex-ante studies tend to be different from those in ex-post studies. One would expect relatively ambitious instruments (in terms of emissions coverage and stringency) to be more common in ex-ante than in ex-post studies, simply because there is little experience with these in reality and hence limited empirical data to work with. Moreover, while ex-ante studies can typically focus on one policy instrument of interest, ex-post research faces the complication that in reality climate policies tend to be implemented in a form of a policy mix (van den Bergh et al., 2021). This creates the problem that it is not easy to attribute policy impacts to an instrument of interest. Finally, for completeness it is good to note there is a third category next to substitute and complement relation, namely when results of ex-post studies serve as inputs (e.g., to set parameter values) in ex-ante studies. In that case one must be careful to compare for robustness purposes, as the studies will not be independent.

Regarding the second aspect of socio-economic heterogeneities, this is relevant as one can imagine that the amount of attention given to these – notably explicitly describing certain heterogeneities – will affect the results of associated policy analysis. This holds true for various socio-economic and attitudinal dimensions: age, education, gender, health, household size, income, political views, religion and settlement (e.g., urban vs countryside). This is illustrated for the context of integrated assessment modelling of climate change by Emmerling and Tavoni (2021).

We contend that the ex-ante and ex-post approaches tend to differ in their treatment of socio-economic heterogeneities. One reason is that ex-ante approaches may use modelling types – such as traditional equilibrium analysis – that tend to focus on aggregates or averages through assuming representative agents, in turn assumes away many socio-economic diversities. There is a huge literature in behavioural economics criticizing this (Kirman, 1992; Farmer et al., 2015), arguing that associated ex-ante models often offer a highly aggregate and oversimplified representation of a complex socio-economic reality. More recent modelling approaches, notably agent-based modelling, facilitate addressing heterogeneities and associated distributional (equity) performance of policies (Safarzynska and van den Bergh, 2022). One might then conclude that ex-ante will generally be poorer in accounting for socio-economic heterogeneities. However, it is also true that the ex-post approach is often limited by data availability, meaning that certain features of individuals, households, firms or other stakeholders are not elicited and hence not part of the empirical data.

3. Search and selection of studies

To illustrate and where possible test some of the statements in the previous section, we undertake a systematic literature review. On 1st of March 2024, we retrieved relevant studies on socio-economic heterogeneity and climate policy from the publication database Scopus.[1] To this end, we applied the following search query on titles, abstracts, and keywords of publications:

(income OR wealth OR education OR gender OR age OR health OR race OR "family size" OR "household size" OR "political view" OR religion OR profession OR urban OR rural OR "town size" OR "city size") AND (inequality OR heterogeneity OR diversity OR disparity OR distribution) AND ("climate policy" OR "carbon pric" OR "carbon tax*" OR "cap and trade" OR "cap-and-trade" OR "carbon market*" OR "emissions trading system" OR ets OR quota* OR subsid* OR nudge*) AND (climate OR carbon).*

The query consists of keywords capturing four relevant aspects: (1) socio-economic characteristics; (2) inequality synonyms; (3) instruments of climate policy; and (4) other terms relating to climate. The search yielded a total number of 1098 documents published in the period from 2008 to 2024. We carried out the systematic review in accordance with the established PRISMA protocols. It excluded non-English studies (n=52). Since our interest is in peer-reviewed journal articles, we omitted all books, book chapters, reviews, editorials, conference papers, short surveys, letters, notes and errata (n=206). In addition, one duplicate article was removed. This reduced the sample to 839 articles.

Next, we reviewed these articles to identify the relevant ones given our study's objective as described in Section 2. The process of screening involved checking paper titles and abstracts. If abstracts were insufficiently informative, the full text of the paper was consulted. We removed papers that did not include an abstract (n=2) or whose full text was inaccessible (n= 7). Additional exclusion criteria used were the following:

1. Studies lacking a quantitative analysis of some type (n= 63). This includes opinions, literature reviews and qualitative studies.
2. Studies exploring the impact of climate policy instruments on socio-economic heterogeneities rather than the reverse (n= 250). The dominant category here is formed by studies assessing the influence of climate policy on income inequality.
3. Studies that do not focus on climate policy but instead address climate change impacts or damages (n=244).
4. Studies that investigate environmental issues distinct from climate change (n=188).

Applying these exclusion criteria, we end up with 85 papers that align with our research objectives. Figure 1 gives an overview of the search and selection process. This may strike the reader as a small sample. The reason is that few studies examine or explicitly mention the impact of heterogeneity factors on performance of, or support for, climate policy. Moreover, most studies

[1] Scopus from Elsevier is, together with the Web of Science from Thompson Reuters, the most widely used index and citation databases. We opted to use Scopus as it covers a considerably larger number of journals (Mongeon and Paul-Hus, 2016) and is easier to navigate (Burnham, 2006; Pranchkute, 2021).

addressing heterogeneities are of the type 2 above which is deleted as it concerns the reverse causality.

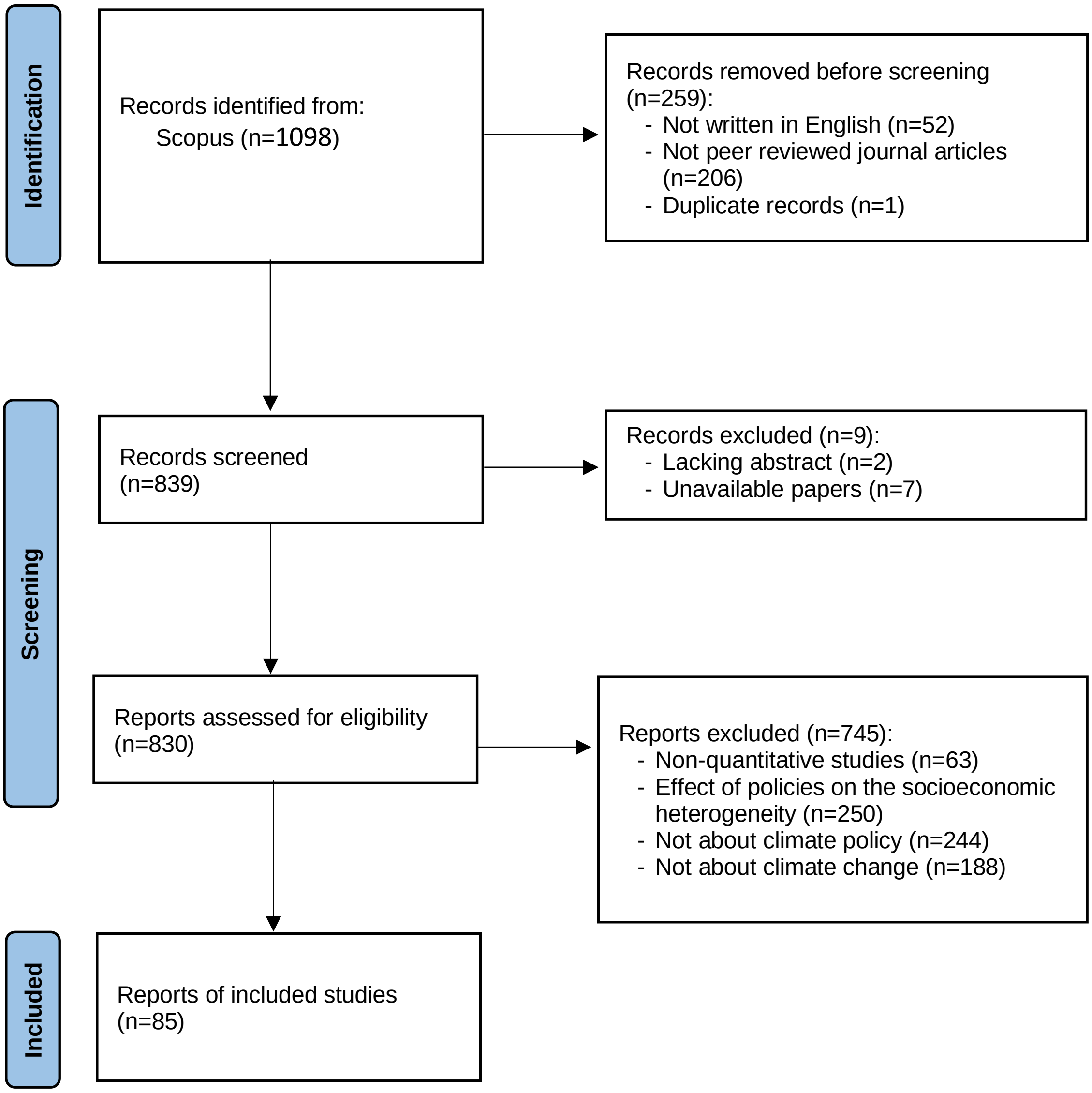

Figure 1. An overview of the systematic review process

4. Results

4.1 General information

The distribution of studies over time is shown in the left plot of Figure 2. The number of publications increased a lot over the last two decades starting from a few at the beginning of the 2010s reaching as many as 26 in 2023.

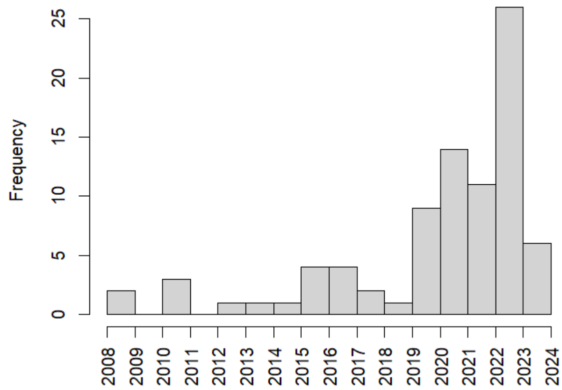

Figure 2. Number of studies in our sample by year of publication

Table 1 lists ten journals that appear most often in our sample. As one can see, these include some major outlets in the areas of climate policy, energy policy and environmental science. It may surprise that few studies were found in journals specialized in climate policy. The reason is that while there are many studies of climate policy in these journals, apparently few deal explicitly with the role of heterogeneities in socio-economic and attitudinal characteristics.

Table 1. Journals with highest number of publications in our sample. Number of citations is calculated based on the articles in our sample

Journal	*Number of studies published*	*Average number of citations per year*
Energy Policy	8	4.84
Applied Energy	6	8.81
Ecological Economics	5	12.67
Environmental Research Letters	5	6.56
Journal of Cleaner Production	5	4.35
Climate Policy	3	2.00
Climatic Change	2	7.46
Energy Research and Social Science	2	0.50
Environmental Science and Pollution Research	2	1
Global Environmental Change	2	22.43

As shown in Figure 3, authors of studies in the sample work in 36 distinct countries, with China and the USA leading by a large margin, followed by Spain, the UK and Germany.

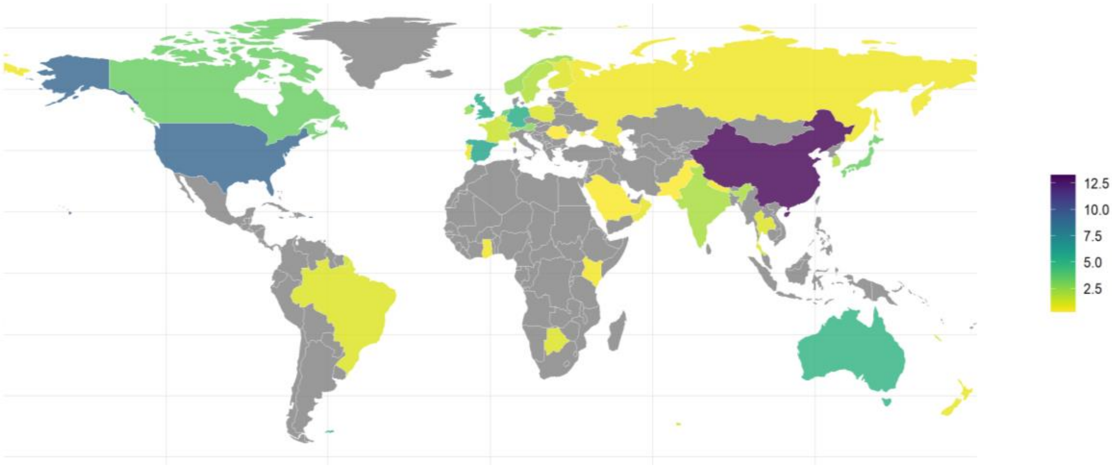

Figure 3. Country coverage in our sample

Note: The heatmap shows global coverage of studies with authors affiliated to institutes in more than one unique country being equally split between countries.

4.2 Computational linguistics

For textual analysis we use textual documents that combine the titles, abstracts, and keywords of studies. The distribution of the textual documents in terms of length ranges between 200 and 350 words. To reveal hidden structure in our textual data, we use topic modelling, a technique of computation linguistics. It clusters words into topics based on how often any pair of words appears in the same texts (Blei, 2012; Savin, 2023). For example, if we see the words "policy", "support" and "opinion" in one of the topics presented in the next section, it means that these words appear relatively often in combination. Compared to simple count of keywords, topic modelling considers words not as isolated, but based on other words they appear with, which can influence the meaning of the text. An advantage of structural topic modelling over classical is that it can include additional information about the publications (Savin and van den Bergh, 2021), such as year of publication, number of citations per year, and whether we classified the study as an ex-ante or an ex-post policy evaluation. We apply the method using the associated R package by Roberts et al. (2019).

A necessary step before building a topic model is pre-processing of textual data. We used the standard steps described in recent literature (Aggarwal, 2018; Uglanova and Gius, 2020). In particular, the text documents were divided into separate elements (tokens); capital letters were replaced; punctuation and stop words were removed; and words were converted to their dictionary form using lemmatization; words that are very rare (i.e., that appear less or equal to 3 times in all the documents) were removed; in addition, we formed stable word sequences called n-grams (e.g., "input_output", "economic growth" "logistic_regression" and "greenhouse_gas"). As a result, our final dataset contains 592 unique words for building a topic model and 5764 if we count all word repetitions.

To determine the optimal outcome, we run the model for different number of topics between 3 to 20 and record model performance on the following metrics: held-out log-likelihood (i.e. predictive power of the model), exclusivity (degree of overlap between popular words within each topic), and semantic coherence (the degree of co-occurrence of words from the same topic in text documents). In Figure A1 in the Appendix, we demonstrate that 9 topics results in the best trade-off in terms of good predictive power and coherence while reaching reasonable exclusivity.

The resulting topics are presented in Table 2. Next to most frequent and exclusive words for each topic and an illustrative title of a paper with the highest prevalence of the topic we also provide concise topic labels we have formulated after studying titles, abstracts and keywords of top twenty documents with highest prevalence in the respective topics.

Table 2. Main topics in our sample based on titles, abstracts, and keywords

	Topic label	Most discriminating terms and illustrative titles	Topic share
T1	Carbon emissions	input_output, province, emission, footprint, regional, per_capit, consumption, intensity, residential, greenhouse_gas, top, inequality, emit, expenditure, account, total, household, sector, car, region "Mapping the carbon footprint of EU regions"	15.6%
T2	Carbon tax	tax, taxation, distributional, household, cost, footprint, age, affect, revenue, socio_economic, pricing, carbon, effectiveness, price, demographic, impact, total, effect, production, input " Distributional impacts of carbon pricing in developing Asia "	14.0%
T3	Energy poverty	energy, poverty, technology, fuel, transition, efficiency, income, awareness, distribution, live, renewable, system, demand, residential, subsidy, product, share, global, decomposition, housing "Measuring energy sufficiency: A state of being neither in energy poverty nor energy extravagance"	12.3%
T4	Public policy support	support, opinion, public, political, fuel, policy, network, subsidy, canada, local, climate, citizen, structural, oppose, receive, standard, whether, associate, influence, wind Public support for carbon tax in South Korea: The role of tax design and revenue recycling"	11.6%
T5	Perception of climate change	perception, adaptation, response, community, risk, loss, climate_change, adoption, perceive, information, questionnaire, face, evidence, adult, age, adopt, wealth, poor, measure, survey "Perception of climate change and adoption of climate smart fisheries among artisanal fishers"	11.4%
T6	Climate justice	justice, mitigation, climate, woman, challenge, economic_growth, intensive, land, political, representation, instrument, region, vulnerable, world, increase, issue, fossil_fuel, less, party, politics "Effects of democracy, social inequality and economic growth on climate justice: An analysis with structural equation modelling"	10.6%
T7	Urbanization and transport	city, new, urbanization, urban, vehicle, development, industrial, infrastructure, greenhouse_gas, density, china, ghg, green, industry, home, behavioral, efficiency, resident, area, willingness "Dense downtown living more carbon intense due to higher consumption: A case study of Helsinki"	9.8%
T8	Consumer preferences	preference, personal, social, green, system, resource, neutrality, design, heterogeneity, optimization, electric_vehicle, model, reduction, meet, scale, consumer, difference, demand_side, norm, carbon "Choosing the right policy: Factors influencing the preferences of consumption-side personal carbon reduction policies"	8.2%
T9	Gender equality	board, gender, quota, gender_diversity, index, female, performance, market, woman, stakeholder, equality, governance, relationship, country, sustainable_development, association, positive, methodology, investigate, theory "Women in the boardroom and their impact on climate change related disclosure"	6.5%

Note: The terms shown are those that are the most frequent as well as exclusive to each topic. Illustrative titles are chosen from the ten documents with the highest topic prevalence.

Topic 1 (Tx henceforth stands for topic x) on carbon emissions has the largest prevalence in our sample of documents (9.9%). This topic was among the dominant ones at the beginning of period covered, but later in time its share reduced (from about 50% to about 20% today). As opposed, T3 on energy poverty and T4 on public policy support have gained more attention in recent years. Among the most cited topics are topics 1 and 2 on carbon emissions and carbon tax. In contrast T5 and T8 on perception of climate change and consumer preferences are among the least cited ones.

We further tested if certain topics are systematically more or less related to ex-ante vs ex-post studies. To this end, we statistically regress prevalence of each topic (bounded between 0 and 1) in the sample of our studies on the type of study (1 if it is ex-post and 0 if it is ex-ante). Results of the regression are presented in Figure 4. Studies addressing T1 on carbon emissions and T9 on gender (in)equality tend to be predominantly ex-post in nature, while studies focusing on T8 about consumer preferences are using more ex-ante approaches. This finding makes sense since evaluating emissions requires factual data, while assessing consumer preferences of (hypothetical) policies is commonly done using surveys or experiments.

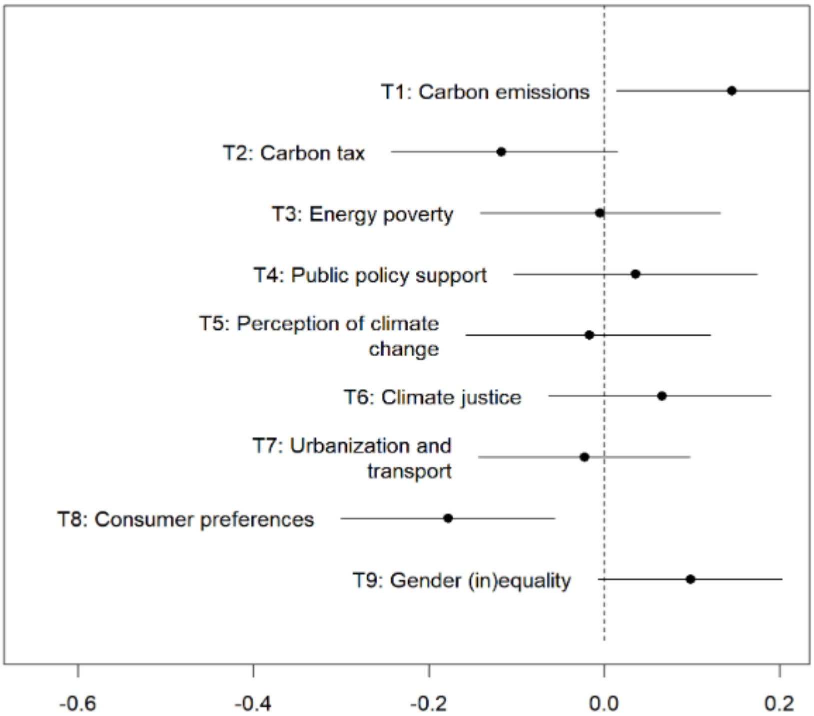

Figure 4. Statistical association between ex-ante vs. ex-post type of study and topic prevalence

Note: a positive value on the X-axis indicates a larger prevalence of that topic among ex-post studies, while a negative value – among ex-ante studies. The error bars represent mean +/- 2 standard errors.

4.3 Impact of heterogeneous factors on climate policy for ex-ante and ex-post studies

The 85 studies in the sample consist of 26 ex-ante and 59 ex-post studies. We extracted three distinct types of information from the full texts of the studies in each approach: policy instrument analysed, model types employed in ex-ante, and data sources utilized in ex-post studies. In addition, we identified the heterogeneity types for each approach and assessed their impact on the policy conclusions.

Figure 5 presents the frequency of policy instruments in the sample. Carbon pricing receives most attention, followed by direct regulation and adoption subsidies, while information provision is least studied. Regarding ex-ante studies, the chart indicates a focus on carbon taxation followed by adoption subsidies and information provision, whereas direct regulation is not addressed. Regarding ex-post studies, we find direct regulation and adoption subsidies being more frequently studied in this approach.

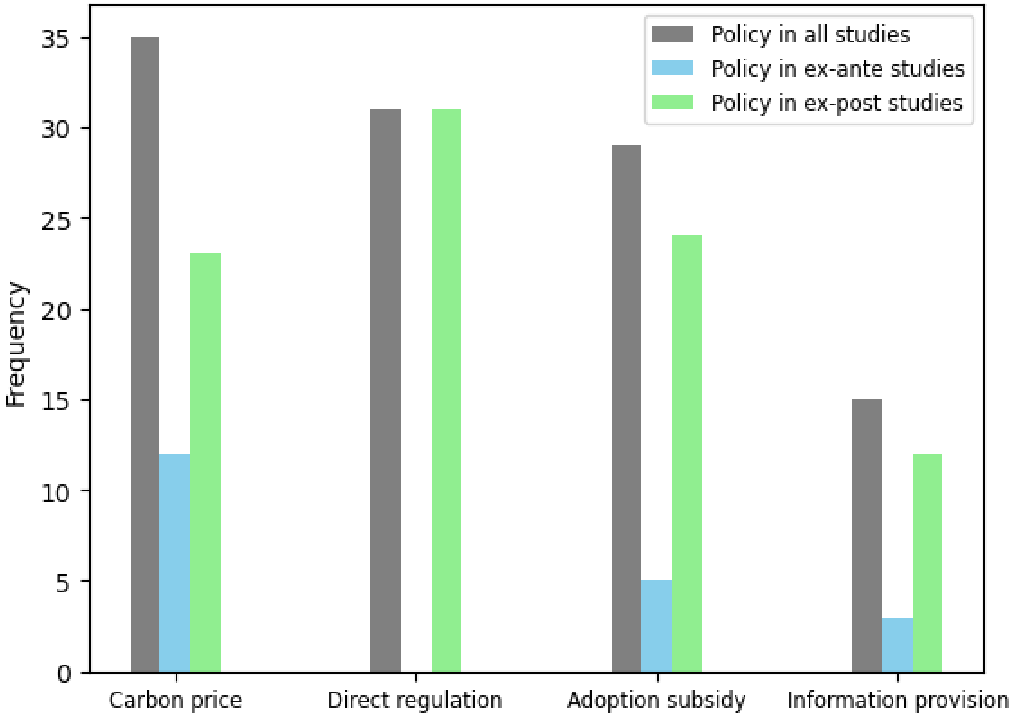

Figure 5. Frequency of policy instruments in all, ex-post and ex-ante studies

For the ex-ante studies, Table 3 lists the variety of model types used. It shows that general equilibrium and statistical models dominate, followed by, agent-based and input-output models. For the ex-post studies, Table 4 indicates the diversity of data sources (primary/secondary data, originating from a questionnaire survey or from statistical databases). Most use objective data.

Table 3. Approaches used in the 26 ex-ante studies

Approach	*Frequency*
Opinion survey of hypothetical policies	6
General equilibrium modelling	5
Agent-based modelling	3
Input-output modelling	3
Integrated assessment modelling	2
Stated preference modelling	2
Behavioural experiment	2
Optimization modelling	2
Neural network modelling	1

Table 4. Data collection methods in the 59 ex-post studies

Type of data	*Source*	*Frequency*
Primary subjective data (self-generated)	Surveys, interviews, focus groups	18
Secondary subjective data (using existing data)	Global, European- and national-level statistical databases	5
Objective data		36

In the sample of 85 studies, 25 distinct types of socio-economic heterogeneity were identified: the most frequent category is income (n=50), followed by education (n=24), region (n=22), and age (n=19). In addition, heterogeneities like previous experience with natural disasters ("Experience with natural disasters"), perception of inequality and marital status appear in a smaller number of studies. Income is the most frequently examined factor in both ex-post and ex-ante studies, representing 20% and 21% of the total of heterogeneous factors in the respective categories. Education is the next most frequently studied factor in ex-post studies (11%), followed by region (8.5%), age (8%), and gender (7%). As opposed, in ex-ante studies, the importance of education is comparatively low, accounting for around 5%, while other factors appear more often: region (10.5%), age (7%) and dwelling characteristics (8.7%). Certain heterogeneous factors appear exclusively in one method, such as political orientation, ethnicity, and health in ex-post studies, and marital status in ex-ante studies. Figure 6 displays the full list of the heterogeneity dimensions, along with their respective frequencies. The larger number of heterogeneities than studies is due to several studies addressing more than one type of heterogeneity.

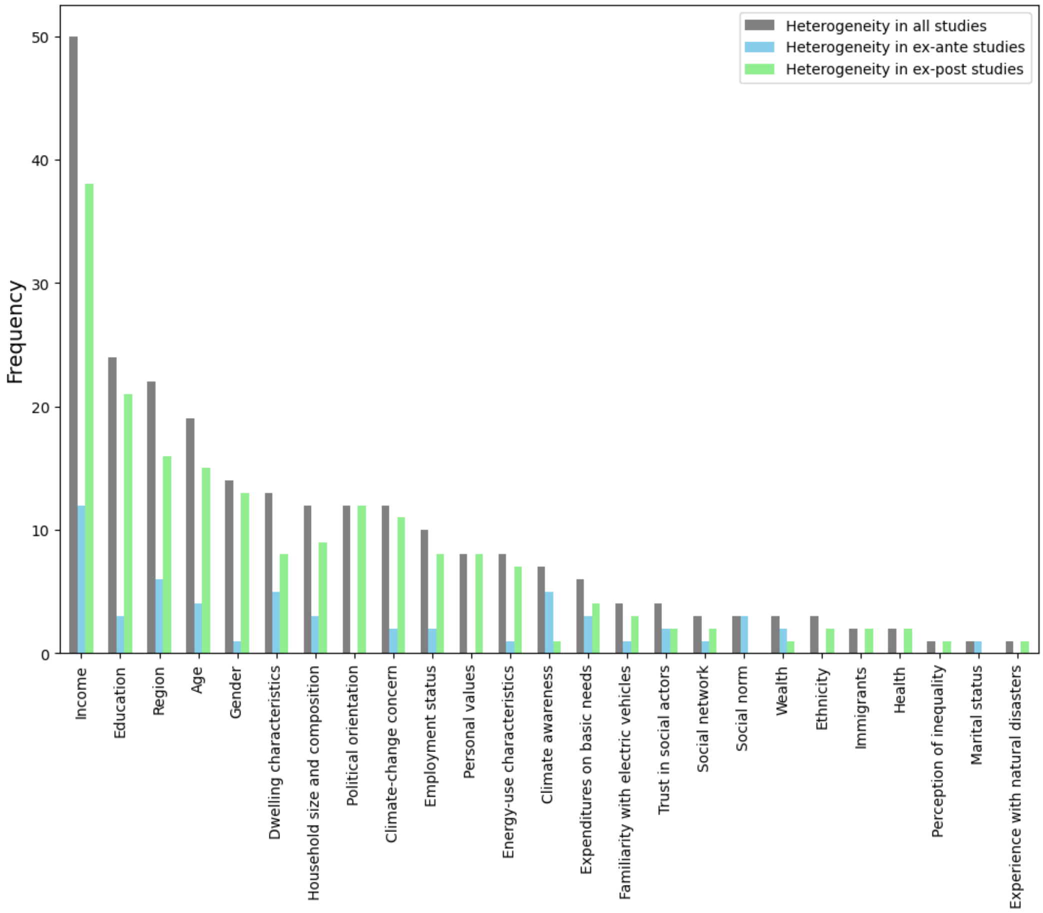

Figure 6. Frequency of heterogeneous factors in all, ex-post and ex-ante studies

To assess the influence of socio-economic heterogeneity on insights about climate policy, we analysed the full texts of the 85 selected studies and systematically extracted relevant data. Out of the 85 papers reviewed, we identified two main themes:

1. *Policy support* (n=34) relating mostly to topics on public policy support (T4), perception of climate change (T5), climate justice (T6), consumer preferences (T8) and gender (in)equality (T9). Topic T2 on carbon tax is present both, among ex-ante and ex-post studies. Next, we report for each of these themes how much attention heterogeneities have received, how they

affect climate policy (positively or negatively), and how this differs between ex-post and ex-ante analyses.

2. *Policy effectiveness* (n=51) relating mostly to topics on carbon emissions (T1), energy poverty (T3) and urbanization and transport (T7).

Public support of climate policy

Figure 7 illustrates the direct impact of heterogeneous characteristics on public support of climate policy, as established by ex-post and ex-ante studies. The results indicate that the impact of heterogeneous socio-economic and attitudinal factors is predominantly positive, particularly in ex-post studies. For ex-ante studies we find that generally heterogeneous factors receive little attention, which is partly a consequence of the lower share of ex-ante studies in the sample. The factors studies mainly concentrate on are income, education, age, political orientation, climate-change concerns, region, and gender, in both ex-post and ex-ante analyses.

As further shown in Figure 7, in ex-post studies education emerges as the most frequently examined socio-demographic characteristic, demonstrating mostly a significant positive impact. A similar impact is observed in ex-ante studies, though with lower frequency. The second most frequent factor in ex-post studies is income, which generally exhibits a negative effect. However, in ex-ante studies, the impact of income is more positive. The third most frequent factor in ex-post studies is political orientation, which has an equal distribution of positive and negative effects on policy support. While ex-post studies devoted much attention to the role of political orientation, with evidence indicating that the effects of right-wing (left-wing) party affiliation are more negative (positive), ex-ante studies did not consider this factor at all. The next most common factors in ex-post studies are age and concern about climate-change concern which positively related to support for climate policy. The impact of climate-change concern is also positive in ex-ante studies while age is found here to have a slightly more negative effect. Next urban location of households predominantly has a positive effect in ex-post studies while it is hardly addressed in ex-ante studies. The results further demonstrate the positive effect of women (gender) and personal values in ex-post studies. All other factors appear considerably less often. In addition, in ex-ante studies heterogeneities ranked by frequency are as follows: income, climate awareness, age, and social norms. These factors typically have a positive impact on policy support.

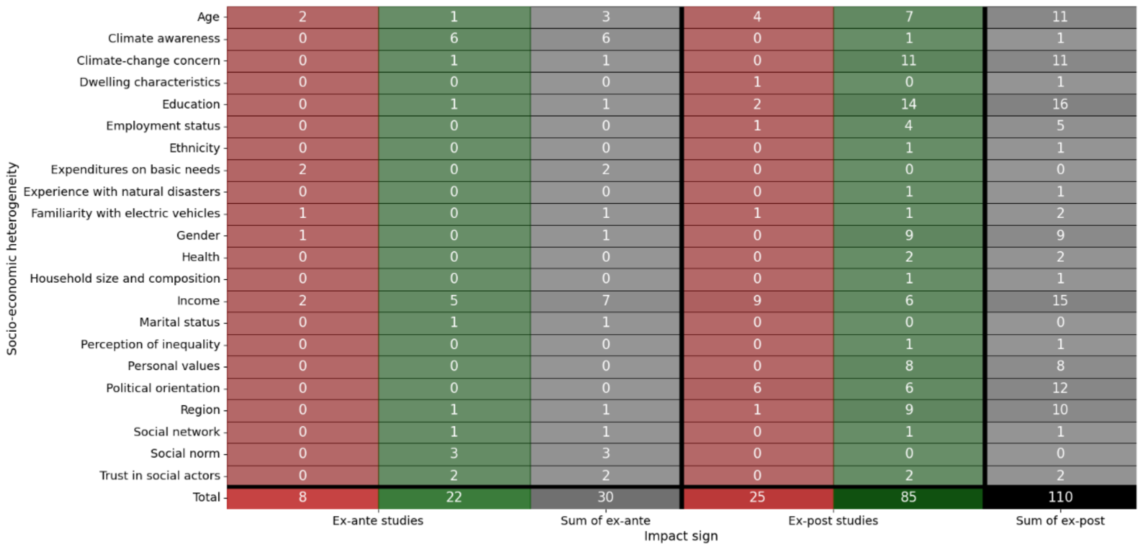

Figure 7. Association of socio-economic heterogeneity dimensions with support for climate policy
Note: green-coloured columns indicate positive effects, red-coloured negative effects and grey-coloured the total number of studies for each combination of method and heterogeneous factor.

Policy effectiveness in terms of CO_2 emissions reduction

Figure 8 demonstrates the association of socio-economic characteristics with carbon emissions. Income is the most frequently studied factor in ex-post studies, which generally correlates with an increase in emissions. This effect is also observable in ex-ante studies. In ex-post studies, the second socio-economic factor is household size which mostly leads to a reduction in emission level, likely due to economies of scale in energy use in households. This reduction effect is also generally observed in ex-ante studies. The next most frequent socio-economic characteristics in ex-post studies are energy-use and dwelling characteristics. Region and education are also frequently examined factors. In ex-ante studies a high prevalence of dwelling characteristics, region and household size is found.

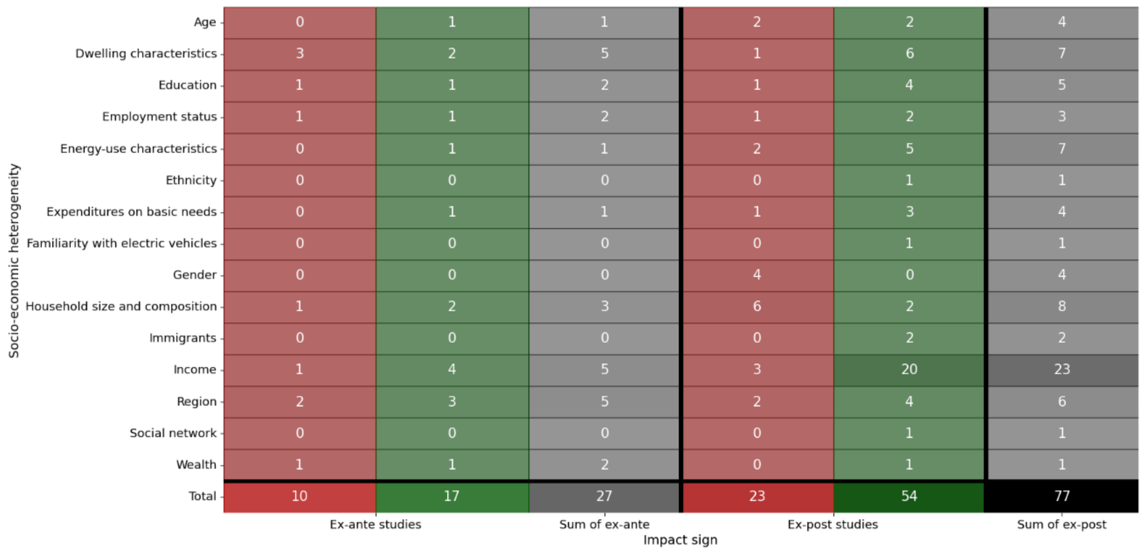

Figure 8. Association of socio-economic heterogeneity dimensions with carbon emissions
Note: green-coloured columns indicate positive effects, red-coloured negative effects and grey-coloured the total number of studies for each combination of method and heterogeneous factor.

.

5. Conclusions

Heterogeneity in socio-economic and attitudinal characteristics plays a crucial role in how individuals perceive climate risks, judge strategies, and respond to policies in terms of political support and behavioural change. In this study, we have focused on how this plays out in the context of the distinction between ex-ante and ex-post approaches to assessing climate policy. Through a systematic literature review, we collected 85 studies giving explicit attention to the socioeconomic heterogeneities in the setting of climate policy analysis. Using computational linguistic methods, we classified them into 9 main topics ranging from energy poverty and policy support to consumer preferences and gender inequality. Overall, 25 distinct types of socio-economic and attitudinal characteristics were identified: dominant is income (n=50), followed by education (n=24), region (n=22), and age (n=19). Several studies address more than one heterogeneity. We categorized the policies studied in the sample into four main categories: carbon tax, direct regulation, adoption subsidies, and information provision. Ex-post studies encompass all types of these policies, with greater emphasis on direct regulation and adoption subsidies. However, ex-ante studies focus more on carbon pricing and neglect direct regulation.

We next investigated the extent to which heterogeneity in socio-economic and attitudinal characteristics influences climate policy by directly impacting policy support and affecting the carbon emissions of individuals and household. The results indicate that in some instances, both approaches yield similar outcomes. They also recognize the importance of factors such as income, education, region, and age. However, our sample study reveals some differences between these two types of studies. For instance, unlike ex-anted studies, ex-post studies highlight the positive role of gender and climate-change concern on climate policy. Additionally, factors such as political orientation, health, immigrant, and ethnicity tend to be neglected by ex-ante studies, Conversely, ex-ante studies pay attention to factors like social norms and marital status, which are entirely overlooked by ex-post studies.

In conclusion, our investigation into the heterogeneity of socio-economic characteristics reveals that ex-post and ex-ante studies converge on the importance of factors like income, education, region and age in influencing climate policy support and effectiveness. However, the differences in the diversity of heterogeneity characteristics considered by these two methods suggest that ex-post and ex-ante approaches can be complementary. By integrating findings from both approaches, a more comprehensive and nuanced understanding of the factors influencing climate policy can be achieved. This integration can ultimately lead to more effective and inclusive policy-making. In addition, there is a need for achieving more coherence between prospective and retrospective studies, to understand better the reasons for diverse findings. It would be good if future research expands the scope of especially ex-ante studies to include a wider range of heterogeneous factors so as to assess their impact on the effectiveness of, and support for, climate policies.

Appendix 1: Additional information about application of structural topic modelling

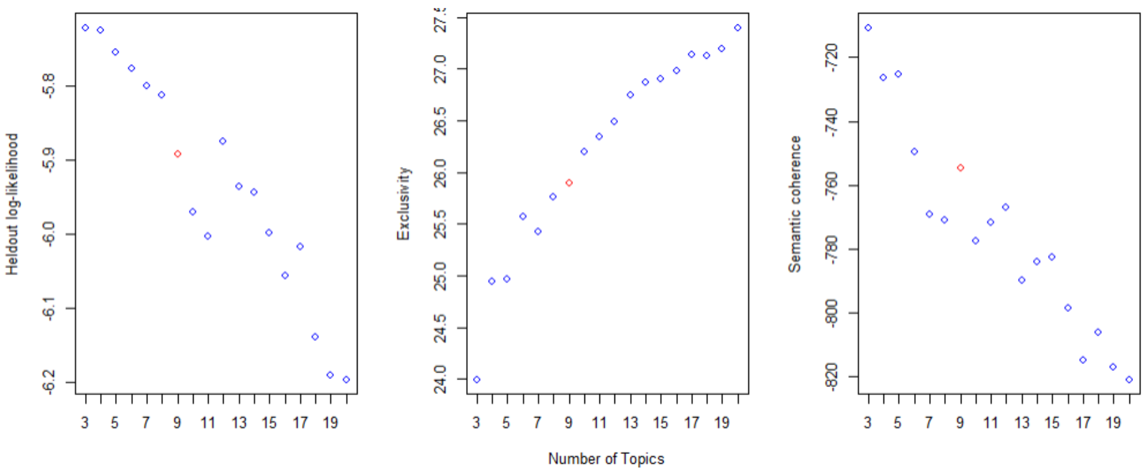

Figure A1. Model performance depending on the number of topics

Appendix 2. References to the 85 studies in the sample

Ahmed, N., Padda, I. U. H., Khan, A., Otil, M. D., Cismas, L. M., Miculescu, A., & Rehman, A. (2023). Climate change adaption strategies in urban communities: new evidence from Islamabad, Pakistan. *Environmental science and pollution research*, *30*(14), 42108-42121.

Aryanpur, V., Balyk, O., Daly, H., Gallachóir, B. Ó., & Glynn, J. (2022). Decarbonisation of passenger light-duty vehicles using spatially resolved TIMES-Ireland Model. *Applied Energy*, *316*, 119078.

Ayisi, C. L., N'souvi, K., Baidoo, K., Asare-Nuamah, P., Larbi, I., Asiamah, T. A., ... & Ayeh, S. O. (2024). Perception of climate change and adoption of climate smart fisheries among artisanal fishers. *Sustainable Technology and Entrepreneurship*, *3*(3), 100072.

Bae, J. H. (2018). Impacts of income inequality on CO 2 emission under different climate change mitigation policies. *The Korean Economic Review*, *34*(2), 187-211.

Basso, H. S., Dimakou, O., & Pidkuyko, M. (2024). How consumption carbon emission intensity varies across Spanish households. *SERIEs*, *15*(1), 95-125.

Beiser-McGrath, L. F., & Bernauer, T. (2021). Current surveys may underestimate climate change skepticism evidence from list experiments in Germany and the USA. *Plos one*, *16*(7), e0251034.

Beiser-Mcgrath, L. F., & Busemeyer, M. R. (2023). Carbon inequality and support for carbon taxation. *European Journal of Political Research*.

Bel, G., & Teixidó, J. J. (2020). The political economy of the Paris Agreement: Income inequality and climate policy. *Journal of Cleaner Production*, *258*, 121002.

Büchs, M., & Schnepf, S. V. (2013). Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO2 emissions. *Ecological Economics*, *90*, 114-123.

Cai, Q., Ji, Z., Ma, F., & Liang, H. (2023). The Green Effects of Industrial Policy—Evidence from China's New Energy Vehicle Subsidies. *Energies*, *16*(19), 6811.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., ... & Wise, M. (2017). The SSP4: A world of deepening inequality. *Global Environmental Change*, *42*, 284-296.

Chancel, L. (2022). Global carbon inequality over 1990–2019. *Nature Sustainability*, *5*(11), 931-938.

Chen, L., Xu, L., Wang, Y., Xia, L., & Yang, Z. (2023). Inequality and its driving forces in residential CO2 emission: Perspective of energy use pattern. *Journal of Cleaner Production*, *414*, 137538.

Chung, W., Kam, M. S., & Ip, C. Y. (2011). A study of residential energy use in Hong Kong by decomposition analysis, 1990–2007. *Applied Energy*, *88*(12), 5180-5187.

Foley, B., Degirmenci, K., & Yigitcanlar, T. (2020). Factors affecting electric vehicle uptake: Insights from a descriptive analysis in Australia. *Urban Science*, *4*(4), 57.

Furlan, M., & Mariano, E. B. (2024, May). Effects of democracy, social inequality and economic growth on climate justice: An analysis with structural equation modelling. In *Natural Resources Forum* (Vol. 48, No. 2, pp. 435-467). Oxford, UK: Blackwell Publishing Ltd.

Gao, J., Xu, G., Ma, W., Zhang, Y., Woodward, A., Vardoulakis, S., ... & Liu, Q. (2017). Perceptions of health co-benefits in relation to greenhouse gas emission reductions: a survey among urban residents in three Chinese cities. *International journal of environmental research and public health*, *14*(3), 298.

Gentle, P., Thwaites, R., Race, D., Alexander, K., & Maraseni, T. (2018). Household and community responses to impacts of climate change in the rural hills of Nepal. *Climatic Change*, *147*, 267-282.

Gonenc, H., & Krasnikova, A. V. (2022). Board gender diversity and voluntary carbon emission disclosure. *Sustainability*, *14*(21), 14418.

Harring, N., Ndwiga, M., Nordén, A., & Slunge, D. (2024). Public acceptability of policy instruments for reducing fossil fuel consumption in East Africa. *Climate Policy*, 1-16.

Heinonen, J., Kyrö, R., & Junnila, S. (2011). Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki. *Environmental Research Letters*, *6*(3), 034034.

Helliesen, M. S. (2023). Unequal Representation of Women and Youth on Climate Policy Issues. *Representation*, *59*(4), 615-632.

Hossain, M., Al Farooque, O., Momin, M. A., & Almotairy, O. (2017). Women in the boardroom and their impact on climate change related disclosure. *Social Responsibility Journal*, *13*(4), 828-855.

Hu, A. T., Tok, N., Bratu, A., Card, K. G., Martin, G., & Closson, K. (2023). Community satisfaction and risk perception of local devastation due to climate change. *The Journal of Climate Change and Health*, *14*, 100271.

Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P. C., Wood, R., & Hertwich, E. G. (2017). Mapping the carbon footprint of EU regions. *Environmental Research Letters*, *12*(5), 054013.

Kerkhof, A. C., Benders, R. M., & Moll, H. C. (2009). Determinants of variation in household CO2 emissions between and within countries. *Energy policy*, *37*(4), 1509-1517.

Kilian, L., Owen, A., Newing, A., & Ivanova, D. (2023). Achieving emission reductions without furthering social inequality: Lessons from the 2007 economic crisis and the COVID-19 pandemic. *Energy Research & Social Science*, *105*, 103286.

Klebl, C., & Jetten, J. (2024). Perceived inequality increases support for structural solutions to climate change. *Social Psychological and Personality Science*, *15*(2), 225-233.

Konc, T., Drews, S., Savin, I., & Van Den Bergh, J. C. (2022). Co-dynamics of climate policy stringency and public support. *Global Environmental Change*, *74*, 102528.

Kordsachia, O., Bassen, A., Fieberg, C., & Wolters, K. (2023). Market perceptions on the role of female leadership in adapting to climate change. *The Journal of Risk Finance*, *24*(4), 424-448.

Kornek, U., Klenert, D., Edenhofer, O., & Fleurbaey, M. (2021). The social cost of carbon and inequality: When local redistribution shapes global carbon prices. *Journal of Environmental Economics and Management*, *107*, 102450.

Lee, J., Shigetomi, Y., & Kanemoto, K. (2023). Drivers of household carbon footprints across EU regions, from 2010 to 2015. *Environmental Research Letters*, *18*(4), 044043.

Lei, M., Ding, Q., Cai, W., & Wang, C. (2022). The exploration of joint carbon mitigation actions between demand-and supply-side for specific household consumption behaviors—A case study in China. *Applied Energy*, *324*, 119740.

Levi, S., Wolf, I., Sommer, S., & Howe, P. D. (2023). Local support of climate change policies in Germany over time. *Environmental Research Letters*, *18*(6), 064046.

Lin, B., & Yang, M. (2023). Choosing the right policy: Factors influencing the preferences of consumption-side personal carbon reduction policies. *Journal of Environmental Management*, *326*, 116706.

Lipari, F., Lázaro-Touza, L., Escribano, G., Sánchez, Á., & Antonioni, A. (2024). When the design of climate policy meets public acceptance: An adaptive multiplex network model. *Ecological Economics*, *217*, 108084.

Long, D., West, G. H., & Nayga, R. M. (2021). Consumer willingness-to-pay for restaurant surcharges to reduce carbon emissions: default and information effects. *Agricultural and Resource Economics Review*, *50*(2), 338-366.

Long, Z., Kitt, S., & Axsen, J. (2021). Who supports which low-carbon transport policies? Characterizing heterogeneity among Canadian citizens. *Energy Policy*, *155*, 112302.

Maestre-Andrés, S., Drews, S., Savin, I., & van den Bergh, J. Carbon tax acceptability with information provision and mixed revenue uses. Nat Commun. 2021; 12 (1): 7017.

Mahadevia, D., & Advani, D. (2016). Gender differentials in travel pattern–the case of a mid-sized city, Rajkot, India. *Transportation Research Part D: Transport and Environment*, *44*, 292-302.

Martínez, M. D. C. V., Santos-Jaén, J. M., Román, R. S., & Martín-Cervantes, P. A. (2022). Are gender and cultural diversities on board related to corporate CO2 emissions?. *Journal of Cleaner Production*, *363*, 132638.

Martínez, M. D. C. V., Santos-Jaén, J. M., Román, R. S., & Martín-Cervantes, P. A. (2022). Are gender and cultural diversities on board related to corporate CO2 emissions?. *Journal of Cleaner Production*, *363*, 132638.

Martinsson, J., Lundqvist, L. J., & Sundström, A. (2011). Energy saving in Swedish households. The (relative) importance of environmental attitudes. *Energy policy*, *39*(9), 5182-5191.

Mattioli, G., Büchs, M., & Scheiner, J. (2023). Who flies but never drives? Highlighting diversity among high emitters for passenger transport in England. *Energy Research & Social Science*, *99*, 103057.

McCulloch, N., Moerenhout, T., & Yang, J. (2021). Fuel subsidy reform and the social contract in Nigeria: A micro-economic analysis. *Energy policy*, *156*, 112336.

Mehleb, R. I., Kallis, G., & Zografos, C. (2021). A discourse analysis of yellow-vest resistance against carbon taxes. *Environmental Innovation and Societal Transitions*, *40*, 382-394.

Mildenberger, M., Howe, P., Lachapelle, E., Stokes, L., Marlon, J., & Gravelle, T. (2016). The distribution of climate change public opinion in Canada. *PloS one*, *11*(8), e0159774.

Mrówczyńska, M., Skiba, M., Bazan-Krzywoszańska, A., & Sztubecka, M. (2020). Household standards and socio-economic aspects as a factor determining energy consumption in the city. *Applied Energy*, *264*, 114680.

Nagpure, A. S., Tong, K., & Ramaswami, A. (2022). Socially-differentiated urban metabolism methodology informs equity in coupled carbon-air pollution mitigation strategies: insights from three Indian cities. *Environmental Research Letters*, *17*(9), 094025.

Niamir, L., Kiesewetter, G., Wagner, F., Schöpp, W., Filatova, T., Voinov, A., & Bressers, H. (2020). Assessing the macroeconomic impacts of individual behavioral changes on carbon emissions. *Climatic change*, *158*, 141-160.

Odland, S., Rhodes, E., Corbett, M., & Pardy, A. (2023). What policies do homeowners prefer for building decarbonization and why? An exploration of climate policy support in Canada. *Energy Policy*, *173*, 113368.

Okushima, S. (2024). Measuring energy sufficiency: A state of being neither in energy poverty nor energy extravagance. *Applied Energy*, *354*, 122161.

Oswald, Y., Steinberger, J. K., Ivanova, D., & Millward-Hopkins, J. (2021). Global redistribution of income and household energy footprints: a computational thought experiment. *Global Sustainability*, *4*, e4.

Qiu, Y. Q., Ng, A. T. S., & Zhou, P. (2022). Optimizing urban electric vehicle incentive policy mixes in China: Perspective of residential preference heterogeneity. *Applied Energy*, *313*, 118794.

Rainard, M., Smith, C. J., & Pachauri, S. (2023). Gender equality and climate change mitigation: Are women a secret weapon?. *Frontiers in Climate*, *5*, 946712.

Rajeev, M., & Nagendran, P. (2023). Protecting land and livelihood under climate risks: What hinders crop insurance adoption?. *Land Use Policy*, *131*, 106711.

Rausch, S., & Schwarz, G. A. (2016). Household heterogeneity, aggregation, and the distributional impacts of environmental taxes. *Journal of Public Economics*, *138*, 43-57.

Reaños, M. A. T. (2021). Fuel for poverty: A model for the relationship between income and fuel poverty. Evidence from Irish microdata. *Energy Policy*, *156*, 112444.

Running, K. (2015). Towards climate justice: How do the most vulnerable weigh environment–economy trade-offs?. *Social science research*, *50*, 217-228.

Saelim, S. (2019). Carbon tax incidence on household consumption: Heterogeneity across socio-economic factors in Thailand. *Economic Analysis and Policy*, *62*, 159-174.

Sekelemani, A., Mogomotsi, P. K., Stone, L. S., Mogomotsi, G. E., & Lekhane, O. (2020). Farmers' perceptions of climate change and their adaptation strategies: The case of Ngamiland East, Botswana. *Transactions of the Royal Society of South Africa*, *75*(2), 213-221.

Starr, J., Nicolson, C., Ash, M., Markowitz, E. M., & Moran, D. (2023). Assessing US consumers' carbon footprints reveals outsized impact of the top 1%. *Ecological Economics*, *205*, 107698.

Steckel, J. C., Dorband, I. I., Montrone, L., Ward, H., Missbach, L., Hafner, F., ... & Renner, S. (2021). Distributional impacts of carbon pricing in developing Asia. *Nature Sustainability*, *4*(11), 1005-1014.

Stewart, F. (2022). Friends with benefits: How income and peer diffusion combine to create an inequality "trap" in the uptake of low-carbon technologies. *Energy Policy*, *163*, 112832.

Tan, F., Yang, S., & Niu, Z. (2023). The impact of urbanization on carbon emissions: Both from heterogeneity and mechanism test. *Environment, Development and Sustainability*, *25*(6), 4813-4829.

Theine, H., Humer, S., Moser, M., & Schnetzer, M. (2022). Emissions inequality: Disparities in income, expenditure, and the carbon footprint in Austria. *Ecological Economics*, *197*, 107435.

Tian, X., Zhang, Q., Chi, Y., & Cheng, Y. (2021). Purchase willingness of new energy vehicles: A case study in Jinan City of China. *Regional Sustainability*, *2*(1), 12-22.

Tomás, M., López, L. A., & Monsalve, F. (2020). Carbon footprint, municipality size and rurality in Spain: Inequality and carbon taxation. *Journal of cleaner production*, *266*, 121798.

Van Der Cam, A., Adant, I., & Van den Broeck, G. (2023). The social acceptability of a personal carbon allowance: a discrete choice experiment in Belgium. *Climate Policy*, *23*(7), 859-871.

Vasconcelos, V. V., Santos, F. C., Pacheco, J. M., & Levin, S. A. (2014). Climate policies under wealth inequality. *Proceedings of the National Academy of Sciences*, *111*(6), 2212-2216.

Waichman, I., Requate, T., Karde, M., & Milinski, M. (2021). Challenging conventional wisdom: Experimental evidence on heterogeneity and coordination in avoiding a collective catastrophic event. *Journal of Environmental Economics and Management*, *109*, 102502.

Wang, M., & Feng, C. (2021). The inequality of China's regional residential CO2 emissions. *Sustainable Production and Consumption*, *27*, 2047-2057.

Wang, R., Cao, T., He, X., & Fan, Y. (2023). Energy financing, energy projects retrofit and energy poverty: a scenario-analysis approach for energy project cost estimation and energy price determination. *Environmental Science and Pollution Research*, *30*(50), 108865-108877.

Weber, C. L., & Matthews, H. S. (2008). Quantifying the global and distributional aspects of American household carbon footprint. *Ecological economics*, *66*(2-3), 379-391.

Whitley, C. T., & Bowers, M. M. (2023). Queering climate change: exploring the influence of LGBTQ+ identity on climate change belief and risk perceptions. *Sociological Inquiry*, *93*(3), 413-439.

Wu, H., & Wang, Y. (2024). Integrating green resources and mineral dependency to address the urban-rural divide in China's carbon neutrality transition. *Resources Policy*, *88*, 104322.

Xing, R., Hanaoka, T., Kanamori, Y., & Masui, T. (2018). Achieving China's Intended Nationally Determined Contribution and its co-benefits: Effects of the residential sector. *Journal of cleaner production*, *172*, 2964-2977.

Xiong, B., & Sui, Q. (2023). Does Carbon Emissions Trading Policy Improve Inclusive Green Resilience in Cities? Evidence from China. *Sustainability*, *15*(17), 12989.

Yadav, P., Davies, P. J., & Khan, S. (2020). Breaking into the photovoltaic energy transition for rural and remote communities: challenging the impact of awareness norms and subsidy schemes. *Clean Technologies and Environmental Policy*, *22*, 817-834.

Yazar, M., Hermwille, L., & Haarstad, H. (2022). Right-wing and populist support for climate mitigation policies: Evidence from Poland and its carbon-intensive Silesia region. *Regional Sustainability*, *3*(4), 281-293.

Zeigermann, U., Kammerer, M., & Böcher, M. (2023). What drives local communities to engage in climate change mitigation activities? Examining the rural–urban divide. *Review of Policy Research*, *40*(6), 894-919.

Zhai, X., An, Y., Shi, X., & Cui, H. (2023). Emissions trading scheme and green development in China: Impact of city heterogeneity. *Sustainable Development*, *31*(4), 2583-2597.

Zhang, H., Shi, X., Wang, K., Xue, J., Song, L., & Sun, Y. (2020). Intertemporal lifestyle changes and carbon emissions: Evidence from a China household survey. *Energy Economics*, *86*, 104655.

Zhang, Z., Cui, Y., & Zhang, Z. (2023). Unequal age-based household carbon footprint in China. *Climate Policy*, *23*(5), 577-592.

Zhong, H., Feng, K., Sun, L., Cheng, L., & Hubacek, K. (2020). Household carbon and energy inequality in Latin American and Caribbean countries. *Journal of Environmental Management*, *273*, 110979.

References

Aggarwal, C. C. (2018). Text Preparation and Similarity Computation. In: Machine Learning for Text (pp. 17–30). New York: Springer

Alberini, A. (2019). Revealed versus stated preferences: what have we learned about valuation and behavior? *Review of Environmental Economics and Policy* 13(2): 283-298.

Blei, D. M. Probabilistic topic models. *Communications of the ACM* 55, 77–84 (2012).

Callaghan, M., Banisch, L., Doebbeling-Hildebrandt, N., Edmondson, D., Flachsland, C., Lamb, W., ... & Minx, J. (2024). Mapping climate mitigation policy literature using machine learning: disparities between scientific attention, policy density, and emissions. Research Square, https://www.researchsquare.com/article/rs-3817176/v1

Carson, R.T., N.E. Flores, K.M. Martin, J.L. Wright (1996). Contingent valuation and revealed preference methodologies: comparing the estimates for quasi-public goods. *Land economics* 72(1): 80-99.

Burnham, J. F. (2006). Scopus database: a review. *Biomedical digital libraries*, 3(1), 1-8.

Chen, L., Xu, L., Wang, Y., Xia, L., & Yang, Z. (2023). Inequality and its driving forces in residential CO2 emission: Perspective of energy use pattern. *Journal of Cleaner Production* 414, 137538.

Elliott, J., R Lawrence, JC Minx, OT Oladapo, P Ravaud, B. Tendal Jeppesen, J. Thomas, T. Turner, P.O. Vandvik and J.M. Grimshaw (2021). Decision makers need constantly updated evidence synthesis. *Nature* 600(7889): 383-385.

Emmerling, J., and M. Tavoni (2021). Representing inequalities in integrated assessment modeling of climate change. *One Earth* 4: 177-180.

Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A third wave in the economics of climate change. *Environmental and Resource Economics* 62, 329–357.

Kirman, A.P. (1992). Whom or what does the representative individual represent*? Journal of Economic Perspectives* 6: 117–136.

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: a comparative analysis. *Scientometrics*, 106, 213-228.

Pranckutė, R. (2021). Web of Science (WoS) and Scopus: The titans of bibliographic information in today's academic world. *Publications*, 9(1), 12.

Qiu, M., Weng, Y., Cao, J., Selin, N. E., & Karplus, V. J. (2020). Improving evaluation of energy policies with multiple goals: Comparing ex ante and ex post approaches. *Environmental Science & Technology*, *54*(24), 15584-15593.

Roberts, M. E. et al. Structural Topic Models for Open-Ended Survey Responses. American *Journal of Political Science* 58, 1064–1082 (2014).

Safarzynska, K., and J. van den Bergh (2022). ABM-IAM: Optimal climate policy under bounded rationality and multiple inequalities. *Environmental Research Letters* 17, 094022.

Savin, I. Evolution and recombination of topics in Technological Forecasting and Social Change. *Technological Forecasting and Social Change* 194, 122723 (2023).

Savin, I., & van den Bergh, J. (2021). Main topics in EIST during its first decade: A computational-linguistic analysis. *Environmental Innovation and Societal Transitions*, 41, 10-17

Tol, R.S.J., (2022). The IPCC and the challenge of ex post policy evaluation. Papers 2207.14724, arXiv.org, revised Jan 2023.

Uglanova, I., & Gius, E. (2020). The Order of Things. A Study on Topic Modelling of Literary Texts. In: CHR 2020: Workshop on Computational Humanities Research (pp. 57–76). Amsterdam, The Netherlands.

van den Bergh, J. C. J. M., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., ... & Savin, I. (2021). Designing an effective climate-policy mix: accounting for instrument synergy. *Climate Policy*, 21(6), 745-764.

Wang, Z., Ding, J., Wang, L., & Zhu, Z. (2022). Ex-ante and ex-post approaches of evaluating carbon emission reduction in urban rail transit. *Mitigation and Adaptation Strategies for Global Change*, *27*(7), 46.

Wu, H., & Wang, Y. (2024). Integrating green resources and mineral dependency to address the urban-rural divide in China's carbon neutrality transition. *Resources Policy*, *88*, 104322.

Ecological Economics 220 (2024) 108182

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Multidimensional welfare indices and the IPCC 6th Assessment Report scenarios☆

Johannes Emmerling[a,b,*], Ulrike Kornek[c,d], Stéphane Zuber[e,f]

[a] CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
[b] RFF-CMCC European Institute on Economics and the Environment, Italy
[c] Christian-Albrechts-Universität Kiel, Department of Economics, Kiel, Germany
[d] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[e] Centre d'Economie de la Sorbonne, Université Paris 1 Panthéon Sorbonne and CNRS, France
[f] Paris School of Economics, France

ARTICLE INFO

Keywords:
Welfare
Climate scenarios
Multidimensional
Substitutability

ABSTRACT

The IPCC's 6th assessment report (AR6) has provided a wide range of variables and scenarios that meet climate targets of varying ambition. Many variables reported in the AR6 affect human welfare through climate change and mitigation, including but not limited to economic output, the natural environment, human health, and food and energy supply. In some of these dimensions, trade-offs exist between better performance in welfare-relevant dimensions and reaching more ambitious climate targets. Here, we apply recent advances in the theoretical multidimensional measurement of welfare, like the Human Development Index, to the AR6 database. The welfare metric is based on a welfare function approach, simple to apply, and intuitive. We apply a range of specifications of the welfare metric, aiming to derive robust rankings of climate policy targets that perform best in terms of the multidimensional welfare index. Across a large range of weights on welfare-relevant variables, we find that lower temperature is associated with higher welfare in 2100 unless there is a high weight on food supply.

1. Introduction

Human development in the 21st century faces significant challenges. The Sustainable Development Goals call for human progress in a wide range of economic, social and ecological dimensions (United Nations, 2019), where there may be synergies in achieving some goals but where progress in other dimensions may compete for limited resources (Moyer and Bohl, 2019). The Sustainable Development Goals are thus broadening our understanding of what is important for human development for the next decades. While economic growth has been an engine of development in the 20th century, though not universally (Ranis et al., 2000; Suri et al., 2011), the Human Development Index (HDI) introduced in 1990 adds education and health to economic development as important determinants of human wellbeing (UNDP, 2020). The HDI allows ranking different development pathways across space and time to identify strategies that further human wellbeing. Considering the Sustainable Development Goals, multidimensional welfare metrics such as the HDI need to be amended to include more dimensions, most importantly those pertaining to environmental issues such as climate change and biodiversity.

We apply a class of multidimensional welfare metrics based on the HDI to rank alternative scenarios of climate change mitigation. The welfare metric aggregates indicators for economic development, education, health, climate change and biodiversity. By ranking alternative scenarios of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), we test in which cases meeting more stringent climate targets improves welfare. We find that in many scenarios, welfare improves with lower global temperature. There are, however, important exceptions. First, strong climate policy is associated with lower welfare in the short-term especially if there is low substitutability between different dimensions. In the short term, costly climate action hinders economic development and adversely affects food supply that

☆ The research leading to these results received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 821124 (NAVIGATE) and from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056891 (CAPABLE) and No 101081604 (PRISMA).

* Corresponding author at: CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy.
E-mail address: johannes.emmerling@cmcc.it (J. Emmerling).

https://doi.org/10.1016/j.ecolecon.2024.108182
Received 11 August 2023; Received in revised form 11 March 2024; Accepted 13 March 2024
Available online 26 March 2024

cannot be offset by progress in other indicators if substitutability is low. Second, welfare improves if less stringent climate targets are met when there is a relatively high weight on food supply, because stringent climate change mitigation competes with higher global food supply.

Our welfare metrics extend concepts such as the Planetary pressures adjusted HDI (PHDI, (Roy et al., 2023)) by incorporating environmental indicators for human wellbeing but allowing for flexible assumptions about normative parameters, such as the OECD's Better Life Index (Decancq, 2015). The normative parameters allow varying the importance that certain dimensions play in aggregate welfare and allow varying in how far a low score in one dimension may be offset by a high score in another dimension. The welfare metric thus quantifies trade-offs between reaching multiple dimensions of human development. Such trade-offs have been described in previous literature (Moyer and Bohl, 2019; von Stechow et al., 2016), and make it more difficult to prioritize alternative development strategies. Indeed, assessing environmental dimensions or sustainability in a broad sense using a unique index has many conceptual and practical issues. While our approach is based on a conceptually founded welfare function approach, notably weighting exhibits still a great degree of arbitrariness (Böhringer and Jochem, 2007), which we address by performing a large sensitivity analysis on the vector of weights applied. Our indices also satisfies the conditions of being "meaningful" environmental indices (Ebert and Welsch, 2004). Our welfare metrics allow ranking alternative strategies and explicitly stating normative preferences about the importance of different dimensions, and their trade-offs, for human wellbeing.

We apply our welfare framework to the question of climate change mitigation. Limiting climate change is one of the key societal goals over the next decades as unmitigated climate change leads to significant impacts on human wellbeing (Franchini and Mannucci, 2015; IPCC, 2022; Pecl et al., 2017). However, climate change mitigation also has adverse impacts on other indicators for human wellbeing that belong to the Sustainable Development Goals (IPCC, 2022). We thus aim at investigating when meeting stringent climate change targets improves global welfare, and when and why it does not. In that respect, our paper is part of a growing literature highlighting the importance of a multidimensional perspective in the context of environmental and climate policy (Botzen and van den Bergh, 2014; Pillarisetti and van den Bergh, 2010; van den Bergh, 2010), for instance using Integrated Assessment Models (Bastien-Olvera and Moore, 2020; Drupp and Hänsel, 2021). Here we explore such multidimensional approaches in the rich AR6 scenario database to draw more general conclusions regarding welfare.

The paper is organized as follows. Section 2 summarizes our methods by introducing the welfare metric and the climate change mitigation database. Section 3 shows the indicators for welfare that follow from the database as well as presents our results on welfare. Section 4 shows a large ensemble of weights used, and Section 5 discusses caveats of the paper. Section 6 concludes.

2. Methods

2.1. Multidimensional welfare metrics

Multidimensional indices are useful to assess welfare or sustainable development in a concise and transparent way when multiple dimensions are deemed relevant. In this paper, we consider a broad class of such indices that encompass and generalize some existing approaches.

To be more specific, let ℓ denote the number of dimensions considered in the analysis, and $(I_1, I_2, \cdots, I_\ell)$ the vector of the ℓ indicators for the performance in each dimension. The general formula for our synthetic indicators will be[1]:

$$I = \left(\sum_{j=1}^{\ell} \omega_j \times (I_j)^{1-\rho}\right)^{1/(1-\rho)} \quad (1)$$

where ρ is the substitutability parameter and ω_j the weight put on dimension j.

The substitutability parameter measures how difficult it is to compensate for a bad score in some dimension with a good score in another dimension. When $\rho = 0$, we are in a situation where dimensions are completely substitutable. When $\rho \to \infty$, there is no compensation possible between dimensions.

The weights describe the importance of each dimension. To be meaningful, those weights must be applied to commensurable variables. In turn, commensurability depends on how the indicators are normalized. (Böhringer and Jochem, 2007) highlight that there are three key steps in the construction of multidimensional indices: aggregation, weights, and normalization.

The aggregation method displayed in Eq. (1) is characterized by (Ebert and Welsch, 2004) in a case where the different indices are comparable and ratio-scale measurable: this requires a common meaningful 0 for all dimensions, a comparable value at 1, and the independence of measurement to changes in scales. To ensure those conditions, the common practice is to normalize indices so that 0 corresponds to the worst imaginable (or acceptable, or existing) value of the variable, 1 corresponds to the best imaginable (or acceptable, or existing) value of the variable, and the index is interpreted as the relative achievement of the best situation. So, we need that the indices are normalized, i.e. to decide explicitly the cases where they take values 0 and 1. In the HDI methodology, these are called "dimension indices". We discuss the exact formula for the normalization of the indicators in the next subsection. Remark that if instead we require the weaker condition that variables are non-comparable but still ratio-scale measurable, that is we need not set the value at 1, only case $\rho = 1$ remains possible.

Even within our family of indices displayed in Eq. (1), there is still a large variety of choices depending on the value of parameter ρ and of the weights. As rightly pointed out by (Böhringer and Jochem, 2007), there is some degree of arbitrariness (or "subjectivity" as they put it) in the choice of those values that reflect normative views. To be transparent about this, the present paper explores how those changes affect welfare evaluation.

Our family of indices covers several special cases that have been proposed in the literature. In particular, the HDI is a key multidimensional measure of development produced annually by the United Nation Development Program (see UNDP, 2020). It is based on indicators of three dimensions of human development: a normalized indicator of education I_E (average years of schooling), a normalized indicator of health I_H (life expectancy), and a normalized indicator of income I_Y (log of average income).

These indicators are combined in a specific way. The initial formula was an arithmetic mean:

$$HDI_{old} = \frac{1}{3}(I_E + I_H + I_Y) \quad (2)$$

But in 2010, a new formula was introduced, namely a geometric mean:

$$HDI_{new} = (I_E \times I_H \times I_Y)^{1/3} \quad (3)$$

As explained by (Fleurbaey, 2018), the new formula implies some complementarity between the dimensions. This reflects a preference for balanced development in which income, health and education make progress together. The new formular implies a specific assumption about the degree of substitutability: the old formula assumed perfect substitutability, while the new formula allows more limited substitution possibilities. Both formulas assume equal weights on all three variables. The simple sum version of the HDI has for instance been applied to the

[1] In the case $\rho = 1$ the formula becomes $I = \prod_{j=1}^{\ell} (I_j)^{\omega_j}$.

status and benefits from the oceans (Halpern et al., 2012), but it has been shown that the more general framework proposed in the present paper can significantly alter the assessment of the human-ocean system (Rickels et al., 2014).

The HDI has been extended in several ways. First, an Inequality-adjusted Human Development Index (IHDI) was proposed to adjust for inequality in each dimension. To do so, it draws on Atkinson (1970) approach of adjusting social welfare for inequality, and on the associated family of inequality measures. Specifically, let X a dimension of interest and $(X_1, \cdots, X_n)$ denote the underlying distribution in that dimension. The Atkinson index A_X^ε for parameter $\varepsilon \geq 0$ is[2]

$$A_X^\varepsilon = 1 - \left(\frac{1}{N}\sum_{i=1}^{n} \frac{X_i^{1-\varepsilon}}{\overline{X}}\right)^{\frac{1}{(1-\varepsilon)}} \tag{4}$$

where $\overline{X} = \frac{1}{N}\sum_{i=1}^{n} X_i$ is the average value.

The IHDI adjusts each variable (life expectancy, mean years of schooling and disposable household income) for inequality, using the Atkinson index with parameter value $\varepsilon = 1$. The formula is then:

$$IHDI = \left(\left(1 - A_E^1\right)I_E \times \left(1 - A_H^1\right)I_H \times \left(1 - A_Y^1\right)I_Y\right)^{\frac{1}{3}} \tag{5}$$

Parameter ε in the Atkinson index embodies the degree of aversion to inequality. When $\varepsilon = 0$ (no inequality aversion) the Atkinson index is always equal to 0. When $\varepsilon \rightarrow \infty$, we tend to a Rawlsian case that focuses on the worst-off and the Atkinson index is equal to one minus the ratio between the minimal value and the average value.

More recently (UNDP, 2020), the UNDP has introduced another index named Planetary pressures–adjusted HDI (PHDI). It adjusts the HDI for the level of planetary pressures through a composite index P (based on CO2 emissions per capita and material footprint per capita) that takes value 0 for maximal pressure, and value 1 for minimal pressure. The formula is:

$$PHDI = P \times (I_E \times I_H \times I_Y)^{1/3} \tag{6}$$

The PHDI corresponds to a special case of our general Eq. (1) where $\rho = 1$ and the weight on the Planetary pressure index P has as much importance as the three other indices combined.

There are important limitations of indices in the HDI family (HDI, IHDI and PHDI), especially from the viewpoint of analyzing climate policy. First, they all make very specific assumption both on parameter ρ and on the weights. Regarding the weights, this is for instance in contrast with the Better Life Index of OECD that allows flexibility in that respect (Decancq, 2015). There is a lack of justification for the specific assumptions of HDI (Decancq et al., 2009). Second, all the indices except the PHDI neglect important dimensions that particularly matter, as the focus focuses on three anthropocentric dimensions (income, education, health). The PHDI includes the adjustment for planetary pressures. However, it does so in a specific way (specific weight on HDI and planetary pressures, specific substitutability). Also, by focusing on the per capita footprint of humans, it neglects other aspects like the state of biodiversity.

Inequality adjustment in the IHDI offers an interesting enrichment of the welfare framework, although the methodology again takes a specific value for inequality aversion in the Atkinson family (namely $\varepsilon = 1$). However, in this paper we have not been able to include this important dimension of human sustainable development. Indeed, the AR6 database only has data at the regional level, which is a not very detailed level for inequality analysis. We keep this for future research.

In this work, our central case will be $\rho = 1$ and equal weight on different dimensions that we describe below. This central case corresponds to a situation where the different dimensions need not to be measured on the same scales, and it is a typical dividing case between small a large substitutability. It is also a common choice in the literature (this is the choice made in the new version of the HDI and it is also often in IAMs including multidimensional welfare measurement (Drupp and Hänsel, 2021)). But we will also consider how the choice of those parameters may change our results.

2.2. Data selection from the AR6 scenario database

We compute the welfare level of scenarios in the AR6 scenario database (Byers et al., 2022). The AR6 scenario database is part of the Sixth Assessment Report of the IPCC. The database collected model-based scenarios where varying climate change targets are met, and reports the level of key variables related to, e.g., temperature, emissions, and socio-economic dimensions like GDP. In an open call, scenarios could be submitted which belong to a peer-reviewed publication or approved grey literature. The AR6 database includes over 3000 scenarios from close to 200 modelling frameworks.

In accessing the AR6 database using the "pyam" package (Huppmann et al., 2021), we evaluated a total of 1656 variables, which are available for at least one scenario and model. However, a large part of the variables comprises energy system variables and (post-processed) climatic variables at the global level. Moreover, most variables are scarcely reported, and only available for a small subset of models. Finally, many variables measure very similar dimensions (e.g., capacity, investment, costs, or installation data on energy technologies). Therefore, we limited the number of scenarios and models, aiming to have a sufficient number of models and scenarios while capturing the largest possible number of dimensions, notably economic affluence, health, nutrition, energy availability, and land-use. Since emission data is widely available, and pollutants have different impact channels, we included two types of pollutants, and finally we also added global temperature as just one dimension capturing global warming. Ultimately, our multidimensional welfare measure includes seven indicators that are part of the AR6 scenario database. These indicators represent relevant well-being dimensions:

- Temperature represents the degree of global warming (GMT increase) and related impacts
- NOx emissions are a proxy for health impacts
- Sulfur emissions are a similar proxy for health impacts
- Food supply is a proxy for health impacts related to changes in agriculture and food consumption
- Electricity production is taken as an indicator of energy access and clean energy provision. Moreover, it has been found to be highly correlated with education levels (see Ahmad et al., 2014; Banerjee et al., 2021; Kanagawa and Nakata, 2008). In general, it has indeed been shown that access to affordable, clean, and safe sources of energy is essential to achieving universal and equitable access to education (United Nations Department of Economic and Social Affairs, 2014), which we cover through this indicator.)
- GDP is the usual index of economic development
- Forest cover is an index of biodiversity preservation

For the welfare metric, NOx and sulfur emissions, food supply, electricity and GDP enter on a per-capita basis. In addition, we combine the indicators for NOx and sulfur emissions to one indicator by letting them equally share a welfare weight.

To calculate welfare, the seven variables are transformed into dimension indicators, meaning that they are normalized between a worst state (corresponding to a value of 0) and a best state (corresponding to a value of 1). Minimum and maximum values are set to perform this transformation of indicators.

[2] In the case $\varepsilon = 1$ the formula becomes

$$A_X^1 = 1 - \frac{\left(\prod_{i=1}^{n} X_i\right)^{1/n}}{\overline{X}}$$

.

More specifically, the dimension indicators are computed in the following way, depending on whether we measure a good or a bad: for the goods log of GDP, Food supply, Electricity, and Forest Cover, the indicator is $\overline{I_j} = \frac{I_j - I_{j,min}}{I_{j,max} - I_{j,min}}$; for the bads Temperature, NOx emissions, and Sulfur emissions, the indicator is computed as $\overline{I_j} = \frac{I_{j,max} - I_j}{I_{j,max} - I_{j,min}}$.

Thus, we need minima and maxima ($I_{j,min}$ and $I_{j,max}$) to enter the indicator specification for the seven dimensions. As elaborated in 2.1, for a good (bad) the minima should correspond to some worst (best) case while the maxima reflect a best (worst) case. To define the extrema for our analysis, we take a pragmatic approach and either set these extrema equal to the minima and maxima across all scenarios and time steps in the AR6 database (after removing outliers) or use exogenous reference scenario. Doing so, we know that the level of indicators varies between sensible boundaries that match the AR6 database.

For all variables except GDP, maxima correspond to values observed in the AR6 database (see Table 1). We take this approach because values in AR6 may go beyond observed data as the economy transforms to be either more or less climate friendly. Food supply is a good example, where future production may exceed observed historical values. For GDP, we keep the maximum of 75,000 USD set by the United Nations' definition of the HDI. This means that GDP may go beyond this maximum in some scenarios, which is however already the case for some countries today.

For minimum values, we either use AR6 minima or sensible exogenous data. For temperature, a value of zero refers to pre-industrial levels. For NOx and sulfur emissions, sources are both natural and anthropogenic where both sources can change with scenario projections. We use the AR6 database for their minima. For electricity, we set the value at zero as life without education is possible (the minimum expected schooling years are zero in the HDI definition of the United Nations). For our food indicator, we use the “Minimum dietary energy requirement” of the FAO. For GDP we use the minimum value used in the HDI by the United Nations. Concerning forest land cover, a minimum is hard to define, and we rely on the observation that some regions do not have any forest and set the minimum to zero.

In Fig. 1, the seven variables that enter our welfare metric are depicted as the AR6 data base reports them, together with population as we use per-capita values for several indicators (emissions, electricity, food supply, GDP). One can see that the scenarios cover a range of possible futures. Population and socio-economic activity including climate policy drive temperature change, emissions of air pollutants, land use change as well as energy and food supply. As we intend to compare the welfare level of different scenarios, we limit our analysis to only scenarios of the second Shared-Socioeconomic-Pathway (SSP2).

Fig. 1 shows that the number of scenarios that report certain variables varies: Food Supply is reported by only few scenarios compared to, for example, Temperature or GDP. Overall, we find a total of 198 scenarios that belong to SSP2 and offer values of all 7 variables chosen to enter our welfare metric.[3] Table 2 reports which models provided the 198 scenarios, which are in most cases the same across categories. In addition, we show how many scenarios belong to the 7 climate assessment categories used by the IPCC. These categories vary from meeting the stringent climate change target of below 1.5 °C (C1) to high temperature changes of 4 °C (C7). (See Table 3.)

Already by observing these variables for different climate target categories, several important trends are visible: the more stringent scenarios in line with the 1.5-degree target (C1-C2, blue colors) show clearly higher electricity production (due to electrification being an important mitigation strategy in the transportation and buildings sector), and a higher forest land cover. On the other hand, air pollutant emissions are significantly lower. GDP and Food supply show a mixed picture, where costs of mitigation and impacts on land-use due to bioenergy crops can lead to higher or lower values under the stringent scenarios.

3. Results

We first analyze the indicators derived from the seven variables that enter our welfare metric. We structure our analysis along the seven climate impact categories of the IPCC that rank the stringency of the entire temperature trajectory until 2100 (see Table 2). This allows us to assess how climate targets influence each of the indicators. We next analyze how different weighting schemes and levels of substitutability to aggregate indicators shape the correlation between yearly temperature levels and welfare.

Fig. 2 reports the indicators for the years 2030, 2060 and 2100 and only for the 198 scenarios that reported all 7 variables. The indicators take on values between 0 and 1.2. To foster comparison between all 7 variables, the scale in Fig. 2 is 0 to 1.2 even if a certain variable's indicator varies little (see Fig. 8 in the Appendix for adjusted scales). For each year, indicators are grouped by the climate assessment categories of the IPCC (C1 to C7). Fig. 9 in the Appendix shows the correlation matrix between all indicators for the years 2060 and 2100.[4]

Temperature is one of the key variables reported in the AR6 database. Fig. 2 shows that the indicator for Temperature is at roughly 0.7 across all scenarios in 2030 and declines over time unless stringent climate targets are met by 2100 (C1 and C2). As expected, a climate category with higher temperature, i.e., going from C1 to C7, exhibits a lower indicator level, where the indicator reaches its lowest value at around 0.3 in 2100 for the category C7.

The indicator for GDP is always above 0.7 and varies around 1 in 2100 (Fig. 2). Note here that we only consider global GDP per capita in the indicator and thus abstract from any national or even subnational income inequality. Driven by economic growth, later points in time exhibit a higher indicator for GDP. There is a slight tendency for GDP to increase with meeting less stringent climate change targets, i.e., going from C1 to C7, but the effect is small as climate change mitigation is expected to cost only a few percentage points of GDP in most scenarios in the AR6 database. Important to note is that the scenarios in the AR6 database do not account for climate impacts.

Meeting more stringent climate change targets tends to improve the indicators for NOx emissions, Sulfur emissions and Forest cover in each time step (Fig. 2). The indicators tend to increase with lower temperature because climate change is mitigated through less fossil fuel combustion, which releases these emissions, and afforestation. Both NOx and Sulfur emissions' indicators tend to increase over time and almost reach 1 in 2100. If moderate to stringent climate targets are met, the indicator for Forest cover also increases over time.

Higher forest cover competes with food supply for land. Fig. 2 shows that, in each time step, the indicator for Food supply tends to increase when less stringent climate change targets are met. To reiterate, in the scenarios in the AR6 database there are by construction no impacts from climate change on the economy, neither on energy nor on agriculture. While this is clearly a limitation, further integration of climate mitigation and impacts is a very active research field, for which however no large-scale databases of scenarios are yet available. The indicator is below 0.5 in most scenarios and tends to increase over time, though only to a limited degree.

The indicator for electricity is rather low across all scenarios and tends to increase over time. Meeting more stringent climate change targets is associated with an increase in the indicator, albeit to a limited extent (Fig. 2), as the decarbonization is typically leading also to a further electrification of energy end uses in the transportation and buildings sector (Rockström et al., 2017).

[3] We removed one scenario that belongs to the C8 climate category for comparability.

[4] We do not show the correlation matrix for 2030 as temperature only varies very little.

Table 1
Minima and Maxima that are used in the welfare indicators.

Variable [unit]	Temperature [K]	NOx Emissions [kg/cap]	Sulfur Emissions [kg/cap]	Electricity [GJ/cap/yr]	Food Supply [kcal/cap/day]	GDP [USD/cap/yr]	Forest Cover [share of total land]
Type of variable	Bad	Bad	Bad	Good	Good	Good (log enters indicator)	Good
AR6 variable name	"AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3|50.0th Percentile"	"Emissions|NOx"	"Emissions|Sulfur"	"Final Energy|Electricity"	"Food Energy Supply"	"GDP|PPP"	"Land Cover| Forest" combined with "Land Cover"
minimum	0	0.49	0.12	0	1827	100	0
Source	MAGICC (relative Temperature)	AR6	AR6	see text	FAO[a]	UN[b]	see text
maximum	5.25	59	58	254	4505	75,000	0.61
Source	AR6	AR6	AR6	AR6	AR6	UN5	AR6

[a] FAO Food and Agriculture Organization (2020). Food Security Indicators. Access - Prevalence of undernourishment, yearly estimates. Update 13 July 2020.
[b] https://hdr.undp.org/sites/default/files/2021-22_HDR/hdr2021-22_technical_notes.pdf.

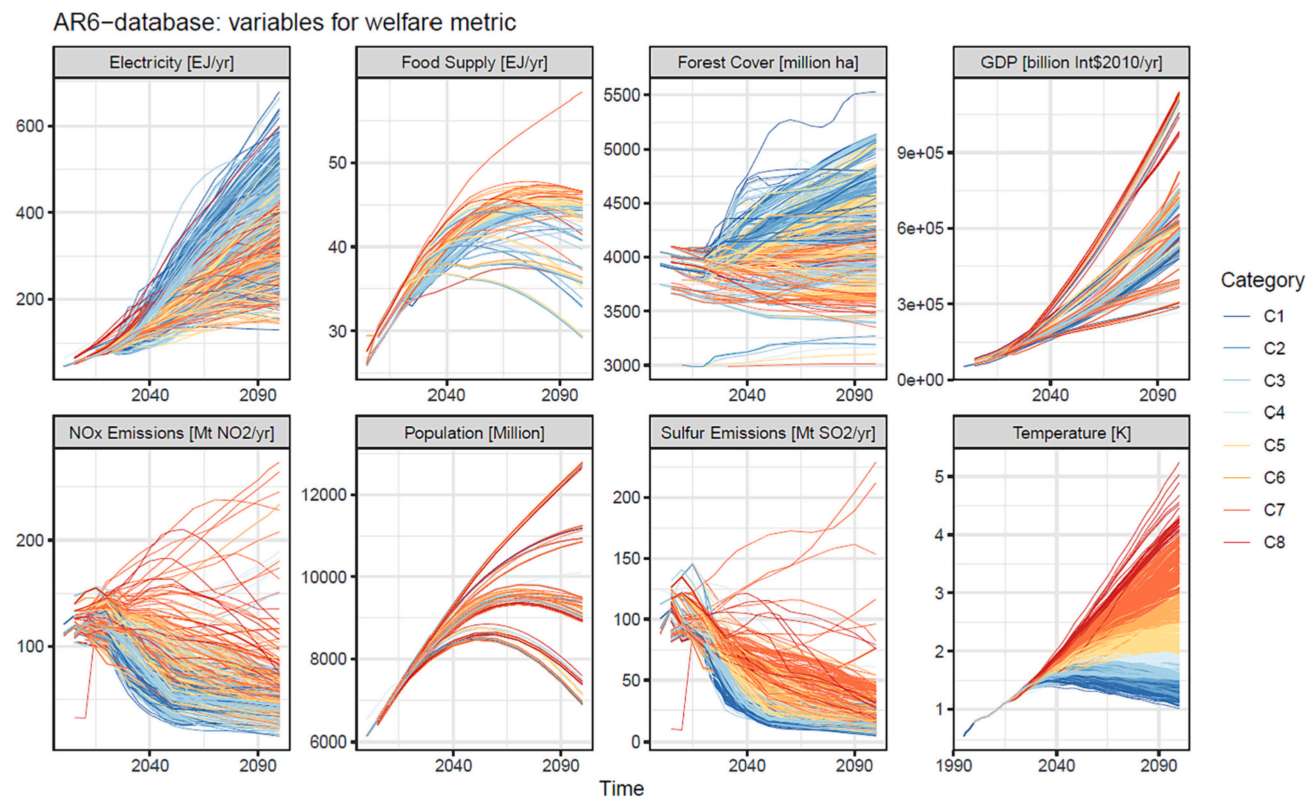

Fig. 1. Variables used for the welfare metric across all AR6 scenarios over time. Colors indicate the climate assessment category of the AR6 data base (see Table 2).

In conclusion, 5 out of 7 seven indicators tend to increase when more stringent climate change targets are met (Temperature, NOx and Sulfur emissions, Forest Cover, Electricity) while the other two indicators do not (GDP, Food supply). Fig. 9 in the Appendix confirms these relationships through correlation between the temperature indicator and all other indicators in 2060 and 2100. In addition, all indicators except for Temperature tend to increase over time.

The behavior of the seven indicators translates to welfare depicted in the last panel of Fig. 2, where the indicators are aggregated with a substitutability of $\rho = 1$ and equal weights (see Footnote 8). Welfare tends to increase over time and when more stringent climate change targets are met. In 2030, welfare is almost constant across climate assessment categories: meeting the different climate targets has only minor impacts on bio-socioeconomic variables in the short term and any variation is balanced by the welfare aggregation. In 2060, welfare is on average higher in almost all scenarios compared to 2030, which reflects the positive time trend of most indicators. The positive effect of meeting more stringent climate targets on welfare is already felt in 2060: on average, welfare is highest for stringent mitigation categories C1 and C2, which is higher than in C3 and so on. As 5 out of 7 indicators tend to improve with meeting more stringent climate change targets, welfare improves as well. These observations carry over to 2100: welfare tends to be higher compared to 2060 and welfare increases with more ambitious climate change targets. However, welfare in some scenarios of C7 is below some welfare levels in 2030. As some indicators are at their lowest level in 2100 (Temperature, Forest cover), overall welfare could decline if climate change is not mitigated.

Fig. 3 explores welfare in the AR6 scenario database when normative parameters take on different values. We tested the combination of three values for substitutability and three sets of welfare weights. For the former, we assume perfect substitutability ($\rho = 0$), limited substitutability ($\rho = 1$) and low substitutability ($\rho = 5$). For the latter, we vary

Table 2
Number of scenarios, and numerical model submitting them, that included all seven variables chosen for the welfare metric in the AR6 database and belong to SSP2; reported by IPCC climate category.

Category	Description	Number	Models
C1	Limit warming to 1.5 °C (>50%) with no or limited overshoot	13	AIM/CGE 2.2, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C2	Return warming to 1.5 °C (>50%) after a high overshoot	21	AIM/CGE 2.2, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C3	Limit warming to 2 °C (>67%)	56	AIM/CGE 2.1, AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0
C4	Limit warming to 2 °C (>50%)	31	AIM/CGE 2.2, IMAGE 3.0, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C5	Limit warming to 2.5 °C (>50%)	39	AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, REMIND-MAgPIE 1.7–3.0, WITCH 5.0
C6	Limit warming to 3 °C (>50%)	18	AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0
C7	Limit warming to 4 °C (>50%)	20	AIM/CGE 2.1, AIM/CGE 2.2, IMAGE 3.0, IMAGE 3.2, WITCH 5.0

Table 3
Regression results of the welfare index on GMT temperature increase.

Weight	Rho	Point estimate	Standard error	t-Statistic
Low GDP	0	−0.05100	0.00269	−18.95046
Equal	0	−0.04261	0.00244	−17.46432
High GDP	0	−0.00259	0.00205	−1.26447
Low GDP	1	−0.05067	0.00388	−13.05808
Equal	1	−0.04786	0.00373	−12.83819
High GDP	1	−0.00509	0.00210	−2.42060
Low GDP	5	−0.02590	0.00561	−4.61928
Equal	5	−0.02705	0.00586	−4.61814
High GDP	5	−0.04729	0.01050	−4.50255

the relative weight of GDP: the indicator for GDP receives a low, equal, or high weight relative to all other indicators[5].

Broadly summarizing Fig. 3, welfare tends to increase when more stringent climate change targets are met, and welfare tends to increase over time. Welfare increases because most indicators tend to increase over time and with more stringent climate change targets (Fig. 2). There are important exceptions to this broad picture.

First, average welfare in 2030 is lower in the stringent climate target category C1 compared to the lenient C7 category if substitutability is low ($\rho = 5$, bottom row), though the magnitude of the effect appears small. There can thus exist a trade-off between meeting stringent climate policy targets and some welfare dimensions in the short term.

Second, the relative importance of GDP in the welfare metric matters. In 2030 and 2060, average welfare tends to be slightly lower with meeting stringent climate change targets C1 and C2 compared to C3-C5 if the weight on GDP is high (column to the right in Fig. 3) and substitutability between indicators is perfect or limited ($\rho = 0$ or 1, top and middle row in Fig. 3). Meeting more stringent climate change targets induces costs for the current and near-term generations, which leads to lower welfare if the weight on those costs in welfare is high.

Third, it is important whether high scores of some indicators can substitute low scores of other indicators. If substitutability between indicators is low ($\rho = 5$, bottom row in Fig. 3), welfare does not further decrease across climate categories C3 to C7 in 2060 and 2100 but shows a more U-shaped form. On average, welfare is highest in the C1 and C2 categories and then declines to almost constant levels in C3 to C7. Interestingly, some scenarios in the C7 category have higher welfare than in the C6 and even the C5 category. With lower substitutability, welfare is driven more by those indicators that take on low levels. Fig. 2 shows that the indicators for Electricity and Food supply are on average lowest compared to the other indicators, as well as Temperature in 2100 when less stringent climate targets are met. While the Temperature indicator increases with more stringent climate change targets, Food supply tends to be negatively correlated with more stringent climate change targets and the indicator for electricity takes on higher values in some scenarios in the C7 category than in the C5 and C6 scenarios. Thus, for low substitutability, welfare displays the trade-off between increasing welfare through lower temperature versus higher food, and somewhat electricity supply. Some scenarios with high temperature but higher food and electricity supply exhibit higher welfare compared to scenarios with low temperature and lower food and electricity supply if substitutability is low.

Lastly, average welfare does not increase with time if less stringent climate targets are met (C7), GDP receives a low weight and there is perfect substitutability between indicators (top left panel in Fig. 3). In this case, economic growth cannot offset higher temperatures and the sharp decrease in the indicator for temperature over time drives the declining welfare level.

Taken together, for our central specification, Figure Fig. 4 shows the multivariate welfare index across the seven scenario categories of the IPCC in 2100. It shows the secular decline in average welfare as the temperature target becomes less stringent, while also for low temperature targets, the model uncertainty is larger indicating that the Paris Agreement compatible scenarios exhibit significant model differences and uncertainty. Only for the most stringent 1.5-degree target without or with overshoot (C1 and C2) the ranking is reversed, in that the scenarios without overshoot show a slightly lower level of welfare on average, albeit also a higher degree of uncertainty.

When looking at the relationship between the multidimensional welfare index, the parameter of the substitutability (ρ), and GDP per capita, Fig. 5 shows that in general (here shown for 2100), higher values of ρ lead to a lower value of welfare, and a larger dispersion. Moreover, higher values of GDP predominantly increase welfare.

When comparing the value of welfare to temperature increase by the end of the century, across models and scenarios, Fig. 6 highlights that lower values of global warming are associated with higher values of welfare, and the effect tends to be stronger for lower values of rho.

When comparing the slope as of how the welfare index on average changes with global mean temperature, Table 3 shows a change of between −0.01 and −0.05 of welfare for each degree of additional warming across scenarios, with a preferred value of −0.048 for equal weights and a unity elasticity.

4. Large ensemble of individual variable weights

We test our findings with a large set of runs varying the weights of all variables individually to capture a full simplex of weights. A variable either receives a weight of 100, 1 or 0.01 and we compute all combinations of those weights. After normalizing weights to sum to 1, 665 unique sets of weights emerge.[6] Combined with the three values for ρ, we have 3*665 = 1995 combinations of normative parameters. We then run the regressions from the previous section across all scenarios to

[5] Weights are (0.01,0.5,0.5,1,1,1,1) for low GDP, (1,0.5,0.5,1,1,1,1) for equal weights and (100,0.5,0.5,1,1,1,1) for high GDP, where the order of variables is GDP, NOx Emissions, Sulfur Emissions, Temperature, Electricity, Food Supply, Forest Cover. Weights are normalized to sum to 1 for the welfare computation.

[6] Note that as explained in Section 2, the indicator for NOx and Sulfur emissions are combined into one indicator that shares the same weight as the other dimensions, thus taking on values of 50, 0.5 and 0.005.

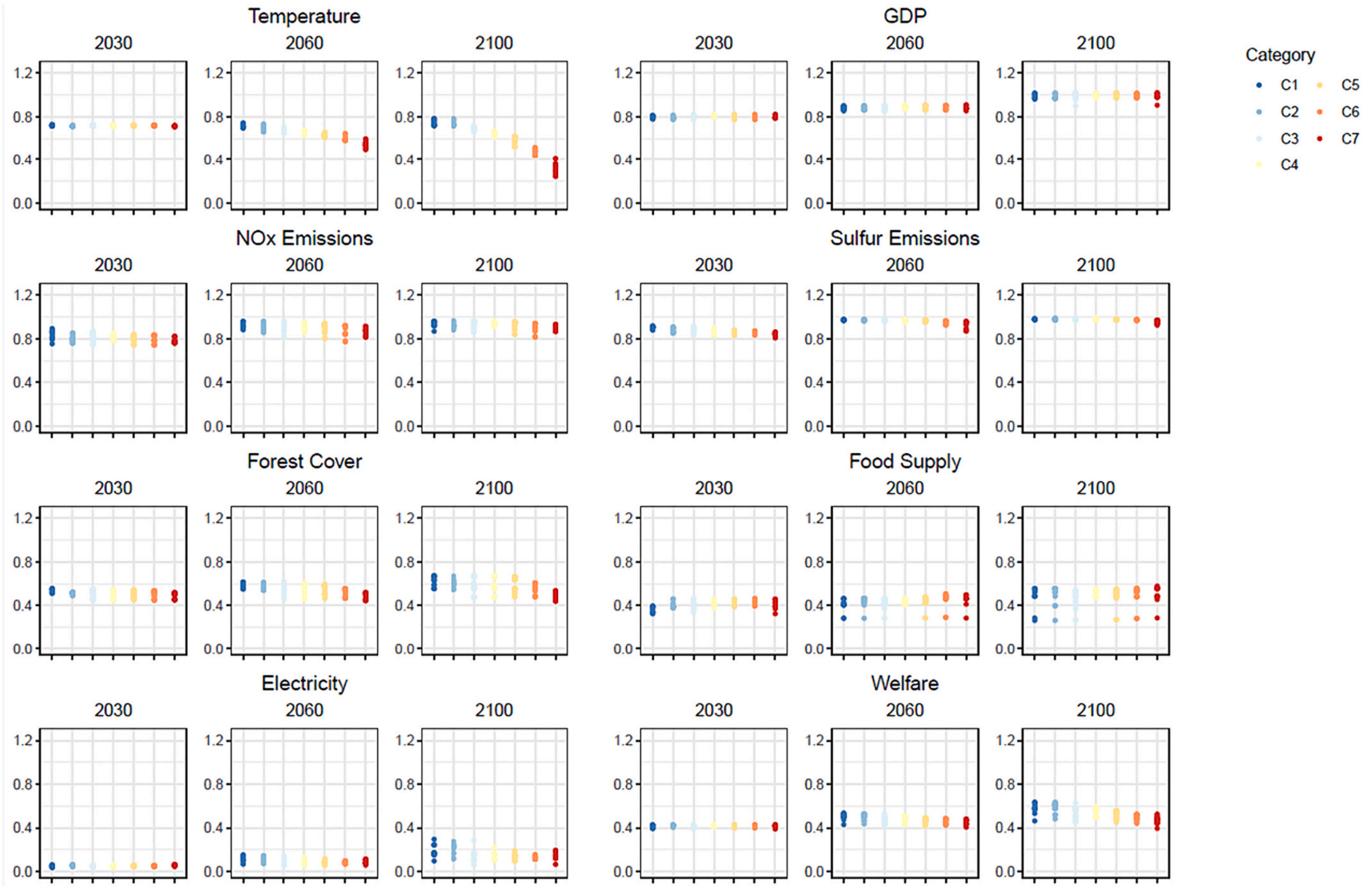

Fig. 2. Indicators of the seven variables entering the welfare metric for three points in time, and the welfare level for an elasticity of substitutability of $\rho = 1$ and equal weights (see Footnote 8). Colors indicate the climate assessment category of the AR6 database.

estimate the relationship between the degree of global warming (GMT increase) and the welfare index.

We first investigate the relationship between welfare and temperature in 2100. The estimated slope for all scenarios is shown in Fig. 7, where we indicate by the color the relative weight of Food Supply, which we find to be the most influential variable in potentially affecting this relationship.[7] Only for relatively high weights for Food Supply, approaching one (in blue) at the extreme, the relationship becomes slightly positive, indicating that the scenarios without stringent climate action and hence much higher degree of potential warming could lead to a higher level of welfare. In all other cases, the relationship is negative as found in the previous section. Considering all other variables, as shown in Fig. 10 in the Appendix, we don't find other variables for which a high weight leads to welfare and temperature increase being positively correlated. In terms of the absolute value of this relationship the median and mode lie within the range of -0.01 and -0.05, as reported in the preceding section, but can extend to up to -0.20, and in the extreme cases of highest weights on Food Supply turn to $+0.01$.

The average of the welfare index across all models and over time is 0.46, while its standard deviation in the whole sample with all weights and elasticity specification is 0.26. Therefore, we can conclude that the estimated impact of one degree warming on welfare is also sizable. For our preferred estimate of a decrease in welfare of 0.048 with 1 degree of warming (equal weights, medium substitutability), the estimated impact is around one-fifth of the standard deviation in the sample. Still, it can reach up to one standard deviation of the welfare index, which is a very wide range on a scale from 0 to 1. In equivalent terms, a reduction in per capita GDP of 39% on average would lead to the same decrease in welfare as 1 degree of warming for our preferred estimate.[8]

Fig. 11 and Fig. 12 in the Appendix show the relationship for 2060 and 2030, respectively. Here, differences in temperature increase are less pronounced across scenarios. For 2060 and for most weights and parameters considered, we find a similar relationship between welfare and temperature increase as for 2100, while now a positive relationship is possible of up to $+0.1$ per degree, but only in about 5–15% of the considered welfare weights and substitution elasticity. Only for the very near term (2030), and high elasticity values ($\rho = 5$), welfare always tends to increase with temperature increase (Fig. 12). This finding again highlights the trade-off between reaching more stringent climate mitigation and achieving other development goals, such as economic growth and food supply, in the near term. The trade-off is most pronounced when society views more progress in climate change mitigation as insufficient to offset less progress in other dimensions.

5. Limitations and caveats

This study has some limitations that should be considered. First, the welfare indices make specific assumptions about parameters and weights, albeit they can be changed to reflect substitutability and preferences. Eventually, the final weights used in our indices are still a choice of the analyst (Böhringer and Jochem, 2007). Allowing varying

[7] In the appendix, Figure 10 shows these estimated slope coefficients colored by the relative weight of each of our variables for 2100.

[8] We take the slope of the line in Figure 5 for our central case to calculate the absolute change in per capita GDP necessary for a reduction in welfare of 0.048. The absolute change is reported relative to mean global per capita GDP in 2100.

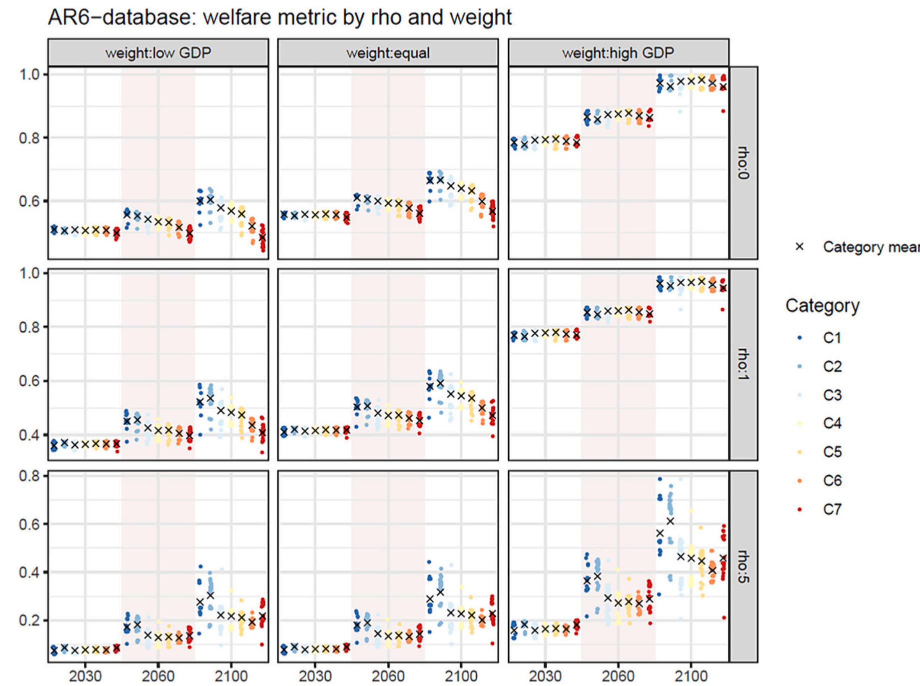

Fig. 3. Welfare metric in 2030, 2060 and 2100 for three values for the elasticity of substitutability ρ, which measures how difficult it is to compensate for a bad score in some dimension with a good score in another dimension (ρ=0 (=perfect substitutability), 1, 5). Moreover, we show the values for three sets of weights (low, equal, and high weight on GDP combined with equal weights for the other variables). Colors indicate the climate category.

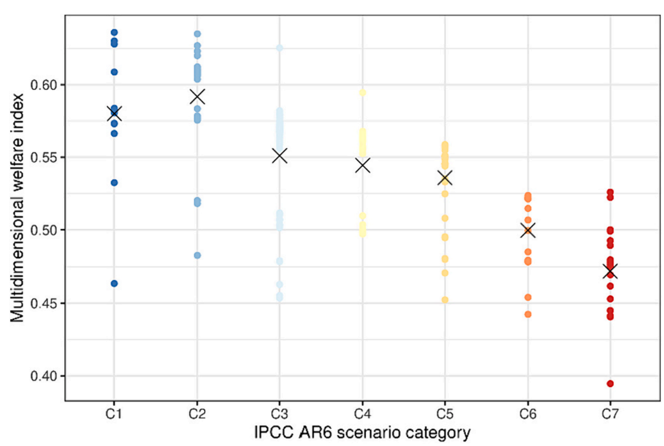

Fig. 4. Central case, welfare across climate categories (equal weights, ϱ = 1) in 2100; black crosses indicate mean across models.

weights such as in the Better Life Index of the OECD could allow flexibility in that respect (Decancq, 2015). Secondly, the list of available relevant variables (albeit we consider seven dimensions here) for these indices neglect important dimensions such as biodiversity, inequality, or water, which is limited by the database under consideration here. In addition, electricity is only a proxy for education with a partial but not a universal link, which limits the interpretability of our results in terms of this welfare dimension.

Thirdly, the degree of substitutability is not calibrated but rather considering intermediate values of one, while exploring different values in the sensitivity analysis. As for the weights, the choice of substitutability is left to the analyst. Fourth, our analysis is performed only at the global level, masking important regional and country-level differences. While this analysis can be easily performed also at a finer regional scale, accounting for inequality multiplies the dimensions of results to analyze and visualize through the choice of inequality measure. However, such an analysis could be easily performed, e.g., for a national analysis.

Despite these limitations, our study provides broad valuable insights into the importance of considering multiple dimensions of human wellbeing including environmental considerations, in particular by using a conceptually founded welfare function approach and performing a large sensitivity analysis on the vector of weights and substitution elasticities applied.

6. Conclusion

We analyze indicators derived from seven variables (Temperature, GDP, NOx emissions, Sulfur emissions, Forest cover, Food supply, and Electricity) to measure a multidimensional welfare metric for 198 scenarios of the IPCC AR6 database. The results show that meeting more stringent climate change targets tend to have a positive effect on 5 out of 7 indicators (Temperature, NOx and Sulfur emissions, Forest Cover, and Electricity) while only 2 indicators (GDP, Food supply) tend to increase with less stringent targets. The welfare metric increases over time and with more stringent targets for our central welfare metric. The study also tests different combinations of substitutability and welfare weights and finds that welfare generally increases with more stringent climate targets in 2100. However, meeting these more stringent targets may result in decreased welfare especially in the near-term or with a high weight on food supply. The reason food supply has this particular role is that in the IPCC scenario framework, climate impacts including on agriculture are not considered. On the other hand, the demand for bioenergy in particular drives up crop prices and induces land competition between food and energy crops, leading potentially to decreases of food production.

Overall, we find that even without considering impacts and damages from global warming, human welfare will be affected differently in

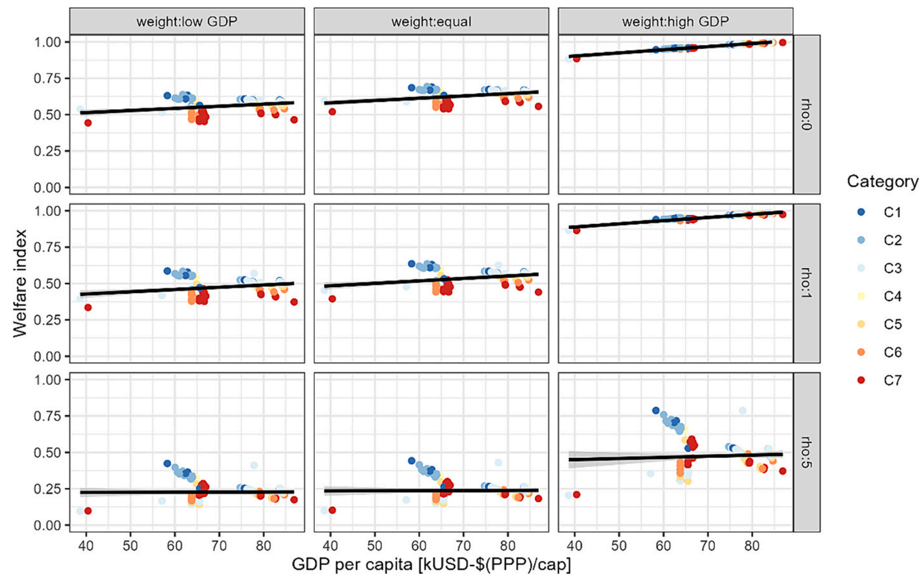

Fig. 5. Relationship of the welfare index with GDP per capita in 2100.

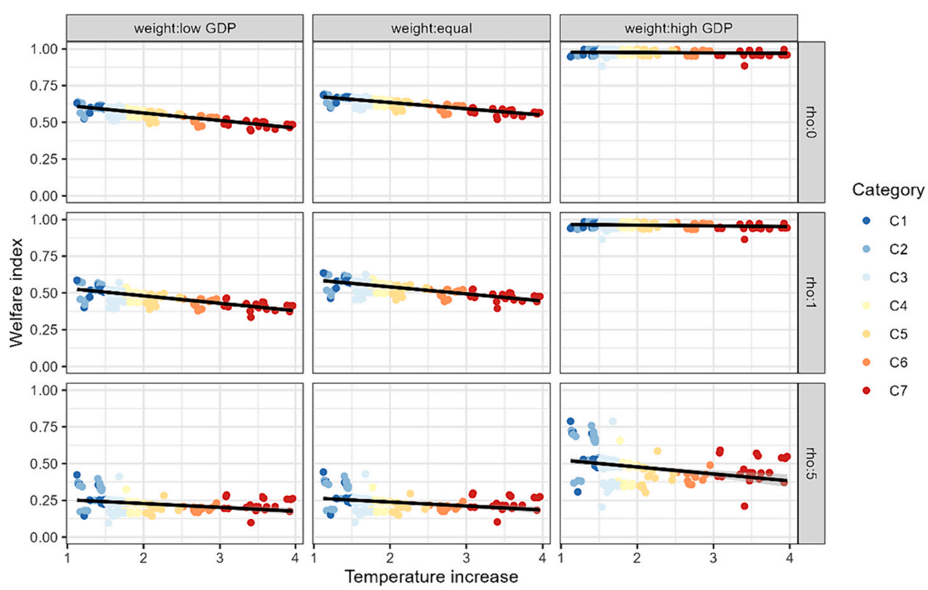

Fig. 6. Welfare index and GMT temperature increase in 2100.

different climate scenarios. The IPCC's 6th assessment report (AR6) has provided a wide range of variables and scenarios of different levels of climate policy ambition for this analysis. Since in several of these dimension trade-offs exist between more or less stringent climate targets and other dimensions that are relevant for human welfare, we use a general welfare evaluation framework with different weights and substitution elasticities to account for trade-offs and co-benefits. We find that a recently advanced theoretical multidimensional measurement of welfare can then provide a useful tool to derive robust rankings of climate policy stringency. Notably, we find that, on average, a one-degree higher global mean temperature is associated with a loss of about 0.05 on the welfare index at the global level in 2100. When exploring very extreme weights on the different variables, we find that placing a high weight on food supply alters this relationship, at the extreme, leading to slightly higher welfare levels with higher temperatures. For the full set of weights, welfare can decrease up to −0.20 points per degree of global warming.

Our results have important policy implications. Meeting more stringent climate policy targets generally improves human welfare in the medium- and long-term, even when climate change mitigation hinders development in other dimensions of human welfare, such as food availability and income. Thus, efforts to reduce emissions are of utmost importance. However, food security issues could reverse this conclusion as meeting stringent climate targets is often associated with afforestation and generating bioenergy that competes with land use to secure food supply. This important finding indicates that alleviating the trade-off between climate change mitigation and food supply is also of utmost importance. Ambitious efforts to increase food security thus also have important implications for climate policy and overall human welfare.

Finally, one important message from our findings is that GDP losses from stringent climate targets is a very narrow concept of policy costs. Only by adding the six other indicators available in the IPCC database the relationship between target stringency and GDP reverses in most cases. This indicates we should consider welfare beyond GDP

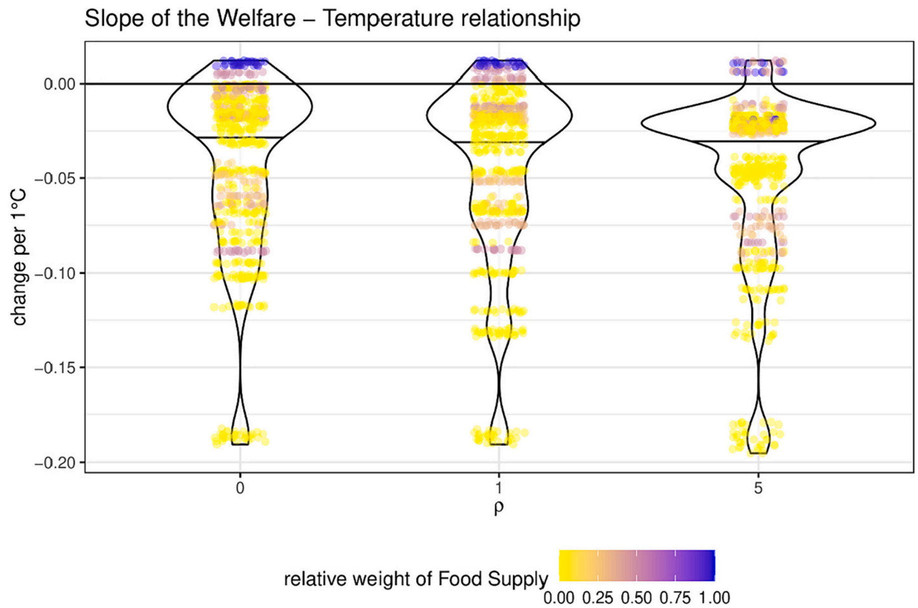

Fig. 7. Estimated slope of the relationship between global mean temperature (GMT increase) and the welfare index, here colored by the relative weight of Food Supply.

(Fleurbaey, 2009), as argued for also in the literature on alternatives to the growth paradigm such as a-growth (van den Bergh, 2011) or post-growth (Hickel et al., 2021) or degrowth (Hickel et al., 2022). Including more important dimensions, for instance, climate impacts (potentially non-linear and with tipping elements), distributional concerns, inequality, leisure and biodiversity impacts etc., may strengthen the beneficial welfare outcomes of the more stringent climate scenarios.

Our results also talk to the literature on the threshold hypothesis (Max-Neef, 1995). The hypothesis is that "for every society there seems to be a period in which economic growth (as conventionally measured) brings about an improvement in the quality of life, but only up to a point – the threshold point – beyond which, if there is more economic growth, quality of life may begin to deteriorate".

Our results highlight that policies that maximize the growth of conventional economic activity are indeed unlikely to maximize welfare as measured by our more comprehensive measure and that other aspects – like environmental quality – may be more important. On the other hand, economic growth is not incompatible with an increase in welfare or quality of life because we do have economic growth in almost all the scenarios of the AR6 database, even with very stringent climate policy. This is consistent with the results from Van der Slycken and Bleys (2024), who found no conclusive evidence so far regarding the threshold hypothesis in the EU-15.

CRediT authorship contribution statement

Johannes Emmerling: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ulrike Kornek:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Stéphane Zuber:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and code to generate all results and plots is available at https://github.com/JohannesEmm/multidimensional_welfare_ar6.

Acknowledgements

The research leading to these results received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 821124 (NAVIGATE) and from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056891 (CAPABLE) and No 101081604 (PRISMA).

Appendix A. Appendix

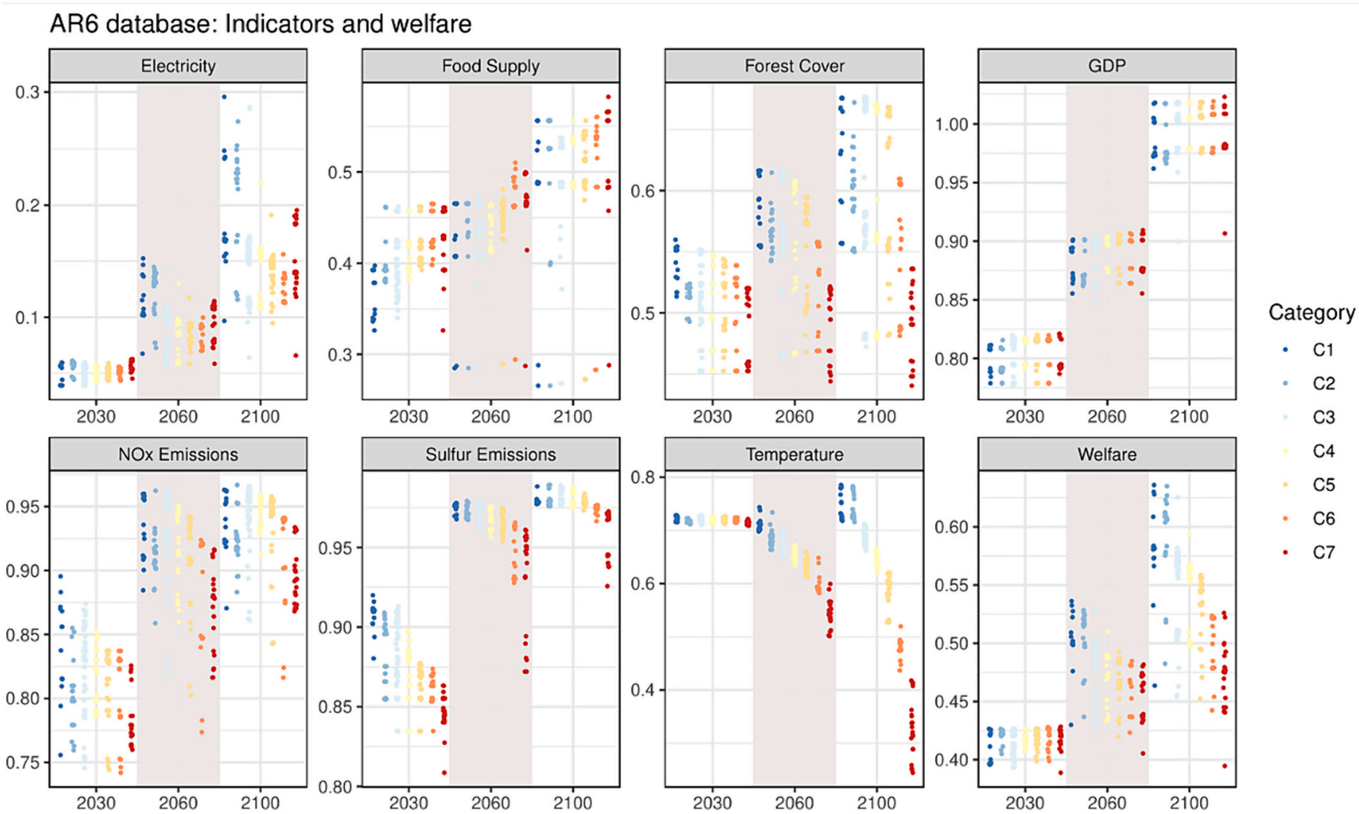

Fig. 8. Indicators of the seven variables entering the welfare metric for three points in time, and the welfare level for ρ=1 and equal weights. Colors indicate the climate assessment category of the AR6 database.

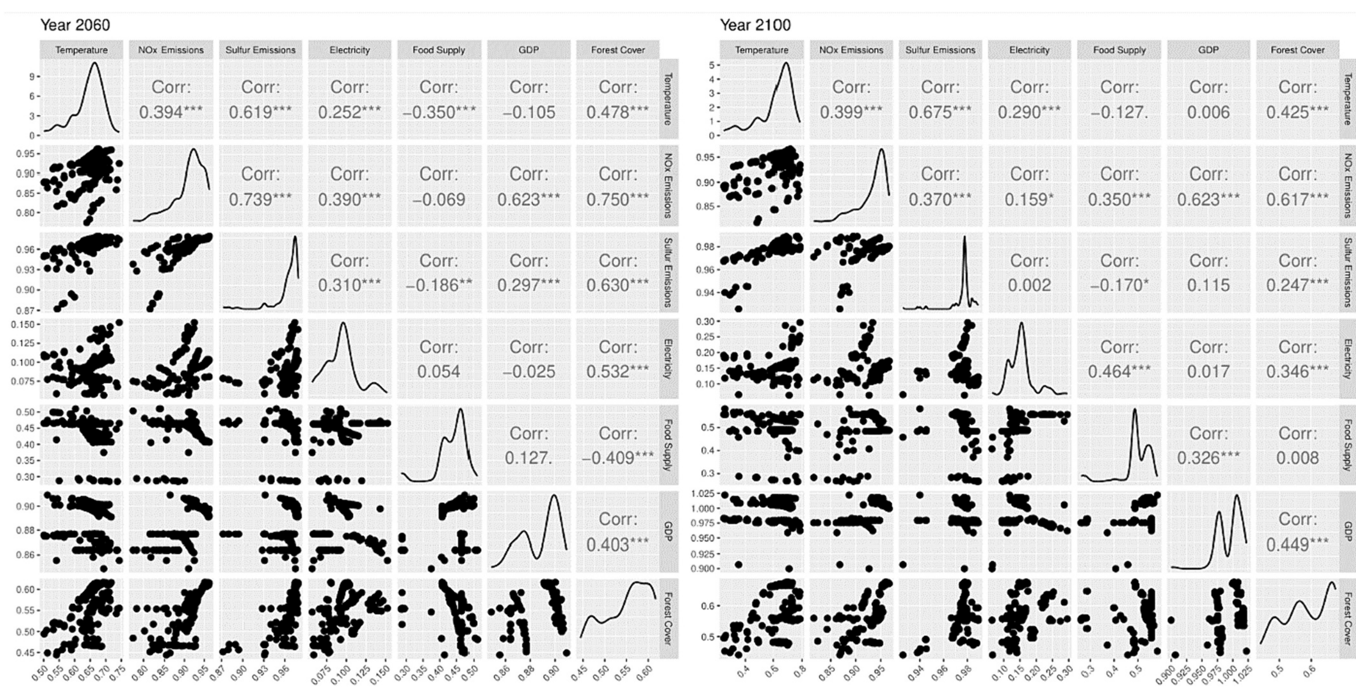

Fig. 9. Correlation matrix between indicators displayed in Fig. 2; "***" if the p-value is <0.001, "**" if the p-value is <0.01, "*" if the p-value is <0.05, "." if the p-value is <0.10, ""otherwise.

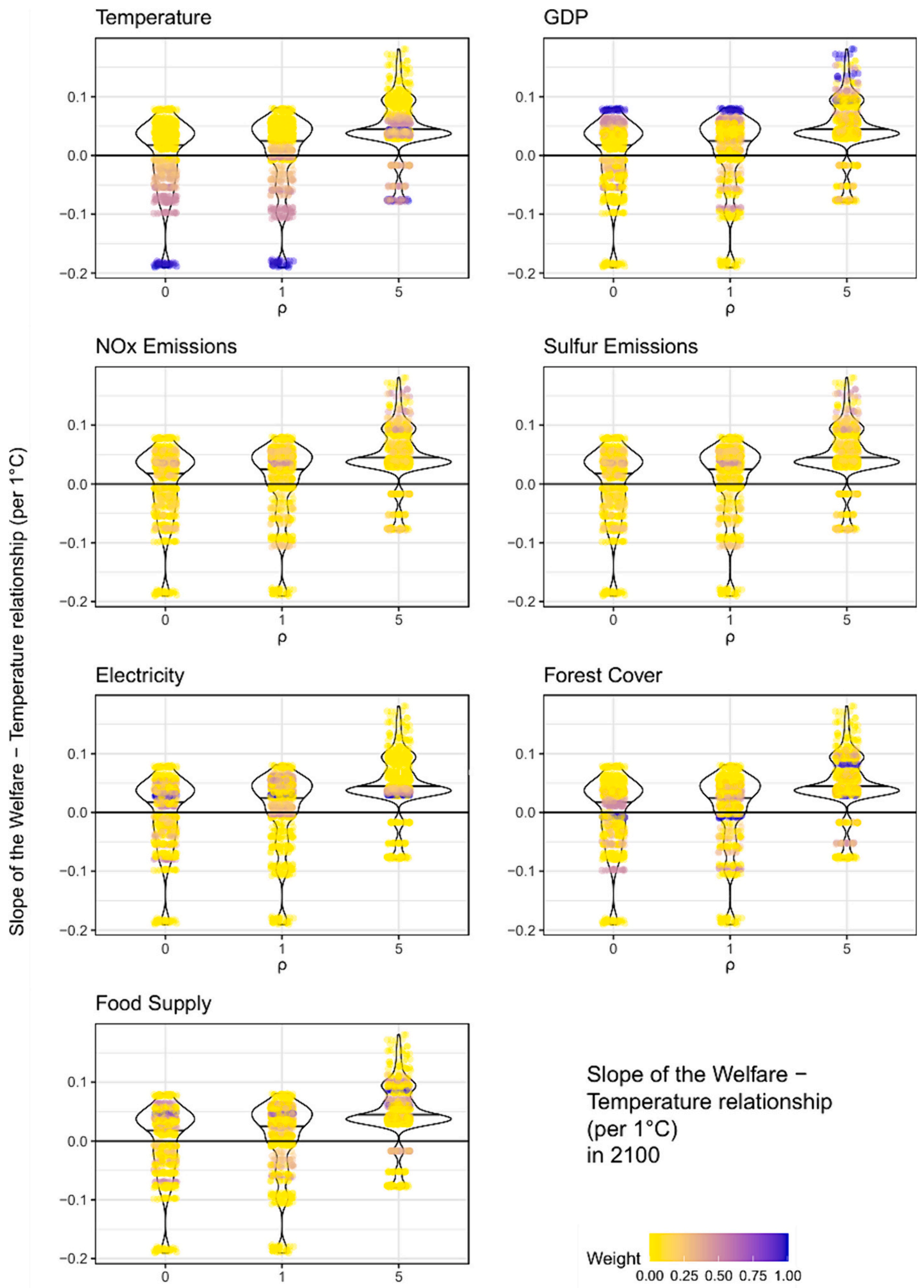

Fig. 10. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2100, for all combinations of weights and ρ. The different plots show by color the weights of each variable.

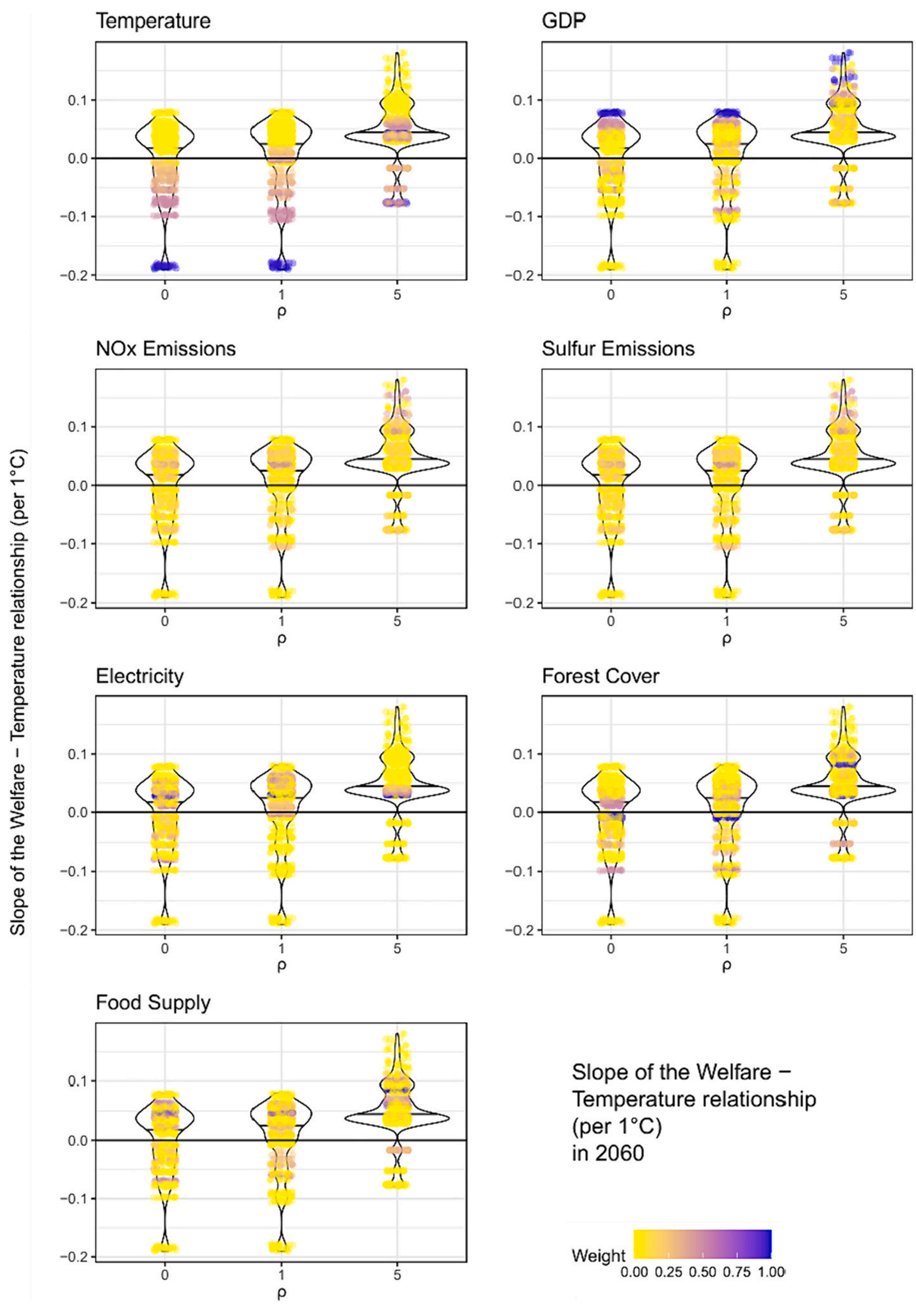

Fig. 11. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2060, for all combinations of weights and ρ. The different plots show by color the weights of each variable.

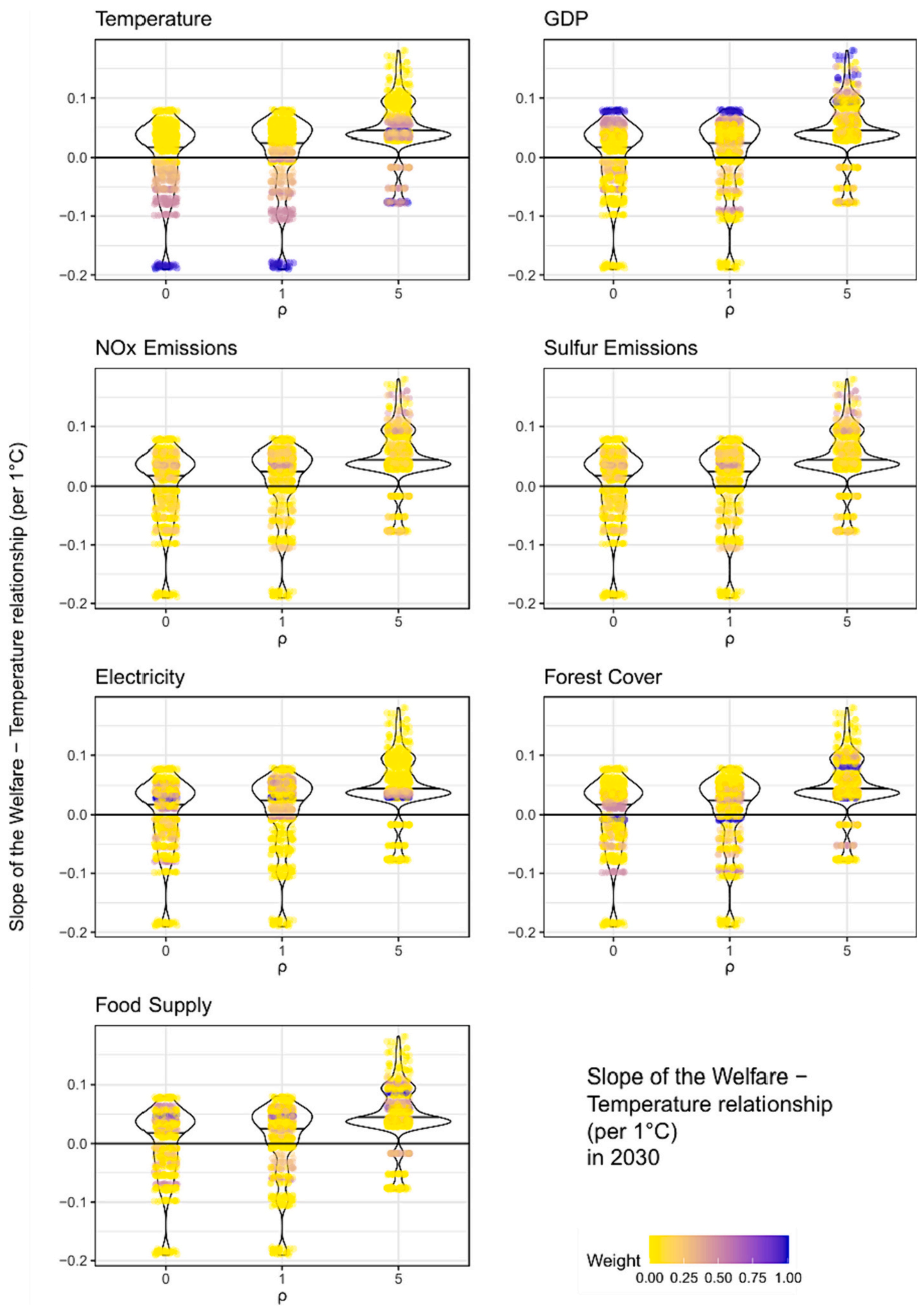

Fig. 12. Estimated slope of the relationship between global mean temperature (GMT) and the welfare index in 2030, for all combinations of weights and ρ. The different plots show by color the weights of each variable.

References

Ahmad, S., Mathai, M.V., Parayil, G., 2014. Household electricity access, availability and human well-being: evidence from India. Energy Policy 69, 308–315. https://doi.org/10.1016/j.enpol.2014.02.004.

Atkinson, Anthony B., 1970. On the Measurement of Inequality. Journal of Economic Theory, Journal of Economic Theory 2 (3), 244–263. https://doi.org/10.1016/0022-0531(70)90039-6.

Banerjee, R., Mishra, V., Maruta, A.A., 2021. Energy poverty, health and education outcomes: evidence from the developing world. Energy Econ. 101, 105447 https://doi.org/10.1016/j.eneco.2021.105447.

Bastien-Olvera, B.A., Moore, F.C., 2020. Use and non-use value of nature and the social cost of carbon. Nat. Sustain. 1–8 https://doi.org/10.1038/s41893-020-00615-0.

Böhringer, C., Jochem, P.E.P., 2007. Measuring the immeasurable — A survey of sustainability indices. Ecol. Econ. 63, 1–8. https://doi.org/10.1016/j.ecolecon.2007.03.008.

Botzen, W.J.W., van den Bergh, J.C.J.M., 2014. Specifications of social welfare in economic studies of climate policy: overview of criteria and related policy insights. Environ. Resour. Econ. 58, 1–33. https://doi.org/10.1007/s10640-013-9738-8.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Al-Khourdajie, A., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromman, A., Winkler, H., Auer, C., Brutschin, E., Gidden, M., Hackstock, P., Harmsen, M., Huppmann, D., Kolp, P., Lepault, C., Lewis, J., Marangoni, G., Müller-Casseres, E., Skeie, R., Werning, M., Calvin, K., Forster, P., Guivarch, C., Hasegawa, T., Meinshausen, M., Peters, G., Rogelj, J., Samset, B., Steinberger, J., Tavoni, M., van Vuuren, D., 2022. AR6 Scenarios Database. https://doi.org/10.5281/zenodo.7197970.

Decancq, K., 2015. Towards a distribution-sensitive better life index: design, data and implementation. In: OECD Stat. Work. Pap. OECD Statistics Working Papers.

Decancq, K., Decoster, A., Schokkaert, E., 2009. The evolution of world inequality in well-being. World Dev. 37, 11–25. https://doi.org/10.1016/j.worlddev.2007.12.006.

Drupp, M.A., Hänsel, M.C., 2021. Relative prices and climate policy: how the scarcity of nonmarket goods drives policy evaluation. Am. Econ. J. Econ. Pol. 13, 168–201. https://doi.org/10.1257/pol.20180760.
Ebert, U., Welsch, H., 2004. Meaningful environmental indices: a social choice approach. J. Environ. Econ. Manag. 47, 270–283. https://doi.org/10.1016/j.jeem.2003.09.001.
Fleurbaey, M., 2009. Beyond GDP: the quest for a measure of social welfare. J. Econ. Lit. 47, 1029–1075. https://doi.org/10.1257/jel.47.4.1029.
Fleurbaey, M., 2018. On human development indicators (no. March 2018). In: UNDP Humand Development Report Discussion Paper.
Franchini, M., Mannucci, P.M., 2015. Impact on human health of climate changes. Eur. J. Intern. Med. 26, 1–5. https://doi.org/10.1016/j.ejim.2014.12.008.
Halpern, B.S., Longo, C., Hardy, D., McLeod, K.L., Samhouri, J.F., Katona, S.K., Kleisner, K., Lester, S.E., O'Leary, J., Ranelletti, M., Rosenberg, A.A., Scarborough, C., Selig, E.R., Best, B.D., Brumbaugh, D.R., Chapin, F.S., Crowder, L. B., Daly, K.L., Doney, S.C., Elfes, C., Fogarty, M.J., Gaines, S.D., Jacobsen, K.I., Karrer, L.B., Leslie, H.M., Neeley, E., Pauly, D., Polasky, S., Ris, B., St Martin, K., Stone, G.S., Sumaila, U.R., Zeller, D., 2012. An index to assess the health and benefits of the global ocean. Nature 488, 615–620. https://doi.org/10.1038/nature11397.
Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., Steinberger, J., Ürge-Vorsatz, D., 2021. Urgent need for post-growth climate mitigation scenarios. Nat. Energy 6, 766–768. https://doi.org/10.1038/s41560-021-00884-9.
Hickel, J., Kallis, G., Jackson, T., O'Neill, D.W., Schor, J.B., Steinberger, J.K., Victor, P. A., Ürge-Vorsatz, D., 2022. Degrowth can work — here's how science can help. Nature 612, 400–403. https://doi.org/10.1038/d41586-022-04412-x.
Huppmann, D., Gidden, M., Nicholls, Z., Hoersch, J., Lamboll, R., Kishimoto, P., Burandt, T., Fricko, O., Byers, E., Kikstra, J., Brinkerink, M., Budzinski, M., Maczek, F., Zwickl-Bernhard, S., Welder, L., Alvarez Quispe, E., Smith, C., 2021. Pyam: analysis and visualisation of integrated assessment and macro-energy scenarios [version 2; peer review: 3 approved]. Open Res. Eur. 1 https://doi.org/10.12688/openreseurope.13633.2.
IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers.
Kanagawa, M., Nakata, T., 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36, 2016–2029. https://doi.org/10.1016/j.enpol.2008.01.041.
Max-Neef, M., 1995. Economic growth and quality of life: a threshold hypothesis. Ecol. Econ. 15, 115–118. https://doi.org/10.1016/0921-8009(95)00064-X.
Moyer, J.D., Bohl, D.K., 2019. Alternative pathways to human development: assessing trade-offs and synergies in achieving the sustainable development goals. Futures 105, 199–210. https://doi.org/10.1016/j.futures.2018.10.007.
Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C., Clark, T. D., Colwell, R.K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A., Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J.B., Strugnell, J.M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S.E., 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science 355, eaai9214. https://doi.org/10.1126/science.aai9214.
Pillarisetti, J.R., van den Bergh, J.C.J.M., 2010. Sustainable nations: What do aggregate indexes tell us? Environ. Dev. Sustain. 12, 49–62. https://doi.org/10.1007/s10668-008-9179-7.
Ranis, G., Stewart, F., Ramirez, A., 2000. Economic growth and human development. World Dev. 28, 197–219.
Rickels, W., Quaas, M.F., Visbeck, M., 2014. How healthy is the human-ocean system? Environ. Res. Lett. 9, 044013 https://doi.org/10.1088/1748-9326/9/4/044013.
Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., Schellnhuber, H.J., 2017. A roadmap for rapid decarbonization. Science 355, 1269–1271. https://doi.org/10.1126/science.aah3443.
Roy, A., Dutta, T., Li, Y., Dong, X., 2023. Human development at the cost of the environment?-an application of planetary pressures-adjusted human development index in the lens of planetary boundaries. Environ. Sci. Pollut. Res. Int. 30, 32383–32405. https://doi.org/10.1007/s11356-022-24399-2.
Suri, T., Boozer, M.A., Ranis, G., Stewart, F., 2011. Paths to success: the relationship between human development and economic growth. World Dev. 39, 506–522.
UNDP, 2020. Human Development Report 2020. UNDP U. N. Dev. Programme.
United Nations, 2019. The Sustainable Development Goals Report 2019. UN.
United Nations Department of Economic and Social Affairs, 2014. Electricity and Education: The Benefits, Barriers, and Recommendations for Achieving the Electrification of Primary and Secondary Schools. UNDESA, Rome.
van den Bergh, J.C.J.M., 2010. Safe climate policy is affordable—12 reasons. Clim. Chang. 101, 339–385. https://doi.org/10.1007/s10584-009-9719-7.
van den Bergh, J.C.J.M., 2011. Environment versus growth — A criticism of "degrowth" and a plea for "a-growth.". Ecol. Econ. 70, 881–890. https://doi.org/10.1016/j.ecolecon.2010.09.035.
Van der Slycken, J., Bleys, B., 2024. Is Europe faring well with growth? Evidence from a welfare comparison in the EU-15 (1995–2018). Ecol. Econ. 217 https://doi.org/10.1016/j.ecolecon.2023.108054.
von Stechow, C., Minx, J.C., Riahi, K., Jewell, J., McCollum, D.L., Callaghan, M.W., Bertram, C., Luderer, G., Baiocchi, G., 2016. 2 °C and SDGs: united they stand, divided they fall? Environ. Res. Lett. 11, 034022 https://doi.org/10.1088/1748-9326/11/3/034022.

A Welfare Analytic Approach to Climate Policy

Matthias Kalkuhl
Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany; Faculty of Economics and Social Sciences, University of Potsdam, Germany

Kai Lessmann
Potsdam Institute for Climate Impact Research, Germany; Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany

Charlotte Plinke
Potsdam Institute for Climate Impact Research, Germany; Faculty of Economics and Social Sciences, University of Potsdam, Germany

Lennart Stern
Potsdam Institute for Climate Impact Research, Germany; Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany

Michael Sureth
Potsdam Institute for Climate Impact Research, Germany; Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany; Technical University Berlin, Germany

June 7, 2024

Abstract
We develop an analytical framework for evaluating climate policies to inform policy-makers. Our approach allows to consider (i) various policy instruments like carbon pricing, taxes, subsidies, standards or bans, (ii) multiple market failures and externalities, related to market as well as non-market good consumption and (iii) the social cost of distributional effects of policies. Our approach is a generalization of cost-benefit analysis to facilitate the comparability of climate policy measures within a consistent welfare-economic perspective. It can be substantiated by synthesizing ex-post and ex-ante works on policy instruments. We outline the information needed to apply the framework. We illustrate the approach by evaluating a tax reform on meat products an a price on greenhouse gas emissions on food products.

Acknowledgments: This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101056891 - CAPABLE - ClimAte Policy AcceptaBiLity Economic framework. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

E-mail: kalkuhl@mcc-berlin.net (Kalkuhl); lessmann@pik-potsdam.de (Lessmann); plinke@pik-potsdam.de (Plinke); lennarts@pik-potsdam.de (Stern); michael.sureth@pik-potsdam.de (Sureth)

1. Introduction

The EU has set broad and ambitious goals for its environmental policies in its Green Deal. The Green Deal covers a broad range of areas, including resource use, pollution, biodiversity, and climate neutrality, to name but a few. To implement this agenda, the EU needs to specify policies. Reaching an agreement on policies is, however, a challenge, as different policies not only differ in their intended direct effect, for example, to reduce emissions, but also in the costs they impose on consumers and firms, in their distributional effects on consumer income and wealth, or in their effect on other policy areas (so-called co-benefits). The continued debate which policies are "best" to reduce carbon emissions is testament to the scope of this challenge.

Support for the decision process is offered by assessments and comparisons of policies, which offer guidance on how to select and prioritize policies, ranging from studies that identify optimal use of selected instruments such as the carbon price, to side-by-side evaluations of alternative instruments along multiple criteria. The wealth of different approaches provides a wealth of information but due to the heterogeneity in methods and evaluation criteria it is often hard to arrive at a conclusion.

In this study, we suggest an approach that may provide a unified perspective on the comparison of policies. We aim for the proposal to be informative for policymakers and at the same time attractive to use for researchers, that is, we aim for an approach that is at the same time pragmatic and applicable as well as back-up by a theoretical foundation. We reduce complexity by focusing on one comprehensive welfare metric but allow for heterogeneity social inequality aversion. More specifically:

- We adopt a utilitarian perspective such that our approach is founded in welfare theory. This choice also reflects that we take as given that the objective of any policy is ultimately to improve human well-being and counting well-being of every individual equally.
- We follow pragmatic choices to extend our welfare considerations to include multiple criteria beyond consumption, such as (environmental) co-benefits of the policy, or the distributional implications of the policy. This addresses the challenge of considering a policy's effects in many policy areas.
- To increase comparability across instruments and studies, we compare the welfare effect of a policy instrument (or package of instruments) relative to its contribution towards a policy goal, that is, we normalize the welfare costs (or welfare benefits) by their contribution to the policy's main objective, for example, by emissions reduction.

Our proposal complements a broad and extensive literature on environmental and climate policy instruments evaluation as summarized, for example, in the chapters on policies in the two most recent assessment reports by the IPCC (Somanathan et al. 2014; Dubash et al. 2022, hereafter AR5 and AR6). Both reports highlight two perspectives on the evaluation of policies. AR6 puts a focus on ex-post evaluation of policies, i.e. empirical analyses of observed implementations of policies. The increasing reliance on ex-post analysis of climate policies is facilitated by the rising number of actual implementations of climate policies. By utilization observations, ex-post studies cannot be biased from neglecting side effects or real word detail. Of course, isolating the effects of the policy under consideration from other events during the observation time is also a central challenge of this approach. Additionally, ex-post focus mostly on identifying causal effects but provide only in limited cases welfare or benefit-cost calculations.

Lessons from ex ante evaluation of climate policies, i.e. evaluation of policies based on economic theory and modeling, are more prominent in the AR5. Ex ante evaluation is particularly useful to analyze policies without historic precedence, to test policies in specific settings and to design policies (or policy packages) to their best effect.

At the level of assessment reports, the guidance on policy instrument choice is stated in general terms. For example, carbon pricing is identified as effective (based on observations) and particularly cost-efficient but often regressive (depending, of course, on revenue recycling) and less acceptable in public perception than subsidies or regulation (which can also complement carbon pricing by addressing sector specifics). A wealth of cited publication supports these broad findings (as reviewed, for example, in Döbbeling-Hildebrandt et al. 2024).

The generalizations that are necessary to arrive at this valuable guidance somewhat limits its applicability for specific policy decisions. Both reports highlight the need to evaluate policies along multiple criteria, but there is little advice on how to trade of the different criteria. A welfare theoretic approach, as outlined here, could provide information on how to value trade-offs between criteria.

The developed analytical framework is based on two fundamental concepts: (i) what matters to individuals is their well-being and (ii) what matters to societies – i.e. from a normative or social perspective – is how well-being is aggregated and distributed among individuals. These two aspects allow for a very flexible consideration of monetary and non-monetary impacts, uncertainties and risk aversion, status-quo bias and loss aversion and, finally, distributional outcomes and inequality aversion.[1] This approach combines a fundamental liberal idea (what matters for individual well-being is ultimately determined by individual preferences) with a the idea of distributive justice (what matters for social welfare is how large aggregate well-being is and how it is distributed). We assume that well-being can be measured and is fully determined by consumption of market goods and non-market goods (like amenities). We adopt here a Utilitarian perspective on social welfare as this gives equal weight to the well-being of every individual. It is motivated by Harsanyi's Impartial Observer Theorem (Harsanyi, Hammond) that shows that if both individual preferences and social preferences satisfy the von-Neumann-Morgenstern Axioms then social preferences must be representable as the sum of the utility representations of the individual preferences as long as social preferences satisfy the Pareto Axiom. Thus the theorem proves that summation is the only aggregation method compatible with a set of compelling rationality axioms (the von Neuman Morgenstern axioms) and the compelling requirement that if everyone is better off then a world is better from a social perspective (the Pareto axiom). Therefore, all that

1. This framework cannot consider procedural aspects of normative theories that are very important and dominant in the public discourse. We understand such procedural approaches, or rules, as heuristics that are very useful in practical life but cannot give a satisfactory answer on the desirability of outcomes of policies.

the theorem leaves open is how the utility functions are to be normalized (Greaves). For that, we stipulate that the same experience (of suffering or happiness) should be given equal weight, regardless who experiences it. Pragmatically, we assume that the impact of marginal disposable income on the expected well-being is the same across people.

In the remaining sections, we show how this framework can be operationalized to evaluate policies, what type of information is needed and how welfare effects can be decomposed in different components to illustrate the multi-dimensional nature of individual well-being and social welfare.

2. The formal model

2.1. Social welfare

In our economy, consumer i chooses her private consumption vector, denoted $c^i = (c^i_1, ..., c^i_n)$. The consumer has income denoted by y^i that she fully spends on private consumption. The price she has to pay for a unit of good k is $q_k := p_k(1+t_k)$, where t_k denotes an ad valorem tax (e.g. a value-added tax, VAT). Her budget constraint is $\sum_k c_k q_k \leq y^i$.

The vector $a = (a_1, ..., a_n)$ denotes amenities (and disamenities) that can include air quality, temperature and other weather variables, noise levels, traffic, parks and natural spaces for recreation etc.

DEFINITION 1. Let $U_i(c^i, a)$ denote person i's expected well-being conditional on (c^i, a).

We assume that social welfare of a group of N consumers can be expressed by a function W of the individual utilities U_i, $i = 1, \dots, N$.

$$W = f(U_1, \dots, u_N) \tag{1}$$

Utilities depend on a vector of policies p (for example, ad valorem taxes as mention above, or a carbon tax). We use the shorthand $u_i(p)$ to denote the utility of i in the equilibrium that is induced when the policy package p is implemented.[2] Similarly, $W(p)$ captures the level of social welfare in the equilibrium induced by p, and $E(p)$ are the associated emissions (or, more generally, the externality under consideration).

The policy p under evaluation is expressed as a change from the status quo policies p^* (which may also be non-existent, i.e. zero) such that $p = p^* + dp$. The effect of the policy p on social welfare and emissions is hence:

$$dW(p) = f(u_1(p^* + dp), \dots, u_N(p^* + dp)) - f(u_1(p^*), \dots, u_N(p^*)) \tag{2}$$

$$dE(= E(p + dp) - E(p^*) \tag{3}$$

2. This notation is similar to an indirect utility function $v_i(P)$, which captures the maximum attainable utility for a given prices P.

The welfare-cost of an emission reduction policy $\psi(p)$ (relative to an initial policy p^*, which can also be “no policy”) can therefore be expressed as

$$\psi(p) := \frac{dW(p)}{dE(p)} \tag{4}$$

The *welfare implication of a policy* $\psi(p)$ capture all costs and benefits of a policy, including co-benefits of addressing other externalities or how the revenues (if any) of the policy are recycled. Normalizing by the effect of the policy on emissions ensures a ’fair’ comparison between policies of different ambition levels. It therefore creates a measure that is more easily comparable across different instruments and studies at it conveys which policy provides the biggest emission reduction at the lowest welfare cost.

In the following sections we show how this approach allows to take multi-dimensional welfare implications and distributional implications of the policy into account.

2.2. Consumer

From now on we shall make:

ASSUMPTION 1 (*The “revealed well-being assumption”*). Each agent i maximizes $U_i(c^i, a)$.

We will not postulate any specific theory of well-being. However, it is helpful to think through particular theories. For example, under certain versions of Preference Satisfaction Theories of well-being, the preceding assumption corresponds to the "revealed preference assumption". However, it is important to note that from the normative perspective the "revealed preference assumption" is much more substantive than the assumption that observed behavior can be explainable as coming from the optimization of *some* preference relation. In fact, the assumption states that the behavior comes from the optimization of the agent’s *actual* preference relation.

To avoid these potential confusions associated with preference satisfaction theories of well-being, we invite the reader to instead consider "mental state theories of well-being". Under certain such theories of well-being, $U_i(c^i, a)$ would be the expected number of moments of happiness (weighted by their intensity) minus the expected number of moments of suffering (weighted by their intensity). It is then immediately clear that the above "revealed well-being assumption" is substantive and likely to be wrong in many situations. However, as a benchmark for operationalizing well-being-based ethics, it seems useful.

LEMMA 1. *Suppose $u_i(c^i, a)$ is a function that correctly predicts agent i’s behavior in all situations (formalized as under all possible choice sets for (c^i, a), all lotteries over choices and under some choices involving the possibility of death). Then there exists some λ_i such that $\lambda_i u_i(c^i, a) = U_i(c^i, a) \forall c^i, a$*

Proof. By the von-Neumann Morgenstern expected utility theorem, we know that from choices under uncertainty we can infer $u_i(c^i, a)$ up to affine-linear transformations. Of the corresponding two free dimensions, one is pinned down by any choice involving life and death (In practice, this can be done using "value of a statistical life year" (VSLY, e.g. Kniesner and Viscusi 2019). What remains is one free dimension. Multiplication by a constant leaves both choices under uncertainty and under life-and-death trade-offs unchanged, so it is exactly the remaining dimension. □

In practice, we have good estimates for functions $u_i(c^i, a)$ that can explain behavior. Given such estimates $(u_i(c^i, a))_{i=1,\ldots,N}$, the operationalization of utilitarianism requires the further step of finding the correct vector of $(\lambda_i)_{i=1,\ldots,N}$. For example, consider a hedonistic theory of well-being. Then we could, with sufficiently advanced non-intrusive neuroscience measure the changes in the number of moments of happiness and suffering (both weighted by intensity) that arise from a change in a given consumption good k. We could thus in principle measure $\frac{dU_i}{dc^i_k}(c^i, a)$. Given our pre-existing estimate $u_i(c^i, a)$ of a function that correctly predicts behavior, we could then pin down λ_i by the condition

$$\lambda_i \frac{du_i}{dc^i_k}(c^i, a) = \frac{dU_i}{dc^i_k}(c^i, a).$$

Instead of the hypothetical approach just sketched, we will provide a simple pragmatic approach for pinning down the values of the λ_i. We will argue that it has plausibility as a decent approximation in a way that is robust to the particular theory of well-being that one subscribes to.

Before laying out our pragmatic approach to the "problem of interpersonal comparison of utility", let us introduce some standard notations.

The consumer's problem is:

$$\max_{c^i_1,\ldots,c^i_n} u_i(c^i, a) \tag{5}$$

$$\text{such that } p_1(1+t_1)c^i_1 + \ldots + p_n(1+t_n)c^i_n \leq y^i \tag{6}$$

Let us denote by $c^i(q, y^i, a)$ the consumer's optimal consumption choice, given that her disposable income is y^i and given that the vector of consumption prices is q and given that the amenity vector (which is outside of her individual control) is a.

ASSUMPTION 2. Suppose for each i we have chosen λ_i to equal the unique (by Lemma 1) value such that $\lambda_i u_i(c^i, a) = U_i(c^i, a) \forall c^i, a$.

Then there exists a constant κ such that

$$\lambda^i \frac{d}{dy^i}(u^i(c^i(q, y^i, a), a)) \approx (y^i)^{-\eta} \kappa \forall i \forall y^i \forall a \tag{7}$$

In other words, the marginal well-being effect of additional income is roughly the same across people with the same income and depends on income according to a CRRA function.

Let us consider a revenue-neutral tax reform that changes consumer prices by an increment dq and that changes incomes by increments $(dy^i)_{i=1,\dots,N}$. We focus here on completely specified reforms (i.e. where tax revenues are fully used up, e.g. for transfers) because only such reforms can be directly evaluated in terms of their impact on aggregate well-being. However, since we are considering a marginal reform, we can evaluate the overall reform as the sum of its parts, firstly the increment in consumer prices (corresponding to a tax reform) and secondly the change in incomes (corresponding to a transfer scheme fully paying out the increase in tax revenues).

Using a first-order Taylor expansion, the change in well-being due to a change in prices dq is:

$$u^i(c^i(q+dq, y^i+dy^i, a+da), a+da) - u^i(c^i(q, y^i, a), a) = \tag{8}$$
$$u^i(c^i(q+dq, y^i, a), a) - u^i(c^i(q, y^i, a), a) + \tag{8a}$$
$$u^i(c^i(q, y^i+dy^i, a), a) - u^i(c^i(q, y^i, a), a) + \tag{8b}$$
$$u^i(c^i(q, y^i, a+da), a+da) - u^i(c^i(q, y^i, a), a) + \tag{8c}$$
$$o(dq^2, dy^{i2}, da^2)$$

In the following sections, we will find approximations for the terms in (8).

2.2.1. The well-being impact of a tax rate change (the increment dq). Consider first (8a), the utility change induced by a small change in prices dq. Let us denote by $EV_i(dq)$ the equivalent variation corresponding to the price increment dq. The EV_i is by definition Collel et al. (cf., for example, 1995):

$$u_i(c(q, y^i + EV_i(dq)), a) = u_i(c(q+dq, y^i), a) \tag{9}$$

Substracting $u_i(c(q, y^i), a)$ from both sides turns the LHS of (9) into (8a), to which we once more apply a Taylor expansion:

$$u_i(c(q, y^i + EV_i(dq)), a) - u_i(c(q, y^i), a) = u_i(c(q+dq, y^i), a) - u_i(c(q, y^i), a) \tag{10}$$
$$\frac{d}{dy^i} u_i(c^i(q, y^i), a) EV_i(dq) = \frac{d}{dc} u_i(c^i(q, y^i), a) \frac{dc^i}{dq} dq + o(dq^2) \tag{11}$$

To a first order, the term $\frac{d}{dc} u_i(c^i(q, y^i), a) \frac{dc^i}{dq} dq$ on the RHS is the change in u_i induced by dq. Thus, the LHS provides an proximation via the equivalent variation, such that we can compute (8a) as $\frac{d}{dy^i} u_i(c^i(q, y^i), a) EV_i(dq)$. With Assumption 2 we can approximate the change in utility from a price increment by a simple expression of equivalent variation and income level:

$$\frac{dU_i}{dq} dq \approx (y^i)^{-\eta} \kappa EV_i(dq) \tag{12}$$

2.2.2. The well-being impact of the marginal income change dy_i. Now consider the utility effect of a change in income dy^i as in (8b).

$$u^i(c^i(q,y^i+dy^i,a),a)-u^i(c^i(q,y^i,a),a)\approx\frac{d}{dy^i}u_i(c^i(q,y^i),a)dy^i \tag{13}$$

Suppose the tax reform has generated tax revenue dT_0 and that exactly this revenue gets rebated to consumers as lump-sum transfers, with a proportion σ_i going to consumer i (e.g. $\sigma_i=\frac{1}{|I|}$ in the case of a uniform transfer). Then this rebate will generate further tax revenues of $dT_1=\sum_{i=1}^N\sigma_i dT_0\sum_k\frac{dc_k^i}{dy^i}p_kt_k$

Let us rewrite:

$$dT_1=dT_0\gamma \tag{14}$$

with:

$$\gamma=\sum_{i=1}^N\sigma_i\sum_k\frac{dc_k^i}{dy^i}p_k(1+t_k)\frac{t_k}{1+t_k} \tag{15}$$

$$\gamma=\sum_{i=1}^N\sigma_i\sum_k\frac{y^i}{c_k^i}\frac{dc_k^i}{dy^i}\frac{c_k^ip_k(1+t_k)}{y^i}\frac{t_k}{1+t_k} \tag{16}$$

Denoting by $\varepsilon_k^{i,y}$ the income elasticity and by φ_k^i the share of income that i spends on good k, we can rewrite this as:

$$\gamma=\sum_{i=1}^N\sigma_i\sum_k\varepsilon_k^{i,y}\varphi_k^i\frac{t_k}{1+t_k} \tag{17}$$

Note that from the fact that each consumer spends her entire budget we know that:

$$\sum_k\frac{dc_k^i}{dy^i}p_k(1+t_k)=1.$$

Given that $\sum_{i=1}^N\sigma_i=1$, this reveals that γ is a weighted sum of the $\frac{t_k}{1+t_k}$, where the weights are the proportions of additional spending accruing to the different goods.[3] Iterating this analysis, we see that the total additional transfers being made to consumers is:

$$dT_0+\gamma dT_0+\gamma dT_0^2+...=\frac{dT_0}{1-\gamma} \tag{18}$$

Hence we know that $dy^i=\sigma_i\frac{dT_0}{1-\gamma}$

Again, based on Assumption 2, we get:

$$\frac{dU_i}{dy^i}dq\approx(y^i)^{-\eta}\kappa dy^i\approx(y^i)^{-\eta}\kappa\sigma_i\frac{dT_0}{1-\gamma} \tag{19}$$

3. In our model, γ is also the marginal tax revenue generated per dollar of transfers paid out to consumers (split across consumers according to the proportions σ_i). However, this should be viewed in an intertemporal sense and is thus difficult to estimate.

2.2.3. The well-being impact of the marginal change in amenities da. Now consider the third component, the utility effect of an increment in amenities (8c):

$$u^i(c^i(q,y^i,a+da),a+da) - u^i(c^i(q,y^i,a),a) \tag{20}$$

Since c^i is chosen optimally by i to maximise u^i, we can infer by the envelope theorem that this equals to first order:

$$u^i(c^i(q,y^i,a),a+da) - u^i(c^i(q,y^i,a),a) \tag{21}$$

Let us define $EV_i(da)$ to be the corresponding equivalent variation. Then we get:

$$u^i(c^i(q,y^i,a),a+da) - u^i(c^i(q,y^i,a),a) = u^i(c^i(q,y^i+EV_i(da),a),a) - u^i(c^i(q,y^i,a),a) \tag{22}$$

To first order, we thus get:

$$\frac{\partial u^i}{\partial a}(c^i(q,y^i,a),a)da = EV_i(da)\frac{du^i}{dy^i} \tag{23}$$

The term $\frac{\partial u^i}{\partial a}(c^i(q,y^i,a),a)da$ on the LHS is clearly the change in u_i induced by da, again given the envelope theorem. From the RHS we see that if we know the equivalent variation $EV_i(da)$, we can compute this as $\frac{d}{dy^i}u_i(c^i(q,y^i),a)EV_i(da)$. From assumption 2 we now deduce that:

$$\frac{dU_i}{da}da \approx (y^i)^{-\eta}\kappa EV_i(da) \tag{24}$$

2.2.4. A method to compute the overall change in well-being induced by a revenue-neutral tax reform with lump-sum transfers. With the approximation from Sections 2.2.1-2.2.3 we can compute the welfare effect of a revenue-neutral tax reform with lump-sum transfers. Consider how the welfare effect dW of a policy can be rewritten along the effects discussed above.

$$dW = \sum_{i=1}^{N} dU^i = \sum_{i=1}^{N}\frac{dU_i}{dq}dq + \sum_{i=1}^{N}\frac{dU_i}{dy^i}dq + \sum_{i=1}^{N}\frac{dU_i}{da}da \tag{25}$$

To compute dW from consumption equivalent variations:

1. For each person i:
   (a) Compute the Equivalent Variation $EV_i(dq)$ resulting from the change in consumer prices dq
   (b) Compute their weighted sum

$$\frac{1}{\kappa}\sum_{i=1}^{N}\frac{dU_i}{dq^i}dq \approx \sum_{i=1}^{N}(y^i)^{-\eta}EV_i(dq)$$

2. Compute the change in tax revenue dT_0 from the pure tax adjustment.

3. Compute $\frac{1}{\kappa}\sum_{i=1}^{N}\frac{dU_i}{dy^i}dy^i \approx \sum_{i=1}^{N}(y^i)^{-\eta}\sigma_i\frac{dT_0}{1-\gamma}$, where $\gamma = \sum_{i=1}^{N}\sigma_i\sum_k \varepsilon_k^{i,y}\varphi_k^i\frac{t_k}{1+t_k}$ with $\varepsilon_k^{i,y}$ denoting the income elasticity, φ_k^i the share of income that i spends on good k and σ_i denoting the share of transfers reaching agent i.
4. Compute the changes da in the amenity vector a as follows:
   (a) Compute $da(dq)$ that results purely from the change in consumer prices induced by the tax reform.
   (b) Compute the da_0 that results from redistributing the tax revenue increment dT_0 from 4(a) (without taking into account that this will itself change the overall tax revenue). Multiply by $\frac{1}{1-\gamma}$ to obtain the change in a resulting from the full redistribution of revenue (including the tax revenue from the increase in spending induced by the redistribution itself)
   (c) Add the results from 4(a) and 4(b) together to obtain the actual $da = da(dq) + \frac{da_0}{1-\gamma}$.
   (d) Compute $\frac{1}{\kappa}\sum_{i=1}^{N}\frac{dU_i}{da^i}da^i = \sum_{i=1}^{N}(y^i)^{-\eta}\kappa EV_i(da)$, where $EV_i(da)$ denotes agent i's willingness to pay for da.
5. Add up the three components to obtain (up to the multiplicative constant κ) the overall change in aggregate well-being:

$$\frac{1}{\kappa}(\sum_{i=1}^{N}\frac{dU_i}{dq^i}dq + \frac{1}{\kappa}\sum_{i=1}^{N}\frac{dU_i}{dy^i}dy^i + \sum_{i=1}^{N}\frac{dU_i}{da^i}da^i) = \sum_{i=1}^{N}(y^i)^{-\eta}((EV_i(dq) + \sigma_i\frac{dT_0}{1-\gamma} + EV_i(da(dq) + \frac{da_0}{1-\gamma})) \quad (26)$$

3. Analytical illustration for simplifying assumptions

Concrete examples for the three components of the LHS of (26) could be the change in consumer surplus (ΔCS_j), net transfers from the government (T_j, either including the compounding effect of rebated taxes, or using the simplifying assumption $\gamma = 0$) and other (e.g. environmental) net benefits NB_j^i of type i of the policy (see Table 1 for examples of relevant dimensions). The RHS then reads

$$\sum_{i=1}^{N}(y^i)^{-\eta}(\Delta CS_j + T_j + \sum_i NB_j^i) \quad (27)$$

If the exact distribution of the net benefits is unclear, we could approximate type i with an income-elasticity Φ_i, such that

$$NB_j^i = \overline{NB}_i\left(\frac{y_j}{\bar{y}}\right)^{\Phi_i} \quad (28)$$

where $\overline{NB}_i$ is the average net-benefit in category i, $\bar{y}$ the average income and y_j the income of person j. (We could also create different sub-types of individuals with different 'average' net benefits and different income elasticities).

Special case: When all EV-components can be described with an income-elasticity, and when income equals consumption, we can simplify (using a person with mean income as reference person):

$$\Delta W^C = \sum_j \left(\frac{\bar{y}}{y_j}\right)^{\eta} \left(\Delta\bar{CS}\left(\frac{y_j}{\bar{y}}\right)^{\Phi_{CS}} + \bar{T}\left(\frac{y_j}{\bar{y}}\right)^{\Phi_T} + \sum_i \bar{NB}_i\left(\frac{y_j}{\bar{y}}\right)^{\Phi_i}\right) \tag{29}$$

$$= \sum_j \left(\Delta\bar{CS}\left(\frac{y_j}{\bar{y}}\right)^{\Phi_{CS}-\eta} + \bar{T}\left(\frac{y_j}{\bar{y}}\right)^{\Phi_T-\eta} + \sum_i \bar{NB}_i\left(\frac{y_j}{\bar{y}}\right)^{\Phi_i-\eta}\right) \tag{30}$$

This equation gives us a useful decomposition of the welfare-effects of different components of the policy-package. Every component involves equity weights, so is distribution-sensitive. We see further, that fulfilling the Kaldor-Hicks criterion, $\Delta\bar{CS} + \bar{T} + \sum_i \bar{NB}_i > 0$ is not sufficient (or necessary) to have a positive welfare effect.

We further see some special cases: When all costs and benefits have elasticity equal to η, the effects in all components is distribution-neutral and the welfare effects are just equal to the sum of $\Delta\bar{CS} + \bar{T} + \sum_i \bar{NB}_i$. Also, when $\eta = 0$ (implying a linear utility function), all $y_j/\bar{y}$ terms cancel out since the equity weights are always one and then, only the aggregate effect (average effect times number of persons) matters for welfare.

4. Operationalization: Ex-ante and ex-post analyses

The methods that we put forward here have at least three use cases: (i) comparing different policies in a given country in terms of how much net burden they impose (or benefit they create) on the domestic population per ton of emission abated; (ii) evaluating whether a given policy increases global aggregate well-being; (iii) aggregating evidence on classes of policies to measure the impact on well-being as comprehensively as possible.

The relevance of (ii) is clear: ultimately, this is *the* relevant question, at least from a Utilitarian normative perspective. The relevance of (iii) is also indisputable: It is essential evidence for an overall answer to (ii) for any given policy.

The relevance of (i) is as follows: The loss in well-being imposed domestically by a given policy might be a good predictor for the amount of opposition or backlash that it will induce. If a society has a limited willingness to sacrifice to provide a global public good then our metric of "well-being loss per emission reduction" can provide a useful indicator for prioritization across policies.

For each of the 3 use cases, it is helpful to adhere to the following:

DEFINITION 2 (*The principle of complete reform specification*). Consider reforms that are fully specified. For example when considering a tax reform or a reform of government spending programs, fully specify how the additional tax revenue will be spent (e.g. on transfers) or how the resulting budget deficit will be financed via tax increases.

TABLE 1. Dimensions of equivalent variation

Cost/Benefit Categories	Scope
Consumer surplus	National vs. other countries
Income effects	Current vs. future generations
Direct tax/transfers	
Labor market / investment responses	
Revenue use or compensation policies	
Other non-market effects	
Environmental	
Health	
Other amenities	

In fact, adherence to this principle is necessary to make the questions raised by (i) and (ii) even well-defined. Moreover, for (iii) adherence to the principle greatly facilitates the comparability of the reforms that are considered.

At first glance, the principle of complete reform specification seems to impose significant limitations: Many proposed and actual reforms do not respect it. For example, a green subsidy program (e.g. the green parts of the IRA) are funded "via the general budget". Thus there is much ex-post evidence on incompletely specified reforms. Moreover, many ex-ante studies on the Equivalent Variations associated e.g. with tax reforms like the ones discussed in the next section take a partial equilibrium perspective and do not explicitly model the effect of a scheme of transfers funded via the additional tax revenue. Such a partial equilibrium perspective has great tractability benefits. Moreover, far from precluding the adherence to the principle of complete reform specification, they can be combined with a standardized way of specifying and evaluating ex ante complementary policy adjustments that make the resulting reform package respect the principle of complete reform specification.

Consider the case of the tax policy reform in the food sector that we will detail in the next section. There, we provide the results of an ex ante analysis of an increase in the VAT rates on meat using a demand system for consumers' spending on food. The reform generates tax revenue. Now consider a complementary element to the reform such as "pay out uniform lump sum transfers such that overall the reform is budget-balanced". A nice feature of the concept of Equivalent Variation is that the impacts on each consumer from the post-tax price changes are already expressed in the same units as direct lump-sum transfers. In particular, to compute the overall effect on a person's well-being, all we have to do is to add up all the impacts in terms of Equivalent Variation (of the price changes, of the amenity-change related benefits, etc.) with the transfers received multiply by the person's marginal utility of consumption. To be as comprehensive as possible, it would be important to estimate the Equivalent Variation effects across all relevant dimensions as illustrated in the first row of Tab. 1.

However, there is one complication here: the consumers' spending will itself generate additional tax revenue which, by definition of the completely specified reform package will also be rebated. This in turn will create further tax revenue and so on. Thus we need to multiply the initial additional tax revenue generated by the tax reform by a multiplier to compute the actual total amount of transfers that people get. In Section 2.2.2 we provide a formula for this multiplier. It only depends on the consumers' income elasticities for the different consumption goods, their corresponding income shares and the ad valorem tax rates on the different goods. All that is left to implement this approach is thus to find an estimate for the income elasticities of demand of all the different goods. Here econometric estimates can be used. They should be normalised such that they imply that of an additional euro in income exactly one euro is spent on additional consumption. Whilst this assumption is not literally true in the short term, it is a reasonable approximation that allows to account for the fact that money not spent today can be spent in the future. The assumption also has the advantage of being fully logically consistent with the model for equivalent variation that we have given here. Importantly for when it comes to comparing and aggregating evidence across different partial equilibrium studies, the same numbers for the income elasticities can be used.

5. Application: Tax policies in the food sector to reduce GHG emissions

5.1. Underlying structural model and policy analysis

We demonstrate the usefulness of our methodological approach by comparing two distinct policy instruments and their respective welfare costs and benefits analysed by Plinke et al. (2024). The main objective of the policies under investigation is the reduction of greenhouse gas emissions induced by food consumption in the European Union (EU27). We compare the removal of existing value-added tax (VAT) reductions on meat products to a greenhouse gas (GHG) emission price on all food products, which is endogenously determined to achieve the same GHG emission reductions as the former policy. By normalizing the outcome of the primary objective of the policies, the two policies can be compared in terms of additional relevant welfare dimensions: their environmental co-benefits, utility losses for consumers, revenue use in the form of different compensation policies as well as the resulting distribution of costs.

Consumer reactions to policy-induced price changes and the resulting consumer surplus losses are modeled using the linearly approximated Exact Affine Stone Index (EASI) Implicit Marshallian demand system (Lewbel and Pendakur 2009).

Environmental co-benefits included in this analysis are the effects of the policies on physical quantities such as land use, biodiversity loss, water consumption, nitrogen and phosphorus emissions. When robust estimates of the social costs are available, these environmental dimensions are monetized. Due to missing empirical evidence, we do not account for the distributional effects of environmental co-benefits.

Consumer surplus losses are quantified in monetary terms, reflecting the utility losses due to policy-induced price increases. Using the estimates of the EASI demand system, we employ the cost-of-living index as an approximation of the equivalent variation. These losses in consumer utility are contrasted with the increased tax income induced by the policies, considering two revenue recycling schemes: per capita and proportional to expenditures. A per capita redistribution mechanism is more progressive, as it equally reallocates resources to each individual. However, it requires substantial administrative capacity for effective implementation. Alternatively, a redistribution mechanism based on expenditures can be implemented more easily, e.g. through income tax adjustments, but tends to be more regressive. The expenditure-based mechanism could also serve as upper-bound benchmark for a policy with no explicit specification of the revenue use.[4] The application of equity weights allows us to incorporate distributional considerations and compare net consumer surplus losses under varying levels of societal inequality aversion.

The following assumptions are used to derive these equity weights: We assume a standard constant relative risk aversion (CRRA) utility function, which is expressed as

$$u(c_h) = \frac{c_h^{1-\eta}}{1-\eta}$$

where c_h is the total expenditure of household h and η is the coefficient of relative risk aversion. As we use a static model of demand shifts, we disregard intertemporal aspects. They are implicitly accounted in the social cost of carbon calculation (through the choice of the discount rate) for valuing climate benefits. The equity weight for a specific household is derived by comparing the marginal utility of expenditures for that household to a reference point. The reference point is defined as a hypothetical household with median expenditures across all EU27 countries, denoted as $\overline{c}$. The household-specific equity weight w_h is then given by

$$w_h = \frac{u'(c_h)}{u'(\overline{c})} = \left(\frac{\overline{c}}{c_h}\right)^{\eta}$$

The consumption-equivalent change in social welfare function incorporating these equity weights is described by

$$\Delta W = \sum_{h=0}^{N} w_h \cdot \text{costs}_h$$

where N is the total number of households, w_h is the equity weight for household h, and costs_h represents the costs associated with household h (where negative costs imply net welfare gains). Thus, higher weight is given to the costs borne by poorer households, reflecting the diminishing marginal utility of expenditures.

5.2. Results

Plinke et al. (2024) show that removing current VAT reductions on meat products has the potential to decrease annual food consumption-related greenhouse gas (GHG) emissions by

4. In that case, tax revenues go into the general government budget, expanding it marginally, implying either marginal additional public spending or a marginal reduction in the income tax scheme. The distributional effects are then simply determined by the distributional incidence of the overall income-tax and spending scheme. As the income-tax scheme (including indirect taxes) is rather flat, see e.g. Isaak et al. (2021) for Germany, using a redistribution proportional to expenditure can serve as an upper bound when an explicit revenue use is not specified.

29.9 Mt CO_2eq. The equivalent emission reduction can be achieved by a GHG emission price of approximately 52 EUR/tCO_2eq on all food products. The normalization allows to compare the two policies in terms of additional welfare dimensions. We here focus on (1) aggregate environmental co-benefits and (2) consumer surplus losses under varying redistribution schemes and levels of societal inequality aversion.

In comparison with the VAT reform, the GHG emission price policy yields additional global co-benefits of 16,818 t nitrogen, 894 t phosphorus, 486 Mm^3 water consumption, 0.688 Mha land use reductions. Only for biodiversity loss, the associated co-benefits of the VAT reform are marginally higher (0.0001 global potentially disappeared fraction of species, i.e. the committed share of global loss of species richness as a direct consequence of anthropogenic impacts on ecosystem quality) than those achieved under the GHG emission price policy. To allow for an overall evaluation to what extent the policies increase global aggregate well-being, we monetize the changes in environmental footprints using the global social cost of greenhouse gases (CO_2, CH_4, N_2O) (EPA 2023), the domestic social cost of nitrogen (van Grinsven et al. 2018) and the domestic social cost of phosphorus (Matthey and Bünger 2020). Changes in biodiversity loss, land occupation and water consumption are not monetized due to a lack of social cost estimates.

In addition to the environmental co-benefits, the two policy options generate tax revenue. We thus contrast the monetarized environmental co-benefits and the increase in tax revenue with the reduction in consumer surplus for the two policies. Figure 1 shows the cost components and the aggregate result for the two policies across all EU27 countries for the case of no inequality aversion, i.e. utility is linear in expenditures ($\eta = 0$). While both policies improve overall welfare, the GHG emission price policy results in a higher overall net welfare increase driven by slightly higher environmental co-benefits in nitrogen and phosphorus reductions and a smaller difference in welfare losses to increased tax revenue. The net aggregate welfare benefit of the two policies amounts to 45.4 EUR per household for the removal of VAT reductions for meat products, and 30.5 EUR per household for the introduction of a GHG emission price of approximately 52 EUR/tCO_2eq on all food products. Noteworthy, both policies result in positive aggregate welfare changes as the environmental benefits exceed the costs for consumers. This is even true when 'global' benefits from reduced climate change are disregarded and only 'local' benefits from reducing nitrogen and phosphorus emissions are considered.

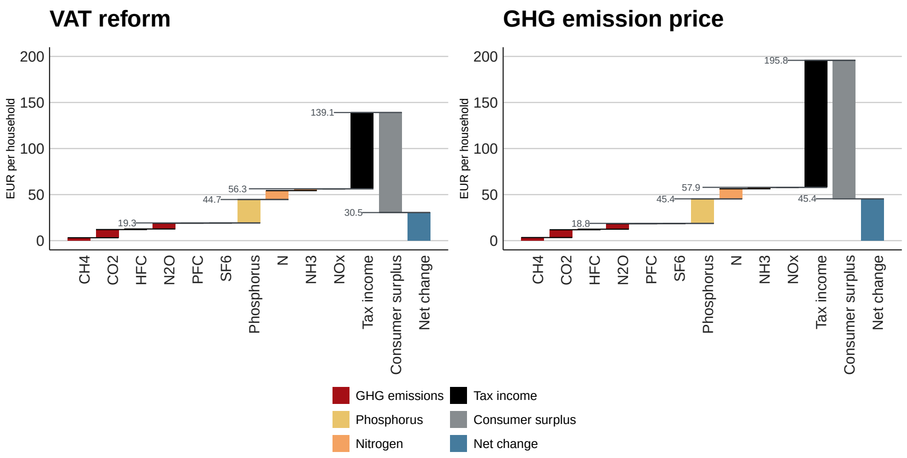

FIGURE 1. Changes in welfare resulting from removing value-added tax reductions for meat products (*VAT reform*) and implementing a GHG emission emission price of 51.62 EUR/tCO_2eq on all food products (*GHG emission price*), measured in EUR per household. GHG emission benefits are valued based on the global social cost of greenhouse gases (CO_2, CH_4 and N_2O). Phosphorous and nitrogen (N, NH_3 and NO_x) emission benefits are based on domestic social costs.

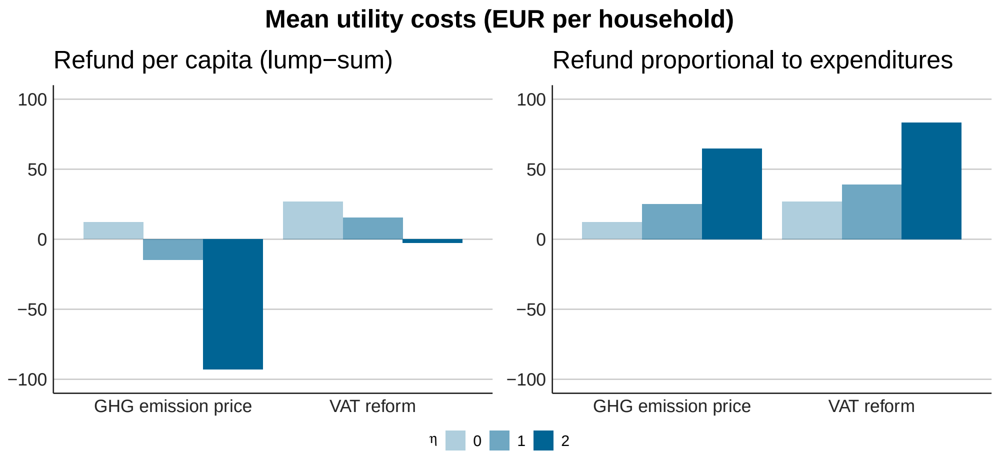

FIGURE 2. Mean utility costs (in 2019 EUR PPP per household) without environmental benefits, resulting from removing value-added tax reductions for meat products (*VAT reform*) and implementing a GHG emission emission price of 51.62 EUR/tCO_2eq on all food products (*GHG emission price*) across all EU27 countries, considering two distinct revenue redistribution mechanisms and varying levels of inequality aversion (η). Positive values reflect mean utility losses, negative values reflect mean utility benefits.

In addition, policymakers may choose to redistribute tax revenues to compensate consumers for the utility losses due to the policy-induced price increases. We investigate two distinct mechanisms for redistributing revenue: a simple per capita refund and a refund proportional to expenditures, ensuring that the total change in generated tax income is fully redistributed in each case. Figure 2 displays the mean total welfare costs expressed in 2019 EUR PPP per household, disregarding the environmental (co-)benefits of the policy. For both redistribution mechanisms, removing current VAT reductions on meat products leads to higher consumer surplus losses than implementing a GHG emission price of 51.62 EUR/tCO_2. Under no inequality aversion ($\eta = 0$), mean utility losses amount to 27 EUR per household for the VAT reform and 12 EUR per household for the GHG emission price. A per capita refund is a more progressive redistribution mechanism since lower-income individuals receive a larger relative increase in their income compared to higher-income individuals. Thus, utility losses are reduced with higher levels of inequality aversion, leading to overall mean utility gains for the GHG emission price policy when $\eta > 0$. The distributional gain increases for larger η that captures the inequality aversion inherent in the Utilitarian social welfare measure. For high inequality aversion ($\eta = 2$), the redistributive property of the per-capita revenue recycling leads to social welfare gains even when aggregate policy costs (ignoring inequality aversion) would be negative (see left panel in Fig. 2). Conversely, a mechanism that redistributes proportionally to expenditures proves to be regressive. In this case, higher levels of inequality aversion correspond to substantially higher welfare costs.

6. Conclusions

This paper provides a conceptual framework for evaluating and comparing the welfare costs of different policies that are normalized to an outcome variable (such as emission reductions, for example). Our framework is flexible enough to account for consumption impacts as well as non-market impacts; it can incorporate co-benefits of policies and the implications of tax and transfer rules as part of a policy package. Furthermore, the distributional effects of policies can be considered within with framework. Its key strength is to aggregate various information and evidence on multi-dimensional outcomes of policies into a one-dimensional metric. This constitutes a great step in reducing complexity in evaluating trade-offs of policies to a simple ranking.

However, the framework also allows to decompose aggregate effects into its components to shed light on the relevance of specific welfare dimensions for the overall assessment. This latter property makes it valuable for researchers and analysts with an interest in a consistent overall welfare assessment or policy makers that with a specific interest in a particular welfare-related aspects.

With increasing evidence on the impacts of policies on environmental outcomes but also on relevant welfare dimensions, this approach can be put into practice. We illustrate this for the case of policies in the food sector to reduce greenhouse gas emissions but also other environmental footprints. Our framework stresses that, for a comprehensive welfare evaluation, the distributional effects with respect to costs but also benefits of a policy should be considered. While a growing literature focuses on the distribution of the costs of climate policy, more evidence is needed regarding the distribution of the benefits.

References

Collel, Andreu Mas, Michael Whinston Andreu, and Jerry Green (1995). *Microeconomic Theory*. Oxford University Press.

Döbbeling-Hildebrandt, Niklas, Klaas Miersch, Tarun M Khanna, Marion Bachelet, Stephan B Bruns, Max Callaghan, Ottmar Edenhofer, Christian Flachsland, Piers M Forster, Matthias Kalkuhl, et al. (2024). "Systematic review and meta-analysis of ex-post evaluations on the effectiveness of carbon pricing." *Nature Communications*, 15(1), 4147.

Dubash, Navroz K, Catherine Mitchell, Elin Lerum Boasson, Mercy J Borbor Córdova, Solomone Fifita, Erik Haites, Mark Jaccard, Frank Jotzo, Sasha Naidoo, Patricia Romero-Lankao, et al. (2022). "National and sub-national policies and institutions." In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

EPA (2023). "Report on the Social Cost of Greenhouse Gases: Estimates incorporating recent scientific advances."

Isaak, Niklas, Philipp Jäger, and Robin Jessen (2021). "Die Verteilung der Steuer-und Abgabenlast." *Wirtschaftsdienst*, 101(4), 284–289.

Kniesner, Thomas J and W Kip Viscusi (2019). "The value of a statistical life." Forthcoming, Oxford Research Encyclopedia of Economics and Finance, Vanderbilt Law Research Paper.

Lewbel, Arthur and Krishna Pendakur (2009). "Tricks with Hicks: The EASI demand system." *American Economic Review*, 99(3), 827–63.

Matthey, Astrid and Björn Bünger (2020). "Methodenkonvention 3.1 zur Ermittlung von Umweltkosten - Kostensätze."

Plinke, Charlotte, Michael Sureth, and Matthias Kalkuhl (2024). "Assessing the Potential of Tax Policies in Reducing Environmental Impacts from European Food Consumption." Manuscript submitted for publication.

Somanathan, Eswaran, Thomas Sterner, and Taishi Sugiyama (2014). "National and Sub-national Policies and Institutions." In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, and T. Zwickel. Cambridge University Press, Cambridge, UK and New York, NY, USA.

van Grinsven, Hans J., Jan D. van Dam, Jan Peter Lesschen, Marloes H. Timmers, Gerard L. Velthof, and Luis Lassaletta (2018). "Reducing external costs of nitrogen pollution by relocation of pig production between regions in the European Union." *Regional Environmental Change*, 18(8), 2403–2415.

Appendix A: Welfare effects

To discuss the welfare effect of moving from the reference case policy p^* to policy $p = p^* + \Delta p$, we consider $\Delta W(p)$:

$$\Delta W(p) = W(p^* + \Delta p) - W(p^*)$$

We approximate $W(p^* + \Delta p)$ using the linear terms of a multidimensional Taylor series.

$$\begin{aligned} TW(u_1(p),\dots,u_N(p)) &= f(p^*) + \frac{\partial f(p^*)}{\partial u_1}\left[u_1(p^*+\Delta p) - u_1(p^*)\right] + \dots \\ &\quad \dots + \frac{\partial f(p^*)}{\partial u_N}\left[u_N(p^*+\Delta p) - u_N(p^*)\right] \\ &= f(p^*) + \frac{\partial f(p^*)}{\partial u_1}\Delta u_1 + \dots + \frac{\partial f(p^*)}{\partial u_N}\Delta u_N \end{aligned} \tag{A.1}$$

To simplify further, we introduce equivalent variation EV_i in consumption, defined by the following equation such that consumer i is indifferent between extra income of EV_i or implementing policy p (see, for example, $v(p^0, w+EV) = u^1$ in Mas-Colell 1995, p82):

$$u_i(c_{i1}(p^*),\dots,c_{iM}(p^*), y_i + EV_i(p)) = u_i(p)$$

Equivalent variation is introduced by a (linear) approximation of Δu_i by a Taylor series.

$$Tu_i(c_{i1}(p^*),\dots,c_{iM}(p^*), y_i^* + EV_i(p)) = u_i(c_i(p^*), y_i^*) + \frac{\partial u_i}{\partial y_i}EV_i(p) + \dots$$

$$\begin{aligned} \Delta u_i &\approx Tu_i(c(p^*, y_i^*) + EV_i(p)) - u_i(c(p^*, y_i^*)) \\ \Delta u_i &\approx \frac{\partial u_i}{\partial y_i}EV_i(p) \end{aligned} \tag{A.2}$$

Use (A.2) in (A.1) (with $c_i^* = c_i(p^*)$)

$$\begin{aligned} TW(u_1(p),\dots,u_N(p)) &= f(p^*) + \frac{\partial f(p^*)}{\partial u_1}\frac{\partial u_1}{\partial y_1}EV_i(p) + \dots \\ &\quad \dots + \frac{\partial f(p^*)}{\partial u_N}\frac{\partial u_N}{\partial y_N}EV_N(p) \end{aligned}$$

$$\begin{aligned} \Delta W &\approx f(p^*) + \frac{\partial f(p^*)}{\partial u_1}\frac{\partial u_1}{\partial y_1}EV_i(p) + \dots \frac{\partial f(p^*)}{\partial u_N}\frac{\partial u_N}{\partial y_N}EV_N(p) - f(u_1^*) \\ &= \sum_{i=1}^{N} \frac{\partial f}{\partial u_i}\frac{\partial u_i}{\partial y_i}EV_i(p) \end{aligned}$$

Appendix B: Supplementary material

TABLE B.1. Social cost estimates

Unit	Stressor	Value
Global	CO2	170.2
Global	CH4	1453.5
Global	N2O	47751.1
EU	Phosphorus	152.4
Austria	NOx	33.5
Austria	NH3	19.3
Austria	N	30.9
Belgium	NOx	20.2
Belgium	NH3	39.5
Belgium	N	28.9
Bulgaria	NOx	9.6
Bulgaria	NH3	7.8
Bulgaria	N	2.8
Cyprus	NOx	14.4
Cyprus	NH3	12.9
Cyprus	N	20.7
Czechia	NOx	25.8
Czechia	NH3	26.0
Czechia	N	14.7
Denmark	NOx	15.8
Denmark	NH3	11.0
Denmark	N	42.4
Estonia	NOx	4.3
Estonia	NH3	6.0
Estonia	N	2.9
Finland	NOx	6.9
Finland	NH3	4.4
Finland	N	25.7
France	NOx	26.9
France	NH3	16.8
France	N	23.3
Germany	NOx	36.2
Germany	NH3	26.5
Germany	N	24.4
Greece	NOx	2.8
Greece	NH3	4.0
Greece	N	17.6
Hungary	NOx	19.1
Hungary	NH3	14.5
Hungary	N	9.6
Ireland	NOx	12.9
Ireland	NH3	3.5
Ireland	N	29.6
Italy	NOx	20.5
Italy	NH3	15.9
Italy	N	22.2
Latvia	NOx	5.4
Latvia	NH3	5.2
Latvia	N	3.5
Lithuania	NOx	6.6
Lithuania	NH3	2.9
Lithuania	N	2.5

TABLE B.1. Social cost estimates *(continued)*

Unit	Stressor	Value
Luxembourg	NOx	33.7
Luxembourg	NH3	35.3
Luxembourg	N	81.2
Malta	NOx	15.3
Malta	NH3	14.6
Malta	N	15.9
Netherlands	NOx	25.5
Netherlands	NH3	30.5
Netherlands	N	32.0
Poland	NOx	14.6
Poland	NH3	13.9
Poland	N	6.6
Portugal	NOx	4.5
Portugal	NH3	4.9
Portugal	N	15.1
Romania	NOx	9.8
Romania	NH3	7.9
Romania	N	3.3
Slovakia	NOx	19.7
Slovakia	NH3	19.2
Slovakia	N	12.8
Slovenia	NOx	26.7
Slovenia	NH3	19.9
Slovenia	N	17.0
Spain	NOx	8.7
Spain	NH3	5.6
Spain	N	21.3
Sweden	NOx	10.8
Sweden	NH3	8.0
Sweden	N	40.2

Table B.1 displays social cost estimates applied in section 5. Social cost of greenhouse gases are taken from (EPA 2023) using a discount rate of 2 percent. CO_2, CH_4 and N_2O are valued at their respective global social cost, HFC, PFC, SF6 (in CO_2eq) are valued at the global SC-CO_2. Social cost of nitrogen (N, NO_x, NH_3) cover only country-specific domestic social cost based on (van Grinsven et al. 2018). Social cost of phosphorus (P) cover domestic social cost assuming the value provided by (Matthey and Bünger 2020) for all EU27 countries. Values are provided in 2019 EUR.