CLIMATE POLICY
2025, VOL. 25, NO. 3, 504–510
https://doi.org/10.1080/14693062.2024.2392744

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COMMENT

Climate policy curves highlight key mitigation choices

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ABSTRACT
The extent of future climate change is largely a policy choice. We illuminate this choice with *climate policy curves* (CPCs), which link climate policies to subsequent global temperatures. The estimated downward sloping CPCs highlight the key trade-off between initial policy ambition, expressed via an overall effective carbon price, and the subsequent policy burden left for future generations. We also demonstrate how different CPCs can illustrate the range of climate policy paths towards attaining the Paris Agreement temperature goals. Based on the latest Intergovernmental Panel on Climate Change (IPCC) integrated-assessment model scenarios, we estimate an implicit CPC, which provides a high-level summary of assumptions underlying the IPCC's assessment about climate policy trade-offs. We show that by virtue of their reductionism, CPCs serve as a useful model diagnostic and communication tool for climate policy discussions.

Key policy insights

- Climate Policy Curves (CPCs) are a simple, new heuristic device for quantifying projected climate outcomes of different climate policies.
- CPCs can elucidate the various uncertainties surrounding climate policies and crystalize the importance of comparing climate policy today with its future path.
- CPCs can serve as a model diagnostic and communication tool for climate policy discussions by helping to understand and evaluate policy implications of alternative climate-economy models.

ARTICLE HISTORY
Received 29 December 2023
Accepted 9 August 2024

KEYWORDS
Climate policy; carbon tax; climate-economy models; model comparison

Introduction

Understanding the linkage between policy instruments and desired outcomes is important for appropriately setting public policies. Economists have developed straightforward tools, such as policy multipliers, to summarize economic policy transmission. However, similarly simple characterizations of climate policy have been elusive given the associated socio-economic and physical climate uncertainties and complexities. To better understand the efficacy of various climate policy instruments, we propose the concept of Climate Policy Curves (CPCs), which quantify the relationship between the effective price of carbon dioxide (CO_2), and the future increase in global average temperature. CPCs can also illuminate this complex relationship by changing shape and slope within the carbon price – temperature space. While we will illustrate CPCs for a specific climate-economy model, our main contribution is the general introduction of CPCs as novel tool to guide high-level climate policy discussions that may be informed by a range of climate-economy models.

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/14693062.2024.2392744

CPCs incorporate two important relationships: the link from climate policy ambition to emissions and the link from emissions to climate outcomes and global temperatures. The first link involves technology and economics – how much emissions abatement will result from a rise in the *effective* price of CO_2 (Andersson, 2019; Bayer & Aklin, 2020; Pretis, 2022). This effective carbon price, which we here summarize in terms of carbon price equivalents, can be understood as a summary measure of a range of possible energy and climate policies – including carbon and fuel taxes, emissions trading programmes, green subsidies, energy-efficiency regulations, renewable-energy mandates, or behavioural interventions. These diverse policy levers, in turn, can all be broadly summarized in terms of a direct price on each ton of CO_2 emitted (Gillingham & Stock, 2018; OECD, 2023; Parry et al., 2021). We illustrate how the CPC is affected when other policy approaches are implemented as a substitute for, or as a complement to, a uniform carbon price. The second link involves climate and earth system science – and depends on how sensitive the earth's climate is to CO_2 emissions. We use the global average surface temperature as a summary measure to encompass a whole host of other environmental shifts, including rising sea levels, shifts in weather extremes, and other related climate hazards.

We obtain CPCs by quantifying these two links using an integrated assessment model (IAM). Such models imply a relationship between carbon prices and global temperature outcomes, but previous work has typically focused on individual carbon price paths required to meet a specific temperature goal or maximize social welfare (Dietz & Venmans, 2019; Hänsel et al., 2020). Viewed through the CPC lens, these estimates typically provide only a single point on the curve. But a complete accounting of climate-economy interactions and alternative climate policy choices requires mapping the entire CPC, which describes the climate consequences of a wide range of possible carbon policies. Figure A1 in the Supplementary Information summarizes the conceptual idea of a CPC.

Thinking about climate policy in terms of the relationship between effective CO_2 prices and global temperatures is helpful as it focuses on the key policy question: What climate outcomes will result from a given climate policy setting? In this way, CPCs can describe how much more ambitious climate policies need to be to reduce future global warming by, say, 0.1°C. Moreover, CPCs can quantify the climate-economic trade-off between current and future action that policymakers face. For example, the same 2°C limit for global temperature increase can be achieved with a *high* initial carbon price that grows slowly over time or a *low* initial price that grows rapidly. The latter path postpones significant action – and mitigation burden – to the future (Gollier, 2021). Thinking about climate policy in terms of CPCs is helpful precisely because they can capture the essential features of an otherwise complex policy response mechanism. Furthermore, comparing CPCs from different climate-economy models – including different generations or iterations of the same model – can serve as a useful diagnostic tool for assessing IAMs.

Quantifying climate policy curves

To calculate CPCs, we project emissions, CO_2 concentrations, and temperature trajectories under alternative exogenous paths for the carbon price using the global Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 1992) as updated by Hänsel et al. (2020), which provides a better calibration of the carbon cycle and energy balance model, improved climate damage estimates, updated timing of the availability of negative emissions technologies, and updated projections of non-industrial emissions. CPCs can be illustrated in any IAM. We use DICE for a proof-of-concept illustration due to its popularity in striking a balance between parsimony and realism, while noting that DICE does not capture many important real-world dynamics and uncertainties that would be desirable features to include when formulating concrete policy advice (Gillingham et al., 2018; Grubb et al., 2021). We rearrange the marginal abatement cost equation to obtain the emissions path resulting from a pre-specified global carbon price path. We then vary the carbon price in the first period, assume an annual constant growth rate for future carbon prices, and plot the resulting atmospheric temperature in 2100. Hence, our specific quantification of CPCs with the DICE model relies on a uniform global carbon price as a proxy for the effective carbon price of other climate policy instruments. Our analysis illustrates the concept of CPC by focusing on the global mean temperature in 2100 to be comparable to available IPCC Sixth Assessment Report (AR6) (2021) data on carbon prices and temperatures. As the Paris Agreement temperature goals are often interpreted to aim at limiting peak temperature increase to consider irreversible climate damages, we compare CPCs that result from using 2100 temperature increases to the ones when using peak temperature increase in the Supplementary Information.

Both the initial level of the effective carbon price and its expected future growth rate are fundamental climate policy choices that determine future emissions and global temperatures. Figure 1 plots CPCs for annual carbon price growth rates of 2, 4, and 6%, which are consistent with a survey of expert recommendations that revealed a median growth rate of global carbon prices of 4.1% from 2020 to 2050, with a 66-percentile range of 2.3% to 6.5% (Drupp et al., 2024). For simplicity, we assume carbon price growth rates that are constant over time – consistent with some official policy guidelines (e.g. in the United Kingdom). However, neither the CPC concept nor the DICE model we use for our illustrations require that growth rates of carbon

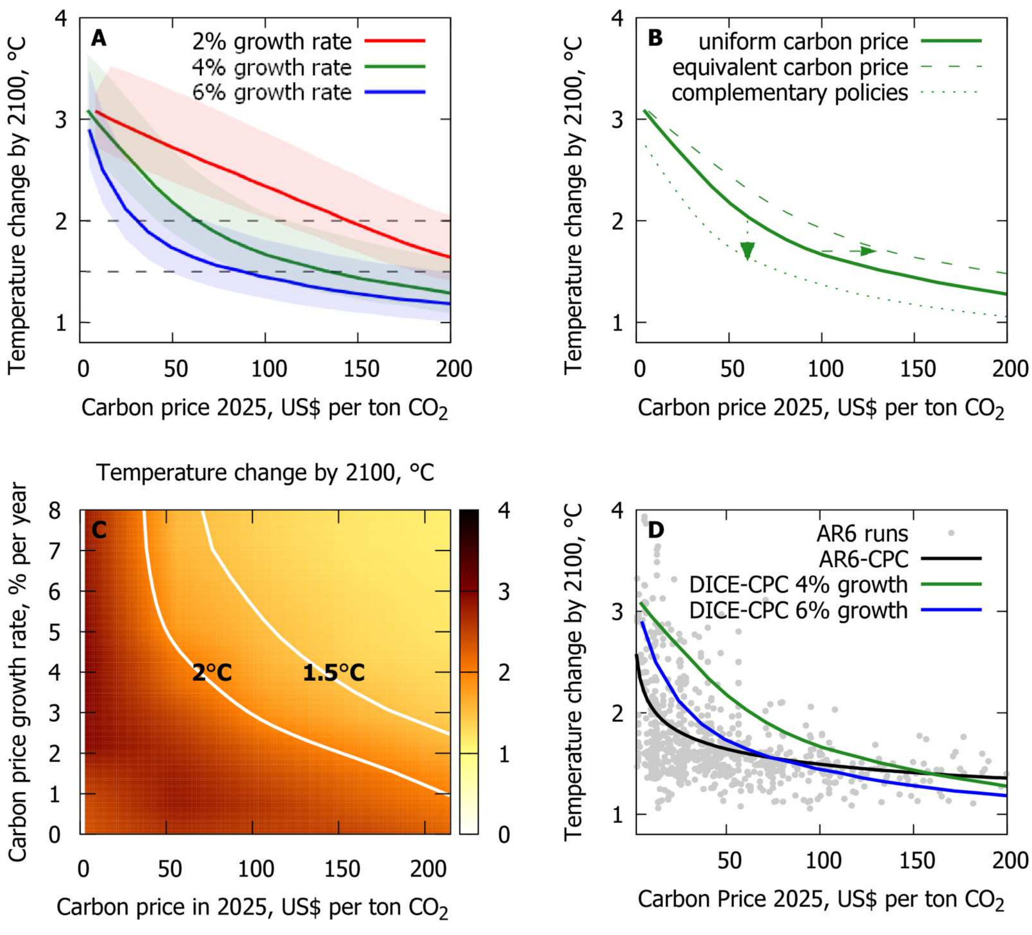

Figure 1. Quantifying Climate Policy Curves (CPCs). The relationship between the carbon price per ton of CO_2 in 2025, the annual constant growth rate for future carbon prices (2% (red), 4% (green) and 6% (blue)) and the global temperature by 2100 (above the 1850–1900 average). Panel **A** shows climate uncertainty shaded regions based on 'likely' ranges (66% probability) for the equilibrium climate sensitivity between 2.5 and 4°C in the IPCC AR6 report (World Bank 2023). Panel **B** illustrates how the 4%-CPC shifts when alternative policies that are translated into an equivalent carbon price trajectory are implemented either as a substitute for (dashed green line) or a complement to the uniform carbon price (dotted green line). For our illustration we assume that complementary policies increase the emission reduction rate by an arbitrary 20% in each period, while policies that only substitute a uniform carbon price reduce the emission reduction rate by a factor of 20% (see Supplementary Information B for details). Panel **C** shows a heatmap of global average temperature increase by 2100 for various combinations of initial carbon prices in 2025 and annual carbon price growth rates. The temperature colour scale is shown on the right. Contours that indicate carbon price paths that lead to Paris Agreement temperature goals are denoted by white lines. Panel **D** shows a comparison of DICE-based CPCs with a CPC fitted to AR6 model simulations. The grey dots represent AR6 data on the 2025 carbon price per ton of CO_2 and the global-mean surface air temperature (GSAT), and the black line fits a power function to these data. The green and the blue line are the CPCs based on an updated DICE model with 4% and 6% carbon price growth rates. All prices are in 2022 dollars. See the Supplementary Information for a description of methods.

prices are constant. In general, CPCs can feature any kind of growth rates. In Figure B1 in the Supplementary Information we compare our constant growth rates to the non-constant ones obtained under two different optimized versions of the DICE model.

The CPC's causal chain from carbon prices to global temperatures is subject to *socio-economic uncertainties* in the link from effective carbon prices to emissions and *climate uncertainties* in the link from emissions to global temperatures (Christensen et al., 2018). Here, we illustrate how policy implementation uncertainty – an example of the former – and equilibrium climate sensitivity (ECS) uncertainty – an example of the latter – affect climate policy tradeoffs. We employ an intuitive and transparent approach that varies key model parameters from their baseline estimates to high and low values that either summarize available evidence as in case of the ECS or are purely illustrative when empirical evidence is still lacking as in the case of policy uncertainty. The resulting curve shifts reveal potential magnitudes of CPC changes in both level and shape (additional uncertainties are examined in the Supplementary Information section E).

Panel A in Figure 1 shows our DICE-based CPCs and how they are affected by uncertainty about the ECS. The horizontal axis measures the 2025 carbon price in constant (2022) US dollars per ton of CO_2, which is the initial policy choice variable. The vertical axis measures climate outcomes: global mean temperature in 2100 relative to the 1850–1900 average. The shaded regions reflect uncertainty about the ECS, which measures the temperature change from a doubling of atmospheric carbon. We vary ECS within the 'likely' range of 2.5°C to 4°C with a baseline estimate of 3°C – consistent with the IPCC's AR6 assessment based on Sherwood et al. (2020). A higher ECS results in a higher temperature – of about 0.4°C – at any given initial carbon price, and at the resulting higher CPC, the Paris goals are much harder to attain.

At very low levels for the initial CO_2 price, all of the CPCs in Figure 1 Panel A imply, in expectation, about 3°C of warming above pre-industrial levels by 2100. This is consistent with other studies analyzing current global climate policies that are approximated with a global effective carbon price of a few dollars (World Bank 2023). Clearly, climate policy needs to be substantially more ambitious to stay well below 2°C. The CPCs reveal combinations of current carbon prices and growth rates that are consistent with 2°C by 2100, under the ideal conditions of a uniform and fully efficient carbon price. At a growth rate of 4%, the green CPC shows that limiting global warming to 2°C by 2100 in expectation would require a carbon price around US $70. If, instead, there is a slower projected growth rate of only 2%, the requisite current carbon price rises to about US$150.

Panel B in Figure 1 illustrates how a CPC can shift when climate policies other than a uniform global carbon price, e.g. non-uniform prices, subsidies, standards, or bans, are implemented either as a substitute for, or complement to, a uniform carbon price (dashed and dotted green lines, respectively). Economic theory would predict that translating substitutive policy approaches into carbon prices that can attain an equivalent climate outcome means economic efficiency losses. Here, these losses are reflected by higher equivalent carbon prices or marginal abatement costs over the range of possible climate outcomes, such that the resulting CPC will shift up and to the right. Technically, we illustrate economic efficiency losses by constraining the emission reductions associated with a particular carbon price trajectory by 20% in each period. One could similarly assume the opposite, implying that non-price climate policies may be both more feasible, and indeed achieve greater emissions reductions at lower prices, for example by complementing price-based policies. Panel B also shows complementary policies that result in 20% additional emission reduction in reach period, leading to a shift down of the CPC. Either way, these effects might change over time due to dynamic learning effects (Gillingham & Stock, 2018). In section E of the Supporting Information, we discuss additional CPC curve shifters that illustrate the importance of key uncertainties in quantifying CPCs.

The heat map in Figure 1C elaborates on the CPCs to illustrate the effects of a broad range of alternative policy choices. It shows how combinations of 2025 carbon prices and carbon price growth rates (horizontal and vertical scales, respectively) result in a given 2100 mean temperature – denoted by colour. Each CPC in Panel A of Figure 1 can be represented by a horizontal line in Figure 1C. The contour lines for a 2°C temperature increase in Figure 1C illustrate the combinations of 2025 carbon prices and price paths that are compatible with attaining these 2100 temperatures. For example, staying below 2°C by 2100 with only a 1% (8%) annual increase in carbon prices would require a 2025 carbon price of approximately US$200 (US$40). The choice of a combination of an initial carbon price and future trajectory is a key climate policy tradeoff. While climate policy with a high initial carbon price and low subsequent growth rate may be socially optimal (Hänsel et al., 2020; Nesje et al., 2023), policymakers might start with a low carbon price but promise a high carbon price growth rate, which shifts the mitigation burden to the future (Gollier, 2021). Although our quantification of DICE-based CPCs ignores that carbon policies are typically formulated at the country-level, this key climate policy trade-off remains relevant also for country-level policies.

CPCs can also serve as a useful summary metric for IAM evaluation and comparison. Contrasting CPCs obtained from different types and calibrations of IAMs can provide a straightforward means to compare key climate policy implications of these models. Similarly, CPCs may serve as a useful diagnostic tool in intercomparison exercises, adding to previous diagnostic tools that implicitly contained CPCs (Harmsen et al., 2021; Kriegler et al., 2015). As an example, Panel D in Figure 1 plots different model simulations from the IPCC AR6 Scenario Database (Byers et al., 2022) as grey dots in the carbon price and temperature space. Specifically, we extracted data on the 50.0th Percentile of Surface Temperature (GSAT) forecast for the year 2100 from the FaIRv1.6.2 model and carbon prices for the years 2025, 2030, 2050 and 2100. The black line fits a power function to these data and provides the implicit composite 'AR6-CPC' that summarizes a wide variety of modelling choices and carbon price paths (for details see Section D in the Supplementary Information). For a range of 2025 carbon prices between US$80 and US$160, the AR6-CPC settles between our CPCs with constant carbon price growth rates of 4% and 6% (the green and blue lines). The AR6-CPC suggests that carbon prices below approximately US$60 are more effective in reducing temperatures as compared to the 6%-DICE-CPC.

Conclusion

Climate policies come in various forms, including carbon prices and emissions trading systems as well as efficiency standards, clean-energy subsidies, and many more. The objective of this Perspective is not to provide a methodology on how these policies can be translated into effective carbon prices (see for example OECD (2023) on how this can be done). Instead, we introduce Climate Policy Curves (CPCs) as a policy and communication tool to compare policies and elucidate their climate consequences. By focusing on the essential mapping from climate policy to climate outcomes, CPCs can assist in understanding complex climate-economy interactions. For example, CPCs can illustrate the choice of climate mitigation burden-sharing across generations: the trade-off between today's climate policy setting and its future path. Accordingly, CPCs can help frame and navigate the difficult choices between near-term ambition and procrastination.

In the end, CPCs are a simple, new heuristic device for (i) quantifying projected climate outcomes of different climate policies, (ii) understanding and evaluating the policy implications of alternative climate-economy models, and (iii) elucidating the various uncertainties surrounding climate policies. Our DICE and IPCC-based quantification of CPCs should be understood as an initial step, which can be extended in future model inter-comparison exercised using other IAMs. Exploring CPCs in more comprehensive model intercomparison projects could allow policymakers to visualize key climate policy trade-offs build into various models through the lens of a CPC. The main contribution of this Perspective is thus to introduce CPCs as a novel tool to make key climate policy trade-offs salient for general policy discussions.

Acknowledgments

We are very grateful to Frances Moore, Jessica Streffler, and Elijah Asdourian for helpful comments. We thank Jasper Röder for excellent research assistance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Drupp acknowledges support from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under Germany's Excellence Strategy [grant number 390683824], contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg. Bauer acknowledges support from the DFG under [grant number 425909451].

Author contributions

G.D.R. conceived the initial idea of a Climate Policy Curve (CPC), which was subsequently further developed into a research paper concept by all of the authors. M.C.H. performed the numerical modelling, data analysis, and graphical representation of results with substantive input from M.A.D and close feedback from all other authors. All authors contributed to the writing of the manuscript. M.C.H. led the revision of the manuscript.

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