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Implying climate impact from carbon prices and consumption

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ABSTRACT

The value of the social cost of carbon (SCC) remains contested, despite having been described as the single most important concept in the economics of climate change. The SCC represents the discounted reduction in welfare caused by the release of an additional tonne of carbon dioxide equivalent (tCO_2e) greenhouse gas emissions into the atmosphere. In practice, many estimates of the SCC are not robust or comparable, due to technical issues, including parameter estimation in climate assessment models. Using a market-based approach to calculate climate change metrics can avoid some of the controversy associated with calculating the SCC and subjectivity in deriving temperature alignment from transition plans. This study inverts results from an integrated assessment model commonly used to calculate the optimal SCC. A relationship is inferred between carbon price and both climate damages and implied temperature alignment. Using national data on effective cost of carbon (ECC), i.e. current carbon prices, the global market-implied temperature alignment is 3°C of warming. Using carbon consumption data to calculate implied climate impact, the per capita impact of higher-income countries is significantly higher than in low- and medium-income countries. The findings suggest that globally an ECC above $85/$tCO_2e$ may be required for implied temperature alignment to fall below 2°C of warming. However, both higher-income economies and those with high per capita carbon consumption levels may need to set their ECC at twice this level if their climate impact is to fall below a level aligned with limiting warming to 2°C.

KEY POLICY INSIGHTS

- The current global Effective Cost of Carbon is $10/$tCO_2e$. $85/$tCO_2e$ is needed to limit global warming below 2°C as agreed in the Paris Agreement.
- The Effective Cost of Cabon needed to meet this goal will ratchet in real terms to $200, $300 and $500/$tCO_2e$ by 2050, 2075 and 2100.
- Global implied temperature alignment shows 3°C warming with current ECC levels.
- Many higher-income countries exhibit higher priced climate damages but still overconsume carbon.
- Lower growth or decarbonization subsidies alone cannot achieve the Paris below 2°C target; carbon pricing is needed.

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Carbon pricing; environmental economics; integrated assessment modelling; climate policy curves

Introduction

Over the past three decades, global efforts to mitigate anthropogenic climate change have, at best, only slowed the rate of increase in greenhouse gas emissions. The remaining carbon budgets that would limit warming to close to 1.5°C and well below 2.0°C, as agreed in the Paris Agreement, will be exhausted in 7 and 28 years,

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respectively, at current emission rates (Friedlingstein et al., 2023). Climate policy, therefore, needs to shift from slowing increases, to achieving rapid reductions of global emissions (IPCC, 2018). While the decoupling of emissions from economic growth, driven by rapid decarbonization of electricity generation and adoption of renewables, is occurring in many countries (International Energy Agency, 2024), this has not yet translated into cuts in global greenhouse gas emissions. One reason may be because much of the initial progress in harder to abate economic sectors of higher-income countries resulted from the offshoring of their consumption emissions (De Bruyn et al., 1998; Peters et al., 2012a; Ruffing, 2007). More recent research suggests that decarbonization trends are less impacted by offshoring than emission levels (Darwili & Schroder, 2025), and absolute decoupling at the economy level is increasingly evident in many OECD countries.

As documented in the latest IPCC assessment report (AR) (IPCC, 2022b), current economic estimates of expected damages arising from climate change are so uncertain that setting a broadly accepted cost for greenhouse gas emissions is difficult. This uncertainty has led IPCC authors to emphasize other lines of evidence regarding climate risks beyond monetary estimates – including broader Key Risks and Reasons for Concern (RFCs). Notably, in more recent IPCC AR reports, the economic impacts of climate change have become increasingly deemphasized; in AR6, they appear as a concise footnote to the five global RFCs (B. O'Neill et al., 2022), even though RFC 2 (extreme weather events) and RFC 4 (global aggregate impacts) map almost directly onto 'acute' and 'chronic' economic impacts, respectively.

This approach shows how climate scientists are aiming to produce broader policy relevant analytics, rather than direct economic impacts or cost–benefit recommendations. The AR6 approach also illustrates why estimating global climate damages for use in a cost–benefit analysis is fundamentally challenging. It requires accurately estimating impacts across a wide range of channels and aggregating them across countries and regions.

High uncertainty about global economic damage levels makes the usual normative approach in social sciences and economics problematic for policy recommendations. For example, Barrage & Nordhaus (2024) estimate values of SCC in 2025 that range from \$37 to \$4185/tCO_2e. They show that the cost–benefit optimal SCC is highly dependent on assumptions for the long-term social discount rate (with more than an order of magnitude differences between real discount rates of 1% and 5%). Yang et al. (2018) show that it will also depend strongly on the level of global economic growth and the nature of the Shared Socio-economic Pathway (SSP) for economic development (B. C. O'Neill et al., 2014).

A non-normative methodological approach would be to shift from asking 'what is the price' of climate change to 'what is priced?' and to ask whether polluters are paying enough to ensure that policy goals will be met? The use of such an 'inverse approach' is relatively widespread in quantitative finance to derive fundamental values implied by market pricing. Examples include the calculation of yield to maturity for bonds and loans in banking and fixed income investing, credit spread levels in corporate finance, implied volatility in options and derivative markets (Hull, 1995), and distance to default in credit risk modelling (Crosbie & Bohn, 2003). Market-consistent pricing of liabilities has also been implemented in international accounting standards – for example, IFRS 9 and 11 (International Accounting Standards Board, 2018) – demonstrating that it is an important policy concept when determining financial disclosures and adequacy.

This study presents market-implied priced climate damages calculated by inverting input/output dependencies in the DICE model (Barrage & Nordhaus, 2024) and using current estimates for the effective cost of carbon (ECC) (OECD, 2023). By treating climate damages as a latent variable within DICE and using the ECC as an input, a parametric approximation is inferred that shows global temperature alignment. This can be adjusted by per capita carbon consumption to measure the implied climate impact for different countries.

Having introduced the concept of the ECC, it should now be defined more precisely. The level of the ECC represents the effective price used when assessing carbon abatement decisions and investments. If the cost of continued greenhouse gas emissions plus the ECC is greater than the cost of lower-polluting alternatives, agents within the economy choose to decarbonize their activities. Compared to estimates of the SCC, the nature of the ECC calculation is more constrained and more focused on which specific policies should be considered effective in terms of mitigation.

The importance of the ECC is illustrated by the fact that major international statistical agencies, such as the OECD and World Bank, collate data and publish annual reports (e.g. OECD, 2023; World Bank, 2024). One shortcoming of these reports, from a policy perspective, is how to interpret the carbon price and its effectiveness.

Without that context, policymakers, and the public may tend to view them simply as a cost. This is unfortunate, given that economists emphasize that carbon pricing is 'revenue neutral' – for example its proceeds can be reinvested in public services and goods in lieu of broader forms of taxes (Barrage & Nordhaus, 2024).

The market-implied methodological approach presented in this study shifts the focus from trying to determine the optimal SCC to understanding actual pricing and its effects on temperature alignment and climate impact. It asks how much is actually being priced or committed to address the RFCs, and what impact this pricing of climate damages should have in terms of temperature alignment and climate impact. This allows for a better understanding of what is implied in terms of mitigating the level of global warming, the resulting climate change, and therefore the RFCs themselves.

The remainder of the paper is structured as follows. First, a brief review of the relevant theory on the economics of climate change and abatement is presented. This is followed by a section outlining the methodology used and a further section summarizing the main results. The paper concludes with a discussion of both the methodology and results followed by a brief conclusion focusing on policy implications.

Theory

The economic failures that lead to insufficient climate action and a broader environmental crisis (Millennium Ecosystem Assessment, 2005) have been well understood for more than half a century (Hardin, 1968). As the global climate system is a common good, free markets fail to adequately price the damages arising from greenhouse emissions and allowing polluters to profit in the short term.

In theory, the 'polluter pays' principle could help to resolve the issue, if the costs of greenhouse gas emissions are set at a sufficiently high level and enforced globally (Nordhaus, 1992). The appropriate price that polluters should pay for greenhouse gas emissions is known as the social cost of carbon (SCC) (Barrage & Nordhaus, 2024; Nordhaus, 1992). It is defined as the economic cost (change in discounted economic welfare) arising from an additional tonne of CO_2 equivalent (CO_2e) emitted into the atmosphere. The calculated SCC increases with the level of emissions (and decreases as the emission 'control rate' increases) as damages are expected to increase with emissions levels and higher committed global warming. In impact work, the SCC can be calculated based on current high emissions levels. In this case, the welfare impact is assumed to be suboptimal, as marginal abatement costs are much lower, and a welfare increasing policy would be to increase control rates by increased abatement spending, which would also drive the SCC down to a more acceptable level.

To calculate the cost–benefit optimal level for the SCC, the costs of climate damages must first be estimated, and then 'avoided' costs (the additional costs associated with building out net zero technologies and solutions – net abatement costs) are subtracted off by calculating a level of emissions control where the two sources of cost exactly cancel. This can be considered the maximum acceptable level of costs associated with carbon emissions or, in economic terms, a minimum 'sunk cost' resulting from global warming which society will need to bear. Throughout the remainder of the paper, references to SCC will specifically mean the cost–benefit optimal SCC, and will assume that at this level of SCC the per tonne marginal abatement costs are equal to and offset additional physical damages. This equality will allow the calculation of implied metrics for both what is priced in terms of physical damages, but also what is implied in terms of abatement levels, warming and climate impact.

Uncertainty regarding the level of the SCC limits the 'normative' approach typically taken in social sciences and economics (e.g. focusing on policy recommendations). This uncertainty makes it challenging to answer more practical questions such as those framed by Hardin (1968) and Ostrom (2009) including: what is the optimal approach a social planner should take to maximize social welfare, or what is the economic value society should apply to something that does not trade (greenhouse emissions)? A broad range of different underlying assumptions can be chosen by different groups, producing wildly conflicting results and recommendations (Forsyth et al., 2014).

The proposal by some that economic cost–benefit modelling would become more credible if more realistic assumptions are used (Stern, 2016) aims to double down on the normative agenda or reweight it towards the precautionary principle (Howarth et al., 2014). However, these responses circumvent rather than address knowledge limitations and uncertainties (Tol, 2009). More problematically, they also encourage a schism between those that favour a utilitarian or monetized approach to welfare and those who argue for a broader definition of wellbeing (D. W. O'Neill et al., 2018; Raworth, 2012).

Deriving estimates of priced climate damages through a market-implied approach is potentially valuable, as climate damages are particularly uncertain and difficult to derive on an a priori basis, and the level of damage priced or implied in human actions is poorly constrained (Hardin, 1968). Only under certain circumstances are the *actual* societal costs likely to constrain behaviour. When studying common and public goods, the implicit costs actually priced can instead be inferred as a function of behaviour, rather than as either an internal or external constraint on behaviours (Balke & Gilbert, 2014).

The problem of dealing with climate change (and more generally environmental or ecological) economics is substantially more complicated and multidimensional than the financial examples (Meadows, 2008; Raworth, 2012) noted earlier. Perhaps due to this complexity, the inverse approach to understanding climate change pricing has only rarely been applied (Hansel et al., 2025). However, models of the interactions between economic activity, policies and environmental change, such as cost–benefit integrated assessment models (IAMs) are well developed and widely adopted, and could be used as a basis for a market-implied analysis of the problem.

Methodology

The DICE model combines a neoclassical economic growth model, augmented to account for climate damages and abatement costs, with a geophysical model for the evolution of climate and global warming levels, including a reduced-form model for the carbon cycle and atmospheric and ocean temperature dynamics (Barrage & Nordhaus, 2024). DICE is often used to estimate the SCC in normative exercises designed to identify optimal policy. It has also been shown to perform well as a simplified climate model for projecting expected global warming levels (Folini et al., 2024).

The multidimensional model has a total of 24 variables modelled with coupled equations (and hence modelled as time-dependent variables) which cover: economic objectives (e.g. utilitarian social welfare); economic sectors (including, economic output and productivity); damages and abatement (e.g. climate and transition costs); global accounts (i.e. output, consumption and investment); greenhouse gas emissions; geophysical processes (e.g. carbon cycle and climate) and the social cost of carbon.

Barrage & Nordhaus (2024) state the model can be run on both a 'positive' and 'normative' basis. Examples of 'positive' analysis include using the model to project how a predefined policy – such as a path for carbon prices or a cap on warming levels – will impact the economy and climate as they follow long-term equilibrium paths of economic growth and climate change. Examples of 'normative' analysis include cases where 'optimal' policy is solved for, e.g. when estimating the SCC and 'optimal' constraints (limit) on global warming levels. Barrage & Nordhaus (2024) also emphasize that other approaches like precautionary or threshold avoidance, may be preferable (Rockström et al., 2009).

In the optimized configuration of the model, the Social Cost of Carbon, SCC_t, at any particular time, t, can be defined as a function of the evolution of multiple variables, $\boldsymbol{X_t}$, and the values of multiple parameters, $\boldsymbol{P}$:

$$SCC_t = F(\boldsymbol{X_t},\ \boldsymbol{P})$$

This multidimensional functional form is not uniquely invertible as is, but if all parameters are fixed except the climate damages, Ω, and then, the variables are allowed to evolve as defined by the model, then it is possible to calculate:

$$\Omega = F^{-1}(ECC_t|\boldsymbol{X_t},\ \boldsymbol{P'})$$

where all model parameters $\boldsymbol{P'} = \boldsymbol{P}$ (except Ω), are fixed at their 'best estimate' values and the model variables $\boldsymbol{X_t}$ are allowed to vary naturally given the dynamics and cost-spreading optimality constraints of the model. When inverting, the SCC is replaced with the Effective Cost of Carbon (ECC) as there is no longer an optimality implied – just an observable cost of carbon prevailing in markets.

In less formal mathematical terms, the model is run multiple times for different damage levels in order to investigate the dependent relationship between ECC and priced climate damages. The methodology is conceptually very similar to the recently developed idea of climate policy curves (Hansel et al., 2025), which also link the effective price of carbon to implied temperature outcomes. By using a cost–benefit IAM, the analysis is broadened beyond implied temperature alignment to also look at priced damages. A metric for implied climate impact is developed, and approximate parametric forms for the curves suggested.

Ω is assumed to take a quadratic form dependent on the atmospheric temperature increase levels $\Delta T_{AT}(t)$ at different points in time t,

$$\Omega(\mathrm{t}) = \psi_1 \Delta T_{AT}(t) + \psi_2 \Delta T_{AT}(t)^2$$

As in the default calibration of DICE 2023 ψ_1 is set to zero, meaning only one parameter ψ_2 is varied, and allowing a unique inversion of the model dependencies (e.g. ECC as an input and priced climate damages and implied temperature alignment as outputs). It is worth noting that this treatment of ψ_1 as zero, is consistent with the precautionary principle as a non-zero linear term implies a preferred direction for global temperature changes. The quadratic term implies a preference for the current climate and global temperature levels. For robustness alternative forms for the damage function – linear, cubic and quartic were also investigated.

The social cost of carbon is calculated at a fixed time step (the year 2025), and then, the relationship between the cost of carbon and damages is analysed. A linear relationship without offset approximates the data with a high R^2. Priced climate damage results are calculated by extrapolating the damages to $\Delta T_{AT}(t) =$ 2, 3 and 4°C.

The results for implied temperature alignment are derived from the same set of modelled data, but instead of inferring the climate damage parameter, the temperature increase in the year 2100 is analysed. A displaced exponential relationship approximates the model data points well, suggesting a relationship for implied temperature alignment, $\Delta T_{Alignment}$, of the form:

$$\Delta T_{Alignment} = \Delta T_{Minimum} + \Delta T_{Abatable} \exp\left(-\frac{ECC_{Market}}{ECC_{Critical}}\right)$$

where:

- $\Delta T_{Minimum}$ is the minimum amount of global warming still achievable,
- $\Delta T_{Abatable}$ is the additional amount of global warming which can be abated and
- $ECC_{Critical}$ is a critical reference point for carbon pricing which ensures a substantial (approximately 68%) decline in abatable global warming levels.

To examine dependencies on any other parameters (for example economic growth or discount rates), it is possible to rerun the models with a different set of baseline parameters, $\boldsymbol{P}'$, and refit the parametric relationships. For example, when producing the different economic growth results in Figure 1, the total factor productivity (TFP) parameter was varied to show sensitivities to low and high growth. The medium growth setting broadly aligns with the Shared Socio-economic Pathway SSP2, but uses the functional form of DICE, rather than the growth paths suggested by Dellink et al. (2017). The closest matching Shared Socio-economic Pathway for low and high growth are SSP3 and SSP5, respectively.

An implied climate impact metric, ΔT_{Impact}, for each country can be developed based on the implied temperature alignment metric, but which is weighted by per capita carbon consumption, $C_{country}$, as a proportion of global carbon consumption, C_{global}:

$$\Delta T_{Impact} = \Delta T_{Minimum} + \left(\frac{C_{country}}{C_{global}}\right) \Delta T_{Abatable} \exp\left(-\frac{ECC_{Market}}{ECC_{Critical}}\right)$$

Carbon consumption metrics calculated by Friedlingstein et al. (2023), using the method of Peters et al. (2012b), are used rather than the more commonly referenced territorial emissions in order to account for significant levels of 'offshoring' of emissions by wealthier countries to more industrialized countries.

If an individual country's per capita carbon consumption equals the global average, then the implied climate impact equals the global implied temperature alignment. A population-weighted average of all countries' implied climate impacts will also be approximately equal to the global implied temperature alignment.

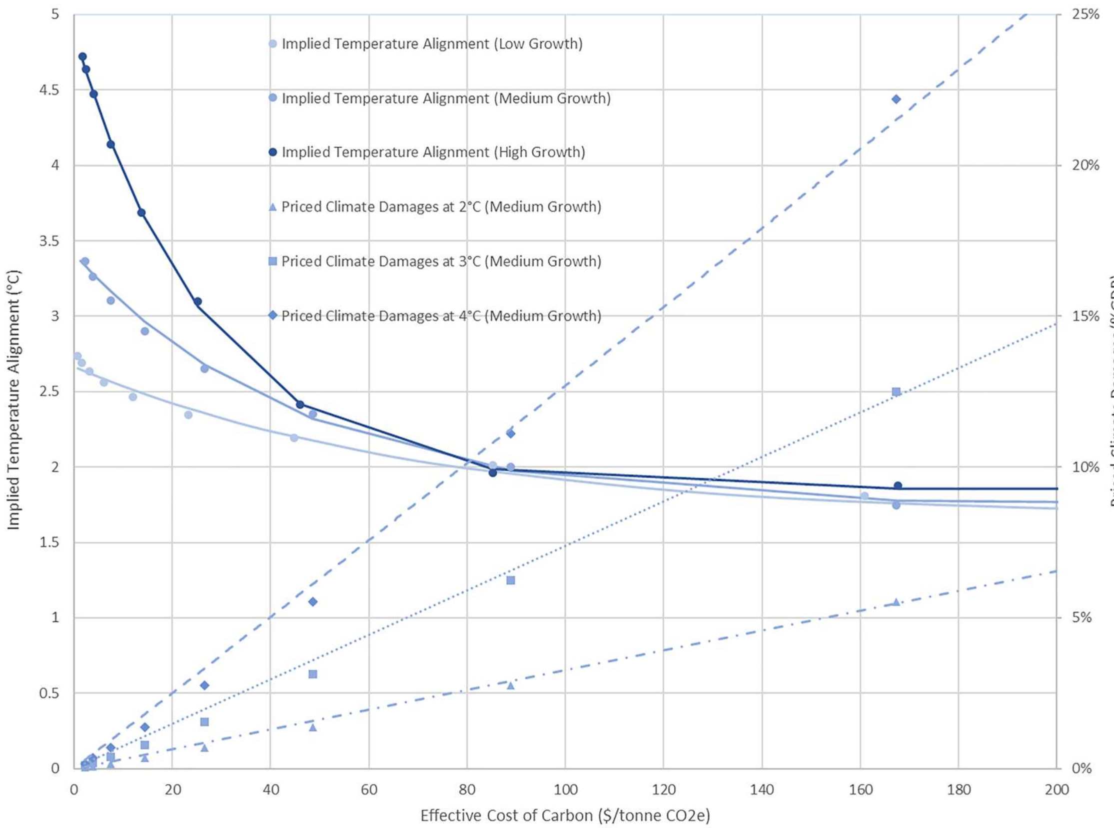

Figure 1. Priced climate damages inferred from different effective costs of carbon. The data points show three series of modelled results produced by DICE 2023, each representing the relationship with ECC at a different level of economic growth. The medium growth fits use the default TFP value of 1.16%/year proposed for DICE 2023 (Barrage & Nordhaus, 2024). For each series, priced climate damages are a linear function of effective cost of carbon (with zero offset). The linear fits for priced climate damages at different temperatures were produced with the least squares method. Fits for different levels of growth were calculated but are not shown as they lie very close to each other. A displaced exponential regression fit is shown for each implied temperature alignment data series. The curve fitting was done using non-linear least squares (NLS) with the Gauss–Newton algorithm. The fitting method is non-statistical, so no formal goodness-of-fit statistic was calculated. Several alternative parametric forms were considered and rejected, with the displaced exponential form chosen based on its apparent high quality of fit and intuitive interpretability.

Although approximate parametric forms for the inversion are presented, inversion can also be performed exactly via an iterative root search. This is more time-consuming but may be preferred if there are concerns regarding the accuracy of the approximation.

Results

By running DICE simulations for multiple climate damage levels (while holding other parameters constant), the resulting relationship to the SCC is analysed. The modelling uses default model parameters suggested for DICE 2023 (Barrage & Nordhaus, 2024), except for abatement costs, where slightly lower values are used to align the modelling with consensus cost estimates (Kotchen et al., 2023). When inverted, these simulation results show a linear dependence between the ECC and market-implied priced climate damages (Figure 1). Damages are quoted at 2, 3 and 4°C of warming to normalize the priced climate damage metrics. Even if DICE simulations limit warming below these levels, extrapolated damages are calculated to infer the pricing of avoided climate damages.

The slope of the 3°C linear fit reveals that for every $100 increase in the ECC, the level of priced climate damages increases by 7.3% of GDP, given the default (labelled as medium) economic growth assumption used in DICE.

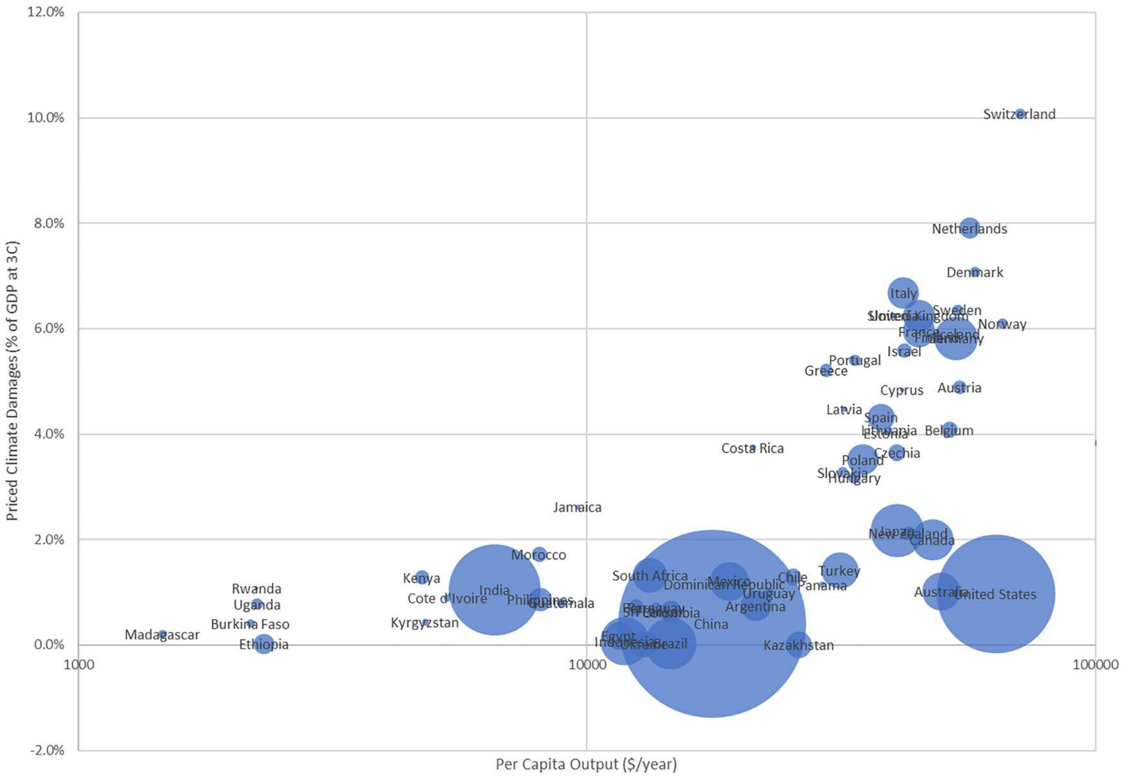

Figure 2. The relationship between priced climate damages across different countries and per capita economic output within countries. Each circle represents a different country. The position of the circles against the axes shows the total per capita output (GDP) and priced climate damages for each country studied. The area of each circle is proportional to the country's total greenhouse gas emissions in 2021. Per capita output is quoted in US dollars/year (as of 2021) and is plotted on a logarithmic scale.

When priced climate damage levels are implied from the ECC, they need not be assumed to be purely monetary or economic (even though quoted in those terms). They could also represent the monetary value associated with a broader set of risks, including the Key Risks and Reasons for Concern identified by the IPCC (IPCC, 2022b), and can be considered to represent willingness to pay (Bockstael et al., 2000) for climate mitigation. This interpretation is particularly relevant for RFCs 1, 3 and 5 which correspond to concerns regarding permanent loss of unique and threatened systems, distributional impacts (climate justice) and large-scale singular events (global tipping points), respectively. These are impacts that are difficult to quantify in monetary terms, but significant to the point of being potentially categorized as 'priceless'.

The ECC range of \$0 to \$200/tCO_2e shown in Figure 1 covers 0–15% of global GDP at 3°C of warming, e.g. the lower portion of reviewed AR6 climate damage estimates which vary between 0 and 50% of global GDP (IPCC, 2022a).

If the priced climate damages parameter is treated as a latent variable and the calculated warming levels at 2100 instead examined, it is possible to infer implied temperature alignment as a function of ECC. A parametric relationship between implied temperature alignment $\Delta T_{implied}$ and ECC can be derived (Figure 1). The results show that the higher the level of priced climate damages (implied by the ECC), the more emissions abatement occurs, and the lower the resulting global temperature increase.

The resulting fits (Figure 1) show a clear distinction between an unabated implied temperature increase of generally greater than 2.6–4.7°C and an abated implied temperature increase of less than 2°C. This indicates that the DICE model distinguishes between two regimes (business as usual/unconstrained, and Paris-aligned) with the tipping or leverage point between the two likely to be driven by both carbon pricing levels and effective growth rates. The results suggest that to meet the goals of the Paris agreement, a global

ECC of \$85/tCO_2e or higher is necessary (the crossover of 2°C in Figure 1). This occurs when priced climate damages are more than 6% of GDP at 3°C.

Results for both price and growth effects are shown to distinguish the split between the optimal climate policy identified in environmental economics – carbon pricing (Nordhaus, 1992) – and an alternative climate policy identified in ecological economics – economic degrowth (Kallis, 2011). The results (Figure 1) suggest that lower growth on its own appears unlikely to be able to limit warming below the 2°C Paris target, but carbon pricing alone may struggle to achieve the more ambitious goal of limiting warming to close to 1.5°C. Combined, these policies might lower implied temperatures by one or two tenths of a degree more, but limiting warming to 1.5°C appears unlikely to be achievable. High growth without effective carbon pricing could lead to significantly higher levels of implied temperature alignment (4–5°C).

For all derived results presented in Figures 2 and 3 and Supplementary Table SI1, the following values were used based on the results shown in Figure 1 for a medium level of economic growth (e.g. a TFP growth rate of 1.16%/year; Barrage & Nordhaus, 2024):

- $\Delta T_{Minimum} = 1.73^{\circ}C$,
- $\Delta T_{Abatable} = 1.69^{\circ}C$,
- $ECC_{Critical} = 46.1\$/tCO_2e$.

For clarity and replicability, these parameters are quoted precisely, but we caution against over interpretation regarding accuracy in the results. DICE is only one example of an IAM that could be used, and some authors

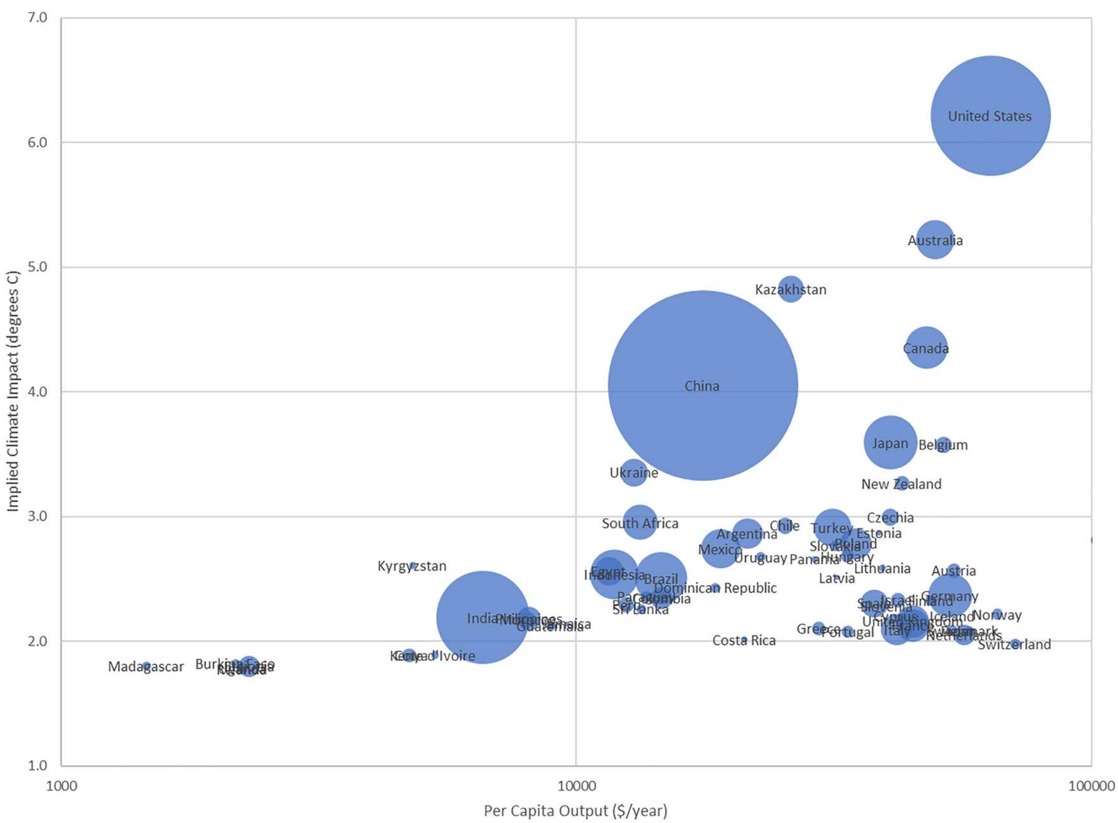

Figure 3. The relationship between implied temperature alignment across different countries and per capita economic output within each economy. Each circle represents a different country. The position of the circles shows the total per capita output (GDP) and implied climate impact for all countries studied. The area of each circle is proportional to the country's total greenhouse gas emissions.

have argued that the DICE 2013 parameterization could be improved (Folini et al., 2024). The parameters presented are conditional on model and calibration choices, which could be further refined by model intercomparison or probability-weighted parameterization. Nevertheless, the overall sensitivities of the results should be relatively robust to these choices, given that the DICE model has been demonstrated to be a robust emulator of climate change dynamics (Folini et al., 2024).

The analysis presented here is for a pricing date of 2025. By projecting the analysis forward to future dates (see Supplementary materials), the $\Delta T_{Minimum}$ and $\Delta T_{Abatable}$ parameters are observed to remain constant, but the $ECC_{Critical}$ value increases to over \$100 (in real terms) by 2050 and continues to rise towards \$300 by the end of the century. The results are dynamic, with increasing levels of pricing stringency required in future years to maintain the same levels of implied temperature alignment.

The Supplementary materials provide additional sensitivity analysis. It is worth drawing attention to two surprising but informative results:

First, the sensitivity of implied priced climate damages to ECC is relatively independent of growth. It does increase slightly as growth in the modelling decreases, but is essentially the same for medium and high growth rates. Therefore, priced climate damages are only shown for medium growth in Figure 1.

The supplementary materials also show how the results change with the parametric form of the assumed damage function. The implied temperature alignment fit is highly insensitive to this choice; estimates for both $\Delta T_{Minimum}$ and $\Delta T_{Abatable}$ remain the same regardless of form. The level of ECC decreases slightly as the exponent in the damage function increases from linear to quartic. An intertemporal analysis of the effect shows this is due to a greater deferral of action (typically to post-2075) when more extreme forms of the damage function (cubic and quartic) are used.

These results likely arise because it is the relative discounted cumulative levels of climate damages that are the critical property in cost–benefit modelling. It is the area under the relative damage curve, rather than the exact form of the curve, that is of primary significance in deriving the SCC levels used for inversion.

As well as providing clear bounds for the degree of global warming that should be expected (given a best estimate of climate sensitivity), the implied temperature alignment method can also give a clear indication of market-implied expectations for the likely level of global warming. To do this, the modelled results are applied to analyse priced climate damages and implied temperature alignment globally. The ECC data used was collated by the OECD for 44 OECD and G20 countries using a methodology developed by the OECD (OECD, 2016), specifically their estimate of 'average effective carbon rate' a weighted average of explicit carbon taxes, carbon permits and fuel excise duties in each country.

Combined, the 44 countries studied are responsible for approximately 80% of total global greenhouse gas emissions. The median priced climate damages are less than 1% of GDP at 3°C of warming and the median implied temperature alignment is 3°C, consistent with a global ECC of \$10/tCO_2e. The median ECC across these countries (and also the median priced climate damages) is almost an order of magnitude lower than \$85/tCO_2e and therefore does not align with the goals of the Paris Agreement.

To extend the analysis to the country level, it is important to recognize that the implied temperature alignment metric will tend to penalize countries which have relatively low levels of economic development and favour higher-income countries that are responsible for a disproportionately large share of emissions. To address this bias, an implied climate impact metric is proposed, based on the implied temperature alignment metric but with the abatable temperature increase weighted by per capita carbon consumption.

Implicit in this calculation is the assumption that the minimum level of warming is a global legacy shared by all (an obvious alternative would be to attribute the minimum level of warming proportionally to historical emissions), but the projected level of abatable temperature increases should be set in proportion to current levels of per capita carbon consumption.

Plotting the priced climate damages against the per capita economic output (GDP per capita) for the different countries studied suggests that implied economic damages tend to be higher when per capita output is higher (Figure 2). This trend is strongest when per capita output is greater than \$10,000/year, and most evident for European countries. This effect is consistent with an environmental Kuznets curve (EKC) (De Bruyn et al., 1998; Liao & Cao, 2013) which demonstrates greater levels of environmental (specifically global warming) concern as income and wealth increase. However, the US, Japan, Canada, New Zealand and

Australia are clear and notable exceptions to this trend, as has been noted in the decoupling literature (Gonzalez et al., 2024). Lower pricing of climate damages can be interpreted as a lower willingness to pay and should be expected to lead to less stringent abatement policies and higher emissions.

The relationship between the implied climate impact and per capita output (Figure 3) shows that although wealthier countries tend to exhibit a higher level of priced climate damages, they nevertheless also have consistently higher levels of implied climate impact. Only one higher-income country (Switzerland) has an implied climate impact of less than 2°C when weighted by per capita carbon consumption. In contrast, many lower- and medium-income economies have very low levels of ECC (and hence high implied temperature alignment) but low implied climate impact due to their low per capita carbon consumption.

The upper bound for the implied climate impact metric is significantly higher than that for implied temperature alignment. This is because if all countries in the world consumed carbon at levels aligned with higher-income nations, the total global level of current emissions would be significantly higher than today.

As illustrated in the case of Switzerland, it is possible to have higher than average per capita carbon consumption and still maintain a relatively low implied climate impact consistent with the Paris Agreement. This occurs if the ECC is high enough to limit the projected abatable temperature increases to close to zero. However, for high carbon consumption countries, it will likely be very difficult to lower the implied climate impact metric well below 2°C without ECC levels of several hundred dollars per tCO_2e.

Discussion

The results presented in this paper suggest that the current global ECC of approximately \$10/tCO_2e lowers the global implied temperature alignment for 2100 from over 3.4°C (expected without any carbon pricing) to about 3.0°C. Linking the ECC with temperature alignment is a well-established concept. A high-profile recent study, the High Level Report on Carbon Pricing (World Bank, 2019), reviewed a variety of sources including IPCC reports and scenarios. The High Levels Report's proposal for a minimum of \$40–\$80/tCO_2e rising to \$100 by 2030 is similar to the \$85/tCO_2e level in 2025 derived as necessary in this study for below 2°C alignment.

Almost all detailed climate impact work, starts with and is conditioned on, projected global warming levels. The Implied Temperature Alignment and Implied Climate Impact metrics could therefore be useful in impact and adaptation contexts. For example, the Implied Temperature Alignment metric developed can be combined with the detailed downscaling of monetary damages at the country level derived by Kotz et al. (2024), to give insight into where and when economic damages might occur.

Detailed abatement dynamics, such as sector based costs and regional differences in carbon pricing, could also be incorporated into the analysis by using more complex 'process-based' IAMs (Krieglar & Wolfgang, 2015), rather than a simpler cost–benefit IAM like DICE. In effect, this is the approach taken by High Level report on Carbon Pricing, and more explicitly by Hansel et al. (2025). However, process-based IAMs do not incorporate physical damages directly, meaning that the inversion must be performed between implied temperature alignment and ECC. They are also significantly more computationally time-consuming to run, making a full inversion impractical to implement.

The High Level Report on Carbon Pricing emphasizes that their estimate of the required level of carbon pricing applies a significant weighting towards non-market-based (e.g. effective technocratic) policy action in their recommendations. One requirement of the ECC implied temperature alignment approach presented is that non-market-based policies would need to be converted into a contribution to ECC in order to be accounted for using the methodology developed. Alternative assessments of committed actions & policies estimate temperature alignment to be slightly lower – approximately 2.7°C (Climate Action Tracker, 2024). Non-monetary policies should result in a lowering of the temperature increase, and this is evidenced in the literature (Stechemesser et al., 2024). Non-monetary mitigation policy measure is probably not fully captured in the OECD estimates for ECC that have been used in this study, and hence, the implied temperature alignment estimates may be biased upwards. Hansel et al. (2025) suggest that ECC estimates might need to be adjusted by up to 20% when used in climate policy curves. Further research regarding optimal methods for estimating the ECC, including how to account for subsidies and non-monetary policies as shadow carbon prices would improve understanding of their potential impact.

The Priced Climate Damages metric needs to be interpreted with some care. While we present a market-implied methodology, we do not intend to suggest any degree of efficient market. It is entirely possible for low damages to be priced, even though significant damages are expected (Hardin, 1968). Priced Climate Damages can be described as a measure of willingness to pay, and it can also be viewed as a measure of break-even pricing for policy 'payback' which indicates the maximum level of climate damages accepted/priced. In finance, the two approaches of market-implied and fundamental (economic) valuation are often combined in a relative valuation framework if markets are thought to be inefficient. In the case of market pricing of climate change impacts, this will depend on whether policy frameworks lead to the explicit or implicit market pricing of externalities, as is the case when carbon and climate damages are adequately priced.

Throughout, this paper has focused on carbon markets and pricing as the basis for market-implied results. Alternatively, one could base the results on estimates for the level of insurable climate-related risks (e.g. floods, storms, drought and heatwaves) priced in insurance markets. Studies by both Swiss Re (Swiss Re Institute, 2024) and Munich Re (Munich Re, 2024) estimate the typical global economic losses arising from climate-related hazards at approximately $250 billion/year, or 0.25% of global GDP. However, even if these estimates of direct losses are increased to allow for significant levels of indirect 'knock-on' impacts, the current level of damages falls well below those implied by the global ECC. This suggests that extreme weather (RFC 2) is not the principal motivation for climate action and broader justification is needed for Paris-aligned abatement efforts.

Most SCC studies suggest that the economic costs associated with RFC 4 (specifically chronic productivity impacts) are likely to be significantly higher than those of RFC 2 (acute and severe weather-related). In recognition of this fact, it is well-established practice to use much higher estimations of damages in policy and SCC studies which capture both acute and chronic productivity impacts (Barrage & Nordhaus, 2024). Recent statistical studies for climate damages, which weight the lagged economic impact of global temperature increases, suggest these combined costs may be higher than previously estimated (Kotz et al., 2024). However, the uncertainty in climate damage and SCC estimates remains high, meaning worst-case climate damages estimates published in the literature may only be given a low, albeit precautionary, policy weighting.

Across the literature, the level of priced climate damages necessary to align with achieving the Paris Agreement's goal is substantially higher than the majority of those used in Social Cost of Carbon (SCC) studies (Tol, 2023). Reaching the 2°C goal requires a DICE assumption of a 6% GDP loss at 3°C, which is double the 3% loss at 3°C assumed by the DICE 2023 default. Part of this discrepancy may be because normative SCC studies often limit damages to monetary/economic impacts, whereas agreed-upon climate policy might imply that broader impacts (e.g. the full set of the IPCC's Key Risks and Reasons for Concern) should also be priced. If this is the case, priced climate damage results indicate that the non-monetary impacts are of a similar magnitude as the monetary damages. Given the previous observation that RFC 2 and RFC 4 map almost directly onto acute and chronic economic damages, this could specifically infer a 50:50 split between the Paris Agreement's 'pricing' of RFC 2 – extreme weather – and RFC 4 – global aggregate impacts, compared to the more challenging-to-monetize trio of concerns: RFC 1 – permanent loss of unique and threatened systems, RFC 3 – distributional impacts (climate justice) and RFC 5 – large-scale singular events (global tipping points). Whether this apportioning of costs understates the significance of RFCs 1, 3 and 5 is open to both a scientific and normative assessment. By applying a non-normative process of inversion and elimination, the results presented in this study suggest that it is possible to imply current willingness to pay for nature (Kedward et al., 2022).

Beyond underestimated non-monetized damages, there are other possible explanations for the Paris pricing gap. A reasonable criticism of the analysis presented here, is that widespread Net Zero, if sufficiently subsidized, will develop sufficiently to be widely chosen as a cost-effective alternative to using fossil fuels for thermal energy. Unfortunately, history tells us that without explicit disincentives 'rebound effects' will likely emerge, leading to prolonged and persistent greenhouse gas emissions (Warr et al., 2010). Many studies of energy policies tend to conclude that fossil fuel subsidies still outweigh renewable subsidies. If energy, carbon and resource use efficiency are to be improved, a policy necessity is cutting fossil fuel subsidies.

The issues associated with effectively maintaining and financing global common resource goods like the global carbon budget have recently risen up the global development agenda (Songwe et al., 2022). One consideration that might trigger a resurgence in interest and support for carbon pricing could be broader recognition of the financing requirements needed to resource non-climate commitments like the SDGs and the Montreal Agreement (Mazzucato, 2024). Collectively, these represent a broader pool of public goods, which society should look to fund. A recent systematic review of implemented global carbon pricing schemes shows that, when implemented, carbon pricing is an effective policy mechanism for achieving emissions reductions (Döbbeling-Hildebrandt et al., 2024). If carbon pricing is recognized as a viable mechanism to contribute towards financing these commitments, it is possible that it might also lead to the effective cost of carbon becoming a more significant contributor towards meeting the Paris Agreement goals of limiting global warming to well below 2°C.

Conclusions

The analysis presented underscores the potential of a 'polluter pays' approach and carbon pricing as mechanisms to support the Paris Agreement. However, it is evident that current global efforts are insufficient.

By analysing the level of priced climate damages, and implied climate impact across different economies, it is evident that priced climate damages are often higher for higher-income countries. However, this trend is neither consistent across these economies (European economies seem to price damages at higher levels than non-European ones) nor strong enough in aggregate to offset the higher climate impacts resulting from their typically higher levels of carbon consumption. It could be argued that while many wealthier economies acknowledge climate damages aligned with the Paris Agreement in their policy frameworks, comparatively few truly address their per capita overconsumption of carbon.

The alignment of market dynamics with climate goals necessitates a more assertive and comprehensive policy framework – one that recognizes and addresses the disparities in carbon consumption across countries with different income levels. Achieving this alignment will require not only heightened international collaboration but also a deepened commitment to integrating both public and commercial sources of global climate finance and abatement spending (Naran et al., 2022) with broader sustainability objectives. The urgency to act decisively has never been greater, as the window to limit global warming to below 2°C is closing. Therefore, more robust and proactive measures are imperative to ensure that the global policy landscape effectively supports the ambitious targets set by the Paris Agreement.

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Code availability

Code can be made available under terms of original providers (TBC). A GAMS licence will be necessary to rerun DICE 2023.

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During the preparation of this work the author(s) used Microsoft Copilot to rephrase some sentences/paragraphs in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data availability

Data can be made available under terms of original providers (TBC).

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