Department for Business, Energy & Industrial Strategy

Carbon values literature review

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Executive summary

The development of carbon values, representing the societal value of carbon emissions impacts, is central to the evaluation of all policies or investments that increase or reduce greenhouse gas emissions. The UK developed its approach to calculating carbon values in 2009, using a target-consistent price path for sectors not covered under the ETS and a traded carbon value approach for ETS sectors. This report seeks to inform BEIS's review of UK carbon values, by reviewing subsequent academic research and international practices in developing carbon values for policy appraisal. Specifically, we seek to identify whether the current approach is still fit for purpose given the increased ambition of emissions targets, and significant advances made in the carbon values literature. The discussion below considers the advantages and disadvantages of different methodologies for carbon valuation, discusses the sources of uncertainties within different models and available mitigation strategies, and explores cases studies of approaches taken in other jurisdictions.

Policymakers regularly conduct evaluations based on cost-benefit analysis (CBA) to support decision-making in different areas of public policy, including decisions on policy design and evaluation of investments. CBA allows policies to be comparable, allowing for prioritisation based on value for money[1], and helps increase transparency in decision making, allowing for greater accountability. To assess climate policies and other policies that have an impact on emissions[2] requires the valuation of carbon emissions,[3] for which it is necessary that carbon has an associated price. Regardless of the methodology chosen to estimate a carbon value for policy appraisal, these remain essential for informed decision making.

The two broad approaches most used to develop carbon values for policy appraisals remain unchanged since the government's approach was developed, these are:[4]

- calculation of a social cost of carbon (SCC), which quantifies the damages of climate change stemming from an additional/marginal greenhouse gas emission, and
- a mitigation cost approach, which quantifies the cost of reducing an additional/marginal greenhouse gas emission on a feasible least-cost path to achieve a jurisdiction's emissions reduction objectives, or as the expected market price in a carbon market5. There are two different mitigation cost approaches: the target consistent price path approach uses techno-economic analysis to identify the carbon price path needed to achieve a given emissions target; the traded values approach uses observed and expected carbon prices in existing carbon markets.

[1] Quinet A., 2019, The Value for Climate Action, https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-the-value-for-climate-action-final-web.pdf
[2] DEFRA (2005). Social Costs Carbon Review - Using Estimates in Policy Assessment. Department for Environment, Food and Rural Affairs
[3] For arguments against monetisation of damage, please refer to Pearce (2002).
[4] Smith, S, Braathen, N. A. (2015). Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues. OECD Environment Working Papers No. 92

[5] DECC (2009). Carbon Valuation in UK Policy Appraisal: A Revised Approach. Department of Energy and Climate Change.

The literature on SCC has developed significantly but key uncertainties remain. A significant part of the literature has focused on uncertainties around the climate system and damages of climate change. Particularly a better representation of severe climate impacts, including tipping points, and a precautionary approach to avoid them has produced multiple large estimates for SCC, although this approach remains subject to debate. Similarly, no consensus has emerged regarding the discounting of future costs and benefits, which has a strong impact on the resulting carbon values. Altogether, the SCC approach incorporates compounding uncertainties that are unlikely to be resolved in the future. These continued uncertainties mean the range of SCCs estimated in the mainstream literature has not narrowed in recent years and may have indeed widened[6].

The mitigation cost approach has not seen such an extensive debate and developments have focused on uncertainty analysis and improving the techno-economic modelling suite. This report focuses on the target consistent price path approach, since the traded value approach is not suitable to obtain economy-wide estimates for carbon values. Where this literature has developed it has focused on the inclusion of uncertainties regarding prices and technological change. It has also seen a development of models and model suite that are able to better represent broader segments of the economy in greater detail, increasing the overall credibility of mitigation cost estimates.

Drawing on recent literature the report develops four key criteria for the assessment of metrics for carbon valuation:

- Robustness; the metric is comprehensive in accounting for the climate-relevant impacts of a policy and is robust to small changes in underlying assumptions.
- Timeliness; the metric should support efficient public decision-making, by being flexible and easy to update for changed information and circumstances.
- Policy alignment; the metric should be capable of responding to meaningful changes to government policies and goals and contributing to their achievement.
- Credibility; the metric is transparent to stakeholders in both the method of its calculation and conclusions, and both should stand up to rigorous public and academic scrutiny.

The SCC approach scores poorly against these criteria and is not recommended for use. Estimates of the SCC remain contentious, with small alterations to underlying assumptions leading to vastly different valuations, with the range of estimates widening in recent years. SCCs score poorly against all elements of our assessment, particularly on robustness and policy alignment. The latter is particularly relevant for the UK. SCC analyses are generally not

[6] Meta-analyses on SCC estimates include: Pindyck, R. S. (2019). The social cost of carbon revisited. Journal of Environmental Economics and Management, 94, 140-160; Wang, P., Deng, X., Zhou, H., & Yu, S. (2019). Estimates of the social cost of carbon: A review based on meta-analysis. Journal of cleaner production, 209, 1494-1507; Tol, R. S. (2014). Correction and update: The economic effects of climate change. Journal of Economic Perspectives, 28(2), 221-26. A meta-analysis on the mitigation cost approach is provided by Huang, S. K., Kuo, L., & Chou, K. L. (2016). The applicability of marginal abatement cost approach: A comprehensive review. Journal of cleaner production, 127, 59-71.

aligned with the net zero target, with most estimations drawing on emissions scenarios that are not aligned with UK reaching net zero in 2050.

The target-consistent price path approach scores better against assessment criteria despite uncertainties. This approach is preferred in two main areas: First, the approach is more credible as the methodology is more transparent and relies less on unobserved functions that are common in Integrated Assessment Models (IAMs) used for SCC analysis. Second, the approach is responsive to changes in emissions targets and can therefore be well-aligned with the UK's net zero target. Nevertheless, this approach involves challenges particularly given its sensitivity to uncertain model assumptions.

A target-consistent price path approach does not seek to determine the optimal level of emissions reductions, so is only appropriate for use given sufficiently stringent targets. The presumption underlying the target consistent price path is that the emissions reductions target is aligned with a socially optimal outcome. Given international consensus on limited warming to well below two degrees Celsius under the Paris Agreement, a domestic target that is broadly consistent with that objective is sufficient. The UK's net zero by 2050 target meets this criterion, but the use of a target consistent price path may be inappropriate for countries with a less stringent target.

Given recent developments in the academic literature and international experience regarding the calculation of carbon values, the UK's continued use of a target-consistent price path appears appropriate.

However, given uncertainty regarding future mitigation costs, the approach to developing this price path should be revised. The UK's climate targets are not conditional on future technological or economic developments, and an appropriate target consistent price path should be consistent with achieving net zero even under contrary circumstances. The target-consistent price-path should also be updated on a regular basis to reflect the latest evidence and utilise advancements in modelling and analysis. This will ensure that an appropriate precautionary approach is being adopted, while relevant new information is being regularly accounted for.

The remainder of this paper is structured as follows:

- Section 2 develops a set of principles for the evaluation of different approaches to carbon valuation
- Section 3 introduces recent developments in the literature
- Section 4 outlines developments in calculations of an SCC
- Section 5 outlines developments in using approaches based on mitigation costs for reaching targets
- Section 6 concludes and provides recommendations for an updated approach

Principles for carbon valuation

There is extensive literature on potential approaches to calculating carbon values, but for these values to be useful in regulatory analysis requires other attributes. There is little specific literature on the principles for developing carbon values, but based on the literature and common practice from jurisdictions implementing carbon values, we propose four criteria for the assessment of these approaches:

- Robustness; the approach is comprehensive in accounting for the climate-relevant impacts of a policy and is robust to changes in underlying assumptions consistent with the prevailing literature.
- Timeliness; the approach should support efficient public decision-making, by being flexible and easy to update for changed information and circumstances.
- Policy alignment; the approach should be capable of responding to meaningful changes in government climate ambitions, and policies contributing to their achievement.
- Credibility; the approach is transparent to stakeholders in both the method of its calculation and conclusions, and both should stand up to rigorous public and academic scrutiny.

These criteria align with general principles for good governance and with several public documents regarding the evaluation of carbon values discussed below.

Robustness requires the approach to demonstrate comprehensive coverage of impacts and insensitivity to changes in underlying assumptions that remain consistent with the prevailing literature. A comprehensive approach will account for the most important social impacts, broadly defined as the potential societal cost of emissions and the societal value of emissions reductions. This was emphasised by the US EPA's preference that a social cost of carbon provides "a comprehensive estimate of climate change damages" and is reiterated by the OECD which suggests "making a full assessment of the consequences of an investment decision" in terms of the costs to social welfare from higher emissions and the benefit to social welfare increased emissions[7]. This does not require that all impacts are considered but considering all impacts that substantively change likely values will be important. Robustness also requires that there is relative consistency in values for a range of underlying assumptions that are consistent with the prevailing literature. That is, that the use of assumptions that would not be considered outliers in the prevailing literature would not substantively change the estimated carbon value and therefore a policy or investment decisions. This draws on the early discussion from Pearce regarding social costs of carbon, that suggests a key role for such approaches is in "determining whether 'too much' or 'too little' abatement is being considered",

[7] Smith, S, Braathen, N. A. (2015). Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues. OECD Environment Working Papers No. 92

where an approach is excessively sensitive to such changes in assumptions, it cannot adequately play this role.[8]

Timeliness relates to the capability to update the approach and its inputs to reflect the latest information. Carbon values can be used for decision making on specific projects or policies, and in decisions regarding the overall allocation of resources where these policies are competing for scarce resources with other projects offering non-climate costs and benefits[9]. It is important that the inputs to the approach can be regularly updated to ensure that the approach chosen remains fit for purpose as external circumstances change. The need for the approach to be updated regularly can be seen through recent rapid technological change, which has seen a steep drop in the cost of renewable electricity and electric vehicles[10], which have far exceeded rates projected in modelling exercises.

Alignment of approaches with government policy is needed to ensure that evaluation of policy or investment is consistent with achieving climate targets and commitments. In practice, this means that shifts in government policy, particularly shifts in terms of the ambition of mitigation should be associated with shifts in carbon valuation in a predictable direction, and of a scale, that aligns with these changes. A carbon valuation seeks to help make short-term decisions aligned with long-term policy. This decision making is made difficult by the inconsistency between climate change as a global problem regarding the “stock” of carbon pollution and the “flow” nature of targets and nationally determined contributions (NDCs) under the Paris Agreement. As discussed in Quinet (2019):[11]

> the rapid shrinking of global carbon budgets is now leading to the stock objectives – responsible management of a multi-year carbon budget – being rounded off with flow objectives: a "net-zero" objective regarding human-driven greenhouse gas emissions.

An approach that sheds light on the global objective of carbon mitigation is insufficient, it must also reflect the ability of governments to meet their national commitments, and in the UK’s case, its net zero target. An approach that fails this test will fail to adequately inform policy and risks lacking social legitimacy.

A credible approach is fundamental, as legitimacy in the eyes of stakeholders is a necessary step for social decision making and continued public support for ambitious climate action. This requires that the method for calculating a carbon value is transparent, with a clear presentation of the methods used in the analysis, the assumptions used and their rationale. This may also require a degree of public input into the determination of valuation and the assumptions and approaches used. Indeed, a transparent approach to the development of a methodology to

[8] Pearce, D. (2003). The Social Cost of Carbon and its Policy Implications. Oxford Review of Economic Policy, 19(3), 362–384. doi:10.1093/oxrep/19.3.362
[9] Smith, S, Braathen, N. A. (2015). Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues. OECD Environment Working Papers No. 92
[10] IEA (2019). Global EV Outlook 2019. IEA. Paris. https://www.iea.org/reports/global-ev-outlook-2019
[11] Quinet A., 2019, The Value for Climate Action, https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-the-value-for-climate-action-final-web.pdf

calculate carbon values was central to the US government's development of a social cost of carbon (Interagency working group on Social Cost of Carbon, 2010):

> Numerous agencies met on a regular basis to consider public comments, explore the technical literature in relevant fields, and discuss key model inputs and assumptions. The main objective of this process was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literature. In this way, key uncertainties and model differences transparently and consistently inform the range of SCC estimates used in the rulemaking process.

The use of a transparent, evidence-based and open approach to the development of carbon values is also consistent with the UK Government's broader approach to climate policy. This includes open engagement and consultation on major regulatory changes, such as through the current net zero review and consultation on carbon pricing, as well as the ongoing role of the Committee on Climate Change as an independent source of expert advice.

The subsequent sections of this report focus on the two main approaches to developing carbon valuation, the social cost of carbon and mitigation cost approaches. In subsequent sections, we apply these principles to the assessment of these approaches and develop broad recommendations for potential improvements to the UK's current approach to such valuations.

Approaches to carbon values

This literature review considers recent literature on approaches to carbon values. This literature review focuses on publication on carbon values since 2009, when BEIS conducted a comprehensive review on carbon values. This review considers publications in peer-reviewed academic journals but also grey literature such as government documents, consultancy reports and work by international organisations such as the OECD and the World Bank's Carbon Pricing Leadership Coalition (CPLC).

This report analyses recent developments in the academic literature and jurisdictions' practical experience of using social costs of carbon (SCC) or mitigation cost approaches to develop carbon values for regulatory appraisal. It then assesses these approaches against selected criteria. The literature review did not identify other established methodologies to obtain carbon values in wide use. This report discusses developments in these approaches in recent years and their use in policy and assesses the approaches against principles for carbon valuation developed by the project team and the academic experts. A compilation of different carbon values and a systematic, quantitative analysis of the differences in values is beyond the scope of this report.

The literature on social cost of carbon has developed substantially in recent years. The literature on social cost of carbon has substantially developed since 2009 as part of a vivid academic debate. Major developments include:

- Increased focus on uncertainties in the climate system
- Changes in damage functions to represent impacts of high temperatures better
- Grounding damage functions in empirical evidence
- A continued detailed debate on the role of discounting
- Alternative approaches to calculate social cost of carbon

There have been fewer substantial developments on the mitigation cost approach. The main developments include:

- Stronger focus on scenario and uncertainty analysis
- Improvement of techno-economic modelling in order to represent the economy in greater detail, including better representation of dynamics of technological change

The following sections expand on these developments and evaluate the performance of these approaches to developing carbon values considering the principles established in Section 2.

Social cost of carbon

The social cost of carbon (SCC) seeks to estimate the economic damage from emitting a tonne of carbon dioxide at a point in time. Carbon emissions contribute to climate changes, which materialises in increased temperatures, rising sea levels, and increased frequency of extreme weather events, among others. These physical damages affect economic outcomes, such as GDP, productivity or welfare. SCC aims to quantify these economic impacts caused by the emission of carbon. Because the damage of carbon is higher when the concentration of greenhouse gases is higher, the SCC usually increases over time. Most estimates measure the costs occurred globally, however; some research has focused on country estimates.

An SCC is often obtained by using Integrated Assessment Models (IAMs) to estimate the impact of emissions on social welfare. IAMs are computable models that link the climate system and socio-economic systems and are based on historic data, assumptions and scenarios. IAMs are used to compare the costs of climate impacts and of climate policy to identify a socially optimal response. The best known IAM for SCC analysis globally is the DICE (Dynamic Integrated Climate Economy) model, but alternatives exist including PAGE (as used in the Stern Review) and FUND[12].

IAMs generally entail the following elements:

- Projections of future emissions, which specify how emissions evolve with economic and population growth in the absence of abatement
- A carbon stock function, which specifies how annual emissions translate into a carbon concentration level, and a climate sensitivity function, which specifies how carbon concentration translates into higher temperatures
- A damage function, which specifies how higher temperatures translate into economic damages
- A social welfare function, which represents the sum of societal utility from consumption over all time periods.
    - The utility today of changes to future consumption from climate change is determined by a specified social discount rate
    - Society can reduce consumption today and invest in climate-related capital goods to reduce emissions and increase consumption in the future
- Abatement costs, the cost of undertaking climate-related investments

All these elements are at least to some degree unknown or unobserved, resulting in large difference of SCC under different assumptions. Among the elements mentioned above, estimations of future emissions and abatement costs are reliably available for the short term. However, SCC values are regularly estimated beyond 2100, for which technological and

[12] Smith, S, Braathen, N. A. (2015). Monetary Carbon Values in Policy Appraisal: An Overview of Current Practice and Key Issues. OECD Environment Working Papers No. 92

economic developments are unpredictable. The damage function is often either an assumed simple (quadratic) function or econometrically obtained function based on the historic relationship between economic growth and (small) temperature rises. This large uncertainty in almost all model inputs results in a large variance in SCCs across studies[13].

The following subsection discusses the uncertainties of some of these model inputs in detail and how developments in the literature have aimed to address them.

Developments in the literature

Recent developments in the calculation of the SCC have focused on the deep uncertainty relating to some of its key parameters as outlined below. There is an increasing focus on risk-based approaches that emphasise the importance of minimising the risk of "catastrophic" outcomes. Furthermore, significant effort has been made to better understand and represent the impact that climate damage may have on the economy and to welfare, and discussions on the ethics of intertemporal and distributional discounting and approaches to calculating an appropriate discount rate have continued. These are discussed in further detail below.

Uncertainties on emissions, climate responses and abatement

The literature has focused on the large physical uncertainties and how to incorporate them in SCC analysis. Starting with Weitzman's contributions on the "dismal theorem" and "fat-tailed uncertainties" [14] , the literature on SCC has put more focus on the large, compounding, physical uncertainties related to the climate system. Since emissions and their impact on the climate system are largely uncharted territory, recent SCC analysis has attempted to include these uncertainties and frame mitigation efforts as insurance against catastrophic climate outcomes[15]. However, not all scholars agree on this framing; for example, Nordhaus sees its importance as limited and has not included it in his recent update on SCC[16][17].

First, annual emissions and atmospheric concentration are uncertain as current concentration is unprecedented in human history and projections depend on policies and technologies. Annual emissions translate into an atmospheric concentration, but the exact relationship is not well established for higher concentrations. The atmospheric CO_2 concentration in 2018 was 407 parts per million, more than 100ppm higher than the second-highest peak concentration in the past 800,000 years[18]. Some SCC analyses suggest optimal policies stabilise

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[13] Pindyck, R (2019). The social cost of carbon revisited. Journal of Environmental Economics and Management, 94, pp.140-160.
[14] Weitzman, M. L. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. Review of Environmental Economics and Policy, 5(2), 275-292.
[15] Dietz, S., & Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. The Economic Journal, 125(583), 574-620.
[16] Nordhaus (2009). An Analysis of the Dismal Theorem. Cowles Foundation Discussion Papers 1686, Cowles Foundation for Research in Economics, Yale University
[17] Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518-1523.
[18] Lindsey R (2020). Climate Change: Atmospheric Carbon Dioxide. Climate.gov, retrieved 24.02.2020 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

concentrations around 700ppm, well beyond anything experienced in human history. An additional uncertainty regarding atmospheric concentrations stems from the unknown level of future annual emissions. These flows depend on uncertain projections on technology, economic, policy and population development, among other variables.

Furthermore, the magnitude of temperature increases stemming from increased emissions is uncertain. The equilibrium climate sensitivity (ECS) measures how temperature rises when CO2 doubles above preindustrial levels once the climate system is balanced out. The latest IPCC report suggests that the likely value for the ECS ranges between 1.5 and 4.5°C. This means that warming beyond 3°C is not unlikely under atmospheric concentration doubled from pre-industrial levels and that there is some residual probability that the temperature increase could be beyond 4.5°C[19]. Some literature has focused on the Transient Climate Response (TCR) instead. The TCR does not assume that the climate system is completely balanced and instead focuses on the near term where uncertainties are lower. The range of TCR estimates is generally smaller and Otto et al find that the use of TCR substantially reduces variance in SCCs compared to ESC[20].

Moreover, many SCC analyses have failed to include tipping points. Tipping points describe significant climate events caused by small temperature changes that are often irreversible. This includes the melting of the Greenland Ice Sheet, the dieback of the Amazon or thawing of permafrost. Lontzek et al included some of these tipping points in their calculation and found that the SCC increased by almost 50% compared to their previous calibration[21]. To date, many SCC analyses still exclude tipping points, leading to an underestimation of SCC. The exact relevance of tipping points depends on the model specification and the nature of the tipping point; for example, Nordhaus finds only a small effect from the melting of the Greenland Ice Sheet as damages are far in the future and highly discounted[22].

Recently, some researchers have included more complex abatement cost functions in these analyses. Historically, IAMs have used abatement functions that are temporally independent; the costs of abatement in a given year is independent of abatement undertaken in previous years. This approach does not account for cost-reducing innovation and inertia in infrastructure and the energy system[23]. Grubb and Wieners' include that costs of present abatement depend on past mitigation efforts and find that optimal emissions levels and temperature increases are

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[19] "Fat-tailed uncertainties" describe a probability density function with a higher probability for extreme outcomes than a normal distribution. For climate change, this implies that there is a substantial probability of an extremely high loss of welfare. The "dismal theorem" states that these fat-tailed uncertainties, in combination with other factors such as risk aversion, can lead to an infinite willingness to pay to avoid these outcomes. Weitzman concludes that economist should take these considerations into account when advising on policy. Weitzman, M. L. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. Review of Environmental Economics and Policy, 5(2), 275-292.

[20] Otto, A., Todd, B. J., Bowerman, N., Frame, D. J., & Allen, M. R. (2013). Climate system properties determining the social cost of carbon. Environmental Research Letters, 8(2), 024032.

[21] Lontzek, T. S., Cai, Y., Judd, K. L., & Lenton, T. M. (2015). Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. Nature Climate Change, 5(5), 441-444.

[22] Nordhaus, W. (2019). Economics of the disintegration of the Greenland ice sheet. Proceedings of the National Academy of Sciences, 116(25), 12261-12269.

[23] This was first discussed in Farmer et al but subsequent research on the topic has been limited. Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A third wave in the economics of climate change. Environmental and Resource Economics, 62(2), 329-357.

lower as a result[24]. Nevertheless, further research is needed to identify more robust abatement costs functions and understand their impact on the SCC.

Calibrating damage functions

The damage function specifies how increases in emissions affect economic outcomes and is generally obtained by bottom-up economic modelling or statistical analysis of macroeconomic changes. The damage function translates temperature increases into economic damages. There are two ways to specify a damage function. The first uses economic modelling and studies of sector-specific impacts of temperature change on economic activity to aggregate economy-wide damages in a bottom-up manner. This approach benefits from drawing on a large number of sector-specific studies but can misses macro-economic impacts. Alternatively, statistical analysis looks at how macro-economic outcomes have varied with changes in the climate in the past. This approach does not require a bottom-up aggregation but relies on studies of small-scale temperature changes that may not be representative of more significant changes.

Recently, research has focused on developing more sophisticated damage functions, particularly for higher temperatures. Many early calculations of SCC used simple linear or quadratic damage functions, with damages represented as a simple function of the temperature. Weitzman[25] illustrates that with the most common quadratic damage function an increase in temperature by 10°C would only cause a 19% decrease in world output at the time of impact. Subsequently, he uses a higher-order polynomial function to model more severe damages from high temperatures[26]. More recently, Bretschger and Pattakou[27] use an alternative higher-order polynomial function and find that the SCC increases by a factor of more than 10 compared to a linear function after 14 years. There has been a general trend to using more complex damage functions in recent years, but there remains variance amongst researchers, with some continuing to use a quadratic function[28]. However, these functions are often only minimally grounded in empirical estimates.

Better data availability has improved econometric estimates of economic damages from temperature increase, allowing the estimation of empirical damage functions. Recent literature has developed damage functions based on historic relationships between temperature increases and economic damages instead of assumed damage functions. Earlier literature suffered from limited data availability and methodological issues. Recently, Burke et al[29] used more than 50 years of country-level data to find that the slope of the damage function is much

[24] Grubb, M., & Wieners, C. (2020). Modeling Myths: On the Need for Dynamic Realism in DICE and other Equilibrium Models of Global Climate Mitigation. Institute for New Economic Thinking Working Paper Series, (112).
[25] Weitzman, M. L. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. Review of Environmental Economics and Policy, 5(2), 275-292.
[26] Weitzman, M. L. (2012). GHG targets as insurance against catastrophic climate damages. Journal of Public Economic Theory, 14(2), 221-244.
[27] Bretschger, L., & Pattakou, A. (2019). As bad as it gets: how climate damage functions affect growth and the social cost of carbon. Environmental and resource economics, 72(1), 5-26.
[28] E.g. Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518-1523.
[29] Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235-239.

higher than estimated in previous empirical studies. As a result, expected climate change costs are 2.5-100 times higher than previous estimates for a 2°C warming and at least 2.5 higher for larger temperature increases. Ricke et al[30] use the damage function from Burke et al but disaggregate it by region. They find that India, the United States and Saudi Arabia have the highest SCCs while some regions have a negative SCC[31]. Their estimation of a global SCC finds a median value of 2010US$417/tCO2 in 2020.

Additionally, many models have incorporated the impact of climate change on economic growth rather than just annual economic output. Early estimations of the SCC treated economic growth as exogenous; it is an input to the model and not affected by climate change[32]. In these specifications, climate change only affects annual output. However, this assumption is not supported by empirical literature[33] [34]. Dietz and Stern (2015)[35] allow for endogenous growth and include the possibility of tipping points. They derive a substantially larger SCC than earlier estimations without endogenous growth.

The use of damage functions that are only minimally grounded in empirical estimates risk underestimating climate damages. The CPLC[36] concludes that most damage functions are likely downward biased because they ignore many risks and costs associated with climate change, such as biodiversity loss, impacts on economic growth, and impacts on the poorest and most vulnerable, among others. This can lead to an underestimation of SCC; Sterner and Persson (2008)[37] included an assumed consumption of environmental goods and services and find substantially higher SCC. Empirical estimations of damage functions can overcome some of these challenges, but they also represent only a limited part of climate damages. Multiple scholars have called for a review of current methodologies given the large amount of unconsidered impacts[38],[39].

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30 Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. Nature Climate Change, 8(10), 895-900.
31 This includes the UK. The SCC estimate is negative because these countries' temperatures are currently below the economic optimum. However, the estimates do not include a variety of impacts that exceed the local scope, such as trade disruptions, large-scale migration or liabilities.
32 E.g. Nordhaus, W. D. (2007). A review of the Stern review on the economics of climate change. Journal of economic literature, 45(3), 686-702.
33 E.g. Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. American Economic Journal: Macroeconomics, 4(3), 66-95.
34 Vivid Economics (2017). Impacts of higher temperatures on labour productivity and value for money adaptation: lessons from five DFID priority
country case studies.
https://assets.publishing.service.gov.uk/media/59e0a95f40f0b61ab035cb3d/VIVID_Heat_impacts_on_labour_productivity_and_VfM_adaptation.pdf
35 Dietz, S., & Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. The Economic Journal, 125(583), 574-620.
36 CPLC (2017). Report of the High-Level Commission on Carbon Prices.
https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59b7f2409f8dce5316811916/1505227332748/CarbonPricing_FullReport.pdf
37 Sterner, T., & Persson, U. M. (2008). An even sterner review: Introducing relative prices into the discounting debate. Review of Environmental Economics and Policy, 2(1), 61-76.
38 Rose, S., Turner, D., Blanford, G., Bistline, J., de la Chesnaye, F., & Wilson, T. (2014). Understanding the social cost of carbon: A technical assessment. EPRI technical update report (Electric Power Research Inst, Palo Alto, CA).
39 National Academies of Sciences, Engineering, and Medicine. (2017). Valuing climate damages: updating estimation of the social cost of carbon dioxide. National Academies Press.

Discounting

The social discount rate (SDR) determines the weight society gives to consumption at different time periods. The general idea is that consumption today is preferred over consumption in the future. This preference is generally observed in markets and laboratory experiments. Reasons for this preference are that consumers expect to be richer in the future, the risk of not experiencing the future, or simply the need for immediate gratification, among others. For the estimation of SCC, the SDR weights future benefits and damages[40]. Generally, a higher SDR results in lower SCC as future damages are weighted less.

Most academics use the Ramsey Rule to determine the SDR.[41] The Ramsey rule is an equation that is used to compute an SDR for future wellbeing. It is used widely, however its use has been disputed[42]. The Ramsey Rule states that under certain circumstances[43] the SDR depends on the utility discount rate, the elasticity of marginal utility of consumption and annual consumption growth [44]:

$$SDR=\rho+\eta g$$

where ρ is the utility discount rate (itself a sum of the pure time preference δ and a component of (catastrophic) risk L); the elasticity of marginal utility of consumption η, which also includes aversion to inequality; and the annual per capita growth of consumption g[45].

Academics dispute how to obtain the values for the SDR and its components. There are two schools of thoughts on how to derive the values above: The descriptive position is to obtain the SDR based on observed market data, such as long-term, risk-free investments. Critics argue that discounting should not apply to long-term, intergenerational consumption decisions such as climate change[46]. The prescriptive position is to make normative judgements, most notably on the pure time preference δ and the risk component L. The difference in methods results in substantially different SDRs. Most prominently, the Stern Review [47] represents the prescriptive position and uses a central SDR of 1.4%, while Nordhaus follows the descriptive position and uses an SDR of 4.5% in earlier work and recalibrated to 4.25% in more recent work.

[40] Drupp, M. A., Freeman, M. C., Groom, B., & Nesje, F. (2018). Discounting disentangled. American Economic Journal: Economic Policy, 10(4), 109-34.
[41] Earlier literature included a discussion of whether discount rates should be calculated using ‘positive’ criteria, reflecting the discount rates seen in markets or ‘normative’ criteria calculated using ethical judgements using frameworks like the Ramsey rule. In practice most literature now does not support the use of positive discount rates for long-lived policy guidance as is relevant for climate change.
[42] A discussion of the limitation of the Ramsey Rule for Cost Benefit Analysis can be found in: Freeman, M., Groom, B., & Spackman, M. (2018). Social discount rates for cost–benefit analysis: a report for HM treasury.
[43] Such as the absence of risk and a certain shape of the utility function
[44] This excludes the notion of non-catastrophic risk, which can play a role in SDRs as well. An overview is provided by Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Cariño-Olvera, M., Fullerton, D., ... & Khan, M. R. (2014). Social, economic and ethical concepts and methods; A recent estimation is provided by Dietz, S., Gollier, C., & Kessler, L. (2018). The climate beta. Journal of Environmental Economics and Management, 87, 258-274.
[45] : Freeman, M., Groom, B., & Spackman, M. (2018). Social discount rates for cost–benefit analysis: a report for HM treasury.
[46] Gollier, C. (2013). Pricing the planet's future: the economics of discounting in an uncertain world. Princeton University Press.
[47] Stern, N. (2007). The Economics of Climate Change: The Stern Review. Cambridge University Press.

The size of the SDR has significant implications for SCC. Even though the SDR is just one weight within a larger model, it has substantial implications on the SCC. This stems from the large time horizon of SCC are conducted. For example, £100 in 2050 discounted with the Stern SDR are £66 in 2020, but only £27 with the traditional Nordhaus SDR. Table 1 shows this difference in practice. It displays Nordhaus'[48] estimation of SCCs in 2010 international USD for different SDRs. Even though all other model parameters are constant, SCCs in 2020 are more than three times as high under a 2.5% SDR than a 4.25% SDR.

Table 1: SDRs have a significant impact on SCCs

SDR	2015	2020	2025	2030	2050
2.5%	128.5	140.0	152.0	164.6	235.7
3%	79.1	87.3	95.9	104.9	156.6
4%	36.3	40.9	45.8	51.1	81.7
4.25%	31.2	37.3	44.0	51.6	102.5
5%	19.7	22.6	25.7	29.1	49.2

Note: SCC in 2010 international USD

Source: Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518-1523.

Despite many unresolved discussions, many economists seem to agree on a smaller, declining SDR based on the prescriptive approach. Drupp et al[49] surveyed more than 200 experts on the topic to understand commonalities and differences in approaches in outcome. They find that the median SDR for long-run projects is at 2% and that this value is within the acceptable range of 77% of experts[50]. Overall, many economists agree that long-run SDRs should be smaller than under Nordhaus' approach and decline over time. There is also growing support in the academic literature for the use of discount rates that decline over time. This idea, based on precautionary principles on risks and empirical findings from behavioural economics, is now used in policy appraisal not only in the UK, but also in France and Norway[51].

Alternative approaches

Some research has developed alternative ways to develop SCC estimates that deviate from the traditional way described above. Most of the recent literature has focused on developing

[48] Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518-1523.
[49] Drupp, M. A., Freeman, M. C., Groom, B., & Nesje, F. (2018). Discounting disentangled. American Economic Journal: Economic Policy, 10(4), 109-34.
[50] It is important to note that SDR for other, shorter-term policy appraisal can vary. See e.g.: Smith, S, Braathen, N. A. (2015). Monetary Carbon Valuas in Policy Appraisal: An Overview of Curent Practice and Key Issues. OECD Environment Working Papers No. 92
[51] Groom, B., & Hepburn, C. (2017). Reflections—looking back at social discounting policy: the influence of papers, presentations, political preconditions, and personalities. Review of Environmental Economics and Policy, 11(2), 336-356.

certain elements of the SCC analysis further by making parts of the model more sophisticated. However, some researchers have also developed substantially different methodologies that are worth mentioning. Box 1 describes a recent approach to estimate averages SCC based on expert elicitation, Box 2 two approaches that use asset theory to estimate SCCs.

Box 1: expert elicitation on average SCC

Pindyck uses expert elicitation on economic damages and emissions reductions to obtain SCC estimates. Pindyck has been a long-standing scholar and critic in the SCC debate. In his recent paper[52], he uses expert elicitation to circumvent contested elements like the damage function or the discount rate. He asks economists and climate scientists two main questions: 1) What is the probability of a certain large economic damage due to climate change in 50 years? and 2) what are the required emissions reductions to avoid this outcome? He takes a tailored sample of responses and fits a functional form to obtain estimates.

He finds an average SCC of US$200 and a trimmed estimate near US$80. Pindyck uses the average rather than marginal SCC to obtain a more time-robust estimate. He finds a central estimate of US$200. However, if he trims the sample to allow only for respondents with high confidence, economists and removes outliers, the SCC estimate is reduced to US$80. Climate scientists report on average much higher SCCs and the results are largely driven by the occurrence of high economic damages.

Box 2: SCC and asset pricing theory

Alternative specifications of preferences based on asset pricing theory, have also seen recent focus in the literature. A recent paper utilising an alternative specification of risk preferences has argued that when accounting for catastrophic risk suggests a declining price path over time.[53] It finds that a high price today that declines over time but remains high is justified as the “insurance” value of mitigation declines and technological change makes emissions cuts cheaper. Second, higher risk aversion increases both the CO2 price and the risk premium relative to expected damages. This suggests that in calculating carbon price paths a precautionary approach with higher upfront prices could be justified, or as the authors state:

“Bad news late, when it is more difficult to counteract with more active policy, is worse. It is precisely the inability to know upfront when good or bad news arrives that accounts for the insurance value of early mitigation and, thus, the role that the resolution of risk over time plays in the declining CO2 price.”

[52] Pindyck, R. S. (2019). The social cost of carbon revisited. Journal of Environmental Economics and Management, 94, 140-160.
[53] Kent et al 2019, Declining CO2 price paths https://www.pnas.org/content/pnas/116/42/20886.full.pdf

An underlying feature of the analysis is the notion of risk. Risk is inherent in climate change analysis. Nevertheless, some SCCs are calculated in deterministic models, such as DICE. In contrast, stochastic models include randomness and the SCC include a risk premium. Dietz et al (2018)[54] use asset pricing theory to investigate the structure of risk and how it varies with the source of risk. They find that risk increases the discount rate, but also expected climate benefits. As a result, they find that the inclusion of risk overall rises the SCC compared to a risk-free environment.

These alternative approaches are still new to the literature and their overall implications for approaches to developing social costs of carbon, and integration into the broader literature is still unclear.

Policy developments

The US is the most prominent example of the application of SCC in policy appraisal. SCC estimates are used in policy appraisal despite the large disagreements and uncertainties around SCC estimates. Most prominently, the US Government uses various IAMs to obtain SCCs estimates for policy appraisal as described in Box 3. In Germany, the Environmental Agency also publishes SCC values as described in Box 4. Those are much higher than the US values, however, they do not have to be used in policy appraisal. Another country that uses SCC is Canada, a summary of their approach can be found in a recent OECD paper [55].

Despite both using an SCC approach, differences in carbon values between the US and Germany are substantial. Germany and the US' carbon values vary substantially; Germany's carbon values are at least twice as high as the US' in 2050 outside the high-impact scenario. Germany's higher values are mostly driven by a lower discount rate and equity weighting. For the latter, Germany increases the weight of damages in low income countries. This comparison illustrates the sensitivity of SCC values based on a few model assumptions.

Case study: the USA's use of an SCC

The US government's Interagency Working Group (IWG) developed the Social Cost of Greenhouse Gases from 2009 until 2017. The IWG developed estimates of the social cost of carbon (SCC) to be used by governmental agencies when undertaking cost-benefit analysis for proposed regulatory interventions. These values were compulsory for governmental agencies until March 2018[56].

Throughout the initial development and revisions, the IWG assessed the social cost of carbon using the marginal cost of global damages arising from global emissions. To develop the social

[54] Dietz, S., Gollier, C., & Kessler, L. (2018). The climate beta. Journal of Environmental Economics and Management, 87, 258-274.
[55] Smith, S, Braathen, N. A. (2015). Monetary Carbon Valuas in Policy Appraisal: An Overview of Curent Practice and Key Issues. OECD Environment Working Papers No. 92
[56] The Trump Administration has reduced the SCC to $1 after. See https://www.spglobal.com/marketintelligence/en/news-insights/trending/iczho9kfj3sim06kjcedpw2

cost, the IWG used three Integrated Assessment Models (IAMs), DICE, PAGE and FUND. The results from each were given equal weighting to create the SCC estimates.

To develop carbon values for use in cost-benefit analysis, the IWG made the decision to use three different discount rates[57]. The objective of three discount rates was to cover a plausible range, between 2.5% and 5%, with a central rate of 3%. In addition to the SCC, values generated from these discount rates, a fourth value was introduced to reflect higher than expected climate-related damages. Each annual figure is generated from thousands of runs of the IAMs under different socioeconomic scenarios. The fourth value is based on the 95th percentile of the SCC values generated for the central SCC value.

	5% Average	**3% Average**	**2.5% Average**	**High Impact (95th at 3%)**
2010 estimates[58]	$6.8	$26.3	$41.7	$80.7
2013 estimates[59]	$12	$43	$64	$128
2016 estimates[60]	$12	$42	$62	$123

The IWG presented the following evolution of prices (in 2007 dollars per metric ton of CO2) in its 2016 Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis:

	5% Average	**3% Average**	**2.5% Average**	**High Impact (95th at 3%)**
2015	$11	$36	$56	$105
2020	$12	$42	$62	$123
2030	$16	$50	$73	$152
2040	$21	$60	$84	$183
2050	$26	$69	$95	$212

57 This is despite the common practice of using two; 7%, the average before-tax rate of return to private capital in the U.S. economy, and 3%, the real rate of return on long-term government debt. (OMB Circular A-4. https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A4/a-4.pdf)
58 https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf
59 https://obamawhitehouse.archives.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf
60 https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc_tsd_final_clean_8_26_16.pdf

Case study: Germany's calculation of an SCC

In 2019, the German Environment Agency (Umweltbundesamt) updated its calculation of a social cost of carbon. It used the Anthoff model[61], an integrated assessment model based on FUND that includes equity weighting. This means it considers different nominal monetary values for damages based on the average income of the country in which the damages took place. In turn, this means that a given absolute value of damages is given more weight in a low-income country than in high-income countries.

This approach used two different discount rates, 1% and 0%, which are low compared to the discount rates used by other countries but still within the range of estimates in the literature. The 0% discount rate weight the current generation the same as all future generations and is primarily presented as a sensitivity analysis. The costs recommended by are shown in the table below[62]. The prices are in 2016 euros per metric ton of CO2. The 2016 value, at 1% discount rate, of €180 per metric ton of CO2 is close to the estimation of the IPCC AR5 SCC of €173.5 per metric ton of CO2, but is much higher than that of other countries, such as that used in the USA.

	1% pure rate of time preference	**0% pure rate of time preference**
2016	€180	€640
2030	€205	€670
2050	€240	€730

Assessment against criteria

The development of an SCC is a theoretically appealing approach to the development of carbon values, but the deep uncertainties associated with the calculation of an SCC suggest it may not be appropriate as the basis of carbon values for policy analysis. This section evaluates the SCC against the criteria robustness, timeliness, policy alignment and credibility.

Summary of assessment for the SCC approach

Robustness: red

Timeliness: amber

Policy alignment: red

[61] Anthoff, D. (2007). Report on marginal external damage costs inventory of greenhouse gas emissions. NEEDS–New Energy Externalities Developments for Sustainability, Delivery, (5.4-RS).
[62] https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-02-11_methodenkonvention-3-0_en_kostensaetze_korr.pdf

Credibility: amber

Specifically, the significant uncertainty associated with the calculation of an SCC, and the use of a social cost of carbon metric faces challenges in terms of its robustness. Significant developments in the calculation of SCCs since 2009, particularly the implications of uncertainties for the assessment of SCCs, have reshaped this field of study and led to important conclusions regarding the insurance value of mitigation and the appropriate treatment of risk. These findings have also seen estimates of the SCC increase substantially, however this has not meaningfully constrained the distribution of potential SCCs – if anything the defensible range of estimates for the SCCs has become wider. These developments are built on the insight that estimating an SCC involves dealing with nested complexities regarding the impact of emissions on climate outcomes, the calculation of damage functions regarding the impact of temperature change and other climate outcomes on economic outcomes, and the valuation of these damages across time and communities. The SCC is highly sensitive to changes in assumptions, which can lead to vastly different valuations and limits the SCC’s utility in informing public policy decision making. This issue can be seen by the vast differences in prices for SCC derived by the US government and German government, despite both utilizing assumptions that are broadly within the mainstream of the SCC literature. Some even conclude that resulting SCC have “little to no value” for evaluating climate policies[63].

There is also the potential that due to uncertainty regarding specific parameters, the calculation of an SCC could be downward biased. This assessment is best summarised by the findings of the High-Level Commission on Carbon Prices, which concluded:

> *… many of the impact functions used in modeling exercises to calculate the social costs of carbon are biased downward because they fail to consider many vitally important risks and costs associated with climate change—particularly the widespread biodiversity losses, long-term impacts on labor productivity and economic growth, impacts on the poorest and most vulnerable, rising political instability and the spread of violent conflicts, ocean acidification, large migration movements, as well as the possibility of extreme and irreversible changes… for these reasons, many past modeling exercises to calculate the global social costs of carbon have produced numbers that probably underestimate these costs by very large margins.*

Further, the SCC may not perform well in terms of timeliness and policy alignment. A broader limitation of the SCC literature in this context, that because these pathways are not usually estimated on paths to limit warming to two degrees Celsius or below, uncertainties aside, they are inconsistent with the UK’s net zero target. Indeed, the policy conclusions derived from an SCC estimate would be invariant to the choice of UK climate target. While the calculation of an SCC may result in carbon values that are broadly consistent with the Paris Agreement under certain calibrations, the SCC calculated will be invariant to the specific target of the UK government. As such, the use of an SCC approach would see no difference in the benefit-cost

[63] Pindyck, R. S. (2013). Climate change policy: What do the models tell us? Journal of Economic Literature, 51(3), 860-72.

ratio and therefore in the assessment of policies and projects before and after the UK's adoption of its net zero targets. Targets informed by science, and broader economic and ethical considerations may provide a more solid policy base than the narrow framing of interactions between climate and economics in most SCC analysis[64]. SCC allows for some timeliness in terms of updating, however, elements like changes in technology would have to be translated into the functions of the IAM.

Given these challenges, there is a risk that if SCC is used as the basis for developing carbon valuations could face credibility issues. As although a defensible approach to developing an SCC is possible, the sensitivity of these measures to alternative reasonable assumptions creates risks for that any SCC calculated may not be robust to rigorous public and academic scrutiny. Further, the invariance of the SCC to a certain emissions reductions target creates potentially severe problems for the communication of the metric to the public. In addition, the approach to calculating an SCC creates further challenges for credibility. The reliance on integrated assessment models reduces transparency for stakeholders. IAMs used for SCC are often a black box and many functions lack empirical grounding. This can provide a challenge for the credibility of SCC, particularly for higher values.

[64] Pezzey, J. C. (2019). Why the social cost of carbon will always be disputed? Wiley Interdisciplinary Reviews: Climate Change, 10(1), e558.

Mitigation cost approaches

Mitigation cost approaches model the costs of achieving a certain emissions reduction target at lowest cost. Mitigation cost approaches take a certain emissions reduction target as given, for example from climate science or existing legislation. They then calculate the required carbon value to achieve this target at lowest cost. There are two general approaches:

1. A target consistent price path approach relies on techno-economic analysis to estimate the required carbon value that makes the required emissions reductions cost-efficient.
2. The traded carbon value approach uses observed and expected carbon prices in existing carbon markets to understand the value of carbon

The traded carbon value approach is insufficient to represent economy-wide, societal carbon values. Traded carbon values have the advantage that they can represent actual prices of carbon or abatement that are discovered through the operation of carbon markets. However, these values only represent a snapshot of current carbon prices in regulated sectors, which may only form a small subset of the broader economy. Under current regulation, the EU ETS price would only provide carbon values in electricity, industry and parts of aviation. Furthermore, market failures such as myopic behaviour or imperfect information can result in carbon prices that are different from optimal carbon values[65]. Given its limited utility across the economy and the potentially biased estimates, this approach is not considered further in the analysis.

A target consistent price path approach can be expert-based or model-derived. There are two main approaches to obtain a target consistent price path[66]. The expert-based, or technology cost curve, approach calculates bottom-up estimates for certain technologies and their abatement potential and ranks them by their £/tCO2e price. The price needed to achieve the required emissions reduction would be the resulting carbon value to achieve the target. The model-derived approach uses economy-wide general equilibrium or sectoral partial-equilibrium models to obtain these costs. They can be run over a given time horizon to obtain a cost-efficient pathway. Repetitive model runs at different emissions constraints for a given year can be used to obtain a static abatement curve at a point in time.

While both the SCC and the target consistent price path approach comprise large uncertainties, the target consistent price path relies on fewer assumptions and leads to a narrower range of carbon values across studies. This approach is subject to large uncertainties, as discussed in the following sections. However, it does not rely as much on as many critical assumptions on unobserved functions as SCC analysis, such as the social welfare function, the damage function or how the climate system reacts to a change in carbon

[65] See e.g. Edenhofer, O., Flachsland, C., Wolff, C., Schmid, L. K., Leipprand, A., Koch, N., ... & Pahle, M. (2017). Decarbonization and EU ETS Reform: Introducing a price floor to drive low-carbon investments. Berlin: Mercator Research Instituteon Global Commons and Climate Change.

[66] Kesicki, F. (2010). Marginal abatement cost curves for policy making–expert-based vs. model-derived curves. Energy Institute, University College London, 1-8.

concentration[67] [68]. As a result, the range of carbon values obtained from a target consistent price path approach is generally narrower[69].

The following section discusses recent developments in the literature and how they aim to address key uncertainties.

Developments in the literature

The literature has identified key limitations of the expert-based approach, such as ignoring intertemporal and inter- and intra-sectoral interactions. Kesicki and Ekins provide a comprehensive overview of limitations of both approaches[70]. The expert-based approach cannot consider intertemporal issues and interactions within and between sectors; abatement in a certain project is assumed to not have any impact on the costs of another project or the costs of abatement a few years later. Past abatement can trigger innovation and reduce costs over time, and abatement in sectors like electricity changes mitigation potentials across many other sectors. The expert-based approach also regularly fails to incorporate behavioural barriers for abatement, such as information failures, financial hurdles or inertia. Furthermore, cost estimates are very sensitive to their assumptions such as investment costs or discount rates.

The model-derived approach overcomes some of these shortcomings, but key uncertainties remain. The model-derived approach, particularly with a general equilibrium model, can represent interactions and feedback loops between different abatement decisions. However, other elements remain unrepresented, such as behavioural aspects or innovation. Furthermore, most models focus on the energy system and sectors like Agriculture, Forestry and Other Land Use (AFOLU) are often not incorporated in detail[71].

Recent modelling includes a better representation of technological changes in the analysis. Multiple papers have aimed to include technological change in more detail within the model-derived approach. Wang et al include endogenous technological change through R&D to

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[67] However, some of these assumptions can apply indirectly as the already set target often relies on other modelling. Nevetheless, for many civil servants the target is already set through previous work or politics, and the challenge subsumes to evaluation policies accurately.
[68] Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G. J., Fisher-Vanden, K., ... & McCollum, D. (2015). Assessing Transformation Pathways. 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 (No. PNNL-SA-102686). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).
[69] Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., & Mundaca, L. (2018). Mitigation Pathways Compatible with 1.5 C in the Context of Sustainable Development. Global Warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.
[70] Kesicki, F., & Ekins, P. (2012). Marginal abatement cost curves: a call for caution. Climate Policy, 12(2), 219-236.
[71] Kesicki, F., & Ekins, P. (2012). Marginal abatement cost curves: a call for caution. Climate Policy, 12(2), 219-236.

estimate mitigation costs[72]; Levinh et al add feedback loops to explore path-dependencies in mitigation[73]; while Kesicki adds technological details into a bottom-up model[74]. Nevertheless, there are still large uncertainties on techno-economic assumptions used across studies that are often neither harmonised nor transparent[75].

The literature has also focused on the effect of uncertainties on target consistent price paths. As discussed above, these mitigation costs are very sensitive to multiple model inputs. Kesicki performs sensitivity analysis on key model parameters and finds that the hurdle rate of different technologies, the availability of abatement options and the demand level have the most significant impact on mitigation costs[76]. Huang et al provide an overview of additional papers that provide uncertainty analysis[77]. They conclude that a set of sensitivities provides richer results on carbon values than a single curve, particularly since many model uncertainties remain.

Recent model developments also include using advanced model suites and further develop non-energy sectors to cover all parts of the economy in greater detail. Earlier modelling has often used either one, mainly an energy-system, model or relatively simple representations of non-energy sectors. Those models either focus on one sector in detail or have an economy-wide cover that represents the sectors with restricted detail. Some existing models have developed over the years to provide more details across the economy[78]. Another strand of the research has attempted to overcome these shortcomings by combining multiple models. For instance, the UNPRI Inevitable Policy Response (IPR) scenario combines four independent models, a macro-economic, an energy-system, a land-use and an asset pricing model to estimate the potential impacts of climate policies. Similarly, Betram et al[79] and Kriegler et al[80] use a macro-economic, an energy-system and a land-use model to develop mitigation pathways with greater details in all sectors. Linking several specialised models is not a new approach, but the level of granularity and coverage of impacts has substantially improved in

[72] Wang, K., Wang, C., & Chen, J. (2009). Analysis of the economic impact of different Chinese climate policy options based on a CGE model incorporating endogenous technological change. Energy policy, 37(8), 2930-2940.
[73] Levihn, F., Nuur, C., & Laestadius, S. (2014). Marginal abatement cost curves and abatement strategies: Taking option interdependency and investments unrelated to climate change into account. Energy, 76, 336-344.
[74] Kesicki, F. (2013). Marginal abatement cost curves: Combining energy system modelling and decomposition analysis. Environmental Modeling & Assessment, 18(1), 27-37.
[75] Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., ... & He, C. (2019). Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. Energy, 172, 1254-1267.
[76] Kesicki, F. (2013). What are the key drivers of MAC curves? A partial-equilibrium modelling approach for the UK. Energy Policy, 58, 142-151.
[77] Huang, S. K., Kuo, L., & Chou, K. L. (2016). The applicability of marginal abatement cost approach: A comprehensive review. Journal of cleaner production, 127, 59-71.
[78] See e.g. for a history of the IMAGE model here: https://models.pbl.nl/image/index.php/IMAGE_framework/A_brief_history_of_IMAGE
[79] Bertram, C., Luderer, G., Popp, A., Minx, J. C., Lamb, W. F., Stevanović, M., ... & Kriegler, E. (2018). Targeted policies can compensate most of the increased sustainability risks in 1.5 C mitigation scenarios. Environmental Research Letters, 13(6), 064038.
[80] Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., ... & Mouratiadou, I. (2017). Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Global environmental change, 42, 297-315.

recent years. These combined model suites can overcome some of the trade-off and provide a more comprehensive analysis of mitigation costs.

Lastly, tighter emissions budgets have increased the role of greenhouse gas removals (GGRs) of in target-consistent price path analysis but they have not been fully integrated yet. GGRs, or negative emissions technologies (NET), play an important role limiting global warming to 2°C and particularly to 1.5°C[81]. Therefore, they also become more important in the analysis of target-consistent price paths. While some technologies can now rely on substantial literature, such as bioenergy with carbon capture and storage (BECCS), the literature on other technologies remains sparse[82]. Furthermore, interactions of GGRs with other technologies are rarely modelled, such as the impacts of BECCs on land prices and agriculture[83]. The high uncertainty around technology costs and deployment for GGR technologies – and technologies in general – pose difficulties for the mitigation cost approach. Conducting a large range of sensitivities, particularly with pessimistic technology assumptions, can reduce uncertainty as part of a precautionary approach.

Box 3 describes the approach the Carbon Pricing Leadership Coalition has taken to develop global costs.

Box 3: developing a global costs approach

In 2017, the World Bank's Carbon Pricing Leadership Coalition (CPLC) engaged a group of prominent economists to assess the economic case for carbon pricing. This High-Level Commission On Carbon Prices assessed a wide range of evidence on carbon pricing, including assessing appropriate levels of carbon prices drawing on a mitigation cost approach. [84] This included examining recent studies to estimate carbon values to reach a 2°C target and comparing expert-based approaches that estimate switching costs for key technologies with the model-derived approaches used in IPCC reports.

They find that switching costs are highly sensitive to capital costs, regional differences and other model inputs. They find that even for a given technology, required carbon values to facilitate switching vary substantially. A main driver is differences in capital costs as many new technologies require expensive capital. However, assumptions on technology development, fuel prices and market structure matter as well. As a result,

[81] The Royal Society, and Royal Academy of Engineering. (2018). Greenhouse gas removal. Retrieved from https://royalsociety.org/topics-policy/projects/greenhouse-gasremoval/?gclid=Cj0KCQjw9NbdBRCwARIsAPLsnFb5JGNk2PsPm8ec0nboi24KtqTCDoMpKLNixX8R2C43dhYvRFj-XJAaAguJEALw_wcB
[82] Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... & Luderer, G. (2018). Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 13(6), 063002.
[83] For a global analysis see Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B. L., ... & Drouet, L. (2019). A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability, 2(5), 386-396.
[84] CPLC (2017). Report of the High-Level Commission on Carbon Prices. https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59b7f2409f8dce5316811916/1505227332748/CarbonPricing_FullReport.pdf

switching costs can vary substantially, for example the switching cost from coal to wind are estimated to be eight times higher in Germany than in the US.

Model-derived values vary with assumptions on technology availability, baseline growth and resource flexibility. The CPLC report compares different model-derived estimates on carbon values and illustrates the main determinants of difference. Most estimates for carbon values in 2050 for a 2°C target are within the 2005US$100-250/tCO2 range. Models that are more pessimistic about the availability and costs of technology, include higher baseline economic growth and assume lower flexibility in the economy to distribute resources produce generally higher estimates. Furthermore, more recent estimations tend to result in higher prices.

Policy developments

Examples from New Zealand and France show how the mitigation cost approach is put into practice. The UK is currently using a target consistent price path, and similar approaches are used around the world to inform decision making. Box 6 describes the role of mitigation modelling in decisions for tighter climate targets in New Zealand. In 2019, the Government of France developed a set of carbon values using the mitigation costs approach through its “Value for Climate Action Commission” as described in the below case study. Comparison of estimates between countries is not advisable, carbon values are often very different even in the absence of model uncertainties because mitigation costs depend on the specific structure of the economies. In order to implement a mitigation cost approach, importantly, countries need quantified climate targets. For example, the US does currently not have a fixed climate target, which means it is not possible to develop carbon values using a target-consistent price path approach.

New Zealand’s modelling of more ambitious climate targets provides a good example of dealing with uncertainty. Uncertainties in various model assumptions are a main driver of resulting carbon values. New Zealand’s modelling team used scenario analysis to explore the uncertainties around key assumptions, particularly around technology availability. The various scenarios show how sensitive carbon values are with respect to different technological or economic assumption. However, they also illustrate which results are robust to various assumptions, for example, that earlier action reduces mitigation costs under all scenarios.

Case study: modelling costs of mitigation in New Zealand

In 2018, the government of New Zealand commissioned a major study into their climate change policies, to examine the existing policy mix and the potential case for strengthening its mitigation targets. This review developed several new strands of thinking regarding the modelling of mitigation costs and the treatment of uncertainties. As part of this review, the New Zealand Productivity Commission and Ministry for Environment commissioned Vivid Economics, Concept Consulting, Motu Economic and Public Policy Research to develop modelling of the potential implications of climate policy approaches under uncertainty. The modelling explored the costs of reaching a zero or 25 MtCO2e emissions economy-wide in

2050. It did not include international offsets and forest sequestration was the only GGR considered.

This modelling sought to assess the robustness of different mitigation strategies to unexpected changes in external circumstances, for instance the rates and nature of technological change and external economic drivers like commodity prices and exchange rates. This modelling utilised scenarios to test how effective strategies were, both in cases where future outcomes align with expectations, and when they do not. This provides scope for uncertainty to enter the modelling at numerous stages. Different expectations on technology prices and different preferences for climate change will influence the decisions made on the severity of policy implemented and how soon they are introduced. If a government takes strong, early policy actions, the achievement of emissions targets is less reliant on external technological and economic drivers. Equally, different technology developments and prices of commodities and carbon prices will influence how effective any given set of policies will be. For example, rapid technology developments can make cutting emissions cheaper and quicker regardless of the policy strategy a government adopts.

This modelling tested three policy strategies, which were tested in situations where the underlying assumptions informing policies were correct, and when they were wrong. These strategies were:

1. The policy-driven scenario, represented a policy mix developed assuming that technological change would be slow, requiring early aggressive policy action.
2. The disruptive decarbonisation scenario, represented a policy mix developed assuming rapid disruptive innovation that would lead to new industries and low-cost mitigation.
3. The stabilising decarbonisation scenario represented a policy mix developed assuming that technological change would support mitigation in existing industries and technologies.

The results of this modelling suggested that a strategy of early action was rewarded with lower carbon prices in the future regardless of the actual degree of technological development. It also suggested that mitigation strategies that rely on significant technological change are more expensive if this doesn’t eventuate, as additional action is needed to make up for lost time.

Despite the large range of uncertainty analysis, the variance of carbon prices remains relatively low. The study varies 17 main variables across 24 scenarios and explores a wide range of price, technology and policy assumptions. Nevertheless, the range of carbon prices remains relatively low. Across all scenarios, the price to reach 25 MtCO2e in 2025 remains between NZ$118 and NZ$224 per tCO2e. The only exception is the disruptive scenario, where existing industries are largely disrupted by innovation and the carbon price remains at just over NZ$50.

These findings emphasise the need to explicitly test underlying assumptions regarding technological and economic developments, to assess the potential mitigation costs and appropriate carbon values in situations where these assumptions don’t eventuate.

Source: Vivid Economics, Concept Consulting, Motu (2018). Modelling the transition to a lower net emissions New Zealand.

Case study: developing carbon values in France

France recently approved a net-zero greenhouse gas emissions target for 2050, and as part of these policy reforms, sought to estimate the monetary value of carbon for policy appraisal. The modelling conducted considered a domestic economy-wide net zero target in 2050. The analysis considers a wide range of GGR technologies, including BECCS and direct air capture (DAC). International offsets are not considered.

The Value for Climate Action Commission used five different models to assess potential mitigation costs associated with reaching its emissions reductions target. The aim of this approach was to have a range of estimates of the costs of meeting net zero that does not depend on specifications. These models included two techno-economic models, TIMES and POLES, and three sectoral macroeconomic models, IMACLIM, ThreeME and NEMESIS.

For calculating the shadow price of carbon after 2030, two complementary approaches were considered. The first was forecasting the costs of the technological developments required to fulfil the decarbonisation goal – a mitigation cost approach. The second was gradual alignment of the shadow price with the Hotelling rule[85], using a discount rate of 4.5%.

The approach developed suggests a substantial increase compared to the carbon values. In 2008, the 2030 shadow carbon cost that was estimated at €100/tCO2e. As shown in the figure below, this updated analysis suggests an appropriate value would be €250/tCO2e (in 2018 Euros), with this increase reflecting the tightened global carbon budget. For the medium and long run (2040 and 2050) the proposed values are €500 and €775, respectively.

- 2018: €54/tCO2e
- 2020: €87/tCO2e
- 2030: €250/tCO2e
- 2040: €500/tCO2e
- 2050: €775/tCO2e

Source: France Strategie (2019). The Value for Climate Action.

Assessment against criteria

The use of the target consistent price path has clear limitations but remains a more appropriate approach for the calculation of carbon values in the UK. As with calculations of social cost of carbon, developing a target-consistent price path that is robust to uncertainty is key to developing an appropriate carbon value as the UK implements policies to achieve with its net zero target. The carbon value should be anchored on the domestic target if it exceeds the Paris Agreement pledge. The approach allows tailoring for different targets once they are

[85] The basic version of the Hotelling rule states that a non-renewable resource should grow at the public discount rate in order to be well managed.

revised upwards. This section evaluates the target consistent price path against the criteria robustness, timeliness, policy alignment and credibility.

Summary of assessment for the target-consistent price path approach

Robustness: amber

Timeliness: green

Policy alignment: geen

Credibility: amber

Source: Vivid Economics

Although uncertainties are lower in mitigation cost approaches than under an SCC, a key challenge for the target-consistent price path approach is developing a robust metric given uncertainties regarding future mitigation costs. The costs of mitigation are highly dependent on government policy action, and on future technological and economic developments that are largely outside the UK's control. Modelling an efficient mitigation cost pathway relies on nested assumptions regarding these developments. To address these limitations, it is important that the method of implementing a mitigation cost approach is robust to uncertainties. Uncertainty regarding mitigation costs also creates challenges for the sensitivity of the metric – if mitigation costs are heavily dependent on assumptions regarding technological change, then this metric may be highly sensitive to these underlying assumptions. The underlying logic of the need to adopt an insurance type approach considering climate damages is similarly persuasive when considering the appropriate method for calculating mitigation costs and has not been considered sufficiently in the literature. This challenge is reflected in the OECD conclusions regarding mitigation cost approaches:

> *Even if it is true that uncertainty about future marginal abatement costs is less than that surrounding marginal damage costs, uncertainty about the social benefits that can be achieved through climate change abatement measures does not disappear as a result of adopting a policy target that can be achieved with relative certainty. The same uncertainties about social benefits remain but have been partly subsumed in the decision to set a particular target.*

These issues of uncertainty are challenging but can be addressed, as is discussed in further detail below.

Models developed for target-consistent price paths are complex but provide greater timeliness to be frequently updated as information becomes available. Most models used to obtain a target-consistent price path are complex. However, compared to models used for SCC analysis they can be more flexibly updated when new information becomes available. In the models used, different technologies can be directly represented in significant detail, whereas in IAMs used for SCC analysis more generic cost functions are used. As such in this approach, updating cost estimates is relatively straightforward. This allows for a frequent update of carbon values as technology and emissions evolve.

An advantage of the target-consistent price path approach is more explicit policy alignment with the UK's net zero target. This approach sees the calculated carbon value adjust with target ambition and changing circumstances, with the recent adoption of a net zero target unambiguously requiring a higher carbon price. While the direction of change in carbon value is clear, the scale of increase is more uncertain[86]. In this case moving to net zero increases the importance of the negative emissions back stop. Rather than anchoring the cost-efficient price path on the marginal cost of an 80 per cent reduction of emissions, it will now be in part determined by the expected cost of developing large scale negative emissions technologies in 2050. This in turn requires a detailed interrogation of the prospects of greenhouse gas removal technologies and associated learning curves, rather than more standard marginal abatement cost curve analysis.

Despite these benefits, the credibility of a target-consistent price path is open to challenge particularly given the challenges of addressing uncertainty. The mitigation cost approach has the potential to be transparent, through detailed engagement on assumptions and the design of modelling approaches. Yet uncertainty regarding mitigation costs is deep, and modelling exercises are highly dependent on assumptions regarding future mitigation. Given these uncertainties an obvious critique of carbon values using a best estimate regarding the likely set of future mitigation technologies is that, if accurate, the prices assumed would be insufficient to achieve the net zero target a large share of the time.[87] A credible set of carbon values may be those that are able to achieve targets even in the face of adverse technological or economic developments.

A potential solution could be to focus on identifying a carbon consistent price path that is sufficient to meet decarbonisation targets with high confidence. This would mean adopting deliberately conservative assumptions regarding the development of technology to ensure that the net zero target is likely to be met even in the event of slow technological change. With regular recalculation of carbon values, this could see prices decline over time if technological change eventuates.

This approach can also be expressed as a constrained welfare maximisation problem under uncertainty. In this case the UK's net zero goal in this case becomes a constraint on carbon emissions that the government seeks to meet while maximising welfare. Under this constraint abatement cost minimisation is equivalent to welfare maximisation (ignoring damages) – as the approach that minimises expected abatement costs will also maximise welfare. Under uncertainty, the government will need to meet the constraint even when mitigation costs are high, resulting in a price premium.[88] Given potential mitigation costs associated with large scale greenhouse gas removal technologies this premium could be high.

[86] This also holds for other countries updating their climate targets.
[87] Half of the time if median estimates are used
[88] see https://www.sciencedirect.com/science/article/pii/S0095069618302122?via%3Dihub.

This has an additional advantage when considered in the context of potential catastrophic climate change by easing the closing of any future ambition gap. Conservative approaches regarding the rate of technological change will result in higher carbon values, which all else equal makes increasing target ambition cheaper. A clear implication of modelling in New Zealand (discussed in section 4.2 above) and elsewhere is that early action makes future emissions reductions cheaper. As such if climate feedbacks or impacts are worse than anticipated, with higher carbon values in the near term a future government will be more able to ratchet up future mitigation ambition. Equally important is that this information base is updated regularly. Given the rapid pace of recent technological change the underlying assumptions that inform a given price pathway may be out of date very quickly. Regular updating (for instance annually or biannually) of these assumptions to reflect the latest literature will be important to ensure that carbon values remain robust. Regular updates also reduce the risk that conservative assumptions lead to unduly high carbon values for extended periods, or that excessively optimistic assumptions result in the need for sudden forceful policy actions.

Conclusions for the UK

This paper has considered recent developments in the literature on the calculation of carbon values, focusing on social cost of carbon and the mitigation cost approaches. Carbon values represent the societal value of carbon emissions reductions and are crucial for policy appraisal. This paper has reviewed the development in the literature on carbon values since the UK's last review in 2009 and assessed these approaches for their utility in the UK context. We find that, with some minor changes, the UK's existing methods remains fit for purpose.

Drawing on recent literature we developed four key criteria for the assessment of metrics for carbon valuation:

- Robustness; the metric is comprehensive in accounting for the climate-relevant impacts of a policy and is robust to small changes in underlying assumptions.
- Timeliness; the metric should support efficient public decision-making, by being flexible and easy to update for changed information and circumstances.
- Policy alignment; the metric should be capable of responding to meaningful changes to government policies and goals and contributing to their achievement.
- Credibility; the metric is transparent to stakeholders in both the method of its calculation and conclusions, and both should stand up to rigorous public and academic scrutiny.

SCC and mitigation costs approaches were then assessed against these criteria.

The academic literature on SCCs has developed substantially in recent years, particularly with regards to the specification of damage functions and approaches to discounting. SCC analysis entails significant uncertainties in all parts of the analysis. Recent research has focused on two elements: First, damage functions have become more sophisticated or grounded in historic evidence. Earlier SCC analysis has used simple, often quadratic damage functions to model temperature impacts on GDP. More recent papers have used empirical estimates of historic climate change damages to help calibrate the damage function, often resulting in much higher estimated damages. The second focus in recent years has been on discounting. The research has elaborated on how to discount future benefits and damages, with a general trend towards using lower discount rates than in earlier research however this remains a source of debate.

With these compounding uncertainties, an SCC approach is not recommended for use. Estimates of SCC's remain contentious, with small alterations to underlying assumptions leading to vastly different valuations, with the range of estimates widening in recent years. SCCs score poorly against all elements of our assessment, particularly on robustness and policy alignment. The latter is particularly relevant for the UK. SCC analyses are not aligned with the net zero target, most estimations lead to emissions level much higher than net zero in 2050.

Mitigation cost approaches represent an alternative method, which models the costs of achieving a certain emissions reduction target at lowest cost. Mitigation cost approaches take a certain emissions reduction target as given, for example from climate science or existing legislation.

The most utilised mitigation cost approach is the use of a target-consistent price path, the method currently used by the UK. This approach uses techno-economic analysis to estimate the required carbon value that results in the most cost-efficient emissions reductions. The target-consistent price path approach relies on fewer assumptions than SCC approaches as the optimal level of emissions is already given. Nevertheless, the approach is highly sensitive to model assumptions and structure and can produce a wide range of estimates. Recent developments include the inclusion of innovation and learning, the use of model suites to represent more sectoral details across the economy, and the consideration of GGR technologies.

Compared to the SCC, the target-consistent price path approach scores better against assessment criteria despite significant uncertainty. The target-consistent price path is preferred in two main areas: First, the approach is more credible as the methodology is more transparent and relies less on unobserved functions. Second, the approach is well aligned with the net zero target. Nevertheless, this approach involves challenges particularly given its sensitivity to uncertain model assumptions.

Given recent developments in the calculation of carbon values, and the latest academic literature, the continued use of a target-consistent price path appears appropriate if used carefully. However, given uncertainty regarding future mitigation costs the approach to developing this price path should be revised. This can ensure that the price path adopted is consistent with achieving the UK's targets (even in the event of contrary technological developments), and to ensure that the latest evidence is being reflected on a regular basis. The UK's climate targets are not conditional on future technological or economic developments, and an appropriate target consistent price path should be consistent with achieving net zero even under contrary circumstances. The target-consistent price-path should also be updated on a regular basis to reflect the latest evidence and utilise advancements in modelling and analysis. This will ensure that an appropriate precautionary approach is being adopted, while relevant new information is being regularly accounted for.

Vivid Economics

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