The Cost of Mitigation Revisited

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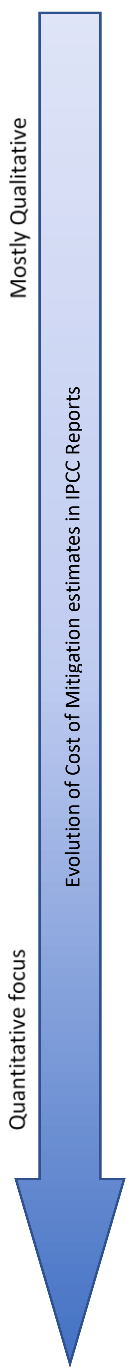
Estimates of economic implications of climate policy are important inputs into policymaking. Despite care to contextualize quantitative assessments of mitigation costs, one strong view outside academic climate economics is that achieving Paris Agreement goals implies sizeable macroeconomic losses. Here, we argue that this notion might be ill-informed and results from unwarranted simplification or omission of the complexities of quantifying the economic costs of mitigation, which generates ambiguity in their communication and interpretation. We synthesize key factors influencing mitigation cost estimates to guide interpretation of estimates, for example, as provided by the IPCC, and suggest ways to improve the underlying models. We propose alternatives for the scenario design framework, the framing of mitigation costs, and the methods used to derive them, in order to better inform public debate and policy.

The United Nations Framework Convention on Climate Change (UNFCCC) states that "policies and measures to deal with climate change should be cost-effective to ensure global benefits at the lowest possible costs"[1]. Correspondingly, the governments-approved outlines of IPCC reports often explicitly indicate that the macroeconomic costs of mitigation should be assessed. For example, the outline for the upcoming 6th Assessment Report (AR6) requests authors to assess "Economics of mitigation and development pathways, including mitigation costs"[2], reflecting concerns about the costs of climate policy. This concern is mirrored in national policy documents such as the 2007 Stern Review[3], and more recently from the US[4], the UK[5], and the European Union[6].

For decades now, the IPCC has been tasked with assessing the literature on macroeconomic costs of mitigating climate change and has responded by publishing both estimates of – and the limitations inherent in – long-term macroeconomic projections[7,8] (Figure 1 and Section S1). Making such estimates is a complex undertaking that, although rooted in economics, requires consideration of elements from engineering, political science and sociology. It is not surprising that these complexities have led to misunderstandings and controversy. For example, numerical estimates of the costs of climate mitigation reported in the IPCC's 5th Assessment Report (AR5) have elicited reactions ranging from "their bills have become enormous"[9] to "salvation gets cheap"[10]. Relevant stakeholders, especially those more at risk from a transition to a low-carbon economy, have emphasised the interpretation that efforts to mitigate climate change will lead to substantial macro-economic losses. This emphasis may have succeeded despite the cautious framing of the estimates in IPCC reports, especially in AR5. The caveats, clearly stated in the report, caution against taking these estimates at face value, but they risk getting lost when these numbers are used in the general audience discourse.



Report	Main Messages	State of Scenario Literature
FAR (1990)	• Limitation* and adaptation strategies must be considered as an integrated package and should complement each other to minimize net costs. • Synergies between limitation* and adaptation strategies. • Reducing emissions brings co-benefits (reducing acid rain and ozone depletion e.g.) • uncertainty surrounding CoM cited as a reason why the information available was "inadequate to make sound policy decisions" (p.124)	• No assessments had been made of economic costs and benefits of mitigation
SAR (1996)	• Net costs are what matters • "No-regret potentials" exist • Insights from models more important than numerical results • CoM critically dependent on choice of reference scenario	• Very few studies on CoM available
TAR (2001)	• Large NRPs exist • Co-benefits of CP may offset CoM leading to "double dividends" • Challenges to realising NRPs reduce their size • Benefits may offset costs but rarely exceed them.	• emergence of studies on local and regional co-benefits of climate mitigation policies
AR4 (2007)	• First numerical estimates of global CoM to 2030 • Most models show GDP losses but some show gains by assuming baseline is non-optimal (second best). • Modelled costs depend on regional/sectoral resolution, GHG coverage, reference scenarios, and carbon revenue recycling	• First global estimates of CoM
AR5 (2014)	• First numerical estimates of global CoM at century scale • All assessed scenarios led to consumption losses relative to baselines. • strong focus on non-idealized 2°C scenarios, showing the extra costs due to e.g. delayed participation • High confidence given to statement of large variability for CoM across scenarios assessed and to higher CoM in delayed or fragmented scenarios • Consumption in baseline grows 300-900%, so losses represent small reduction in wealth	• Growing number and sophistication modelling approaches • Over 900 CoM scenarios assessed • Multi-model comparisons
SR1.5 (2018)	• No numerical estimates of impacts on aggregate economic activity were provided • Focus instead is on carbon prices and investments levels • Total energy-related investments increase by about 12% in 1.5°C pathways relative to 2°C pathways • wide range of global carbon costs are roughly 3-4 times higher in 1.5ºC pathways than in 2oC • There is a persistent gap between current investment patterns and what would be aligned with Paris goals • High confidence given to statement of large variability for cost of carbon • Very high confidence that socio-economic conditions influence cost of carbon • Limited to medium evidence, high agreement of a gap between current investment patterns and those compatible with 1.5ºC target.	• New scenario framework of Shared Socioeconomic Pathways (SSPs) • Literature on total mitigation costs c 1.5°C mitigation pathways was limit and was not assessed

*Instead of mitigation, "limitation" was the term used in the early days of the IPCC to refer to reduction of GHG emissions
CoM = Cost of Mitigation; NRP = no-regret potential

Figure 1 – Evolution of representation of mitigation costs in IPCC reports.

So that this discourse can become more critically informed by the underlying facts, we here review the process of developing and interpreting mitigation cost estimates and unpack key elements that form the basis for their estimation. Earlier IPCC Assessment Reports (ARs) explored costs of mitigation more theoretically, but their treatment has gradually shifted towards a more quantitative basis since (Figure 1). Scenario quantification with models such as integrated assessment models (IAMs) has been part of IPCC assessment reports since the beginning[11] (See Box 1: Estimating costs through models).

Currently, climate mitigation scenarios do not consider important determinants of net costs. Here, we discuss missing elements, highlighting the uncertainties involved and the ambiguities in the size and sign of the changes resulting from these deficiencies. We also illustrate opportunities for an improved presentation of mitigation costs that may help size opportunities for social, environmental and economic benefits beyond those from direct climate mitigation.

Costs of a changing climate

Perhaps the most important omission in estimates of economic impacts of mitigation is that calculated costs do not include impacts from climate change itself, and the associated economic benefits of avoided impacts[11–14]. That is, reported estimates represent the gross costs of mitigation. Impacts include loss of agricultural productivity[15]; heat-induced mortality and morbidity[16,17] and loss of labour productivity[18,19]; infrastructure losses from extreme events and sea-level rise[20]; biodiversity losses[21], and many others[22]. Climate stress also has a complex relationship with migration and related geopolitical instability[23] and with financial instability[24,25]. Omission of impacts in estimates of economic costs of mitigation reflects the historical structure of the IPCC, with mitigation benefits (i.e. avoided impacts) and mitigation costs featured in different so-called Working Groups II and III. However, this separation has created room for scholars and policymakers to focus only on the cost side of mitigation, ignoring the benefits[26–30]. Moreover, this separation also results in unrealistic reference scenarios since they ignore climate damages.

The challenge of estimating the aggregate economic effects of the physical impacts of climate change lies in a dearth of data, high uncertainties in regional climate change and the controversial or impossible nature of assigning costs to human lives, biodiversity, or cultural heritage. We do not assess these complex aspects here in detail. However, studies that also include economic impacts of climate change in detailed process-based IAMs are emerging in the literature[31–33], but robust comprehensive estimates are not available. Bringing new elements such as non-market damages[34] into the analysis adds further value to avoiding damages, but also adds sources of uncertainty to the overall outcome. Continuing use of no-impacts baselines in most studies and assessments is therefore likely. Still, refining the granularity of climate impacts, and bridging results of bottom-up approaches (e.g. Ciscar et al. [35]), that start from detailed biophysical impact modules, and econometric top-down methods (Burke et al. [36]) provide fruitful avenues for future research[37].

While methodological improvements in estimating economic impacts of climate change are welcome, available literature already indicates that structural uncertainty about damages and the risk of tipping points warrant ambitious climate action [38,39]. Furthermore, climate change poses serious risks to economic and geopolitical stability via, for example, risk transmission channels in the financial[24,25,40,41] and agricultural[42,43] sectors. Finally, climate change increases the risks of extreme events at the "tail end" of distributions, low-probability but high-impact events potentially causing catastrophic and irreversible damage[38,44]. However, the high uncertainty attached to the economic implications of such events[38] means including them in numerical cost estimates may further obscure rather than clarify policy options. Still, the avoided impacts resulting from mitigation must be present in the framing of the economic impacts of climate policy, and the social cost of carbon remains an important concept, particularly when political commitment is uncertain[45,46].

Crucially, estimating costs of mitigation by comparing to a hypothetical reference without climate impacts provides a skewed image to policymakers and stakeholders. A more relevant question might be how to implement mitigation in a way compatible with improving human welfare or promoting sustainable development. One way to abstract from climate change impacts in the discussion on mitigation pathways is to explore sets of scenarios that achieve similar cumulative emissions, as this would compare scenarios with similar climate impacts. Such temperature-clustered scenarios could differ in how they achieve their climate goals (timing, technology and instrument choices), and would therefore provide insight into the corresponding costs and how they are distributed across society. Although IAMs routinely produce these types of scenarios (see for example Schaeffer et al[47] or the Illustrative Scenarios in the IPCC 1.5-degree report[48]), currently the macroeconomic costs of mitigation are calculated by comparing mitigation scenarios to a baseline with very different temperature outcomes. While climate impact variability is reduced across temperature-clustered scenarios, it is not necessarily eliminated altogether. Temperature overshoot may imply strong impacts, particularly when thresholds for tipping points are crossed. For this, recent literature[49] can guide design of temperature-clustered scenario ensembles. Furthermore, how climate policy itself is implemented may influence impacts of global warming by affecting the capacity of vulnerable socio-economic groups and regions to adapt to changing climate conditions. This should be acknowledged in future work, for instance by revealing the economic impacts for heterogeneous agents and regions in the world[50,51].

Minor losses to a wealthier world

A common instinctive reaction of an untrained reader to the estimates of numerical losses is that mitigation leads to a reduction in economic output and is not worth the cost. However, when presented differently, mitigation scenarios can highlight that decarbonising the economy is understood to happen alongside persistent growth of per capita income over time. This key perspective of the economic impacts of climate change mitigation points to a communication opportunity for the upcoming IPCC AR6. We illustrate this in Figure 2. At the basis of mitigation cost estimates typically lie annual global consumption (and GDP) growth rates between 1% and 4% throughout the century (e.g. SSP2 projections in Dellink et al[52]). As such, the consumption losses reported in AR5 represent a small reduction in wealth over the entire century, when considered in the context of a reference in which consumption “grows anywhere from 300% to more than 900% over the century”[53]. As is clearly explained in AR5 text, the median annualised reduction in the growth rate of consumption is only 0.06 percentage points (0.04 to 0.14) compared to consumption that grows between 1.6 and 3% per year in the baseline[53]. The order of magnitude of this cost estimate arguably represents a negligible number when put in the perspective of economic growth over the century and the corresponding uncertainties involved in projecting long-term economic activity (Figure 2, panel a). This presentation of the economic impacts of mitigation could be reinforced in future estimates (including IPCC reports), emphasizing that steady economic progress is consistent with reaching the climate goals of the Paris Agreement, and that comparable levels of per capita income can be obtained while enhancing the economy’s carbon efficiency with a factor 5 (Figure 2, panel b). Furthermore, highlighting channels that can bring economic gains of climate policy in key figures and headline statements in the report would provide a more balanced representation of the economics of mitigation.

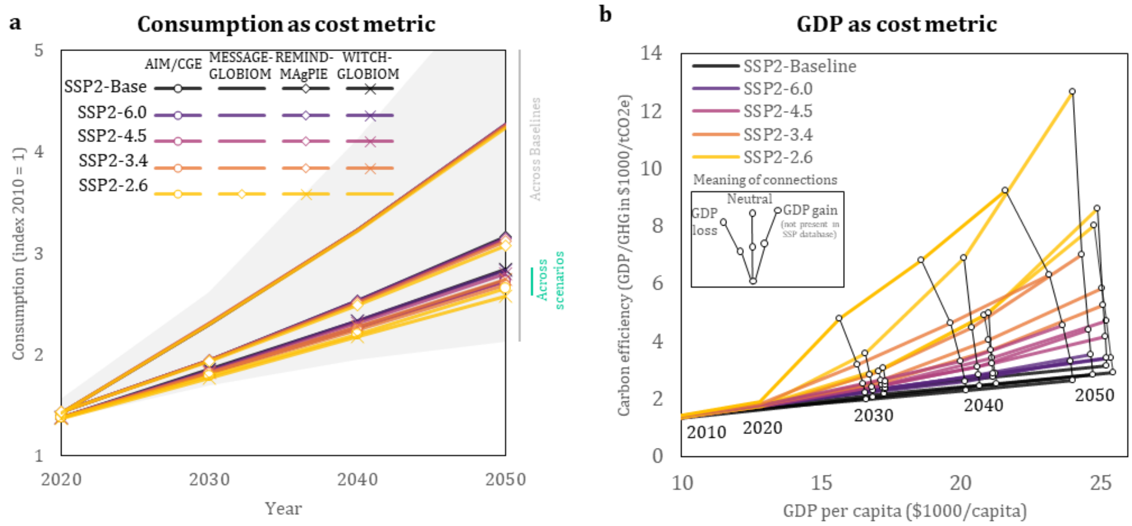


*Figure 2 – **Mitigation costs in a growing economy. a,** Consumption growth variation across baselines, models and mitigation scenarios. Grey wedge is range of consumption growth across all SSP Baselines from SSP database. **b**, Producing more (GDP) with less (GHG emissions). Model results from four Integrated Assessment Models (IAMs) with endogenous GDP estimation for scenarios that combine middle-of-the-road socioeconomic assumptions (SSP2) with five different levels of climate change mitigation stringency. Thin black lines in panel b indicate GDP per capita-mitigation frontiers for milestone years for each model. Perfectly vertical lines would indicate no reduction in GDP per capita. Negative slopes indicate decreasing GDP per capita with growing mitigation effort. See Section S4 for variations of **b** using other SSP scenarios. Data source: SSP database[54].*

What is not evident in the panels in Figure 2 is how this growing wealth, as well as the mitigation costs, are distributed across geographies, income classes and socio-economic groups. In fact, moderate GDP changes hide deep transformations in economic structures that may lead to regionally and sectorally differentiated economic decline or prosperity[8,55,56]. Mitigation creates new low-carbon value chains ("sunrise" industries) and phases out old carbon-intensive industries and occupations ("sunset" industries). For example, levels of stranded fossil fuel assets will vary by region and by commodity[57], with the lowest-cost producers potentially gaining or maintaining market share while higher cost producers see sunset industries diminish or disappear completely[58]. While there is potential for well-designed policy to reduce undesired effects of mitigation, ill-designed transitions can cause rapid repricing of assets and economic uncertainty, raising the risks of financial instability[25] and social unrest[59]. For instance, coal phase-out raises acute issues of just transition for coal-dependent communities[60,61]. Similarly, the avoided climate damages would be different across geographies and income-classes. Climate action can potentially benefit vulnerable households that may be disproportionally impacted by climate change, if mitigation policies and complementary measures seek to strengthen the resilience of low-income households, reduce energy poverty and enhance social protection simultaneously[62,63]. Failing to do so would further exacerbate the challenges to adapt to climate change for vulnerable socio-economic groups and regions[64]. Also, emissions taxation has important distributive effects[65]. Revenues from emissions taxation can be used to lessen its regressive distributional impacts or even turn the policy into a progressive policy, reducing inequality or improving wellbeing of lower income households [66–69].

In addition to highlighting the small relative consumption losses overall, IPCC assessments could put more emphasis on distributional issues of climate policies and corresponding complementary policy measures that ensure an equitable transition to a low-carbon economy. Regional cost estimates are presented in AR5 Chapter 6[8] but, due to political sensitivity, were excluded from the Summary for Policy Makers (SPM). Scenarios exploring how to mitigate distributional inequities could help increase ambition in the revised Nationally Determined Contributions. Furthermore, clearly acknowledging the caveats of GDP as a mitigation cost metric, and reporting broader and additional welfare metrics such as distribution of income will enable a science-based societal debate and the design of appropriate complementary measures to ensure a fair transition.

Imperfections define reality

Climate action in line with the Paris Agreement will require structural changes to the economy[70–72]. Rather than isolated climate policies, this deep transition will need to be supported by policy *packages* containing sector-specific instruments which can, and arguably should, be designed in coordinated ways that enhance cross-sectoral synergies and minimise trade-offs. Such packages can concomitantly reduce emissions and improve economic efficiency by enhancing policy coordination across sectors and geographies; lifting information barriers and removing incumbent power; ensuring a stable climate for long-run investments through credible government signals; or enabling innovators to be rewarded for socialised benefits of their investments. A broad-based policy package approach can help accelerate the transition to meet ambitious societal objectives[73–75]. This transition also likely requires a full quiver of fiscal, financial and monetary policy instruments to be deployed to enable a favourable financial environment to unlock required investments across geographies and sectors[76]. It stands to reason then that such far-reaching policy packages should be aimed at also removing existing inefficiencies by including pro-development measures that ensure broader human welfare gains.

The reference scenario against which the costs of climate action are calculated is by design reflecting the assumptions and concepts underlying the modelling approach with which it was created. Currently, models that assume well-functioning economic systems dominate the literature (although there are notable exceptions[77–82]). Assumptions of such 'first-best' or idealised economies, often include that agents make rational choices under perfect information, markets operate under perfect competition (no market power), and goods, capital and workers move across sectors of the economy without transaction costs[11,83]. Clearly, this represents an overly stylized view of the real-world economy, which is characterised by biases and imperfections in information, competition and access to capital[84], as well as by limitations to the flow of goods, capital[77] and labour, across regions, sectors and social classes. Such imperfections are often referred to as market failures[85–87].

These imperfections imply resources are allocated in sub-optimal ways by the economy. This keeps the economy from operating at its production frontier and may lead to a misallocation of capital from its most productive uses as well as persistent unemployment. However, typically these market failures are not explicitly represented in studies estimating the macro-economic costs of climate policy. When limits on greenhouse gas emissions are introduced into such an idealised reference economy, model simulations will invariably result in economic losses. The constraint restricts the choice set of economic agents (e.g. no fossil fuel use in a production process) and the benefits of mitigation are not accounted for. Hence, models that take a simplified first-best economy – without distortions, imperfections and market failures – as a starting point of their analysis tend to limit the potential range of outcomes on both ends. On the one hand, they exclude the economic gains which would come from correcting the market failures and imperfectons. On the other, they do not include the economic losses which would come if the climate transition would not resolve economic inefficiencies, or even exacerbate them by for example further concentrating market power. In this sense, the current estimates span a narrow range of economic outcomes, which will depend on the way in which climate policies will be implemented. Capturing and quantifying a broad set of behavioural imperfections and market failures, however, is a daunting task, while a stylised or simplified representation of the economy makes it possible to model the transformation and to explain the results transparently. More research effort is needed to explore the size and sign of the change in economic activity that results from including second-best elements into a modelling framework.

Useful policy insights can be provided by including such channels in models and scenarios, which are useful tools with which to explore the interlinkages and ramifications of policy packages. Overlooking these opportunities in models that intend to inform policies may come at the risk of mitigation costs estimates that are biased high, and potentially diminishing both societal support for strong climate action and the identification of win-win opportunities. Conversely, it can also highlight transition assistance costs that add to the mitigation burden. Reskilling workers, re-industrialising states that lose their vital fossil fuel revenues, and other such policies will take coordinated effort and additional resources.

Comparing to appropriate benchmarks

A no-climate policy world does not exist, and assuming away all existing policies is neither trivial nor desirable. A reference that ignores already adopted climate policies artificially inflates the divergence with ambitious pathways[12,88,89], driving up the mitigation cost. Recent research[89,90] shows that current policies are compatible with global temperature increases that are lower than projected warming in scenarios that neglect any existing climate policy measures. Starting from a reference scenario that represents a plausible future emissions pathway, including technological progress and climate impacts, is a first step at ensuring mitigation cost estimates are realistic. The next step is designing a reference scenario accounting for economic imperfections that can be potentially resolved with smart climate policy packages.

When imperfections and multiple externalities are introduced in a model-based assessment and the implications studied explicitly (a situation referred to as a "second-best" setting), well-designed policy interventions could enhance economic efficiency and generate positive economic impacts[91]. We next explore some of the relevant mechanisms by which this can be done. However, including real-world features does not automatically imply that mitigations costs will be lower. Accounting for some types of market failures in models may actually work in the opposite direction, since some mechanisms may raise estimates of the costs of climate action, as is the case of potential short- to medium-run frictions in the transition to a low-carbon economy. For example, frictions to reallocation of workers from one sector to another or other rigidities in labour markets have been found to increase cost estimates if left unresolved[78,92]. Conversely, by explicitly including such dynamics, it becomes possible to assess how specific compensatory policies can alleviate these burdens[59,80,92–94].

Capturing real-world features

Explicitly modelling the key channels affecting the cost of mitigation will improve our understanding of the implications of any effective set of climate policy measures. We identify and review five categories of institutional or behavioural imperfections, instances in which the idealized world view often adopted in modelling exercises (first-best) behaves markedly and often persistently differently from reality (second-best). These categories include co-benefits, behavioural imperfections, knowledge spill-overs, investment and finance, and pre-existing distortions (we summarise them here and provide a detailed discussion in Section S5).

In addition to avoided climate impacts, well-designed climate policies can result in **co-benefits** such as reduced air pollution. These synergies and co-benefits may offset costs and potentially deliver net benefits (no-regret potentials in SAR[7]). Moreover, they are desirable from a welfare standpoint and should be considered in drafting and evaluation of policy measures, whether in monetised form[95,96] or not; for example, simply as health outcomes[97–99].

Humans often **behave** in ways detrimental to our health, well-being and pocketbooks, outright irrationally in some instances and boundedly rationally in others. For example, food and energy consumption may deviate from the optimum for welfare maximisation due to habit formation and myopic views. A first-best reference based on rational behaviour implies optimal decision-making for energy and health, leaving no margin for welfare gains from climate policies that spur energy efficiency or nudge towards healthier diets. However, it is challenging to steer decisions towards energy efficiency and healthy diets, mitigation options typically considered very cheap in IAMs. Importantly, bringing this kind of behavioural bias into the analysis has implications for the optimal mix of policy instruments[100]. As many existing models and scenarios rely on (implicit) carbon pricing as the primary policy lever, they do not represent the opportunities of alternative instruments explicitly.

First-best references also imply optimal R&D investment levels to produce **innovation** in new technologies and market design. But innovators may not fully capture the benefits of their innovation since knowledge spillovers allow other agents to benefit from the new knowledge and capture some of the benefits (known as positive externalities). Second-best reference scenarios may imply low R&D, providing an opportunity for climate policy packages to address this imperfection through incentives.

On finance and investment, first-best references or scenarios that assume optimal allocation of resources at all times are ill-equipped to explore policies that address capital under-allocation, a situation we are currently living in[101–103] as indicated by negative interest rates. This was true even before COVID-19 and is relevant for stimulus package discussions. Some models operate under equilibrium paradigms which limit annual investments to the amount of savings available each year. In reality, fiscal and monetary policies such as quantitative easing aimed to stimulate the economy inject cash beyond available savings and increase available funds for debt-financing through loans[104,105]. In times of low growth, low-interest rates and apparent **underinvestment**, taxing carbon emissions rather than capital can increase economic efficiency[106].

Finally, pre-existing **distortions** are often the result of inefficient taxation and some constituencies with particularly inefficient tax systems can leverage climate policy to deliver ("double-dividends"[107,108] and improve economic performance by using revenues from carbon taxation to, for example, remove labour market imperfections by lowering labour taxes[80] or raising the efficiency of other types of taxes (see Section S7 for a discussion on EU's energy excise tax reform).

The assessment of policy design comes from the ability to compare costs and benefits – and how they are distributed across sectors, households and regions – between scenarios that differ in terms of instrument choice, policy coverage and speed of implementation. An encompassing approach to climate policy may provide the leverage and momentum to address some of these imperfections through institutional reform and broad policy packages. Studies that start from a second-best situation explicitly incorporating these channels, can identify positive economic outcomes and inform policy design. In addition, these mechanisms affect GDP through Total Factor Productivity (TFP). TFP is an exogenous input to many models because endogenizing it involves complexities and uncertainties, but doing so can provide policy-relevant insights (See Box 2: Endogenising TFP).

Although we do not enter into a detailed discussion here, shortcomings of GDP as a metric for progress have widely been acknowledged (including in AR5[55]), along with potential alternatives [109–111]. Recent work suggests that decreasing consumption [112], such as reductions in final energy demand [113] and food waste [114], can form an integral part of the climate solution with desirable features from a societal point of view. The narrower concept of economic activity is still used as a measure of impact in policy documents such as, for example, the UK Climate Change Commission's report on reaching net-zero[5]. While economic growth and the associated living standards and fiscal revenues remain important, there are other considerations that should weigh in on policy assessment. As noted, GDP is a poor metric for welfare, and the underlying structure of the economic flows that make up GDP should be unpacked and assessed for their desirability or alignment with broader policy objectives. Although there are tensions between the concepts of green growth and degrowth, there are also synergies[115], suggesting climate action can benefit from wider scope policies[116]. When extending the concept of GDP to properly account for the environment, evidence from the US suggests that environmental regulation brings macroeconomic benefits, not costs[117,118]. Recent evidence from Europe indicates that the direct link between air pollution and GDP growth may be larger than thought previously[119]. Conversely, GDP is sometimes linked to welfare-reducing activities, creating opportunities to decouple GDP from resource use and GHG emissions[120].

Net welfare is what matters

The mechanisms explored above map onto three transmission channels for the impacts of mitigation action on economic activity: avoided impacts from climate change; co-benefits of mitigation measures; and resolution of socio-economic distortions and imperfections (including behavioural imperfections, knowledge spill-overs, and suboptimal investment and finance). This paper argues that measures feeding into these channels are expected to increase economic activity and welfare, potentially offsetting mitigation costs such that net gains arise. It is not possible to say *ex ante* whether the benefits exceed the costs or vice-versa, that is, whether mitigation action will lead to higher or lower economic activity. It will depend on the measures being analysed and the context into which new policies are introduced.

Accounting for uncertainties, Figure 3 is a conceptual representation of the effect on aggregate economic activity through each channel. Rather than absolute values, the arrows indicate the direction of change resulting from these effects. Mitigation applied to a first-best reference that does not account for avoided damages, co-benefits, underinvestment and other imperfections in the economic system invariably leads to losses to the aggregate economy (grey arrow pointing down). These losses can be offset by the three transmission channels. The first two involve including avoided impacts and co-benefits (green and blue arrows pointing up). The third channel involves implementing second-best features into the reference scenario that are corrected via policy packages (orange arrows pointing up). Insight on each of these four arrows can inform policy design and investment decisions. Depending on how successfully the policy packages resolve reference scenario imperfections, the larger the positive contributions of the green, blue and orange arrows. If the magnitude of these gains is larger than the direct losses typically captured by economic models, the scenario results in welfare gains or higher economic activity.

Models that explicitly represent these channels can provide deeper insight to inform policy decisions. Quantifying each of the channels individually and transparently may help identifying policy options that justify lower temperature targets, earlier mitigation or different combinations of policy instruments (the variations in Figure 3). Although these actions entail costs (e.g. higher short-term costs from earlier mitigation, dark grey tips in variation case), they generate economic benefits that accrue through the three other transmission channels (dark tips on the orange, green and blue arrows).

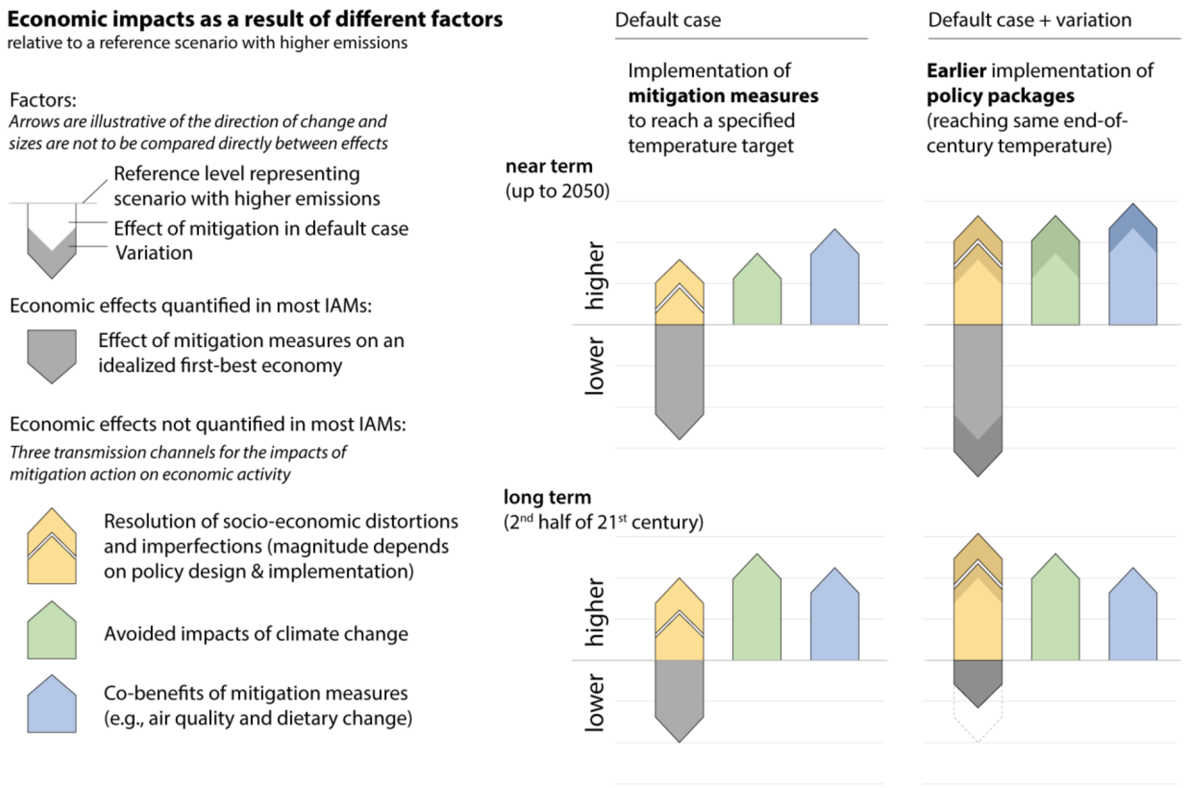


*Figure 3 - **Economic impacts of mitigation action through three transmission channels in the short-term (top row) and long-term (bottom row) and across variations in mitigation timing.** The three channels include avoided climate change impacts (green), co-benefits of the mitigation policies (blue), and the resolution of socioeconomic distortions and imperfections (yellow). Light shading represents the economic impacts through each channel. The additional dark-shaded tips represent the impacts that earlier action may have through each channel (see text).*

If scenarios do not account for any of these channels, this should be clearly acknowledged when providing estimates for costs of mitigation action. Better yet, scenarios can be designed in ways that account for the channels (we provided some examples) or minimise the consequences of excluding them. As mentioned, temperature-clustered scenarios can circumvent the challenges in modelling economic impacts of climate damages, by exploring alternative policy packages that achieve the same temperature outcomes. For example, such a framework could use as benchmark (or base case) a (second-best) scenario that achieves its climate objective via a globally uniform carbon price or emissions cap. This could then serve as the counterfactual to possible policy intervention scenarios including pro-growth measures that, for example, improve resource efficiency, eliminate unfair market power, or use carbon tax revenues to boost employment opportunities, enhance labour mobility by re-skilling workers, or ensure progressivity of a broader tax reform. This way, various policy interventions can be tested to identify economic trade-offs or synergies across potential policy packages and mitigation strategies. As such, a temperature-clustered scenario framework could help focus the policy debate on the appropriate combination of instruments to reach a given emission reduction target effectively.

An important concern for policy making is the net outcome of the costs of action and the benefits that may accrue, including the results of their interactions. However, this is not to say that it is possible to determine a single best policy alternative or temperature target that is free from value judgements or political decisions regarding the distribution of “impacts over time and across individuals when values are heterogeneous"[55]. Still, a reasonable range of cost estimates is useful and should not rule out potential positive outcomes. Ethical considerations of intergenerational justice should also inform the risk appetite towards, for example, large scale tail events that may lead to irreversible changes in the earth system. These considerations can be part of multi-criteria analysis approaches that enable the assessment of conflicting priorities. When facing uncertainty, adaptive decision making allows for dynamic realignment to changing circumstances[121]. Most policies can be amended if their costs are found to be too high, but this does not apply to the climate system (AR5 Synthesis Report, p79[55]).

The cost of mitigation, reloaded

To refine the role of economic analyses of the cost of mitigation in support of policy and the societal debate, we offer three suggestions for future work.

First, and starting immediately, existing and upcoming scenario studies should provide appropriate context and framing of findings, including not only caveats, but also risks and opportunities, surrounding the cost of climate change mitigation, supported by the literature and discussion provided in this very paper. Reallocating economic resources from activities that have undesirable causes (e.g. health care spending due to air pollution-related diseases) or consequences (e.g. global warming induced by fossil fuel subsidies) to productive and sustainable uses will improve welfare outcomes, and modelling frameworks should differentiate accordingly to enable exploration of policy alternatives that maximise the latter. Emphasising the risks associated with inaction places mitigation costs within a context of potential irreversibility of impacts and the more profound consequences for welfare and economic activity. Highlighting opportunities from alternative climate policy outcomes can help guide transition decisions.

In communicating climate policy, the choice of words can skew public opinion[122]. Properly communicating the benefits of climate action and the stakes involved helps dissipate public opposition, as demonstrated for the case of British Columbia, Canada, where carbon revenues were redistributed directly to families via carbon dividend checks[123,124]. Framing the policy as a "carbon dividend" instead of a "carbon tax" allows for an explicit discussion of the benefits of climate action rather than just the costs. This is relevant in current debates around the EU's Green Deal, the USA's Green New Deal, and the inclusion of sustainability criteria in post-COVID19 recovery efforts[125].

Second, a temperature-clustered second-best scenario framework allows exploration of alternative climate policy packages and their associated macroeconomic costs. A scenario protocol could describe an ensemble of 1.5°C or 2°C compatible scenarios with alternative climate policy implementations. These alternatives can be measured against a benchmark scenario with similar temperature outcome that, for example, assumes the immediate introduction of globally uniform, comprehensive carbon prices. Relying only on carbon taxes has significant welfare costs[126], but by enabling explicit exploration of mechanisms that may lead to welfare gains, this framework may help capture the opportunities presented by the deep transformations that a low-carbon transition entails. Importantly, it also paves the way for an open discussion of the limitations of current estimates of macroeconomic costs of mitigation. This framework's central idea is to compare welfare and development outcomes of similar climate trajectories but stemming from different policy packages. It resembles recent proposals[127] in the field of impacts and adaptation, translated to the context of mitigation.

Third, combining various approaches to estimate mitigation costs can provide a more comprehensive view. Different model types each have their strengths; they are complementary tools, but the research community could put more effort in learning from each other[128,129]. In this respect, including relevant insights and tools from financial economics may help to better capture risk and uncertainty[130]. A more diverse modelling landscape with fertilization across different fields could result in improved understanding of the costs of climate change mitigation. Embracing uncertainty in scenario design to explore risks and opportunities [131,132] and endogenizing key parameters can broaden the possibility space [133,134] (See Box 2: Endogenising TFP). Importantly, while diversity is desirable and a lot can be learned from it, the risk that broadening the range of estimates may create confusion, misinterpretation and even distrust, calls for nuanced communication. Empirical work[135] on the propagation of policy effects can provide important input.

Further work on the cost of climate action is important for several reasons. Costs need to be analysed in order to inform smart policy design that strives for effective emission reductions in an efficient manner and with the largest benefits to society. Importantly, the cost of climate policy needs to be acknowledged in order to develop complementary measures that guide vulnerable people and regions in the transition towards a carbon-neutral economy.

The framework proposed here will not invariably reveal that there are net welfare gains from climate mitigation policy. But by not including the mechanisms and channels that could lead to growth, an overly pessimistic picture is sketched, one that suggests irreconcilable trade-offs between climate action and development. This framework rebalances the odds by introducing options to align the climate action narrative with one of increasing welfare and sustainable development. Recovery from the COVID19 recession is an opportunity for policy makers around the world to revive flailing economies through public investments (e.g. in renewable energy) in a time when they are likely to have large positive impacts. We hope the ideas proposed here will contribute to a better understanding of how to use the recovery and climate policy packages to spur growth that is green, inclusive and self-sustaining.

BOX 1: Estimating costs through models

The Second Assessment Report (SAR) emphasized that modelling studies provide insights, such as identifying low-cost opportunities, that are more important than the “specific numerical results of any one analysis” [7]. It highlighted that what matters are net costs, that is, the difference between the required expenditures and the accrued benefits from the structural changes implied in a transition. Subsequent reports have taken an increasingly quantitative approach (Section S1). This evolution comes with the increased importance of a proper framing of numerical estimates.

Understanding critical debates about mitigation costs requires clear definitions of what is meant by costs[7] (Section S2). Four types of cost concepts exist in the climate mitigation literature: technical, sectoral, macroeconomic and welfare costs. These types of costs are not comparable or equivalent. Technical or engineering costs represent the difference in cost between incumbent and new technologies; sectoral costs represent the transition cost for a full sector, say the transport sector, without accounting for broader effects in the rest of the economy; macroeconomic costs are typically measured as a reduction in GDP; and welfare costs may account for factors such as distribution of income, environmental degradation or health outcomes. Different models can provide estimates of different types of costs, depending on their structures. Paltsev & Capros[136] identify cost concepts often used in modelling studies as change in GDP, change in consumption, change in welfare, energy system cost, and area under the marginal abatement cost (MAC) curve. In AR5, the deliberate choice of the consumption loss metric to report estimates of mitigation costs ensured comparability between model outputs. However, this diversity of cost concepts in the IAM literature can lead to inadvertent comparison of unequivalent quantities.

Independently of the metric adopted, costs can be calculated for scenarios that represent varying degrees of ideality in the conditions surrounding the transition. Structural changes resulting from disorderly mitigation actions may lead to transition risks [137] that would unavoidably add to the cost of mitigation. Recent literature explores concerns over how transition costs are distributed across time, regions and societies[138–140]. Such concerns are evident in government reviews of climate policy[141], and an assessment of the new literature will be in the forthcoming IPCC's AR6.

To explore low-carbon transitions, researchers employ mathematical tools to produce numerical pathways integrating the economy, energy, climate and land use sectors. These range from bottom up-energy system models, to computable general equilibrium (CGE) models, to agent based models. For simplicity, we will use the term Integrated Assessment Models (IAMs)[11] here to label this heterogenous set of tools. Although IAMs vary widely in their structure and behaviour[11,83], the majority of IAMs has traditionally represented the results of policies in an idealised economy with perfectly functioning markets (market clearing and profit or individual utility maximisation). In this Perspective we focus on the detailed-process IAMs as opposed to the Cost-Benefit IAMs[11] (CBA-IAMs, Section S3) since the former are most commonly used in IPCC assessments and the estimates we discuss here typically come from such models.

Estimates of the costs of public policies must be measured against some reference scenario which does not include the policies in question – that is, they are calculated as the difference between a counterfactual world without climate policy and one where climate policies and the related production, consumption and investment choices take place[12]. This counterfactual – interchangeably referred to as baseline, reference, benchmark or business-as-usual – has long been identified as a key determinant for the magnitude and even sign of estimated costs of mitigation scenarios (e.g. see IPCC SAR, Hourcade et al. [7]). Therefore, defining a realistic reference is essential to contextualize estimates of the cost of climate policy scenarios appropriately. As already recognised in Grant et al[12] several countries are likely to remain in a paradigm where they will need to keep reassessing the economy-wide cost of mitigation to different emissions levels, for example as they seek to ratchet their NDCs. Currently, these reference scenarios do not consider important determinants of net costs[12].

*** END OF BOX 1***

BOX 2: Endogenising TFP

An important driver of economic growth is Total Factor Productivity (TFP) growth. TFP is measured as the ratio of aggregate output (GDP) to inputs like labour (L) and capital (K) (the production factors). TFP growth is factor neutral, that is it increases the productivity of labour and capital (and other factors of production, such as human capital) in proportional ways. Examples of factors driving TFP growth are technological change and innovation, (e.g. ICT), education and human capital, and quality of institutions.

Input factors and their productivity are impacted by climate change in different ways, intermediated by the role of behaviour, policy, markets and many other factors. Arguably, the radical structural changes to the economy required to achieve climate neutrality (as well as the radical changes brought about by climate impacts in those scenarios) will affect productivity of specific and generic factors. In particular, innovation and the introduction of new, more efficient, products and processes will affect total factor productivity, possibly leading to higher aggregate output from the same level of inputs, or direct innovation towards certain factors[142]. A combination of demand-pull forces, learning and scaling, and the cumulative nature of innovation can lead to virtuous cycles that are path-dependent and endogenous to the process (Grubb et al 2021). Conversely, unabated climate change can be a drag on TFP through downward pressure on factor productivity, decreasing aggregate output [15,143].

Most (but not all) models used in climate policy assessment assume exogenous TFP growth, meaning changes in aggregate output are independent of the structural changes projected by the scenario. In addition, in many cases the exogenous TFP growth assumptions are the same across reference and mitigation scenarios. A mitigation cost estimate arising from this set up is inaccurate since it assumes TFP is unchanged from the reference, even though the technological mix, the climate impacts, and behaviours are likely to be radically different. This constrains the capacity of models to compute the economic consequences of climate policies.

This points to an opportunity for future research or model development to explore various approaches for endogenizing innovation and TFP. Endogenous growth models have been developed more than 30 year ago and have led to the award of the 2018 Nobel prize in economics[144]. For general equilibrium models, Baccianti and Löschel[145] provide a review and examples of methods used while Hughes & Narayan[146] report on challenges and approaches for endogenizing an aggregate indicator like TFP. The complexities and uncertainties, especially for model calibration, involved in endogenizing growth need to be acknowledged, making this a log-term research agenda. Statistically, identifying the determinants of TFP growth has been a challenge. However, certain factors of productivity enhancement such as education and Schumpeterian innovation have been included in IAMs and agent based models[147,148]. In addition, TFP changes "feed forward to economic growth and on to the various subsystems that indirectly or directly drive those same variables affecting it" [146]. This circularity relates to the endogeneity of growth and the path-dependence of innovation and investments.

Another issue is that some drivers of TFP change are not related to economic structure. Technology, in particular, may evolve regardless of policy changes once market forces react to initial innovation stimuli. Diffusion of new products and processes follow technological and social learning dynamics that can be mutually reinforcing [149–152]. The combination of these forces drives TFP changes which are challenging to model but can provide useful insights [149,152,153]. In sum, there is much to be done to holistically incorporate TFP considerations in mitigation (and reference) scenarios.

END OF BOX 2

Author contributions

A.C.K. coordinated, and all authors contributed to the study design and drafting of the manuscript. A.C.K. and T.V. led the drafting of specific sections of the manuscript. A.C.K., T.V., J.R. V.B. and C.G. prepared the figures.

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Competing interests

The authors declare no competing interests.

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