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Article (Published version) (Refereed)

Original citation:
Dietz, Simon and Bowen, Alex and Doda, Baran and Gambhir, Ajay and Warren, Rachel (2018) The economics of 1.5°C climate change. Annual Review of Environment and Resources, 43 (1). pp. 455-480. ISSN 1545-2050
DOI: 10.1146/annurev-environ-102017-025817

ANNUAL REVIEWS

Annual Review of Environment and Resources

The Economics of 1.5°C Climate Change

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Annu. Rev. Environ. Resour. 2018. 43:455–80

First published as a Review in Advance on September 5, 2018

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-102017-025817

Keywords

1.5°C target, carbon price, climate change, cost-benefit analysis, deep decarbonization, Paris Agreement

Abstract

The economic case for limiting warming to 1.5°C is unclear, due to manifold uncertainties. However, it cannot be ruled out that the 1.5°C target passes a cost-benefit test. Costs are almost certainly high: The median global carbon price in 1.5°C scenarios implemented by various energy models is more than US$100 per metric ton of CO_2 in 2020, for example. Benefits estimates range from much lower than this to much higher. Some of these uncertainties may reduce in the future, raising the question of how to hedge in the near term. Maintaining an option on limiting warming to 1.5°C means targeting it now. Setting off with higher emissions will make 1.5°C unattainable quickly without recourse to expensive large-scale carbon dioxide removal (CDR), or solar radiation management (SRM), which can be cheap but poses ambiguous risks society seems unwilling to take. Carbon pricing could reduce mitigation costs substantially compared with ramping up the current patchwork of regulatory instruments. Nonetheless, a mix of policies is justified and technology-specific approaches may be required. It is particularly important to step up mitigation finance to developing countries, where emissions abatement is relatively cheap.

Contents

1. INTRODUCTION

The 2015 Paris Agreement, in pursuit of the objectives of the United Nations Framework Convention on Climate Change (UNFCCC), aimed toward "[h]olding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels" (Article 2; see **https://sustainabledevelopment.un.org/frameworks/parisagreement**). Previously, in Copenhagen in 2009 and Cancun in 2010, the agreement was simply to hold warming below 2°C; as such, the Paris Agreement implies an increase in ambition, albeit the wording affords 1.5°C aspirational status.

From an economist's point of view, there is an obvious question to ask of the 1.5°C warming target, in relation to other warming targets: Is it efficient, in the sense of increasing welfare? In more straightforward terms, will the benefits to society of limiting warming to 1.5°C exceed the costs? This is the primary focus of our article. However, we should point out that there are other approaches to evaluating the 1.5°C target that could substitute for, or complement, cost-benefit analysis (CBA), including multi-criteria decision analysis, the precautionary principle, and human rights, to name but a few (see 1 for a review in the context of climate change).

It is not easy to provide a clear answer to the question of whether the benefits of the 1.5°C target exceed the costs, for two basic reasons. The first is uncertainty about the costs and benefits of mitigating climate change (2–4). This uncertainty is particularly acute when it comes to evaluating the 1.5°C target. Estimates of the cost of meeting the 1.5°C target are just beginning to emerge. And whether one tackles the question by estimating the net benefits of allowing a further 0.5°C warming beyond the 1°C that the planet has already warmed, or by estimating the net benefits of reducing warming by 0.5°C below 2°C, the signal is likely to be small in relation to the noise of the climate system (5)—and the economy for that matter. The second reason is that CBA of climate change is contentious. The opposing views of Stern (6) and Nordhaus (7) exemplify this well, although the literature has become large and the debating points more numerous (8). CBA of climate change requires a series of methodological choices to be made, some of which have an ethical or otherwise philosophical character (9, 10), where economics can provide limited guidance.

Therefore, we mostly refrain from undertaking a formal CBA of the 1.5°C target, using a cost-benefit integrated assessment model (IAM) (11–16). Rather, we use the basic principles of CBA to structure this article into, firstly, an assessment of the benefits of limiting warming to 1.5°C, usually in natural rather than monetary units, and, secondly, an assessment of the costs of doing so, where monetary units are more straightforward. The reference point is typically the 2°C target.

Nonetheless, some of the contentious methodological choices in CBA are still relevant, because they determine the weight that we place on different kinds of benefits and costs, and different benefits/costs occurring in different places, at different times and with different probabilities. They are inescapable, whether or not the comparison of benefits and costs is formalized.

The most famous debate is probably about the appropriate discount rate to apply to future benefits/costs (6, 17, 18). A higher discount rate favors smaller reductions in greenhouse gas (GHG) emissions by placing lower weight on future benefits/costs. Although the costs of reducing emissions tend to be front-loaded, the benefits accrue mainly in the future, due to the long residence time of CO_2 in the atmosphere. Therefore, a high discount rate would count against the 1.5°C target.

Another choice is how to aggregate benefits/costs accruing to individuals living in different places. It may be that a relatively small proportion of the world's population would enjoy large net benefits from limiting warming to 1.5°C. This is of course an empirical question that the remainder of the article tackles, but some aspects of the climate negotiations indeed suggest it; the 1.5°C target was advocated above all by small island developing states (SIDS) (19, 20). Insofar as a policy provides concentrated net benefits to relatively few, these will tend to be outweighed by net costs to the majority. However, recently, "prioritarian" approaches have been proposed (21–23), which place greater weight on those with lower levels of utility/wellbeing, itself proportional to income.[1] If these individuals enjoy large net benefits from limiting warming to 1.5°C, the cost-benefit logic could be overturned.

A third methodological choice is how to treat uncertainty. There are at least two facets to this large topic. One is the prospect of learning about benefits/costs and reducing uncertainty over time. Could we not learn then act, rather than acting before learning? This boils down to what the appropriate near-term hedging strategy is with respect to GHG emissions, while we wait to find out more about benefits/costs. Such a strategy will generally maintain option value by avoiding making irreversible decisions (24, 25), but both GHG emissions and investments to reduce them are partly irreversible (26). Consequently, the evidence on whether it is better to act then learn or vice versa is ambiguous (27, 28), but if GHG emissions significantly increase the risk of catastrophic climate impacts, then the hedging strategy is likely to entail deep emissions cuts in the near term (29, 30). Alternatively, if we pose the problem in terms of which of a range of temperature targets to hit (31), and that range includes 1.5°C, then irreversibility may give us no choice but to aim toward 1.5°C; otherwise, the possibility will be permanently eliminated, save for large-scale carbon dioxide removal (CDR) or solar radiation management (SRM).

The other aspect of uncertainty is whether it can be reduced to risk, i.e., whether each possible future state of the world can be assigned a unique, precise probability. Most research on acting versus learning does so. However, it has been argued that risk is not a good characterization of our knowledge about climate change; rather, we have at best imprecise estimates of these probabilities, which is uncertainty in the Knightian sense (32) and is often described in economics as a situation of ambiguity (33, 34). Recent contributions stress that this is an additional justification for strong climate policy (35–37). The reason is that ambiguity about the impacts of GHG emissions increases ambiguity about future incomes, and ambiguity-averse decision makers would prefer to reduce this uncertainty, which appears to be achieved by cutting GHG emissions. One of the primary sources of ambiguity about the impacts of GHG emissions is the possible existence of tipping

[1]A consistent CBA would also place more weight on monetary benefits/costs accruing to individuals on low incomes, through the assumption of diminishing marginal utility of income. That is, an extra dollar is worth more, the lower one's income is. Diminishing marginal utility is also a justification for discounting; hence, this approach is "consistent" in the sense that it treats as the same comparisons over time and space.

elements in the climate system (38, 39). Insofar as limiting warming to 1.5°C avoids triggering damaging, large-scale climate discontinuities, ambiguity aversion may favor the 1.5°C target. Of course, this is also an empirical question we address in the review. In addition, ambiguity aversion is particularly relevant when considering the benefits/costs of relying on SRM to limit warming to 1.5°C.

Lastly, limiting warming to 1.5°C might provide particularly large benefits to natural ecosystems. Estimating the value of these benefits in terms of social welfare is notoriously difficult, as markets, which could be used to reveal the strength of preferences via prices, are usually missing. Such benefits are beyond the scope of CBA as originally envisaged, although there is a large body of work in environmental valuation that tries to estimate them (40). Recent work has also emphasized that if natural ecosystem services become relatively scarce in comparison with material goods, then conserving them via limiting warming should be afforded higher value (41, 42).

The rest of the article is structured as follows. Sections 2 and 3 survey the literature on the benefits and costs, respectively, of the 1.5°C target. Limiting warming to just 1.5°C raises questions about the desirability of geo-engineering technologies (i.e., CDR and SRM). Section 4 discusses these. Limiting warming to 1.5°C also poses many challenging questions of public policy; economics has some important insights to contribute, which are the subject of Section 5. Section 6 concludes by pulling together the analyses of benefits/costs.

2. THE BENEFITS OF LIMITING WARMING TO 1.5°C

This section focuses on the benefits of limiting warming to 1.5°C compared with 2°C, in both human systems and ecosystems. We consider both managed and unmanaged ecosystems. An emerging literature is beginning to quantify these benefits in a variety of metrics, using deterministic models that often account for uncertainty in regional climate-change projections. The focus here is on the global scale. We highlight some key regional benefits, but our intention is not to provide a comprehensive regional analysis, which is in any case infeasible at present, given the available literature. This review does not include the possible environmental side effects of mitigation itself. For example, large-scale bioenergy with carbon capture and storage (BECCS), based on dedicated secondary biofuel plantations, could lead to further exceedance of the Earth's planetary boundaries for biogeochemical flows, biosphere integrity, and land use and would be close to exceeding the planetary boundary for freshwater use (43).[2]

Recent studies using different approaches project that the Arctic Ocean will become ice-free in the summer under 2°C warming, whereas if warming is limited to 1.5°C then ice will persist through the summer in most years (44–47). This has important implications for Inuit culture and species such as polar bears, walruses, and seabirds, which are dependent on sea ice for their survival (48). Limiting warming to 1.5°C would also reduce the positive temperature feedback that would come from changing albedo associated with reduced ice extent. These studies improve on earlier projections of Arctic sea ice extent, which were inconsistent with recent observations of declining summer sea ice (49).

Limiting warming to 1.5°C would also avoid the melting of an estimated 2 million km^2 of permafrost, relative to 2°C (50). Thus, it would significantly reduce damages to Arctic ecosystems, buildings, and infrastructure (48), as well as avoid significant releases of carbon to the atmosphere, which would further accelerate warming otherwise (51).

[2]The projected impacts here are due to climate change alone and do not consider changes in land use. However, they generally do account for projected increases in population.

The risk of triggering irreversible melting of the Greenland or Antarctic ice sheets, key tipping points in the global climate system, is lower under 1.5°C warming than 2°C, but the literature cannot definitively say whether such melting would be triggered at either level of warming. For instance, the trigger point for the Greenland ice sheet is thought to lie between 0.8°C and 3.2°C (52, 53). Reducing these risks would lower the rate of sea level rise in the near term, as well as the future magnitude of sea level rise over the next several millennia. Complete melting of both ice sheets is projected to result in an eventual sea level rise of 18 m.

Sea level rise in 2100 is projected to be approximately 0.1 m less and 30% slower (4.0–4.6 mm/year compared with 5.6 mm/year) if warming is constrained to 1.5°C compared with 2°C (46, 54–56), with a corresponding reduction in the global area of land lost to inundation (an estimated 87,000 km^2 under 2°C, compared with 73,000 km^2 under 1.5°C). In turn this is estimated to reduce the number of people exposed to coastal flooding annually by 5 million by 2050 [including 40,000 fewer in SIDS (55)] and 8 million by 2100 (57). In particular, the frequency of coastal floods in the Eastern United States and in Europe is projected to be approximately 50% lower under 1.5°C compared with 2°C (55). Projections also discern lower flood risk in the vulnerable Ganges-Brahmaputra-Meghna delta by the 2040s on a 1.5°C pathway (58).

The 30% slower rate of sea level rise associated with 1.5°C warming significantly reduces losses of natural wetlands and human systems to the sea, because natural sedimentation rates are able to offset more of the sea level rise. The projected rate of sea level rise is the factor that determines the rate of loss of saltmarshes: Approximately 60% loss of global saltmarsh has been projected (59) for a rate of sea level rise of 4.4 mm/year. Avoiding faster sea level rise associated with 2°C warming is thus projected to be critical for preserving saltmarsh globally, as well as reducing the risk of mangrove losses. Both saltmarsh and mangroves protect coastlines from the damaging effects of storm surges.

Under 1.5°C warming, the risks to coral reefs are already very high, with an estimated 90% of reefs potentially at risk by 2050 (albeit allowing some recovery to ~70% persistence by 2100). In contrast, it is projected that ~99% of reefs will be eliminated by 2100 under 2°C warming (56, 60). Ocean acidification would be lower under 1.5°C warming, reducing risks to pteropods and bivalves, as well as coral reefs. More generally, limiting warming to 1.5°C would also reduce risks to krill and fish. Risks to low-latitude fisheries due to climate change are already significant, and Cheung et al. (61) estimated that the potential global marine fishery catch will decline by more than 3 million metric tons per additional degree of warming. Lotze et al. (62) estimate corresponding declines of 5% in global fish biomass and fisheries production per degree of warming. Taken together, limiting warming to 1.5°C compared with 2°C would reduce the risks to the organisms underpinning the marine food chain and upon which the survival of cetaceans, seabirds, fisheries, and aquaculture depend.

Global and regional studies indicate substantially lower risks of temperature-related mortality under 1.5°C warming compared with 2°C (63, 64). The geographical area exposed to heat-stress-related risks is also projected to be smaller (65). Human exposure to heat waves in the Shared Socioeconomic Pathway scenario 2 (SSP2) would be reduced by a mean of 62% (range 61–63%) by 2100 (66). These benefits are larger than the disbenefits associated with reductions in cold-related mortality. Worker productivity is projected to be reduced more and more with increased warming (67), particularly in Southeast Asia. Several vector-borne diseases are expected to expand geographically as the planet warms, including dengue fever and Lyme disease (68, 69). The distribution of other vector-borne diseases, such as malaria, is projected to change, with risk increasing in some areas and decreasing in others (57).

Several studies that quantify impacts on water resources under 1.5°C warming find significant benefits relative to 2°C. Extensive benefits are projected for half the terrestrial land surface that is drylands, in terms of avoiding reduced runoff (70). With 2°C global warming, aridification beyond what is expected due to natural climate variability is projected to emerge in an estimated 24–32% of the global land area. Under 1.5°C global warming, the area affected would be reduced by approximately two-thirds (71). Other examples of quantified global-scale benefits in 2100 include 180–274 million fewer people exposed to an increase in water scarcity (72) [a related study estimates this to be a reduction from 8% to 4% of the global population exposed, with greater than 50% confidence (73)] and a 25% reduction in freshwater stress in SIDS (74). By the end of the century, drought exposure is also projected to be reduced by an estimated 39% (range 36–51%) globally (66), with extreme drought exposure reduced by an estimated 25% (57), the greatest benefits being in the Mediterranean, Southern Africa, and Northeast Brazil (75–77). In the Mediterranean, water availability is projected to fall by 17% (range 8–28%) under 2°C warming, but by only 9% (range 4.5–15.5%) under 1.5°C warming (56). Declining water quality can often accompany declines in streamflow, leading to adverse ecological effects.

As the planet warms, it is projected that some regions will experience decreases in precipitation while others experience increases, with more of the rain falling in extreme precipitation events, increasing the risk of flooding. At 1.5°C warming, changes in annual stream flow exceeding 10% are estimated to affect 15% of the global land area, compared with 27% at 2°C (75). Limiting warming to 1.5°C is also projected to reduce flood risk at the global scale. It has been estimated that 1.5°C warming will result in a 100% increase in the global population exposed to fluvial flood risk, compared with 170% under 2°C, assuming constant population (78). Other studies suggest that if warming is constrained to 1.5°C rather than 2°C, the population exposed to fluvial flood risk by 2100 will be reduced by 36–46% (66) or 55–62% (57).[3] The global land area exposed to increases in 7-day high flows would be reduced from 21% to 11% (75).

Climate change is projected to change the geographical distribution of major terrestrial biomes and individual species. Limiting warming to 1.5°C may halve the number of plants and animals that will lose more than half their range, compared with 2°C, and it may reduce by two-thirds the number of insects that will lose more than half their range, again compared with 2°C (79). Limiting warming to 1.5°C would also reduce biome shifts (80), with 13% (range 8–20%) of biomes transforming at 2.5°C warming, but only 4% (range 2–7%) doing so at 1.0°C, suggesting 7–8% may be transformed at 1.5°C. The slower rates of regional climate change associated with 1.5°C pathways would also allow ecosystems and species, in particular mammals, birds, and some insects such as butterflies, a greater chance to adapt through natural processes of dispersal (81). Warming has already increased fire frequency and is projected to progressively increase fire risk (82) as global temperatures rise to 1.2°C and beyond, including in North America (83). Increased fire risk, in combination with increases in storminess and the geographic spread of pests and diseases, increases the risk of forest dieback. Limiting warming would also reduce the potential for climatic mismatch between predators and their prey, or plants and their pollinators (81), resulting in a greater proportion of terrestrial ecosystem functioning and services being maintained under 1.5°C compared with 2°C. Risks to terrestrial biodiversity hotspots, including the Fynbos, Namib-Karoo-Karooveld, Madagascar, African Rift Lakes, and Coastal East Africa (79, 84), decrease strongly as warming is reduced. An almost linear relationship between warming and species extirpation risks in plants and animals has been found between 2°C and 4°C warming. Hence, risks of extirpation, and potentially therefore extinction, would be expected to be lower if warming is limited to 1.5°C rather than 2°C. Risks of the commitment of species to extinction have previously been shown to increase with warming (85).

[3] Both studies allow for increases in population using SSP2, but they use different hydrological models.

Climate change is already affecting crop yields, with more negative impacts than positive ones, and with the positive impacts being predominantly at high latitudes (86). As the climate warms to 1.5°C and 2°C, the number of negative impacts is expected to rise, and to become predominant in most world regions, although positive effects could still be seen in some regions if CO_2 fertilization occurs (87, 88). However, the CO_2 fertilization effect is very uncertain and may be offset by declines in the protein content of crops, or damage from tropospheric ozone (86). The impacts are projected to be greatest in tropical regions, where crops are grown closer to their thermal limits. In particular, limiting warming to 1.5°C compared with 2°C is projected to lower the risks to crop production in Sub-Saharan Africa, West Africa, Southeast Asia, and North, Central, and South America (56, 57, 89), including low-income countries at low latitudes (90). In particular, maize impacts are projected to be widespread, and limiting warming to 1.5°C would be beneficial for maize grown in drylands, which occupy half the terrestrial land surface (70).

Overall, limiting warming to 1.5°C compared with 2°C would have significant benefits in both human and natural systems, including both terrestrial and marine ecosystems and the services they provide. In particular, it would be expected to retain Arctic summer sea ice, protect 2 million km^2 of permafrost, allow some coral reefs to survive, and prevent a significant portion of the increase in extreme weather events such as heatwaves, floods, and droughts. Significant reductions in risk are projected for water resources, agriculture, human health, and infrastructure. In ecosystems, risks to terrestrial species would be greatly reduced, with a projected 50% reduction in local extirpation, and marine ecosystems would be significantly healthier as well. Taken together, this means that both human livelihoods and ecosystem services will be significantly greater in a 1.5°C world than in a 2°C world.

3. THE COST OF ACHIEVING 1.5°C

Mitigation assessments tend to focus on the maximum cumulative CO_2 that can be emitted while limiting warming to a given level (with specified probability or risk tolerance)—the carbon budget. This is made easier by the approximately linear relationship between cumulative CO_2 and warming (91–93). The focus on CO_2 is justified by the long-lived nature of atmospheric CO_2 and its dominance in total GHG emissions (94). However, there are different measures of a carbon budget, depending on whether it is measured along an emissions path that exceeds the temperature target as well as on the degree of warming that results from non-CO_2 GHGs and other climate forcers, such as aerosols (95).

The first consideration has given rise to two measures of a carbon budget: the threshold exceedance budget (TEB), measured up to the time the temperature limit is exceeded (95), and the threshold avoidance budget (TAB), for a specified time period over which the temperature limit is never exceeded (95). A further measure that has been discussed is the overshoot net carbon budget, which is the net cumulative CO_2 to the point where a temperature target has been restored (having been exceeded) as a result of emissions removals (96). Hence, the TEB and overshoot net carbon budget are associated with temperature pathways that overshoot the target, whereas the TAB is associated with pathways that do not. The second consideration gives rise to measures of the carbon budget with different warming contributions from non-CO_2 GHGs, the extreme case including CO_2 only.

In addition to these two considerations, the remaining carbon budget compatible with 1.5°C is affected by climate uncertainties. One is around the linear relationship between cumulative CO_2 and warming, termed the Transient Climate Response to Cumulative Carbon Emissions (TCRE). The TCRE likely (i.e., with >66% probability) falls in the range 0.8–2.5°C per 3,660 $GtCO_2$ (94). Another uncertainty stems from the disparity between recent observed warming and warming projected by climate models (97). Previous carbon budget estimates have been based on climate models.

Nonetheless, the remaining budget for 1.5°C is likely to be very small. The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report indicates that (based on a TCRE of 1.6°C) the TEB for limiting warming to 1.5°C for >66% of model simulations is 400 $GtCO_2$ from 2011, some 600 $GtCO_2$ (60%) below the equivalent 2°C budget (94). However, more recent estimates have put a rather higher number on the 1.5°C TEB, up to 900–1,000 $GtCO_2$ from 2011, for >66% of model simulations (97, 98).

The lower 1.5°C carbon budget necessitates faster and deeper decarbonization of the global economy. Annual CO_2 emissions in scenarios that limit end-of-century warming to 1.5°C (with 50% probability) reach net zero between 2045 and 2060, 10–20 years before scenarios that limit warming to 2°C (with >66% probability) (99). This requires much more rapid emissions reductions in the 1.5°C scenarios, at 2.0–2.8%/year over the period 2010–2050, compared with 1.2–1.8%/year for 2°C scenarios. Emissions reductions over a decade or more at this rate have been achieved at the country scale, but largely as a side effect of policies to reduce dependence on oil rather than reducing CO_2 (100). The most rapid of these was in Sweden, with a linear 3%/year emissions reduction from 1974 to 1984 (101).

All of the aforementioned 1.5°C scenarios overshoot the target before returning to it by 2100. In addition, the majority of scenarios see significant emissions reductions starting from 2010, which has not happened (102). If global mitigation efforts are consistent with the current Paris pledges to 2030, then even a 5% annual rate of decarbonization post-2030 would provide less than a 5% probability of keeping warming below 1.5°C (103). Finally, they rely heavily on negative emissions technologies such as BECCS to remove atmospheric CO_2 at a scale, which achieves net negative emissions in the second half of the century. Disallowing negative emissions also increases required rates of decarbonization in the models.

For non-CO_2 gases, analysis suggests that, on the one hand, there is little additional mitigation in 1.5°C scenarios compared with 2°C scenarios, since most available measures are already used up in 2°C scenarios, given their relatively low cost (104, 105). On the other hand, there appears to be considerable additional potential compared with what has been implemented in the available energy systems models (106).

The more rapid decarbonization in the 1.5°C scenarios is driven by greater energy demand reductions (through increased energy efficiency) in the buildings, industry, and transport sectors, faster decarbonization of the power sector, and more significant deployment of negative emissions technologies (primarily BECCS) (99, 107). **Figure 1** compares the 2050 values of 10 key metrics for the energy system under 1.5°C and 2°C scenarios, drawing on a range of scenarios published in recent years. **Figure 1*a*** shows the increased role of carbon capture and storage (CCS) in fossil-fuel usage, the increased deployment of BECCS, and increased electrification in the buildings, transport, and industry sectors. **Figure 1*b*** shows decreased energy demand in the buildings, transport, and industry sectors, the lower carbon intensity of electricity and the reduced share of fossil fuels in primary energy. Although the faster decarbonization to limit warming to 1.5°C results in a speedier transformation of the whole energy system, certain sectors are particularly affected. As **Figure 1** shows, there is relatively little change in the CO_2 intensity of electricity generation, as well as in the share of BECCS in total primary energy. By contrast, the energy end-use sectors see more significant changes when going from 2°C to 1.5°C, particularly buildings (through decreased energy demand) and transport (through reduced energy demand and increased electrification).

Carbon prices are consistently higher in 1.5°C scenarios. As **Figure 2** shows, the median global carbon price from a range of 1.5°C scenarios is $85/$tCO_2$ in 2020. This is in 2005 prices; adjusting

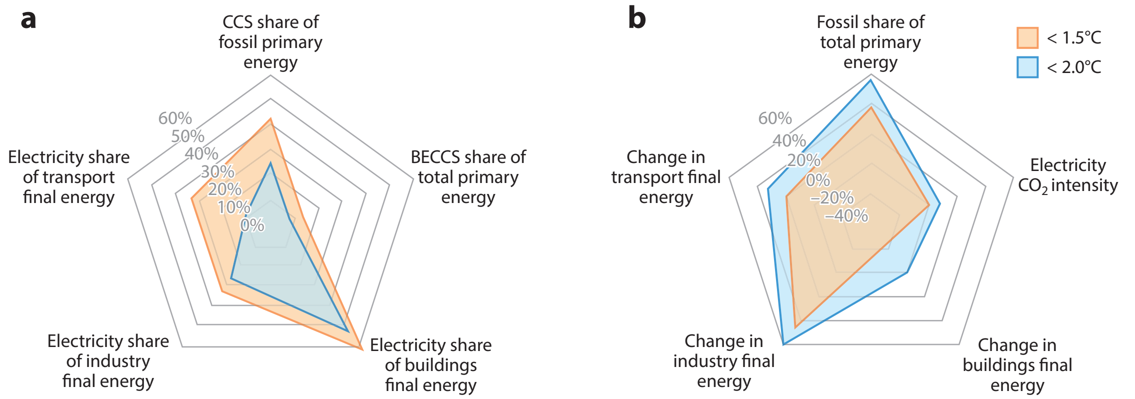


Figure 1

Indicators of energy system change in 2050 in 1.5°C and 2°C scenarios. (*a*) Metrics for which 1.5°C scenarios (*orange*) have higher 2050 values than 2°C scenarios (*blue*). (*b*) Metrics where 1.5°C scenario values are lower than 2°C scenario values. Panel *b* shows change in final energy for buildings, transport, and industry on 2010 levels and electricity CO_2 intensity as a share of 2010 levels. For each variable shown, values are medians across a range of <1.5°C and <2°C scenarios. Median values for the <1.5°C scenarios were computed from a scenario set obtained by pooling the 37 scenarios in Reference 99 and the five scenarios in Reference 187 that have a >50% probability of limiting warming to 1.5°C by 2100. Median values for the <2°C scenarios were computed from the 125 scenarios in Reference 187 with a >50% probability of limiting warming to between 1.75°C and 2°C. Abbreviations: BECCS, bioenergy with carbon capture and storage; CCS, carbon capture and storage.

for inflation it amounts to $105/t$CO_2$ in 2018 prices. The median carbon price rises to $145/t$CO_2$ in 2030, and by 2100 it is almost $4,500/t$CO_2$ (both in 2005 prices).[4] It is approximately three times higher than the 2°C scenarios' median carbon price throughout the century. In addition, in the last two decades of the century the median carbon price in the 1.5°C scenarios increases at more than $1,000/t$CO_2$/decade, a signpost of extreme challenge in achieving the low-carbon transition (108, 109). **Figure 2** also makes clear the large uncertainties associated with deep decarbonization, especially to limit warming to 1.5°C. These uncertainties have many sources, including boundary assumptions about economic and population growth, energy and resource efficiency, and policy (110), as well as different views about the marginal costs of emissions reductions, the degree of substitutability of producers' inputs and households' consumption items, the determinants of technological progress, the drivers of investment, and how to set carbon prices over time (111).

In the near term (over the period 2010–2030), 1.5°C mitigation costs are estimated to be approximately 150% higher than 2°C costs, with longer-term (2010–2100) costs approximately 50% higher (99). These differentials reduce annual GDP growth by an average of approximately 0.04 percentage points per year over the period 2010–2100, compared with 2°C scenarios, which have average growth of 2.20%/year (112). More stringent scenarios will also require greater investment, as demonstrated by the International Energy Agency's "66% 2°C" scenario, which requires 25% higher investment in energy supply and demand technologies to 2050, compared with a New Policies Scenario in line with current Paris pledges (113).

The additional costs of the 1.5°C scenarios are felt through marginally higher electricity prices by 2030 (99), but a detailed analysis of other sectoral and regional cost differences remains to

[4]A recent model intercomparison of scenarios achieving 1.5°C across a range of socio-economic pathways suggests a median carbon price of $137/t$CO_2$ in 2030, rising to $3,200/t$CO_2$ by 2100 (130), values which are broadly in line with the range shown in **Figure 2**.

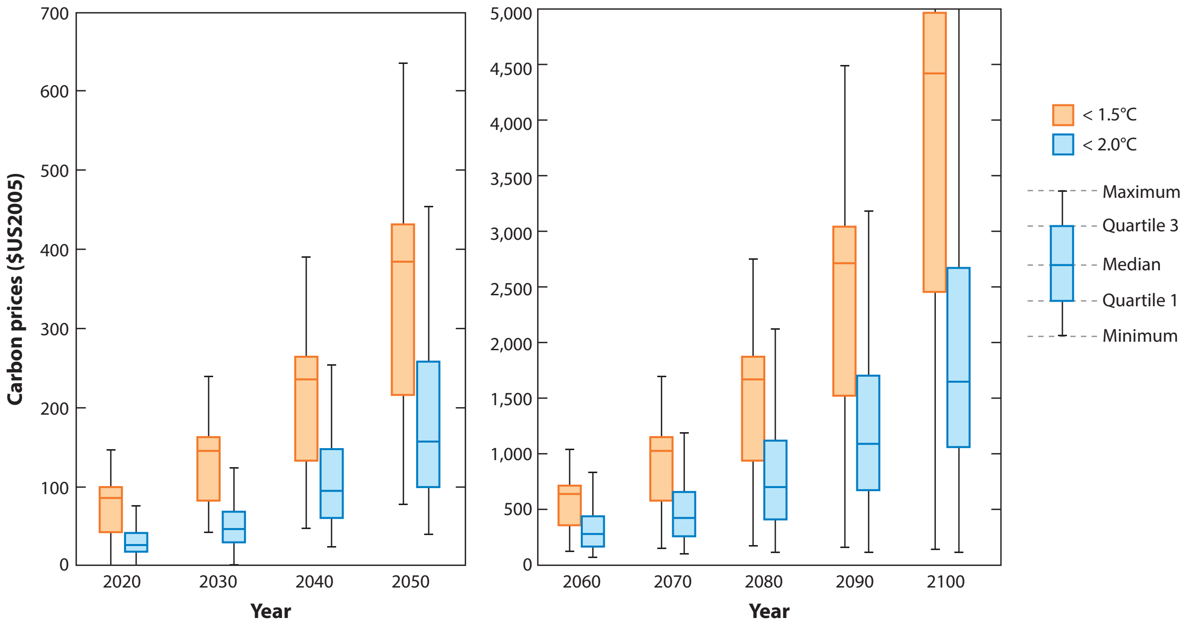


Figure 2

Carbon prices ($2005) in 1.5°C and 2°C scenarios. Carbon prices for the <1.5°C scenarios were computed from a scenario set obtained by pooling the 37 scenarios in Reference 99 and the five scenarios in Reference 187 that have a >50% probability of limiting warming to 1.5°C by 2100. Carbon prices for the <2°C scenarios were computed from the 125 scenarios in Reference 187 with a >50% probability of limiting warming to between 1.75°C and 2°C.

be undertaken. As has been demonstrated for 2°C scenarios (100, 108, 109), delayed mitigation is likely to increase costs, as is globally fragmented action (114). Analysis of 2°C scenarios also suggests that different regions could face different mitigation costs, with fossil-fuel exporters [Middle East OPEC (Organization of the Petroleum Exporting Countries), Russia, and Former Soviet States of Central Asia] particularly affected (114), whereas global carbon trading regimes could help lower overall mitigation costs by more than 50% compared with no-trade regimes (115).

The more rapid decarbonization required by 1.5°C scenarios is likely to result in a faster realization of air quality benefits from reduced local pollutants. The value of such benefits has been estimated to be in the range of \$2–196/tCO_2 (mean \$49/tCO_2), with the highest benefits in developing countries (116). Strategies to decarbonize the power sector based on wind and solar power are particularly beneficial in terms of reduced air and water pollution, whereas biomass has a substantial land footprint and higher local environmental impacts than other renewables (99, 107).

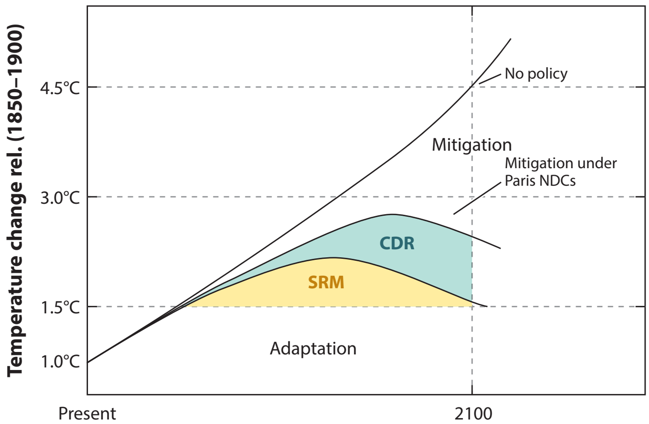
Analysis of low-carbon pathways has been dominated by the use of energy systems models, and this discussion has been no exception. However, these models have been criticized on several grounds, including a lack of transparency regarding input assumptions, particularly on technology costs (117); out-of-date technology cost projections, such as on solar photovoltaics and electric vehicles (118, 119); a lack of representation of real-world technology innovation processes (120); and a relative lack of focus on energy demand-side technologies and measures (121). In addition, their reliance on negative emissions technologies to meet very stringent mitigation goals has been called into question (122). Each of these limitations could have a significant impact on technology portfolios and mitigation cost estimates. Nonetheless, the models provide a useful, structured method to assess technological possibilities to meet stringent climate targets using known or feasible future technologies, and—when combined with other methods of scenario analysis such as sector-specific models—they can provide important insights into the dynamics of the required energy system transition.

4. CARBON DIOXIDE REMOVAL AND SOLAR RADIATION MANAGEMENT TO LIMIT WARMING TO 1.5°C

A central message from Section 3 is that keeping emissions within a 1.5°C budget is significantly costlier than an equivalent 2°C budget. This high cost has redoubled interest in alternatives to conventional mitigation involving large-scale interventions in the Earth system. These alternatives are collectively known as geo-engineering and are typically grouped into two broad categories; CDR and SRM. As its name suggests, CDR works by directly reducing the atmospheric GHG concentration, whereas SRM operates on the planet's energy balance between incoming shortwave and outgoing longwave radiation.

Both techniques have been the subject of reviews from natural science (123–126) and economics (127, 128) perspectives. The main CDR and SRM techniques are listed on the right side of **Figure 3**. Rather than reviewing them individually, we structure our review around the high-level characterization that Keith et al. (129) provide. Specifically, SRM is cheap and fast-acting, but targets only one symptom of global climate change, namely, increasing temperatures (e.g., it does not target ocean acidification). In contrast, CDR is expensive and slow-acting, but it addresses the root cause of the problem, namely, the high GHG concentration in the atmosphere.

It is possible to obtain a back-of-the-envelope estimate of the additional direct deployment costs of CDR and SRM. A recent model intercomparison suggests that net cumulative CO_2 emissions at the end of this century will be approximately 600 $GtCO_2$ lower for the 1.5°C target than the 2°C target (median values) (130). Approximately 180 $GtCO_2$ of this is due to additional CDR, which is split roughly 2:1 between the two most prominent techniques, namely, BECCS, and



CDR techniques
• Bioenergy with carbon capture and storage (BECCS) • Afforestation and reforestation (AR) • Direct air carbon capture and storage (DACCS) • Soil carbon sequestration and biochar (SCS&B) • Enhanced weathering (EW)
SRM techniques
• Stratospheric aerosol injection • Marine cloud brightening • Cirrus cloud thinning • Ground-based albedo management

Figure 3

CDR and SRM options and a hypothetical climate policy portfolio. A version of this figure originally appeared in Reference 188. It loosely incorporates the results of the analysis in Reference 189 to illustrate the temperature impacts of two scenarios in 2100: "No policy" and "Paris NDCs."

afforestation and reforestation (AR). Estimates of the technical potential and costs of BECCS and AR suggest that removal at this scale is technically feasible and can be achieved at a total cost of \$5.1–13.5 trillion (131).[5] However, assuming that the lowest-cost BECCS and AR opportunities are exploited first, the actual cost is likely to be closer to the upper end of this range, because meeting the 2°C target itself relies heavily on these CDR techniques.

Using Lenton & Vaughan's (125) results, we estimate that SRM calibrated to deliver -0.3 W/m^2 could substitute for 180 $GtCO_2$ of CDR.[6] Stratospheric aerosol injections or marine cloud brightening could in theory reduce radiative forcing by this amount. Focusing for the time being solely on the deployment cost, a system "capable of altering the radiative energy balance in a measurable way and the associated observing and modelling capabilities for assessing their radiative impact" would cost approximately \$3–30 billion per year, per the National Research Council (123, p. 147). This is trivial relative to current global GDP of approximately \$75 trillion. If deployed in perpetuity and assuming a discount rate of 5%, it is equivalent to \$0.06–0.6 trillion, which is one or two orders of magnitude cheaper than the direct deployment costs of removing 180 $GtCO_2$ using BECCS and AR.

CDR and SRM may have significant external costs, however. In the case of BECCS and AR, the additional land, water, and nutrient demand generated by large-scale deployment presents enormous challenges for agricultural production, sustainability, and biodiversity (132, 133).[7] In this context, the heavy reliance on CDR of most IPCC 1.5°C and 2°C scenarios has drawn much criticism in recent years (122, 134).

The deployment costs of SRM techniques are unlikely to be a significant barrier to their use. On the contrary, precisely because these techniques are inexpensive, a nation may deploy them unilaterally in response to real or perceived climate emergencies, or simply to set the global "thermostat" to its preferred level. This renders the effective governance of SRM techniques extremely difficult (135–138). Moreover, SRM deployment does little to address ocean acidification and can impose spatially heterogeneous external costs, including changes in precipitation patterns, greater ozone depletion, and reduced productivity of solar power generation. SRM also introduces new risks; for example, the techniques' effectiveness in controlling temperatures has not been tested in field experiments, and the risk of rapid warming following an abrupt termination could be devastating (139, 140). Some of these risks are "ambiguous" in the sense set out in Section 1, because any relatively small-scale field experiment is unlikely to produce the data required to quantify the emerging risks precisely (141).

Therefore, the role CDR and SRM can play in a broader climate policy portfolio remains an open question. Several recent economic analyses have considered the characteristics of the least-cost climate policy portfolio under highly stylized assumptions (142–149). Although the primary focus of most is the interaction between mitigation and SRM, an emerging conclusion is that there is room for both conventional mitigation and adaptation, as well as CDR and SRM in the policy mix, consistent with the left side of **Figure 3**.

[5]The same study estimates the costs at \$40–100/tCO_2 for BECCS and \$4–25/tCO_2 for AR, which makes BECCS a very expensive option relative to currently existing low-cost abatement opportunities in developing countries in Reference 190.

[6]We use the simple analytical approach for comparing geoengineering options Lenton & Vaughan (125) developed to calculate the approximate radiative forcing equivalent of 180 $GtCO_2$ of CDR. Assuming the atmospheric CO_2 concentration in 2100 is at the low end of the RCP2.6 scenario range in the IPCC Fifth Assessment Report, we compute this value to be -0.3 W/m^2, based on Lenton & Vaughan's Equation 14 (125).

[7]DACCS and EW, listed in **Figure 3**, require substantial carbon-free energy, and their employment costs are much higher than BECCS (132). In contrast, SCS&B can remove up to 5.2 $GtCO_2$ per year and has a low impact on land/water/nutrient/energy demand. Moreover, the deployment costs of SCS are relatively modest [\$40–80 (SCS) and \$117–135 (B) per tCO_2, on the basis of 131]. However, these techniques are constrained by sink saturation and reversibility (191).

However, the results of these economic analyses depend sensitively on contestable assumptions about the costs and risks of CDR and SRM in particular. A no-SRM portfolio, which achieves the 1.5°C target, may well do so at much lower social cost than the portfolio depicted in **Figure 3**, given the strongly negative side effects of SRM that are thereby avoided. The limited evidence on SRM and some CDR techniques makes formidable the sustainability and governance challenges that these techniques present, which is probably an important reason why public policy on geoengineering appears precautionary at this stage. To develop effective climate policies consistent with the 1.5°C target, the evidence base, particularly on SRM, needs to be strengthened urgently. This may well imply new small-scale field experiments, as recommended by some of the world's leading scientific bodies (123, 124, 150).

5. IMPLICATIONS FOR MITIGATION POLICY

In broad terms, meeting the 1.5°C target entails earlier emissions reductions across a broader range of economic sectors and low-carbon technologies. But policymakers must decide how to intensify mitigation policies while minimizing the increase in short- to medium-term costs (see Section 3). Doing so would not only minimize the overall costs of a more ambitious climate goal; it would also reduce political opposition from those most likely to bear any cost increases.

The main policy tool advocated by economists to reduce emissions in a cost-effective fashion is carbon pricing (151–153).[8] In the absence of market failures other than the GHG externality itself, a common carbon price will ensure that mitigation is cost-effective. Producers will reduce emissions up to the point where the marginal cost is equal to the carbon price. Consumers will reduce purchases of carbon-intensive goods and services up to the point where their marginal welfare benefits equal the price.

Carbon prices provide a pervasive incentive across all industries and households to reduce emissions. This could be of particular importance, given that tightening the target to 1.5°C places extra emphasis on reductions in energy demand across the whole economy (see Section 3). Carbon prices also provide an incentive for low-carbon innovation and combats the so-called rebound effect that boosts demand for a carbon-intensive product when low-carbon innovation lowers its price. An important advantage from the point of view of policymakers is that detailed knowledge of the technologies available to producers, or the preferences of consumers, is not required. Most methods of carbon pricing, such as carbon taxation or tradable emissions permits with initial auctioning of quotas, raise revenue for governments, which can be used to compensate people or firms hit particularly hard by carbon pricing. The flow of funds can also be used for other climate-related objectives (154).

Section 3 reported modeling that suggests a global carbon price of more than \$100/tCO_2 would be required as early as the 2020s, to limit warming to 1.5°C. However, the contrast between "ideal" carbon prices in energy systems models and real-world carbon prices is stark. At the moment, 85% of global emissions are unpriced and approximately three-quarters of the rest are priced below \$10/tCO_2 (153). Moreover, emissions are effectively subsidized through fossil-fuel subsidies, which still amount to approximately 6.5% of global GDP and promote extensive use of coal (155). Raising the price of emissions around the world and eliminating fossil-fuel subsidies are all the more important in light of the 1.5°C target. But these measures need to be accompanied by an

[8]The term carbon pricing is shorthand for pricing of emissions, including non-CO_2 emissions (e.g., using 100-year global warming potentials).

understanding of their distributional consequences, which may require compensatory adjustments to tax-benefit systems and poverty alleviation policies (e.g., 156, 157).

However, it is difficult to establish what the appropriate level of the carbon price is and how it should change over time. Section 3 illustrated and diagnosed the large uncertainties about future carbon prices. These uncertainties are not just a curiosity within the research community; they also affect real-world expectations, where uncertainty is further fueled by, and reflected in, price volatility in schemes such as the European Union's Emissions Trading System (158). This is likely to have discouraged low-carbon investment and innovation, for example in CCS (159). So limiting warming to 1.5°C requires not only higher carbon prices across a much higher proportion of emissions, but also less volatile pricing over time with greater predictability of future carbon prices. An officially sanctioned guide price or pricing corridor might help (153, 160).

More importantly, carbon pricing is only directed at one source of market failure, GHG emissions. There are several other market failures that may impede cost-effective mitigation. The 1.5°C target requires greater action on these fronts, as well. It is well-known that R&D is likely to be undersupplied in a competitive market, because new knowledge is a public good and it is difficult to establish property rights over new ideas. Public subsidy of low-carbon research can help rectify this problem and reduce the size of the incentive to private researchers that carbon pricing would need to provide (161). However, public spending on R&D in the energy sector has fallen back as a share of total public R&D spending (162), and there is evidence that public support for renewable energy has been skewed toward deployment subsidies, instead of R&D and demonstration projects (163). Other market failures that require more attention include short-termism and principal-agent problems in infrastructure provision (including housing), the difficulties in establishing new networks (e.g., power grids and transport systems), and coordination problems in location decisions (e.g., city design and zoning laws). Reducing demand for high-carbon products is one area where many researchers have concluded price signals may need to be supplemented (164), including by exploiting insights from psychology and behavioral economics (165), although some debate the merits of such "nudging" (166). Emissions from nonmarket sectors such as subsistence farming and the natural environment require special attention, given the difficulties of introducing market mechanisms on the timescale required, even where this is seen as desirable in the long run. This is a particular problem for many developing countries. Section 3 pointed out that abatement of land-use emissions plays a key role in most 1.5°C scenarios.

A case can also be made for more direct command and control measures under the 1.5°C target. The lower temperature target reduces the technological options available, so that certain economic choices appear unavoidable. Relying on the necessarily uncertain effects of intermediary policy measures, such as carbon pricing and technology-blind R&D support, can be risky. For example, BECCS and other means of CDR become crucial in 1.5°C scenarios (see Section 3). Some have therefore argued for mandatory sequestration (167). The inadequacy to date of carbon pricing in stimulating private R&D has encouraged more direct approaches, such as the mission-oriented new Apollo Program to combat climate change (168). Some researchers have found that setting standards is more effective in reducing emissions and more acceptable to public opinion, despite its costs (111). On this view, there may not be time to adjust economic instruments, such as a carbon price, in response to learning more about their potency.

However, command and control methods are often considerably more expensive than market instruments. This is demonstrated in the automotive sector, for example (169), where corporate automotive fuel economy standards place a heavier burden on the economy than an increase in gasoline prices (170). There is no escape from the need for careful evaluation of all policy instruments in theory and practice; exercises in this vein, such as those in References 171 and 172, are becoming more common.

At the international level, adoption of the 1.5°C ceiling suggests three priorities for policy making. First, successive UNFCCC summits must keep up the pressure on countries to adopt more ambitious NDCs. Second, the flow of finance to developing countries that adopt strong NDCs must be increased. The theoretical desirability of a global carbon price depends on there being appropriate lump-sum transfers to compensate the heaviest losers. Various schemes have been devised for equitable transfers among nations to accompany global carbon pricing, or other ways to make climate action fair (173–176). Empirically, it appears that mitigation opportunities are disproportionately concentrated in developing countries (177). Without appropriate receipts, developing countries will be unlikely to set as high a carbon price as developed countries (153), with adverse consequences for global efforts on aggregate and for cost-effectiveness. Third, better mechanisms to encourage the international dissemination of low-carbon technologies are required. These could build on the global Technology Mechanism established by the Paris Agreement, but they need to be incorporated in broader efforts to promote sustainable low-carbon development, as well.

6. CONCLUSIONS

This review has compared the benefits and costs of limiting warming to 1.5°C and has developed the implications of the 1.5°C target for mitigation policy. Because of space constraints, several other important issues have been ignored, e.g., adaptation policy. Interested readers are directed to the IPCC's extensive Special Report on Global Warming of 1.5°C (**http://www.ipcc.ch/report/sr15/**).

Section 2 detailed many potential benefits of limiting warming to 1.5°C, while emphasizing the uncertainties. The impacts avoided by limiting warming to 1.5°C compared with 2°C are significant for water resources, agriculture, and human health and are particularly large in poorer regions. SIDS, parts of Southeast Asia, and the Mediterranean are among the regions that would benefit most. Limiting warming to 1.5°C would provide particularly large benefits to natural ecosystems. Arctic summer sea ice would also be preserved. A key issue is whether limiting warming to 1.5°C reduces the risk of crossing climate tipping points. Although there is evidence to suggest that it would, the reduction in risk cannot presently be quantified.

Section 3 showed that the remaining carbon budget consistent with 1.5°C is very small and that the global economy would need to be decarbonized at an unprecedented rate. According to energy systems models, a global carbon price of more than \$100/tCO_2 would be required as early as 2020 (approximately three times higher than the carbon price necessary to limit warming to 2°C), more if policy implementation is delayed and fragmented. Indeed, any further delay likely renders the 1.5°C target unattainable by conventional means. Scenarios that limit warming to 1.5°C involve particularly large reductions in energy demand across the whole economy, and heavy reliance on negative emissions technologies, principally BECCS. Large-scale BECCS brings with it large environmental risks. Fossil-fuel exporters are likely to bear disproportionate mitigation costs.

Despite our reservations, the question of whether limiting warming to 1.5°C would pass a cost-benefit test in a formal, model-based assessment is an "elephant in the room"; we offer a relatively simple and transparent approach within this tradition, in the sidebar titled Formal Assessment of Whether 1.5°C Warming Is Economically Efficient (see also **Table 1**). The main point it makes is that the uncertainties about the economic benefits and costs of limiting warming to 1.5°C are so large, particularly on the benefits side, that 1.5°C is within the range of peak temperature increases that could be optimal from an economic standpoint. We think this conclusion also flows from the informal comparison of benefits and costs in Sections 2 and 3, where issues such as regional distribution, natural ecosystems, co-benefits, and ambiguity can be more fully incorporated.

FORMAL ASSESSMENT OF WHETHER 1.5°C WARMING IS ECONOMICALLY EFFICIENT

Historically, economists have built numerically solved IAMs to carry out CBA of climate targets. These cost-benefit IAMs have delivered many key insights, but they have been repeatedly criticized for resting on shaky empirics (e.g., 1–3). They are also complex enough to be branded "black boxes," stimulating recent interest in simpler analytical models (14–16), especially given the limitations of the underlying data, which mean that intricate modeling may not be warranted. Initial tests show these simpler models are able to closely replicate the results of more complex cost-benefit IAMs under comparable assumptions (15).

In this new tradition of analytical modeling, Dietz & Venmans (179) make use of the linear relationship between cumulative CO_2 emissions and warming to derive an expression for optimal peak warming, T^*:

$$T^* = \frac{[\rho - n + (\eta - 1)\, g]\, \phi}{\zeta \gamma},$$

where ρ is the pure rate of time preference and η is the elasticity of marginal utility. (This expression for T^* is not valid for emissions paths that temporarily overshoot 1.5°C.) These are parameters determining the discount rate (the discount rate $r = \rho + \eta g$). Population growth is represented by n and growth of GDP per capita by g; these are assumed constant. φ is the marginal cost of zero emissions, ζ is the Transient Climate Response to Cumulative Carbon Emissions (TCRE), a physical parameter, and γ is the coefficient of the damage function. **Table 1** lists the parameter values we assume and their sources.

Dietz & Venmans find that T^* depends sensitively on most of these parameters, and most of these parameters are subject to large uncertainty. This means that T^* itself is highly uncertain, which is consistent with the state of the wider literature on CBA of climate change.

Arguably, there is especially poor evidence on damages, γ (3, 178). Therefore, we use the above formula for optimal peak warming to ask the following question: On the basis of representative values of the other parameters, how large would damages have to be for optimal peak warming to be 1.5°C?

We find that $T^* = 1.5$°C if $\gamma = 0.0412$, which corresponds with the assumption that 3°C warming, which is a common point of comparison, would result in a welfare loss equivalent to 9.8% of global GDP. [To replicate this calculation, the damage function $D(T) = \exp(-\gamma/2^* T^2)$.] Compared with most of the literature on damages, this is an outlier. According to Nordhaus & Moffat's (180) recent survey, mean damages at 3°C are approximately 2% of global GDP, with a 95th percentile estimate of 6.5%. However, in stark contrast, recent empirical analysis of how temperature fluctuations have affected GDP growth worldwide since the middle of the twentieth century suggests much higher damages; 9.8% of global GDP at 3°C is close to the middle of the range of estimates from this work (181).

There are unanswered questions about the validity of these recent empirical estimates, compared with the prior literature. The quality of these recent estimates is much higher in a statistical sense, although they may lack external validity, having been derived from past data and from climate fluctuations over small periods (182, 183). They do not include the "nonmarket" impacts of climate change, such as on health and natural ecosystems. And none of the damage estimates discussed here includes the co-benefits of reducing emissions in terms of improved local air quality (see Section 3). However, the mitigation cost estimates reflected in the φ parameter do not incorporate the environmental risks of mitigation, notably of large-scale BECCS (see Section 2).

The alternative way to limit warming to 1.5°C is to make use of CDR techniques over and above those deployed in energy systems models and/or SRM. Such CDR techniques are expensive and slow-acting. Some SRM techniques are cheap and fast-acting, but they pose ambiguous risks to the environment. Whether society is prepared to take these risks is a value judgement, but its revealed preference to date is to not take such risks.

Table 1 Parameter values for T^*

Parameter	Value	Source
ρ	1.1%	Expert survey (184)
η	1.35	Expert survey (184)
n	0.5%	UN population projections (185)
g	2.06%	Expert survey (186)
φ	0.00126	Intergovernmental Panel on Climate Change (IPCC) AR5 Working Group III multiple models (106)
ζ	0.00048	IPCC AR5 Working Group I multiple models (49)

The case for carbon pricing has been made many times, but it is at least as important to do so in relation to limiting warming to 1.5°C. The potential cost savings from decentralizing the incentive to reduce emissions and bringing marginal abatement costs toward equality are very large. However, not only is there a strong normative case to complement carbon pricing with other policy tools, due to multiple market failures and barriers to mitigation, the urgency of the challenge here and the seemingly essential role of some technologies such as carbon sequestration make the case for more interventionist policy measures. At the international level, the Paris process must find a way to ratchet up the ambition of NDCs quickly, and channel finance and technology to developing countries to take advantage of cheap abatement.

SUMMARY POINTS

1. Due to large uncertainties about the economic costs and, in particular, the benefits, there can be no clear answer to the question of whether the 1.5°C target passes a cost-benefit test.
2. The benefits of limiting warming to 1.5°C, compared with 2°C, are particularly significant for natural ecosystems and they are also significant for water resources, agriculture, and human health, especially in poorer regions of the world. There is evidence to suggest that limiting warming to 1.5°C reduces the risk of crossing climate tipping points, such as melting of the Greenland and Antarctic ice sheets, but the reduction in risk cannot presently be quantified.
3. The remaining carbon budget consistent with 1.5°C is very small and the global economy would need to be decarbonized at an unprecedented rate to stay within it, likely entailing large costs.
4. Scenarios that limit warming to 1.5°C involve particularly large reductions in energy demand across the whole economy and heavy reliance on negative emissions technologies, principally bioenergy with CCS.
5. Any further delay in pursuing an emissions path consistent with 1.5°C likely renders that target unattainable by conventional means, instead relying on expensive large-scale CDR, or risky solar radiation management.
6. The case for carbon pricing as the central plank of mitigation policy is stronger than ever, although there may be a place for more interventionist policies alongside it, given the urgency, the political economy, and the existence of other market failures.

7. The UNFCCC/Paris process must find a way to ratchet up the ambition of NDCs quickly, and channel finance and technology to developing countries to take advantage of cheap abatement.

FUTURE ISSUES

1. How can cost-benefit analysis best give reliable decision support in situations involving very long timescales, global scope, deep uncertainties, and significant nonmarket benefits?
2. Although a literature on the benefits of reducing warming to 1.5°C is rapidly emerging, there needs to be better quantification of the uncertainties surrounding these benefits, both within and between models.
3. There needs to be more focus in the future on quantifying the benefits and costs of limiting warming to 1.5°C at the regional level.
4. Can the reduction in the risk of crossing key tipping points in the global climate system, brought about by limiting warming to 1.5°C, be quantified?
5. What is the 1.5°C carbon budget?
6. Can the environmental risks associated with solar radiation management by quantified, could field experiments help in this effort, and how could solar radiation management be effectively governed at the global level?
7. Given its centrality in most 1.5°C scenarios, how can policy effectively promote the deployment of carbon capture and storage (CCS) technology?
8. What policies are effective in rapidly reducing energy demand, as well as rapidly increasing the electrification of, the residential buildings, and transportation sectors?

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

A.B., B.D., and S.D. acknowledge the financial support of the United Kingdom's Economic and Social Research Council and the Grantham Foundation for the Protection of the Environment. R.W. has carried out consulting work for the UK Department for Business, Energy and Industrial Strategy on the implication of a global warming of 1.5°C. She has received funding from the Natural Environment Research Council to investigate the risks associated with 1.5°C warming.

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