The appropriate use of reference scenarios in mitigation analysis

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Abstract

Comparing emissions scenarios is an essential part of mitigation analysis, as climate targets can be met in various ways, with different economic, energy system and co-benefit implications. Typically, a central 'reference scenario' acts as a point of comparison, and often this has been a no-policy baseline, with no explicit mitigative action taken. The use of such baselines is under increasing scrutiny, raising a wider question around the appropriate use of reference scenarios in mitigation analysis. In this Perspective, we assess three critical issues relevant to the use of reference scenarios, demonstrating how different policy contexts merit the use of different scenarios. We provide recommendations to the modelling community on best practice in the creation, use and communication of reference scenarios.

The Paris Agreement commits the global community to limiting warming to 'well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C'[1]. To meet these ambitious goals, countries must embark on mitigation pathways towards a decarbonised future. Such pathways can be explored through the use of integrated assessment[2,3] and energy system[4] modelling. Integrated assessment models (IAMs) are a heterogeneous set of tools, varying substantially in model structure and behaviour. All IAMs however, attempt to couple different socio-economic, technical and biophysical systems together, allowing low-carbon futures to be explored in a systematic and self-consistent manner. In this Perspective, we focus on the use of detailed-process IAMs to conduct mitigation analysis, as opposed to aggregate benefit-cost IAMs[2]. Our justification is that such IAMs (containing detailed representations of energy systems, as well as in many cases land and agricultural systems) are widely used in the scientific assessment of mitigation pathways, as reported in Intergovernmental Panel on Climate Change (IPCC) reports[5–8]. We also consider the use of standalone energy system models (i.e. those not integrated with biophysical systems) to produce low-carbon pathways at a national, regional and global scale.

Many different mitigation scenarios could comply with the Paris Agreement. Scenarios may differ in their demographic, socio-economic and technological features, and hence there is a vast solution space of possible low-carbon futures meriting consideration. Making comparisons between scenarios is therefore an essential part of mitigation analysis.

Modellers often rely on reference scenarios to enable different mitigation scenarios to be evaluated. We define a reference scenario as: 'a scenario which is referred to when evaluating mitigation scenarios, and hence is a central point of comparison in the analysis'. Such reference scenarios are often generated by one actor but intended for use by a wide range of other actors in mitigation analysis. Pertinent examples include the SSP-RCP framework[9–13], scenarios generated by the International Energy Agency[14], and the Annual Energy Outlook of the Energy Information Administration[15].

Historically, much mitigation analysis has used no-policy scenarios, often referred to as 'baselines' or 'counterfactuals', as a central reference case or input against which to frame results[16–22]. These are a

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specific form of reference scenario in which no explicit mitigative action is taken[23]. In much of the literature, the terms reference scenario, baseline, and counterfactual are used interchangeably, despite the fact that baselines/counterfactuals are actually a specific form of reference scenario. No-policy baselines or counterfactuals have also often been considered as equivalent to 'business as usual' (BAU) scenarios[24].

In addition to the multiple terms used to describe reference scenarios, there is also a lack of clarity around their appropriate use in mitigation analysis. In light of the global growth of climate and energy policy in recent years[25], the validity of reference scenarios which represent a state of no mitigative action is being questioned[26–28]. Some reference scenarios have also been criticised[29] for failing to account for the rapid pace of cost-reduction and technological deployment of new low-carbon technologies such as solar photovoltaics[30]. The debate around the utility of no-policy baselines and the concept of BAU, given recent developments in climate policy and the energy system, has been highlighted by recent, at times heated, discussions around RCP8.5[28,31,32].

This Perspective explores the appropriate use of reference scenarios for mitigation analysis, focusing on the modelling community utilising detailed-process IAMs and energy system models.

Critical issues for appropriate reference scenario use

Here we discuss some critical issues relevant to the appropriate use of reference scenarios in mitigation analysis.

Absence of climate impacts.

Many reference scenarios produced by detailed-process IAMs and energy system models fail to account for the economic impacts of climate change. This is an issue for all scenarios, but is of particular importance for no-policy baselines, where the extent of global warming is likely to be greatest. Neglecting these impacts contravenes current scientific understanding, which suggests that they could be severe[33,34]. This can produce reference scenarios with limited realism, such as SSP5-Baseline, where significant growth in fossil fuel demand results in warming of 5°C by 2100, with no negative economic impacts taken into account[35].

Neglecting to account for climate impacts creates reference scenarios with overly optimistic economic projections. If these scenarios are used to assess the macroeconomic impact of mitigation, extreme care must be taken to communicate the results while noting the unquantified but substantial climate impacts which have been neglected in the analysis. Otherwise mitigation cost estimates based on no-policy baselines which neglect climate impacts may be used to paint mitigation as a highly costly endeavour[36]. In reality, given that climate change is the '*greatest and widest-ranging market failure ever seen'*[37], mitigation is a welfare enhancing strategy[38]. This message, however, is not always clearly portrayed by mitigation analysis, which has produced a large (and very useful) body of work on the cost of mitigation[16–19,39]. This work is highly important but there is a need to ensure that the results of mitigation analysis conducted using reference scenarios which neglect climate impacts are framed correctly.

Greater collaboration between the impacts, adaptation and vulnerability community and integrated assessment modellers is an intended goal of the SSP-RCP process[12], and therefore future reference scenarios may well include greater representation of climate impacts. However, to the extent that current reference scenarios fail to do so, their use, interpretation and communication requires care from the modelling community.

The global growth of climate policy

Current global climate policy remains insufficient to limit warming to well below 2°C[24]. Nor is it negligible however, with a recent survey identifying over 1200 different climate laws and policies[25]. Reference scenarios which fail to account for current policies (i.e. no-policy baselines) can therefore differ significantly from reality, especially in regions where climate policy is relatively well-developed, such as the EU. This discrepancy between no-policy baselines and trends in global climate policy will only grow as the Paris Agreement's ratcheting mechanism increases the ambition of nationally determined contributions (NDCs)[40].

If no-policy baselines are used to evaluate mitigation scenarios, relevant metrics such as the macroeconomic impact of mitigation are being measured against an already non-existent world, rather than against a reference scenario accounting for current levels of mitigation. This can lead to the calculated cost of mitigation being overestimated, reducing the willingness of governments to undertake stringent mitigation.

The substantial disconnect between no-policy baselines and current trends in climate policy reduces their utility as reference scenarios. In response to this, a range of reference scenarios accounting for current climate policy are entering the literature[41–44]. Creating such current-policy scenarios necessitates making assumptions around the persistence of current policies, and the extrapolation of effort post the policy time period. Given these uncertainties, it may at times be justified to present current-policy scenarios alongside a no-policy baseline[43], providing a range of reference scenarios for the end user. The utility of using no-policy baselines in isolation, however, is substantially limited by the global diffusion of climate policy, a fact which remains in stark contrast to their prevalence in mitigation analysis.

The pace of technological change

The pace of technological change is a critical driver of results in long-term energy scenarios. A variety of sources of technological change have been identified in the literature, including learning-by-doing, research & development, economies of scale and spillovers[45,46,55–57,47–54]. The majority of models represent technological change in some form[46,52], whether endogenously or exogenously.

Modelling teams can however fail to capture recent trends in technological progress sufficiently quickly. Modellers have been criticised for underestimating the pace of cost-reduction in low-carbon technologies such as solar photovoltaics[58] and electric vehicles[59,60]. As this progress is partly attributable to supportive climate and energy policy[61], failing to account for recent trends can be interpreted as neglecting the impact of recent climate policy on the energy system, as well as any component of technological change which is independent of policy intervention.

Modellers can also underestimate the future potential for technological change. While most models contain some level of progress[62] (with declining costs and improving efficiencies), the pace of change represented in many models for key technologies such as solar photovoltaics lags behind other projections in the literature[14,30,63–66].

Failing to account for recent trends in technology development and underestimating the potential for future progress can lead to reference scenarios with a greater deployment of carbon-intensive technologies than should be expected. This could result in countries setting emissions targets of insufficient ambition, if their targets are expressed relative to baseline projections[67]. Similar issues would result from any underestimation of energy efficiency improvements or energy-conserving behaviours. We also note that there remains the possibility for faster-than-assumed technological progress in incumbent carbon-intensive technologies and lower rates of energy intensity improvements to have the opposite impact: the key is to ground assumptions in the most up-to-date data available.

Appropriate scenario use in differing policy contexts

In light of these issues, we explore the appropriate use of reference scenarios in three different policy contexts.

Government acting under a cost-effectiveness paradigm

Mitigation analysis can take place under a range of different analytical paradigms, with the most prevalent being those of *cost-effectiveness* and *cost-benefit* analysis. Cost-effectiveness analysis (CEA) involves finding the 'least-cost approach to meeting a particular goal, such as a [CO_2] concentration goal in 2100'[23]. CEA takes a predetermined target and attempts to find pathways which meet this target at least cost. If a government is operating within the CEA paradigm therefore, the mitigative ambition of that government could be deemed to be fixed, particularly if that target is set in law. For example the UK has now legislated for a net-zero territorial emissions target by 2050[68]. Climate policy in the UK is currently focused on *how* to achieve net-zero by 2050, rather than on what target to set.

In this context, there is arguably no need for no-policy baselines. Instead, analysis can compare different scenarios which all meet the predetermined target, assessing their relative strengths and weaknesses. Here the reference scenario would be a 'central mitigation scenario', which meets the predetermined target with a central set of input parameters. The exact definition of a central mitigation scenario would likely be analysis-specific, but could include the availability of a full portfolio of current technologies, extrapolating current trends in individual and societal behaviours, and with no deployment of highly novel technologies. Central mitigation scenarios have already been used to frame analytical results that explores the value of different low-carbon technologies[69–72].

However, given pervasive and deep uncertainties around many variables influential to the cost and feasibility of reaching given mitigation targets, an alternative method to evaluating low-carbon policies and strategies on the basis of central mitigation scenarios is to use a Robust Decision Making (RDM) approach[73]. RDM avoids the need to make central estimates for key variables like technology costs or socio-economic developments, which will significantly influence the central mitigation scenario. Instead, it allows exploratory modelling to run a diverse range of future scenarios under different policies and strategies, highlighting their vulnerabilities and – using scenario discovery and visualisation methods – illuminating those which perform best, or with least regret, under a wide range of possible futures[74–76]. In uncertain times when the energy modelling community should systematically explore extremes[77], such an approach allows the design of resilient actions under deep, often irreducible uncertainties around the future.

However, RDM is still relatively nascent as a methodology applied to mitigation analysis, and (at least at this time) arguably rather more complex to perform and convey than simply using a clearly specified central scenario. In addition, central optimised mitigation scenarios are still compatible with RDM approaches, since they themselves can form part of a portfolio of diverse scenarios which together allow the stress-testing of different mitigation policies and strategies[78]. As such, there remains considerable merit in retaining and clearly communicating central mitigation scenarios even if mitigation analysis increasingly transitions away from a best guess, "predict-then-act" to an RDM methodological paradigm[79].

Using central mitigation scenarios (or indeed RDM-derived policies that perform well in scenarios that meet desired mitigation targets) circumvents the challenge of including climate impacts in reference scenarios; since these mitigation scenarios will all experience a similar degree of warming, climate impacts should be equivalent across scenarios. They also account for the global expansion of climate policy: by assuming *a priori* that sufficient climate policy will be developed to meet the predetermined target, the analysis instead focuses on the form of climate policy that is most desirable, for example comparing different technology deployment strategies to achieve least-cost (or most robust) pathways.

Even in these circumstances, however, comparison to a current-policy reference scenario *could* be useful. A current-policy scenario attempts to represent currently implemented and planned climate and energy policies and extrapolate them into the future. Reference scenarios constructed using this methodology are used by a variety of institutions[14,24,80,81], and can provide a measure of the *additional* effort necessary to reach a predetermined goal, relative to current levels of effort. This is an important metric, even in a CEA paradigm, as it provides a scale for comparing mitigation scenarios. For example, if one mitigation scenario requires £20bn more investment than another, this information could usefully be viewed in the context of both scenarios requiring £200bn more investment than a current-policy scenario. Such a contextualisation ensures that the relative merits of different mitigation scenarios are viewed in light of the overall scale of effort necessary.

Comparison to a no-policy baseline, however, is inappropriate in this context. A no-policy baseline represents a world which is both non-existent (if countries have already diverged from this by enacting policy), and that policymakers are not considering returning to (given that we are in a CEA paradigm). Indeed, comparison to this scenario only risks overemphasising the scale of the challenge (while neglecting significant climate impacts), which could erode willingness for rapid mitigation.

Government determining a level of ambition to set

Due to the bottom-up structure of the Paris Agreement[82], we cannot however assume that the paradigm of CEA is dominant in all domestic contexts. Absent a formal allocation mechanism, it is left to individual countries to determine an appropriate level of ambition in their NDC[83]. In all countries, there is a need to decide what targets to set. And even once a target has been set, the Paris Agreement mandates that NDCs must be progressively updated over time, through the ratcheting mechanism[40]. There is therefore a wide range of domestic contexts in which determining an appropriate level of ambition remains a central question. In such contexts, where the mitigative ambition of a government is not fixed, there remains a need to compare scenarios with differing levels of mitigation.

The appropriate reference scenario should here represent the current level of mitigative ambition of the government, before any update has taken place. We term such a scenario a ‘current-ambition’ scenario. However, this current level of mitigative ambition may well be non-zero. For a country updating its NDC, the appropriate reference scenario would now become the current national NDC. The analysis would then assess the implications of increased ambition relative to the current level[27]. The IPCC’s Special Report on 1.5°C, by taking the 2°C commitment as the lowest level of international ambition, and assessing the implications of pursuing efforts to limit warming to 1.5°C, utilises this framing[84]. In domestic contexts in which a long-term goal has yet to be set, the current-ambition scenario can be represented by a current-policy scenario.

There are domestic contexts in which no-policy baselines are still used when setting the level of mitigative ambition, as some governments express their climate targets relative to a no-policy baseline[67]. If a government chooses to express its NDC in this form, it is necessary to calculate a no-policy baseline in order to define the NDC.

A pressing issue here is representing the pace of technological change appropriately, to ensure that emissions in the no-policy baseline are not overestimated. While the literature is clear that technological change can be induced by climate policy[85–87], there is also the potential for progress to be driven by factors which are independent of policy[45]. In addition, the cost of technologies could fall due to policy-driven deployments in other countries, with international spillovers leading to technological change in the absence of domestic climate policy[88]. Accounting for these (potentially substantial) levels of technological change in the no-policy baseline can ensure that emissions in the reference scenario are not overestimated, and that the NDC therefore expresses an appropriate level of ambition.

There are significant issues relating to basing climate targets on a no-policy baseline. First, some Parties to the Paris Agreement have indicated that they might revise their baseline over time[67], which could potentially reduce the level of ambition in their NDC. Second, this baseline is inherently unknowable, and setting and measuring progress towards an NDC based on such a baseline introduces substantial uncertainty around the ambition and compliance of a country with its NDC. It would therefore seem appropriate to move beyond climate targets which are expressed relative to no-policy baselines, as actively encouraged by the Paris Agreement[1,67].

Impact Evaluation of Climate Policies

The third use-case of reference scenarios is in the impact evaluation of climate policies. The most obvious example of this is in an international setting, in the United Nations Environment Program (UNEP) Emissions Gap report[24]. Here no-policy baselines are essential to allow the impact of current energy and climate policies to be assessed. This shows that currently implemented climate and energy policies only reduce emissions by ~4GtCO_2 in 2030[24]. This important information can be used by NGOs and civil society actors to push for more ambitious emissions reductions from policymakers.

However, while an indication of the progress made is important, much more important is an indication of the progress that remains to be made. The gap remaining between an mitigation target and observed emissions reductions is more important than the progress made on emissions reductions. This means that when evaluating the impact of climate policies, while no-policy baselines can be used as one reference scenario, the central reference scenario should be a mitigation scenario. The emissions gap report follows this approach, using both no-policy baselines and 2/1.5°C compatible scenarios to evaluate the impact of current policies and NDCs, but with greater emphasis placed on the emissions gap (with reference to mitigation pathways) than on the progress made (with reference to no-policy baselines).

In the above policy contexts, four reference scenarios have been presented. These scenarios are presented in Table 1, alongside their appropriate use and examples of this use.

Reference Scenario	Definition	Appropriate Use	Examples
No-Policy Baseline	Accounts for the impact of climate and energy policies up to the base-year (in terms of technological change and deployment) but assumes no climate policy beyond this point.	Conducting an impact evaluation of current climate policy, or for use in contexts where the persistence of climate policy is uncertain.	[24,43]
Current-Policy	Represents current implemented and planned climate and energy policies and extrapolates them into the future.	Within the CEA paradigm to provide a scale against which to compare mitigation scenarios. When a government is determining an appropriate level of mitigative ambition, in the absence of a long-term goal, this scenario could also be used.	[41]
Current-Ambition	Represents the implications of current policy ambitions†, such as NDCs or mid-century strategies.	When a government is updating their level of mitigative ambition in their climate policy (for example updating NDCs as part of the Paris Agreement).	[27,84]
Central Mitigation Scenario	A mitigation scenario which meets a given climate target, with a central set of input parameters (e.g. technology costs/availability and extent of behavioural and societal change).	Within the CEA paradigm, to compare and contrast different mitigation scenarios. It can also be used to calculate the emissions gap when conducting an impact evaluation of current climate policy.	[24,69–72]

Table 1: The four different reference scenarios available for use in mitigation analysis. For each scenario, it provides a brief definition of the scenario, discusses the appropriate use of such a scenario, and provides examples from the literature where this scenario has been defined and utilised appropriately.

†We distinguish between current-ambition scenarios, which represent the aspiration to mitigate in a domestic context (e.g. as represented by a mid-century strategy), and current-policy scenarios, which capture the impact of actual climate and energy policies applied in a jurisdiction. There may be a discrepancy between these scenarios, if mitigative ambition is not supported by the commensurate climate policy.

Conclusions and Recommendations

By reviewing the use of reference scenarios for mitigation analysis, we highlight three issues relevant to their appropriate use, relating to the inclusion of climate impacts, mitigation policy and the pace of technological change. We consider three different policy contexts and suggest how the appropriate use of reference scenarios could differ between these contexts. We now provide a set of recommendations on how best to use reference scenarios for mitigation analysis.

Reflect technology developments in reference scenarios

The plummeting cost of renewables is one of the great success stories of the past decade. Reference scenarios which portray a carbon-intensive future without accounting for this progress therefore have limited utility to end users of mitigation analysis. Continually updating techno-economic parameters and model calibration years can ensure that reference scenarios at least start from a point which is consistent with real-world developments. Modellers should give this issue appropriate time and resources in modelling exercises, given the potential impact this can have on the outcomes of analysis.

Choose the appropriate reference scenario

It is important that scenarios are designed with the end user in mind[89]. We have shown that there are a variety of policy contexts in which the most useful and appropriate reference scenario may no longer be a no-policy baseline, but could instead be a central mitigation scenario, a current-ambition scenario or a current-policies scenario. We present a taxonomy of these scenarios, with suggestions for their appropriate use (Table 1). Modellers should think carefully about which reference scenario is appropriate for the particular task in hand, to ensure that the results of mitigation analysis are relevant to the policy context within which the end user is operating.

Communicate reference scenarios clearly

Part of the appropriate use of reference scenarios is effective communication between scenario generators and scenario users[90–92]. We make two specific recommendations here.

First, increased transparency around the assumptions which underly the reference scenario would be beneficial. This includes whether climate impacts have been accounted for, the representation of future climate policy and the pace of technological change assumed.

Secondly, both the modelling and policymaking community would benefit from improved clarity of terms, particularly around the distinction between reference scenarios, baselines, and the term 'business as usual'. The conflation of reference scenarios and no-policy baselines is unhelpful, as baselines are actually a specific form of reference scenario (and one with diminishing utility). Modellers should use the term 'reference scenario' as a general term, and within any given piece of analysis be explicit about which particular reference scenario is being used.

Moreover, the term 'business as usual' is ill-suited to the challenges facing society in the 21st century, in that there is no future which does not involve substantial disruption – whether from climate policy or climate impacts. As such, 'business as usual' is no longer a valid concept for futures analysis and should no longer be used to label scenarios.

Ultimately, the future is unknown, and no reference scenario is going to be 'right'. The aim of modelling is not to predict the future, but to understand it[93]. Reference scenarios should not be interpreted as predictions of the future, but as tools by which to compare and contrast different low-carbon futures, with their relative costs and benefits. If chosen carefully, contextualised correctly and communicated clearly, they can be very useful tools indeed.

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Acknowledgements

N.G. would like to thank the ‘Science and Solutions for a Changing Planet Doctoral Training Programme’ (SSCP DTP) by the Natural Environment Research Council (NERC), and the Grantham Institute for supporting their PhD research. A.G. and A.H. acknowledge support from the H2020 European Commission Project “PARIS REINFORCE” under grant Agreement No. 820846. The authors would like to thank Joeri Rogelj and Simon Dietz for insightful comments on an earlier draft.

Author Contributions

N.G. and A.G. conceived of the initial theme for the perspective. N.G. wrote the paper. A.G., A.H. and T.N. supported in the development of the arguments and editing of the paper.

Competing Interests

The authors declare no competing interests.