A multi-model analysis of long-term emissions and warming implications of current mitigation efforts

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Abstract

Most of the integrated assessment modelling (IAM) literature focuses on cost-effective pathways towards given temperature goals. Conversely, using seven diverse IAMs we project global energy CO_2 emissions trajectories based on near-term mitigation efforts, and two assumptions on how these efforts continue post-2030. Despite finding a wide range of emissions by 2050, nearly all the scenarios have median warming of less than 3°C in 2100. However, the most optimistic scenario is still insufficient to limit global warming to 2°C. We furthermore highlight key modelling choices inherent to projecting where emissions are headed. First, emissions are more sensitive to the choice of IAM than to the assumed mitigation effort, highlighting the importance of heterogenous model intercomparisons. Differences across models reflect diversity in baseline assumptions and impacts of near-term mitigation efforts. Second, common practice of using economy-wide carbon prices to represent policy exaggerates carbon capture and storage (CCS) use compared to explicitly modelling policies.

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Mitigation pathways tend to focus on an end temperature target and calculate how to keep within these bounds. This work uses seven integrated assessment models to consider current mitigation efforts, and project likely temperature trajectories.

The goal of the Paris Agreement is to limit global warming to “well below 2°C and pursue efforts to limit temperature increase to 1.5°C”[1]. Although global emissions are still increasing, climate policies are clearly having an effect[2,3] and common ‘no policy’ baselines represent increasingly unlikely futures[4,5].

While many scenarios explore emissions pathways below baselines[6,7], the majority of these are based on ‘backcasting’[8], meaning they identify pathways that meet pre-defined climate targets. Backcasting scenarios typically represent climate policy using economy-wide carbon prices that ensure that emissions reductions necessary to meet the pre-defined climate target take place when and where they are cheapest (sometimes following periods of delay or staged accession[9]).

Real-world climate mitigation, however, will likely differ from such backcast pathways for two reasons. First, the Paris Agreement’s design around nationally determined contributions (NDCs) mean mitigation effort will vary between countries and over time. Second, real-world climate policies consist of a mixture of different policy instruments[10,11], with implied carbon prices that vary by sector[12]. To reflect such real-world features, we explore, using seven integrated assessment models (IAMs), how global energy CO_2 emissions and temperatures evolve when assuming mitigation efforts in line with current policies and NDCs to 2030 and commensurate levels of effort thereafter.

Several modelling studies have analysed the impacts of current policies and NDCs on future emissions and global warming[13–22]. Most of these, however, focus on the gaps in 2030 between current policies and NDC scenarios and well-below-2°C backcasts[3,14–16]. Other studies have used the IPCC Fifth Assessment Report (AR5) scenario database, again comprising mainly backcast scenarios, to derive a relationship between NDC and current policies emissions in 2030 and temperature increase in 2100[16,17].

Of the few studies that explicitly model mitigation efforts post-2030, most are single-model studies[13,18–20], or multi-model studies[21] based on a single assumption of future efforts. Two studies[22,3] provide detailed representations of current policies through to 2030 and assume “no further intensification of emission reduction commitments”[23] thereafter, but do not focus on these results.

By contrast, our focus on explicit forward projections of mitigation efforts post-2030 to explore where global CO_2 emissions and associated temperatures may be headed fills a critical gap in the scenario literature[24].

Scenarios of current and continuing mitigation efforts

Forward projections of emissions necessitate i) assessments of near-term mitigation efforts and their impacts on emissions, and ii) assumptions of how these efforts will be extended in the longer-term. Simulating these emissions pathways using a diverse set of IAMs further allows an exploration of the many possible energy system changes driving them.

The most reliable information regarding near-term mitigation efforts stems from databases containing regional climate policies currently in place. The most relevant information on how current policies might be strengthened comes from NDCs. We therefore use two different assumptions regarding the level of likely near-term efforts. First, we assume only current policies, and secondly, we assume NDCs on top of current policies. NDC targets thus act as additional constraints on emissions in regions where current policies are insufficient to meet NDC targets. Emissions reductions in NDC scenarios are therefore never less ambitious than what current policy implies, reflecting plausible strengthening of ambition in the near-term. All scenarios also include all emissions reductions seen in the baselines. We use the terms *current policy constrained* and *NDC constrained* scenarios to distinguish these from scenarios defined directly by NDCs without considering overachievement (see Methods, Supplementary Text 1-2, and Extended Data Figure 1 for details on current policy, NDC, and scenario implementation).

The scenarios are extended post-2030 using two different methods designed to capture the varied mitigation efforts implied by current policies and NDCs across IAMs in a consistent manner. The first method is based on continuing rates of emissions intensity reductions (emissions per unit GDP) and the second on increasing carbon prices in line with per capita economic growth (see Methods).

The two assumptions regarding near-term efforts and the two ways of extending these efforts post-2030 give rise to four scenarios exploring where emissions are headed (Table 1). Additionally, our scenario design includes a third set of scenarios that meet the same emissions reductions in 2030 as current policy and NDC constrained scenarios but using economy-wide prices only (see Methods). These scenarios are used to analyse the role of policy representation.

We use seven global IAMs that span a highly diverse set of approaches to explore the scenarios (see Methods, Supplementary Text 3, and Supplementary Table 3). To enhance relevance and comparability of results across models, we update and harmonise population, GDP, technology cost, fuel efficiency, and technology lifetime assumptions (see Methods, Supplementary Text 4, and Supplementary Tables 2-4 for details on harmonisation and assumptions used).

Global emissions outcomes and temperature implications

We focus on global energy CO_2 emissions to 2050 as all our IAMs represent these emissions sources as a minimum. Current policy constrained scenarios reach levels of emissions between 32-36 $GtCO_2$ in 2030 and 26-40 $GtCO_2$ in 2050 (Figure 1a) and NDC constrained scenarios reach levels of emissions between 30-34 $GtCO_2$ in 2030 and 23-38 $GtCO_2$ in 2050 (Figure 1b). Global differences in emissions between current policy and NDC constrained scenarios arise because not all regions are on track to meet their NDC targets.

The method used to extend efforts post-2030 can have a large impact on emissions by 2050 (Figure 1). The impact is larger for some IAMs (GEMINI, ICES, GCAM) than for others (TIAM, MUSE, E3ME)—FortyTwo includes only emissions intensity extensions. In models where the difference is large, carbon price extensions lead to higher emissions than emissions intensity extensions. This implies that a constant rate of emissions intensity reductions post-2030 requires carbon prices that increase faster than per capita incomes (as is assumed in the carbon price extension method), making our intensity scenarios more optimistic with regards to future efforts than our price scenarios.

We use the transient climate response to cumulative carbon emissions (TCRE) to calculate the temperature changes implied by energy CO_2 emissions and use GCAM to account for assumptions around the greenhouse gases not represented in all models (see Methods). Across the range of scenarios considered, we find a median 2100 temperature outcome of 2.2-2.9°C (Figure 1c). As expected, NDC constrained scenarios give lower 2100 temperatures than current policy constrained scenarios, reflecting their greater ambition by 2030 at a global level (see Supplementary Figure 1). In addition, and as expected from their greater optimism on effort, intensity scenarios give lower 2100 temperature estimates than price scenarios. Because our temperature range considers all emissions intensity scenarios but only three (of six) carbon price scenarios, the low end of our temperature range is more robust than the high end (see Methods).

The temperature range in this study is considerably lower than temperature ranges based on current policies and NDCs estimated by Rogelj et al.[16] (2.6-3.4°C) and in the UNEP emissions gap report[25] (3.0-3.9°C with a 66% probability). Since the methods used to infer temperatures are very different, it is difficult to analyse the reasons behind the temperature differences (see Supplementary Text 5). Instead, to understand why our temperature estimates are lower, it is useful to compare emissions in our current policy and NDC constrained scenarios with emissions trajectories in similar studies. Global energy CO_2 emissions in our scenarios are below those in CD-LINKS[22] scenarios (Supplementary Figure 2), and emissions intensity per GDP are below International Energy Agency (IEA) World Energy Outlook (WEO) 2019 scenarios (Supplementary Figure 3). Emissions in our NDC constrained scenarios are expected to be lower because they account for regions (e.g India and China) that are on track to outperform their NDCs. Emissions in our current policy constrained scenarios are also lower partly because our baseline emissions are lower (Supplementary Figure 4). The baseline emissions are likely lower due in part to the use of updated technology cost assumptions, which reduced baseline emissions in all our models[26]. Despite lower emissions and temperature estimates, however, even our most optimistic scenarios (NDC constrained intensity scenarios) give median global warming in 2100 above 2°C.

While scenario choice has a significant impact on emissions projections, the model used matters more (Figure 1). Some models (TIAM, MUSE) project significant emissions reductions by 2050 in all scenarios, whereas others (GEMINI) project either stable or increasing emissions in all scenarios. In general, differences in emissions between current policy and NDC constrained scenarios are smaller than differences in emissions between different models. The model used to project where emissions are headed is thus a better predictor of emissions (and temperature outcomes) than the scenario used. This finding is in line with other studies that have shown that model differences play an important role in scenario analysis[27,28]. Our study further demonstrates that the impacts of different post-2030 mitigation assumptions can also be highly model-dependent.

Differences in emissions projections between models can be explained by i) differences in historical emissions, ii) differences in baseline emissions, iii) differences in the modelled impacts of current policy and NDCs, and iv) differences in the impacts of using different extension methods (Figure 2). First, differences between modelled and historical emissions in 2020 (Figure 2, blue bars) are small compared to differences in baseline emissions increases (red bars) and differences in emissions reductions caused by current policies and NDCs (yellow bars). Second, emissions reductions caused by current policies and NDCs (yellow bars) vary across models in all scenarios. This is expected because model structure affects both the types of policies that can be represented and the ways in which those policies are represented in different models (see Supplementary Data 1 and Supplementary Figure 5 for policies implemented in each model). And the NDC constrained scenarios include emissions reductions above NDCs in current policy constrained scenarios and baselines, where the latter are more model-dependent. Even if this was not the case, NDCs are also only sometimes defined relative to baselines. This explains why emissions reductions from baselines also vary in NDC constrained scenarios.

Third, baseline emissions vary considerably across models. Because we harmonise population and GDP, this variation reflects differences in model assumptions that translate GDP and population into energy and emissions. The harmonisation thus helps isolate those assumptions. As seen more clearly when looking at specific regions, the baseline variation can be important for explaining differences in emissions in other scenarios (Supplementary Figure 6). In India, for instance, NDC scenarios are defined by current policy scenarios, because the latter are already on track to meet NDCs (as also found in other studies[29]). Current policies in India, however, exert only a small impact on emissions relative to baselines. This means that emissions in India in both current policy and NDC constrained scenarios are determined primarily by baselines, which vary considerably across models. For economies that are expected to grow significantly, such as India, small differences in assumptions regarding, for instance, the elasticity of energy demand with respect to GDP have a large impact on baseline emissions. Such differences reflect real uncertainties regarding where energy demand and emissions are headed[30], in line also with other studies[31].

Overall, the variation in emissions outcomes across models reflects uncertainties both with regard to baseline emissions and with regard to the impacts of current policies and NDCs. These uncertainties are, at least in part, irreducible and fundamental to the task of projecting where emissions are headed.

Changes in energy demand

Behind differences in global energy CO_2 emissions across models and scenarios lie differences in final energy demand (Figure 3). Relatively lower global final energy demand in MUSE and TIAM helps explain the lower energy CO_2 emissions in these models. Total final energy demand alone, however, is not sufficient to explain the level of CO_2 emissions. ICES, for instance, has the highest final energy demand in 2050 in all scenarios but, due to a high share of electricity in final energy (and less solids), does not end up with the highest emissions. Over time, electricity in ICES, which is characterised by a low share of fossil fuels (and higher shares of hydro and nuclear) (Supplementary figure 7), displaces gases and solids in the industry and residential and commercial sectors, but not in transport where most other models show higher degrees of electrification (Supplementary figures 8-10).

While final and secondary energy analysis helps explain the differences in emissions between models and scenarios, the picture remains complex due to the many degrees of freedom in how energy CO_2 emissions are reduced in different models. More generally, however, the importance of model baselines is demonstrated (Figure 3 and Supplementary Figures 7-10): final and secondary energy mixes in modelled scenarios tend to remain relatively close to baselines, which means the differences in energy demand across models are larger than the differences across scenarios. Thus, baseline characteristics – reflecting differences in assumptions that translate population and GDP growth into energy demand – have a significant impact on current policy and NDC scenarios.

Among the robust findings we see that global final energy demand generally (with the exception of MUSE between 2030 and 2050) increases over time, as reflected also in global primary energy (Supplementary Figure 11). This indicates higher decarbonisation of the energy system in those models where energy CO_2 emissions decline (TIAM, MUSE, and in some scenarios ICES, GCAM, and E3ME). Global final energy demand is lower in NDC constrained scenarios than in (corresponding) current policy constrained scenarios, and lower in intensity scenarios than in (corresponding) price scenarios, thus matching the ordering of CO_2 emissions in these scenarios. Global final energy in all scenarios and in all models is reduced relative to baselines, with the only exception to this being MUSE, which has very low baseline final energy demand compared to other models (Figure 3). This contributes to very low baseline energy CO_2 emissions in MUSE in 2050 (Figure 1), which is brought down further by current policy and NDC constraints.

Key model characteristics and differences in baseline emissions and policy and NDC impacts (Table 2) provide a qualitative understanding of the relative differences in emissions outcomes across our models. IAMs are valued for their ability to compute the impacts on global or regional emissions from the multiple and complex interactions across the socio-economic-technical system. These multiple and complex interactions are precisely why it is difficult to map individual model characteristics and assumptions to emissions outcomes. Efforts have emerged to create diagnostic indicators for IAMs[32,33] to help describe how a model responds to climate policy, but these indicators do not yet explain the links to model characteristics.

The variation in emissions across models in this study can be explained by variation in baseline emissions and in the impacts of current policies and NDCs (Figure 2). We find that energy demand growth, electrification, efficiency improvements, and renewable energy deployment are important for explaining emissions outcomes (Table 2). GCAM, GEMINI, and FortyTwo, for example, have the highest 2015-2050 baseline emissions increases due to continued strong growth in energy service demands, as increasing economic growth more than offsets efficiency gains. This contrasts with MUSE, TIAM, ICES, and E3ME, where demand growth is moderated by efficiency improvements to a greater extent. *Ex-ante* evaluation of which approach is ‘correct’ is not possible nor necessarily appropriate, but rather highlights that future energy service demand growth in the absence of targeted action is a key uncertainty across models.

We find no general relationship between model type and emissions levels (Table 2). While technology-rich bottom-up models, such as GCAM, TIAM, or MUSE, capture the technological impact of current mitigation efforts in greater depth than macroeconomic models, such as ICES, GEMINI, and E3ME, this comes at the expense of not fully representing most economy-wide spill-over effects, which macroeconomic models capture. With the relative importance of energy sector versus economy-wide impacts uncertain, the impact of this on emissions, however, remains unclear. Similarly, and as supported by the literature[34], we find no clear relationship between model solution dynamic and emissions outcome.

The accuracy of the emissions outcomes in this study hinges on the accuracy of the modelling of baseline emissions and current policy and NDC impacts. While it is crucial to update input assumptions in line with current knowledge, the lack of consensus on what modelling approach is preferable and what key characteristics are 'correct' are indicative of genuine uncertainties. This motivates the use of diverse sets of models in assessments of where emissions may be headed.

The importance of policy representation

The representation of climate policies in IAMs affects how emissions reductions are achieved in modelled scenarios. A key feature of this study is the detailed and explicit representation of current policies (see Methods). The scenario design, which involves modelling the same levels of near-term emissions reductions based on both real-world policies and on economy-wide carbon prices, allows us to analyse the impacts of this modelling choice. The use of CCS is found to be significantly higher in scenarios using economy-wide carbon prices to represent current policies than in scenarios representing current policies explicitly (Figure 4a).

After 2030, carbon prices start to play a larger role in all our scenarios (relative to current policies, which are kept "constant", see Supplementary Text 2), as a proxy for future climate policy. By 2100, the levels of CCS in our scenarios (for the models that run to 2100) rival the levels seen in some deep mitigation scenarios[6] (Figure 4b). Based on our finding that current policies do not stimulate CCS to the extent seen when using economy-wide carbon prices to represent current policies, these future levels of CCS may also not materialise unless they are targeted by specific policies.

Challenges in projecting emissions forward

Forward projections of global CO_2 emissions represent an underexplored area of climate mitigation research. Such projections necessitate both the assessment of impacts of current mitigation efforts and assumptions of how these efforts will be continued into the future. Doing so reveals several important drivers of future emissions and associated temperature pathways.

First, we find that the model used has a larger impact on results than the method used to extend mitigation effort forward, which in turn has a larger impact on results than whether current policies or NDCs are assumed in 2030. The answer to where emissions are headed—which is a critical question to inform policymakers about how much ambition needs to be raised to reach climate targets—might therefore depend more on the choice of models used and the post-2030 assumptions than on the 2030 target assumed. This renders estimates of temperature consequences of NDCs and current policies sensitive to study design and highlights the importance of using a diversity of models and extension methods to capture this uncertainty.

Second, we find policy representation can have a significant impact on how emissions are reduced in modelled pathways. The use of CCS is higher in scenarios that use carbon prices as proxies for real-world policies. Given the prevalence of the use of carbon prices to represent climate policy in IAMs, this has potentially widespread consequences for IAM scenarios. Further research should be done into the effects of this modelling choice and whether a more granular representation of policy effort is preferable.

One of the major challenges for decision makers acting on the information in this study, which shows a diverse range of future pathways, is to understand how to act in the face of this diversity. The many modelling approaches here, which are responsible for this diversity, are reflective of real-world uncertainty in how socio-economic development and climate policy will drive future emissions. These are uncertainties that cannot easily be resolved, but their breadth must be considered if robust decisions on mitigation are to be made.

Using seven IAMs that span a diverse set of approaches, and two different methods for extending likely 2030 mitigation efforts forward, even our most optimistic scenario is insufficient to meet the Paris Agreement goal of limiting global warming to “well below” 2°C. To achieve this goal, global mitigation efforts will most likely have to be strengthened, and new pledges will need to be followed up by concrete policies.

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Methods

PARIS REINFORCE project. The scenarios presented in this paper are based on the first global modelling exercise in the PARIS REINFORCE project, which aimed to develop a new set of global reference scenarios.

Scenarios. All our scenarios take as their starting point the explicit and detailed representations of current policies based on an updated version of the CD-LINKS current policies database, as provided in Supplementary Data 1. Current policies are implemented by region in each model, leading to emissions reductions relative to baselines. When NDCs in a region are more ambitious than current policies, additional mitigation efforts are assumed in that region on top of current policies to achieve the required emissions reductions. Consequently, current policies and NDCs act as increasingly stringent constraints (or upper bounds) on baseline emissions, and we use the terms *current policy constrained* and *NDC constrained* scenarios to distinguish our scenarios from scenarios that are defined directly by NDCs without considering potential overachievement.

The scenarios are extended post-2030 using two different methods. The first method assumes that the rates of emissions intensity (emissions per GDP) reductions implied by current policies and NDCs in 2030 in each model region are continued post 2030. The second method assumes that the model-specific “equivalent” carbon prices implied by current policy and NDCs in 2030 increase with per capita economic growth post 2030 in each model region. The “equivalent” carbon prices are the model-specific economy-wide prices required to achieve the same levels of emissions reductions as current policies or NDCs in each model region when no other (climate) policies are in place.

Both extension methods assume that mitigation efforts post-2030 depend on mitigation efforts leading up to 2030 and that there is no backtracking. This can be justified on two grounds. First, the Paris Agreement requires each successive NDC to “represent a progression beyond the Party’s current” NDC (Article 4.3)[1]. Second, the existence of institutional and political inertia, and enduring behavioural changes, supports the assumption that effort in later periods is related to effort in earlier periods. For this reason, current policies remain in place in all scenarios as “constant” or “minimum” levels after 2030. This is done to ensure no backtracking on sectoral and technology-specific progress made by 2030, such as on renewables shares and fuel efficiency standards.

Additionally, the use of “equivalent” carbon prices to extend scenarios post-2030 leads to a third set of scenarios that reach 2030 targets based on *carbon prices only*. These scenarios are used in this study to analyse the impacts of policy representation on energy systems change.

See Supplementary Text 1 for more information on current policies and NDC implementation. The detailed scenario protocol is provided in Supplementary Text 2.

Models included. Seven global models were included in the exercise. The models were selected to reflect the broad diversity of modelling theories, spanning a range from least-cost energy system optimisation to partial and general equilibrium and to macroeconometric modelling. This diversity, typically sought in model inter-comparison exercises, is crucial for capturing the uncertainty of modelled outcomes and for reaching robust estimates of where emissions may be headed[35]. Despite their differences in economic approach and level of sectoral/technology/emissions coverage or geographic granularity, all seven models feature detailed representation of the energy sector technologies and emissions as well as coverage of the globe and major emitters, which is critical to the scope of this study. Brief descriptions of the models are given below. More detailed model descriptions are provided in Supplementary Text 3.

GCAM and TIAM are partial equilibrium models that achieve equilibrium between the supply and demand for energy in each sector represented, taking into account the changes in energy prices that result from the changes in fuels and technologies used to satisfy energy service demands in these sectors. TIAM operates on a “perfect foresight” welfare cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction and energy price changes over the entire time horizon are considered when minimising the cost of the energy system, so as to provide energy service demands within specified emissions constraints. By contrast, GCAM operates on a “recursive dynamic” cost-optimisation basis, which means that, rather than considering all future time periods, it solves for the least-cost energy system in a given period, before moving to the next time period and performing the same exercise.

MUSE is an energy system models that provides a detailed account of the energy sector, i.e. energy technologies and their associated costs, in order to determine the least-cost ways of attaining GHG emission reductions or the costs of alternative climate policies. It is a bottom-up models that assumes short-term microeconomic equilibrium on the energy system, which is achieved by iterating market clearance across all sector modules, interchanging price and quantity of each energy commodity in each region. In addition, MUSE is also an agent-based model, as it tries to determine a mitigation pathway by providing an as realistic as possible description of the investment and operational decision making in each geographical region within a sector.

Also focusing on the energy system, FortyTwo is a simulation model providing the detailed energy balances for a wide range of countries and regions. The process of energy consumption is modelled as a combination of gross, structural, and technological factors. The model considers the energy intensities trajectories of various sectors and uses their historical trends to estimate the most realistic and smooth pathways for the transition to CO_2 emissions targets.

GEMINI-E3 (called GEMINI throughout the paper) and ICES-XPS (called ICES throughout the paper), two computable general equilibrium (CGE) models with a more detailed, multiple-sector representation of the economy, which consider how the impacts of specific policies spread across economic sectors and regions affect environmental parameters. Their operation is similar to that of GCAM and TIAM but differs in that market equilibrium is assumed to take place simultaneously in each market/region. Their richer representation of the economy requires calibration to data on national and international socio-accounting information, as well as input in the form of a series of elasticities of substitution. Contrary to all other models, market prices of input and outputs are endogenously determined.

E3ME, a highly disaggregated macroeconometric model that, is quite detailed in terms of energy technologies, like CGE models, but differs in that it does not assume consumers and producers to behave optimally or markets to clear and reach equilibrium in the short term. Instead, it uses historical data and econometrically estimated parameters and relations to dynamically and more realistically simulate the behaviour of the economy, by assuming that markets achieve equilibrium in the longer run.

Harmonisation of socioeconomic and techno-economic parameters. We harmonised socioeconomic assumptions (GDP and population growth), technology parameters, and fossil fuel prices to the extent possible across models, using up-to-date data sources to reflect current trends. To increase the comparability of results, we also ensured a high degree of consistency across historical emissions. See Supplementary Text 4 for details on harmonisation.

Temperature estimates. Since we aimed to maximise model diversity, we were limited by the emissions covered by each model. All models provided fossil energy CO_2 emissions, some models provided all GHGs, and only GCAM had forcing and temperature data (based on MAGICC 5.3[36]). To estimate the temperature, we therefore used the transient climate response to cumulative carbon emissions (TCRE) with the temperature contribution from non-CO_2 based on GCAM. This assumes linearity in line with the carbon budget[37] and was calculated using[38]

$$T_{model}(t) = T_{GCAM}(2020) + TCRE \times (1+\Delta n) \times (\sum C(t) - \sum C(2020))$$

where $T_{GCAM}(2020)=1.24°C$ estimated from MAGICC 5.3[36], $TCRE = 0.4503°C/1000GtCO_2$, Δn is the contribution of non-CO_2 components to temperature, and C are fossil energy CO_2 emissions. The method assumes that the non-CO_2 emissions in every model behaves like GCAM. The non-CO_2

contribution, Δn, was back calculated from GCAM. First, the median non-CO_2 forcing relative to total forcing was estimates across all GCAM scenarios to be 19.5% (standard deviation of 0.9%), in line with other scenario datasets (such as the SSP database[39]). Second, this was converted into a scaling factor relative to CO_2, Δn=*s*/(1-s) where *s* is the non-CO_2 share, leading to a value of Δn=0.24. These assumptions gave the reported range of the median temperature response of each scenario of 2.2-2.9°C.

We assessed several uncertainties in our approach. For the non-CO_2 contribution, we tested values of Δn ranging from 0 to 0.33 (which assumes a range from zero non-CO_2 contribution to a share of 33%, the latter which is an outlier value in the SSP database), and these assumptions changed the minimum temperature outcome to 2.0°C with zero non-CO_2 contribution (down from 2.2°C) and the maximum temperature outcome to 3.0°C with maximum non-CO_2 contribution (up from 2.9°C). This small variation due to non-CO_2 assumptions shows that cumulative CO_2 emissions (and associated TCRE assumptions) dominate at these temperature levels. To assess the uncertainty in the climate system, we took the likely range of the TCRE (IPCC) from 0.2183°C/1000GtCO_2 to 0.6824 °C/1000GtCO_2. This changes the temperature range down to 1.7°C (instead of 2.2°C) and up to 3.8°C (instead of 2.9°C), indicating the uncertainty in the TCRE is much larger than the uncertainty in the impact of non-CO_2 emissions.

Extrapolation of emissions intensity scenarios to 2100. For those models with a 2100 time horizon (TIAM, MUSE, GCAM) all scenarios were run to 2100 to get the temperature estimates. For the remaining models (E3ME, FortyTwo, ICES, GEMINI), emissions in all emissions intensity scenarios were extrapolated to 2100. This was done by continuing the rates of emissions intensity reductions implied by current policies and NDCs in 2030 in each of the native regions in these models to 2100 (instead of just to 2050 (2045 for FortyTwo)). Carbon price scenarios could not be extrapolated in the same way for models with a 2050 time horizon (ICES, GEMINI, E3ME) because emissions in these scenarios are solved endogenously post-2030. This means that our temperature range includes all emissions intensity scenarios and three (out of six) carbon price scenarios. Since the former are more optimistic, the low end of our temperature range is more robust than the high end, which does not, for instance, include the high GEMINI current policy constrained carbon price scenario.

Data availability

The datasets[41] generated during, and analysed in, the current study are available from a public repository (https://doi.org/10.5281/zenodo.5528951).

Code availability

The code for the analysis in this paper is available upon request to the corresponding author. The code availability for the individual models used in this paper varies and contact should be made to individual modelling groups. The GCAM model is available for download from https://github.com/JGCRI/gcam-core. Detailed model documentation for all seven models is available online at https://www.i2am-paris.eu/detailed_model_doc.

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Competing interests. The authors declare no competing interests.

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Tables

Table 1 Scenarios

Scenario	2030 target[a]	Post-2030 assumption	Description
CP_Intensity	Current policy	Constant rate of emissions intensity[b]	Scenario exploring where emissions are headed assuming current policy to 2030 and constant rates of emissions intensity reductions thereafter
CP_Price	Current policy	Carbon price[c] increasing with per capita GDP	Scenario exploring where emissions are headed assuming current policy to 2030 and carbon prices increasing with per capita GDP thereafter
NDC_Intensity	NDCs	Constant rate of emissions intensity[b]	Scenario exploring where emissions are headed assuming NDCs to 2030 and constant rates of emissions intensity reductions thereafter
NDC_Price	NDCs	Carbon price[c] increasing with per capita GDP	Scenario exploring where emissions are headed assuming NDCs to 2030 and carbon prices increasing with per capita GDP thereafter
Baseline			Model baseline scenario. May or may not include policies. Harmonised socio-economic and techno-economic parameters.
CP_PriceOnly	Current policy	Carbon price[c] increasing with per capita GDP	Scenario reaching same 2030 levels of emissions as CP_Price using economy-wide carbon prices only (no explicit representation of policies before or after 2030).

[a] Current policy and NDCs are implemented as increasingly stringent constraints on baseline emissions in each native model region. That is, emissions reductions in baseline scenarios beyond those implied by current policies are included in current policy scenarios and emissions reductions in current policy scenarios above those implied by NDCs are included in NDC scenarios in each native model region.

[b] Emissions per GDP

[c] Carbon prices vary by model (see Methods).

The scenarios are explained in more detail in Methods. The full scenario logic and scenario protocol are included in Supplementary Text 2.

Table 2 Model key characteristics

Model	Model type	Solution dynamic	Time horizon	Baseline emissions	Policy/NDC impact	Emission outcome	Key characteristics explaining emissions outcomes across models
E3ME	Macro-econometric	Co-integration	2050	M	L	M	The baseline incorporates IEA WEO (2019) current policies, leading to only moderate emissions increases. This also explains the low policy/NDCs impact.
FortyTwo	Energy system	Simulation	2045	H	M	M	Relatively high final energy in transport and buildings leading to relatively high baseline emissions. Moderate impacts from policy and NDCs by 2030 leading to noticeable emissions reductions.
GCAM	Partial equilibrium	Recursive dynamic	2100	H	H	M	Baseline emissions continue historical trends based on increasing energy demand met predominantly with fossil fuels. Current policies and NDCs have a moderate impact on emissions, bringing them down through both renewable energy penetration and electrification.
GEMINI	Computable general equilibrium	Recursive dynamic	2050	H	H	H	Global energy demand depending on fossil energy with limited deployment of renewable leads to high baseline emissions. Both current policies and NDCs substantially impact emissions, but not sufficiently to offset the high increase of emissions in the baseline.
ICES	Computable general equilibrium	Recursive dynamic	2050	M	M	M	Efficiency measures in the baseline lead to a moderate increase of CO_2 emissions. Current policies have a moderate impact on emissions due to the limited number of policies that can be accounted for in ICES. NDCs have a stronger impact.
MUSE	Partial Equilibrium – Agent Based Model	Recursive dynamic	2100	L	L	L	Conservative assumptions on energy service demand growth in industry and efficiency improvements in transport leads to a transition away from oil and gas (in favour of biofuels and electricity) and strong decarbonisation already in the baseline. Current policies are quite close to this baseline, whereas NDCs result in some additional decarbonisation through renewable energy penetration and electrification.
TIAM	Partial equilibrium	Inter-temporal optimisation	2100	M	H	L	Conservative assumptions on energy service demand growth in transport sector and electrification and efficiency measures leading to decreasing oil and stable baseline emissions. High current policy and NDC impacts by 2030 leading to significant emissions reductions when efforts are extended.

H-High, M-Medium, L-Low give relative measures of emissions and emissions reductions caused by current policy and NDCs (from baselines). For Baseline CO_2: H: > 40 $GtCO_2$ by 2050, L: < 30 $GtCO_2$ by 2050, M: 30-40 $GtCO_2$ by 2050. For Policy/NDC impact and emission outcomes: H, M, L based on considering ranges spanned by CP/NDC scenarios for each model relative to the ranges spanned by other models. Further details on model types and solution dynamics are provided in Supplementary Text 3 and in the online model documentation (links in Supplementary Table 1).

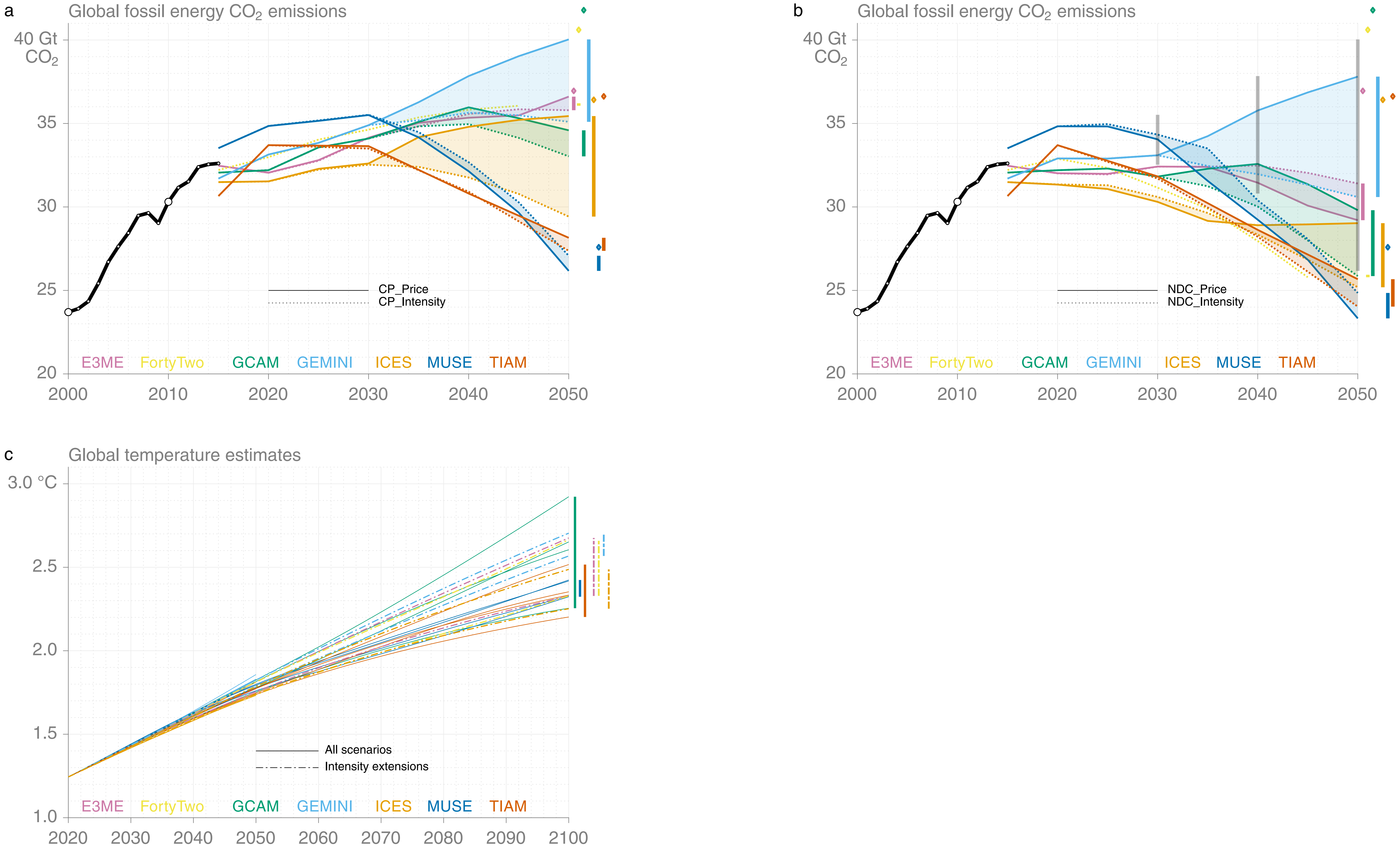
Figures Captions

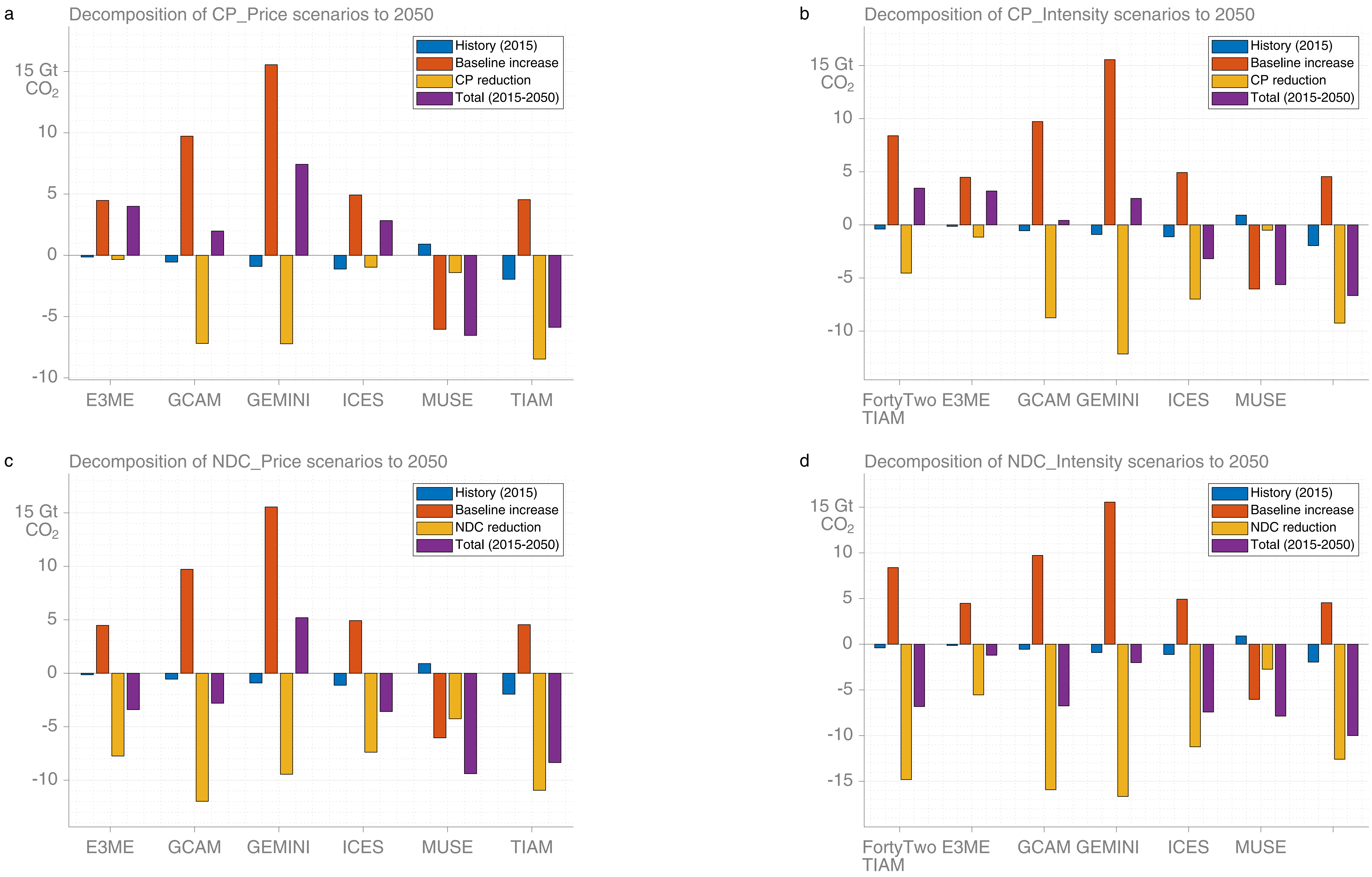
Figure 1 Global energy CO_2 emissions and temperature estimates. a, Global energy CO_2 emissions to 2050 in CP scenarios. Shaded areas show emissions spanned by CP_Price and CP_Intensity scenarios for each model and colored bars show 2050 ranges (2045 value for FortyTwo, which only has intensity scenarios). Markers above bars show baseline values in 2050 (in 2045 for FortyTwo). GEMINI baseline value in 2050, 47.25 Gt CO_2, s outside the range shown in the figure. Historical emissions (black lines) from ref.[40]. **b,** Global energy CO_2 emissions to 2050 in NDC scenarios. Shaded areas show emissions spanned by NDC_Price and NDC_Intensity scenarios for each model and colored bars show 2050 ranges (2045 value for FortyTwo, which only has intensity scenarios). Markers above bars show baseline values in 2050 (in 2045 for FortyTwo). GEMINI baseline value, 47.25 Gt CO_2, is outside the range shown in the figure. Grey bars show CP scenario emissions ranges (all models). Historical emissions (black lines) from ref.[40]. **c,** Global temperature estimates (as described in Methods) with bars showing 2100 ranges. 2100 temperature ranges include all scenarios (CP_Intensity, CP_Price, NDC_Intensity, NDC_Price) for the three models that run to 2100 (GCAM, TIAM, MUSE) and intensity scenarios (CP_Intensity, NDC_Intensity) for the remaining models (FortyTwo, GEMINI, ICES, E3ME) (see Methods). Temperature estimates from all scenarios shown up to 2050 (2045 for FortyTwo).

Figure 2 Decomposition of global energy CO_2 emissions. Blue bars show baseline emissions in 2015 minus CEDS[40] emissions in 2015, red bars show baseline emissions in 2050 minus baseline emissions in 2015, and yellow bars show scenario emissions in 2050 minus baseline emissions in 2050. Purple bars show scenario emissions in 2050 minus CEDS emissions in 2015 (the sum of the blue, yellow, and red bars). FortyTwo does not model price scenarios and runs only to 2045, hence 2045 values are used for FortyTwo.

Figure 3 Final energy consumption by fuel and by sector. Data is presented for 2020 (top), 2030 (middle), and 2050 (bottom). The left column shows the fuel consumption in all the demand sectors of electricity, gases (from bioenergy, such as biogas and biomethane, or from fossil, such as natural gas), heat, hydrogen, liquids (from bioenergy, such as biofuels, or fossils, such as petrol and kerosene), solids (from biomass or fossils such as coal), and other fuels (including solar and geothermal) across models and scenarios over time. The right column shows total sector final energy consumption in industry, transport, residential and commercial (buildings), other sectors (such as agriculture, forestry, fishing, and livestock) and in non-energy across models and scenarios over time. *In 2050, 2045 values are shown for FortyTwo (the end year of the model).

Figure 4 Carbon capture and storage (CCS) in carbon price only scenarios and in main scenarios. a, CCS in CP scenarios to 2030 (where CP_Price is equal to CP_Intensity) and in CP_PriceOnly scenarios. CP_PriceOnly scenarios reach the same level of emissions in every modelled region in 2030 as CP scenarios but use economy-wide carbon prices as a proxy for current policies. Four models include CCS and CP_PriceOnly scenarios (GCAM, TIAM, MUSE, GEMINI), but GEMINI does not deploy CCS until after 2030. E3ME has CCS but did not run carbon price only scenarios because the E3ME baseline already includes explicit policies. **b,** CCS to 2100 in all main scenarios for all models that include CCS (TIAM, MUSE, GEMINI, GCAM, E3ME). GEMINI includes only fossil CCS; all other models have fossil CCS and bioenergy with CCS (BECCS). Only GCAM has industry CCS (contributing 1.1Gt CO_2 in NDC_Intensity scenario in 2100). ICES and FortyTwo do not have CCS.


a
Global fossil energy CO$_2$ emissions
40 Gt CO$_2$
35
30
25
20
2000
2010
2020
2030
2040
2050
CP_Price
CP_Intensity
E3ME
FortyTwo
GCAM
GEMINI
ICES
MUSE
TIAM
b
Global fossil energy CO$_2$ emissions
40 Gt CO$_2$
35
30
25
20
2000
2010
2020
2030
2040
2050
NDC_Price
NDC_Intensity
E3ME
FortyTwo
GCAM
GEMINI
ICES
MUSE
TIAM
c
Global temperature estimates
3.0 °C
2.5
2.0
1.5
1.0
2020
2030
2040
2050
2060
2070
2080
2090
2100
All scenarios
Intensity extensions
E3ME
FortyTwo
GCAM
GEMINI
ICES
MUSE
TIAM

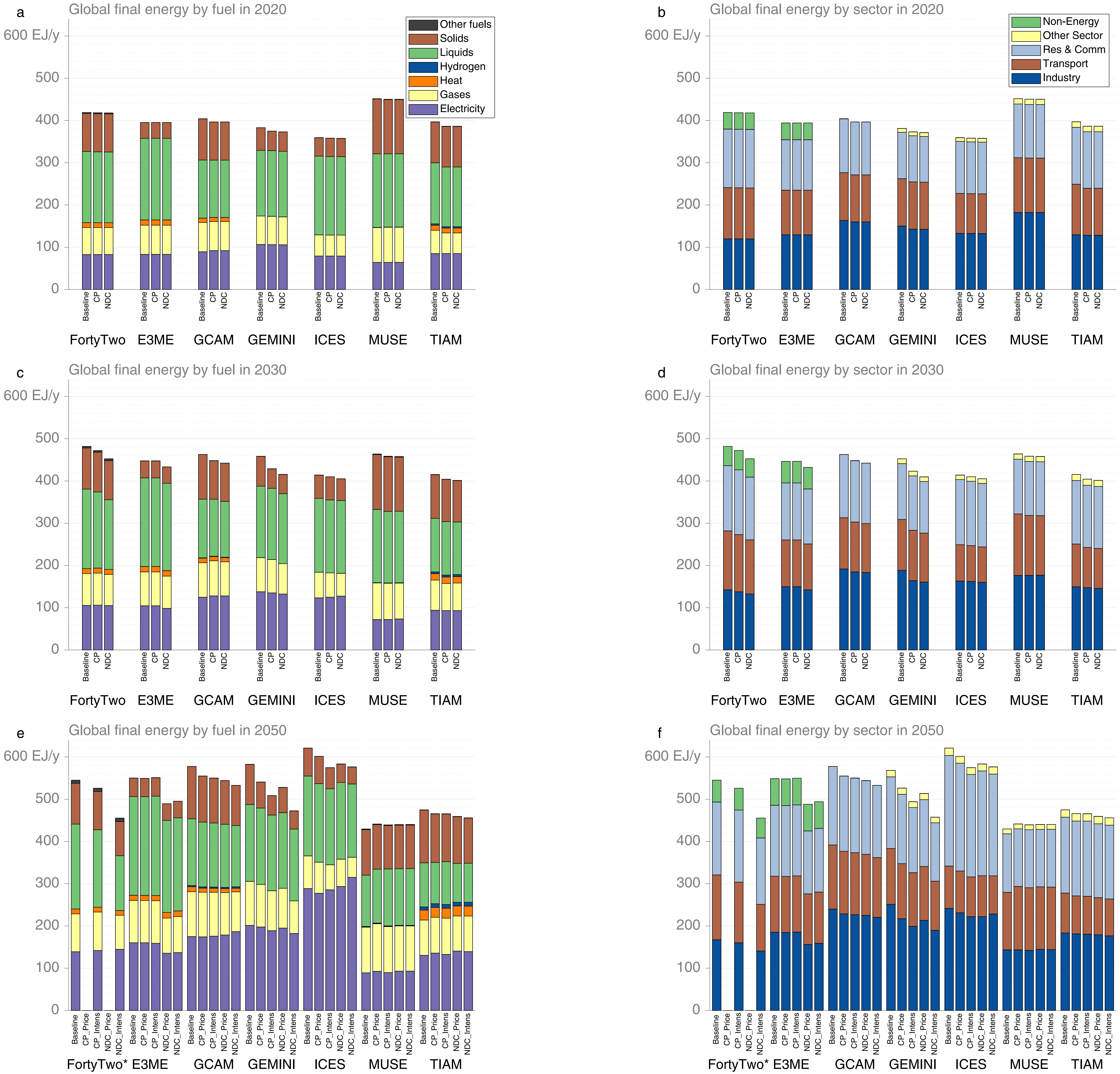


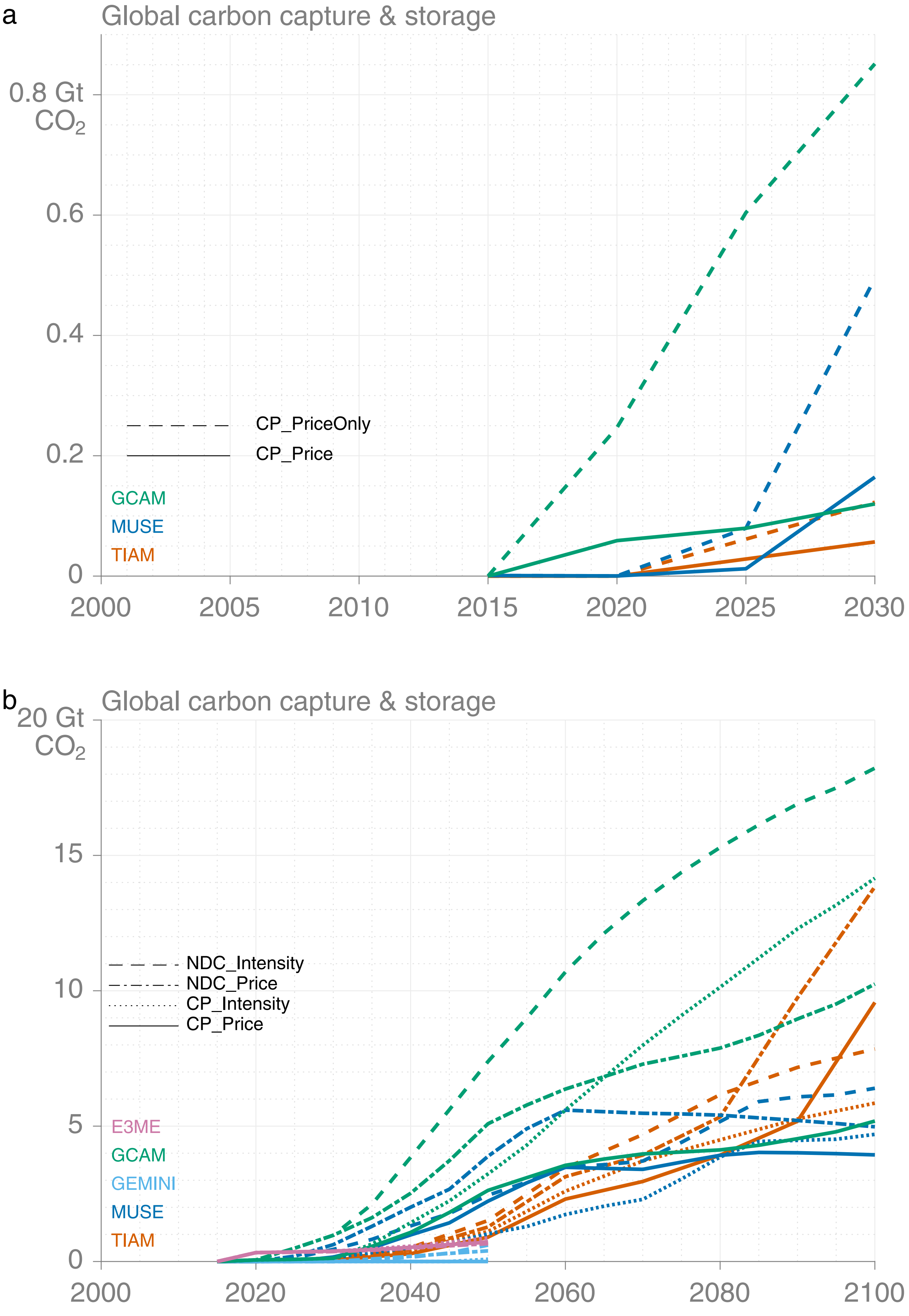
a Decomposition of CP_Price scenarios to 2050

b Decomposition of CP_Intensity scenarios to 2050

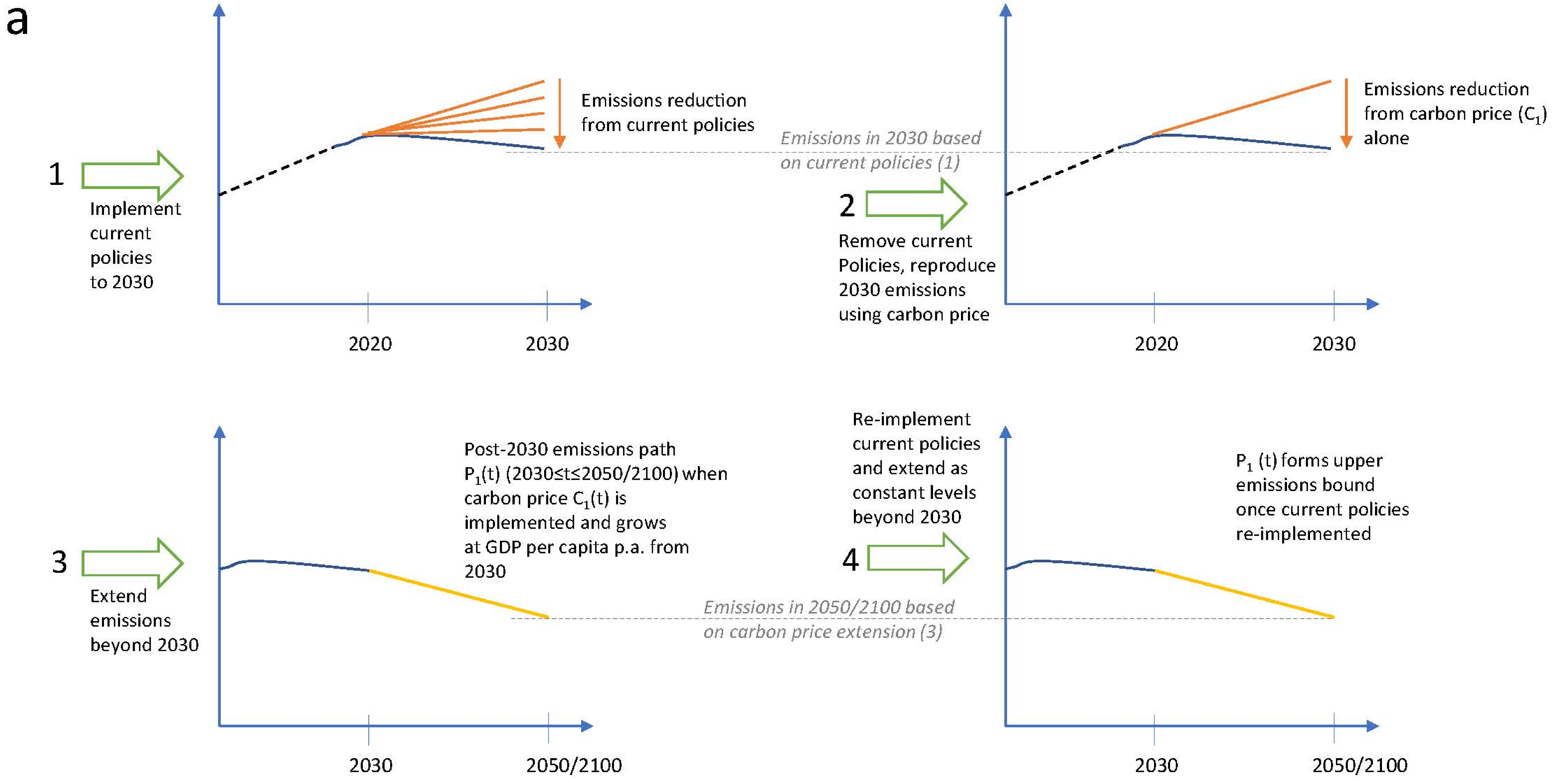
c Decomposition of NDC_Price scenarios to 2050

d Decomposition of NDC_Intensity scenarios to 2050

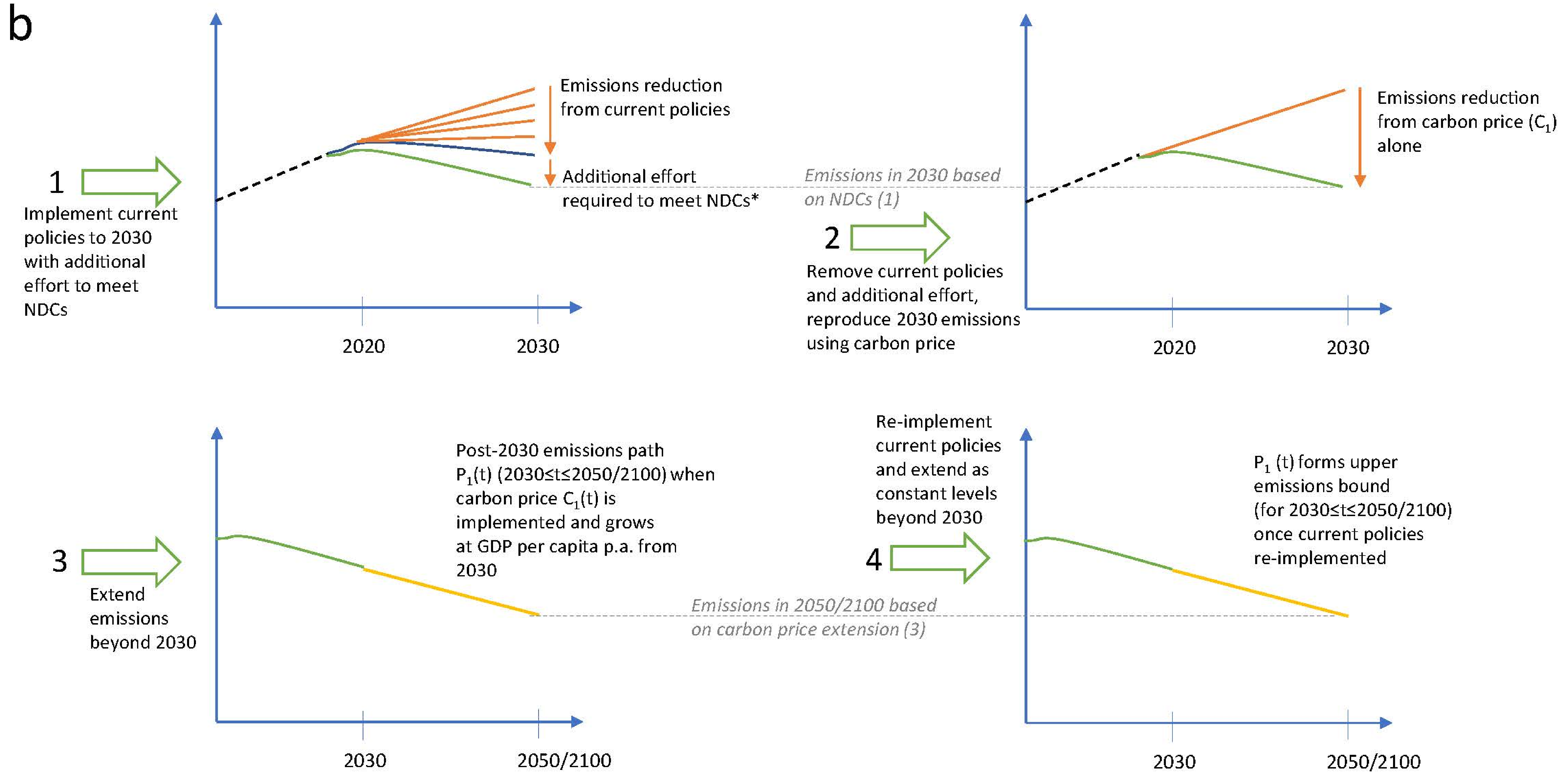

a
Global final energy by fuel in 2020
b
Global final energy by sector in 2020
c
Global final energy by fuel in 2030
d
Global final energy by sector in 2030
e
Global final energy by fuel in 2050
f
Global final energy by sector in 2050
600 EJ/y
500
400
300
200
100
0
Other fuels
Solids
Liquids
Hydrogen
Heat
Gases
Electricity
Non-Energy
Other Sector
Res & Comm
Transport
Industry
Baseline
CP
NDC
CP_Price
CP_Intens
NDC_Price
NDC_Intens
FortyTwo
FortyTwo*
E3ME
GCAM
GEMINI
ICES
MUSE
TIAM


a
Global carbon capture & storage
0.8 Gt CO$_2$
0.6
0.4
0.2
0
2000
2005
2010
2015
2020
2025
2030
CP_PriceOnly
CP_Price
GCAM
MUSE
TIAM
b
Global carbon capture & storage
20 Gt CO$_2$
15
10
5
0
2000
2020
2040
2060
2080
2100
NDC_Intensity
NDC_Price
CP_Intensity
CP_Price
E3ME
GCAM
GEMINI
MUSE
TIAM

CP_Price: Current policies with carbon price extension



NDC_Price: NDCs with carbon price extension



*For most models additional effort will be represented by the carbon price required (on top of current policies) to meet NDC targets. This carbon price is independent of the carbon price (C_1) in 2. Note, if for any region, current policies outperform NDCs (i.e. current policies lead to larger emissions reductions than NDCs), emissions are defined by current policies, not the NDC targets.