A framework for national scenarios with varying emission reductions

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Editor's summary

Currently there is no common structure to how national emissions scenarios are created, hindering efforts for comparison and analysis at the larger scale. This Perspective presents a framework to guide individual national scenario creation in a standardized way.

National-level climate actions will be vital for achieving global temperature goals in the coming decades. Near-term (2025-2030) plans are laid out in Nationally Determined Contributions (NDCs); the next step is submission of long-term strategies (LTS) for 2050. Currently, national scenarios underpinning LTSs are poorly coordinated and incompatible across countries, preventing assessment of individual nations' climate policy. Here we present a systematic and standardised, yet flexible, scenario framework varying 2050 emissions to build long-term national energy and climate mitigation scenarios. Applying the framework to six major Asian countries reveals individual challenges in energy system transformation and investment needs in comparable scenarios. This framework could be a starting point for comprehensive assessments as input to the global stocktake over the coming years.

Main text

Introduction

The Paris Agreement[1] defines a long-term temperature goal for international climate policy: "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". While this global goal defines the fundamental direction of international climate policy, its achievement critically depends on national actions and policy making at the national level. As part of the agreement, countries are required to submit Nationally Determined Contributions (NDCs) outlining their greenhouse gas (GHG) emissions reduction efforts at the national scale. Within the Paris Agreement, there are several mechanisms to ensure that national actions align with the global goals; first, parties are required to regularly report on their progress towards implementing their NDCs. These reports form part of the so-called global stocktake, i.e., an assessment of the sum of the national contributions. Second, countries are also required to submit long-term strategies (LTS) to the UNFCCC (also called mid-century strategies). Some countries have already submitted them, and others are preparing to do so (at September 2020). Third, the Paris Agreement contains provisions to increase efforts over time, through what has been dubbed the "ratchet mechanism". In summary, one objective of the agreement is to have national actions aligned with long-term goals, with routine checks and revisions of short- to medium-term national goals and policies.

Model-based climate and emissions scenarios are pivotal instruments for determining whether proposed actions are in line with the long-term goals [2, 3]. In the fifth assessment report of the IPCC (AR5), over a thousand scenarios were summarized in the database, assessed and classified by both assumption and mitigation levels[4]. The special report on 1.5°C was also accompanied by a large set of global scenarios that depict emissions pathways through the 21st century[5]. A large number of global model scenarios have been developed under specific model inter-comparison projects (MIPs) by sharing scenario implementation protocols that prescribe the characteristics of the scenarios (e.g. carbon budgets, technological availability). This allows for a systematic assessment of a set of research questions and to identify robust insights on climate change mitigation[6, 7, 8, 9].

Similarly to the role of global emissions scenarios in international negotiations, national scenarios have widely contributed to national policy making[2]. In several countries and regions, this is done by national modeling teams, but results are largely disseminated in governmental reports or as internal information, and only occasionally shared in academic papers[10, 11, 12]. Taking Japan as an example, a task force was established to determine the 2020 emission target in 2008, and its recommendations were published in a book[10] (only available in Japanese) while for the NDCs submission, there was no official scenario assessment. MIPs exist not only at the national level (for the US, China, Brazil and Japan[13, 14, 15, 16]), but also for specific regions such as the EU[17], Asia[18], Latin America[19]. There have been a few attempts to collect national scenarios such as in the CD-LINKS (Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing)[20, 21] which also includes indiviual national scenarios[22, 23, 24, 25, 26, 27, 28], COMMIT (Climate pOlicy assessment and Mitigation Modeling to Integrate national and global Transition pathways): https://themasites.pbl.nl/commit/)[29] and DDPP (The Deep Decarbonization Pathways Project) [30, 31] projects. Moreover, there have been various studies assessing national NDC implications from sectoral perspectives [32, 33, 34, 35] to the broader SDGs context[36, 37, 38, 39]. It should also be noted that many countries do not have publicly available national energy or emissions scenarios.

Some major emitting countries rely on the scientific basis of existing national scenarios for national climate policymaking[36, 40], while many others do not. Furthermore, the emissions reduction targets of national scenarios are either determined by their own countries' interpretation of global goals (e.g. such as taking 2 °C consistent pathways and judging these by themselves) or are derived from global scenarios such as those based on either cost-optimal scenarios or effort sharing schemes[41] (see left in Table 1). While recent efforts made by national MIPs (e.g. CD-LINKS) have shared a scenario protocol across countries based on global IAM results, these allow only an assessment of quite specific conditions (.e.g cost-optimal and global uniform carbon price). Moreover, the modeling capability and the main strategies of GHG emissions reduction can be diverse across nations. Consequently, the level of emissions mitigation in national scenarios varies, which implies challenges for comparing mitigation costs, and the degree of energy system changes across countries and scenarios. Apart from scenarios, real national emissions targets for both the near-term and long-term have often changed and will continue to do so in the future as well under various political and social circumstances. If only scenarios under specific but limited emissions reduction targets are available, the national scenarios are quickly outdated and become irrelevant (complexity of national scenarios are discussed more in the section "**Complexity in the assessment of national scenarios**").

Given this current situation, what if there were a standardized scenario framework which covers a wide range of emissions targets under the same reduction targets that are shared and implemented by many countries? For example, suppose that there were publicly available scenarios to reduce national emissions by 80% or 100% (not cumulative emissions) in 2050 for dozens of countries. What would be the benefits for national policy making of such a scientific basis standardized scenario framework? There are at least four key benefits. One, it would reveal the dynamics of each nation's energy, land-use, and agricultural systems as well as economic implications if the selected countries were to reduce emissions by similar levels. For example, a Japanese energy model comparison study was conducted, which found that even under the 80% reduction target in 2050, Japan would still have relatively high industrial sector energy demands because of its large dependency on heavy industry and limited renewable energy sources due to the small area of the country in comparison with the EU and the United State[14]. This kind of assessment would become available on a broader scale. Two, the transparent publication in scientific literature of the scenarios, the simulation models, and how the scenarios were generated would contribute to ensuring that the scientific basis and quality of models and scenarios are maintained, to some extent, although it happens more frequently than before[21]. This is critical for evidence-informed policymaking. Three, this might allow a direct comparison of the challenges that countries are facing in achieving emissions reduction targets, which would be valuable when assessing the forthcoming national long-term climate targets from the perspective of social transition. Finally, four, this would allow climate policymakers to compare each country's emissions targets and assess whether their own national targets are compatible with other countries' multiple reduction targets possibilities or sufficient to reach the global long-term goals. Ultimately, policymakers may want to update the national targets; these are already supposed to undergo routine reviews as part of the global stocktake under the Paris Agreement. Although individual nations would have their own interests and priorities and the standardized simple scenario may not be completely sufficient to assess the national climate policies, such scenarios could at least be an entry point to communicate with policymakers in many countries. From there, each country could build their own specialized and customized scenarios. We summarized the global and national modeling and scenarios circumstances in Table 1.

Here, we present the issues with current national scenarios, propose a systematic and standardized scenario framework, and demonstrate the implementation of such a framework for a few selected countries. Our proposal can ultimately contribute to the establishment of a central national scenario datahub for further national scenario assessments, similar to what has already been done for global scenarios (see Table 1). Next, we discuss the complexity and expected criteria of national scenarios.

Table 1 Summary of the characteristics of global and national scenarios

	Global scenarios	National scenarios
Producers	Integrated Assessment Models	National energy/Integrated Assessment Models
Main users of the research outcomes	IPCC, UNEP, UNFCCC, international and national policymakers	National policymakers, private companies, stakeholders and IPCC
Main study target	Global climate goals and associated implications for climate, energy, economy and land-use etc.	Individual national climate goals/targets and their implications for energy, economy, land-use, etc.
Scenario implementation	Individual studies or standardized modeling protocols implemented by multiple models	Some standardization in projects, but mostly specific and varied
Community organization	Well established as Integrated Assessment Modeling Consortium (IAMC)	Partially organized in different communities, often as part of a modeling framework (e.g., The Energy Technology Systems Analysis Program (ETSAP)), but also to an extent in IAMC

Complexity in the assessment of national scenarios

For short- to medium-term perspectives, focusing on the next ten years, national policies and policy options as well as stakeholder interests are the primary concerns. In contrast, from a long-term perspective, a simple, comparable and systematic approach has clear benefits, facilitating a reassessment of the option space. It should be recognized that there are many determinants that are relevant for the specification of national emissions pathways, such as i) global climate targets in the context of international commitments; ii) how to select global pathways in line with global long-term goals (e.g. multi-IAMs uncertainty and physical climate science uncertainty); iii) selection of effort sharing schemes; iv) economic development stages in individual countries; v) other societal and development priorities that may be critical factors to determining the challenges of emissions reductions. The emissions reduction levels and challenges to achieving them naturally vary across countries and scenarios, and there is no need to have identical reduction levels across countries. Additionally, the current NDCs, which are based upon each nation's voluntary actions, are in many cases ambiguous, leading to significant uncertainty regarding the actual level of emission reduction targets[42]. This may be or may not be because nations would prefer to keep some flexibility in the interpretation of their target statements, resulting in a remarkable degree of flexibility significant enough to change long-term global implications[42]. Either way, this would imply that, in principle, it is inevitable to have some degree of uncertainty in the actual national targets, and we should eventually develop strategies to cope with such uncertainties. (See more explanation for each uncertainty in Supplementary Note.)

Expected criteria for upcoming national scenarios

Given the above-mentioned uncertainties, here we discuss the expected characteristics of the national scenarios, as listed below:

- Cross-national comparability
- Compatibility and cohesion with global climate goals
- Policy relevance
- Ability to address critical national target uncertainties
- Simple implementation without ambiguities in the interpretation of the modeling protocol

The comparability, which enables exploration of the comparative stringency of national targets, is particularly beneficial for assessing national scenarios. One possible way to achieve this is fixed reduction rates across countries (e.g., 80% reduction compared to a base year). The implications for the energy, land-use, and economic transitions can reveal the associated challenges. Regarding the cohesion with global emissions pathways, global emissions scenarios with the climate goal specifications (e.g., 2 and 1.5 °C) in conjunction with effort sharing assumptions[41] can bridge national and global scenarios. There can be a large variation in national emissions pathways derived from the combination of effort sharing and global pathways, but we will show how our proposed framework in this paper can be easily mapped with global scenarios. For scenarios to be policy relevant, the emission reduction levels should not be far from the targets laid out in forthcoming national LTSs. Exploring multiple mitigation levels has the advantage of identifying potential ambiguities in forthcoming LTSs, as well as enabling sensitivity analyses around the eventual LTSs. For example, supposing that the LTS for a country does not specify the GHG coverage but declares a 50% reduction target in 2050, multiple scenarios would be mapped with full Kyoto gases cases and only CO_2 cases. A similar approach can be applied to other ambiguities. Finally, the simplicity of a modeling protocol that avoids ambiguities in its interpretation and the ease of implementing scenarios are of key importance to (i) allow such exercises to be performed in a decentralized manner, and (ii) keep the barrier for joining such an effort as low as possible. The simplicity would facilitate the updating of these scenario exercises on a regular basis, which will be discussed in the next section in more detail.

Proposal for a systematic national scenario framework

We, thus, propose a systematic and standardized approach for national scenarios that appropriately cover plausible future ranges of mitigation pathways and enables comparison across countries. Here we refer to this framework as “National Long-term Pathways” (NLPs), which comprises a set of national scenarios explained below. The role of NLPs could resemble Representative Concentration Pathways (RCPs)[43] in formulating the ambition and range of climate targets. As defined by the earlier study, we use the term scenario to describe a plausible, comprehensive, integrated and consistent description of how the future might unfold whereas the term pathway is used for a set of scenarios[44]. This NLPs approach permits hedging against future national target uncertainties by not specifying a single emission reduction target, instead, exploring multiple systematic scenarios associated with percentages of emissions reductions in 2050, the commonly considered target year for LTS, as a default set.

We classify two kinds of scenarios. One is the so-called baseline, which excludes climate change mitigation policy but can include currently implemented and planned policies as implemented in earlier literature[2]. Other socioeconomic assumptions are up to the individual modeler’s choice but are encouraged to be without unusual specific assumptions such as without CCS[45] and low energy demand[46]. Although this modeler’s choice might sometimes make the assessment and interpretation of the results difficult because socioeconomic backgrounds can differ among countries, there is an advantage in being able to skip a process to discuss what socioeconomic assumptions should be used and reach an agreement. More importantly, globally standardized socioeconomic scenarios such as the Shared Socioeconomic Pathways (SSPs) [47] would not be best for individual countries and thus, the selection and assumption of socioeconomic conditions would depend on each country. If the national modellers cannot access national socioeconomic perspectives, the use of globally standardized SSPs would be recommended. The second kind are climate scenarios which target 10 to 100% of emissions reduction in 2050 compared to base year emissions, with 10%-point increments covering the space between them. This can also be mapped with intensity targets, such as carbon intensity with GDP assumptions. For 2030, NDC targets can be adopted but these may have variations associated with conditional/unconditional targets. Considering the current political situation, in which many countries are announcing carbon neutrality targets for different years, which are not always 2050, our proposed emissions pathways can be easily extrapolated linearly beyond 2050 and can be assessed from the timing of zero emissions and the required transition towards that goal. If a model is unable to get feasible solutions for specific scenarios because emissions reductions are too strict, this information would also be reported. Energy-related CO_2 emissions are the default emissions coverage. As we will discuss later, although there can be multiple options in the coverage of species and sectors (e.g. full GHG, including land sector), we chose specific emissions as defined above for two main reasons. First, energy-related CO_2 emissions are currently the major source of emissions in most countries. Second, national modeling concerned with climate change mitigation policy is, in many cases, initiated from energy modeling, and considering developing countries whose modelling capability is relatively low, limiting the scope of coverage would be effective for enhancing participation. Incorporation of other CO_2 and non-CO_2 emissions is not limited because they are critical elements that determine the total GHG emissions. Additionally, it is important to design a holistic human system from the energy, land-use, and economic perspectives. The reduction percentages are relative to the specific base year (e.g., 2010) for which the national emissions inventory is available for most countries and can thus exclude unnecessary uncertainties in the current NDCs. In this way, the NLPs proposal meets the criteria stated above, with comparability across countries, compatibility and cohesion with global climate goals, policy relevance and a relatively simple implementation protocol, and a strategy to address uncertainties.

There should be flexibility in this proposal regarding at least the following two points. First, there are several options for emissions gas coverage. Full Kyoto GHG would yield the best coverage, but sectoral and gas coverages can vary. For the gas coverage, this could include only CO_2 or three major GHGs (CO_2, N_2O and CH_4). The sectoral coverage would be either full-sector or energy related emissions only. This coverage should be considered depending on the availability of the information, composition of gases (e.g. Brazil could have a large portion of emissions from land-use sector) and model capability for each country. For non-CO_2 emissions, the Global Warming Potential (GWP) should be standardized and a GWP100 metric should be used, as applied by UNFCCC and IPCC as the default choice in their reporting. Second, the reduction levels can be changed depending on country. For example, baseline emissions would not be increased for developed countries, while most developing countries can have much higher emissions in the future than now and starting the reduction percentage from 0% could still be deemed ambitious. For developed countries, more granularity might be needed for the range of deep reductions, and thus 5%-point increments between 70-100% could be also attractive. The base year can also be flexible if needed (see further flexibility options in Supplementary Table 1).

We also propose to routinely and periodically run this systematic scenario framework. In the global IAM community, there are series of almost routine-basis MIPs (e.g. Energy Modeling Forum (EMF)), which now have a large influence on global climate policies. In contrast, national scenarios are not yet so well-established and can derive much more benefit from a scenario generation routine. There are multiple options for the routine intervals, such as every five years, every IPCC assessment cycle, or international political milestones (e.g., every global stocktake). The pros and cons of these choices can be considered later, but here we emphasize the advantages of having a regular scenario exercise under a similar protocol. First, the research community would be able to routinely provide policy-relevant information, tracing the model development history and tracking how the scenarios have changed over the period. Second, these regular exercises would allow individual countries' researchers to anticipate the forthcoming exercises and prepare a plan for model development as well as take advantage of funding opportunities. In particular, this would be useful for developing countries where the energy models/IAMs are not yet fully developed. Note that it might be challenging to have completely harmonized protocols over time as political circumstances change (e.g., NDC and its updates). The need for the routine exercise can also be extended to the global integrated assessment modeling community; the climate modeling community has such an experimental design, namely the Diagnostic, Evaluation and Characterization of Klima (DECK), under the umbrella of so-called Coupled Model Intercomparison Project (CMIP)[48].

Keeping the scenario protocol simple is important, which would enable modelers to implement the scenarios in regular intervals. In the meantime, in theory, tens of scenario variations depending on socioeconomic, technological availability/cost, and policy assumptions could be developed. For example, SSPs in the global modeling community allows us to explore the variation of future socioeconomic assumptions[47]. Concerning variations in technological availability and cost, there are well-known examples in the global study carried out under EMF27 and AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates) projects[45, 49] (e.g. none carbon capture and storage (CCS) scenario). Furthermore we can see similar national or regional implementations[50, 51, 52]. These scenario variations can be added to the standard set as supplementary (extended) scenarios which are similar as proposed in the SSPs[53].

Regarding the relationships with policymakers, there are at least three main roles. First, for those countries that have not yet developed national scenarios, obviously, NLPs can provide opportunities to generate national scenarios, which would create dialogue between modellers and policymakers. Second, regardless of the existence of the national scenarios, comparable multi-national scenarios can provide meaningful insights for each national policymaker because national climate policy cannot be independent of the international context. These two benefits are valid for both short-term and long-term. Third, while it would be valuable to continue routine-based standardized scenario making, more customization of the scenarios for each country might be needed in terms of socioeconomic assumptions and some specific national interests in the long-term (e.g. no more nuclear power in Japan). The role of NLPs would then become an entry point for shifting from the standardized and systematic approach to creating such individual and unique national scenarios. Eventually, NLPs would be a platform to maintain the national scenario modeling community which can enhance a dialogue among modelers and policymakers similar to CMIP as mentioned earlier.

Demonstration of the proposal scenario design

To explore how this newly proposed scenario set can be used, we have implemented the proposed framework in selected Asian countries which have a large diversity in economic development stages, economy size and energy consumption patterns: China, India, Japan, Korea, Thailand, and Vietnam. Each country individually runs national models, which means that countries do not change international market conditions. For scenario quantifications, we used AIM (Asia-Pacific Integrated Model) which has been extensively applied in global and national climate change mitigation studies (see **Methods**).

We first focus on an assessment of a single country, in this case, Japan (Fig. 1). The emissions in the baseline scenario (BaU) are almost unchanged throughout the period, whereas climate mitigation scenarios, named CM30, CM40 to CM100, meet the NDC emission reduction target of 26% in 2030 and hit incremental 10% reductions levels as prescribed in the protocol in 2050 (Fig. 1**a**). Then, we compare projected emissions in 2050 with the global emissions pathways in conjunction with effort sharing schemes (Fig. 1**bcd**) (see **Methods**). Since we consider the multi-scenario uncertainties of global IAMs emissions pathways for 1.5°C and 2°C climate stabilization, at the national level there is a large range of emissions levels associated with various effort-sharing schemes (Fig. 1**d**). Here we also illustrate emissions target space with the long-term national goal for 2050, which in case of Japan is an 80% reduction, but there is a range because the reference year and the GHG coverage is unspecified.

Then, the energy system and economic implications for each emission reduction level are presented which depend on the emissions reduction target levels (Fig. 1**efg**). For example, the total energy supply is almost constant under a 30-60% reduction, while the scenario with a 100% reduction in emissions implies a drop in supply by around half of the baseline. In other words, beyond 60-70% of emission reductions a significant contribution of demand-side measures, including both energy efficiency improvements and behavioral change, are needed. Regarding the composition of energy sources, the contribution from low carbon energy technologies sources such as CCS and renewable energy sources gradually increase as reduction levels rise. Macro-economic costs of mitigation increase remarkably with more ambitious targets (Fig. 1**f**) and could rise to 3%, 4%, and 4.5% of GDP losses with emission reduction targets of 80, 90, and 100% in 2050, respectively. Carbon prices are much more sensitive to reduction levels, increasing sharply to over 5,000\$/tCO_2 in a 100% reduction scenario, and to around 2,000 and 1,000\$/tCO_2 in 90 and 80% reduction scenarios, respectively. The carbon price would become extremely high under stringent reduction targets, but this is due to the availability of negative emissions in Japan where only a small area is left for energy crops and BECCS. Below target reductions of 60%, prices are lower than 200\$/tCO_2 over the period. More indicators are presented in Supplementary Figure 1 for Japan and Supplementary Figures 2 to 6 for other countries, and several basic trends in many variables can be observed. There are gradual changes, with carbon price reductions in most cases, but it should be noted that there are some variables and countries where convergences are apparent. For example, carbon prices and GDP losses in India and Vietnam display a trend that is due to the availability of CCS, including BECCS. Once CCS becomes widely available, the carbon price is reduced. Final energy consumption in China, India and Vietnam therefore decreases along with the increasing rates of carbon price reduction in the 2020s and 2030s, but then converges in the 2040s. These results are due to the enhancement of electrification under mitigation[54], which offsets the energy efficiency improvements.

Applying the framework to a country that submitted a LTS, the scenario outcomes could provide policymakers and analysts with an independent sensitivity around the LTS which allows judgement on whether the targets are plausible or feasible from the energy and economic perspectives. In addition, putting the LTS into the context of different equity principles sheds some light on the fairness of the target. However, policymakers need to interpret the results of model estimates carefully because they include uncertainties. The socioeconomic conditions were prescribed as SSP2 in this case, but the implications would change substantially if other conditions were assumed. Population and GDP are such key socioeconomic drivers, but technological availability and national energy policies are also sources of uncertainty. For example, unavailability of CCS pushes the policy cost much higher than usual [45], whereas low energy demand substantially mitigates the cost [46]. Finally, periodic reviews and assessments of the LTS, and the forthcoming 2035 or 2040 emissions reduction targets will provide opportunities to revise and update the goals.

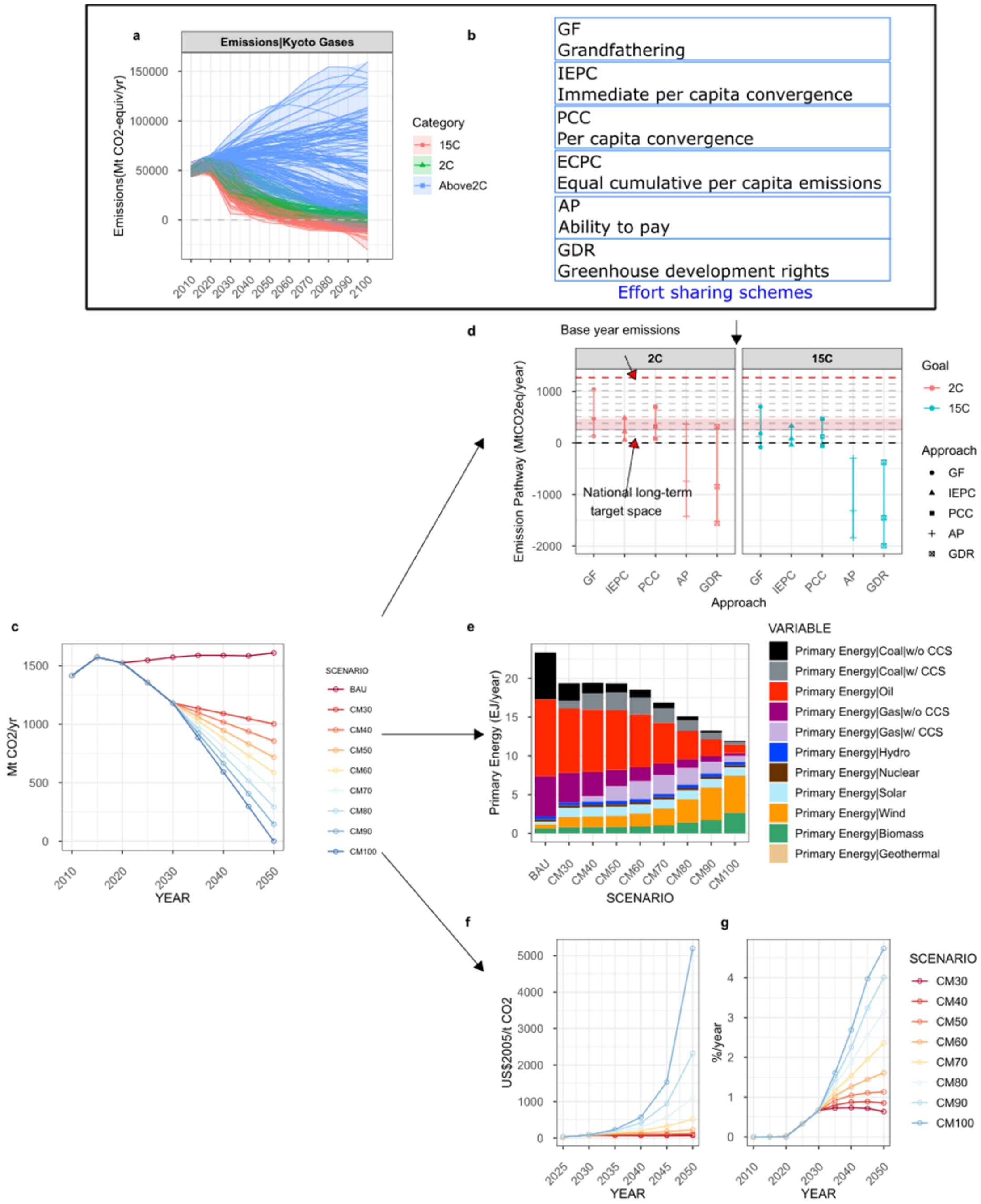

Fig. 1 Illustrative example of the interpretation of the national scale long-term scenarios (NLPs) using Japan as a case study. Panel **a** *shows national emissions pathways,* **b** *shows emissions global pathways, and* **c** *is a list of effort sharing schemes.* **d** *shows emissions in 2050 considering global pathways (all available scenarios are considered), effort sharing*

schemes and the long-term national goal of an 80% reduction, with an uncertainty range (red shaded area) associated with an unspecified reference year and gas coverages. The dashed red lines are emissions in 2010, and black dashed lines correspond to incremental 10% reduction levels from base year emissions. **e** *shows the energy system implications represented by primary energy supply in 2050, while* **f,g** *indicate policy cost implications represented by GDP loss rates and carbon prices.*

Regarding comparative assessments of multiple countries, in Fig. 2 we show selected indicators, namely mean annual rate of energy intensity change (Fig. 2**a**) and carbon intensity change (Fig. 2**b**), share of low carbon energy sources (Fig. 2**c**), electrification rates which is electricity final energy consumption divided by total final energy consumption (Fig. 2**d**), carbon price (Fig. 2**e**) and GDP loss rates (Fig. 2**f**). These indicators were chosen because they are fundamentally critical variables for assessing climate change mitigation, and since the scale of economy, energy consumption, and emissions of the countries assessed in this demonstration vary substantially, indicators that take percentages or relative rather than absolute values are more suitable for this analysis. We also carried out a regression analysis to clarify the common characteristics and the extent to which the reduction target rates in 2050 would change each indicator with country dummy parameters, as shown in the **Methods** section, and results are summarized in Supplementary Table 2 and Fig. 2.

We see a strong correlation with emissions reduction rates in most indicators except for the mean annual rate of energy intensity change. The mean annual rate of carbon intensity change indicates 0.025% improvements per incremental 1% of emissions reduction. In contrast, the response of mean annual rate of energy intensity change to reduction levels varies across countries, and the regressed slope is statistically insignificant. Japan's behavior, in which energy intensity rises when increasing mitigation ambitions, is normal whereas some other countries like India, China, and Vietnam appear to respond inversely. This is due to the requirement for negative emissions associated with bioenergy combined with CCS (BECCS). This result would imply that improvements in carbon intensity are a common and effective strategy to reduce CO_2 emissions, while energy efficiency improvements do not always yield the expected reduction in emissions. The share of low carbon energy sources also shows a clear correlation with emissions reduction levels and a 0.56% increase is expected per 1% of incremental emissions reduction. Electrification is a well-known and critical strategy for decarbonizing the energy system, and 0.36% is the regressed slope for change in electrification rates. Note that in Korea and Vietnam (see Supplementary Figure 4 and 6), the time series of electrification crosses over in 2030s. In the near-term, with modest emissions constraints, the electricity generation cost increases, which lowers electricity consumption while gas consumption increases. In the long term, under tighter emissions constraints, electrification needs to be enhanced. Carbon prices vary substantially by country, while the slope of regression is statistically significant at 12.50\$/tCO_2. Finally, the GDP loss rates would increase by 0.055% per 1% of additional emissions reductions. GDP loss rates also show variations across countries; Vietnam shows relatively high GDP loss rates, over 10%, while Japan presents small values, less than 5% even in a 100% emissions reduction scenario. This variation comes from socioeconomic conditions such as the share of energy and food expenditures which is largely influenced by abatement of non-CO_2 emissions from agricultural sector and carbon tax imposition on them (if these are large, the relative influence on industrial structures and household consumption patterns would be large) and GDP per capita (if low, the carbon price intervention effects would be large) as well as assumptions on the availability of technology. It could be argued that this regression analysis would be affected by extreme country data. To test this, we conducted a sensitivity analysis to determine the robustness by withdrawing one country from the regression and then iterating the results for all countries. The results indicated that the carbon price and some other indicators were affected by the Japanese data (see Supplementary figure 7).

Note that this study uses single model results. The use of multiple models, including multiple types of models (e.g. top-down and bottom-up, or CGE and energy system models) could lead to different results[55], which would enrich the implications of the study by introducing diversity in future prospects, and in particular, might not indicate the clear relationships shown here.

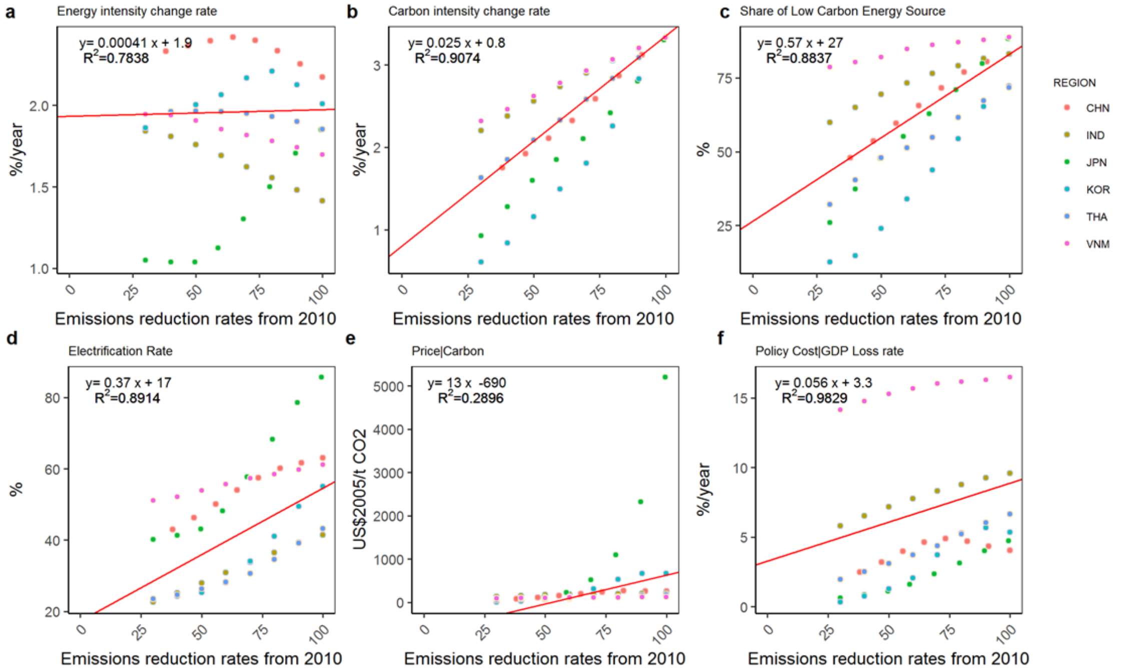

Fig. 2 Cross-national comparison of national long-term scenarios (NLPs). Six scenario indicators for 2050 are plotted against reduction targets. Panels **a**, **b**, **c**, **d**, **e**, and **f** *represent mean annual rate of energy intensity change (%), mean annual rate of carbon intensity change (%), share of low carbon energy sources in primary energy supply (%), electrification rates in final energy consumption (%), carbon prices (\$/tCO_2) and GDP loss rates (%). The solid lines indicate regression results using the derived slope and intercept + mean of dummy country results shown in Supplementary Table 2.*

Caveats to the proposal and discussion

We recognize that there are potential limitations to our proposal. First, policy relevance is the primary concern for this approach. This scenario set with its incremental 10% reduction levels might not exactly match the forthcoming LTS. As discussed, even if one of the scenario values of reduction rates hits a target, there will still be uncertainty in the inventory of the base year and coverage of GHGs. Second, there need to be several model runs (around 10 or more). However, in contrast to existing large scale global models, national models tend to have relatively small computational loads, which could allow them to run relatively a large number of scenarios. In this sense, it is crucial to keep the simplicity of the scenario requirements as the simple scenario protocol allows researchers to systematically deal with scenarios running in the programing codes. To manage these issues, we view this proposal as a default core standard set, to which supplementary scenarios can be added, such as using varying technological availability taking into account individual countries' circumstances[45]. Moreover, NDCs can be updated and ambitious LTSs may motivate countries to achieve more reductions in the near-term, which would pose the question of whether more variations should be added in near-term reduction targets. Although such scenarios are excluded from this study, the updated NDC scenario could also be another set of supplementary scenarios. It would be worth noting that such additional scenarios would have different roles from the above-proposed scenario set, and requires additional work to check and maintain the quality of results. Third, the protocol ignores possible interactions with the rest of the world. Increasing ambitions in one country might go in hand with actions in other countries. This could lead to impacts across countries. For example, fossil fuel prices could be low if many major countries decarbonized their economies. International price scenarios derived from global IAMs could be used as boundary conditions for national models, and in such a case, global models should also provide multi-level mitigation scenarios which could be prescribed by carbon budgets[5]. Still, the most direct impacts of more ambitious targets are nearly always felt simply within each country – and thus should serve as a caveat in the light of proposed simplification. Future study will be needed to investigate cross-border impacts. Fourth, the proposed scenarios always come with the risk of being outdated at some point, which can be critical in some cases. For example, long-term strategies were supposed to be submitted by the year 2020, and our proposal may not be able to keep up with them. Another possibility is that some extreme economic, social and political events may completely change the relevant energy-economic system. The the disaster at the Fukushima nuclear power plant was one such turning point, and the COVID-19 pandemic has the potential to be another one. A financial crisis, in general, could also result in structural change, which may imply that additional scenarios may be needed to take these extreme (or simply outlier) events into account. However, this depends on individual events and national circumstances. It may not be able to generalize and will probably need to generate specific scenarios to address such events.

Finally, the current proposal can be a first step to have systematic national scenarios, much as global scenarios are currently stored and utilized effectively. Meanwhile, even if the scenarios are developed by many countries, building up a valuable database, there would be still the need for better communication with policymakers. This is obvious from global IAM exercises. Even though there have been efforts to create transparent models[56] and socioeconomic assumptions behind scenarios[57], as well as making code open-source[58, 59] consistent with the recent demand for transparency, there is still an increasing demand to explain scenarios to decision makers. Furthermore, the misinterpretation of current scenarios is an ongoing problem, for example, in the lack of climate change impacts[60]. Therefore, just developing national scenarios is not sufficient, and better translation and communication of the scenarios to the policymakers is still needed.

Community and capacity development

The development of national scenarios fundamentally needs the involvement of researchers from each country. Many countries, including developing countries, have national models, but there are also many countries still missing national energy or integrated assessment models. Even if national models exist, a certain portion of models need to improve their systematic model output reporting, model validation (including diagnostics and documentation), and will require significant work to reach state-of-the-art modeling representation. In many cases, global integrated assessment modeling activities and experiences accumulated in the Integrated Assessment Modeling Consortium (IAMC)[61] community should greatly help national modeling capacity development[56, 59, 62, 63, 64, 65]. Note that global models are themselves not always the best; some national models have much more granularity in the representation of geographical and temporal resolutions, taking advantage of relatively smaller model coverage[55, 66]. IAMC members have been actively involved in capacity development (e.g., for Asian[67] and Latin American[15] capacity building activities, National Institute for Environmental Studies Japan (NIES) and Pacific Northwest National Laboratory USA (PNNL) have taken part in some exercises) and the IAMC itself sometimes coordinating them so far. However, this proposed standardized scenario exercise can be a more meaningful and practical catalyst for enhancing capacity building activities within the climate mitigation modeling community.

Conclusions

In this Perspective, we propose a new systematic and standardized scenario framework for long-term national scenarios and discuss its rationale, the advantages, and possible disadvantages. We believe that this proposal is valid and useful for policymaking and building a research community. National climate change mitigation modelling and scenario implementations might inherently have had relatively little motivation for building up a research community and conducting cross-national comparisons in the past. However, the political and societal conditions have changed over the last decade, and we believe that national countermeasures are now a necessity for combatting climate change. The climate policy circumstances and the need for national modeling and scenarios are expected to continue for at least the next couple of decades until emissions drop to sufficiently low levels. This research community should, therefore, devote much more attention and resources to national scenarios that guide or enhance the actual societal transformative movement. We envisage that the proposed framework could be a great milestone for national climate policy research and many countries and models would engage with it. Thus, we call for community-level activities that will let a wide range of researchers involved in national climate policy assessment consider dedicating efforts to these important new activities.

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Methods

Overview

We carried out scenario analysis for selected Asian countries, namely China, India, Indonesia, Japan, Korea, Thailand, and Vietnam. As stated in the main text, we implemented 8 scenarios for each country. They all have different reduction rates relative to the base year of 2010, and, furthermore, Vietnam and Thailand indicated conditional and unconditional target statements in their NDCs. We thus additionally simulated variations for these conditional statements. In scenario implementations, we considered currently planned national policies as much as possible. We used AIM/Hub (formerly AIM/CGE) for the proposed scenario design implementation and as the core tool of this study. It is a computable general equilibrium model and has been intensively applied to assessments of Asian national climate policies in past years [68, 69, 70, 71, 72]. In the scenario implementations, we used three major GHG gases (CO_2, CH_4 and N_2O) for emission coverage, considering that the countries have relatively large emissions of non-CO_2 gases. The reductions start from 30% in all countries because we took into account that Japan's baseline emissions have been quite stable over time and thus it may not be meaningful to see the lower reduction levels such as 10%. Finally, a regression analysis has been conducted on the scenario results. Note that the scenarios in this study excluded climate change impacts, because global emissions scenarios are needed for each national emission scenario to determine such impacts, which is an important factor for national policymakers to consider[60, 73, 74, 75].

Simulation model and data

AIM/Hub is a one-year-step recursive-type dynamic general equilibrium model covering all regions of the world. The AIM/Hub model includes 42 industrial classifications. For assessing bioenergy and land use competition, agricultural sectors are disaggregated[76]. The details of the model structure and mathematical formulae have been described previously[77, 78]. Version 2.2 of the AIM/Hub model was used, and the main revisions from the previous version are described below.

Production sectors are assumed to maximise profits using multi-nested constant elasticity substitution (CES) functions and input prices. For energy transformation sectors, to handle energy conversion efficiency appropriately in these sectors, input energy and value added are fixed coefficients of the output. Power generation values from several energy sources are combined with a logit function [79]. This functional form was used to ensure energy balance, as it was not guaranteed by the CES function. Electricity and bioenergy are produced by multiple sectors (e.g. coal-fired, nuclear and solar, agricultural residue, energy crops and sugarcane), which are aggregated by the logit function so that energy production by individual sectors is balanced to match total generation. Household expenditures on each commodity are described with a linear expenditure system (LES) function. The parameters adopted in the LES function are recursively updated in accordance with income elasticity assumptions. The savings ratio is endogenously determined to balance savings and investment, and capital formation for each good is assigned a fixed coefficient as an exogenous assumption. The Armington assumption is used for trade (using CES and the constant elasticity of transformation function), and the current account is assumed to be balanced.

In addition to energy-related CO_2, CO_2 from other sources, CH_4, N_2O, and fluorinated gases (F-gases) are treated as GHGs in the model. Energy-related emissions are associated with fossil fuel combustion. Non-energy-related CO_2 emissions consist of changes in land-use and industrial processes. Emissions from changes in land-use are derived from the change in forest area relative to the previous year multiplied by the carbon stock density, which is differentiated into AEZs (Agro-Ecological Zones). Non-energy-related emissions other than those associated with changes in land-use are assumed to be proportional to the level of each activity (e.g. based on output). CH_4 emissions arise from a range of sources, mainly rice production, livestock, fossil fuel mining, and waste management. N_2O is emitted as a result of fertiliser application and livestock manure management, as well as by the chemical industry. F-gases are emitted mainly from refrigerants used in air conditioners and industrial cooling devices. Air pollutant gases (black carbon, CO, NH_3, non-methane volatile organic compounds, NO_x, organic carbon, and SO_2) are also associated with fuel combustion and activity levels. Emission factors change over time with the implementation of air pollutant removal technologies and other regulations[80].

The implementation of mitigation actions in the model is represented by constraints on CO_2 emissions. The carbon price is imposed on CO_2 as well as other GHG types, such as CH_4 and N_2O, arising from every sector. The carbon price increases the price of fossil fuel-based goods when emissions are constrained and promotes energy savings and substitution away from fossil fuels to sources and transport methods with lower GHG emissions. The carbon tax also functions as an incentive to reduce non-energy-related emissions. Gases other than CO_2 are weighted based on their global warming potential and summed as total GHG emissions. Further parameter settings and changes under the future scenarios are documented in Fujimori et al. (2017)[81].

The main revisions from version 2.0, which was used in SSP quantification[72], to version 2.2 are described in Fujimori et al. (2020)[82] and the most relevant one for this study is the reflection of historical energy data (2005 to 2015). This methodology is the same as model integration with an energy system model where we exogenously provide the final energy, transport energy share and power energy technological share, while the corresponding parameters in the production function and household consumption are endogenized. Consequently, the autonomous energy efficiency in energy consumption and logit share parameters used to determine the share of power generation by different technologies were calibrated during that period and then used for the future scenarios (for more methodological details, see Fujimori et al.[55]). We used the IEA Energy Balances as the historical energy information[83].

National policies

We adopted current national policies that can be considered relevant for the scenarios as much as possible. The NDCs are all taken into account as emissions constraints for the year 2030. For all countries, population and GDP projections are based on the national perspective until either 2030 or 2035. Rates of SSP2 annual change are extrapolated afterward. There are some vital energy and climate mitigation-related policies at national levels which are reflected as either model constraints or as reference information to serve as a check that the scenarios are not far from the corresponding national perspectives. For example, in China, the next five-year plan, to be implemented in 2021, is scheduled to be published in late 2020 to early 2021 and thus we decided not to use the latest available five-year plan but have incorporated the best available current energy information. Another example is Thailand, where the power development plan has been established by the Ministry of Environment[84, 85, 86] as is being used for model constraints. The full list of national policy information considered in this study is shown in Supplementary Table 3.

Effort sharing

To map the national scenarios with global goals, we used multiple effort sharing schemes shown by van den Berg *et al.*[41]. For the global scenarios, we adopted the latest global scenarios from the IPCC Special Report on 1.5 °C database[87] by taking minimum, median, and maximum ranges of IAMs pathways categorized as 1.5°C or 1.5°C-consistent and 2°C or

2°C-consistent for 1.5 and 2 °C goals, respectively, regardless of the scale of global mean temperature overshoot.

Regression analysis of the scenario indicators

A regression analysis was carried out for the cross-country comparative assessment. The aim of this regression is to derive the general relationships which can be observed in multiple countries between each indicator and reduction levels. The equation applied is shown below.

$$Y_{r,s} = aX_{r,s} + b_r + c + \boldsymbol{\varepsilon}$$

Where:

$Y_{r,s}$ is an individual six indicators (annual mean rate of energy intensity change, annual rate of mean carbon intensity change, share of low carbon energy sources, electrification rate, carbon price and GDP loss rates) in country r and scenario s, $X_{r,s}$ is the emissions reduction percentage relative to those of 2010. a, b_r and c represent estimated parameters and they are the slope of the reduction levels, dummy countries, and intercept respectively. $\boldsymbol{\varepsilon}$ is an error term.

All figures in this paper is generated by the code at a Github repository[88].

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Data Availability

Scenario data is accessible online via the ENGAGE Scenario Database at https://data.ene.iiasa.ac.at/engage/. Data derived from the original scenario database, which is shown as figures but is not in the above database, is available upon reasonable request from the corresponding author. The scenario name mapping table between this paper and the database are shown in Supplementary Table 3.
URL: https://data.ene.iiasa.ac.at/engage/
DOI: 10.5281/zenodo.4653341

Code availability

All code used for data analysis and creating the figures is available at
https://github.com/shinichirofujimoriKU/AsianMCSAnalysis
DOI: 10.5281/zenodo.4677638

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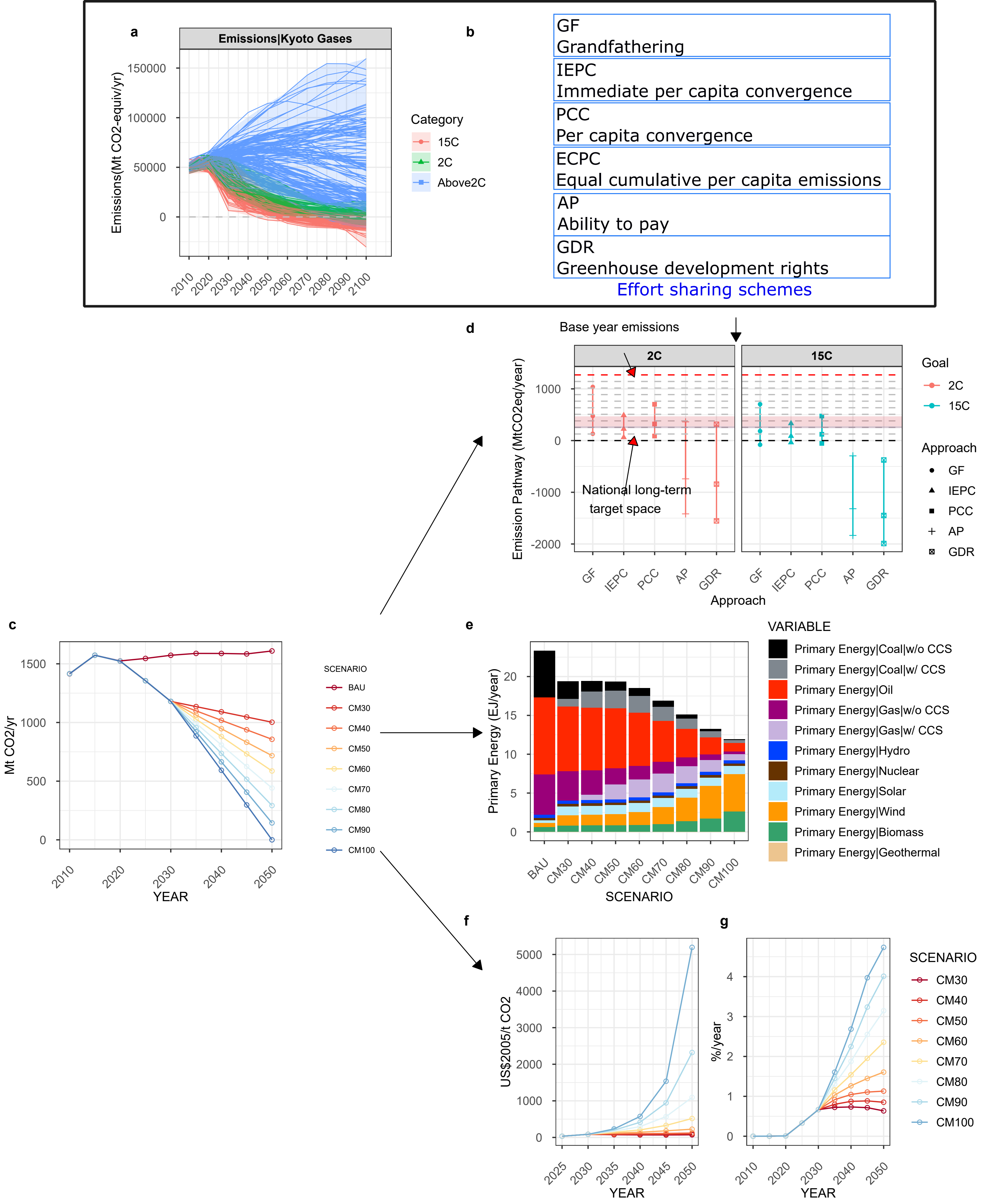
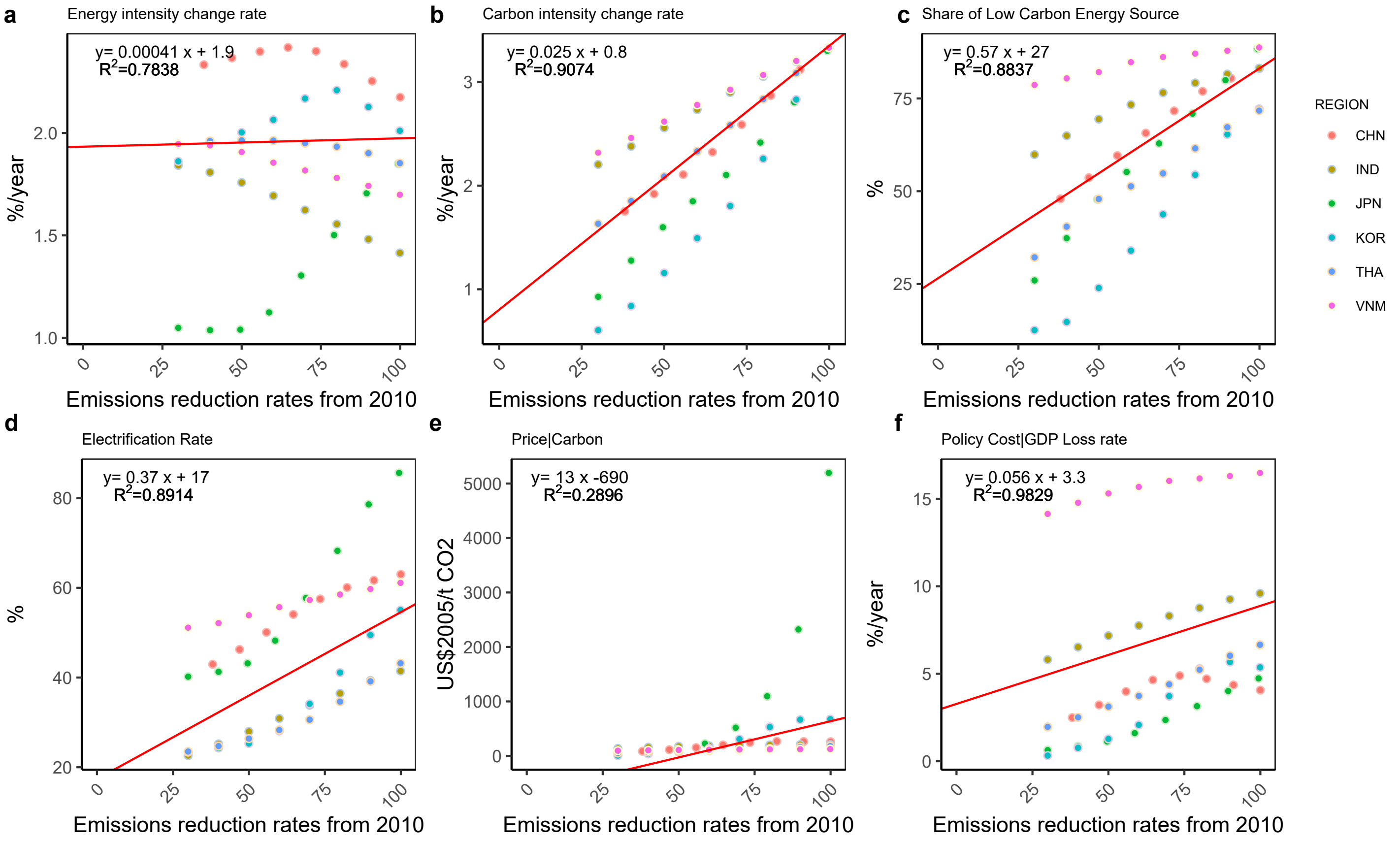
Conflict of interest

The authors declare no competing interests.

Author contributions

S.F, V.K., DvV, M.S and K.O. designed the research; S.F and Y.O carried out analysis of the modelling results; S.F and Y.O created figures; S.F wrote the draft of the paper; S.F, K.O, O.N. and D.H.S. set up the model; P.C., S.M., C.P., D.H.S., T.T.T., and S.Z. simulated the model and P.C., S.M., C.P., D.H.S., T.T.T., P.N. and S.Z. provided national policy information; and all authors contributed to writing the entire manuscript.


a
Emissions|Kyoto Gases
Emissions(Mt CO2-equiv/yr)
150000
100000
50000
0
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Category
15C
2C
Above2C
b
GF
Grandfathering
IEPC
Immediate per capita convergence
PCC
Per capita convergence
ECPC
Equal cumulative per capita emissions
AP
Ability to pay
GDR
Greenhouse development rights
Effort sharing schemes
d
Base year emissions
2C
15C
Emission Pathway (MtCO2eq/year)
1000
0
-1000
-2000
National long-term target space
GF
IEPC
PCC
AP
GDR
Approach
Goal
2C
15C
Approach
GF
IEPC
PCC
AP
GDR
c
Mt CO2/yr
1500
1000
500
0
2010
2020
2030
2040
2050
YEAR
SCENARIO
BAU
CM30
CM40
CM50
CM60
CM70
CM80
CM90
CM100
e
Primary Energy (EJ/year)
20
15
10
5
0
BAU
CM30
CM40
CM50
CM60
CM70
CM80
CM90
CM100
SCENARIO
VARIABLE
Primary Energy|Coal|w/o CCS
Primary Energy|Coal|w/ CCS
Primary Energy|Oil
Primary Energy|Gas|w/o CCS
Primary Energy|Gas|w/ CCS
Primary Energy|Hydro
Primary Energy|Nuclear
Primary Energy|Solar
Primary Energy|Wind
Primary Energy|Biomass
Primary Energy|Geothermal
f
US$2005/t CO2
5000
4000
3000
2000
1000
0
2025
2030
2035
2040
2045
2050
YEAR
g
%/year
4
3
2
1
0
2010
2020
2030
2040
2050
YEAR
SCENARIO
CM30
CM40
CM50
CM60
CM70
CM80
CM90
CM100


a
Energy intensity change rate
y= 0.00041 x + 1.9
R^2=0.7838
%/year
2.0
1.5
1.0
0
25
50
75
100
Emissions reduction rates from 2010
b
Carbon intensity change rate
y= 0.025 x + 0.8
R^2=0.9074
%/year
3
2
1
0
25
50
75
100
Emissions reduction rates from 2010
c
Share of Low Carbon Energy Source
y= 0.57 x + 27
R^2=0.8837
%
75
50
25
0
25
50
75
100
Emissions reduction rates from 2010
REGION
CHN
IND
JPN
KOR
THA
VNM
d
Electrification Rate
y= 0.37 x + 17
R^2=0.8914
%
80
60
40
20
0
25
50
75
100
Emissions reduction rates from 2010
e
Price|Carbon
y= 13 x -690
R^2=0.2896
US$2005/t CO2
5000
4000
3000
2000
1000
0
0
25
50
75
100
Emissions reduction rates from 2010
f
Policy Cost|GDP Loss rate
y= 0.056 x + 3.3
R^2=0.9829
%/year
15
10
5
0
0
25
50
75
100
Emissions reduction rates from 2010