

Comparing transformation pathways across major economies

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Abstract

This paper explores the consequences of different policy assumptions and the derivation of globally consistent, national low-carbon development pathways for the seven largest greenhouse gas (GHG)–emitting countries (EU28 as a bloc) in the world, covering approximately 70% of global CO₂ emissions, in line with their contributions to limiting global average temperature increase to well below 2 °C as compared with pre-industrial levels. We introduce the methodology for developing these pathways by initially discussing the process by which global integrated assessment model (IAM) teams interacted and derived boundary conditions in the form of carbon budgets for the different countries. Carbon budgets so derived for the 2011–2050 period were then used in eleven different national energy-economy models and IAMs for producing low-carbon pathways for the seven countries in line with a well below 2 °C world up to 2050. We present a comparative assessment of the resulting pathways and of the challenges and opportunities associated with them. Our results indicate quite different mitigation pathways for the different countries, shown by the way emission reductions are split between different sectors of their economies and technological alternatives.

Keywords Climate change mitigation · Paris agreement · Carbon budgets · National transformation pathways · National energy-economy models · Integrated assessment models

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1 Introduction

One hundred and ninety-three governments adopted the Paris Agreement on Climate Change in 2015 (UNFCCC 2015). The agreement established a new bottom-up process in which countries have pledged (Intended) Nationally Determined Contributions (INDCs/NDCs¹) for reducing their greenhouse gas (GHG) emissions until 2025 or 2030. At the same time, the Paris Agreement defines the long-term objective to limit global temperature increase to well below 2 °C and to pursue efforts to limit it further to 1.5 °C. The (I)NDCs and their consistency with the long-term temperature goals are planned to be regularly assessed in global stocktaking exercises as part of international negotiations, starting in 2023 and continuing to take place every 5 years thereafter. As of today, however, the currently proposed (I)NDCs are, collectively, not heading in the right direction for achieving the temperature objective of the Paris climate agreement (Fawcett et al. 2015; Rogelj et al. 2016a; UNEP 2019; Höhne et al. 2020).

This article aims at a detailed scientific assessment of the (I)NDCs and some of their mid-century implications for selected low-carbon mitigation pathways across major GHG-emitting regions and countries (from now on, we refer to only countries). A distinctive feature of this assessment is that it is based on an **iterative dialog between global and national research teams working with global IAMs, and national energy-economy models and national IAMs, respectively, identifying viable scenarios at the national level that are also coherent and consistent globally. Through this process, roadmaps for strengthening the (I)NDCs' ambition consistent with the 1.5–2 °C objective were developed.** While previous studies have primarily explored the implications of cumulative emission budgets for the global economy (see, for example, Riahi et al. 2017), **the combination of national low-carbon development pathways within a long-term global transformation framework toward a 1.5–2 °C world is thus far almost nonexistent in the published literature. In fact, what is unique here is the methodology deployed, where global IAMs informed national energy-economy models and national IAMs in terms of national emission budgets consistent with long-term climate targets, which were then used as boundary conditions for the national runs.**

This work, then, explores the consequences of different policy assumptions and the derivation of **globally consistent, national low-carbon development pathways** for the seven largest GHG-emitting countries in the world (Brazil, China, EU28 as a bloc, India, Japan, Russia, and the USA), covering approximately 70% of the global CO₂ emissions, in line with their contributions to limiting global average temperature increase to well below 2 °C as compared with pre-industrial levels.

To do so, this exercise brings together seven different global research teams with their **global Integrated Assessment Models**—IAMs (COPPE-Brazil with its COFFEE model, CMCC-Italy with its WITCH-GLOBIOM model, IIASA-Austria with its MESSAGEix-GLOBIOM model, IES-Japan with its AIM/CGE model, JRC-EU with its POLES model, PBL-The Netherlands with its IMAGE model, and PIK-Germany with its REMIND-MAGPIE model), **and ten different national research teams from those seven large-emitting countries with their national energy-economy models and national IAMs** (COPPE-Brazil with its BLUES model, ERI-China with its IPAC model, HSE-Russia with its RU-TIMES model, ICCS-Greece with its GEM-E3 and PRIMES-EU models,² IIMA-India with its AIM/

¹ As soon as a country ratifies the Paris Agreement, its INDC becomes a NDC.

² In fact, GEM-E3 is a global model, but because of its great resolution for the EU-28 region, it is being referred to, here, as if it was a national model for the EU. The same applies to the GCAM model here, which is also a global IAM but because of its high resolution for the USA, it is being used as a national model for this country.

Enduse[India] model, JGCRI-USA with its GCAM model, NIES-Japan with its AIM/Enduse[Japan] model, RITE-Japan with its DNE21+ model, TERI-India with its India-MARKAL model, and Tsinghua University-China with its China-TIMES model), for deriving low-carbon pathways in line with a well below 2 °C world up to 2050.

This study summarizes the insights from the international modeling comparison conducted under the umbrella of the EU Horizon-2020 CD-LINKS project (*CD-LINKS: Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing project*) (www.cd-links.org). At the heart of the analysis are globally consistent, national CO₂ budgets for the near and long terms. The studies we rely upon, and which are all part of this special issue (SI), explore the diversity of the national approaches, including the differences across countries with respect to the requirements for the deployment and upscaling of new technologies, investment, and finance needs, as well as national (near-term) gaps compared with the aspiration implied by the long-term objective of a 1.5–2 °C world.

2 Methodology

Starting from global pathways to inform national studies (e.g., by incorporating internally consistent boundary conditions, such as national carbon budgets), national development pathways consistent with local development goals were explored. These boundary conditions served to determine the carbon budgets of different countries, which were then used in eleven different national energy-economy models and national IAMs for deriving low-carbon pathways in line with a well below 2 °C world. The resulting scenarios benefit particularly from the much greater granularity of national models to explore low-carbon development pathways that ensure the achievement of a wide range of sustainable development objectives.

2.1 Scenarios description

The four scenarios explored here (Table 1) were derived using eleven national energy-economy models and national IAMs from Brazil, China (two models), the EU (two models), India (two models), Japan (two models), Russia, and the USA, which were implemented by different national teams (see the [Supplementary Material](#) for a brief description of each national model used in this collective effort). These model-based scenarios assessing national-level (I)NDCs and low-carbon pathways were developed using the most influential national energy-economy models and national IAMs available for these countries from national teams who regularly support domestic climate policy-making in their respective countries, without any specific a priori preference between optimization or simulation models. These models have sufficient quality and granularity in the form of policy, technology, sectoral detail, and country specificities, are regularly used by national policymakers and relevant stakeholders, and are the teams/models that are part of the CD-Links project, the backbone of this SI. This is exactly the case for the teams/models from Brazil, China, EU, India, Japan, Russia, and the USA. The scenarios cover mid-century (2011–2050) reference and decarbonization pathways and are, in most cases, consistent with least-cost emission trajectories. These scenarios are explored from a variety of perspectives, most importantly including consistency of national action with global climate targets.

The four scenarios explored here are:

- **NPi:** The current policies NPi (“National Policies implemented”) scenario, which includes currently implemented climate, energy, and land policies until 2015 and extrapolates the implied efforts beyond the direction of the policies, and impacting emissions in each region. This scenario has no explicit emission constraints, and functions as a reference scenario against which additional efforts to stay within the 1.5 °C and 2 °C temperature targets are measured. A list of current climate policies implemented by the global and national models can be found in Roelfsema et al. (2020) and in the Climate Policy Database (<http://www.climatepolicydatabase.org/>, May 2017 version used here).
- **NPi1000 and NPi400:** To assess climate change mitigation pathways, two different cumulative carbon emission constraints were added to the NPi scenario consistent with a >66% chance of fulfilling the 2 °C and 1.5 °C targets of the Paris Agreement, respectively. These carbon budgets derived for the specific countries from the global IAMs were introduced so as to take effect starting in 2020, and thus the national models follow the NPi trajectory through 2020 and then optimize the system to stay within the allowed carbon emission budget for the whole period of 2011–2050. By applying country-level carbon budgets emerging from global mitigation scenarios (a) consistent with >66% chance for a 2 °C target (“NPi1000” with a global 2011–2100 carbon budget of 1000 GtCO₂) and (b) >66% chance for a 1.5 °C target (“NPi400” with a global 2011–2100 budget of 400 GtCO₂), these NPi1000 and NPi400 scenarios were generated. Not all countries represented in this analysis have been able to explore all these scenarios, though.
- **NDC1000:** In addition, in order to assess the consequences of delayed climate change mitigation, a NDC1000 scenario forces countries to follow their own (I)NDCs until 2030 without a carbon budget, and only after that are the models allowed to optimize emissions to remain within the allowed national carbon emission budget also consistent with >66% chance for a 2 °C target with a global 2011–2100 carbon budget of 1000 GtCO₂. Again, the assumptions on the (I)NDC projections and on the scenarios themselves for the various countries can be found in the underlying papers in this SI.

2.2 Boundary conditions from global models: carbon budgets

Because climate change mitigation is a global effort, national energy-economy models and national IAMs rely on exogenous emission trajectories from global IAMs when developing techno-economic pathways to stay within given temperature targets. This is because the only way to ensure consistency with a global temperature increase limit is through a globally consistent methodology.

How much mitigation is demanded from one country depends on how much the other countries contribute to the expected global effort. Therefore, to create globally consistent national budgets, we started with the cumulative emissions for the countries of interest resulting from global IAMs’ least-cost runs with globally uniform carbon prices, for global carbon budgets of 1000 GtCO₂ and 400 GtCO₂ for the 2011–2100 period (see also Roelfsema et al. 2020). These were then fine-tuned using least-cost national model runs, resulting in an iteratively agreed upon “high” and “low” carbon budgets for each country.

The high budget was informed by the 1000 GtCO₂ global carbon budget, but additionally considered national techno-economic and policy specificities. The low-carbon budget was

Table 1 Scenario definition and country carbon budgets

Short-term policy dimension	NPI	Long-term CO ₂ budget (2011–2050 cumulated) in GtCO ₂		
		None	Low	Very low
		NPI	Npi2020_low (NPI1000)	NPI2020_verylow (NPI400)
		(I)NDC	(I)NDC	(I)NDC
			INDC2030 low (NDC1000)	INDC2030 verylow
	World		1000	400
Country carbon budgets (Gt CO ₂ , energy and industrial process emissions)	Brazil	-	22	15–17
	China	-	290	258–346
	EU28	-	95	100–128
	India	-	145	45–126
	Japan	-	31	28–35
	Russia	-	45	42–57
	USA	-	119	132–193

For the “Low” budget category: left, national carbon budgets resulting from interactions between national and global model teams; right, indicative carbon budgets from global models. Scenarios used in this paper are in bold. For more details on the scenarios listed here, see Supplementary Material

informed by the 400 GtCO₂ global carbon budget, again considering national circumstances, but representing highest ambition conceivable (for more details on national policies see Roelfsema et al. 2020).

More specifically, first global IAM teams ran the scenarios with global carbon budgets of 1000 GtCO₂ (with mitigation measures starting to take place in 2020 in the case of NPI1000, and in 2030 in the case of NDC1000, as this latter scenario meets the NDC in 2030 and then is allowed to implement new mitigation measures after that) and of 400 GtCO₂ (with mitigation measures starting to take place already in 2020 in the case of NPI400), for the period between 2011 and 2100. These global IAMs represent multiple regions and divide the mitigation effort across regions cost-optimally, meaning emissions are reduced where they are cheapest.

Second, resulting emissions per region and per mitigation scenario were summed over the 2011–2050 period, giving national “carbon budgets” from global models in line with the global mitigation goals.

Third, as multiple global models participated in this exercise, a range of regional carbon budgets could be used as inputs for the least-cost, national model runs.

Fourth, the national model teams took the globally identified carbon budgets for their regions, constraining their models so that cumulative emissions over the 2011–2050 period would be within the global model range. In most cases, national models met these constraints. In some cases, however, the global models range turned out to be too tight, so the closest outcome (most stringent feasible regional carbon budget according to the national models) was taken (this was particularly critical in the case of India).

It is important to flag here, and we come back to this later in the “[Final considerations](#)” section, that the approach followed in this manuscript allocates mitigation efforts by handing out carbon budgets to national models based on globally judged, least-cost scenarios from global IAMs. Different allocation schemes could also be explored beyond a “least-cost” approach, but this is the subject of another paper of this special issue (see van den Berg et al. 2019, this issue, for a specific discussion on allocation schemes and their national implications). The global IAMs ran each scenario explored here (section 2.1 “[Scenarios description](#)” above) using cumulative emission constraints (carbon budgets) consistent with each temperature target. Global carbon budgets were informed by the most recent

Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC 2014, Table 2.2 from the IPCC Synthesis Report).³

Figure 1 provides CO₂ budgets for the seven regions and scenarios from the global IAMs, as well as from the national models, for the period 2011–2050. In almost all cases, national budgets are similar to globally consistent, mid-century budgets for the various scenarios.

For a short description of the national models used in this paper, see the [Supplementary Material](#) and also Roelfsema et al. (2020). For a more detailed description of the national models, however, the reader is referred to the relevant national papers in this special issue (Feijoo et al. 2020—this issue, Köberle et al. 2020—this issue; Mathur and Shekar 2020—this issue; Oshiro et al. 2019—this issue; Safonov et al. 2020—this issue; Vishwanathan and Garg 2020—this issue; Vrontisi et al. 2019—this issue; Wang et al. 2019—this issue).

3 Results

3.1 CO₂ budgets and emission trajectories

Figure 2 shows emission trajectories to 2050 for the different scenarios across countries according to the national models, where China and India are projected to increase emissions more strongly, with some variations across models when more than one national model is available for the same country. All countries contribute to global emission reductions across all budget scenarios, with emission trajectories from national models broadly in line with global IAMs. The exception here is India, which is projected to continue an upwards emission trajectory, driven by rising population and income levels (although with different economic growth assumptions across the two Indian national models). Energy CO₂ emissions continue to increase to levels 200–350% higher in 2030 and 2050 compared with 2010. The only scenario showing a reduction in energy CO₂ emissions in India by 2050 is the 1.5 °C scenario (NPi400). Both China models show peaking emissions even under current policies, with steep reductions in the 2 °C scenarios, approaching carbon neutrality by 2050. For Brazil, global and national models agree in projecting the country as a CO₂ sink in the second half of the century in budget scenarios, given the large availability of land for biofuel production and consequent use, and also for biomass carbon capture and storage (BECCS). Finally, models for the developed economies all show deep decarbonization trends under budget scenarios, with a carbon neutral USA region post-2050.

Energy CO₂ emission reductions in Fig. 2b show a ratcheting up of mitigation efforts in the major economies as budgets become tighter, but for some countries, there is disagreement between national models and global IAMs on the rate of decarbonization. In general, global models' CO₂ emissions are below national model ranges, particularly for the large emerging economies of Brazil and India. The divergence decreases in 2050 in the more restrictive budget scenarios, indicating a slower response to emission constraints by these two countries in their respective national models than in the global IAMs. This raises questions about what may be happening in the rest of the world, suggesting global models project more action from the large emerging economies in general in the short to medium terms, thus giving more carbon space to least developed and small countries.

³ Note that more recent literature may present different carbon-budget numbers (see, for example, Rogelj et al. 2016b, Peters 2016, Millar et al. 2017), which can be largely explained by methodological differences.

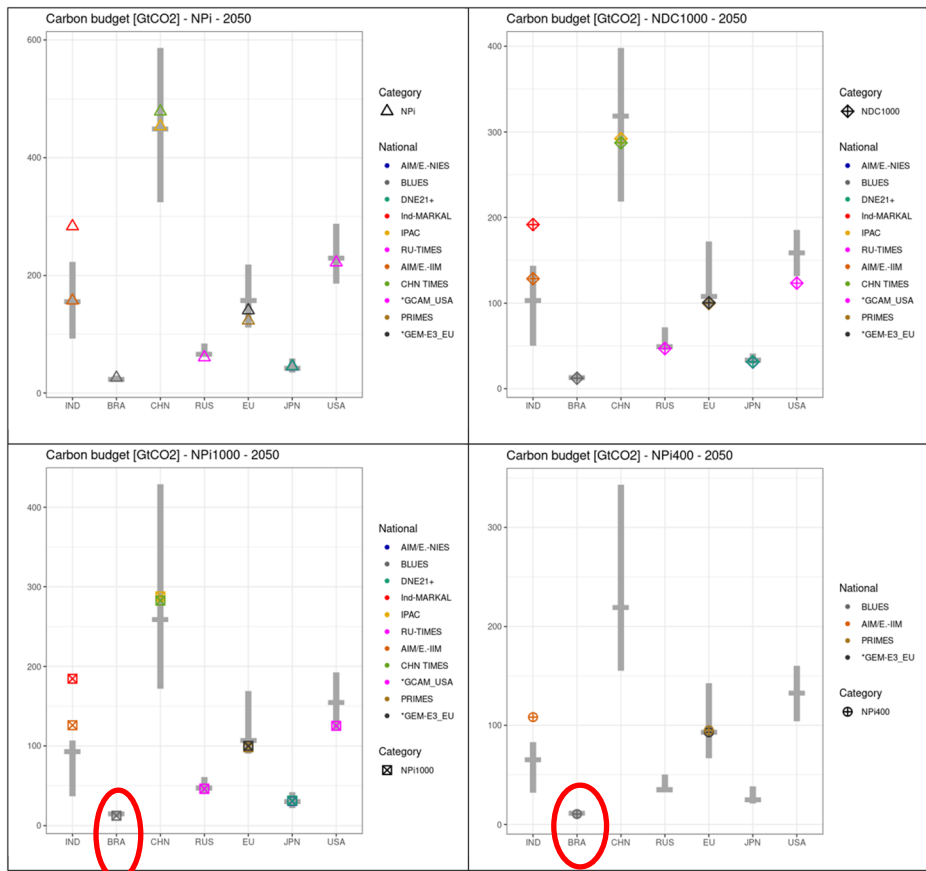


Fig. 1 Carbon dioxide budgets (2011–2050) for the different countries and scenarios (NPI, NDC1000, NPi1000, and NPi400—the latter was not reported by all models). Gray bars indicate the full range of global IAMs in the corresponding scenarios, and the color shapes the national/regional budgets from national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

Per capita fossil-fuel and industry CO₂ emissions, shown in Fig. 2c, indicate that substantial differences persist in 2030, with China, EU, Russia, and the USA exceeding global average emissions, while Brazil and India's per-capita emissions are below average (for an interesting discussion on industry CO₂ low-carbon scenarios for Brazil, see, for example, Borba et al. 2012; Henriques et al. 2010). By 2050, a considerable convergence of per-capita emissions is achieved in the climate stabilization scenarios NPi400, NPi1000, and NDC1000.

Looking at each sector's contribution to mitigation, as projected by the national models, Fig. 3 shows that, in most countries, the energy supply sector takes up the lion's share of the reduction in CO₂ emissions between NPI and NPi1000 in 2050 (see Supplementary Material for similar figures S1, S2, and S3 for 2030, 2050 and for NDC1000 and NPi400). In the EU, however, the transport sector is responsible for the majority of emission reductions because a large part of the energy supply sector emissions is already reduced under currently implemented policies (NPI scenario). In the USA, the transport sector follows energy supply in terms of mitigation contribution (for Brazil even more so in the NPi400 scenario), while in

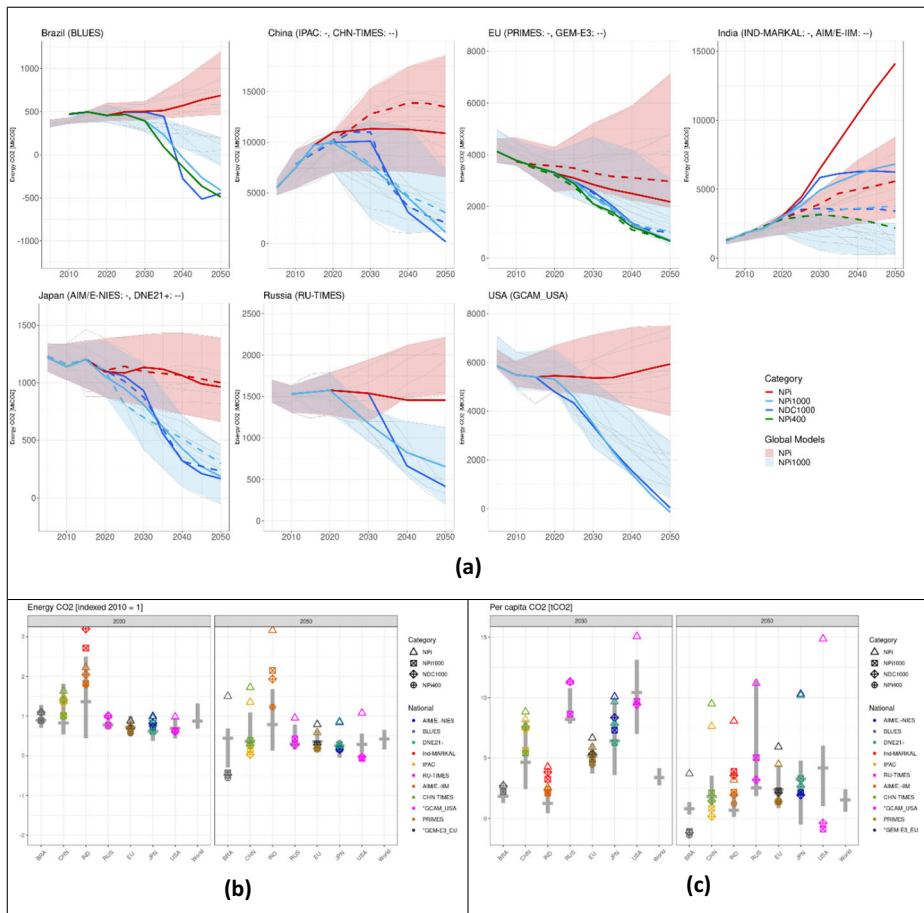


Fig. 2 Emission trajectories to 2050 from national models (lines) and global models (wedges) (a), CO₂ emissions from energy use in 2030 and 2050 (b), and per capita emissions in 2030 and 2050 (note that India-MARKAL results are out of range, being around 4 in 2050) (c) across scenarios and models for the modeled regions. Gray bars indicate the range of results for global IAMs in NPi1000, and the color shapes the results of national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

China and India, industry takes that place. In Japan, the building sector contributes most to mitigation after energy supply. The AFOLU sector, which is not shown in these figures, is a particularly important contributor to mitigation in Brazil.

3.2 Final energy and renewables share

Figure 4 shows final energy consumption per capita and carbon intensity of final energy consumption for the different regions over time. For final energy consumption per capita relative to 2010, Russia is up (excluding NPi1000 and NDC1000), EU and the USA are down (excluding NPi), China and Japan are mixed, Brazil and India are up, but in India, models differ mostly due to different GDP growth assumptions. For the carbon intensity of final energy consumption, a clear decarbonization across budget scenarios can be seen. Also,

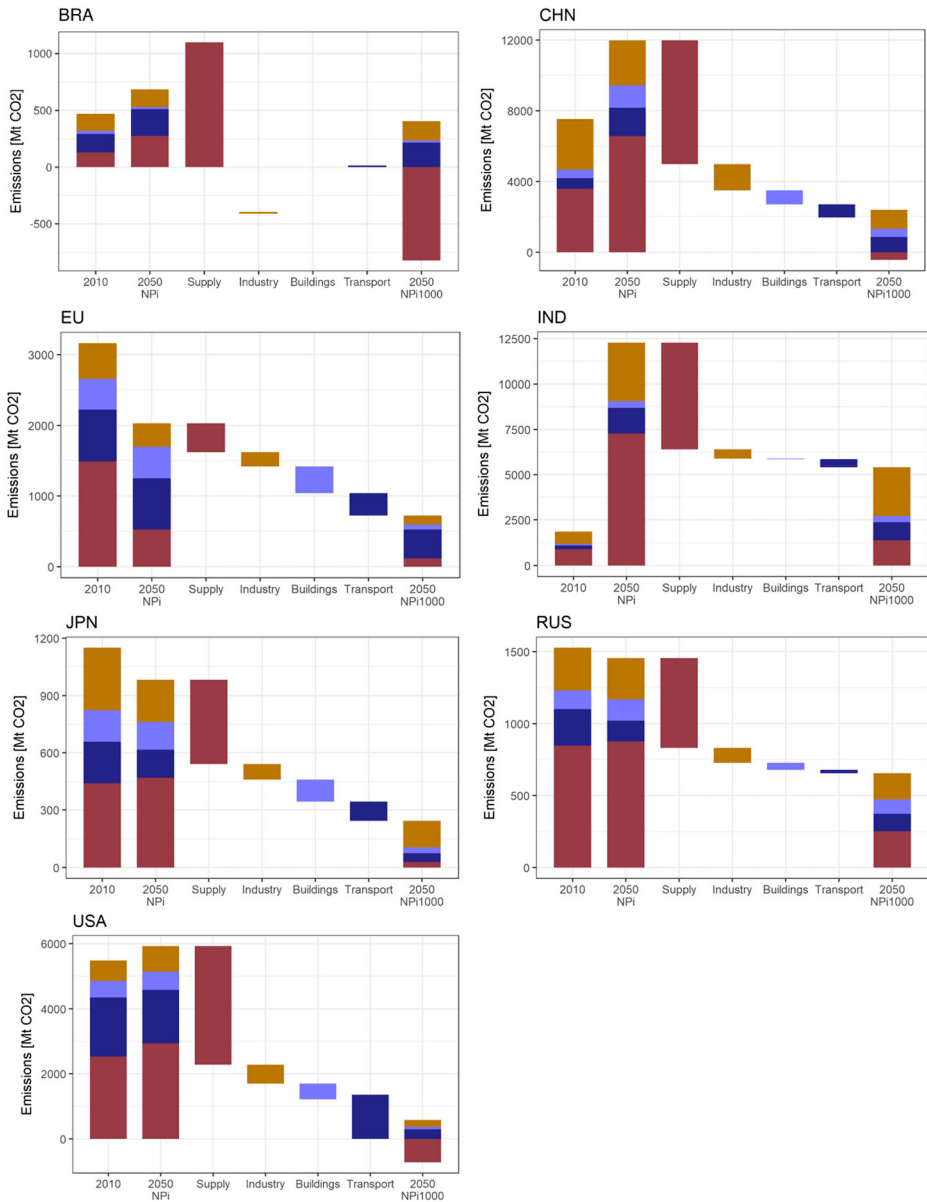


Fig. 3 Sectoral CO₂ emissions and contributions to mitigation in 2050, per region/country. Change between 2010 (first bar), 2050 NPI (second bar), and 2050 NPI1000 (seventh bar). Red: energy supply, yellow: industry, light blue: buildings, dark blue: transportation. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America. For regions covered by two national models, the average was taken. Credits for R script underlying this figure go to Christoph Bertram, PIK

GCAM shows the USA with a negative carbon intensity of final energy by 2050, reflecting more optimistic assumptions about the availability of BECCS, and IPAC is shown to be ambitious on the decarbonization of China.

Figure 4c shows the share of electricity in final energy consumption, where national model results are within the range of global IAMs except for Brazil and the USA in 2050. Significant divergence between Japan models for low-budget scenarios can be identified in 2050. Brazil shows slower electrification of final energy in the BLUES model than in the global IAMs, mostly given a more ambitious penetration of biofuels reflected in BLUES. In the case of Brazil and India, however, flat electricity shares in final energy consumption mask actual increase across scenarios, since total final energy consumption in Brazil and India (not shown) is projected to increase across all scenarios in both Brazilian and Indian national models.

Figure 5a shows the share of low-carbon energy sources in electricity, where high shares of low- or zero-carbon electricity help explain decarbonization of supply across regions in budget scenarios (in 2050, USA > 95% low-carbon, EU ~ 85%, Japan ~ 70%, and ramp up in general across regions). Figure 5b shows penetration of solar and wind in power generation, which to a great extent explains supply decarbonization of Fig. 5a). India and OECD countries lead the way on solar and wind, India with high shares and Russia lags behind. In the case of nuclear power (Fig. 5c), OECD, especially Japan, leads, but also high penetration (>20% in 2050) is projected for China and Russia. Penetration is low in Brazil and India. Global models project higher shares than national models in India and lower shares in the USA, while in Japan, models diverge.

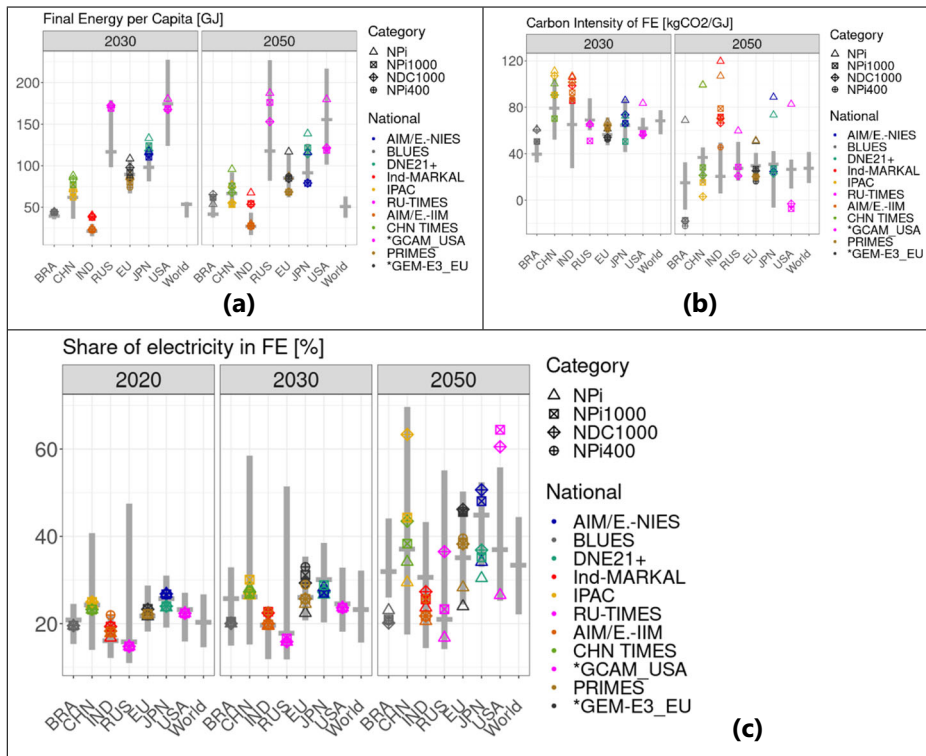


Fig. 4 Final energy consumption per capita (a), carbon intensity of final energy consumption (b), and share of electricity on final energy consumption (c). Gray bars indicate the range of results for global IAMs in NPI1000, and the color shapes the results of national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

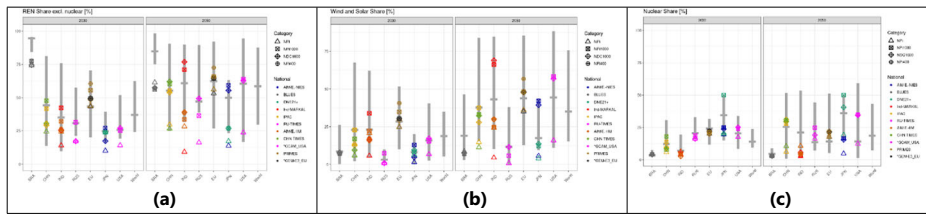


Fig. 5 Share in power generation of low-carbon energy sources including solar, wind, nuclear, hydropower, biomass, and geothermal (a), wind and solar (b), and nuclear (c). Gray bars indicate the range of results for global IAMs in NP1000, and the color shapes the results of national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

3.3 Country-specific discussions

Based on the results presented above, and being more specific, for the different countries/regions, much of the near-term emissions **in Brazil come from the AFOLU sector, especially land use change emissions (deforestation), paving the way for a significant increase in biofuel production, with trade-offs and synergies between the AFOLU, transportation, and power generation sectors** (for more on these see, for example, Schaeffer and Szklo 2001; Rathmann et al. 2012; Nogueira et al. 2014; Köberle et al. 2015; Rochedo et al. 2018; Malagueta et al. 2013). **Electrification of the light-duty vehicle (LDV) fleet is an important driver of final electricity consumption in some budget scenarios, and especially so in the 1.5 °C scenario (NP400, see Supplementary Material). Higher penetration of electric vehicles (EVs) also implies changes to biofuel production, with unused ethanol directed toward production of bio-jetfuel.** For more details, see Köberle et al. (2020), this issue.

In the EU28, GHG emissions by the middle of the century are substantially in the most stringent scenarios as compared with the NPi scenario. The largest contributing sector in 2050 is the transport sector (37% of total CO₂ reductions), which is the largest emitter of the NPi scenario. The power sector has already undertaken a decarbonization effort under the existing policies in 2050, and thus its share in total emissions is lower. Nevertheless, the energy supply sector is the second largest contributor (24% of total CO₂ reductions) followed by the reductions in the residential sector (16%). For more details, see Vrontisi et al. (2019), this issue.

According to AIM/Enduse, the Indian energy system witnesses a system transformation through ambitious renewable energy targets and enhanced energy efficiency actions. The decrease in energy demand during the 2011–2050 period by implementing policies in the NDC1000 scenario has been estimated to correspond to reductions of about 11%. The CO₂ emission reduction from NDC1000 to NP1000 and NDC1000 to NP400 corresponds to 8% and 27%, respectively. Energy efficiency enhancements followed by renewables across supply and demand sectors and followed by CCS are the main contributors to this reduction. In the supply side, a shift to cleaner and renewable energy in the power sector, and the introduction of CCS, accounts for most of the CO₂ reductions in the four different mitigation scenarios as compared with the business as usual (BAU) scenario. For more details, see Viswanathan and Garg (2020), this issue.

In the case of the India-MARKAL model and its scenarios, with the continuous trade-off of energy access and development versus technological progress and decarbonization that India is likely to face, absolute CO₂ emissions from the energy sector would not peak until 2051, unless major transformational changes (technological and behavioral) are forced in. At best,

this enables emission intensity of the energy sector to flatten beyond 2030. Similar to the AIM/Enduse Indian model, improvements in energy efficiency play here a key role in arresting the growth of energy demand, with efforts on the energy demand side alone contributing to a possibility of achieving around 11% reduction in energy consumption by 2050 across the scenarios. For more details, see Mathur and Shekar (2020), this issue.

In Japan, electricity supply is almost decarbonized by 2050 due to a scale-up of low-carbon energy sources, such as nuclear, renewable energy, and fossil fuels with CCS (52–78% by 2030 and 97–98% by 2050 of electricity generation according to the two national models), and energy source dependence differs among models, especially for nuclear. The demand sectors see a 50–69% reduction of CO₂ emissions relative to the current policies scenario (NPi) by 2050 due mainly to switching from fossil fuels to low-carbon energy carriers, such as decarbonized electricity and hydrogen in the buildings and transportation sectors, as well as energy efficiency improvement. For more details, see Oshiro et al. (2019), this issue.

The majority of emissions in Russia come from heat and power plants, most of which were built in the 1960s to 1980s. The main driver of emission reduction in Russia is the electrification of final consumption and the decarbonization of heat and power generation. It mainly occurs by the increasing efficiency of existing heat and power plants, the deployment of CCS technologies, and the reduction of coal and oil consumption for these purposes. In addition, there is an active implementation of renewables, primarily wind, up to about 20% of the total electricity production. These measures allowed reducing emissions in heat and electricity by more than 70% compared with the NPi scenario. The increasing energy efficiency of buildings has reduced their emissions by more than 30% despite the active building construction. For more details, see Safonov et al. (2020), this issue.

Finally, in the case of USA, achieving stringent mitigation pathways leads to a more accelerated deployment of energy-efficient technologies, close to a 100% decarbonization of the power and transport sectors (the latter with a combination of electrification and bioenergy as substitutes for fossil fuels), and a growing electrification of the buildings and industrial sectors. Also, the contribution AFOLU varies greatly depending on the stringency of the different mitigation scenarios. For more details, see Feijoo et al. (2020), this issue.

4 Conclusions and discussion

The Paris Agreement is a bottom-up process, and insights in national transformation pathways are crucial for informed discussions under the umbrella of the facilitative dialog held in 2018 and the Global Stocktake from 2023 onward. Although global IAMs can contribute to this process, national models are essential for a detailed understanding of national policy-making processes, development priorities, and other circumstances influencing national mid-century strategies. The collaboration between these two classes of models, explored here, thus forms a unique contribution to the Paris Agreement, by also implementing a bottom-up process in the assessment of (I)NDCs and identifying opportunities for ratcheting up, while ensuring coherence with the Agreement's long-term, global goals.

This study is one of the first systematic assessments of a collection of regional and national decarbonization pathways consistent with long-term global mitigation targets. The seven countries examined in this work differ considerably in various aspects, including their economic development, resource basis, and the way their emission reductions are split between the different sectors.

In most countries, the energy supply sector is projected to contribute the majority of emission reductions in 2050 compared with the national policies scenario (due to increasing shares of low-carbon electricity), followed by the transport sector in the USA, by the industry sector in China and India, and by the building sector in Japan. In the case of Brazil, as the exception, the AFOLU sector plays the most important role, while in the EU, transport takes up the lion's share of emission reductions. The shares of different technologies and mitigation options also vary considerably between them and between the various scenarios explored.

However, a pattern seems to emerge: roughly, a complete decarbonization of the power sector in almost all economies by 2050, with higher penetration of zero-carbon technologies like solar and wind in their power generation sectors, and accelerated electrification of all end-use sectors in general, in particular the transport sector. And in the case of the transport sector more specifically, for those end users more difficult to decarbonize (like heavy trucks and even aviation, for example), biofuels increase their share in final energy use in more stringent mitigation scenarios. Also, accelerated energy efficiency improvements in most of the end-use sectors are constant among the different mitigation scenarios across countries. Interesting enough, the higher granularity of the eleven national energy-economy models and national IAMs explored here confirms the results of previous studies reviewed by the most recent IPCC WGIII report (AR5), which focused mostly on literature base on the use of global IAMs (IPCC 2014), something that will change in the upcoming IPCC WGIII AR6 due in 2021.

5 Final considerations

This paper provided an overview of the transformation pathways for the seven largest GHG-emitting countries in the world (Brazil, China, the EU28 as a bloc, India, Japan, Russia, and the USA), in line with their contributions to limiting global average temperature increase to well below 2 °C as compared with pre-industrial levels. This overview was only possible because of the methodology here proposed for developing different low-carbon mitigation pathways by initially discussing the iterative process by which global IAMs started discussions by suggesting boundary conditions in the form of carbon budgets for the different countries. The carbon budgets subsequently agreed upon were then used in eleven different national energy-economy models and national IAMs for deriving least-cost, low-carbon pathways in line with a well below 2 °C world. We presented a comparative assessment of the resulting pathways and of the challenges and opportunities associated with them. Our results indicated quite different least-cost mitigation pathways for the different countries, shown by the way emission reductions were split between the different sectors of their economies.

Important to mention here, as one possible limitation of our study, that three of the four mitigation scenarios considered in this paper (NDC1000, NPi1000, and NPi400) assumed that after 2020 (in the case of NPi1000 and NPi400), or after 2030 (in the case of NDC1000), climate policies that are implemented were mostly cost effective (least-cost), independent of socioeconomic or geographical location, and something that is not exactly in line with the equity principle from the Paris Agreement. The Paris Agreement makes it clear that countries will respond based on common but differentiated responsibilities and respective capabilities, in the light of different national circumstances (UNFCCC 2015). However, even if emissions are mitigated where they are more cost effective, these mitigation costs do not necessarily need to be financed domestically, but can be financed through international capital flows. In that case, the final solution can, indeed, be a least-cost one.

One has to have in mind, then, that the scenarios explored here typically provide results for cost-efficient allocation of mitigation efforts, which eventually would lead to relatively high costs for developing countries. Fairness principles are not discussed in the paper, but there is already a vast literature available discussing equity principles, for which many different effort-sharing approaches have been proposed (see, for example, Sheeran 2006, Robiou Du Pont et al. 2017, Bataille et al. 2018, and Kartha et al. 2018). However, a more detailed discussion on this topic is out of the scope of this work. And thus this, indeed, can be seen as a limitation of our work. Carbon budgets of different effort-sharing approaches for the seven different countries examined here are precisely the focus of van den Berg et al. (2019), this issue.

Finally, divergence between national models for same countries in this study points to uncertainties in the indicators within the national reality, which underscores the need for more research involving national modeling (here, three countries, Brazil, Russia, and the USA, were only covered by one national model, but four, China, EU, Japan, and the USA, were covered by two national models each). In fact, this seems to indicate the importance of accumulation of national model experiences toward the global stocktaking exercises, due to start in 2023.

Eventual divergence between national and global model runs also has implications for the rest of the world. The finding that in many cases national models show global model projections to be rather ambitious points to the enormous challenge of meeting the Paris Agreement's objectives and also highlights the importance of accumulating national model experience toward the global stocktaking process agreed upon in Paris in 2015. This paper tried to be an initial step to facilitate this important debate.

Author contribution RS, AK and HvS coordinated the analyses and writing of this paper, to which all authors contributed. HvS created the figs. CB, GL, RS, KR, VK, DvV, EK, FU and HvS coordinated the national modeling study. The national model scenarios were developed by AK and RS (BLUES-Brazil), WC (China-TIMES), CH (China-IPAC), ZV (EU-GEM-E3 and EU-PRIMES), RM and SS (India-MARKAL), SSV and AG (India-AIM), KG (Japan-DNE21+), KO and SF (Japan-AIM/Enduse), GS and VP (Russia-TIMES), and GI (USA-GCAM).

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