Climatic Change (2020) 162:1787–1803
https://doi.org/10.1007/s10584-020-02837-9

# Comparing transformation pathways across major economies

R. Schaeffer[1] · A. Köberle[1,2] · H. L. van Soest[3,4] · C. Bertram[5] · G. Luderer[5] · K. Riahi[6] · V. Krey[6] · D. P. van Vuuren[3,4] · E. Kriegler[5] · S. Fujimori[7,8] · W. Chen[9] · C. He[10] · Z. Vrontisi[11] · S. Vishwanathan[12] · A. Garg[12] · R. Mathur[13] · S. Shekhar[13] · K. Oshiro[14] · F. Ueckerdt[5] · G. Safonov[15] · G. Iyer[16] · K. Gi[17] · V. Potashnikov[18]

Received: 30 December 2017 / Accepted: 17 August 2020/ Published online: 24 August 2020


## 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 $CO_2$ 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

This article is part of a Special Issue on "National Low-Carbon Development Pathways" edited by Roberto Schaeffer, Valentina Bosetti, Elmar Kriegler, Keywan Riahi, Detlef van Vuuren, and John Weyant

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s10584-020-02837-9) contains supplementary material, which is available to authorized users.

✉ R. Schaeffer
roberto@ppe.ufrj.br

Extended author information available on the last page of the article

## 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/NDCs[1]) 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 $CO_2$ 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 is 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 right 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 $CO_2$ 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 $GtCO_2$) and (b) > 66% chance for a 1.5 °C target (“NPi400” with a global 2011–2100 budget of 400 $GtCO_2$), 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 $GtCO_2$. 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 $GtCO_2$ and 400 $GtCO_2$ 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 $GtCO_2$ 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

| | | Long-term $CO_2$ budget (2011–2050 cumulated) in $GtCO_2$ | | | |
|---|---|---|---|---|---|
| | | **None** | **Low** | | **Very low** |
| **Short-term policy dimension** | NPi | **NPi** | Npi2020_low (**NPi1000**) | | NPi2020_verylow (**NPi400**) |
| | (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 | **As low as possible** |
| | China | - | **290** | 258–346 | - |
| | EU28 | - | **95** | 100–128 | **As low as possible** |
| | India | - | **145** | 45–126 | **As low as possible** |
| | 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 $GtCO_2$ 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 $GtCO_2$ (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 $GtCO_2$ (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 $CO_2$ 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 $CO_2$ 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 $CO_2$ emissions continue to increase to levels 200–350% higher in 2030 and 2050 compared with 2010. The only scenario showing a reduction in energy $CO_2$ 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 $CO_2$ 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 $CO_2$ 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' $CO_2$ 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.

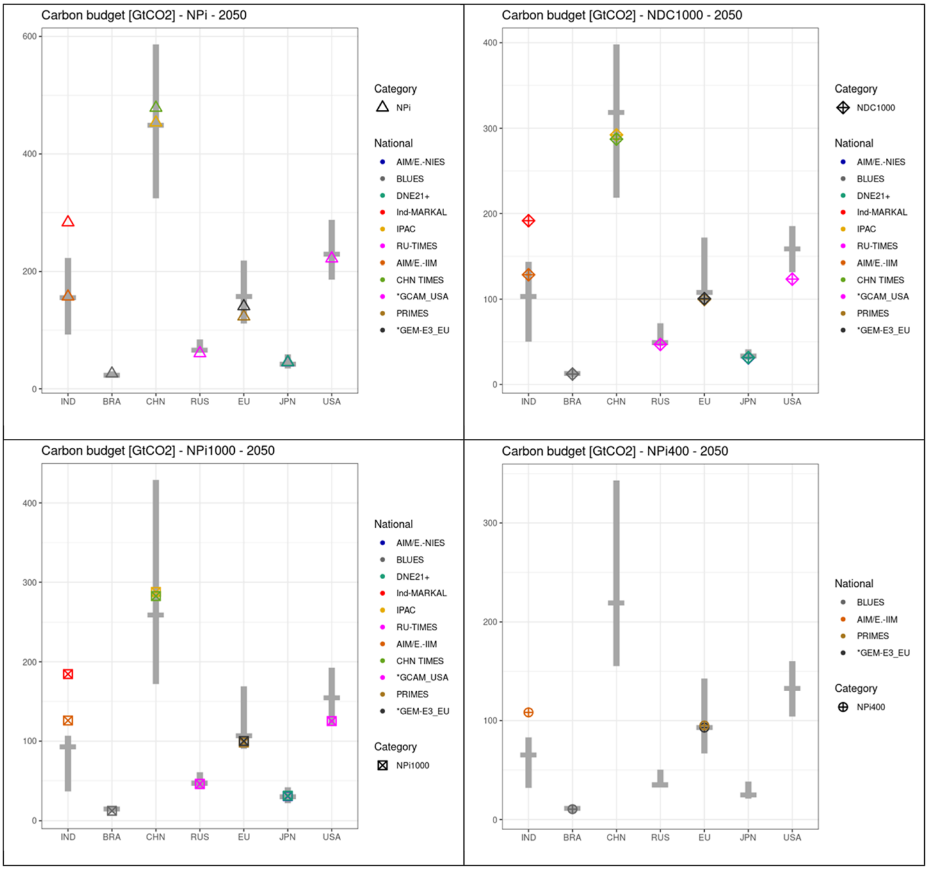


**Fig. 1** Carbon dioxide budgets (2011–2050) for the different countries and scenarios (NPi, NDC1000, NPi1000, and NPi400—the latter was not reported by all models). Gray bars indicate the full range of global IAMs in the corresponding scenarios, and the color shapes the national/regional budgets from 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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

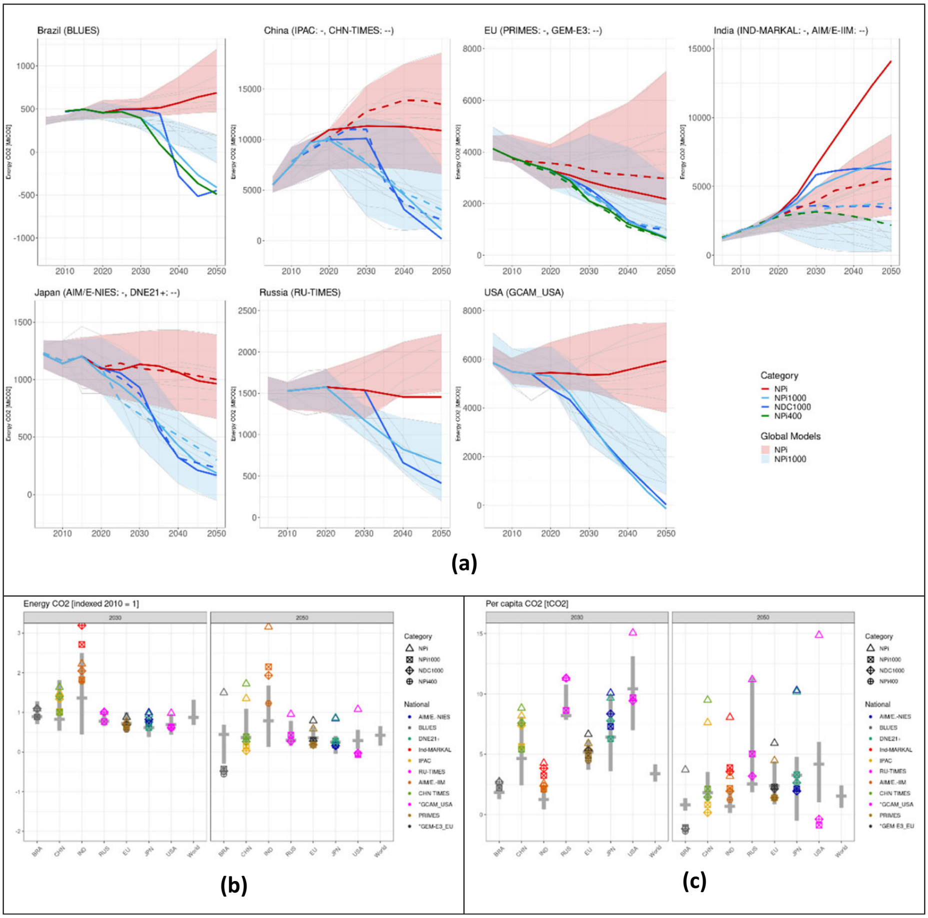


**Fig. 2** Emission trajectories to 2050 from national models (lines) and global models (wedges) (a), $CO_2$ emissions from energy use in 2030 and 2050 (b), and per capita emissions in 2030 and 2050 (note that India-MARKAL results are out of range, being around 4 in 2050) (c) across scenarios and models 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,

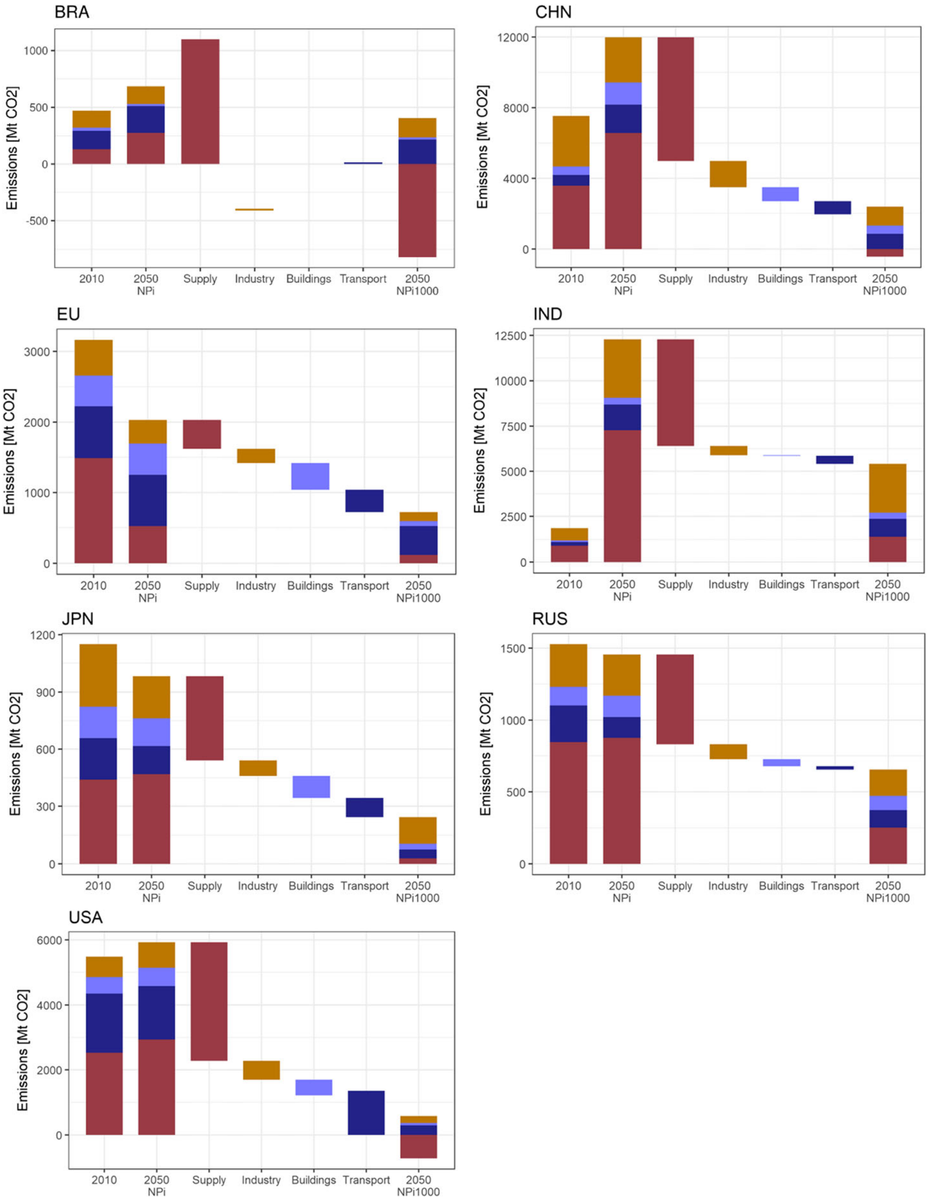


**Fig. 3** Sectoral $CO_2$ emissions and contributions to mitigation in 2050, per region/country. Change between 2010 (first bar), 2050 NPi (second bar), and 2050 NPi1000 (seventh bar). Red: energy supply, yellow: industry, light blue: buildings, dark blue: transportation. BRA Brazil, CHN China, EU European 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.

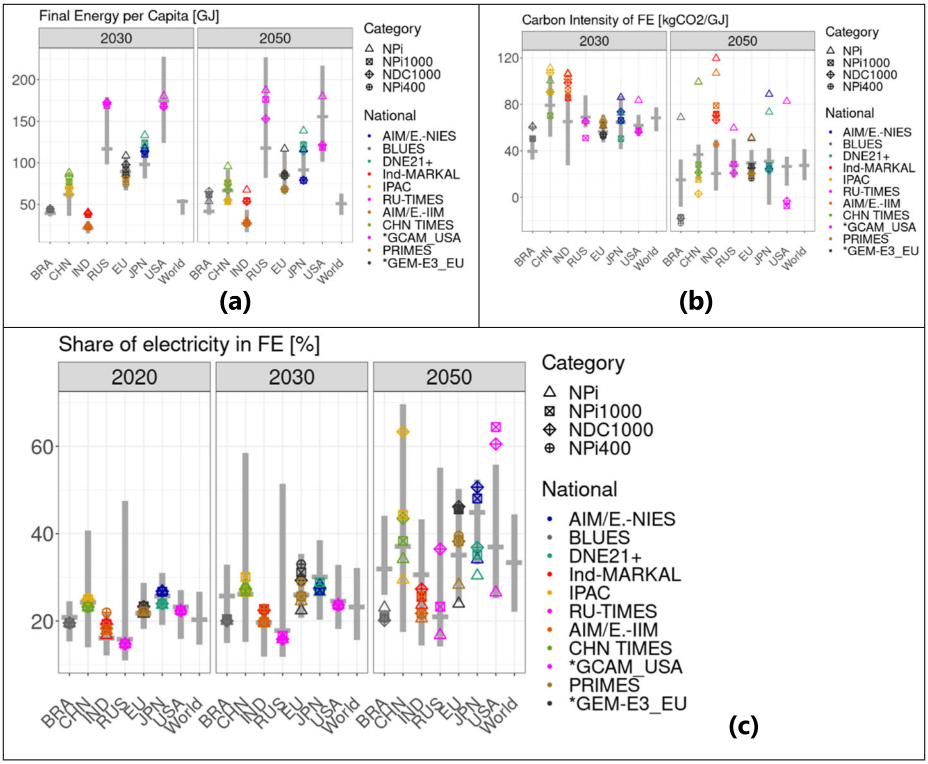


**Fig. 4** Final energy consumption per capita (a), carbon intensity of final energy consumption (b), and share of electricity on final energy consumption (c). Gray bars indicate the range of results for global IAMs in NPi1000, and the color shapes the results of national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

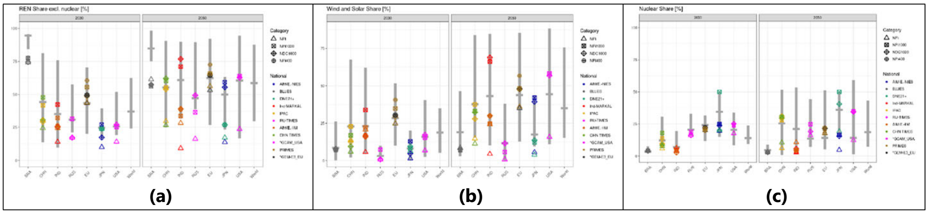

**Fig. 5** Share in power generation of low-carbon energy sources including solar, wind, nuclear, hydropower, biomass, and geothermal (a), wind and solar (b), and nuclear (c). Gray bars indicate the range of results for global IAMs in NPi1000, and the color shapes the results of national models. BRA Brazil, CHN China, EU European Union, IND India, JPN Japan, RUS Russian Federation, USA United States of America

### 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 (NPi400, 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ emission reduction from NDC1000 to NPi1000 and NDC1000 to NPi400 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 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).

**Funding information** This study benefited from the financial support of the European Commission via the *Linking Climate and Development Policies-Leveraging International Networks and Knowledge Sharing* (CD-LINKS) *project*, financed by the European Union's Horizon 2020 research and innovation program under grant agreement no. 642147 (CD-LINKS). We thank all CD-LINKS project partners for contributing to scenario development. Results presented here are not automatically endorsed by CD-LINKS project partners. RS would like to acknowledge the financial support received from the National Council for Scientific and Technological Development (CNPq), and from the National Institute of Science and Technology for Climate Change Phase 2 under CNPq Grant 465501/2014-1 and the National Coordination for High Level Education and Training (CAPES) Grant 88887.136402/2017-00, all from Brazil. WC would like to thank the support from National Science Foundation of China (71690243) for the development and improvement of China-TIMES. SF and KO would like to acknowledge the support received from the Environment Research and Technology Development Fund (2-1702) of the Environmental Restoration and Conservation Agency, Japan.

## References

Akimoto K et al (2010) Estimates of GHG emission reduction potential by country, sector, and cost. Energy Policy 38:3384–3393. https://doi.org/10.1016/j.enpol.2010.02.012

Akimoto K et al (2014) Assessment of the emission reduction target of halving CO2 emissions by 2050: macro-factors analysis and model analysis under newly developed socio-economic scenarios. Energy Strategy Reviews 2:246–256. https://doi.org/10.1016/j.esr.2013.06.002

Akimoto K, Shoai Tehrani B et al. (2015) MILES (modelling and informing low emissions strategies) project - Japan policy paper: a joint analysis of Japan's INDC. Research Institute of Innovative Technology for the Earth (RITE) and National Institute for Environmental Studies (NIES)

Bataille C, Guivarch C et al (2018) Carbon prices across countries. Nature Clim Change 8:648–650. https://doi.org/10.1038/s41558-018-0239-1

van den Berg NJ, van Soest HL et al (2019) Implications of various effort-sharing approaches for national carbon budgets and emission pathways. Climatic Change (this issue). https://doi.org/10.1007/s10584-019-02368-y

Borba BSMC et al. (2012) Energy-related climate change mitigation in Brazil: potential, abatement costs and associated policies. Energy Policy 49: 430–441doi: https://doi.org/10.1016/j.enpol.2012.06.040

Capros P et al (2016) Assessment of the macroeconomic and sectoral effects of higher electricity and gas prices in the EU: a general equilibrium modeling approach. Energy Strategy Reviews 9:18–27. https://doi.org/10.1016/j.esr.2015.11.002

Capros P et al. (2017) Modelling study contributing to the impact assessment of the European Commission of the Electricity Market Design Initiative

Chen W, Xiang Y, Hongjun Z (2016) Towards low carbon development in China: a comparison of national and global models. Clim Chang 136:95–108. https://doi.org/10.1007/s10584-013-0937-7

E3MLab (2016) PRIMES Model Version 6 2016–2017 - Detailed model description

E3MLab (2017) GEM-E3 Model Manual 2017 http://www.e3mlab.ntua.gr/e3mlab/GEM%20-%20E3%20Manual/GEM-E3_manual_2017.pdf

Fawcett AA, Iyer GC, et al. (2015) Can Paris pledges avert severe climate change? Science 350:1168–1169 doi: https://doi.org/10.1126/science.aad5761

Feijoo F, Iyer G, Binsted M et al. (2020) US energy system transitions under cumulative emissions budgets. Climatic Change (this issue) doi: https://doi.org/10.1007/s10584-020-02670-0

Fragkos P, Tasios N, Paroussos L, Capros P, Tsani S (2017) Energy system impacts and policy implications of the European intended nationally determined contribution and low-carbon pathway to 2050. Energy Policy 100:216–226. https://doi.org/10.1016/j.enpol.2016.10.023

Henriques MF Jr, Dantas F, Schaeffer R (2010) Potential for reduction of $CO_2$ emissions and a low-carbon scenario for the Brazilian industrial sector. Energy Policy 38:1946–1961. https://doi.org/10.1016/j.enpol.2009.11.076

Höhne N, den Elzen MGJ et al (2020) Emissions: four times the work or one-third of the time. Nature 579:25–28. https://doi.org/10.1038/d41586-020-00571-x

IPCC (2014) Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland

Iyer G, Ledna C, Clarke L, McJeon H, Edmonds J, Wise M (2017a) GCAM-USA analysis of US electric power sector transitions http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26174.pdf. Pacific northwest National Laboratory

Iyer G, Ledna C, Clarke LE, Edmonds J, McJeon H, Kyle GP, Williams JA (2017b) Measuring progress from nationally determined contributions to mid-century strategies. Nature Clim Change 7:871–874. https://doi.org/10.1038/s41558-017-0005-9

Karkatsoulis P, Siskos P, Paroussos L, Capros P (2017) Simulating deep CO2 emission reduction in transport in a general equilibrium framework: the GEM-E3T model. Transp Res Part D: Transp Environ 55:343–358. https://doi.org/10.1016/j.trd.2016.11.026

Kartha S, Athanasiou T et al (2018) Cascading biases against poorer countries. Nat Clim Chang 8:348–349. https://doi.org/10.1038/s41558-018-0152-7

Kejun J (2012) Secure low-carbon development in China. Carbon Management 3:333–335. https://doi.org/10.4155/cmt.12.42

Kejun J, Zhuang X, Miao R, He C (2013) China's role in attaining the global 2°C target. Clim Pol 13:55–69. https://doi.org/10.1080/14693062.2012.746070

Kejun J et al (2016) China's low-carbon investment pathway under the 2 °C scenario. Adv Clim Chang Res 7: 229–234. https://doi.org/10.1016/j.accre.2016.12.004

Köberle AC et al. (2015) Brazil Chapter. In *Beyond the Numbers: Understanding the Transformation Induced by INDCs. A Report of the MILES Project Consortium* (eds. Spencer T and Pierfedericci R) 80

Köberle AC, Rochedo P, Lucena AFP, Szklo A, Schaeffer R (2020) Brazil emissions trajectories in a well-below 2 °C world: the role of disruptive technologies versus land-based mitigation in an already low-emission energy system. Climatic Change (this issue) doi: to be completed once available

Malagueta D et al (2013) Assessing incentive policies for integrating centralized solar power generation in the Brazilian electric power system. Energy Policy 59:198–212. https://doi.org/10.1016/j.enpol.2013.03.029

Mathur R and Shekar S (2020) India's energy sector choices – options & implications of ambitious mitigation efforts, climatic change under review (this issue) doi: to be completed once available

Millar RJ, Fuglestvedt JS et al (2017) Emission budgets and pathways consistent with limiting warming to 1.5°C. Nat Geosci 10:741–747. https://doi.org/10.1038/ngeo3031 http://www.nature.com/ngeo/journal/v10/n10/abs/ngeo3031.html#supplementary-information
Nogueira LPP et al (2014) Will thermal power plants with CCS play a role in Brazil's future electric power generation? International Journal of Greenhouse Gas Control 24:115–123. https://doi.org/10.1016/j.ijggc.2014.03.002
Oshiro K, Masui T (2015) Diffusion of low emission vehicles and their impact on CO2 emission reduction in Japan. Energy Policy 81:215–225. https://doi.org/10.1016/j.enpol.2014.09.010
Oshiro K, Kainuma M, Masui T (2017) Implications of Japan's 2030 target for long-term low emission pathways. Energy Policy 110:581–587. https://doi.org/10.1016/j.enpol.2017.09.003
Oshiro K, Gi K, Fujimori S, van Soest HL, Bertram C, Després J, Masui T, Rochedo P, Roelfsema M, Vrontisi Z (2019) Mid-century emission pathways in Japan associated with the global 2°C goal: national and global models' assessments based on carbon budgets. Climatic Change (this issue). https://doi.org/10.1007/s10584-019-02490-x
Peters GP (2016) The ´best available science'to inform 1.5°C policy choices. Nature Clim Change 6:646–649. https://doi.org/10.1038/nclimate3000
PNNL (2016) GCAM documentation http://jgcri.github.io/gcam-doc/toc.html
Potashnikov V, Lugovoy O (2014) Projections of the energy balance and greenhouse gas emissions based on RU-TIMES model by 2050. Scientific Vestnik of Gaidar's Institute of Economic Policy, #5 [in Russian]
Pye S et al (2016) Exploring national decarbonization pathways and global energy trade flows: a multi-scale analysis. Clim Pol 16:S92–S109. https://doi.org/10.1080/14693062.2016.1179619
Rathmann R, Szklo A, Schaeffer R (2012) Targets and results of the Brazilian biodiesel incentive program: has it reached the promised land? Appl Energy 97:91–100. https://doi.org/10.1016/j.apenergy.2011.11.021
Riahi K, van Vuuren DP et al (2017) The shared socioeconomic pathways and their energy, land use and greenhouse gas emissions implications: an overview. Glob Environ Chang 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009
RITE (2015) GHG Mitigation Assessment Model DNE21+
Robiou Du Pont Y, Jeffery ML et al (2017) Equitable mitigation to achieve the Paris Agreement goals. Nature Clim Change 7:38–43. https://doi.org/10.1038/nclimate3186
Rochedo PRR, Soares-Filho B et al (2018) The threat of political bargaining to climate mitigation in Brazil. Nature Clim Change 8:695–698. https://doi.org/10.1038/s41558-018-0213-y
Roelfsema M, van Soest H et al (2020) Taking stock of national climate policies to evaluate implementation and ambition in the Paris Aggreement. Nat Commun 11:2096. https://doi.org/10.1038/s41467-020-15414-6
Rogelj J, den Elzen MGJ et al (2016a) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534:631–639. https://doi.org/10.1038/nature18307
Rogelj J, Schaeffer M et al (2016b) Differences between carbon budget estimates unravelled. Nature Clim Change 6:245–252. https://doi.org/10.1038/nclimate2868
Safonov G (2016) Low carbon development strategy in Russia: transition from fossil fuels to green energy sources. Moscow State University - TEIS Publishing House [in Russian]
Safonov G, Lugovoy O, Potashnikov V (2020) The low carbon development options for Russia: business-as-usual or the breakthrough to deep decarbonisation. Climatic Change (this issue) doi: to be included when available
Schaeffer R, Szklo AS (2001) Future electric power technology choices of Brazil: a possible conflict between local pollution and global climate change. Energy Policy 29:355–369. https://doi.org/10.1016/S0301-4215(00)00130-0
Sharma S, Kumar A (eds) (2016) Air pollutant emissions scenario for India. The Energy and Resources Institute, New Delhi, India
Sheeran KA (2006) Who should abate carbon emissions? A note. Environ Resour Econ 35:89–98. https://doi.org/10.1007/s10640-006-9007-1
Shi J, Chen W, Yin X (2016) Modelling building's decarbonization with application of China TIMES model. Appl Energy 162:1303–1312. https://doi.org/10.1016/j.apenergy.2015.06.056
TERI (2015) Energy security outlook: defining a secure and sustainable energy future for India, the energy and resources institute. New Delhi, India
UNEP (2019) The emissions gap report 2019. United Nations Environment Programm (UNEP), Nairobi https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf
UNFCCC (2015), Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev. 1, http://unfccc.int/resource/docs/2015/cop21/eng/IO9r01.pdf
Vishwanathan SS and Garg A (2020) Energy system transformation to meet INDC, 2 °C and 1.5 °C targets for India, Climatic Change (this issue) doi: https://doi.org/10.1007/s10584-019-02616-1

Vishwanathan SS et al (2017) Enhancing energy efficiency in India: assessment of sectoral potentials. Copenhagen Centre on Energy Efficiency, UNEP DTU Partnership, Copenhagen

Vrontisi Z, Fragkiadakis K, Capros P, Kannavou M (2019) Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2°C climate stabilization. Climatic Change (this issue). https://doi.org/10.1007/s10584-019-02440-7

Wang H, Chen W, Zhang H, Li N (2019) Modeling of power sector decarbonisation in China: comparisons of early and delayed mitigation towards 2-degree target. Climatic Change (this issue). https://doi.org/10.1007/s10584-019-02485-8

Zhang H, Chen W, Huang W (2016) TIMES modelling of transport sector in China and USA: comparisons from a decarbonization perspective. Appl Energy 162:1505–1514. https://doi.org/10.1016/j.apenergy.2015.08.124



## Affiliations

**R. Schaeffer[1] • A. Köberle[1,2] • H. L. van Soest[3,4] • C. Bertram[5] • G. Luderer[5] • K. Riahi[6] • V. Krey[6] • D. P. van Vuuren[3,4] • E. Kriegler[5] • S. Fujimori[7,8] • W. Chen[9] • C. He[10] • Z. Vrontisi[11] • S. Vishwanathan[12] • A. Garg[12] • R. Mathur[13] • S. Shekhar[13] • K. Oshiro[14] • F. Ueckerdt[5] • G. Safonov[15] • G. Iyer[16] • K. Gi[17] • V. Potashnikov[18]**

[1] Centre for Energy and Enviromental Economics, Energy Planning Program, CENERGIA/PPE/COPPE/UFRJ, Centro de Tecnologia, Universidade Federal do Rio de Janeiro (COPPE/UFRJ), Bloco C, Sala C-211, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, RJ 21941-914, Brazil

[2] Grantham Institute, Imperial College London (ICL), London, UK

[3] PBL Netherlands Environmental Assessment Agency, Hague, The Netherlands

[4] Copernicus Institute, Utrecht University, Utrecht, The Netherlands

[5] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

[6] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[7] Kyoto University (KyotoU), Kyoto, Japan

[8] National Institute for Environmental Studies (NIES), Tsukuba, Japan

[9] Institute of Energy, Environment and Economy, Tsinghua University (TU), Beijing, China

[10] Energy Research Institute (ERI), Beijing, China

[11] School of Electrical and Computer Engineering, E3MLab, National Technical University of Athens, Athens, Greece

[12] Indian Institute of Management-Ahmedabad (IIMA), Ahmedabad, India

[13] The Energy and Resources Institute (TERI), New Delhi, India

[14] Mizuho Information & Research Institute (MHIR), Tokyo, Japan

[15] Higher School of Economics (HSE), Moscow, Russia

[16] Pacific Northwest National Laboratory (PNNL), Richland, WA, USA

[17] Research Institute of Innovative Technology for the Earth (RITE), Kyoto 619-0292, Japan

[18] Russian Presidential Academy of National Economy and Public Administration (RANEPA), Moscow, Russia