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Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment

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Supplementary material for this article is available [online](#)

Abstract

The Paris Agreement is a milestone in international climate policy as it establishes a global mitigation framework towards 2030 and sets the ground for a potential 1.5 °C climate stabilization. To provide useful insights for the 2018 UNFCCC Talanoa facilitative dialogue, we use eight state-of-the-art climate-energy-economy models to assess the effectiveness of the Intended Nationally Determined Contributions (INDCs) in meeting high probability 1.5 and 2 °C stabilization goals. We estimate that the implementation of conditional INDCs in 2030 leaves an emissions gap from least cost 2 °C and 1.5 °C pathways for year 2030 equal to 15.6 (9.0–20.3) and 24.6 (18.5–29.0) GtCO₂eq respectively. The immediate transition to a more efficient and low-carbon energy system is key to achieving the Paris goals. The decarbonization of the power supply sector delivers half of total CO₂ emission reductions in all scenarios, primarily through high penetration of renewables and energy efficiency improvements. In combination with an increased electrification of final energy demand, low-carbon power supply is the main short-term abatement option. We find that the global macroeconomic cost of mitigation efforts does not reduce the 2020–2030 annual GDP growth rates in any model more than 0.1 percentage points in the INDC or 0.3 and 0.5 in the 2 °C and 1.5 °C scenarios respectively even without accounting for potential co-benefits and avoided climate damages. Accordingly, the median GDP reductions across all models in 2030 are 0.4%, 1.2% and 3.3% of reference GDP for each respective scenario. Costs go up with increasing mitigation efforts but a fragmented action, as implied by the INDCs, results in higher costs per unit of abated emissions. On a regional level, the cost distribution is different across scenarios while fossil fuel exporters see the highest GDP reductions in all INDC, 2 °C and 1.5 °C scenarios.

1. Introduction

Building on the work that started at the Copenhagen and Cancun climate summits, the bottom-up approach to climate change mitigation has been strengthened with the Paris Agreement and the submission of Intended Nationally Determined Contributions (INDCs or now called NDCs). This approach marked a fundamental shift in international climate policy, attracting wide support and thus reaching a participation of 195 parties representing over 98% of global emitters. In addition to this ambitious international coverage, of major importance is also the decision of COP21 to officially set the long-term target agreed in Copenhagen and Cancun, expressing the aim of ‘holding the increase in global mean temperatures to a well below 2 °C and to pursue efforts to limit the temperature increase to 1.5 °C’. A facilitative dialogue, expected to start in 2018 and to reoccur at five year intervals, shall take stock of the combined efforts of the parties in relation to this long-term emission reduction goal and report progress to the COP. The strengthened ambition of the long-term goal poses new challenges for policy makers and indeed society as a whole, but also for scientific analysis. Such a target has long been endorsed by climate scientists despite the debate surrounding its origins and effectiveness (Cointe *et al* 2011, Knutti *et al* 2016, Smith *et al* 2009, Jaeger and Jaeger 2010, Knopf *et al* 2012).

The scientific community is committed to providing input for a potential ratcheting-up of INDCs and to describe possible pathways and necessary actions towards achieving the 1.5 °C target in light of the UNFCCC facilitative dialogue. Climate-energy-economy models have a long tradition in contributing to the global societal challenge of climate change mitigation and in providing scientific insights to the international climate policy proceedings. Such assessments span from an analysis on the impacts of the 1997 Kyoto protocol (Weyant 1999) to assessments of the Cancun pledges (UNEP 2010, UNFCCC 2010, Ricci and Selosse 2013, van Vliet *et al* 2012, den Elzen *et al* 2011, Saveyn *et al* 2011, Peterson *et al* 2011, Kriegler *et al* 2013, Riahi *et al* 2015, Luderer *et al* 2016). Similarly, in the lead-up to COP21, a number of analyses (Labat *et al* 2015, Spencer *et al* 2015, IEA 2015, UNEP 2015, UNFCCC 2015) were published to facilitate an informed negotiation process. In the aftermath of COP21, additional analyses were published, which included the agreed Paris outcome and reaffirmed earlier findings about the insufficiency of the INDCs in meeting the 2 °C target (UNFCCC 2016, Rogelj *et al* 2016, den Elzen *et al* 2016, Vandyck *et al* 2016, UNEP 2016, Fujimori *et al* 2016a).

We further add to this literature and contribute to the ongoing scientific research by providing a first multi-model analysis on the short-term, i.e. to 2030,

effectiveness of INDCs in relation to up-to-date scenarios for a well-below 2 °C (2 °C scenario) and a high probability 1.5 °C (1.5 °C scenario) climate stabilization, as presented in table 1. We discuss the contributions of different sectors and different greenhouse gases and describe the transition of the energy system. Our analysis concludes with an estimation of global macro-economic mitigation costs. Through this, we aim to provide a first harmonized multi-model assessment of the INDCs along with 1.5 °C–2 °C consistent stabilization scenarios. We expect that this analysis can potentially provide quantitative input to the upcoming UNFCCC Facilitative Dialogue on Enhancing Ambition and Support in 2018. Our multi-model assessment enhances the robustness of our findings and provides an insight on the range of uncertainty of model results, due to both an inherent uncertainty of the quantification of INDCs (Rogelj *et al* 2017) and to the different modelling methodologies, techno-economic and structural assumptions of each model. Moreover, we provide a first multi-model short-term estimation of high probability 1.5 °C emission pathways and subsequent system requirements. Current literature includes very limited 1.5 °C scenarios (UNEP 2016), the majority of which assumes that global mitigation action to reach this target started in 2010 (IPCC 2014, Rogelj *et al* 2015) and can thus be considered as out of date given the existing policy framework. An even smaller number of scenarios assume the introduction of global carbon prices in 2020 but only ensure a 50% chance of meeting the 1.5 °C target (Rogelj *et al* 2015, UNEP 2016). Our set of scenarios fill the 1.5 °C scenario gap (UNEP 2016) as we implement a carbon budget that is in line with achieving with a high probability (> 66% chances) temperature increase below 1.5 °C by the end of the century. Comparability and equity considerations of the regional global mitigation effort as well as legal implications of the agreement are beyond the scope of this analysis.

2. Methods

2.1. Scenario set-up

Our set of scenarios enables the assessment of INDCs towards the 1.5 °C–2 °C climate targets. They are described briefly in table 1 and in more detail in the supplementary material available at stacks.iop.org/ERL/13/044039/mmedia.

2.2. Models

The eight state-of-the-art climate-energy-economy models that participate in this analysis feature different characteristics and model structures, providing further robustness of results. A brief description is provided in table 2, while more information can be found in the supplementary material.

Table 1. Brief description of scenarios.^a

Scenario name	Description	Climate stabilization constraint
Reference	Realistic achievement of 2020 Cancun pledges. Low climate policy ambition in the post-2020 period.	No
INDC	Realistic achievement of 2020 Cancun pledges. Full implementation conditional INDCs by 2030. Fragmented climate action after 2030 with following a reduction of carbon intensity as in 2020–2030 period.	No
2 °C	Realistic achievement of 2020 Cancun pledges. Post-2020 cost-optimal global mitigation action to keep total CO ₂ emissions to within a 800 GtCO ₂ carbon budget in 2016–2100.	>67% chance to stay below 2 °C (for more details on the climate evaluation please refer to Luderer <i>et al</i> (in review))
1.5 °C	Realistic achievement of 2020 Cancun pledges. Post-2020 cost-optimal global mitigation action to keep total CO ₂ emissions to within a 200 GtCO ₂ carbon budget in 2016–2100.	>67% chance to return to below 1.5 °C in 2100 (for more details on the climate evaluation please refer to Luderer <i>et al</i> (in review))

^a The 2 °C and 1.5 °C scenarios correspond to the B200|1.5C-T2100| > 67% and B800|2C-Tmax| > 67% scenarios in Luderer *et al* (in review).

Table 2. Brief description of participating models.

Model name	Model type	Disaggregated economic sectors	Land use emissions	GHG coverage
AIM/CGE	Computable GE model	Yes	Yes	All
GEM-E3-ICCS	Computable GE model	Yes	No	All, no CO ₂ from industrial processes
IMACLIM	Computable GE model	Yes	No	Only CO ₂ , no CO ₂ from industrial processes
IMAGE	Energy-Land PE model	No	Yes	All
MESSAGE-GLOBIOM	Energy system—GE growth model	No	Yes	All
POLES	Energy system-PE ^a model	No	Yes	All
REMIND	Energy system—GE growth model	No	Yes	All
WITCH-GLOBIOM	Energy system—GE growth model	No	Yes	All

^a PE: Partial equilibrium, GE: General equilibrium.

3. Results and discussion

This section presents the results of the numerical simulations of the scenarios presented in section 2. Simulations have been conducted by all eight participating models and the results throughout the text are presented as a median of all model results, while minimum and maximum values of the eight model results are provided in the brackets unless indicated otherwise. In all boxplot figures the top of the rectangle indicates the third quartile, the horizontal line near the middle of the rectangle indicates the median, while the bottom of the rectangle indicates the first quartile. We note that especially with regards to the ranges of GHG emission levels, these do not include GEM-E3 and IMACLIM models, as they do not have a full coverage of GHG emissions.

The first subsection of this section discusses the emission pathways for each scenario and the emission reduction contributions by different GHGs and by economic sectors. Next, we analyze the energy system transition that is in line with the climate policy constraints, with a particular focus on the power supply and the transport sector. Finally, we present the short-term macroeconomic costs of the mitigation

action for each scenario, covering both direct and indirect costs but not taking into consideration avoided climate damages nor any potential co-benefits of the mitigation action.

3.1. Emission pathways

In the absence of the Paris pledges, the implementation of current policies (reference scenario) leads to an increase of global emissions at a rate of 0.7% (0.4%–1.1%) per annum during 2010–2050, reaching 60.3 (56.6–64.6) GtCO₂eq in 2030 (table 3), and peak after 2050 in all models, if at all by 2100. Along such trajectories the global mean temperature, projected by the global climate model MAGICC6¹² (Meinshausen *et al* 2011) shows a 3.4 °C (2.9°–3.8°) temperature increase by the end of the century compared to pre-industrial levels and thus falls far short of the climate stabilization targets agreed in Paris, and exposes the world to severe climate risks (e.g. IPCC 2014, World Bank 2012).

¹² All temperature results mentioned in the text refer to year 2100 and to the 50 percentile output of MAGICC6 model. The ranges that are provided include the 50% temperature across models for year 2100, thus full climate uncertainty is not covered.

Table 3. GHG emissions levels in 2030 and GHG, GDP and final energy trends in 2010–2050 for all scenario and models.

		Mean annual global GHG emissions in 2030			Mean annual change in 2010–2050		
		Absolute level	Versus 2010	Versus reference	GHG	GDP	Final energy
Reference	AIM/CGE	63.6	24%		0.8%	2.6%	1.1%
	GEM-E3/ICCS ^b	52.8	26%		0.8%	2.5%	1.4%
	IMACLIM ^a	41.7	36%		1.2%	2.9%	1.8%
	IMAGE	56.6	18%		0.5%	3.0%	1.1%
	MESSAGE	57.4	11%		0.4%	3.8%	1.4%
	POLES	61.8	33%		1.0%	2.6%	1.2%
	REMIND	64.6	29%		1.1%	2.6%	1.6%
	WITCH	58.9	24%		0.7%	2.5%	1.6%
INDC	AIM/CGE	54.5	7%	−14%	−0.3%	2.6%	0.9%
	GEM-E3/ICCS ^b	47.0	12%	−11%	−0.2%	2.4%	1.0%
	IMACLIM ^a	39.2	28%	−6%	0.7%	2.9%	1.6%
	IMAGE	53.8	12%	−5%	−0.1%	3.0%	0.8%
	MESSAGE	53.7	4%	−6%	−0.4%	3.8%	1.2%
	POLES	50.1	8%	−19%	−0.5%	2.6%	0.9%
	REMIND	56.6	13%	−12%	0.3%	2.6%	1.5%
	WITCH	48.8	3%	−17%	0.0%	2.5%	1.5%
2 °C	AIM/CGE	36.0	−30%	−43%	−2.8%	2.5%	0.5%
	GEM-E3/ICCS ^b	43.6	4%	−17%	−2.5%	2.3%	0.4%
	IMACLIM ^a	31.6	3%	−24%	−2.6%	2.7%	0.7%
	IMAGE	38.3	−20%	−32%	−2.8%	3.0%	−0.1%
	MESSAGE	40.4	−22%	−30%	−2.1%	3.8%	0.8%
	POLES	41.1	−11%	−34%	−2.8%	2.6%	0.6%
	REMIND	41.0	−18%	−37%	−2.4%	2.6%	1.1%
	WITCH	28.5	−40%	−52%	−2.1%	2.4%	0.8%
1.5 °C	AIM/CGE	25.5	−50%	−60%	−9.4%	2.5%	0.1%
	GEM-E3/ICCS ^b	23.9	−43%	−55%	−3.8%	2.2%	0.1%
	IMACLIM ^a	26.6	−13%	−36%	−8.2%	2.4%	0.2%
	IMAGE	35.3	−27%	−38%	−9.2%	3.0%	−0.2%
	MESSAGE	27.9	−46%	−51%	−4.0%	3.7%	0.3%
	POLES	30.8	−34%	−50%	−5.7%	2.6%	0.0%
	REMIND	33.1	−34%	−49%	−4.5%	2.5%	0.9%
	WITCH	21.5	−55%	−64%	−3.5%	2.2%	0.4%

^a IMACLIM only covers CO₂ emissions.

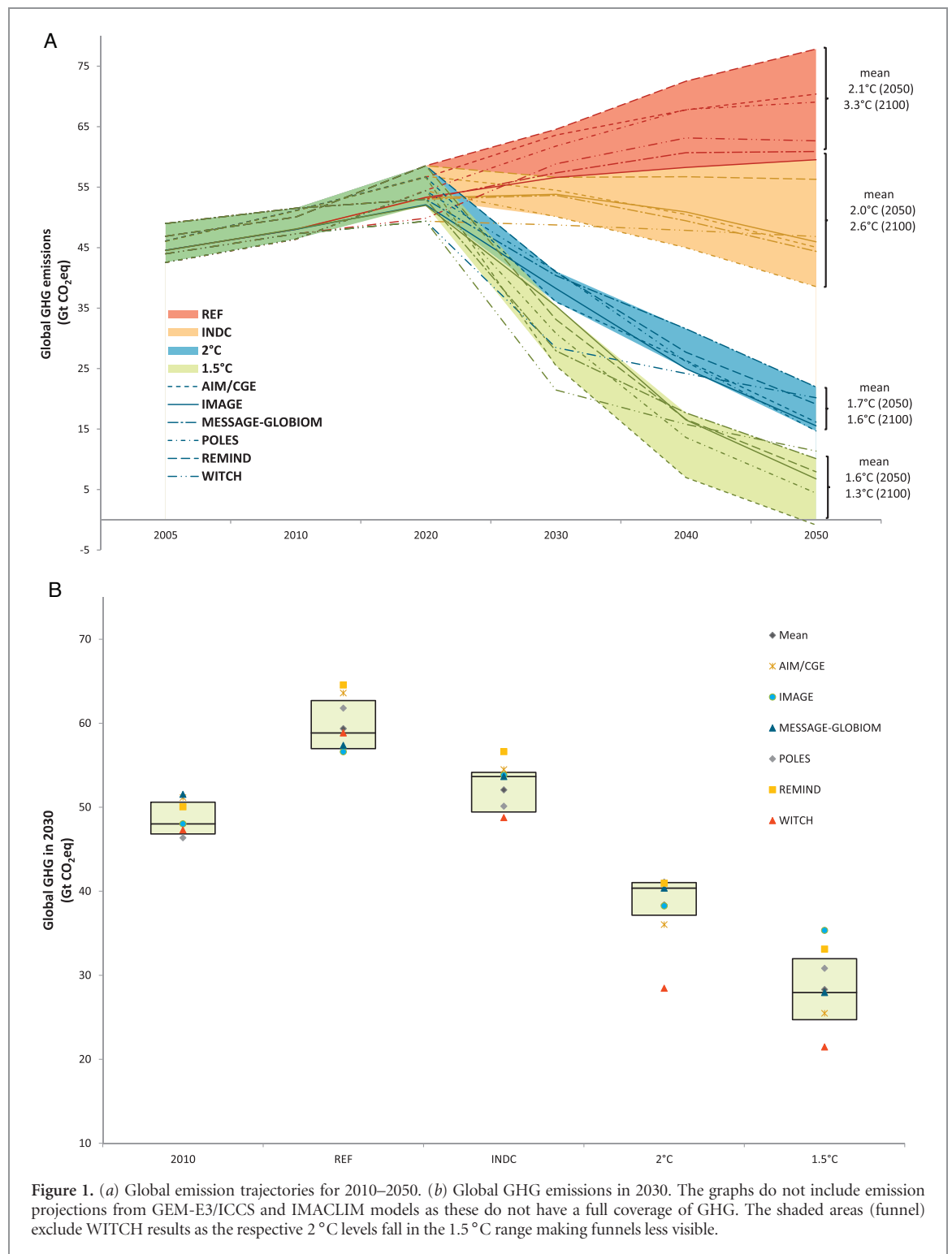
^b GEM-E3/ICCS does not include LULUCF emissions.

The implementation of high-ambition INDCs (conditional INDCs) brings global emissions down by 8.5 (2.8–11.7) GtCO₂eq compared to the reference scenario, thus reaching 53.7 (48.8–56.6) GtCO₂eq in 2030. Our range of results confirms earlier estimations of conditional INDC GHG levels that refer to 51–56 GtCO₂eq (UNFCCC 2016, Rogelj *et al* 2016, UNEP 2016). By keeping the ambition of post-2030 climate policies similar to that of the INDCs, namely by following an annual decarbonization rate equal to that of 2020–2030, we find that the average annual growth rate of global GHG emissions becomes only marginally negative for most models in 2010–2050, while emissions peak in the 2020–2030 period. However, with such an assumption on future climate policies, the temperature increase by the end of the century is still higher than the commonly agreed climate stabilization goals, reaching the range of 2.6 °C (2.4 °C–3.1 °C) as evaluated with MAGICC6 (see also Luderer *et al* (in review) for a more detailed climate evaluation).

In the cost-optimal 2 °C and 1.5 °C scenarios all models find that global emissions peak in 2020, namely when the global climate mitigation action begins with the introduction of a global carbon price. GHG emission levels in 2030 fall to 39.3 (28.5–41.1) and 29.4 (21.5–35.3) GtCO₂eq respectively, corresponding to

a 34% (19%–52%) and 53% (36%–64%) reduction from reference levels. The implementation of conditional INDCs in 2030 leaves an emissions gap (UNEP 2015) of 15.6 (9.0–20.3) and 24.6 (18.5–29.0) GtCO₂eq for the 2 °C and 1.5 °C targets respectively (see figure 1).

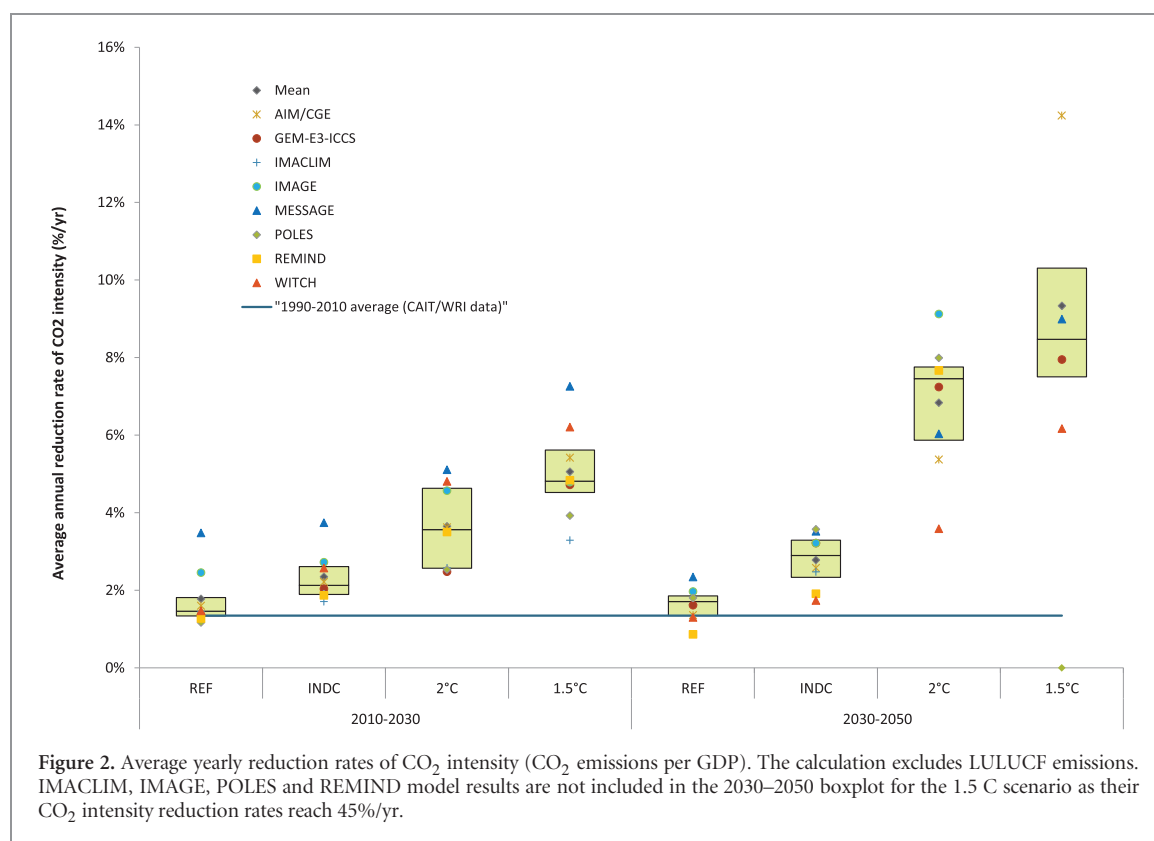
We find that our 2030 2 °C emission levels are on the lower end of the IPCC AR5 scenarios that are reported in the literature (UNEP 2016, Rogelj *et al* 2015), in part due to a later starting year of global climate action in our scenarios. Comparing our 1.5 °C estimations with existing literature is more challenging, since relevant estimations are very limited and based on different assumptions (i.e. earlier starting year of global climate action and higher carbon budget for the period 2011–2100, as described in section 2). Our high probability 1.5 °C scenario falls well below the emission levels of earlier estimations that report a level of 2030 global GHG emissions equal to 33 (26–40) GtCO₂eq (Rogelj *et al* 2015) and 39 (37–40) GtCO₂eq (UNEP 2016), while other recent publications (Robiou du Pont *et al* 2017) provide an estimation of 29 GtCO₂eq but exclude LULUCF and bunker emissions and are thus not comparable. Our estimations are lower than the findings of the literature so far, primarily due to the construction of our scenarios which



features increased chances of meeting the 1.5 °C target (higher than 66% chance instead of higher than 50% chance). In addition, our implementation of a global mitigation action 10 years later than most IPCC AR5 scenarios, i.e. in 2020, results in a smaller available carbon budget for the period 2020–2100.

Apart from the intrinsic uncertainty of GHG emission projections, different historical emissions across participating models may also explain the wide emissions range. In particular, historical emissions are

an important consideration, as INDC targets are largely expressed in relation to historical base years. In line with the above, our harmonized quantification of INDCs is expressed in relation to 2010 emission levels. The differences in historical emissions across models can be explained by the usage of different data sources (EDGAR, UNFCCC, CAIT and PRIMAP) as well as by the different calibration years of each model. While the use of different data sources can provide an indication of the adjacent uncertainty ranges



of emission trajectories, a harmonization of sources remains a challenge for future model ensemble analyses. In order to understand the potential significance of a data harmonization process, we isolate this uncertainty by using the uniform scaling harmonization approach (Rogelj *et al* 2011). For this we select the average 2005 global GHG emissions of all models as a reference value to adjust all GHG projections. We find that this harmonization results in a somewhat reduced range of results, but also in systematically lower median values, with emissions gaps of 15.6 (9.1–19.8) for the 2 °C and to 22.0 (17.8–27.0) for the 1.5 °C targets. All results described in the subsections below have not been adjusted with this harmonization process.

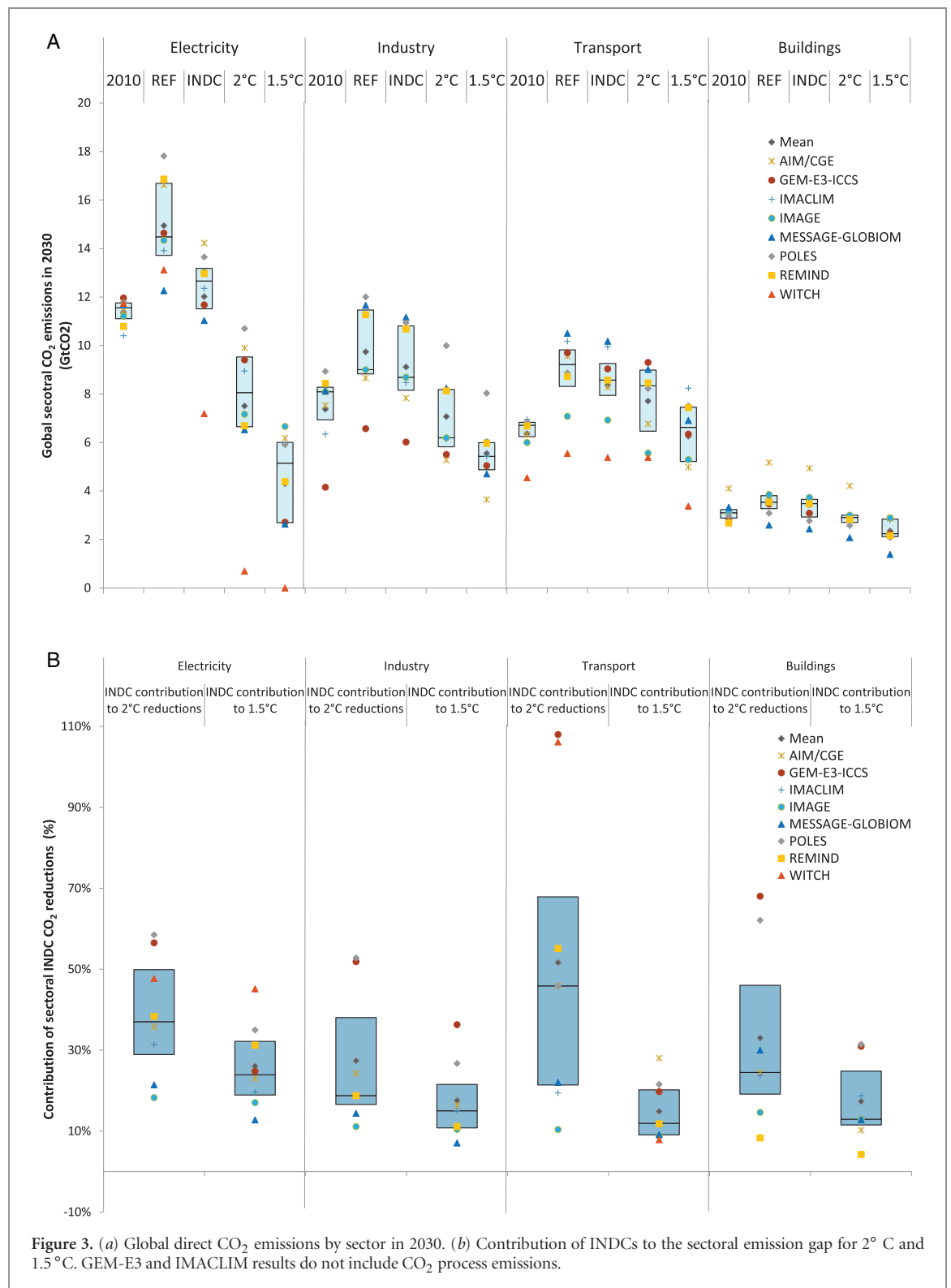
The rate of decarbonization of the economy (namely the reduction of carbon intensity of GDP) is slower in the period 2010–2030 than in 2030–2050 in all scenarios (figure 2). Implementing the INDCs leads to an improvement of carbon intensity towards a rate that exceeds the 1990–2010 average by 1%. The carbon intensity improvement rates of the climate stabilization scenarios in 2010–2030 are below the observed rates of Europe and Central Asia in the period 2004–2014, which are equal to −6%, while in the period 2030–2050 the rates are above the highest observed improvement rate of the 2004–2014 period, which is equal to −11%, thus posing a real challenge for the achievement of this transition.

Around 80% of emission reductions in 2030 in all scenarios come from the reductions of the dominant GHG, CO₂. With regards to the rest of the GHG, CH₄ contributes by around 13%, F-gases by 4% and

N₂O by 3%. In particular, F-gases mark the highest reduction compared to the reference scenario for most models, ranging from 16% in the INDC scenario to 72% in the 1.5 °C scenario. This indicates the cheap abatement potential of F-gases assumed in most models, also in line with the Kigali Agreement of 2016 that sees an 80%–85% reduction of HFCs in 2045¹³ compared to reference projections. On the contrary, N₂O emissions mark the lowest relative reductions in all scenarios, as emissions from agricultural soils have limited abatement options (Smith *et al* 2014).

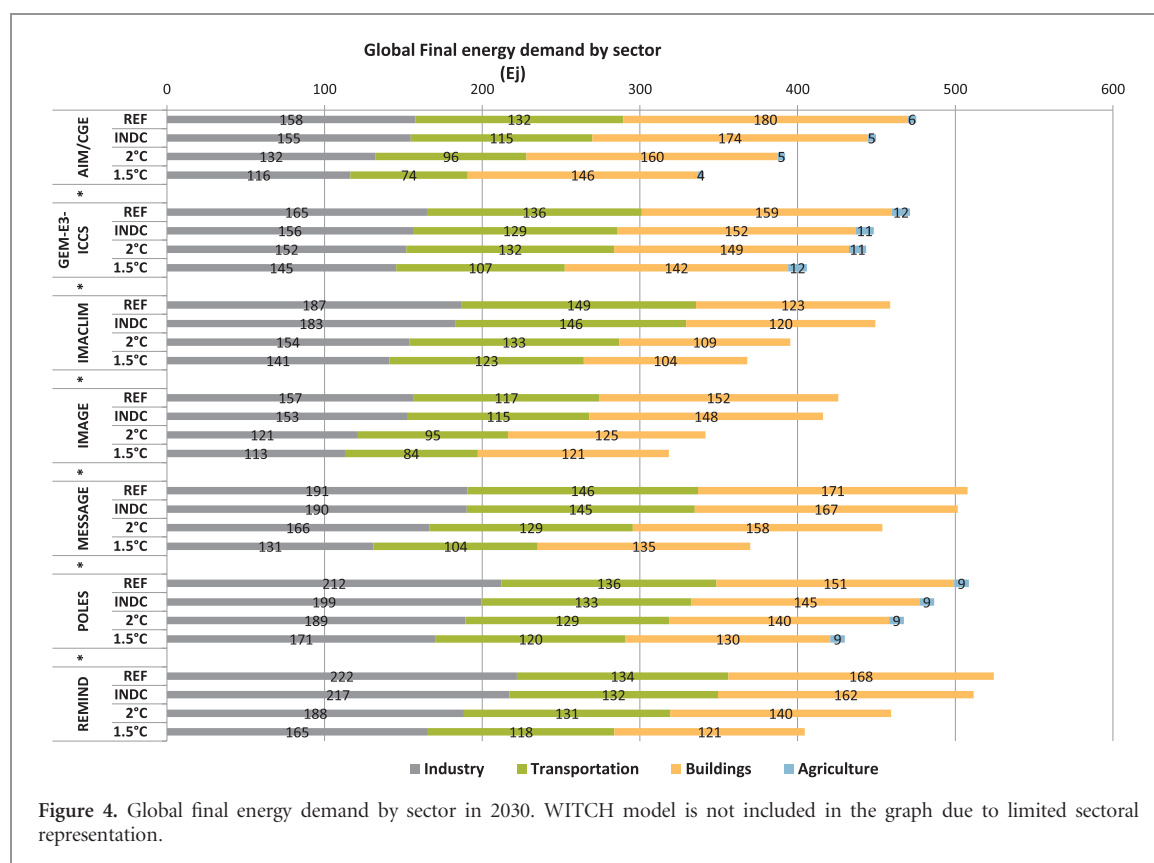
In terms of sectoral contributions, in 2030 the power sector continues to have the highest share of direct CO₂ emissions in both reference and INDC scenarios (figure 3(a)), while its emissions rapidly fall in the climate stabilization scenarios, even below the emission levels of the industry and transport sectors. We find that the decarbonization of the power supply sector accounts for around 50% of total CO₂ emission reductions in all scenarios. The implementation of INDCs contributes substantially to that end, as it achieves 37% (18%–59%) of sectoral reductions of the 2 °C scenario and 24% (13%–45%) of the 1.5 °C reductions. Although the effectiveness of INDCs is noteworthy in the power supply sector, also demand sectors, and especially transportation, register emission reductions induced by the INDCs (figure 3(b)) that account for more than 15%–20%

¹³ Decision XXVIII/1 Further Amendment of the Montreal Protocol. http://ozone.unep.org/sites/ozone/files/pdfs/FAQs_Kigali_Amendment.pdf



of the respective sectoral reductions observed in the 1.5°C–2°C scenarios. The decarbonization of the remaining energy demand sectors is more expensive and thus emission reductions are less pronounced. The overall contribution of the industry sector to total emission reductions in 2030 varies from around 12% in the INDC to 20% and 18% in the 2°C and 1.5°C scenarios respectively. The transport sector contributes by around 12% to total CO₂ reductions

in all scenarios, while the respective share of the buildings sector is close to 6%. However, the transport sector is the only sector whose emissions in 2030 in the decarbonization scenarios are higher than 2010 levels. This is mainly due to increasing demand from emerging economies (Lennert and Schoenduwe 2017), both for private transportation and freight, thus leaving further scope for decarbonization later in the century.



3.2. The energy transformation gap

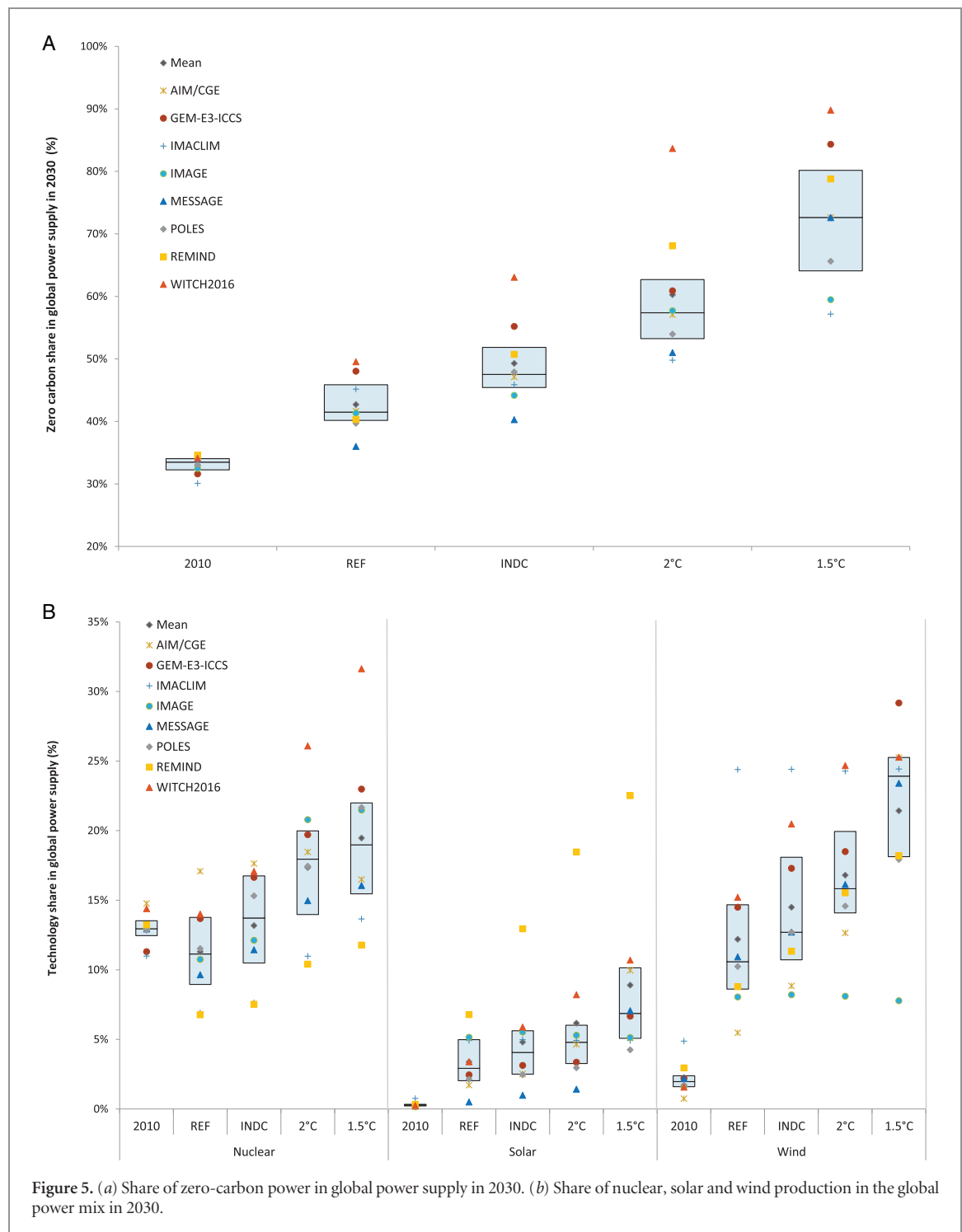
The moderate ambition of the INDCs results in a slow and restrained transformation of the energy system. We here use sectoral indicators to quantify and analyze the energy transformation gap, i.e. the difference in these transformation indicators between INDC scenarios and cost optimal 1.5 and 2 °C scenarios. Final energy intensity of the global economy in 2030 is 25% (20%–44%) lower than 2010 levels but only 3% (1%–8%) below reference levels. In the 2 °C and 1.5 °C scenarios final energy intensity of GDP improves at a much faster pace than under the INDCs. Already in 2030 energy intensity reductions are deep, falling below 2010 levels by 34% (25%–50%) and 39% (30%–57%) respectively.

On a sectoral level (figure 4), industry plays the key role in total energy savings, depicting a large untapped potential for energy efficiency measures. In the INDC scenario in 2030, reductions in industrial final energy demand constitute 38% (7%–58%) of total energy reductions from reference. Much deeper reductions are seen in the climate stabilization scenarios as the INDC industrial final energy reductions are only a fraction of the latter (12% (2%–68%) of 2 °C reductions from reference and 9% (1%–45%) of 1.5 °C reductions from reference). The contribution of industry in total final energy reductions is close to 45% in the climate stabilization scenarios, while the buildings and transport sectors contribute by around 27% each in all scenarios.

The role of industry in total energy savings is facilitated by the use of more efficient energy carriers, and in particular by the extended electrification of various industrial processes and energy needs.

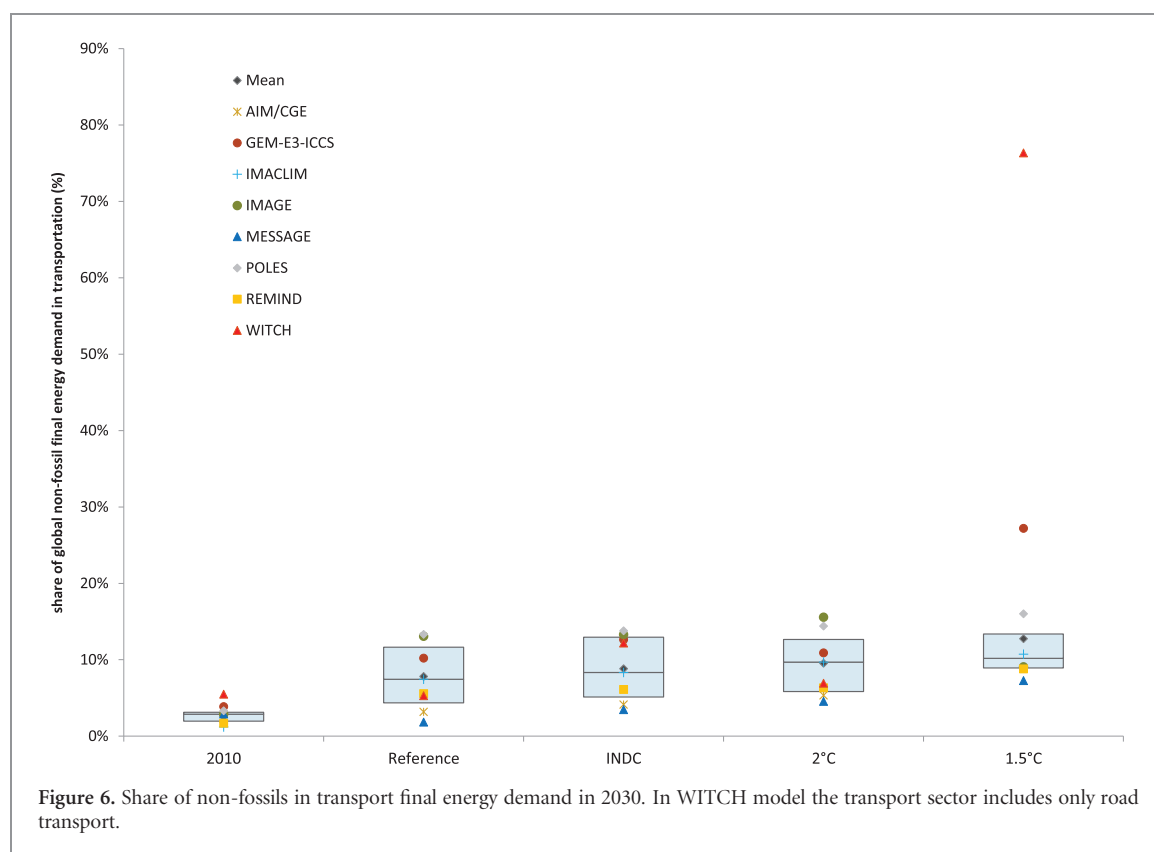
Power supply is the dominant mitigation sector, undergoing a low-carbon transformation in all scenarios (see figure 5). The implementation of INDCs increases the share of zero-carbon¹⁴ power supply in 2030 by 7 (1–14) percentage points from reference levels, reaching a share of 48% (40%–63%) of zero-carbon electricity. The respective share is 15% (5–34) percentage points higher in the 2 °C power mix and 34% (12–40) percentage points higher in the 1.5 °C one (figure 5 (a)). All models find that the penetration of renewable energy is the driving force of this transition. Wind energy has the most notable growth pattern, increasing sevenfold by 2030 from 2010 levels in the INDC scenario and registering a share of 16% (8%–25%) and 24% (8%–29%) in 2 °C and 1.5 °C scenarios respectively (figure 5 (b)). Solar power is also a key zero-carbon technology increasing its share in global power supply from an almost zero in 2010 to 4% (1%–13%) in 2030 in the INDC and 7% (4%–23%) in the 1.5 °C scenario. Nuclear power sustains a share similar to that of 2010, increasing only by 8% (5%–18%) in the 1.5 °C scenario.

¹⁴ Zero carbon power supply includes all renewable power supply (including all hydro and biomass production) as well as nuclear power.



The transport sector shows a less rapid low-carbon transition and thus its decarbonization remains a challenge for the period after 2030. Results (figure 6) indicate that the transition is already taking place in 2030 in the reference scenario but the share of non-fossil final energy demand in transportation increases only marginally with the implementation of the INDCs and remains roughly the same in the 2°C scenario. As shown in figure 3(b), transport CO₂ emission reductions in the INDC scenario are equal to 50% of the 2°C sectoral

reductions, the highest share across all sectors. However, the INDC reductions are around 20% of the reductions registered in the 1.5°C scenario, where non-fossil final energy demand in transportation reaches 13% (7%–27%) (figure 6). The electrification of the global transport sector is found close to 2% of the sector's energy demand in the reference and INDC scenarios and increases to around 4% in the 2°C and 1.5°C scenarios. Similarly, the share of biofuels in the INDC scenario reaches 6%, and increases only to an 8% share in the 1.5°C scenario.



3.3. Macroeconomic costs of mitigation action

Moving to a low-carbon system is a capital-intensive process and entails a reallocation of resources that can result in economy-wide policy costs (Paltsev and Capros 2013). Cost estimates vary widely across models depending on the assumptions for technological progress and technology costs, marginal costs for available abatement options, the overall and sectoral model responsiveness to carbon prices, the model-specific price elasticities, the level of sectoral and regional disaggregation of each model and more. A multi-model analysis can provide some insight into the level of uncertainty of cost estimations (Iyer *et al* 2015).

We contribute to the literature by providing a multi-model assessment of the short-term costs of implementing of the Paris Agreement mitigation targets for 2030 (INDCs) along with cost estimations for achieving the 2 °C and 1.5 °C targets with a >66% probability. To our knowledge, there is no cost estimation of a high probability 1.5 °C scenario in the literature. Our analysis includes a subset of the participating models, as not all models feature an endogenous macroeconomic representation. We calculate the total costs of a low-carbon transition, as we do not only cover the direct costs of emission reductions (as for example in Iyer *et al* (2015)), but also the indirect macroeconomic impacts of this transition. However, our estimations only consider the costs of mitigation and do not include any potential co-benefits of climate action or the benefits from avoided climate damages.

In our 2 °C and 1.5 °C decarbonization scenarios costs are minimized (IPCC 2014) as we implement

a global, unified mitigation framework where reductions are undertaken by the sectors and regions with the lowest marginal abatement costs. On the contrary, INDC emission reductions assume a fragmented mitigation action and are thus expected to result in suboptimal burden sharing and increased costs (Aldy *et al* 2016, Fujimori *et al* 2016b). In addition, it is important to note that a cost-optimal mitigation framework, like in our 2 °C and 1.5 °C scenarios, does not address any equity considerations (Raupach *et al* 2014), but can serve as a benchmark to indicate, among other things, the cost-optimal level of abatement as well as sectors where abatement is cheaper. Equity considerations along with other supplementary policies, like technology transfer, financing schemes and the removal of trade restrictions, could address other socioeconomic considerations or UN sustainable development goals (SDGs), but this is out of the scope of this analysis.

We find that the pace of economic growth is affected by climate change mitigation action only to a limited degree. Global annual GDP growth rates in the period 2020–2030 remain close to reference levels, namely close to 3% in most scenarios and models. The most striking reduction in global annual GDP growth rates for the same period is registered in the 1.5 °C scenario, equal to 0.36 (0.21–0.48) percentage points compared to the reference (table 4). This is much lower than the uncertainty of the pace of economic growth, as can be seen in the different assumptions on reference annual GDP growth rates across models, covering a range from 2.8% to 4.6%.

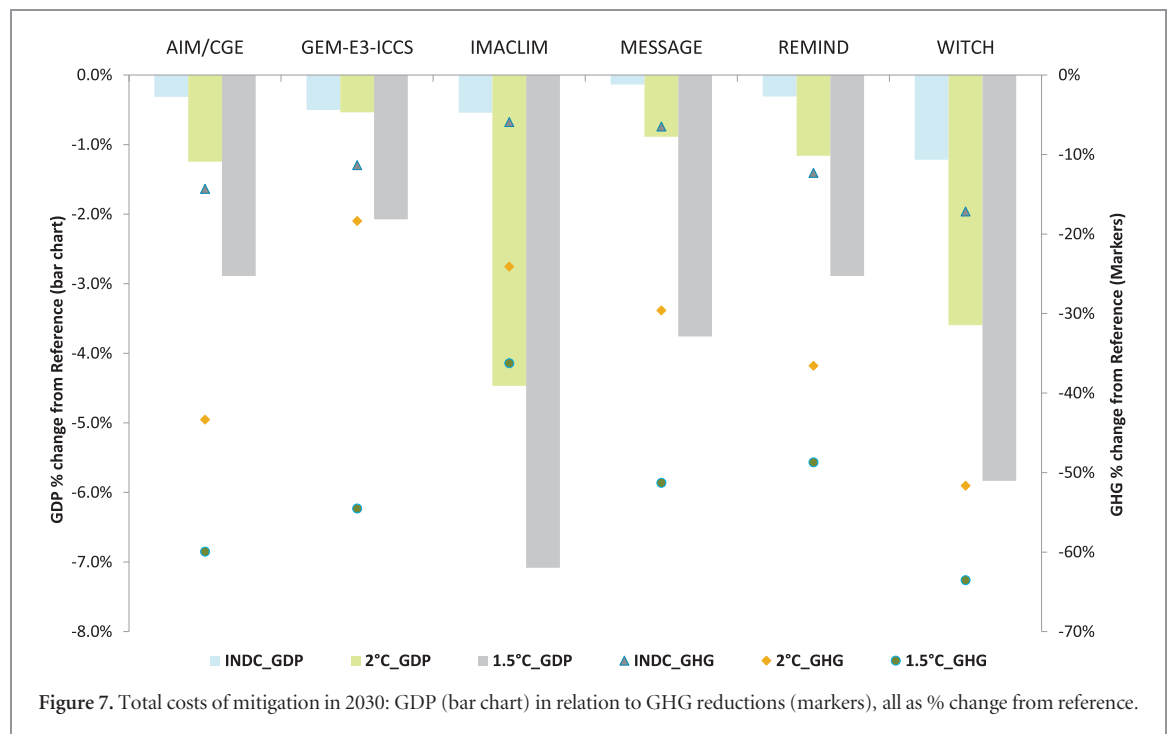


Figure 7. Total costs of mitigation in 2030: GDP (bar chart) in relation to GHG reductions (markers), all as % change from reference.

Table 4. Average annual global GDP growth rates in 2020–2030 period in all scenarios. IMAGE and POLES models are not included as they feature an exogenous GDP.

	REF	INDC	2 °C	1.5 °C
AIM/CGE	2.9%	2.9%	2.8%	2.6%
GEM-E3-ICCS	2.9%	2.8%	2.8%	2.6%
IMACLIM	3.1%	3.1%	2.8%	2.6%
MESSAGE	4.4%	4.4%	4.3%	4.0%
REMIND	2.9%	2.8%	2.8%	2.6%
WITCH	2.8%	2.8%	2.6%	2.3%

All models register increasing costs with increasing abatement efforts. In 2030 the implementation of INDCs results in a global macroeconomic cost of 0.4% (0.1%–1.2%) of the reference GDP, similar to the findings of other macro-economic assessments (Vandyck *et al* 2016). In the 2 °C scenario the respective cost is 1.2% (0.5%–4.5%). To put this number into context we calculate GDP costs from the public IPCC AR5 WGIII Scenario database¹⁵, using results on GDP impacts for 450 ppm scenarios¹⁶, and find that costs are of comparable magnitude, equal to 1.6% (0.7%–6%) of reference GDP. Further, in accordance with the IPCC methods of presenting mitigation costs (IPCC 2014), we compare private consumption losses, reported by AIM/CGE, GEM-E3-ICCS, IMACLIM and MESSAGE-GLOBIOM models. We find that the scale of impacts is similar to that of GDP costs, namely a loss of 1.2% (0.4%–2.5%) of reference consumption in our 2 °C scenario and a

loss of 1.7% (1.0%–3.7%) in the IPCC scenario set which is described above.

The rapid decarbonization required already in 2030 in order to achieve the 1.5 °C target results in higher costs as we move to the part of the global marginal abatement curve with the steepest slope once cheap mitigation options have been exploited in lower ambition scenarios. GDP impacts in the 1.5 °C scenario are equal to 3.3% (2.1%–7.1%) of reference GDP and consumption losses equal to 3.6% (1.6%–4.6%) of reference consumption. In figure 7 we provide the GDP changes in relation to total GHG reductions for each model, so as to highlight the model-specific responsiveness to carbon prices and other resource restrictions that are adjacent to mitigation action. The different responsiveness results in different costs per unit of abated emissions for each model. The graph illustrates that in addition to the different assumptions and model properties that result in varying cost estimations, costs may differ due to different abatement efforts with regards to the reference scenario of each model. We note that the mitigation effort in the climate stabilization scenarios is continued beyond 2030, and that costs might increase further beyond that date.

Despite these differences across models, we calculate an average abatement cost (the ratio of GDP losses to GHG reductions relative to reference) which is similar across most models, within the range of 60\$₂₀₀₅/tCO₂eq for the INDC and 2 °C scenarios and 110\$₂₀₀₅/tCO₂eq for the 1.5 °C scenario. Finding that the average abatement cost of the INDC and 2 °C scenarios is roughly the same confirms the above-mentioned earlier findings (Aldy *et al* 2016, Fujimori *et al* 2016b, Blanford *et al* 2014), namely

¹⁵ IPCC AR5 Scenario database <https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about>.

¹⁶ We used the AMPERE and LIMITS databases taking stock of all models that feature endogenous macroeconomic variables.

that a fragmented action, like the INDC scenario, results in higher costs per unit of abated emissions.

While our analysis focuses on the global scale, we briefly discuss here the regional distribution of abatement efforts and mitigation costs so as to highlight any findings that could prove useful for a future assessment of effort allocation schemes. According to our 2 °C and 1.5 °C scenario set-up, we implement a cost-optimal mitigation so that global costs are optimally minimized without any further assumptions on burden sharing. We find that economic costs, expressed in terms of GDP reductions from reference levels, are shared differently across regions amongst the fragmented and the cost-effective, climate stabilization scenarios. High income economies, like USA, EU28, Canada and Japan, contribute substantially to the mitigation effort in the INDC scenario and thus have high regional GDP costs when compared to the reference (see figure 8). On the contrary, in the cost-efficient global decarbonization scenarios, emerging economies like China, India and Brazil take up most of the mitigation efforts due to untapped cheap abatement potentials, thus resulting in higher GDP reductions relative to the reference than those seen in high income economies. Nevertheless, a common characteristic can be identified in all scenarios, namely that the fossil fuel exporting regions, particularly Middle East, Russia and Indonesia, see high costs compared to the rest of the regions both due to declining global fossil fuel demand that leads to diminishing exports but also due to the carbon intensive structure of their economies.

4. Conclusion

In this paper, we present a multi-model assessment of the effectiveness of the INDCs in achieving the well below 2 °C and the 1.5 °C climate stabilization targets. We provide a detailed description of the low-carbon mitigation pathways which are consistent with meeting these targets, as well as an estimation of the macroeconomic costs of mitigation. Through this, we contribute with scientific insights on the scale of a potential ratcheting up of INDCs and suggest sectors with untapped abatement potentials. The participation of eight state-of-the-art models enhances the robustness of results and provides an estimation of the uncertainties of future emission projections and policy costs.

Our results indicate that the INDCs pledged under the Paris Agreement induce substantial emission reductions, getting to 53.7 (48.8–56.6) GtCO₂eq in 2030. However, we find that this effort is not adequate to put the world on a 1.5 °C or even a well below 2 °C emissions path. By keeping the ambition of post-2030 climate policies equal to the effort required for moving from the Cancun to the INDCs emission levels, the temperature increase by the end of the century compared to pre-industrial levels would reach on average

2.6 °C. Significant ratcheting up of INDC aspirations is required in order to put the world on track for a well below 2 °C or even 1.5 °C stabilization. In 2030, additional emission reductions of 15.6 (9.0–20.3) and 24.6 (18.5–29.0) GtCO₂eq respectively would be consistent with the 2 °C and 1.5 °C cost-optimal emission trajectories.

We find that all sectors can further contribute to an increased mitigation effort even after the implementation of INDCs. The decarbonization of the power supply sector accounts for more than half of total emission reductions in all scenarios and is primarily achieved through the intensive deployment of renewable power technologies. Efforts for a zero-carbon power supply are crucial for the global short- to medium-term mitigation efforts while carbon lock-in investment decisions between now and 2030 would put these efforts at risk. Demand-side emission reductions contribute less to the INDC mitigation effort but become more crucial for the climate stabilization scenarios, where deep emission reductions in industry become important from 2030 onwards. Industry is found to have the largest energy saving potential, as it contributes close to 45% of total final energy reductions in the climate stabilization scenarios. Sector-specific measures could further increase the available demand-side potential. Overall, a deeper transformation of the energy system remains a challenge that can be addressed with more ambitious climate policies in order to keep with the Paris goal of ‘well below 2 °C’.

The assessment of the macroeconomic cost of the low carbon transformation shows that global annual GDP growth rates are only marginally reduced by the climate stabilization action and even less so by the INDC implementation. Interestingly, the fragmented mitigation action commissioned under the Paris Agreement is found to have the same average abatement cost (the ratio of GDP losses to GHG reductions relative to reference) with a global, common mitigation action for achieving a ‘well below 2 °C’ climate stabilization, thus indicating its inefficient burden sharing. On a regional level, the highest costs in all scenarios are seen in the fossil fuel exporting regions, making the diversification of their economies towards alternative economic activities and the gradual decarbonization of their energy systems pivotal in order to avoid significant adverse economic impacts. In the 2 °C and 1.5 °C scenarios, emerging economies take up the biggest mitigation efforts and face the highest economic costs. Cooperation mechanisms, coordinated financing schemes, technology transfer and capacity building, as foreseen in Article 6 of the Paris Agreement, could alleviate the disproportionate costs while still aim for a cost-effective mitigation.

A further advancement of the work presented in this paper could include a detailed mitigation analysis along with an integrated assessment of avoided damages of climate change and the potential co-benefits of the adjacent climate policies.

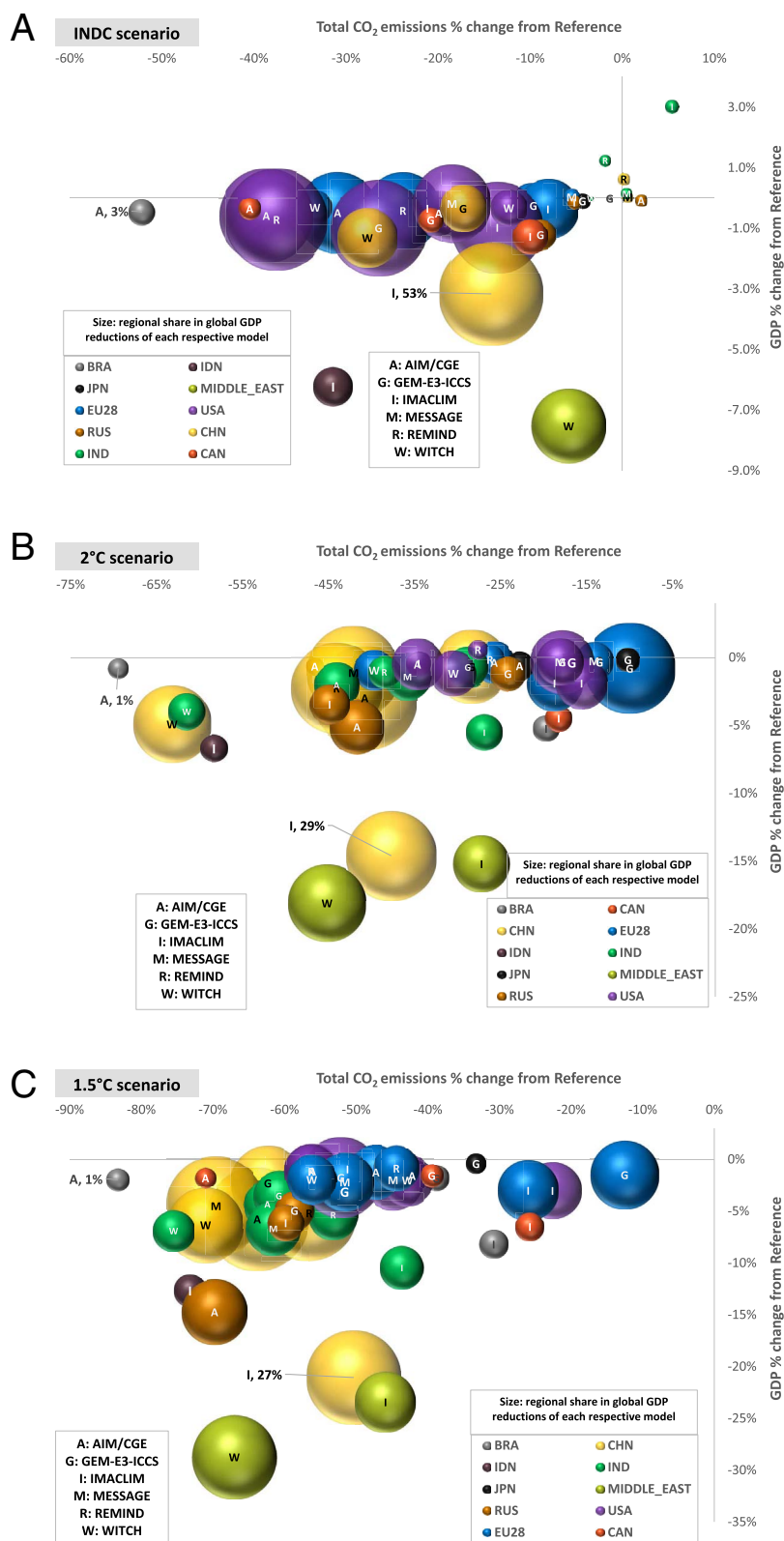



Figure 8. Regional allocation of GDP costs in 2030: GDP losses in relation to total CO₂ reductions, both as % change from reference. The size of each bubble shows the share of each region in global GDP losses and is indexed to the size of maximum and minimum values as indicated in the graph (AIM/CGE;Brazil and IMACLIM;China). (a) INDC scenario, (b) 2 °C scenario, (c) 1.5 °C scenario.

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