AVOID 2

Can we avoid dangerous climate change?

Low-carbon transition patterns in Brazil, Russia, India, China and South Africa (the BRICS countries) - comparing global energy system models to national analysis

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Non-technical summary

Brazil, Russia, India, China and South Africa (BRICS) accounted for almost 40% of global energy-related CO_2 emissions in 2012. Since 2000, these emissions have increased in all of these five countries. For China and India, the two biggest emitters, energy related CO_2 emissions more than tripled and doubled, respectively, since 2000, driven largely by development (as defined through the metric of increased GDP per person), which has been offset to a limited extent by improvements in energy efficiency.

According to the IEA's "current policies" scenario (which does not take into account Paris pledges), the BRICS countries could account for almost half of global energy-related CO_2 emissions by 2040, with India and China alone responsible for 40% of the global total (more than 80% of the BRICS total). The feasibility of mitigating these emissions is therefore of central importance to the overall feasibility of avoiding dangerous levels of climate change.

The key question considered in this study is how for these regions a least-cost global mitigation pathway developed in the AVOID 2 programme, which achieves a below 2°C temperature change in 2100 (with 50% likelihood), the level of technological change compares to the maximum level of ambition proposed by these countries' own analytical and policy groups, whether it be in long-term scenario analysis or nearer term policy and target proposals. The focus of this study is primarily on India and China, since, as well as their accounting for over 80% of current and future projected BRICS emissions, these regions are represented explicitly in the TIAM-Grantham energy systems model which is the central tool of analysis for the AVOID 2 decarbonisation feasibility analysis. The main sources of country-level analysis used to compare to the TIAM-Grantham outputs are: the UN's Deep Decarbonisation Pathways project, which uses a range of country studies to assess the most rapid emissions reduction pathways possible; country 2050 energy/emissions calculators, whose most ambitious scenarios are used as a guide to what these countries' analytical groups deem the maximum feasible level of technology deployment by 2050; and where available specific near-term (mostly to 2020) technology deployment targets stated in these countries' own policy plans.

This comparative analysis suggests that, in most cases, the TIAM-Grantham model's levels of energy technology penetration in China and India in a global mitigation scenario aimed at achieving the below 2°C long-term temperature goal are broadly similar to those in the countries' own studies. However, there are some important exceptions – most notably that the TIAM-Grantham model tends to assume certain technologies are far more rapidly deployed than in the country analyses, including hydrogen vehicles in the transport sector, carbon capture and storage (CCS) in the industrial manufacturing sector, and onshore wind in the power sector. Re-running the global mitigation scenario with specific constraints to re-align these technology penetration rates with those cited in the literature as realistically achievable (albeit with maximum levels of effort) leads to a significantly higher global cost of mitigating towards the 2°C target – rising from 1.0% of global GDP over the period 2012-2100, to 1.5% of GDP over this period. This cost estimate is still within the range of the literature on mitigation costs to achieve the below 2°C goal, but the 50% rise is far from negligible. In addition, constraining CCS in the industrial sectors to the levels in the country analyses leads to a potential over-reliance on gas replacing coal in industrial manufacturing heating processes (when compared to the country level analyses). Whilst a substantial substitution of gas for coal is technically possible, this indicates that the industrial manufacturing sectors in India and China may require very targeted efforts to reach levels of emissions commensurate with a below 2°C pathway.

Also of note is that the intended nationally determined contribution (INDC) pledges of China and India put their CO_2 emissions at levels far above those in the TIAM-Grantham model's cost-optimal pathway to achieve the below 2°C target, with China's projected emissions under its INDC (about 13.8 $GtCO_2$) some 33% higher than the cost-optimal levels in the TIAM-Grantham mitigation pathway, and India's 2030 INDC-consistent emissions (about 4.3 $GtCO_2$) some 200% higher than the model's cost-optimal pathway.

For Brazil and Russia, a comparison of the emissions trajectories of the TIAM-Grantham regions containing these countries with other decarbonisation pathways studies to 2030 and 2050 shows that the TIAM-Grantham model has a more aggressive emissions reduction trajectory to 2030 for these regions. This is particularly the case in its "Former Soviet Union" region (of which Russia makes up about two-thirds by GDP) where in TIAM-Grantham, CCS is rapidly deployed from 2020 onwards, when in reality there is only one commercial-scale demonstration of CCS worldwide, with no explicit plans for CCS deployment at scale in Russia at this time. Since it is not possible to compare precise regions within TIAM-Grantham, these results should be treated with caution, but nevertheless indicate that there is a potential shortfall between the sum of country-level ambition and the necessary actions that would lead to a 2°C-consistent set of emissions reductions.

This study presents an important analogue to other AVOID 2 analysis (AVOID 2 report WPC3) which concludes that constraining global energy technology penetration rates and patterns to better match historical precedents significantly raises costs, and therefore makes the achievability-with-precedent of the below 2°C goal more challenging than the TIAM-Grantham model suggests, on face value. Such challenges are to be expected given the degree to which the below 2°C goal will require in many cases unprecedented rates of new low-carbon technology deployment, and the extent to which current country plans, even in their most ambitious cases, still leave a significant emissions gap compared to what energy systems models like TIAM-Grantham report as a cost-optimal decarbonisation pathway to meet the goal.

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Contents

1 Introduction

In combination, Brazil, Russia, India, China and South Africa (BRICS) are projected to account for almost half of global CO_2 emissions from fossil fuel combustion by 2040 [1], with India and China alone responsible for 40% of global fossil fuel related CO_2 emissions by this time. This study analyses a range of future potential low-carbon transitions in the major emerging economies (Brazil, Russia, India, China and South Africa) to understand the importance of particular technologies in these transitions.

The study first reviews recent emissions trends in these countries, with a view to highlighting the major drivers of their emissions. These are compared to studies which highlight the future changes in these drivers of emissions in scenarios where significant decarbonisation occurs (in line with maximum levels of ambition), to understand where the major focus of emissions reductions should be over the coming decades. Recently announced policies and targets are presented to understand the likely emissions reduction measures of each region in the short term.

China and India, the two most important regions in terms of future unmitigated emissions, are then analysed in detail, by comparing the level of low-carbon technology penetration within these regions in a 2°C-consistent scenario generated by an energy systems model (TIAM-Grantham) with technological penetration levels in recently produced scenarios from national modelling groups. This gives a sense of the degree of optimism or conservatism in the energy model scenario. Where overly optimistic outcomes are observed, specific constraints have been imposed on the rate and degree of technology deployment within the model, to assess what impact such constraints have on the overall cost and achievability of the below 2°C goal.

For the other regions (which are not explicitly represented in the TIAM-Grantham model), a high-level assessment of their feasibility of achieving their deep decarbonisation pathways is given, based on other recent studies. The study concludes with an assessment of the overall impact of injecting additional conservatism – in line with other scenarios – on the TIAM-Grantham model.

2 Emissions sources and future growth in the BRICS countries

Emerging economies are the fastest-growing source of emissions and the BRICS countries could in total constitute around 47% of global CO_2 by 2040. Table 1 shows the emissions growth in the BRICS countries, as well as global emissions, since 2000, and projected emissions to 2040. This means that any global initiative to tackle climate change would have to see significant reductions in emissions in these countries, relative to their current growth path.

Table 1: Fossil fuel combustion CO_2 emissions growth in BRICS countries and globally

	China	India	Brazil	Russia	South Africa	Global
CO_2 emissions in 2000, $MtCO_2$ (and as % of global)	3,350 (14%)	972 (4.1%)	304 (1.3%)	1,498 (6.3%)	297 (1.3%)	23,759
CO_2 emissions in 2012, $MtCO_2$ (and as % of global)	8,229 (26%)	1,953 (6.2%)	440 (1.4%)	1,640 (5.2%)	376 (1.2%)	31,734
CO_2 average annual growth (2000-2012)	7.8%	6.0%	3.1%	0.8%	2.0%	2.4%
Projected CO_2 in 2040 in IEA "Current Policies Scenario", $MtCO_2$	12,938 (28%)	5415 (12%)	796 (1.7%)	1,932 (4.2%)	498 (1.1%)	45,950
Projected CO_2 average annual growth (2012-2040)	1.63%	3.71%	2.14%	0.59%	1.01%	1.33%

Notes: Data 2000-2011: [2]; Data 2012: [3]; Data 2040: [1].

The BRICS countries are very diverse in terms of their physical size and geography, population and energy resources and needs. Nevertheless, they face common challenges in reducing their emissions whilst growing their economies – ensuring that energy supply matches growing demand as populations and/or GDP per capita grows, which means using and developing a diverse range of technologies and fuels, and above all improving the energy efficiency of their economies, in order to increase business competitiveness and reduce the wastage of valuable energy resources. In addition, all BRICS countries have considerable fossil fuel reserves [4], which could have considerable economic value and prove a critical resource in terms of servicing future energy needs.

Figure 1 shows the impact of GDP/capita on the emissions growth of the BRICS countries since 2000. It is clear from this figure that China and India have seen by far the greatest percentage increase in emissions over the period 2000-2012, driven by average annual GDP per capita growth of 9.4% and 4.8% respectively. In India's case, population growth and an increase in CO_2 intensity (driven by the rapid expansion of a coal-dominated electricity sector) have also played a significant role. In all of the BRICS countries other than Brazil, there has been a notable improvement in energy efficiency over this period. In Brazil, there has been little change in energy efficiency, with the power sector seeing a slight fall in efficiency, offsetting gains in the rest of the economy.

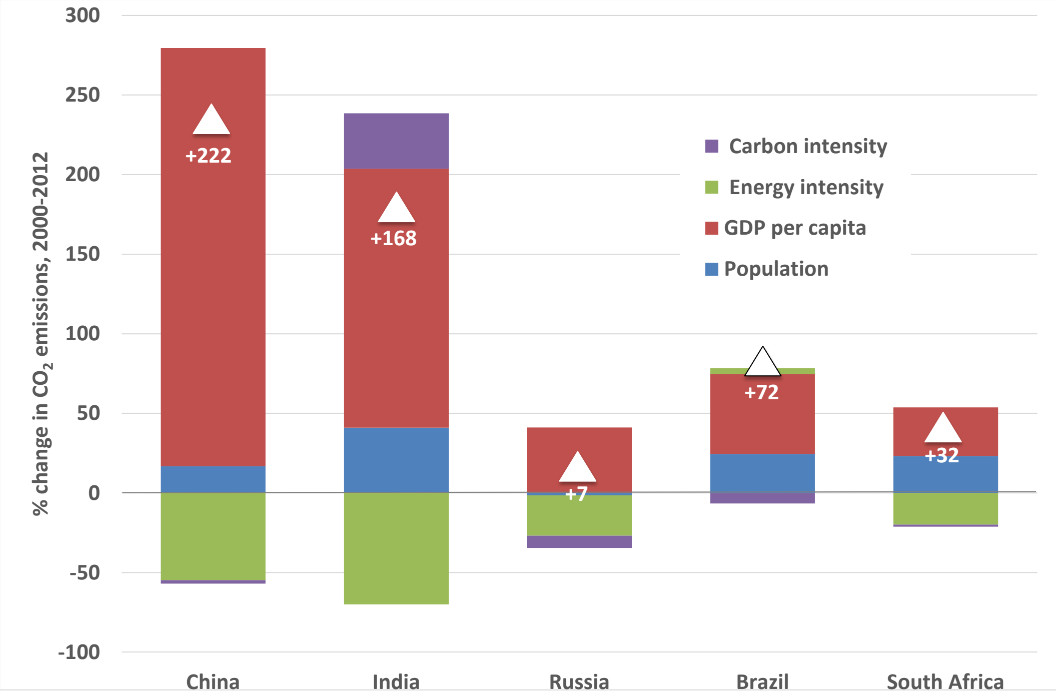

Figure 1: Decomposition of CO_2 emissions percentage change over the period 2000-2012

Notes: Uses Logarithmic Mean Divisia Index (LMDI) decomposition of % change in CO_2 (from fossil fuel combustion) – indicted by white triangles and accompanying figures - over the period 2000-2012. Source: [2], [3].

The primary energy mixes in the BRICS countries are shown in Figure 2. This figure highlights the extent to which China, India and South Africa rely very heavily on coal (for power generation and industrial manufacturing), Russia on gas, and Brazil on oil (primarily for transport).

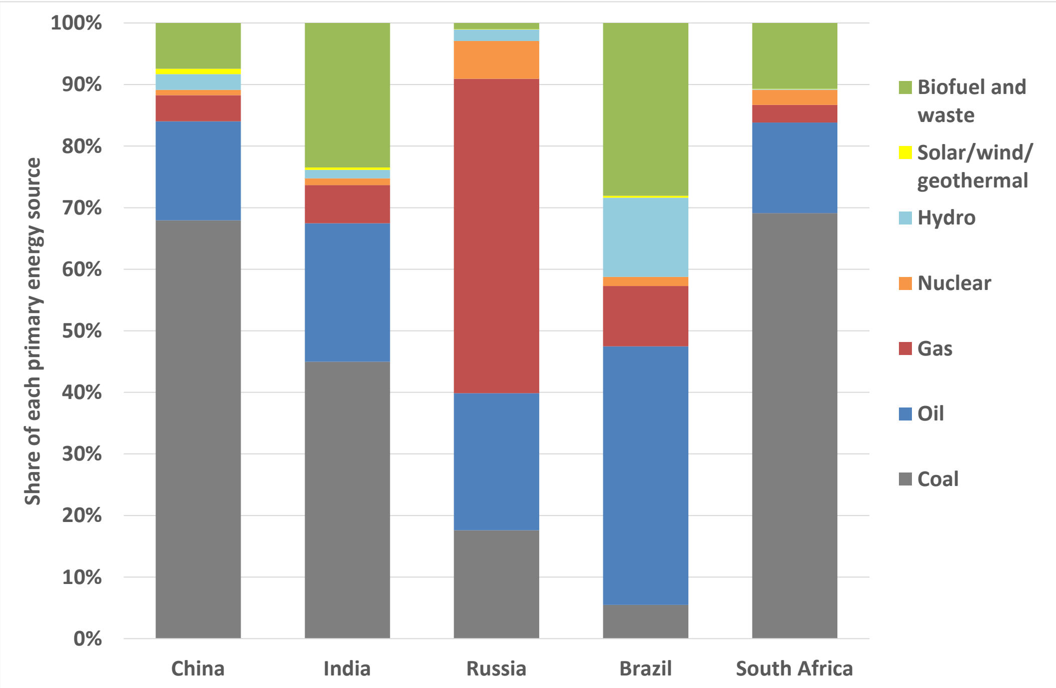

Figure 2: Primary energy mix of BRICS countries in 2012

Source: [1]

Figure 3 shows that, since 2000, this primary energy mix has remained relatively stable.

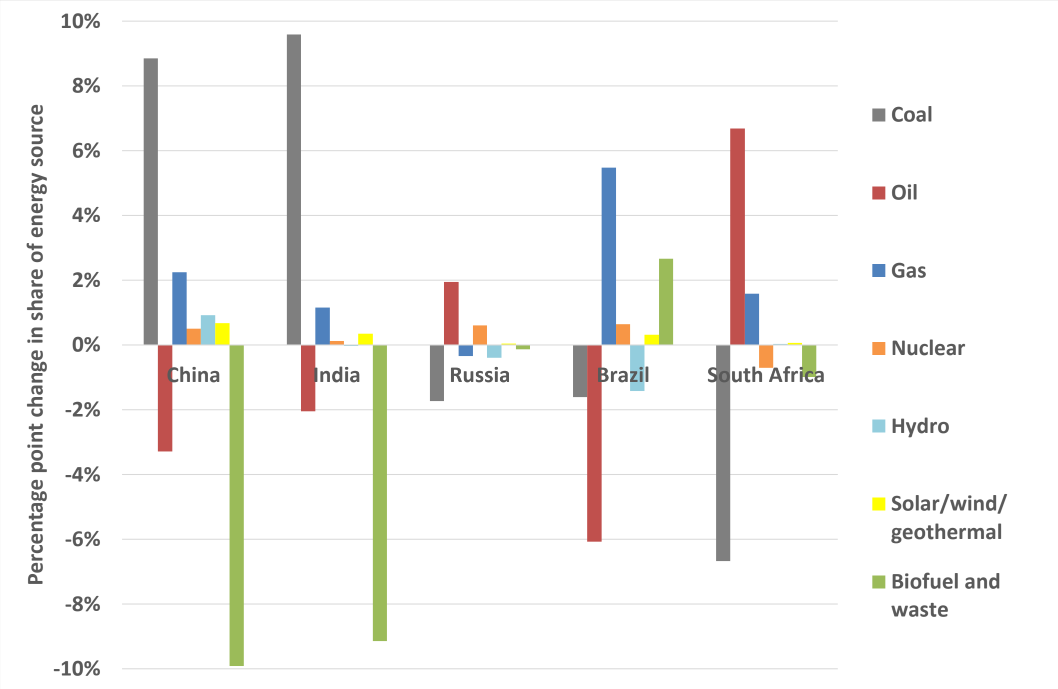

Figure 3: Percentage point change in share of primary energy sources, 2000-2012

As a result of their growing economies, development needs and reliance on fossil fuels, these regions have focused on a range of technologies and measures in order to meet their climate targets and future energy needs, with energy efficiency and investment in a range of renewable electricity sources all central to their plans [1]. The countries have all made pledges under the UNFCCC Cancun Agreements [5], regarding emissions and energy goals for 2020, and have made Intended Nationally Determined Contributions (INDCs) for the period to 2030 as part of the Paris Agreement [6], as shown in Table 2, India and China have supplemented their high-level emissions pledges with specific targets for renewable energy deployment, as well as a range of other sector-specific ambitions.

Table 2: Cancun INDC pledges for the BRICS countries

Country	Cancun pledge	INDC
China	To by 2020: • Reduce CO_2 intensity of GDP by 40-45% on 2005 levels • Increase non-fossil fuel share in primary energy consumption to 15%	To by 2030: • Achieve peak CO_2 (with best efforts to peak earlier) • Reduce CO_2 intensity of GDP by 60-65% on 2005 levels • Increase non-fossil fuel share in primary energy consumption to 20% To by 2020: • Increase share of natural gas in primary energy consumption to 10% • Achieve installed wind capacity of 200 GW • Achieve installed capacity of 100 GW of solar • Achieve a 50% share of green buildings in newly built buildings of cities and towns • Achieve a 30% share of public transport for motorised transport in “big” and “medium” cities
India	To by 2020: • Reduce emission intensity of GDP by 20 to 25% in 2020 compared to 2005 levels (excludes agricultural sector)	To by 2030: • Reduce CO_2 intensity of GDP by 33-35% on 2005 levels • Achieve 40% cumulative non-fossil fuel installed electricity capacity To by 2022: • Achieve installed capacity of 60 GW of wind • Achieve installed capacity of 100 GW of solar
Brazil	To by 2020: • Reduce emissions by 36.1% to 38.9%, compared to business as usual (BAU) emissions.	To by 2030: • Reduce GHG emissions by 43% compared to 2005 levels (equivalent to a 75% reduction in CO_2 intensity of GDP on 2005 levels)
Russia	To by 2020: • Reduce greenhouse gas (GHG) emissions by 15% to 25% below 1990 levels. [In September 2013, committed to the lower end of this range]	To by 2030: • Reduce GHG emissions by 25-30% below 1990 levels
South Africa	To by 2020: • Reduce emissions by 34% below BAU levels (and by 40% by 2025).	• South Africa’s emissions by 2025 and 2030 will be in a range between 398 and 614 Mt CO_2e

Sources: [5], [7]

3 Assessments of low-carbon pathways for the BRICS

A number of scenarios have set out pathways for these regions in terms of technologies and measures to reduce their emissions. There has been far more focus on China and India than on the other regions, given their size and importance, and the large number of energy systems models which represent these regions explicitly.

For China, economy-wide studies to 2050 have set out the potential for deep CO_2 emissions reductions by that time, ranging from 7.4 $GtCO_2$ in the most pessimistic case [8] to less than 2 $GtCO_2$ in the most optimistic cases [9], [10]. It should be noted that these scenarios are not all focused on achieving a 2°C- consistent pathway, but rather a pathway deemed feasible with maximum effort (for a more comprehensive comparison see [11]). Reference emissions (which assume emissions increase in line with energy demand growth, but without any climate change policies), by contrast, have been projected to reach 15 $GtCO_2$ or more by 2050 [12].

For India, economy-wide studies have projected CO_2 emissions in 2050 to reach levels as low as 1-2 $GtCO_2$ compared to reference scenarios closer to 7-8 $GtCO_2$ [13],[14].

Analysis in the first AVOID programme on the long-term low-carbon pathways in India [13] and China [15] highlighted the increasing importance of nuclear, renewables and CCS in both countries' electricity sectors to 2050, replacing coal plant which is increasingly phased out, with increased electrification of end-use sectors, increased energy efficiency across all parts of the economies, and use of biomass to replace coal and other fossil fuels in industrial process heating and (in India's case) building heating also being critical.

More recent analysis for the BRICS appears in the UN's Sustainable Development Solutions Network's Deep Decarbonisation Pathways Project (DDPP) is set out in Table 3. This table shows that all suggested pathways consist of some common features by 2050: considerable electrification of energy end-use sectors (industry, buildings, transport) to around one third of final energy consumption in these sectors; deep decarbonisation of the electricity sector, to between 0 and 68 gCO_2/kWh by 2050 (compared to around 800 gCO_2/kWh or more in the coal-dominated countries of India, China and South Africa; and energy intensity improvements, such that primary energy per unit of GDP is around 2-5 MJ/$ by 2050, much lower than the 17 MJ/$ in China in 2010. Nevertheless, there are also significant differences: most notably, energy and industry-related CO_2 per capita is projected to fall to between 1.21 t/capita (Brazil) and 3.84 t/capita (China), from extremely different starting points in 2010, and India is unique in seeing per capita emissions increase over the period.

Table 3: Summary of key indicators for BRICS countries from Deep Decarbonisation Pathways Project

	China [16]	**India** [17]	**Brazil** [18]	**Russia*** [19]	**South Africa** [20]
CO_2 emissions, 2010, $MtCO_2$ (t/capita)	8,512 (6.25)	1,390 (1.16)	326 (1.71)	1,527 (10.8)	345 (6.70)
CO_2 emissions, 2050, $MtCO_2$ (t/capita)	5,201 (3.84)	2,885 (1.78)	268 (1.21)	200 (1.67)	206 (3.31)
Primary energy increase, 2010-2050	+76%	+258%	+124%	-27%	-10%
Electricity intensity, 2010-2050, gCO_2/kWh	741 (2010) 68 (2050)	771 (2010) 66 (2050)	70 (2010) 0 (2050)	392 (2010) 14 (2050)	879 (2010) 21 (2050)
Energy intensity of GDP, 2010-2050, MJ/$	16.83 (2010) 4.61 (2050)	12.96 (2010) 3.08 (2050)	3.49 (2010) 2.11 (2050)	15.7 (2010) 4.4 (2050)	9.38 (2010) 5.50 (2050)
Electrification rate of end-use sectors, 2010-2050	18% (2010) 34% (2050)	14% (2010) 27% (2050)	18% (2010) 33% (2050)	13% (2010) 34% (2050)	32% (2010) 36% (2050)

Notes: *Data for Russia from draft DDPP report [19] as final report not available as at 15 June 2016

4 Comparison of country low-carbon pathways analysis to TIAM-Grantham modelling

The latest AVOID 2 scenarios for global decarbonisation in line with achieving a 2100 median warming of 2°C, as outlined in AVOID 2 report WPC2a [21], show emissions for a range of regions. Of BRICS, only China and India are represented as distinct regions (with Brazil, South Africa and Russia grouped within larger regions). Figure 4 shows the emissions in the different models for these countries, in both an unmitigated reference scenario as well as the mitigation scenario, which represents achievement of the below 2°C target with global mitigation action beginning in 2020 (following relatively weak regional mitigation action in line with the less stringent level of Cancun pledges). These show a range of projections for emissions in 2050, ranging from 2.63 - 6.79 $GtCO_2$ in China, and 0.54 -1.10 $GtCO_2$ in India. These emissions levels are determined as part of a global least-cost pathway to achieve a cumulative 21st century CO_2 level in line with a 50% likelihood of a less than 2°C temperature change in 2100. The large range reflects differing assumptions in the models on technology costs, fossil fuel costs and availability and energy efficiency potential across these regions.

Also shown in Figure 4 are the levels of CO_2 emissions projected in the central scenarios for the Deep Decarbonisation Pathways Project (in 2030 and 2050), included here as these analyses have been undertaken by research groups from these countries with a view to assessing maximum mitigation potential, without explicit consideration of China's and India's contribution to a 2°C-consistent pathway. It can be seen that China's 2050 projection is between that for the TIAM-Grantham and WITCH models. However, India's projected 2050 level is significantly higher than 2050 emissions projections in any of the three integrated assessment models, indicating a large gap between India's emissions pathway in a least-cost global mitigation pathway (as estimated by these models), and the level of emissions reductions seen as feasible in India.

For 2030, both the three integrated assessment models and the DDPP emissions projections are below the projected INDC-consistent emissions for China and India, in India's case significantly so. This indicates that both least-cost integrated assessment model pathways and the DDPP analysis points towards further technically and economically feasible emissions reductions over and above the INDC estimated pledges.

A key question is the extent to which a cost-optimising mitigation model pathway matches pathways from studies such as the DDPP, which are based on assumed maximum levels of mitigation effort, rather than necessary effort to achieve below 2°C. The following sub-sections explore this question for China and India, by comparing the TIAM-Grantham model outputs for these regions with the assumptions of technology penetration made in near-term policy plans and long-term projections for these countries.

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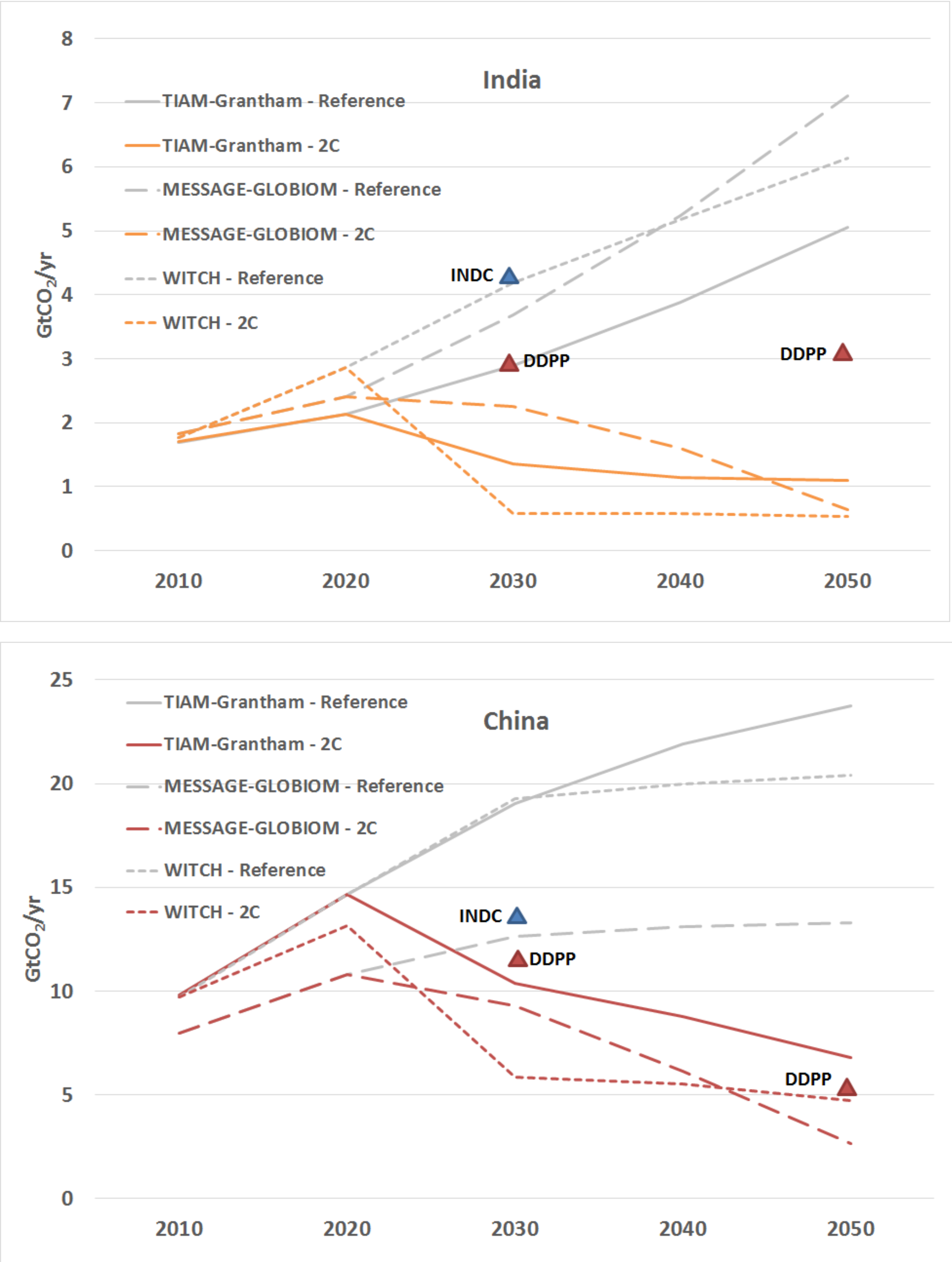

Figure 4: Emissions of India and China in three energy systems models used in the AVOID 2 study, compared to (for 2030) INDC pledges, and DDPP pathways

Notes: INDC values calculated based on EDGAR 4.2 data [22] for 2005 emissions from fossil fuel combustion and industrial processes , Shared Socio-Economic Pathways (SSP) 2 scenario data [23] for economic growth over the period 2005-2030, and mid-range assumptions on carbon intensity improvements in China (62.5% on 2005 levels) and India (34% on 2005 levels) from INDC pledges. DDPP 2050 emissions shown, which correspond to energy and industrial CO_2 emissions projections in 2050 from the central/conventional scenarios in the Deep Decarbonisation Pathways Project (DDPP) for China [16] and India [17].

4.1 China

The TIAM-Grantham model projects a deep decarbonisation of China's economy to 2050, with CO_2 emissions for the energy and industrial sectors in 2012 at 9.81 $GtCO_2$, reducing to 6.79 $GtCO_2$ in 2050. This is driven by changes in the technology mix of the power sector, with the coal-dominated generation replaced by a mixture of renewables, nuclear, and fossil fuels with CCS. Table 4 compares the technology deployment levels in the TIAM-Grantham model for the power sector, and Table 5 the model's outputs for the energy end-use sectors, with those of other studies in which detailed information is included (primarily the Chinese ERI's 2050 Pathways Calculator [24], where maximum ambition levels of technology deployment are used in the comparison, the DDPP analysis [16], and the ERI's High Renewable Energy Roadmap [25]). Two scenarios are shown, denoted S1 and S2, as follows:

- S1 is an original mitigation scenario used in the AVOID 2 analysis, with no specific technology deployment constraints in any of the 15 TIAM-Grantham regions. This scenario is designed to meet a 2°C-consistent level of CO_2 emissions throughout the 21st century, following relatively weak mitigation action in each region to 2020, in line with the less stringent end of their Cancun pledge ranges.
- S2 is a scenario designed to match the CO_2 emissions profile for China and India as in S1, over the period 2012-2100, but with specific technology deployment constraints introduced so as to more closely align its technology deployment levels with the most ambitious technology deployment levels seen in the other sources.

For each scenario, a comparison of how optimistic the TIAM-Grantham scenario is compared to the other sources is given by:

- a green rating (indicating that a lower-carbon technology is deployed comparably or less rapidly in TIAM-Grantham, or that a higher-carbon technology is deployed more rapidly in TIAM-Grantham);
- an amber rating (indicating that TIAM-Grantham is more optimistic on low-carbon / less optimistic on high-carbon technologies);
- a red rating (indicating a significant difference[1] between TIAM-Grantham and the other sources).

[1] Here significance is not defined statistically but subjectively. In general if percentage differences between TIAM deployment levels are deemed large relative to the overall size of the level of deployment, then it is envisaged that – even in the context of uncertainties over future economic growth, supply chain and material availability and energy system size – it is not likely that the TIAM levels of deployment could be achieved if the country studies indicate a maximum or most ambitious level of deployment possible.

Table 4: TIAM-Grantham China power capacity projections (2°C scenario with global mitigation action delayed until 2020) compared to other sources

Power sector - Installed capacity (GW)	Year	S1		S2		Estimate from other sources	
Biomass (including with CCS)	2020	107		30		30	Renewable Energy Capacity Targets (12th Five-Year Plan) [26]
						53	China 2050 High Renewable Energy Roadmap [25]
	2050	0		67		144	China 2050 High Renewable Energy Roadmap [25]
Coal CCS (% of total coal power plants[2])	2050	0%		0%		75%	Deep Decarbonisation Pathways Project [16]
Natural Gas Total	2020	97		142		120	2050 Pathways Calculator [24]
	2050	485		683		460	2050 Pathways Calculator [24]
Gas CCS (% of total gas power plants)	2050	100%		7%		80%	Deep Decarbonisation Pathways Project [16]
Geothermal	2020	0		0		0	China 2050 High Renewable Energy Roadmap [25]
	2050	7		7		6	2050 Pathways Calculator
						11	China 2050 High Renewable Energy Roadmap [25]
Hydro	2020	431		432		420	Renewable Energy Capacity Targets (12th Five-Year Plan) [26]
	2050	547		547		694	2050 Pathways Calculator [24]
						554	China 2050 High Renewable Energy Roadmap [25]
Nuclear	2020	87		87		51	China 2050 High Renewable Energy Roadmap [25]
	2050	140		140		450	2050 Pathways Calculator [24]
						100	China 2050 High Renewable Energy Roadmap [25]
Solar (PV and thermal)	2020	46		94		157	China 2050 High Renewable Energy Roadmap [25]
	2050	88		2205		135	2050 Pathways Calculator [24]
						2,696	China 2050 High Renewable Energy Roadmap [25]
Wind (onshore and offshore)	2020	165		153		200	Renewable Energy Capacity Targets (12th Five-Year Plan) [26]
						317	China 2050 High Renewable Energy Roadmap [25]
	2050	4,393		2,671		1,200	Deep Decarbonisation Pathways Project [16]
						2,397	China 2050 High Renewable Energy Roadmap [25]
Tidal	2050	0		0		41	2050 Pathways Calculator [24]

[2] In TIAM-Grantham coal with CCS is not deployed in the period 2005-2100, with gas plus CCS preferred due to lower costs when emissions constraints are applied.

Table 5: TIAM-Grantham energy end-use technology penetration for China (2°C scenario with global mitigation action delayed until 2020) compared to other sources

Transport	***Year***	***S1***		***S2***		***Estimate from other sources***	
Cars – % conventional	2050	0%		50%		0%	2050 Pathways Calculator [24]
Cars - % hybrid	2050	0%		0%		35%	2050 Pathways Calculator [24]
Cars – % gas	2050	0%		0%		25%	2050 Pathways Calculator [24]
Cars - % electric and hydrogen	2050	100%		50%		40%	2050 Pathways Calculator [24]
Freight vehicles - % oil	2050	29%		73%		3%	2050 Pathways Calculator [24]
Freight vehicles-%hybrid	2050	0%		0%		22%	2050 Pathways Calculator [24]
Freight vehicles - % gas	2050	32%		6%		16%	2050 Pathways Calculator [24]
Freight vehicles-% electric and hydrogen	2050	39%%		21%		59%	2050 Pathways Calculator [24]
Freight transport trains powered by electricity (%)	2050	6%		5%		100%	2050 Pathways Calculator [24]
Industry	***Year***	***S1***		***S2***		***Estimate from other sources***	
Emissions captured with CCS (%)	2050	57%		30%		20%	Deep Decarbonisation Pathways Project [16]
						25%	2050 Pathways Calculator [24]
Share of electricity	2050	21%		19%		47%	2050 Pathways Calculator [24]
Share of gas	2050	29%		64%		6%	2050 Pathways Calculator [24]
Share of coal	2050	39%		3%		37%	2050 Pathways Calculator [24]
Share of oil	2050	10%		9%		6%	2050 Pathways Calculator [24]
Buildings	***Year***	***S1***		***S2***		***Estimate from other sources***	
Share of electricity	2050	56%		41%		47%	Deep Decarbonisation Pathways Project [16]
Share of gas	2050	11%		20%		27%	Deep Decarbonisation Pathways Project [16]
Share of biomass	2050	28%		30%		<5%	Deep Decarbonisation Pathways Project [16]
Share of coal	2050	0%		0%		13%	Deep Decarbonisation Pathways Project [16]
Agriculture	***Year***	***S1***		***S2***		***Estimate from other sources***	
Share of electricity	2050	35%		35%		27%	2050 Pathways Calculator [24]
Share of coal	2050	30%		30%		29%	2050 Pathways Calculator [24]
Share of oil	2050	10%		10%		44%	2050 Pathways Calculator [24]
Share of gas	2050	20%		20%		0%	2050 Pathways Calculator [24]
Share of biomass	2050	5%		5%		0%	2050 Pathways Calculator [24]

Tables 4 and 5 indicate that in S1 the growth of most low-carbon energy technologies is broadly in line with the more ambitious end of those envisaged by scenarios undertaken by Chinese-led groups using scenario analysis. The principal exceptions (indicated by the red rating) are as follows:

- Biomass electricity generation is deployed somewhat too rapidly in the immediate near-term period to 2020, resulting in an installed capacity of about 3.5 times that envisaged in the 12th Five Year Plan [26];
- CCS is only deployed on gas plants, which is in itself not overly optimistic, but may be slightly unrealistic given the greater focus of CCS demonstrations on coal plants,

compared to gas. More importantly, CCS is applied to all gas plants in 2050, as opposed to a lower share (80%) in the DDPP analysis [16];

- Onshore wind is extremely rapidly deployed in the TIAM analysis, to the extent that by 2050 there is more than 3 times the installed capacity of onshore wind envisaged than in the 2050 Pathways Calculator [24] analysis;
- In the industrial sector, almost 60% of emissions are captured by CCS, whereas in other studies the figure is less than 30%, by 2050.
- In the transport sector, the complete switch to hydrogen cars is unrealistic by 2050, given a more balanced portfolio of technologies in other analysis.

S2 uses constraints applied in all of these areas, to explore the cost and feasibility of China achieving the same CO_2 emissions reduction pathway as per the S1 scenario but with some growth constraints applied to key low-carbon technologies:

- Constraints of 20% capacity growth per year are applied to biomass, CCS and wind. This constraint results from analysis of past energy transitions, in which certain low-carbon or pollution control technologies achieved annual rates of growth either globally or in particular regions as high as 20% [27].
- A maximum share constraint of 30% has been applied to emissions captured by CCS in the industrial sector.
- A maximum share constraint of 50% has been applied to alternative fuel vehicles (hydrogen and pure battery electric vehicles) in the road transport sector.

The resulting S2 scenario has power generation technology deployment levels which are more in line with, or more conservative than, the most ambitious estimates from other studies. The major exceptions are that there is more natural gas power generation capacity in China in the S2 scenario, and more solar than even the ambitious ERI High renewables penetration scenario [25]. Nevertheless, the overall balance of low-carbon technologies in the S2 scenario does not appear overly optimistic with regard to technology deployment rates when compared to the other estimates available. On the demand side, the transport sector vehicle shares are now closer to the other studies. There are variations in the specific shares of biomass, oil, gas and coal in the buildings sector, but no strikingly infeasible shares in the TIAM-Grantham S2 scenario, given the potential reliance on all of these fuels for building heating and cooking services. For example commercial buildings rely heavily on biomass in 2050 in S2 (which makes up 30% of final energy usage) but this is not infeasible given the large usage of biomass in building heating in China today.

The major difference between S2 and the other studies is the industrial sector – with CCS now limited to capturing a much lower share of emissions, which results in the use of more gas in place of coal for high grade process heating in this sector. Whilst not infeasible, this would put increasing pressure on China to secure gas supplies, which are already important in the power, buildings and agricultural sectors.

4.2 India

The TIAM-Grantham analysis for India's CO_2 emissions pathway can also be compared to other sources using alternative modelling approaches, as shown in Tables 6 and 7. Here, due to comparability of data, the primary comparisons used are from the India 2047 Energy Security Scenarios calculator [28] and the DDPP [17].

Table 6: TIAM-Grantham India power capacity projections (2°C scenario with global mitigation action delayed until 2020) compared to other estimates for India

Power sector - Installed capacity (GW)	***Year***	***S1***		***S2***		***Estimate from other sources***	
Biomass (including with CCS)	2020	22		10		7	Planning Commission Government of India [29]
	2050	53		43		16	2047 Energy Security Scenarios [28]
Coal CCS	2020	0		0		11	2047 Energy Security Scenarios [28]
	2050	0		0		81	2047 Energy Security Scenarios [28]
Gas CCS	2020	0		0		2	2047 Energy Security Scenarios [28]
	2050	23		26		9	2047 Energy Security Scenarios [28]
Hydro	2020	104		100		60-65	Planning Commission Government of India [29]
	2050	152		169		180	2047 Energy Security Scenarios [28]
Nuclear	2020	26		26		78	Planning Commission Government of India [29]
	2050	51		51		61	2047 Energy Security Scenarios [28]
Solar PV	2020	5		5		10	Planning Commission Government of India [29]
				5		20-200	National Solar Mission [30]
	2050	5		181		479	2047 Energy Security Scenarios [28]
Solar thermal	2020	0		0		5-10	Planning Commission Government of India [29]
	2050	222		222		187	2047 Energy Security Scenarios [28]
Wind (total)	2020	12		24		30	Planning Commission Government of India [29]
Wind Onshore	2020	12		24		30	2047 Energy Security Scenarios [28]
	2050	1,214		419		410	2047 Energy Security Scenarios [28]
Wind Offshore	2020	0		0		0	2047 Energy Security Scenarios [28]
	2050	102		0		141	2047 Energy Security Scenarios [28]

Table 7: TIAM-Grantham energy end-use technology penetration for India (2°C scenario with global mitigation action delayed until 2020) compared to other sources

Transport sector	Year	S1		S2		Estimate from other sources	
Buses – % electric or hydrogen	2050	0%		0%		15%	2047 Energy Security Scenarios [28]
2 wheelers - % electric	2050	0%		0%		80%	2047 Energy Security Scenarios [28]
						~100%	Deep Decarbonisation Pathways Project* [19]
Cars - % electric or hydrogen	2050	100 %		50%		51%	2047 Energy Security Scenarios [28]
						50%	Deep Decarbonisation Pathways Project* [19]
Rail - % electric	2050	95%		27%		70%	2047 Energy Security Scenarios [28]
						60% (passenger) – 80% (freight)	Deep Decarbonisation Pathways Project* [19]
Industry	**Year**	**S1**		**S2**		**Estimate from other sources**	
Share of electricity	2050	21%		20%		20%	2047 Energy Security Scenarios [28]
Share of gas	2050	26%		57%		12%	2047 Energy Security Scenarios [28]
Share of oil	2050	4%		4%		12%	2047 Energy Security Scenarios [28]
Share of coal	2050	41%		8%		35%	2047 Energy Security Scenarios [28]
Share of biomass	2050	7%		8%		10%	Deep Decarbonisation Pathways Project [17]
Residential	**Year**	**S1**		**S2**		**Estimate from other sources**	
Share of electricity	2050	34%		47%		50%	Deep Decarbonisation Pathways Project [17]
Share of gas	2050	8%		6%		5-10%	Deep Decarbonisation Pathways Project [17]
Share of biomass	2050	58%		25%		30%	Deep Decarbonisation Pathways Project [17]
Share of coal	2050	0%		21%		0%	Deep Decarbonisation Pathways Project [17]
Commercial	**Year**	**S1**		**S2**		**Estimate from other sources**	
Share of electricity	2050	19%		3%		80%	Deep Decarbonisation Pathways Project [17]
Share of gas	2050	3%		70%		10%	Deep Decarbonisation Pathways Project [17]
Share of biomass	2050	75%		25%		5-10%	Deep Decarbonisation Pathways Project [17]
Agriculture	**Year**	**S1**		**S2**		**Estimate from other sources**	
Share of electricity	2050	88%		85%		50%	Deep Decarbonisation Pathways Project [17]
						67%	2047 Energy Security Scenarios [28]
Share of diesel	2050	6%		10%		50%	Deep Decarbonisation Pathways Project [17]
						33%	2047 Energy Security Scenarios [28]
Share of gas	2050	5%		5%		0%	Deep Decarbonisation Pathways Project [17]
						0%	2047 Energy Security Scenarios [28]

Notes: Where indicated with a *, the draft (2014) DDPP report [19] has been used rather than the final (2015) report [17], to allow comparability of data to the required degree of granularity.

For India, as with China, the majority of energy technology deployment levels in S1 are broadly comparable to those from other studies. There are four principal exceptions:

- there is a too-rapid increase in biomass-based electricity generation when compared with the scenario analysis of the Energy Security Scenarios calculator [28];
- in common with the China analysis is TIAM's overly rapid deployment of onshore wind

- again as shared with the China analysis, TIAM projects in the S1 scenario a complete switch to hydrogen cars in 2050, compared to a more considered switch to 50% electric cars in both the DDPP [17] and Energy Security Scenarios [28];
- rail electrification, at 95% in TIAM's S1 scenario, is also rather too optimistic compared to rates of 60-80% in the DDPP [17] and Energy Security Scenarios analysis;
- the other major misalignment is in the majority use of biomass in the residential and commercial sectors in TIAM, with biomass constituting 30% in the residential sector and around 5% in the commercial sector in the other study for which data is available.

S2 applies the following constraints in order to address these misalignments:

- Growth constraints of 20% are applied to biomass and wind, again in line with historical energy transitions analysis [27];
- A maximum share constraint of 50% has been applied to alternative fuel vehicles (hydrogen and pure battery electric vehicles) in the road transport sector;
- As with China, a maximum share constraint of 30% has been applied to emissions captured by CCS in the industrial sector – there are no specific alternative data points on this share of emissions captured from other studies, so this constraint is applied to err on the side of caution, given that in the S1 scenario the majority (almost 60%) of India's industrial emissions are captured with CCS, as is the case in China;
- The share of biomass in the residential and commercial buildings sectors has been limited to 25% for both the commercial and residential sectors.

As is the case in the China analysis, with these constraints applied the S2 scenario more closely matches the energy technology penetration estimates from other studies. There are some exceptions:

- biomass (including with CCS) power generation is still deployed too rapidly to 2050, although the overall installed capacity, at 43 GW, is relatively small, making this a relatively insignificant part of the power generation sector;
- gas dominates the industrial sector, as a result of replacing coal, given the limit on CCS capture of emissions;
- biomass continues to be a significant energy vector in commercial buildings, although given its current dominance this is not inconceivable;
- agriculture is arguably too highly electrified with too low a dependence on oil. In emissions terms this sector is relatively small, however.

These misalignments, as with the China analysis, reflect that it is not possible to perfectly constrain a cost-optimising model such as TIAM-Grantham to a range of other sources, as with CO_2 constraints and a range of technology deployment constraints, it has limited degrees of freedom to choose an emissions pathway that meets its least-cost objective.

An apparent implication of this analysis is the importance of CCS in the industrial sector, since with limitations on its deployment in both China and India, there is a much higher reliance on gas in the TIAM-Grantham model, compared to a continued reliance on coal in the national studies. Switching from coal to gas (or other lower-carbon fuels such as biomass) in industrial manufacturing is therefore a key policy imperative if deep decarbonisation targets are to be met in this model.

4.3 Implications of applying constraints to mitigation scenarios for China and India

With the constraints discussed in sub-sections 3.1 and 3.2 applied to the TIAM-Grantham model in order to produce the S2 scenario, the global mitigation cost (2012-2100 present value cost using a 5% discount rate) of achieving the below 2°C long-term temperature goal

(LTTG) increases from 1.0% to 1.5% of GDP, with more dramatic increases in the China and India regions themselves, as shown in Figure 5. The global carbon price, reflecting this magnitude of mitigation cost increase, is higher than in the S1 scenario throughout the mitigation period to 2100, as shown in Figure 6. This underlines the high impact of applying technology constraints to the TIAM-Grantham model such that its choice of technology options deviates from what it calculates to be the least-cost transition pathway. Nevertheless, the mitigation cost estimates both at a regional and global level remain comfortably within the range of estimates of mitigation costs [31].

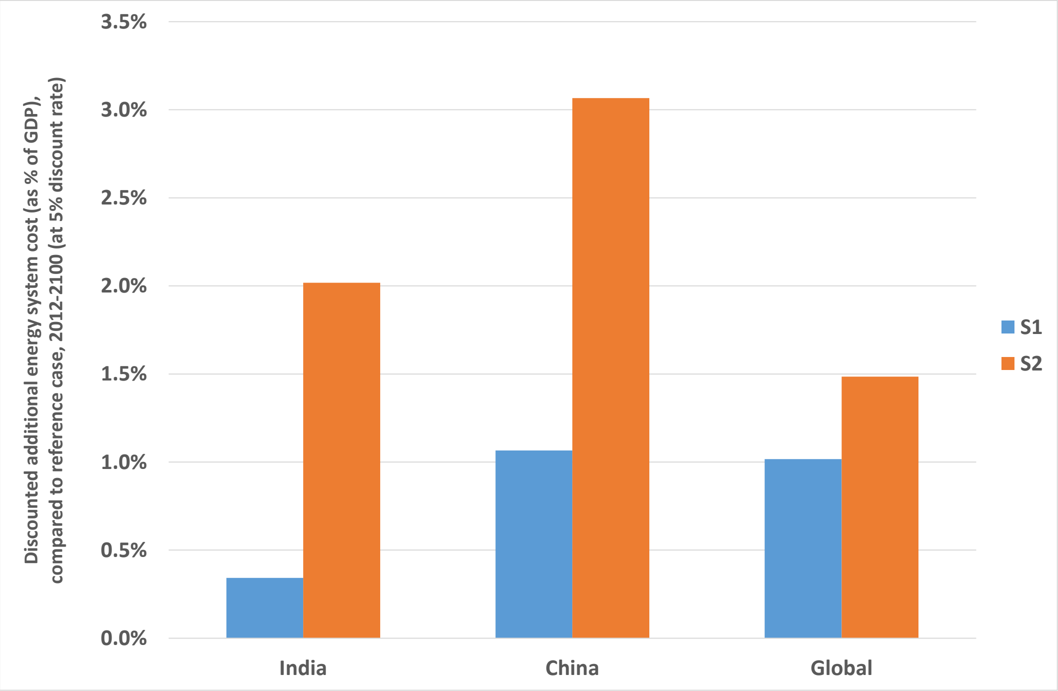

Figure 5: Mitigation cost in mitigation scenarios in China, India and globally

Notes: Scenario is for a 2°C scenario with global coordinated mitigation action delayed until 2020, with weak regional action in line with the less stringent end of the Cancun agreements to 2020. Mitigation cost is the present value of the additional energy system cost in the mitigation scenarios (S1 and S2) compared to the unmitigated reference scenario, using a discount rate of 5%.

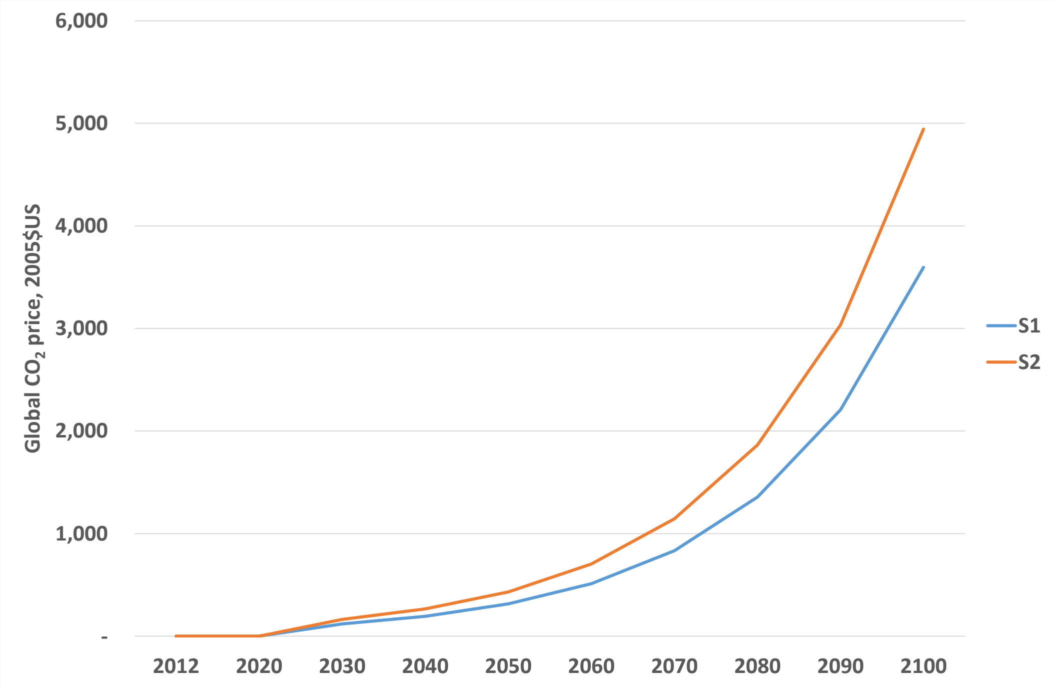

Figure 6: Global carbon price in mitigation scenarios

4.4 Assessing the feasibility of achieving decarbonisation in the other BRICS countries

There is relatively less assessment of long-term low-carbon pathways in Brazil, Russia and South Africa. In addition, these regions are not explicitly represented in the TIAM-Grantham model. Measured according to 2015 purchasing power parity(PPP) GDP[3], South Africa constitutes 17% of the TIAM-Grantham "Africa" region, Russia 67% of the TIAM-Grantham "Former Soviet Union" region and Brazil 43% of the TIAM-Grantham "Central and South America" region.

Nevertheless, modelled scenarios using energy systems models can to some extent be compared to recent bottom-up assessments of these regions' mitigation potential. A recent source of such assessments is the "Enhanced policy scenarios for major emitting countries" [32] which includes analysis of Brazil and the Russian Federation (but not South Africa). This shows that, in an enhanced scenario with implementation of current policies as well as additional policies aimed at lowering local air pollution, increasing energy efficiency and energy security, Brazil would be able to achieve a reduction in energy-related CO_2 emissions from 2020 onwards, such that by 2030 it has returned to approximately 2014 levels of emissions (at just above 400 $MtCO_2$). The DDPP scenario for Brazil [18] has CO_2 emissions (from energy and industrial emissions sources i.e. excluding land use and forestry) rising to almost 500 $MtCO_2$ by 2030. However, TIAM-Grantham's Latin America region has CO_2 emissions down 37% on 2012 levels by 2030, which appears far more optimistic than this trajectory. A study focusing on Brazil-specific scenarios using six least cost optimisation models such as TIAM-Grantham, when a carbon price of \$50/tCO_2e in 2020, rising at 4% per year to \$162/tCO_2 in 2050 is imposed, shows a broad range of outcomes by 2030, with

[3] Purchasing power parity measures of GDP convert country-level GDP in local currency to a chosen currency (in this case $US) by using a measure of value of the currency which accounts for the quantity of the currency needed to purchase a given basket of goods and services, when compared to the quantity of $US required to purchase an equivalent basket of goods and services in the US. Purchasing power parity adjusted exchange rates are generally accepted to be of greater validity in comparing country GDP figures.

one model (GCAM) seeing emissions fall against 2010 levels, two models (Phoenix and EPPA) seeing emissions broadly the same as 2010 levels, and three models (TIAM-ECN, POLES and MESSAGE-Brazil) seeing emissions rise against 2010 levels [33]. This compares to the carbon price of the original TIAM-Grantham 2°C scenario (S1) which rises to \$313/tCO_2 in 2050 and which therefor represents a more stringent mitigation scenario. TIAM-Grantham is therefore not necessarily out of line with some other such optimisation models, but does seem too optimistic compared to the (non-optimisation) studies.

The "Enhanced policy scenarios for major emitting countries" analysis [32] for Russia shows energy-related CO_2 emissions approximately 15% below 2012 emissions by 2030. The Deep Decarbonisation pathways project's [19] Russia scenario sees emissions only marginally changed to 2030, but then falling dramatically between 2030 and 2050, such that by 2050 emissions are almost 90% below 2010 levels. By contrast, the TIAM-Grantham model shows emissions over 50% below 2012 levels by 2030, but only 20% below if CCS captured emissions are not taken into account. This suggests that the TIAM-Grantham model's assumed deployment of CCS, at almost 100 GW of biomass CCS capacity in the 2020s for its "Former Soviet Union" region, is unlikely, and a more realistic scenario would include constraints on CCS deployment in line with those constraints applied to the China and India regions. The following sub-section outlines the implications of constraining all TIAM regions such that technologies including CCS are not deployed as rapidly as the model would choose without constraints.

4.5 Implications of limits to technology deployment in China and India

A global scenario with growth constraints included for a range of the key supply side technologies deployed most rapidly is outlined in the AVOID 2 report WPC3 [27], which assesses the feasibility of future low-carbon pathways in light of historical energy transitions. In combination, these constraints result in the 2°C target no longer being attainable with 50% likelihood (a minimum temperature increase of 2.1ºC can be achieved with 50% likelihood). Table 8 compares the cost impacts of the scenario (denoted S2 in Section 4.3) with constraints applied to the China and India scenarios with the scenario in which global constraints are applied to technology deployment in all regions. The scenario with minimal constraints (denoted S1 in Section 3.3) is also shown. The overall costs of mitigation – and associated carbon prices - increase with the regional coverage of constraints, as expected.

Table 8: Comparison of unconstrained (S1), constrained (S2) and globally constrained scenarios

Method	**S1**	**S2**	**Global highly constrained**
Details of constraints	• Intermittent (mainly wind and solar) electricity generation limited to 70% of total electricity generation, and wind to 50% of total electricity generation	• A range of constraints on China and India • Specifically, power sector growth rates, industrial CCS as a share of industrial emissions, and energy end-use shares of low-carbon fuels, as described in section 3.3.	• Intermittent electricity generation constraints as per 2C_Original • 20% maximum growth rate for all CCS technologies with a 1 GW seed[4] • 20% growth constraint on solar reduced to 4% after 2040 • 5% growth constraint on wind • Minimum capacity factor for unabated coal plants set to 70% for new technologies and 50% for existing technologies
Does the model solve?	Yes	Yes	Model does not solve for 1,340 Gt budget. Solves for 1,540 Gt budget (2.1ºC median temperature change in 2100, as set out in AVOID 2 WPC3 [27]
CO_2 price to 2100 (2005\$US/tCO_2)	118 (2030) 310 (2050) 3,595 (2100)	163 (2030) 431 (2050) 4,944 (2100)	322 (2030) 850 (2050) 9,790 (2100)
Global cost of mitigation in 2005$trillion, 2012-2100 discounted at 5% (and as share of 2012-2100 century GDP)	30.3 (1.0%)	46.7 (1.5%)	70.4 (2.2%)

5 Conclusions

This study compares the regional technology deployment levels in the TIAM-Grantham model when run to simulate a least-cost pathway to achieving the 2°C long-term temperature goal (LTTG), with technology deployment levels in national studies of deep decarbonisation (principally the most ambitious levels in the regional 2050 calculators, and the recent Deep Decarbonisation Pathways Project's assessments). This is done in detail for

[4] Since CCS is not yet deployed, a growth constraint is meaningless without first specifying what initial level of deployment is allowed in each region – a "seed" value of 1 GW of CCS in each region is therefore specified, reflecting that initial deployment is likely to see one or two large-scale CCS plants of the order 0.5-1 GW (i.e. commercial scale) in each region [27].

China and India, which represent the majority (80%) of current and future projected BRICS emissions. Comparisons for the Former Soviet Union region (of which Russia makes up 67%) and Central and South America region (of which Brazil makes up 43%) are also discussed, although given the lack of geographical match, at a more circumspect level.

This comparative analysis suggests that, in most cases, the TIAM-Grantham model's levels of energy technology penetration in China and India are similar to those in the countries' own studies. However, there are some important exceptions – most notably that the TIAM-Grantham model tends to show that certain technologies are very rapidly deployed, including hydrogen vehicles in the transport sector, CCS in the industrial manufacturing sector, and onshore wind in the power sector. Re-running the global mitigation scenario with specific constraints to re-align these technology penetration levels with those in the literature leads to a significantly higher global cost of mitigating towards the below 2°C target – rising from 1.0% of global GDP over the period 2012-2100, to 1.5% of GDP over this period. This cost estimate is still within the range of the literature on mitigation costs to achieve the below 2°C goal. However, constraining CCS in the industrial sectors leads to a potential over-reliance on gas replacing coal in industrial manufacturing heating processes. Hence, without either a significant shift away from coal or a significant deployment of industrial CCS, emissions pathways consistent with below 2°C in these regions are likely to be very challenging.

Also of note is that the INDC pledges of China and India put their CO_2 emissions at levels far above those in the TIAM-Grantham model's cost-optimal pathway to achieve the below 2°C target, with China's projected emissions under its INDC (about 13.8 $GtCO_2$) some 33% higher than the cost-optimal levels in the TIAM-Grantham mitigation pathway, and India's 2030 INDC-consistent emissions (about 4.3 $GtCO_2$) some 200% higher than the model's cost-optimal pathway.

For Brazil and Russia, a comparison of the emissions trajectories of the TIAM-Grantham regions containing these countries with other decarbonisation pathways studies to 2030 and 2050, suggests that the TIAM-Grantham model has a more aggressive emissions reduction trajectory to 2030 for these regions.

This is particularly the case in its "Former Soviet Union" region (of which Russia makes up about two-thirds by GDP) where in TIAM-Grantham, CCS is rapidly deployed from 2020 onwards, when in reality there is only one commercial-scale demonstration of CCS worldwide, with no explicit plans for CCS deployment at scale in Russia at this time. Since it is not possible to compare precise regions within TIAM-Grantham, these results should be treated with caution, but nevertheless indicate that there is a potential shortfall between the sum of country-level ambition and the necessary actions that would lead to a 2°C-consistent set of emissions reductions.

This study presents an important analogue to other AVOID 2 analysis which concludes that constraining global energy technology penetration rates and patterns to better match historical precedents significantly raises costs, and therefore makes the achievability of the below 2°C goal more challenging than the TIAM-Grantham model suggests, on face value. Such challenges are to be expected given the degree to which the below 2°C goal will require in many cases unprecedented rates of new low-carbon technology deployment, and the extent to which current country plans, even in their most ambitious cases, still leave a significant emissions gap compared to what energy systems models like TIAM-Grantham report as a cost-optimal decarbonisation pathway to meet the goal. The challenge is to bridge the gap between what is necessary to achieve the below 2°C goal, and what is deemed an ambitious decarbonisation pathway in different regions.

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