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Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models

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A B S T R A C T

Integrated assessment models are extensively used in the analysis of climate change mitigation and are informing national decision makers as well as contribute to international scientific assessments. This paper conducts a comprehensive review of techno-economic assumptions in the electricity sector among fifteen different global and national integrated assessment models. Particular focus is given to six major economies in the world: Brazil, China, the EU, India, Japan and the US. The comparison reveals that techno-economic characteristics are quite different across integrated assessment models, both for the base year and future years. It is, however, important to recognize that techno-economic assessments from the literature exhibit an equally large range of parameters as the integrated assessment models reviewed. Beyond numerical differences, the representation of technologies also differs among models, which needs to be taken into account when comparing numerical parameters. While desirable, it seems difficult to fully harmonize techno-economic parameters across a broader range of models due to structural differences in the representation of technology. Therefore, making techno-economic parameters available in the future, together with of the technology representation as well as the exact

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definitions of the parameters should become the standard approach as it allows an open discussion of appropriate assumptions.

1. Introduction

Over the past few years, integrated assessment models (IAMs) of climate change have become increasingly influential in informing the climate policy debate. Beyond assessment reports that summarize the findings of the scientific literature (e.g., Refs. [1,2]), they are used in policy impact assessments [3] and in environmental legislative analysis reports of government institutions (e.g., [4,5]). In addition, many national level IAMs have been used to inform the decision of governments in preparing their intended nationally determined contributions (INDCs) submitted to the climate negotiations prior to COP21 in Paris in 2015 [6]. Given the ambition to explore the possibility of limiting global temperature change to 1.5 °C and the associated ratcheting up process of national contributions agreed upon in the Paris Agreement, it is expected that there will be a continuous demand for analysis from both global and national IAMs over the coming years to inform this process. Examples of such recent studies include Fragkos et al. [7], Grubler et al. [8], Gu and Wang [9], van der Zwaan et al. [10] and van Vuuren et al. [11].

IAMs are not a homogenous group of tools, but use quite different methodological approaches and apply different system boundaries (for a review see Ref. [12]). In many cases, these differences originate back to the historical roots of the different IAMs. For example, some have their origins in energy systems analysis and were then expanded to include other human and natural systems (e.g., agriculture and forestry, climate) while others were originally designed to look at economic questions in an environmental context.

On the one hand, there is widespread agreement across – national as well as global – IAMs on high-level characteristics of mitigation strategies (see IPCC TAR, [13]; or IPCC AR4, [14]). On the other hand, significant differences at finer resolution exist which can be highly relevant for deriving more specific policy recommendations. As an example for both agreements and differences, the electricity sector which is responsible for roughly 40% of global greenhouse-gas (GHG) emissions is robustly projected to decarbonize first under climate policy consistent with the 2 °C target. Despite this high-level agreement on the de-carbonization of the electricity sector, the speed of the transition and in particular the resulting technology mix in power generation can be very different across IAMs (e.g., Ref. [14,35]). This can be attributed to three important differences across models, (i) the applied methodologies (e.g., simulation vs. optimization) as well as the associated model structure (e.g., production function with elasticities, discrete technology representation, logit sharing), (ii) the representation of different technology options, and (iii) the parameterization of technologies, typically referred to as techno-economic assumptions, both within the power sector and in other sectors (e.g., resource extraction, energy end-use). This study focuses on the representation of technologies (model structure) and the associated numerical techno-economic assumptions in fifteen national and global IAMs. Beyond comparing among the IAMs, the techno-economic parameters used in a given set of scenarios are also compared to the wider literature on technology evaluation, including IEA [15,16], DIW [17] and GEA [18]. Finally, we also respond to calls for increased transparency of energy-economic and integrated assessment models (e.g., Ref. [19]) and make the full dataset reviewed in this study available as part of the supplementary material.

The comparison reveals methodological differences in how techno-economic characteristics are projected into the future, which provides important background information for the interpretation of model results. Moreover, the comparison between national and global IAMs is particularly interesting for two reasons. First, national models may have a more accurate representation of costs and performance of technologies actually built in the recent past in a given country. Second, technology development typically does not happen in a single country in isolation, but is increasingly interlinked and driven by multi-national companies [20] which is more consistently represented in global IAMs. So there are mutual benefits of sharing techno-economic assumptions within the modeling community.

The paper is structured as follows. Section 2 provides a brief overview of the IAMs, the data collection process and the methods used in the comparison. In terms of region/country coverage, the focus is on Brazil, China, the European Union, India, Japan, and the USA. Section 3 highlights differences in the representation of technologies and differences between the approaches of projecting techno-economic assumptions into the future across the reviewed IAMs. A detailed comparison of techno-economic assumptions is the focus of Section 4, including capital cost, operation and maintenance (O&M) cost, conversion efficiency, lifetime and, derived from the other indicators, levelised cost of energy (LCOE) – excluding fuel costs. Due to data availability, electricity generation technologies are in the center of the comparison. Insights from this comparison and suggested next steps to improve our understanding of differences in key input assumptions are presented in Section 5. The rich supplementary material includes the full data set reviewed in this study and its visualization (Appendices C and E).

2. Methods and data

This section provides an overview of the IAMs that are covered in the comparison, the data sources that were used in compiling a comprehensive data set as well the methods used to harmonize data across regions and models.

2.1. Methods

In this study, techno-economic assumptions from fifteen IAMs, including eight global and seven national ones, are reviewed. Detailed model descriptions of the fifteen IAMs and related references are presented in Appendix A. The comparison of national/regional results focuses on major economies in the world, namely Brazil, China, the EU, India, Japan and the US. In 2015, these six regions accounted for more than half of the world population, some 70% of the global GDP (in current USD [22]), and about two-thirds of global CO2 emissions from fuel combustion, [16]. It is worthwhile to point out that, for all regions, at least one model developed in that region is included in the comparison.

Fig. 1 present the comparison framework of this study in four dimensions, namely models, their technology representation, the techno-economic parameter assumptions and countries/regions of

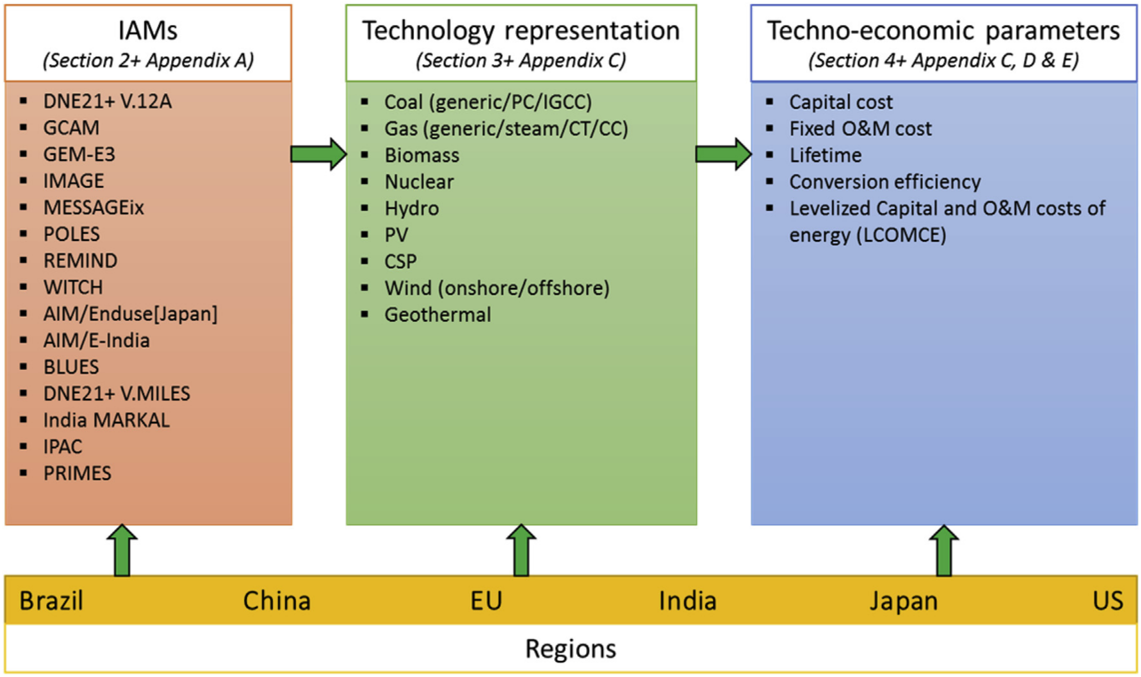


Fig. 1. Comparison framework of this study-models, technologies, assumptions, and regions.

the comparison.

It is important to note that the numerical assumptions of techno-economic parameters that form the basis of this comparison are, in general, scenario dependent. It is therefore not possible to extrapolate the data set presented in this study to all other scenario studies undertaken with the same models. However, our comparison provides insights that hold beyond individual scenarios, for example on the different methods used to project techno-economic assumptions into the future that have actually important implications for the interpretation of techno-economic assumptions.

2.2. Data source and harmonization

The data set used for the comparison has been collected from the four ongoing or recently completed model inter-comparison projects ADVANCE [23,24], AMPERE WP2 [25] and WP3 [26], CD-LINKS [27], and MILES [28].

To enable a direct comparison of the data, some harmonization was required to avoid systematic biases. The price and cost information were collected from different sources which use either constant USD or national currency, and thus need to be made consistent regarding currency and base year. In this paper, all the units are converted to constant 2010 USD (hereinafter referred to briefly as 2010 USD). For this purpose GDP deflators from the World Bank Database [21] are used (see details in Appendix B).

However, when it comes to regional definitions, an exact matching of regions was sometimes not possible. More specifically, in the case of global IAMs the comparison of country level techno-economic parameters included also some model regions that extend beyond the specific country (e.g., using data from the Latin America region for Brazil).

3. Concepts of projecting techno-economic assumptions in IAMs

Before focusing on the comparison of actual techno-economic parameters in Section 4, the differences in how these parameters are projected into the future will be discussed. The methods are to some degree linked to the representation of technologies, most notably whether a single or several technologies for converting a given primary energy source to electricity are represented in the model.

3.1. Projection of techno-economic parameters

The comparison of the different projection methods reveals differences in how this is dealt with across the set of IAMs considered. In summary, the projection strategies can be grouped into four basic categories: 1) "static technology" with "static costs"; 2) "static technology" with "dynamic costs"; 3) "dynamic technology" with "static costs"; and 4) "dynamic technology" with "dynamic costs".

In this context, "static technology" refers to the fact that the technical characteristics, most notably the conversion efficiency, does not change over time, while "dynamic technology" implies a variation of efficiency over time. Likewise, "static costs" implies that capital and O&M costs of a technology do not vary over time whereas they change under the "dynamic costs" category.

IAM teams may only use one of the four strategies for projecting techno-economic parameters of all technologies in their IAMs, or they may adopt different strategies for different technologies. Typically, those models that apply the concept of "dynamic technology" with "static costs" for fossil fuel technologies switch to "dynamic costs" for non-combustible energy conversion technologies (e.g., wind turbines, photovoltaics (PV), nuclear power), given that an efficiency parameter is a less useful concept in the techno-economic characteristics for such technologies. For example, an increase in the conversion efficiency of incoming radiation to electricity in PV cells reduces the required area and therefore material input to produce a given amount of electricity which lowers levelized generation costs. It is worthwhile noting that the two global models in this set that combine "dynamic technology" with "static costs" for fossil conversion technologies utilize an endogenous technological change formulation in the projection of costs of non-combustible renewable technologies ("REMIND 1.6" and "WITCH-GLOBIOM 4.4", see Fig. 3).

In addition, IAMs also vary with respect to representing a single or multiple technology variants for converting a given primary energy carrier (e.g., coal, gas) into a secondary energy form (e.g., electricity) (see Appendix C for more details). For example, while some models include multiple coal power plant types such as "pulverized coal (PC)" combustion with various steam cycle configurations (e.g., sub-, super- and ultra-super critical) as well as "integrated gasification combined cycle (IGCC)", others include a single representative technology per primary-to-secondary-energy conversion route. The concept of single representative technology is therefore more often combined with the "dynamic technology" description for fossil-fuel conversion technologies, implicitly assuming a transition from one (less efficient) type to the other (more efficient) in the predominant technology mix. In models with an explicit representation of multiple technology variants, this transition is instead modeled explicitly by considering the trade-off between more advanced variants with higher efficiency (and therefore lower fuel costs) and higher capital cost on the one hand and other variants with lower efficiency (higher fuel costs) and lower capital cost on the other hand.

Using several combustion-based power generation technologies as examples, Table 1 summarizes the adopted strategies for the projection of techno-economic parameters in the selected IAMs.

3.2. Regional technology variation

In addition to the above-mentioned strategies to project techno-economic assumptions into the future, techno-economic parameters, such as capital cost, may also vary significantly across regions in the global IAMs.

Using the capital cost of combined-cycle gas power plants as an example, regional variation of capital costs is found in four global models, "MESSAGEix-GLOBIOM_1.0", "IMAGE 3.0", "WITCH-GLOBIOM 4.4" and "DNE21 + V.12A" (see Fig. 2). It is worthwhile noting that the regional variation of conversion efficiency is also found for the MESSAGE, WITCH and IMAGE models, but not for the DNE21 + model. The other global models, "GCAM_4.2 ADVANCE", "GEM-E3", "REMIND 1.6" and "POLES MILES", adopt uniform techno-economic assumptions across all regions for new vintages of power plants. For comparison, capital cost projections from the IEA [15,17] are also shown in Fig. 2.

In the "MESSAGEix-GLOBIOM_1.0", "IMAGE 3.0", and "DNE21 + V.12A" models, lower capital costs are assumed for emerging economies (Brazil, China and India), while higher costs are assumed for developed regions (the EU, Japan and the US). In "MESSAGE ix-GLOBIOM_1.0", the absolute cost gap between the two regions gradually shrinks from 2010 (170 USD/kWe) to 2050 (65 USD/kWe), thus assuming some convergence of capital costs.

Qualitatively, this pattern is consistent with the IEA's assessment (2016) that shows similar regional variants as the "MESSAGEix-GLOBIOM_1.0", "IMAGE 3.0", and "DNE21 + V.12A" models, namely higher capital cost for developed regions and lower for emerging economy regions. However, a much larger absolute cost gap is assumed by the IEA [15,17], about 350 USD/kWe until 2040.

The regional variation in "WITCH-GLOBIOM 4.4" is different from the others by assuming that the capital costs in Brazil and Japan are significantly higher (around 25%) than those in the other four regions,[1] the gap between the two ends is as high as about 240 USD/kWe. It is also noteworthy that while in "WITCH-GLOBIOM 4.4" capital costs in the US are the lowest, whereas they are the highest or second highest in the projections adopted by "MESSAGEix-GLOBIOM_1.0", "DNE21 + V.12A" and the IEA.

3.3. Endogenous technological change

As highlighted above, three IAMs reviewed here, "REMIND 1.6", "WITCH-GLOBIOM 4.4" and "IMAGE 3.0", implement endogenous technological change for a subset of the technologies, including PV and wind turbines. These models assume that with increasing cumulative installed capacity of a technology, the technology's capital costs are decreasing which is described by a learning curve [29,30,36].[2] Given that climate policy leads to faster adoption of these technologies, the endogenously derived capital costs tend to be higher in a baseline scenario compared to a mitigation scenario.

Fig. 3 presents the resulting capital cost of PV in "REMIND 1.6", "WITCH-GLOBIOM 4.4" and "IMAGE 3.0" for Brazil. For the "REMIND 1.6" model, the cost gap between the baseline and mitigation scenarios is about 130 USD/kWe in 2020, increases to about 400 USD/kWe in 2030 and 2040, but then decreases again to about 240 USD/kWe in 2050. The gap in "WITCH-GLOBIOM 4.4" is relatively smaller than that in the "REMIND 1.6", with a gap of about 180 USD/kWe after 2020 while in "IMAGE 3.0" under the same baseline and mitigation scenarios the difference remains very small.

4. Comparison of techno-economic parameters

The following section compares techno-economic assumptions of electricity generation technologies, including capital and operating and maintenance (O&M) costs, conversion efficiencies, lifetimes and the resulting levelised cost of energy (LCOE), of national and global IAMs. In the remainder of this paper, parameters for PV and natural gas combined cycle power plants are presented to illustrate the main insights of this comparison. An overview of the

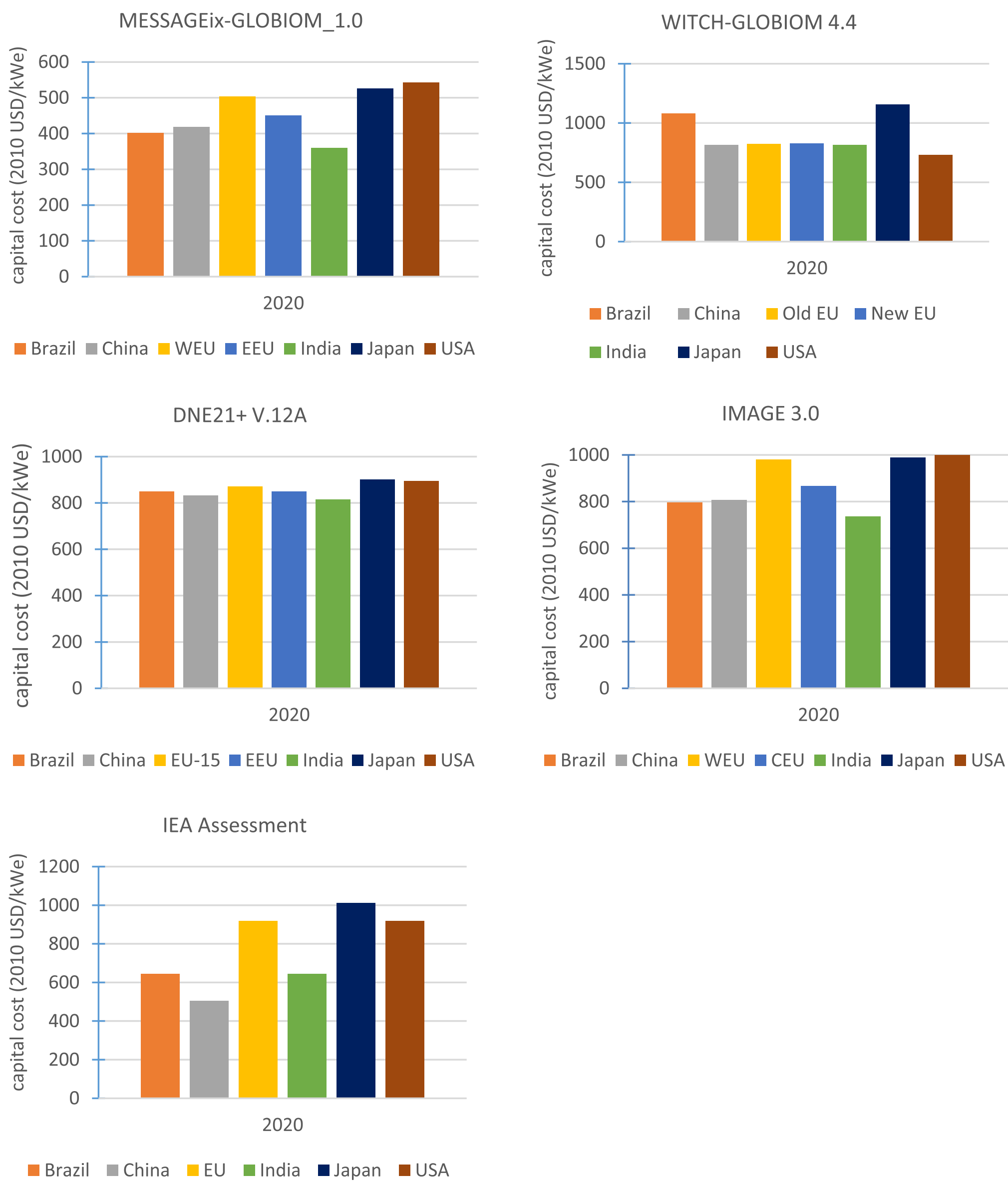
Table 1
Strategies of projecting techno-economic parameters into the future in IAMs.

IAMs		Electricity generation technologies		
		coal power plants	gas power plants	biomass power plants
Global	DNE21 + V.12A	DT-DC	DT-DC	DT-DC
	GCAM4.2_ADVANCE	DT-DC	DT-DC	DT-DC
	GEM-E3	DT-DC	DT-DC	n/a
	IMAGE 3.0	DT-DC	DT-DC	DT-DC
	MESSAGEix-GLOBIOM_1.0	ST-DC	DT-DC	ST-DC
	POLES MILES	DT-DC	DT-DC	DT-DC
	REMIND 1.6	DT-SC	DT-SC	DT-SC
	WITCH-GLOBIOM 4.4	DT-SC	DT-SC	DT-SC
National	BLUES	ST-DC	DT-DC	ST-SC
	IPAC-AIM/technology_V1.0	DT-DC	n/a	n/a
	PRIMES_2015	DT-DC	n/a	n/a
	AIM/E-India [IIMA]	DT-SC	DT-SC	DT-SC
	India MARKAL	ST-SC	ST-SC	ST-SC
	AIM/Enduse[Japan]	ST-SC	ST-SC	n/a

Note: ST-SC (static technology with static costs); ST-DC (static technology with dynamic costs); DT-SC (dynamic technology with static costs); DT-DC (dynamic technology with dynamic costs).

[1] Note that in WITCH-GLOBIOM 4.4 both Brazil and Japan are part of the larger regions Latin America, Mexico and Caribbean and Canada, Japan, New Zealand respectively.

[2] A basic description of the endogenous technological change formulation adopted by the IMAGE, REMIND and WITCH models can be found in the common IAM documentation online at https://www.iamcdocumentation.eu/.



Note: Models are under different scenarios: “MESSAGEix-GLOBIOM_1.0” (NoPolicy_V3); “WITCH-GLOBIOM 4.4” and “DNE21+ V.12A” (AMPERE2-Base-FullTech-OPT); IEA Assessment (450ppm).

Fig. 2. Regional variation of capital costs across global IAMs (combined-cycle gas power plants as the example).

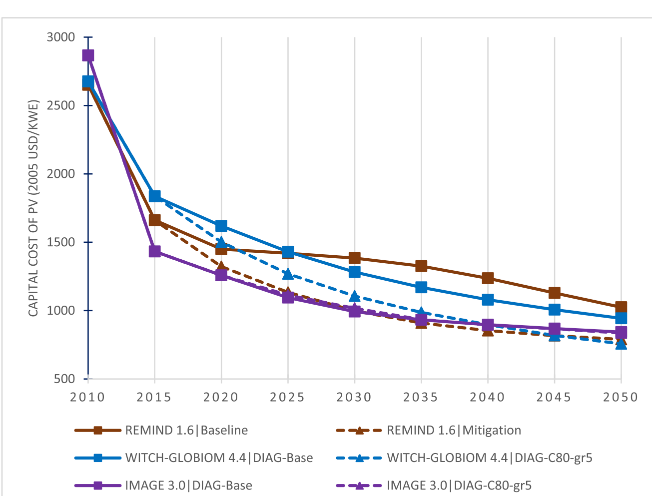


Fig. 3. Endogenous capital cost of PV in selected IAMs for Brazil.

Table 2
Capital cost patterns across the IAMs (for gas power plants).

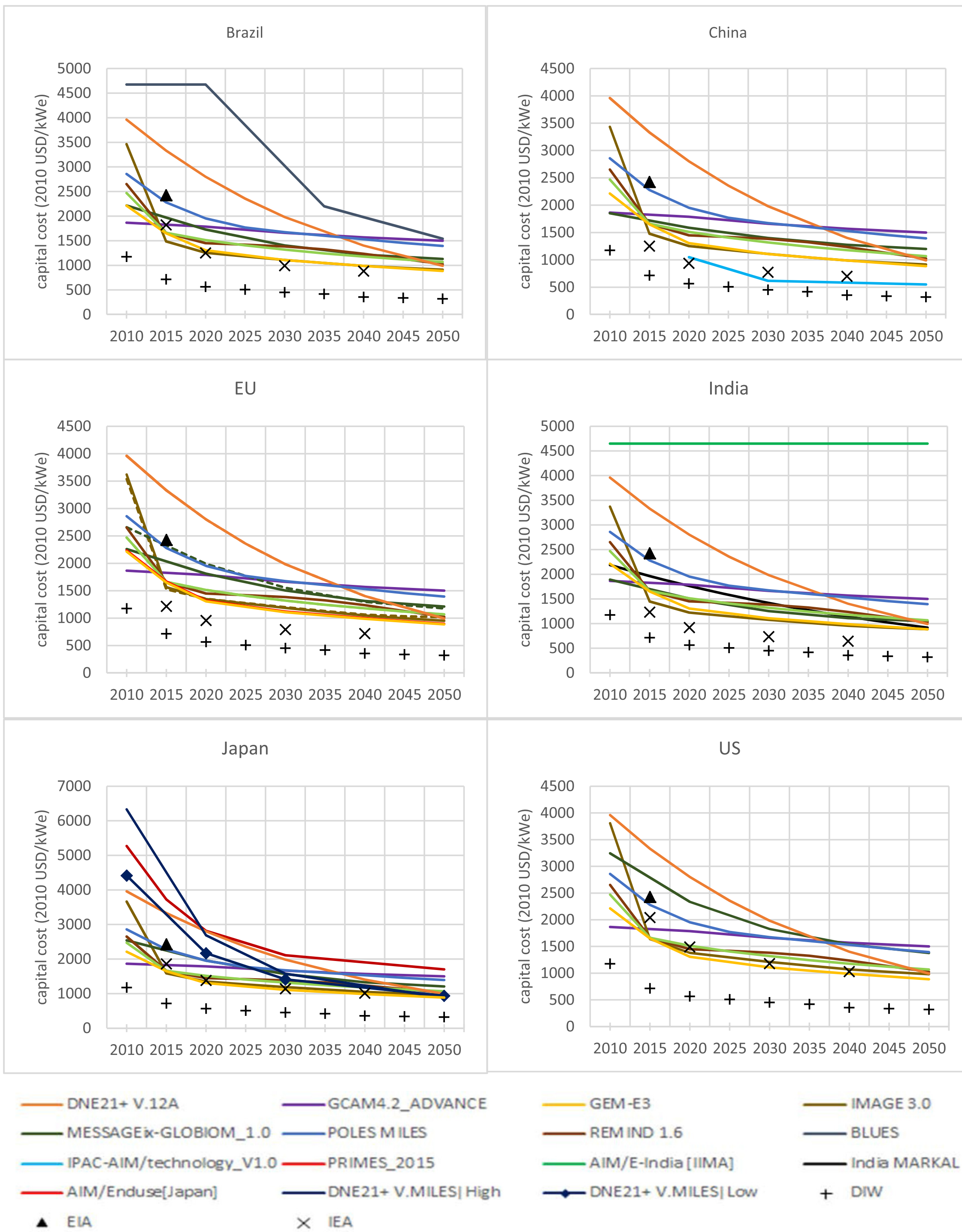
IAMs		Region	Time (2010–2050)	
		Change across regions	Change over time	Change trends
Global	DNE21 + V.12A	Yes	Yes	increase
	GCAM4.2_ADVANCE	No	Yes	decrease
	GEM-E3	No	yes	decrease
	IMAGE 3.0	Yes	Yes	increase
	MESSAGEix-GLOBIOM_1.0	Yes	Yes	no uniform trend
	POLES MILES	No	Yes	decrease
	REMIND 1.6	No	No	constant
	WITCH-GLOBIOM 4.4	Yes	No	constant
National	BLUES	N/A	Yes	decrease
	IPAC-AIM/technology_V1.0	N/A	Yes	decrease
	PRIMES_2015	N/A	Yes	decrease
	AIM/Enduse[Japan]	N/A	No	constant
	AIM/E-India [IIMA] 3.0	N/A	No	constant
	India MARKAL	N/A	No	constant

full data set for capital costs, O&M costs and conversion efficiencies is provided in Appendix C.

4.1. Capital cost

The capital costs of technologies used in the selected IAMs in this report are all so-called overnight construction costs. Therefore, financing costs during the construction period are excluded from the data presented in the comparison below.

As illustrated in the previous section, IAMs may assume dynamic or static capital costs of technologies, and combine them with the dynamic or static assumptions for conversion efficiency. As previously, using the technology of gas power plants as an example, Table 2 summarizes the capital cost patterns. For the



Note: solid lines for the Western Europe and dotted lines for the Eastern Europe.

Fig. 4. Capital cost of PV power plants in selected regions across IAMs.

global models, the capital costs in the “DNE21 + V.12A”, “IMAGE 3.0”, and “MESSAGEix-GLOBIOM_1.0” change across regions as well as over time, while in “REMIND 1.6” the cost is assumed to be constant over regions and time. In the remaining three global models (i.e., “GCAM4.2_ADVANCE”, “GEM-E3”, “POLES MILES”, and “WITCH-GLOBIOM 4.4”) the capital cost is designed to change either across regions or over time. Of the six national IAMs, the Japanese model “AIM/Enduse[Japan]” and the two Indian models, “AIM/E-India [IIMA]” and “India MARKAL”, assume that the capital costs remain constant over the period 2010 to 2050, while the other three generally assume decreasing costs over time.

For the same region, capital cost of a technology vary significantly among different IAMs (both global and national). To illustrate the capital cost range across IAMs for certain regions, Figs. 4 and 5 respectively show the capital cost of PV and gas combined cycle (CC) power plants for the six studied regions. For comparison, data from a range of technology assessments including IEA [16,17], EIA [31], DIW [18] and GEA [19] are also shown in the figures.

Note: solid lines for the Western Europe and dotted lines for the Eastern Europe.

Fig. 5. Capital cost of gas combined cycle power plants in selected regions across IAMs.

Figs. 4 and 5 visually demonstrate the wide range of capital cost adopted by the IAMs for the six regions. For both PV and gas CC power plants, the highest cost is roughly about 3 times higher than the low end.

Three observations emerge from this comparison. First, the capital cost assumed in the different IAMs vary significantly. For example, “MESSAGEix-GLOBIOM_1.0” for gas CC is relatively lower than all the other IAMs and marks the lower end of the spectrum while “DNE21+” and “GCAM4.2_ADVANCE” show the highest capital cost assumptions. The capital cost used in the two Indian models “AIM/E-India [IIMA]” and “India MARKAL” fall into the upper part and the middle of the range, respectively. Thus, a large spread in cost assumptions across national models from the same country is possible.

Second, for the PV technology, most models assume a quick reduction of capital cost before 2020, generally converging to about 1000–1500 $/kW. The only exception is the Indian model “AIM/E-India [IIMA]”, which adopt a constant capital cost for PV until 2050.

Third, the model “DNE21 + V.12A” (a Japanese model with global coverage) has two variants of CC technology (i.e., conventional CC and advanced CC). The advanced CC has the highest capital cost of CC for all the six regions, while the capital cost of conventional CC quite represents the average cost of the rest global models. If excluding the advanced CC in “DNE21 + V.12A”, among global IAMs the “GCAM4.2_ADVANCE” has the highest capital cost for CC for almost all the regions except for Brazil.

These observations translate into two broader takeaways. First, while the spread of capital cost assumptions across IAMs is large, the variation across the other sources reviewed [16–19,31] is almost as large. Second, in case of multiple national models, the spread between them can be as large as between the global and national IAMs.

4.2. O&M cost

O&M costs are usually assumed to be a fixed percentage of the capital cost in IAMs that does not change over time. In the majority of IAMs this percentage is identical in all regions, while in a few cases the percentage varies. Using the example of gas power plants (without CCS), Figs. 6 and 7 demonstrate the two alternatives respectively.

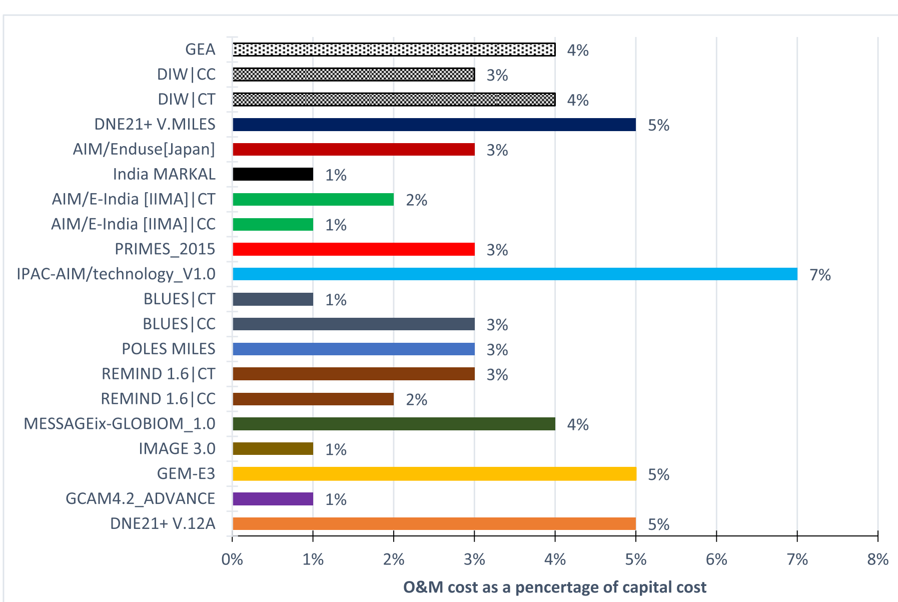
The ratio of O&M cost to capital cost ranges between 1% and 7% among the IAMs. As a reference, IEA [16,17], DIW [18] and GEA [19] report a percentage of 3–6%. While most IAMs assume that the ratio of O&M cost to capital cost is uniform across regions, in “WITCH-GLOBIOM 4.4” the ratios are region-dependent which generally is in line with the IEA [16,17] assessment. From Fig. 7, one interesting observation is that unlike for the other regions, this ratio used by “WITCH-GLOBIOM 4.4” and IEA [16,17] assessment for Brazil show a large difference, 1% for “WITCH-GLOBIOM 4.4” and 4–5% for the IEA.

4.3. Conversion efficiency

Conversion efficiency as reported by IAMs are so-called net efficiencies after subtraction of any internal losses due to fuel conditioning, pumping, etc. In addition, it is important to note that the efficiencies are typically not the design efficiencies, of e.g. a steam cycle, but rather average efficiencies across all modes of operation. For all reviewed IAMs, the conversion efficiency of technology is an exogenous input to the model and evolves over time reflecting expected efficiency improvements. However, the models then choose between available technology options with different efficiency, which can be interpreted as a form of endogenous technological change.

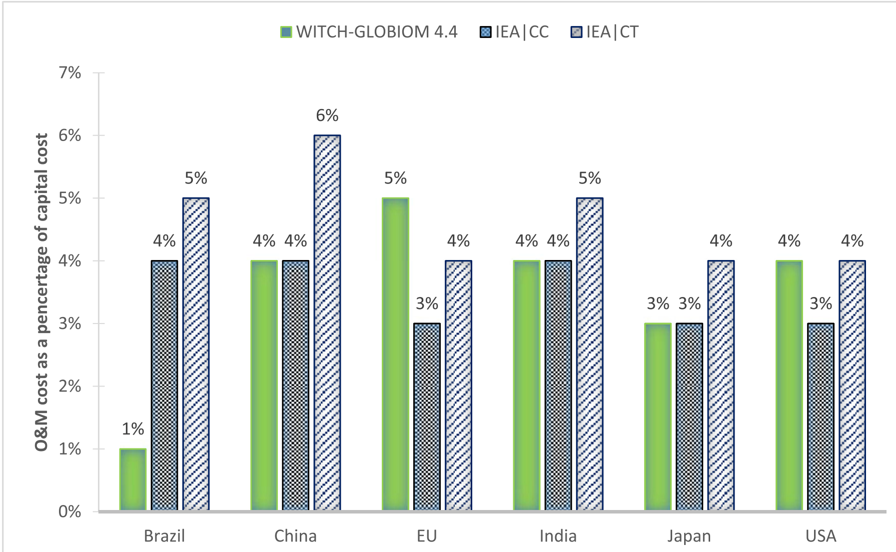
Similar to the capital cost, the conversion efficiency may also be assumed variable or constant across regions and over time (for some models, a convergence is assumed across regions in a certain future time, e.g. 2025 in REMIND 1.6).

Using the technology of gas combined cycle power plants as an example, Table 3 presents the conversion efficiency patterns across the different IAMs. All the global IAMs assume that the conversion efficiency of technologies increases over time with the magnitude of change varying substantially. In contrast, most national IAMs assume a constant efficiency, including “BLUES”, “AIM/Enduse [Japan]”, “AIM/E-India [IIMA]” and “India MARKAL”. It is also worth



Note: CT: combustion turbine; CC = combined cycle.

Fig. 6. O&M cost as a percentage of capital cost for gas power plants – constant across regions.



Note: CT: combustion turbine; CC = combined cycle.

Fig. 7. O&M cost as a percentage of capital cost for gas power plants – varying across regions.

Table 3
Conversion efficiency patterns across the IAMs (for gas combined cycle power plants).

IAMs		Region	Time (2010–2050)	
		Change across regions	Change over time	Change trends
Global	DNE21 + V.12A	No	Yes	Increase
	GCAM4.2_ADVANCE	No	Yes	Increase
	GEM-E3	No	Yes	Increase
	IMAGE 3.0	Yes	Yes	Increase
	MESSAGEix-GLOBIOM_1.0	Yes	Yes[1]	Increase
	POLES MILES	No	Yes	Increase
	REMIND 1.6	Yes	Yes	Increase
	WITCH-GLOBIOM 4.4	Yes	Yes	Increase
National	BLUES	N/A	No	Constant
	IPAC-AIM/technology_V1.0	N/A	Yes	Increase
	AIM/Enduse[Japan]	N/A	No	Constant
	DNE21 + V.MILES	N/A	Yes	Increase
	AIM/E-India [IIMA]	N/A	No	Constant
	India MARKAL	N/A	No	Constant

Note: [1] for regions of Brazil, eastern Europe, Japan and the US, the "MESSAGEix-GLOBIOM_1.0" assumes that the conversion efficiency remains the same over time.

noting that in four of the global models, namely "DNE21 + V.12A", "GCAM4.2_ADVANCE", "GEM-E3" and "POLES MILES", the efficiency is assumed to be identical across regions for new vintages.

Fig. 8 presents the conversion efficiency of gas combined cycle power plants assumed in the IAMs for the six studied regions.

From Fig. 8, it can be seen that three of the models ("DNE21 + V.12A", "AIM/Enduse[Japan]", "IPAC-AIM/technology_V1.0") in contrast to the others include multiple types of combined cycle power plants with different conversion efficiencies which span almost the entire range of efficiencies of the other models. The national models are usually found within the range of the global models. One exception is the efficiency of advanced CC power plants assumed in China's IPAC model. To summarize, quite a wide gap of conversion efficiencies across IAMs exists, roughly ranging from 45% to 60% for technology of combined cycle. However, to a good degree the range can be associated with the representation of different types of combined cycle plants in some IAMs.

4.4. Technology lifetime

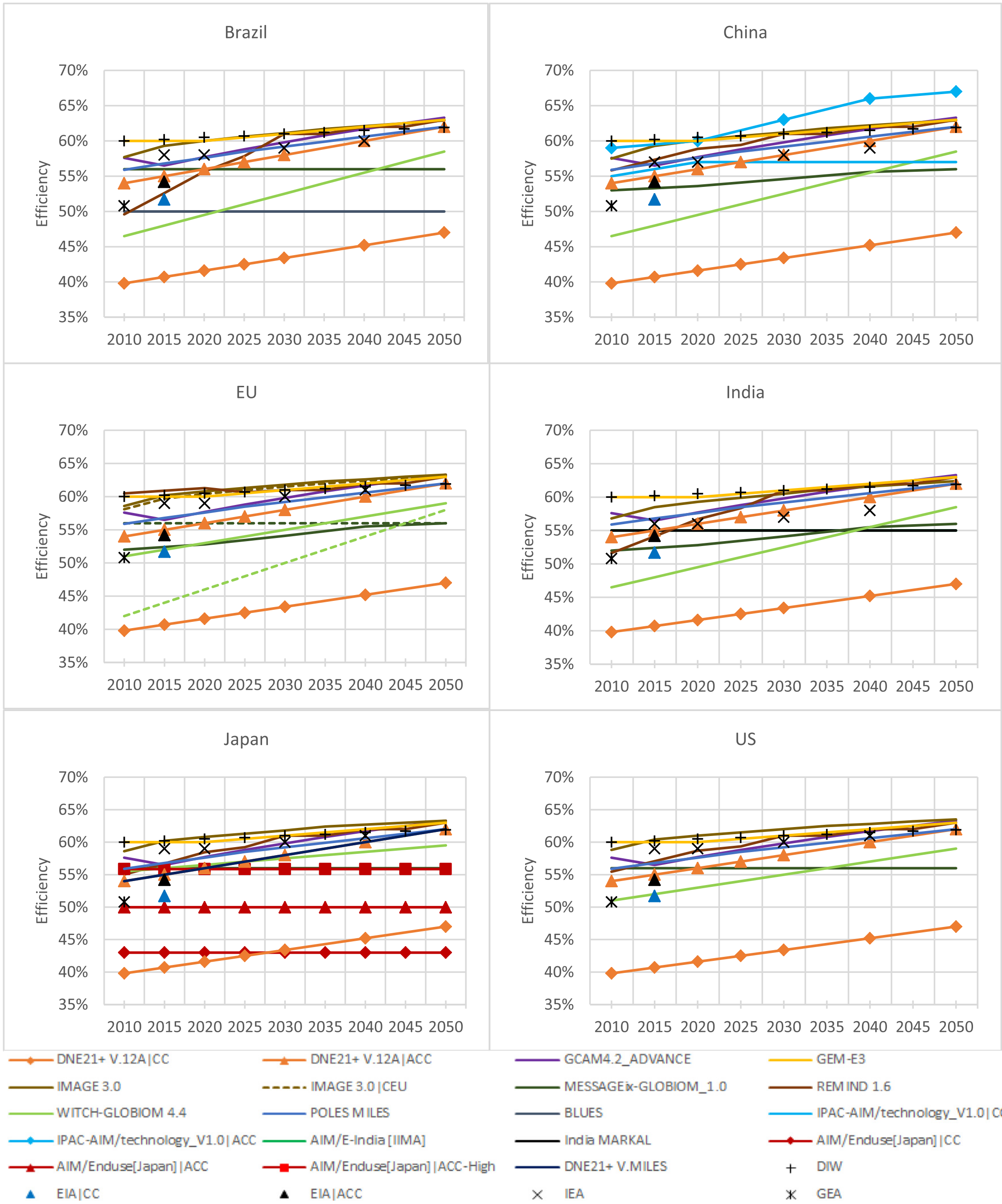
IAMs usually assume that the lifetime of a given technology does not change over time. The only exception is "POLES MILES" for the technology of biomass with CCS, assuming an increase of lifetime from 20 years in 2010 to 25 years in 2050.

Typically, the models explicitly track individual vintages of power plants. For most models, after the lifetime the capacity of certain technologies (e.g., power plants) falls to zero; in the model "GCAM4.2_ADVANCE" the existing stock is assumed to retire according to non-linear smooth functions over the lifetime; "DNE21 + V.12A" and "MESSAGEix-GLOBIOM_1.0" allow early shutdown of power plants.

Table 4 summarizes the lifetime of various electricity generating technologies across the reviewed IAMs. A wide spread of assumptions on technology lifetimes among these IAMs is observed. For instance, "GCAM4.2_ADVANCE" tends to assume a significantly longer technology lifetime than most of the other models. For combustion-based electricity generation technologies (i.e., coal, gas and biomass), "MESSAGEix-GLOBIOM_1.0" marks the lower end of the spectrum, assuming relatively shorter lifetimes, corresponding to only about two-fifth to two-thirds of those assumed by "GCAM4.2_ADVANCE". The lifetimes assumed in the national IAMs generally fall into the spread of lifetimes of the global models. In other words, there is no systematic difference in the assumed technology lifetimes between national and global IAMs.

The technology lifetimes assumed in global IAMs are usually kept constant across regions. The only exception is that of nuclear power plants assumed in "MESSAGEix-GLOBIOM_1.0" in which three different lifetimes (40/50/60 years) are assumed for its eleven regions, with longer lifetimes for developed regions and shorter for emerging economies and developing regions.

It is worth noting that, in some IAMs, different lifetimes are assumed for different technology variants, such as the gas power plants (with CCS) in the model of "REMIND 1.6", the gas (without CCS) and hydro power plants in the Brazil model "BLUES", and gas power plants (without CCS) and CSP in the "POLES MILES".



Note: 1) solid lines for the Western Europe and dotted lines for the Eastern Europe; 2) the conversion efficiencies of gas power plants assessed by IEA are gross efficiency (IEA, 2016).

Fig. 8. Conversion efficiency of gas combined cycle (CC) power plants in selected regions across IAMs.

Only six models include the geothermal power generation technologies, namely “GCAM4.2_ADVANCE”, “MESSAGEix-GLOBIOM_1.0”, “REMIND 1.6”, “POLES MILES”, “IPAC-AIM/technology_V1.0” and “AIM/Enduse[Japan]”.

4.5. Levelised cost

As mentioned before, some IAMs assume higher capital costs along with longer lifetimes (e.g., “GCAM4.2_ADVANCE”) compared to models with lower capital costs and shorter lifetimes (e.g., “MESSAGEix-GLOBIOM_1.0"). To take these partly counter-acting effects into account and thus allow for a comparison of competitiveness across IAMs, levelised cost of electricity (LCOE) – excluding fuel costs – is calculated for twelve power generating technologies, including coal IGCC and PC, gas combined cycle (CC), gas combustion turbine (CT), nuclear, biomass, Hydro, PV, CSP, wind offshore, wind onshore and geothermal.

To avoid confusion with the standard LCOE metric henceforth this metric will be referred to as “Levelized Capital and O&M costs of Electricity (LCOMCE)”. Fuel costs are excluded, because these

Table 4
Lifetime of electricity generation technologies across the IAMs.

IAMs		Electricity generation technologies											
		Coal		Gas		Biomass		PV	CSP	Wind	Nuclear	Hydro	Geo-thermal
		w/o CCS	CCS	w/o CCS	CCS	w/o CCS	CCS						
Global	DNE21 + V.12A	40	40	40	40	40	40	20	n/a	20	50	inf	n/a
	GCAM4.2_ADVANCE	60	60	45	45	60	60	30	30	30	60	inf	30
	GEM-E3	30/40[1]	30/40[1]	30	30	n/a	n/a	20	25	25	50	n/a	n/a
	IMAGE 3.0	40	40	40	40	40	40	25	25	25	60	80	n/a
	MESSAGEix-GLOBIOM_1.0	30	30	30	30	25/30[2]	25	30	30	20/30[1]	40/50/60[3]	60	30
	POLES MILES	30	30	25/30[1]	25	20/25[2]	20/25[2]	25	25/30[1]	20	40	50	30
	REMIND 1.6	40	40	30/35[1]	35	40	40	30	30	25	40	70	30
	WITCH-GLOBIOM 4.4	46	46	25	25	25	25	22	22	31	46	54	n/a
National	BLUES	40	40	25/30[1]	40	30	n/a	25	30	25	50	40/50/60[1]	n/a
	IPAC-AIM/technology_V1.0	35	35	30	30	30	30	25	25	25	50	50	30
	PRIMES_2015	30/40[1]	30/40[1]	30	30	n/a	n/a	20	25	25	50	n/a	n/a
	AIM/E-India [IIMA]	35	35	30	30	25	n/a	25	25	25	40	70	n/a
	India MARKAL	30	n/a	25	n/a	25	n/a	25	25	25	40	50	n/a
	AIM/Enduse[Japan]	40	40	40	40	40	40	20	20	20	40/60[1]	40	40
Lifetime range		30–60	30–60	25–45	25–45	20–60	20–60	20–30	20–30	20–31	40–60	40–80	30–40

Note: [1] varying by technology variants; [2] varying across time; [3] varying by regions. inf means that the lifetime of a technology for modeling purposes is unlimited.

have been shown to differ significantly across IAMs as well as across different scenarios (e.g., Ref. [32]). LCOMCE is calculated based on Equation (1) below [15]:

$$LCOMCE = \frac{\sum_{t=0}^{n}[(Capital_t + O\&M_t) \times (1+r)^{-t}]}{\sum_{t=1}^{n} 8760 \times CF_t \times (1+r)^{-t}} \quad (1)$$

where "$Capital_t$" and "$O\&M_t$" denote the capital cost and O&M cost of that technology in year "t" respectively, with a unit of "USD/kWe" (assuming constant annual O&M cost during the lifetime of a technology); CF_t is the capacity factor of that technology; "n" means the lifetime of a technology; "r" is discount rate, 5% in this study.

Figs. 9 and 10 show the calculated LCOMCE for PV and gas combined cycle (CC) technologies, respectively. In the calculation, the capacity factors reported by EIA [33] for the six regions were used for all models (see details in Appendix D). The calculated LCOMCE for the other power generating technologies are presented in Appendix D of this paper.

Two key observations are worth noting from the calculation of LCOMCE. First, the overall range of LCOMCE across all models is found to be smaller than their capital costs gaps (e.g. the range across the models "GCAM4.2_ADVANCE", "REMIND 1.6" and "MESSAGEix-GLOBIOM_1.0"). However, the calculated LCOMCE ranges are still quite wide. Using PV and gas combined cycle (CC) as examples, the highest value is roughly twice the lowest on average (except for the LCOMCE of advanced CC assumed in the "DNE21 + V.12A" model).

Second, there is also a significant gap of calculated LCOMCE among the selected technology assessments, namely the IEA [16,17], the EIA [31] and the DIW [18]. The LCOMCE obtained from the three references varies by a factor of about 2.8 for PV, and by a factor of about 1.5 for the technology of gas combined cycle. The wide range of techno-economic assumptions identified by these studies may explain to some extent the significant difference of such assumptions across the various IAMs.

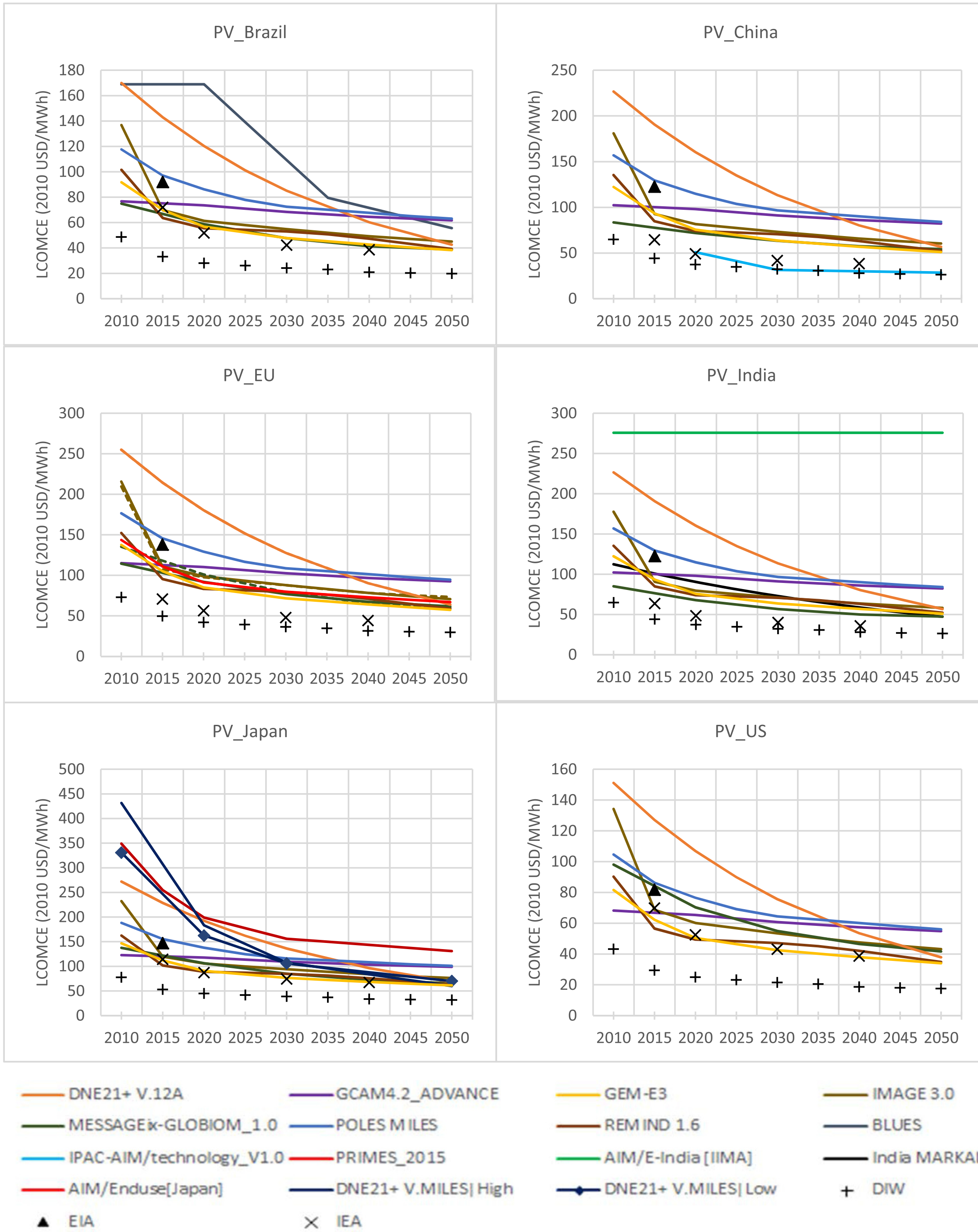
5. Summary and concluding remarks

A comprehensive comparison and analysis of technology representations and techno-economic assumptions for electricity generation technologies across fifteen selected global and national IAMs has been presented. The comparison includes capital cost, operating and maintenance (O&M) costs, conversion efficiency, lifetime and, as an aggregate quantity, Levelised Capital and O&M costs of Electricity (LCOMCE) of technologies. Regionally, six major economies, Brazil, China, the EU, India, Japan and the US, are distinguished which are all among the top ten GHG emitting regions in the world.

Large differences both in the structural representation of technology and its numerical parameterization across the national and global IAMs were found. At the same time, the review makes clear that just looking at the numbers is not enough, in particular when it comes to comparing assumptions across different models, as this may lead to wrong conclusions. In addition to the numbers, the rationale of projecting techno-economic parameters into the future is key to put the numbers into context and to enable a meaningful comparison across different IAMs.

Also, it is important to keep in mind that a certain technology in one model is not competing with technologies in other models, but with other technologies within the same model. Thus, the relative differences between different technologies in the same model are important for the decision making within the model, not the differences across models. In other words, if in one model technology costs are a factor of 2 lower compared to another model across the board, but the relative differences in costs across technologies are similar in both models, the resulting technology portfolios can actually be quite similar. Yet, the resulting total investments in the electricity sector would be different by a factor of 2 in such a situation if demand levels are similar.

When it comes to developing harmonized quantitative techno-economic assumptions across multiple models, caution should be exercised. First, the methods of projecting technological change are quite different across models which is in part related to the technology resolution of different models. For example, in some models efficiency of coal power plants changes while it does not in others. The latter case is often found in combination with representing different variants of the same technology (e.g., different steam cycle configurations of coal-fired power plants) such that the change in the shares of the different power plant types leads effectively to a change in the average efficiency. Similarly, costs are either assumed to be static or change over time. Therefore, a harmonized set of techno-economic assumptions would need to be customized to the representation of technology and the associated projection method used by a specific model. Second, given that cost and performance of one technology compared to other technologies is what matters in a model, taking into account the interaction of harmonized

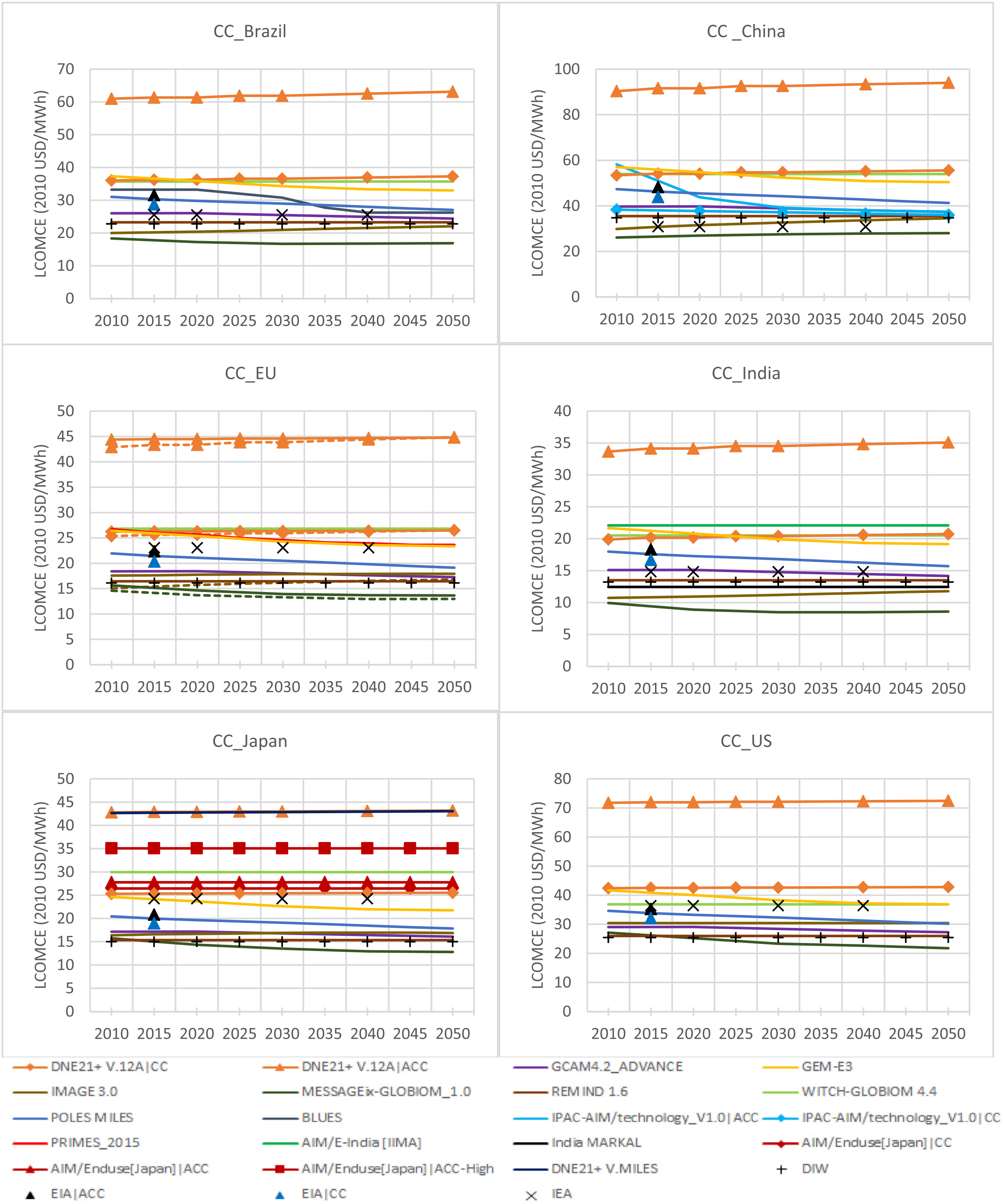


Note: solid lines for the Western Europe and dot lines for the Eastern Europe.

Fig. 9. LCOMCE of PV power plants in selected regions across IAMs.

technologies with non-harmonized technologies is important. As an illustration, if techno-economic assumptions for power generation technologies should be harmonized, this will not only have an implication for the competition among power plants, but also between power plants and technologies that use electricity and the associated electricity saving measures. Thus, if cost and performance of power plants is adjusted substantially, a sizeable effect on the deployment of (possibly non-harmonized) energy efficiency options might be found.

From a practical perspective, developing qualitative or semi-quantitative guidelines on the direction of technological change is a useful direction to take. Such an approach was chosen in the so-called Shared Socio-economic Pathways (SSPs) with qualitative tables providing guidance on the development of technologies in different parts of the energy and also land-use system (see supplementary material of Riahi et al. [34]). Going beyond this qualitative approach by providing indicative quantitative information to reduce the ambiguity of interpreting the qualitative



Note: solid lines for the Western Europe and dot lines for the Eastern Europe

Fig. 10. LCOMCE of gas combined cycle (CC) power plants in selected regions across IAMs.

guidance is a useful extension to consider.

Therefore, publishing techno-economic parameters together with documentation of the technology representation as well as the exact definitions of the parameters will allow an open discussion of these assumptions. The latter seems particularly relevant for improving comparability of assumptions across national and global IAMs. On the one hand, including a regional differentiation of techno-economic parameters that better reflects national circumstances at present will improve realism of global IAMs. On the other hand, energy technologies are rarely developed and deployed at scale in single countries in isolation. Therefore, it is valuable for national modeling teams to connect the development of assumptions into the future to global storylines and scenario analyses that reflect the international dimension of technology development and diffusion.

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2018.12.131.

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