

A Multisectoral Dynamic Model for Energy, Economic, and Climate Scenario Analysis

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How to cite this paper: Chen, Y.-H. H., Paltsev, S., Gurgel, A., Reilly, J. M., & Morris, J. (2022). A Multisectoral Dynamic Model for Energy, Economic, and Climate Scenario Analysis. *Low Carbon Economy*, 13, 70-111.

<https://doi.org/10.4236/lce.2022.132005>

Received: March 14, 2022

Accepted: June 27, 2022

Published: June 30, 2022

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Abstract

The MIT Economic Projection and Policy Analysis (EPPA) model has been widely used in energy, land use, technology, and climate policy studies. Here, we provide details of revisions that form the basis of EPPA7, the current version. Key updates include: 1) using the latest Global Trade Analysis Project (GTAP-power) database as the core economic data for the world economy; 2) updating regional economic growth projections; 3) separating extant and vintage capital of the previously aggregated fossil generation; 4) using an innovative approach to calculate the costs of backstop (i.e., advanced) power generation options based on engineering data from the Energy Information Administration; 5) identifying base year biofuel output from existing sectors; and 6) re-parameterizing electric vehicles based on recent studies. Our simulations demonstrate that with widespread mitigation policies worldwide, regions relying heavily on fossil fuel imports benefit from lower global fossil fuel prices when their domestic emissions targets are lenient, but the benefits dissipate when deeper emissions cuts are imposed domestically. We also provide an illustration how the model output can be used to calculate the net present values of unrealized fossil fuel production and stranded assets from idling coal power generation under various policy scenarios.

Keywords

Economy-Wide Modeling, Climate Scenario, Stranded Assets

1. Introduction

In this paper, we introduce the MIT Economic Projection and Policy Analysis (EPPA) modeling framework, and provide details on updates done for EPPA7, the latest model version. We also present a scenario exercise illustrating some of the capabilities of the model. EPPA projects the world as 18 regional trading

economies, each with 22 sectors (including 9 subsectors for the power sector), and 4 primary factors.¹ It is a dynamic computable general equilibrium (CGE) model that includes savings, investment, population growth, and the evolution of vintaged capital stocks, with particular detail on advanced energy technologies. EPPA tracks the physical flows of energy, air pollutant emissions, and land use and land use change. The model has been widely used in assessing potential impacts of various energy or climate policy proposals.

As a human system model, EPPA can be run independently, and when combined with the MIT Earth System Model (MESM), the two models constitute the key components of the MIT Integrated Global System Modeling (IGSM) framework for climate scenario analyses. The EPPA model framework has also served as a starting point for adding new features or greater detail for special studies. Examples include more detail on technologies or activities, such as household transportation, biofuels, land-use change, and details on refined oil sector and aviation sector (Karpplus, 2011; Gurgel et al., 2007; Choumert et al., 2006; Ramberg & Chen, 2015; Gillespie, 2011). Other project-specific extensions include valuing health impacts from pollution and climate damages in agriculture (Selin et al., 2009; Wang, 2005).

The earliest version of the model, EPPA1 (Yang et al., 1996), was derived from the GeneRal Equilibrium ENvironmental (GREEN) model (Burniaux et al., 1992; Lee et al., 1994). The key departure of EPPA1 from GREEN is that, unlike GREEN, which was coded in C with the solution algorithm being part of the model, EPPA1 was formulated in GAMS and solved by the PATH solver. Under the GAMS platform, the static structure of the model was written in MPSGE (Rutherford, 1994), a subsystem of GAMS that simplifies the effort of building a CGE model. A refined version of the model was presented as EPPA2, with more details for backstop technologies and revised energy sector production functions (Prinn et al., 1998; Webster, 2000).

In EPPA3, Babiker et al. (2001) adopted the Global Trade Analysis Project (GTAP) data base, which has the advantage of being regularly updated. The revision brought the model's base year from 1985 to 1995. In addition, the production and consumption structures, resource module, savings, investment and model parameterization were revised. EPPA4 (Paltsev et al., 2005) used GTAP data for 1997, and, compared with its predecessor, had greater regional and sectoral details, more backstop technology options, improved ability to represent distinct policies, and enhanced treatment for physical stocks, energy flows, and emissions. EPPA5 (Paltsev et al., 2010; Chen et al., 2017) adopted the GTAP data for 2004. A land use change module, private vehicles detail, bioenergy production, and a revised power sector representation were incorporated. Chen et al. (2016) developed EPPA6 using the GTAP data for 2007. New features included non-homothetic preferences, a revised capital vintaging structure, and the potential for total factor productivity improvement.

¹Details for the model's regions, sectors, and primary factors are presented in Appendix A1, A2, and A3, respectively.

Among the updates in EPPA7, the core data are from the latest GTAP-power database with a base year of 2014. Other key revisions are: 1) retaining the GTAP representation of government production of goods and services that include energy use, whereas previously government was treated as a pure transfer, collecting taxes and distributing funds to the household; 2) with more significant use of wind and solar, representing these as extant technologies used in the base year, whereas previously they only entered as backstop technologies; 3) improving the representation for integrating wind and solar with dispatchable generation; 4) recalibrating energy flows based on International Energy Agency (IEA) data; 5) identifying the base year biofuels outputs from existing sectors; 6) using an innovative approach to calculate the markups and cost structure of backstop technologies; and 7) updating EV parameterization and modeling. Our study combines the elaboration of model updates and improvement with analyses for projections for a broad spectrum of variables. The arrangement makes it feasible for readers to comprehend the model response based on settings, parameterization, and structure behind the scenes. Details for the structural improvement of the model are described in Section 2, including the base settings for major parameters. A discussion of data updates is provided in Section 3. Section 4 offers a scenario analysis exercise illustrating some of the capabilities of the model. We consider several global climate mitigation scenarios and analyze simulation results for emissions, the energy mix, economic outcomes, land-use changes, and stranded assets due to climate policies. A concluding remark is provided in Section 5.

2. Model

EPPA7 is a recursive dynamic CGE model that is used to generate scenarios of economic variables, energy production and consumption, greenhouse gases (GHGs), aerosols, and other air pollutants emissions from human activities, and land use change. The basic structure of EPPA7 remains similar to its predecessors. To make available a comprehensive documentation of the current model in one document, with some revisions, we borrow extensively from [Chen et al. \(2016\)](#) for the settings that are unchanged, and add discussion on improvements in the current version of the model.

2.1. Static Component

In each region of the model, there are three types of agents: a representative household, producers, and a government. The household owns primary factors (labor, capital, and natural resources), provides them to producers, receives income (wages, capital earnings and resource rents) in return, pays taxes to the government and receives net transfers from it, and in EPPA7 the government produces services that entail the use of energy. The representative household in each region allocates income between consumption and savings.

Producers (production sectors) convert primary factors and intermediate in-

puts into goods and services, sell them to other domestic or foreign producers, households, or governments, and receive payments accordingly. Each producer maximizes profits by choosing its output level, and under the given technology and market prices—a cost-minimizing input bundle. Production functions for each sector describe technical substitution possibilities and requirements.

In addition to collecting taxes to finance transfer and government expenditure, the government can be viewed as a production sector that takes goods and services it purchases as inputs to produce an aggregated government output—a public good that includes defense, policing, regulatory enforcement, and such. For simplicity, we do not endogenously model the demand for public good, and instead we assume that the representative household exogenously allocates part of the income for acquiring the public good, as in previous versions of EPPA. Besides, in earlier versions of EPPA, the government's energy use is reassigned to other sectors by a rebalancing procedure. In EPPA7, the government's consumption for energy, both in monetary and physical units, are directly from GTAP, and as a result no rebalancing is needed.

As characterized in MPSGE, activities of agents and their interactions in a CGE model are summarized by three conditions: 1) zero-profits; 2) market-clearance; and 3) income-balance. A zero-profit condition expressed in the Mixed Complementarity Problem (MCP) format is:

$$MC - MB \geq 0; Q \geq 0; [MC - MB] \cdot Q = 0 \quad (1)$$

For instance, if a zero-profit condition is applied on a production activity, then if the equilibrium output $Q > 0$, the marginal cost MC must equal the marginal benefit MB , and if $MC > MB$ in equilibrium, the producer has no incentive to produce. Lastly, $MC < MB$ is not an equilibrium since Q will increase until $MC = MB$. Other activities such as investment, imports, exports, commodity aggregation modeled using the Armington assumption (Armington, 1969) and utility maximization have their own zero-profit conditions.

For each market-clearing condition, the price level is determined based on market demand and supply. A typical market-clearing condition in MCP format is:

$$S \geq D; P \geq 0; [S - D] \cdot P = 0 \quad (2)$$

The market-clearing condition states that for each market, if there is a positive equilibrium price P , then P must equalize supply S and demand D . If $S > D$ in equilibrium, the commodity price is zero. Similarly, in Condition (2), $S < D$ is not an equilibrium because in this case, P will continue to increase until the market is clear ($S = D$).

Income-balance conditions specify income levels of household and government that support their spending levels. A typical income-balance condition in MCP format is:

$$E \geq I; E \geq 0; [E - I] \cdot E = 0 \quad (3)$$

The expenditure E equals income I always holds in CGE models. Another important feature of general equilibrium is that only relative prices matter—meaning that the overall price level is not determined. Hence, it requires that a numeraire good be chosen, whose price is set to unity. In EPPA, utility for the U.S. is chosen as the numeraire good, so all other prices are measured relative to it.

2.2. Preferences and Technologies

Many CGE models, including EPPA, use nested Constant Elasticity of Substitution (CES) functions with various inputs to specify preferences and production technologies. CES functions are constant return to scale, which means if all inputs are doubled, the output will be doubled as well. As in EPPA6, we adopt the Stone-Geary preference with a time-varying shift parameter (a.k.a. “subsistence consumption”) to overcome this limitation. Specifically, we calibrate the income elasticities for the final demand of crop, livestock, food, and transportation (including public and private transportation) based on empirical evidence (Reimer & Hertel, 2004; Kishimoto, 2018). A caveat for this treatment is that the consumer’s preference is changed periodically when the shift parameter is recalibrated, which implies the equivalent variation can only be used for measuring the within-period welfare change. More details are presented in Appendix A4 for interested readers. **Figure 1** presents the structure of the expenditure function that characterizes the preference of the representative household. In **Figure 1** and similar figures that follow, “ P_x ” denotes the price index of x , and a CES nest with dashed lines denotes a separate CES function.

The production technologies of EPPA7 remain mostly the same as those of EPPA6, with the exception of power sector and household transportation. In previous versions of EPPA, backstop (i.e., advanced) fossil fuel generation was represented as a single technology, in which gas, oil and coal could be substituted. To provide greater flexibility in the power sector representation, each subsector of power generation now has its own separate vintaged cost function. The subsectors include: coal-fired, gas-fired, oil-fired, nuclear, hydro, wind, solar, other (bio-electricity, geo-thermal, etc.), and transmission and distribution. Note that while renewables (wind and solar) are treated as backstop generation options in previous versions of EPPA, they are now identified in the current GTAP-power database no longer regarded as backstop technologies in EPPA7.

The way non-dispatchable generations (wind and solar) are integrated with dispatchable one is also updated. In the current model, a CES aggregation combines wind and the aggregate of dispatchable generation first, and then another upper nest CES aggregation adds solar into the aggregation (**Figure 2**). Now that transmission and distribution (T&D) is identified explicitly in the GTAP-power dataset, it is treated as a required input that grows proportionally with total domestic electricity output. To represent this relationship, we adopt a nest of Leontief cost function between the cost of T&D input and the cost of generation (**Figure 2**).

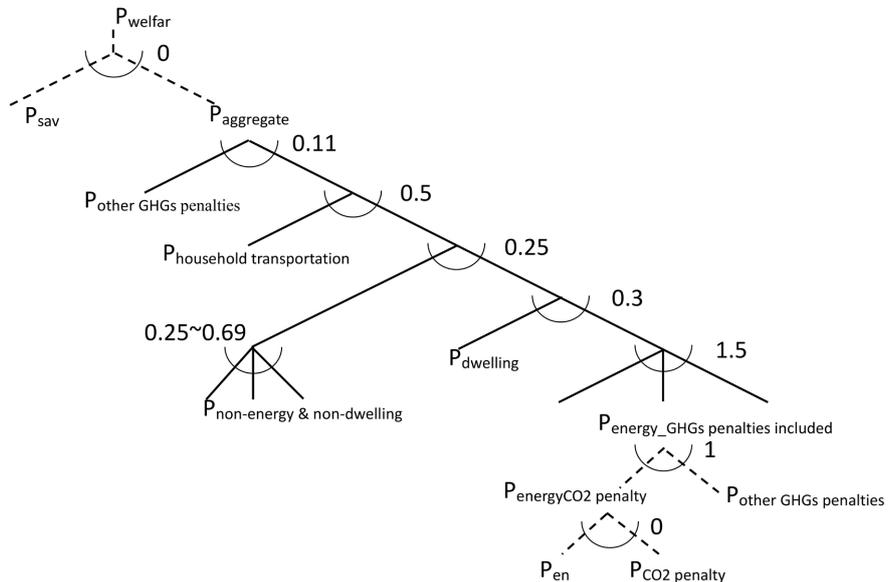


Figure 1. The expenditure function structure. Source: authors’ own elaboration.

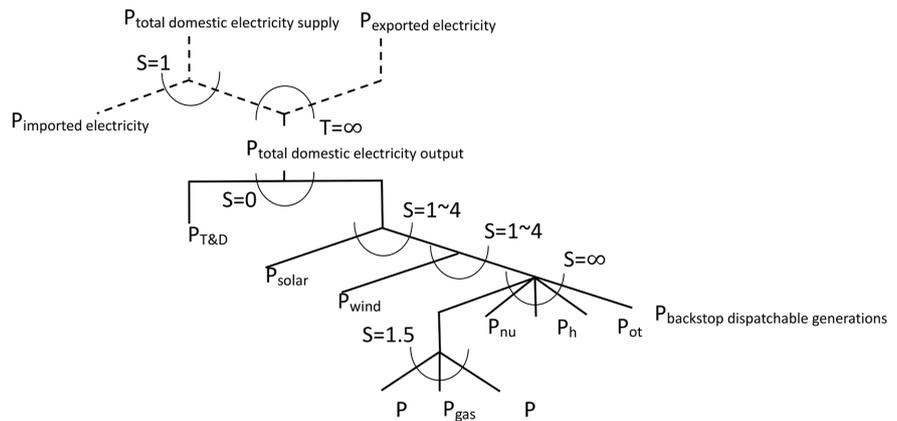


Figure 2. The cost function structure for power sector aggregation. Source: authors’ own elaboration.

Another revision of the production technology is in household transportation, which is based on [Ghandi and Paltsev \(2019\)](#). To better represent the role of EVs, Ghandi and Paltsev considers the case where 80% of light duty vehicles (LDVs) powered by internal combusted engine (ICE) can be easily replaced by some EVs (e.g., extended-range EVs, denoted by EV2s in [Figure 3](#)). ICE LDVs of this type are denoted as “replaceable ICE LDVs”. The rest of ICE LDVs that are less likely to be electrified are called “necessary ICE LDVs”. Ghandi and Paltsev also consider part of EVs that are imperfect substitutes to the replaceable ICE LDVs (denoted by EV1s in [Figure 3](#)).

Minor departures from [Ghandi and Paltsev \(2019\)](#) are: 1) they put the combination of replaceable ICE LDVs and EVs (the combination is called “alternative LDVs”), necessary ICE LDVs, and public transport within the same CES function with a low substitution elasticity. To represent the ongoing technology and infrastructure improvement that facilitates the electrification of household

transportation under more aggressive policies, we aggregate the alternative LDVs and necessary ICE LDVs within the same CES nest with a higher substitution elasticity first (the combination is called “private transport”), and then combine the private transport and public transport together also with a higher substitution elasticity (**Figure 3**); 2) for simplification, we do not consider plug-in hybrid vehicles explicitly, as currently targets to phase out vehicles with ICEs and introduce EVs are more prevalent, and EVs are more likely to dominate under aggressive policies (MIT Energy Initiative, 2019). With that, exploring the roles of plug-in hybrid vehicles could still be included in the next phase of model development.

The services of both replaceable and necessary ICE LDVs are outputs of a production technology, as in Ghandi and Paltsev (2019). The two outputs are combined together through a constant elasticity of transformation (CET) function. On the other hand, inputs of this production technology are services of new and vintage vehicles. The structure for the cost function of this production technology is presented in **Figure 4**. Production technologies for the services of new and vintage ICE vehicles, as well as various types of EVs, are similar to Ghandi and Paltsev (2019).

Production structures for other sectors are provided in Appendix A5. As in previous versions of the model, although factor substitution in response to change in relative price is possible for production activities using malleable capital, input shares are fixed for production activities using non-malleable capital. Besides, while intermediate inputs of the food sector are modeled by a Leontief structure, we update the food sector input shares such that the percentage changes of crops and livestock inputs are represented by the percentage changes of final consumption levels for crops and livestock products, to better capture dietary changes as incomes rise.

2.3. Social Accounting Matrix

To have a clearer mapping between the three fundamental conditions of a CGE model, Rutherford (1999) proposed an alternative SAM representation with the format of a micro-consistent matrix. In this format, each column of the SAM characterizes the zero-profit condition of an activity (Condition 1 in Section 2.1), except for the last column which is the income-balance condition of the economy (Condition 3 in Section 2.1). On the other hand, each row of the SAM corresponds to a market-clearing condition (Condition 2 in Section 2.1).

Specifically, for each column except for the rightmost one, the dark gray cell in **Figure 5** denotes the base year output value (i.e., price times quantity) of each activity, while cells in light gray are input value of each activity. For the rightmost column, the dark gray cells denote the endowment values of the household (i.e., the representative consumer), while the light gray cells are values of expenditure on aggregate consumption plus savings and government output (public good). In contrast, for each row, the dark gray cell denotes the value of supply in a market, and the light gray ones are for the values of demand in that market.

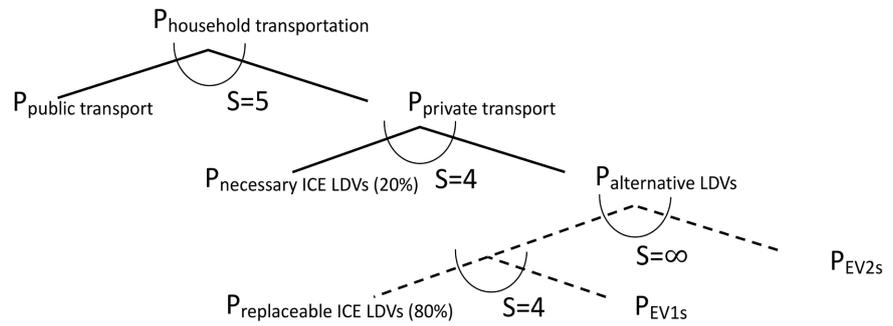


Figure 3. The cost function structure for household transportation aggregation. Source: authors’ own elaboration.

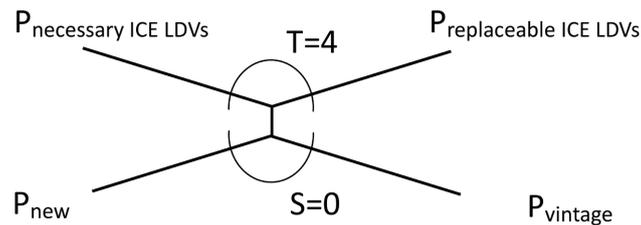


Figure 4. The cost function structure for ICE LDVs. Source: authors’ own elaboration.

		1	2	3	4	5	6	7	8	9	10	11
		D	INV	YT	HTRN	EID	A	M	Z	W	GOVT	RA
1	PD	■										
2	PINV		■									
3	PT			■								
4	PTRN				■							
5	PAL_C					■						
6	PA						■					
7	PM							■				
8	PU								■			
9	PW									■		
10	PL											■
11	PK											■
12	PF											■
13	PG											■
14	PCARB											■
15	PLCARB											■
16	TAX											■

Figure 5. The SAM structure of EPPA7. Source: authors’ own elaboration.

The row names and column names of **Figure 5** are variables for price indices (explained in **Table 1**) and activity levels (see **Table 2**) of the model, respectively. For simplicity, sectorial and regional indices of each variable are dropped. Note that variables shown in **Figure 5** do not constitute an exhaustive list of all variables in the model—they can be, nevertheless, regarded as “key variables” that are instrumental in understanding the model structure. Readers may refer to Appendix A6 for the SAM with greater details of price and activity variables.

Table 1. Price variables (market names) presented in the SAM.

Notation	Definition	Notation	Definition
PD	Price index for domestic production	PW	Price index for welfare
PINV	Price index for investment	PL	Price index for labor input
PT	Price index for international transport	PK	Price index for capital input
PTRN	Price index for aggregate household transport	PF	Price index for fixed factor
PAI_C	Price index: energy input (CO ₂ penalty included)	PG	Price index: aggregate government expenditure
PA	Price index for Armington good	PCARB	Price index for carbon emissions
PM	Price index for import	PLCARB	Price index: carbon emissions land-use change
PU	Price index for aggregate consumption	TAX	Tax revenues

Source: author's own elaboration

Table 2. Activity variables presented in the SAM.

Notation	Definition	Notation	Definition
D	Activity level for domestic production	M	Activity level for import
INV	Activity level for investment	Z	Activity level for aggregate consumption
YT	Activity level for international transport	W	Activity level for welfare
HTRN	Activity level for aggregate household transport	GOVT	Activity level: total government expenditure
EID	Activity level for energy input (w/ CO ₂ penalty)	RA	Income of the representative consumer
A	Activity level for Armington good production		

Source: authors' own elaboration.

For illustrative purposes, let us look at column 1 in **Figure 5**, which corresponds to the zero-profit condition of domestic production and is used to parameterize the associated cost function. The column demonstrates that in equilibrium with a positive output, the value of domestic output is equal to the sum for the values of energy inputs, non-energy inputs, labor input, capital input, fixed factor input, CO₂ penalty (if CO₂ mitigation policies are in place), and tax

revenues. On the other hand, row 1 in **Figure 5** can be mapped to the market clearing condition for domestic production: in equilibrium with a positive supply, the domestic output is either sold domestically or exported, and therefore the value of domestic output equals the sum for the values of domestic and foreign sales.² Based on **Figure 5**, zero-profit conditions of other activities and market clearing conditions of alternative markets can be derived and explained in a similar fashion.

Besides, governments in our model are treated as passive entities that solely collect taxes to finance their expenditures and transfers. Therefore, as the market clearing condition for the aggregate government expenditure (see row 15 in **Figure 5**) shows, the aggregate government expenditure constitutes a “sink” of the income balance condition (column 13 in **Figure 5**), i.e., the sum for the values of the representative consumer’s endowments (labor, capital, fixed factor, and total tax revenues) are used to pay for the welfare and aggregate government expenditure.

2.4. Dynamic Component

The recursive dynamic setting of the model means that production, consumption, savings and investment in each period are determined by prices in that period, with the model solving every 5 years from 2015 onward. The dynamics of EPPA7 are determined by both exogenous and endogenous factors. Exogenous factors include labor endowment growth, factor-augmented productivity growth, autonomous energy efficiency improvement (AEEI), and the initial endowments of capital and natural resources (see Section 3 for details). Dynamics determined endogenously include savings, investment, fossil fuel resource depletion, and penetration rates of backstop technologies.

With regard to exogenous factors, for each region, we assume that the labor endowment increases proportionally to population growth. In the BAU, we target an exogenous GDP growth profile and solve for the proportional factor-augmented productivity growth (i.e. Hicks-neutral) that produces the targeted growth. As the previous version of EPPA, we include a 1% per year of AEEI improvement for all other sectors except for the power sector, and assume a 0.3% per year of AEEI improvement for power sector. Details for the AEEI parameterization of EPPA are provided in [Paltsev et al. \(2005\)](#).

Per those endogenous factors, as in previous versions of EPPA, savings and consumption are aggregated as a Leontief fashion in the household’s utility function, making savings a constant share of income. All savings are used as investment, which meets the demand for capital goods. The capital is divided into a malleable portion KM_t , and a vintage non-malleable portion $V_{n,t}$, where $n = \{5, 10, 15, 20\}$ represents n -year old vintage. $V_{n,t}$ is sector specific, and while factor substitution in response to change in relative price is possible for the

²For the transportation sector it also supplies its output to international transport (denoted by YT in **Figure 5**).

malleable portion, it is not possible for the non-malleable portion. Let us formulate the dynamics of the malleable capital, which can be described by:

$$KM_t = INV_{t-1} + (1-\theta)(1-\delta)^\tau KM_{t-1} \quad (4)$$

In Equation (4), θ is the fraction of the malleable capital that becomes non-malleable at the end of period $t-1$, and INV_{t-1} and δ are the investment and depreciation rate, respectively. The factor of τ represents the years covered by each period ($\tau=5$ from 2015 onward). The newly formed non-malleable capital $V_{5,t}$ comes from a portion of the survived malleable capital from the previous period:

$$V_{5,t} = \theta(1-\delta)^\tau KM_{t-1} \quad (5)$$

We consider the case where part of the vintage capital has a remaining lifespan of 20 years, and the rest (e.g. the capital in power sector) can survive longer. As [Chen et al. \(2016\)](#), we assume that physical productivity of installed vintage capital does not depreciate until it reaches the final vintage. This reflects an assumption that, once in place, a physical plant can continue to produce the same level of output without further investment. We combine this with the assumption that malleable capital depreciates continuously. Hence a physical plant can be considered to be part vintage and part malleable, with the needed updates and replacement (short of the long-term replacement of a plant) accounted in the depreciation of malleable capital.³ This process can be described by:

$$V_{10,t+1} = V_{5,t}; V_{15,t+2} = V_{10,t+1}; V_{20,t+3} = V_{15,t+2} + (1-\delta)^\tau V_{20,t+2} \quad (6)$$

In the above setting, $V_{20,t+3}$ comes not only from $V_{15,t+2}$ but also from $(1-\delta)^\tau V_{20,t+2}$, which is the survived vintage capital beyond 20 years old, i.e., $V_{20,t+3}$ represents the sum of vintage capital stocks that are at least 20 years old. The advantage of this formulation is that we effectively extend the life to capital without the need to create in the model more vintages of capital types. Extra vintages add significantly to model complexity. We retain the formulation that in any given period t , there are always only four classes of vintage capital $V_{5,t}$, $V_{10,t}$, $V_{15,t}$, and $V_{20,t}$ but the effective lifetime of capital is 25 years (the 5-year life of the initial malleable stock, plus the 5-year time step for each of the four explicit vintages) plus the half life of the final vintage.⁴

To capture the long-run dynamics of fossil fuel prices, fossil fuel resources $R_{e,t}$ are subject to depletion based on their annual production levels $R_{e,t}$ at period t . Values of $R_{e,t}$ are then multiplied by a factor of five to approximate depletion in intervening years, to align with the five-year time step:

³This is a heuristic explanation. Malleable capital can be redeployed anywhere in the economy, but a long-lived investment such as a power plant structure or factory building that may last for 30, 40, 50 years or more requires various additional investment over that period to remain functional. The formulation used here simplifies reality to retain computational feasibility while capturing the essence of capital lock-in, with the need for ongoing maintenance investment. In an equilibrium solution, the rental price of old capital may fall to zero, implying that it is not used, or is only partly used (see [Morris et al., 2014](#) for a discussion and example simulations).

⁴The half-life with an annual depreciation rate of 5% used in EPPA is around 15 years.

$$R_{e,t+1} = R_{e,t} - 5F_{e,t} \quad (7)$$

As previous versions of the model, EPPA7 adopts the “technology-specific factor” (Morris et al., 2019) to model the penetration of a backstop technology. The idea is to use a theoretical-based formulation that can capture key observations of technology penetration (gradual penetration, falling costs, etc.), and is parameterized based on empirical evidence. The factor is required to operate the backstop technology, but may only be available in limited supply—especially when the technology is in its earlier stage of introduction. The resource rent of the technology-specific factor goes to the representative household, which is the owner of that factor.

For a given backstop technology, the formulation for the factor is:

$$bbres_{t+1} = \alpha \cdot [bout_t - \gamma \cdot bout_{t-1}] + \gamma \cdot bbres_t \quad (8)$$

In Equation (8), $bbres_t$ is the supply of technology-specific factor for the considered backstop technology in period t , $bout_t$ is the output of that backstop technology for the same period, and $\gamma = (1 - \delta)^5$, where the annual depreciation rate $\delta = 0.05$. The estimate of α (1.064) is from Morris et al. (2019). Morris et al. also specifies a value of 0.3 for the benchmark substitution elasticity between the technology-specific factor and other inputs, which is also adopted in our model.

2.5. Modeling for Land-Use Changes

Explicit modeling of land use that maintains consistent supplemental physical accounts of land is a unique feature of our model. The approach considers five broad land use categories: crop, pasture, managed forest, natural forest and natural grass. In EPPA7, we represent land and model the transformation of natural lands (natural forest and natural grass) to managed land types (crop, pasture, and managed forest) in physical terms. The model considers that land improvements (draining, tilling, fertilization, fencing) can convert pastureland to cropland, or forestland can be harvested, cleared and ultimately used as pastureland or cropland. If investment in cropland is not maintained, the land can then go back to a less intensely managed use (pasture, or managed forest) or be abandoned completely and return to natural grass or natural forest land.

The land use conversion approach in our model assures consistency between the physical land accounting and the economic accounting in the general equilibrium setting. It means that accounts “add up” in physical terms, which is not assured if land use changes are only considered in value terms in the CGE model. This modeling approach also assures consistency with observation as recorded in the CGE data base for the base year. Failure on this account would mean that the base year data would not be in equilibrium, so the model would immediately jump from the base year to the equilibrium state consistent with parameterization of land rents and conversion costs.

The physical consistency mentioned above is achieved by assuming that one

hectare of one type of land is converted to one hectare of another type, and through conversion it takes on the productivity level as the average for that type for that region. The conversion requires using real inputs through a land transformation function (Figure 6). The second consistency is achieved by observing that in equilibrium the marginal conversion cost of land from one type to another should be equal to the difference in value of the types.

The land use transformation approach adopted by our model is well suited to longer term analysis where demand for some land uses could expand substantially. It also explicitly represents conversion costs associated with preparing the soil, spreading seeds and managing the creation of a new agricultural system. In this regard, it is a better alternative than the more common Constant Elasticity of Transformation (CET) approach often used in CGE models. The CET function makes large transformations of land difficult because the function tends to preserve input shares (Gurgel et al., 2007). The CET approach also does not explicitly account for conversion costs. In addition, Schmitz et al. (2014) point out the lack of direct relationship to area in physical units, since land enters the CET function in value terms. As a result, there is no guarantee of consistent update of the supplemental physical accounts. Finally, as the CET elasticities are symmetric to all changes, the ease of conversion from agricultural to forest land is the same as from forest to agriculture, which implicitly assumes the same “costs” and constraints on conversion in both directions.

In the case of conversion of natural forests, the model also accounts for the production of timber products harvested from them (Figure 7). Natural areas transformation to agricultural areas are calibrated to mimic a land supply response, based on rates of conversion observed over the last two decades. This is done by adding a fixed factor with limited substitution possibilities in the conversion costs of natural areas in Figure 7. The observed land supply elasticity is captured by the equivalent elasticity of substitution between the fixed factor and other inputs. This last feature captures a variety of factors that may slow land conversion, including increasing costs associated with larger deforestation in a single period and institutional costs (such as limits on deforestation, public pressures for conservation, or establishment of conservation easements or land trusts).

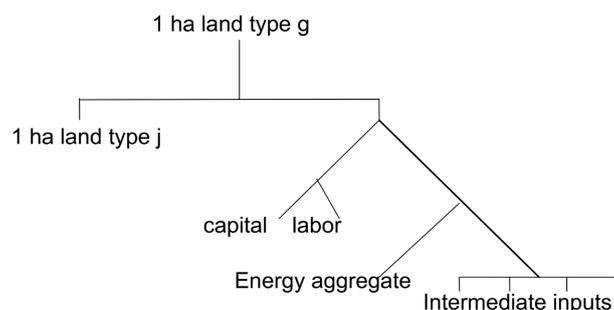


Figure 6. Structure of land transformation functions. Source: authors' own elaboration.

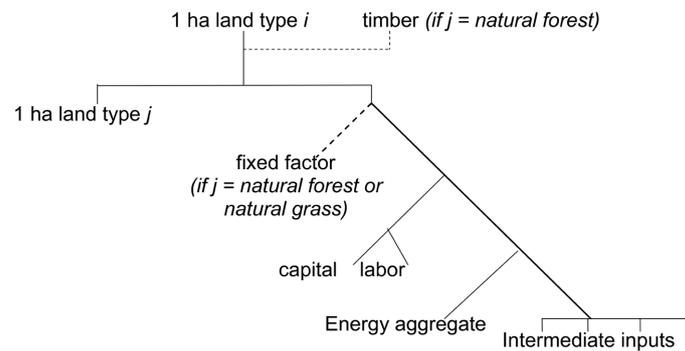


Figure 7. Structure of land transformation functions for conversion of natural forest. Source: authors' own elaboration.

We assume conversion costs from one land use category to another as equal to the difference in value of these types, assuring zero-profit conditions in the MCP equilibrium approach (see Section 2.1). One issue that arises is the current valuation of natural forest and grassland not currently used. Specifically, to appear in the CGE framework these land types must have an economic value. We develop a “non-use value” for these land areas using data from [Sohngen et al. \(2009\)](#) and [Sohngen \(2007\)](#). This approach assumes that, at the margin, the cost of access to remote timber land must equal the value of the standing timber stock plus that of future harvests as the forest regrows. The net present value of the land and timber is calculated using an optimal timber harvest model for each region of the world and for different timber types. Setting the access costs to this value establishes the equilibrium condition that observed current income flow (i.e. rent and returns) from currently non-accessible land is zero (because the timber there now and in the future can only be obtained by bearing the costs to access it equal to its discounted present value). From these data, we calculate the value of an average standing stock of timber for each of regions and the separate value of the land based on the discounted present value of future timber harvests.

The value of natural forest and natural grass areas are considered in the model as part of the initial endowment of households in each region. These areas may be converted to other uses or conserved in their natural state. The reservation value of natural lands enters each regional representative agent welfare function with an elasticity of substitution with other consumption goods and services. Hence, the value the agent derives from natural land itself, is a deterrent to conversion. Thus, if for example current timber demand rises and puts pressure on harvesting more land, it creates a partly offsetting demand to conserve forest area because, implicitly, the agent sees it as more valuable in the future. With the recursive dynamic structure, introducing the natural forest value into the representative agent's welfare function approximates this behavior. [Gurgel et al. \(2016\)](#) and [Chen et al. \(2017\)](#) provide more details about the land use modeling approach we use. Several applications of previous versions of EPPA employing the land use change approach are available in the literature, as in [Melillo et al. \(2009\)](#), [Gurgel et al. \(2011\)](#), [Reilly et al. \(2012\)](#), [Schmitz et al. \(2014\)](#), [Winchester and](#)

Reilly (2015), Calvin et al. (2016), Monier et al. (2018) and Gurgel et al. (2019).

Our model assumes that land is subject to an exogenous productivity improvement of 1% per year for each land type, reflecting assessments of potential productivity improvements showing similar historical crop yields growth albeit with variations among regions, crops and time (Reilly & Fuglie, 1998; Gitiaux et al., 2011; Ray et al., 2013). Besides exogenous yield changes, land can be partially substituted by inputs and other primary factors in the agricultural production functions as relative prices change over time.

3. Data

3.1. Core Economic Data

The core economic database for EPPA7 is GTAP-power 10, the latest GTAP database with power sector details and a base year of 2014. The database classifies the global economy into 140 regions, 76 sectors (including 12 power subsectors) and 8 types of production factors (Chepeliev, 2020). The database provides information such as the input-output structure and bilateral trade for every sector of each region. In reality, global CGE models are often run at more aggregated sectoral and regional levels for efficiency and model computational considerations. EPPA7 aggregates the GTAP database into 18 regions (see Appendix A1), 22 sectors (including 9 power subsectors; see Appendix A2), and 3 classes of factors (labor, capital, and natural resources that include various types of land and fossil fuels). The mapping details for regions, sectors, and production factors from GTAP-power 10 to EPPA7 are provided in Appendices A1 through A3.

Elasticities of substitution for various inputs are key parameters of CGE models as well. The elasticity specifies the extent to which one input can be substituted for by others under a given level of output when the relative price of inputs changes. For instance, the Armington aggregation for imported and domestic products is associated with the elasticity of substitution between imported and domestic products, and the elasticity controls the degree to which products differ. Another example is: in a production activity that uses fossil fuel and others as inputs, the substitution elasticity between fossil fuel and other inputs determines to what level the fossil fuel use can be replaced by other inputs if the price of fossil fuel increases.

Similarly, the elasticity of substitution in a utility function characterizes for a given utility level, the substitution possibility between various consumption goods when facing a price change. EPPA7 draws most elasticities of substitution from its predecessor (see Table 3), and those values are based on literature review (Cossa, 2004). There are a few substitution elasticities that are based on expert elicitation, including the substitution elasticities between electricity and other fossil fuel inputs, and the substitution elasticities between wind (and solar) power and other aggregated generation. Key parameters that may have a larger influence on projections for energy use, combusted emissions and emissions mitigation costs include elasticities of substitution between: 1) energy (fossil energy

Table 3. Key substitution elasticities in EPPA7.

Type of substitution elasticity	Notation	Value	Source
between domestic and imported goods	sdm	1.0 - 3.0	Cossa (2004)
between imported goods	smm	0.5 - 5.0	Cossa (2004)
between energy and non-energy (labor-capital bundle) inputs	e_kl	0.6 - 1.0	Cossa (2004)
between labor and capital	l_k	1.0	Cossa (2004)
between electricity and fossil energy bundle for the aggregated energy	noe_el	1.5	Expert elicitation
between fossil energy inputs for the fossil energy bundle	esube	1.0	Cossa (2004)
between conventional fossil generations	enesta	1.5	Cossa (2004)
between natural resource and other inputs	esup	0.3 - 0.5	Cossa (2004)
between wind power and other aggregated generation	elas_w	1.0 - 4.0	Expert elicitation
between solar power and other aggregated generation	elas_s	1.0 - 4.0	Expert elicitation

Source: authors' own elaboration.

and electricity bundle) and non-energy (labor-capital bundle) inputs; and 2) electricity and fossil energy (see [Table 3](#) for details). The sensitivity of energy use, emissions, and abatement costs to values for these elasticities is discussed in [Chen et al. \(2016\)](#).

For a dynamic CGE applied to long-term projections, the inter-temporal calibration of regional BAU GDP growth is an important consideration. For this study, the regional BAU GDP growths up to 2050 are calibrated based on [OECD \(2020\)](#), by adjusting the total factor productivity levels.⁵ For years beyond 2050, the regional growths are determined by the assumption of a constant total factor productivity growth rate for each region, following the average growth rate of 2045 to 2050. Given the calibrated productivity levels, the regional GDP projections may change under policy runs in response to resource reallocations.

In addition, income elasticities for the final consumptions of CROP, LIVE, and FOOD up to 2020 are from [Chen et al., 2016](#), which updates income levels of an AIDADS demand system estimated by [Reimer and Hertel \(2004\)](#) to get updated income elasticities for recent years.⁶ For income elasticities beyond 2020, we assume that the income elasticity of CROP for each region will decrease exponentially to zero by 2050, and the income elasticities of LIVE and FOOD for each region will decrease by 0.25% in response to a 1% increase in BAU per ca-

⁵For Russia, the GDP growth projection presented in the World Energy Outlook ([IEA, 2020](#)) is adopted, since using OECD's projection (which is lower) results in decline in electricity output over time.

⁶The base year (i.e., 2014) income elasticities are interpolated from the income elasticity projection for 2010 and 2015 calculated in [Chen et al. \(2016\)](#).

pita GDP. Finally, the income elasticities for the demand of aggregate transportation (see Appendix A7) are drawn from [Ghandi and Paltsev \(2019\)](#).

3.2. Energy Data

Besides economic variables, EPPA7 also simulates evolutions of energy use, output and emissions. For tracking these flows, the base year energy use and output (in EJ or TWh) are mapped to the corresponding base year quantity indices (both are unity for the base year) of our model, so that those energy variables change proportionally to the aforementioned quantity indices in response to changes in the economy.

We draw the base year fossil energy use and electricity generation data from the World Energy Outlook ([IEA, 2016](#)), which provides data for 2014, the base year of our model. Where further regional disaggregation is needed, data from the World Energy Statistics and Balances ([IEA, 2019](#)) are used. For nuclear, hydro, and renewables (wind and solar), we impute the “fossil equivalent” energy use based on the electricity output and the average fossil generation thermal efficiency derived from [IEA \(2016\)](#). The base year data for commercial bioenergy are from [IEA \(2019\)](#), as the data are not available in the World Energy Outlook. Similarly, the use of commercial bioenergy (in EJ) in the base year is linked to the quantity index for the model’s bioenergy demand. Since the CGE models tracks market transactions, we need to identify commercial bioenergy in calibrating the model, but “non-commercial” bioenergy does not, by definition enter through markets. For comparison purposes, we often report a total biomass energy use by exogenously adding IEA’s forecast for noncommercial (traditional) bioenergy ([IEA, 2020](#)) to our projected figures for commercial bioenergy. The base year regional structure for primary energy use and electricity generation is presented in Appendix A7.

3.3. Advanced Power Generation Technologies

A major focus of our model is to produce decades-long projections under various decarbonization scenarios. The power sector, currently the largest CO₂ emitting source at the global level, accounts for more than 40% of fossil-related and process CO₂ emissions worldwide ([IEA, 2020](#)). Advanced low-carbon generation options (“backstop technologies” for the power sector) are not widely commercially deployed now but could become economic later, or under mitigation policies that put further limits fossil fuel generation options.

The GTAP-power database only presents power generation technologies that are being operated at commercial scale, including the current level of output and inputs. For calibrating power sector backstop technologies, we draw on engineering and cost data from [EIA \(2019\)](#), using base year regional fuel prices from GTAP-power (Appendix A8). As EIA data are for the U.S., we adjust the capital cost of each technology to reflect the regional cost difference, based on the power sector’s average capital return per KWh in each region provided in GTAP-power.

For an existing sector or technology in a typical CGE model, it is assumed that there is no excess profit derived from each sector's activity (see the zero-profit condition in Section 2.1), and so the value of inputs equals the value of output. To incorporate the costs of backstop technologies into the model, we pick up the generation option from [EIA \(2019\)](#) with the lowest levelized cost of electricity (LCOE) and benchmark that technology so that it meets a zero-profit condition, i.e., the output values of the least cost technology and other competing backstop technologies are benchmarked to the least cost technology's sum of input values, without revising the corresponding energy output and input levels in physical unit (e.g., EJ) provided by [EIA \(2019\)](#), and so that thermal efficiencies, if defined, remain the same as EIA's engineering data.

3.4. Emissions

One of the main applications of the EPPA model is to provide projections of emissions of GHGs and air pollutants, the critical outputs from coupling the model with the MIT Earth System Model (MESM) study issues such as global mean temperature rise. The GHGs emissions considered in EPPA7 are: CO₂, CH₄, N₂O, PFCs, HFCs, SF₆, and the air pollutants included are: CO, VOCs, NO_x, SO₂, BC, OC, and NH₃.

As with the energy data, the base year combusted CO₂ emissions (i.e., emissions from burning fossil fuels) are calibrated to [IEA \(2016\)](#), which provides the base year data. The process-based CO₂ emissions (emissions from industrial processes other than burning fossil fuels) are from [Our World in Data \(2022\)](#) and the CAIT database ([Climate Watch, 2021](#); [World Resources Institute, 2021](#)).

From the base year inventory data, we obtain an emissions coefficient per unit of each fuel combusted CO₂ emissions (without a captured and storage technology), applied to future levels of fuel combustion to determine future emissions. Emissions reductions are the result of substitution among fossil fuels and other inputs. Substituting from coal to gas, or from gas to electricity, or using more capital and other inputs to improve efficiency thus reduces emissions (e.g., using better insulation materials to reduce the need for heating in winter).

Process-based CO₂ emissions are associated mainly with outputs of cement, iron and steel, and chemical industries, which are included in the energy intensive sector of EPPA. When these emissions are priced due to emissions mitigation policies, the substitution possibility between the CO₂ penalty and other production inputs is considered to reflect the price-induced improvement in production processes in reducing emissions. In EPPA7, the aforementioned substitution possibility is parameterized by a substitution elasticity of unity.

We draw the base year non-CO₂ emissions from the GTAP satellite database ([Chepeliev, 2020](#)), whenever feasible, to facilitate the regional and sectoral emissions mappings. GHGs emissions that are drawn from the GTAP database include CH₄ and N₂O, and since the database aggregates different f-gases into a single source and does not include urban pollutants, we draw the latest emissions for PFC, HFC, SF₆ and urban pollutants identified in EPPA from the Emis-

sion Database for Global Atmospheric Research (EDGAR) (European Commission, 2013; 2016; 2019).

Finally, just like the consideration of AEEI in energy use can reflect the role of non-price driven energy efficiency improvement in reducing emissions of combusted CO₂ as time goes by, for other emissions (process CO₂, non-CO₂ GHGs, and urban pollutants), their emissions coefficients are reduced over time, following Chen et al. (2017), to capture reduction in emissions that are not caused by changes in shadow prices of emissions induced by mitigation policies.

3.5. Land-Use Data

We combine several world scale data sources to build the land use change approach in our model. Land use rents are provided by the GTAP database, while land cover and land use areas are obtained and reconciled from the GTAP 10 Land Use and Land Cover Database (Baldos & Corong, 2020), the FAO data, and the Terrestrial Ecosystem Model (Felzer et al., 2004). Table 4 presents the final land cover data at the base year in EPPA7.

Table 4. Land use by region in the benchmark (2014) in EPPA (in million hectares).

	Cropland	Pasture	Managed Forest	Natural Grass	Natural Forest	Other
AFR	277	503	179	358	448	1200
ANZ	33	210	19	143	115	274
ASI	41	0	7	3	39	28
BRA	63	96	61	75	433	107
CAN	38	4	35	16	312	492
CHN	135	200	36	193	172	218
EUR	118	64	74	45	77	113
IDZ	46	10	11	1	81	32
IND	169	3	37	7	34	47
JPN	5	0	5	0	20	7
KOR	2	0	1	0	5	2
LAM	81	178	71	104	303	239
MES	33	130	6	106	8	253
MEX	22	41	23	39	43	27
REA	84	84	20	70	84	144
ROE	88	171	18	102	26	111
RUS	123	20	70	73	745	606
USA	159	82	78	167	231	197

Sources: FAO, Baldos and Corong (2020), Felzer et al. (2004) (combined and reconciliated by authors).

4. Application

4.1. Scenarios

To present a model application, our first step is to construct a reference run, where only existing plans or targets on renewables (wind and solar), bio-electricity and nuclear power considered in IEA (2019) are included (see Appendix A10). Besides, the productivity shock due to the Covid-19 pandemic is also incorporated into our analysis, and biomass with CCS, a negative emissions power generation option, will not be technically available at a commercial scale until 2055 (Paltsev et al., 2021). Policy scenarios are set up with additional policies, measures or GHGs pricing exerted on top of the reference run for achieving proposed targets. We provide two sample policy synopses and conduct simulations up to 2050 for demonstration purposes: 1) *Paris Forever*, and 2) *Accelerated Actions*.

In the *Paris Forever* scenario, the 2020 to 2030 emissions or policy targets are encompassed based on those presented in countries' Nationally Determined Contributions (NDCs) submitted to the UN Framework Convention on Climate Change (UNFCCC) under the Paris Agreement. To achieve the targets, a set of policies and measures (PAMs) on power and transportation sectors are implemented comparable with Jacoby et al. (2017). Besides, PAMs on the use of fossil fuels are also adopted to represent efforts in the transition to a low carbon environment, similar to Paltsev et al. (2021), and PAMs on encouraging EVs are considered to represent current incentives in promoting EVs. Our assumption for PAMs is presented in Appendix A10.

In case the aforementioned PAMs are not enough in bringing down emissions to meet NDCs, GHGs emissions are priced on top of existing PAMs regionally to close the gap. Emissions are not traded internationally but can be traded between GHGs within a region. For years beyond 2030, it is assumed that countries in each region will abide by their 2030 targets through the end of the century. Our interpretation for the targets of this scenario is summarized in Table 5.

The goal of *Accelerated Actions* is to create a global emissions path that is consistent to the "1.5°C scenario."⁷ To achieve this, more aggressive targets are imposed, including new goals for 2030 that were announced in April 2021 (USA reduces by 50% - 52% relative to 2005 emission levels, CAN lowers 40% - 45% relative to 2005, JPN cuts 46% relative to 2013), and targets for other countries that are stricter than their current NDCs (Paltsev et al., 2021).

In this scenario, it is assumed that global GHGs emissions in 2030 are lower by around 20% compared with those of *Paris Forever*. For years beyond 2030, relative to 2005 levels, developed regions (USA, CAN, EUR, JPN, ANZ) cut their 2050 GHGs by 80%, while most of the other G20 regions (CHN, IND, BRA, RUS, MEX, KOR, IDZ) lessen their 2050 GHGs by 50%.⁸ For the rest of the world, AFR and REA achieve their 2015 GHGs levels in 2050, while other re-

⁷It refers to the scenario where the global surface mean temperature by the end of the century does not exceed 1.5°C above pre-industrial levels with a 50% probability. See Paltsev et al. (2021) for details.

⁸Exceptions are the reductions of IND and IDZ (30%), and RUS (40%).

gions reduce their GHGs in 2050 by 50% relative to 2015 levels. Targets for emissions cuts relative to the 2015 levels are presented in **Table 6**.

Table 5. NDCs and assumed performance in 2030.

Region	NDCs		2005 CO ₂ -e Mt or t/\$1000	Other Features	Expected CO ₂ -e
	Type/Base	Reduction			
USA	ABS 2005	26% - 28% by 2025	6600	Alternative 2030 target (announced April 2021) are tested in Accelerated Actions.	36% in 2030
EUR	ABS 1990	55% by 2030	5720 for EU-28 (1990)	EUR in EPPA includes EU-27 plus U.K., Croatia, Norway, Switzerland, Iceland and Liechtenstein. Alternative 2030 target (55% without offsets) is tested in Accelerated Actions.	45%
CAN	ABS 2005	30% by 2030	820	Mainly land use & forestry with 18% reduction in industrial. Alt. 2030 target (announced April 2021) tested in Accelerated Actions.	25%
JPN	ABS 2013	26% by 2030	1320 (2015)	2.5% LUCF. Nuclear = 20% - 22% of electric, solar/wind = 9%, also biomass. Assumes ITMOs. Target = 1.04b ton CO ₂ -e. Alt. 2030 target (announced April 2021) tested in Accelerated Actions.	26%
ANZ	ABS 2005	26% - 28% by 2030	596		20%
BRA	ABS 2005	37% by 2025	2.19	45% of primary energy renewable by 2030; LUCF down 41% 2005-12.	35%
CHN	CO ₂ INT 2005	60% - 65% by 2030	2.55	CO ₂ peak by 2030, Non-fossil 20% of primary energy.	55%
KOR	BAU	37% by 2030	NA		25%
IND	INT 2005	30% - 36% by 2030	2.29	2.5 - 3.0 b tons CO ₂ from forests. 40% non-fossil electric. Assumes un-specified financial assistance.	30%
IDZ	BAU	29% by 2030	NA	Role of LUCF (63% of current emissions) not clear. Industrial emissions increase.	30%
MEX	BAU	25% by 2030	NA	22% of CO ₂ , 51% of BC, Intensity reduction of 40% 2013-2030.	25%
RUS	ABS 1990	25% - 30% by 2030	3530	Reduction subject to “maximum accounting” from forests.	32%
ASI	BAU		NA	Malaysia 45% INT, Philippines 70% BAU, Singapore ABS 36%, Taiwan 50% BAU, Thailand 20% BAU.	10%
AFR	BAU		NA	Nigeria 45% BAU, South Africa 20% - 80% increase (ABS), limited information on other regions.	5%
MES	BAU		NA	Saudi & Kuwait actions only, Iran 15% BAU, UAE non-GHG actions	10%
LAM	BAU		NA	Argentina 15% BAU, Chile 35% INT, Peru 20% BAU, Colombia 20% BAU.	10%
REA	BAU		NA	Bangladesh 5% BAU, Pakistan reduction after unspecified peak, Sri Lanka 7% BAU, Myanmar & Nepal misc. actions.	10%
ROE	BAU		NA	Azerbaijan 13% BAU, Kazakhstan 15% 1990, Turkey 21% BAU, Ukraine 40% BAU.	10%

Sources: Paltsev et al. (2021); Jacoby et al. (2017); and Chai et al. (2019).

Table 6. Emissions reductions relative to the 2015 levels for *Accelerated Actions*.

	2020	2025	2030	2035	2040	2045	2050
USA	-10.4%	-32.4%	-48.0%	-55.8%	-63.6%	-71.4%	-79.2%
CAN	-11.7%	-22.6%	-34.5%	-46.4%	-58.3%	-70.2%	-82.1%
MEX	-11.5%	-19.8%	-29.2%	-38.7%	-48.1%	-57.6%	-67.1%
JPN	-14.6%	-23.2%	-46.0%	-51.5%	-58.3%	-65.9%	-74.0%
ANZ	-6.4%	-16.8%	-30.0%	-43.2%	-56.4%	-69.5%	-82.7%
EUR	-1.6%	-16.4%	-43.3%	-49.6%	-54.7%	-64.3%	-76.4%
ROE	0.3%	-12.0%	-21.2%	-30.3%	-39.4%	-48.5%	-57.6%
RUS	-11.6%	-19.0%	-21.2%	-26.4%	-31.5%	-36.7%	-41.9%
ASI	-0.7%	-10.9%	-20.6%	-30.2%	-39.9%	-49.5%	-59.2%
CHN	-3.5%	-5.6%	-23.6%	-35.2%	-46.8%	-58.5%	-70.1%
IND	13.0%	7.8%	7.5%	-10.8%	-25.9%	-39.4%	-51.0%
BRA	-38.7%	-11.9%	-18.6%	-28.3%	-32.1%	-43.2%	-57.7%
AFR	-17.6%	14.2%	4.3%	1.2%	-1.9%	-5.0%	-8.1%
MES	-29.1%	-25.1%	-26.9%	-32.5%	-38.1%	-43.7%	-49.3%
LAM	-25.0%	-3.8%	-19.3%	-28.9%	-36.0%	-48.6%	-61.3%
REA	-6.0%	6.8%	15.7%	1.9%	-3.6%	-7.8%	-13.1%
KOR	-4.7%	-2.2%	-24.0%	-28.7%	-32.3%	-35.9%	-40.0%
IDZ	2.3%	8.5%	1.9%	-10.2%	-22.2%	-34.3%	-46.4%

In addition to PAMs in *Paris Forever*, aggressive goals in pushing the penetration of EVs are carried out to decarbonize LDVs. These targets translate to around 60% to 85% EV shares out of all LDVs by 2050 across regions (Appendix A11). Finally, GHGs pricing may be used as well to ensure the targets are achieved.

4.2. Economic Impact

We present the economic impact under policy scenarios, taking changes in GDP and sectoral value-added shares as an example. We find that under *Paris Forever*, the world GDP (Figure 8) lowers by about 2.3% in 2030, and 2.9% in 2050, and with *Accelerated Actions*, the world GDP shrinks 2.7% in 2030 and 9.1% in 2050 (Figure 9). Specifically, the GDP impacts under *Paris Forever* are much milder in USA and EUR, even though other regions' NDCs tend to be less aggressive than these two regions. On the contrary, fossil fuel exporting regions such as MES and RUS suffer higher negative GDP impacts, regardless of the more lenient mitigation targets they have (Figure 10). The GDP evolution of each region over time would shape the regional GDP shares (Table 7).

Table 7. Regional GDP shares.

Reference				
	2020	2030	2040	2050
USA	21.08%	19.44%	18.47%	18.18%
EUR	23.82%	20.98%	18.85%	17.27%
CHN	17.27%	19.38%	19.44%	18.32%
MES	3.09%	3.25%	3.69%	4.13%
RUS	2.40%	2.23%	2.12%	2.02%
Rest of world	32.34%	34.71%	37.44%	40.08%
Paris Forever				
	2020	2030	2040	2050
USA	21.16%	19.72%	18.88%	18.59%
EUR	23.81%	21.16%	19.18%	17.63%
CHN	17.10%	19.15%	19.19%	18.03%
MES	3.09%	3.06%	3.33%	3.65%
RUS	2.40%	2.16%	1.99%	1.86%
Rest of world	32.44%	34.75%	37.43%	40.24%
Accelerated Actions				
	2020	2030	2040	2050
USA	21.16%	19.69%	18.98%	19.34%
EUR	23.81%	21.33%	19.64%	18.53%
CHN	17.10%	19.17%	19.39%	18.78%
MES	3.09%	3.03%	3.14%	3.15%
RUS	2.40%	2.13%	1.92%	1.68%
Rest of world	32.44%	34.65%	36.94%	38.52%

Source: Our simulation.

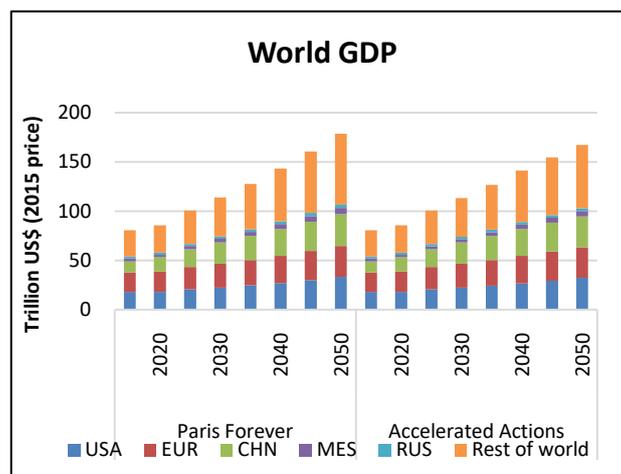


Figure 8. World GDP.

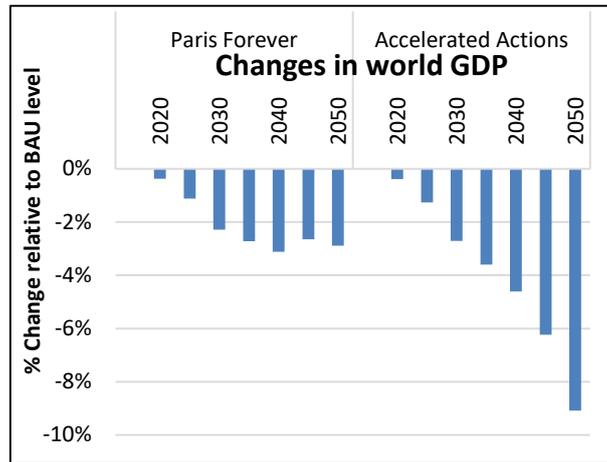


Figure 9. Changes in World GDP.



Figure 10. GDP impacts under different scenarios.

A key factor underlying the aforementioned observations is that the suppressed fossil fuel prices benefit USA and EUR, and hurt RUS and MES (See Appendix A13 for more details). Our finding is consistent to [Makarov et al. \(2020\)](#), which argues that if serious climate policies are in place, it is unlikely that Russia could keep benefiting from its fossil fuel exports that were the major driver of the country's economic development in the 2000s. Our simulation also shows that under *Paris Forever*, the producer price of crude oil would be lowered by almost 22% in 2050, relative to that of the reference run, where the NDCs will not be carried out. While the reduced crude oil price is a key driver for a 14% shrink of GDP for MES in 2050, it helps the economies of USA and EUR, where crude oil imports remain critical in their economic activities.

The lower fossil fuel intensities of GDP in USA and EUR also contribute to the relatively milder GDP impacts of these two regions under GHGs mitigation scenarios. For instance, in 2015, the fossil fuel intensity of GDP in USA is only about a third of that for RUS, or less than 40% of the level of MES. EUR's fossil fuel intensity is even lower—62% of the USA's level ([Figure 11](#)). Regions such as RUS, MES and CHN have much higher fossil fuel intensities, and so these economies are prone to suffer more especially when aggressive emissions cuts are in place. Still, while MES and RUS barely cut any emissions under *Paris Forever*, the suppressed fossil fuel prices worldwide hurt their domestic economies.

Carbon leakages, although beyond the scope of our study, can also result in a mild GDP impacts for USA and EUR under *Paris Forever*, i.e., regions with more stringent climate policies may export carbon intensive activities to regions with much lenient policies or without any policies, and import products with larger carbon footprints from there to alleviate the burden of decarbonization ([Qin et al., 2021](#); [Santos et al., 2019](#); [Caron et al., 2014](#)). This could suggest a challenge in cutting emissions without a more concerted and serious effort worldwide.

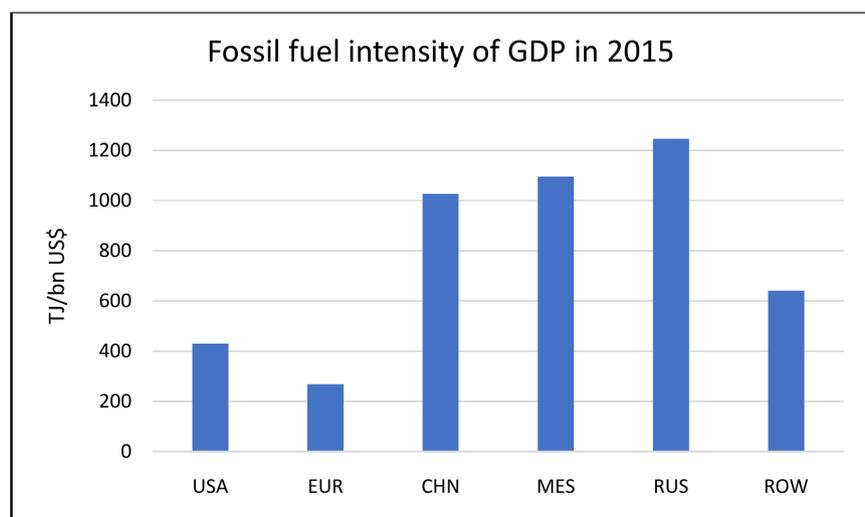


Figure 11. Fossil fuel intensity of GDP by region.

The targets of *Accelerated Actions* dictate deeper emissions cuts than those of *Paris Forever*, and further decarbonization generally implies higher GDP reduction. Nevertheless, when conducting regional comparison, the observation is still similar qualitatively: fossil fuel importing regions suffer less and fossil fuel exporting regions are hurt more. For instance, under *Accelerated Actions*, the crude oil price would be cut by more than 41%, compared with that of the reference run, and for MES, the depressed crude oil price constitutes a key factor that contributes to around 31% GDP loss of that region in 2050 relative to its projected GDP under the reference run. Besides, the impacts on welfare (aggregate consumption) are also provided in Appendix A12 and in general, they are quite similar to GDP impacts both qualitatively and quantitatively.

To understand the economic implications of PAMs in *Paris Forever* and *Accelerated Actions*, we also run the versions of the two scenarios where additional PAMs imposed on them are removed, and emissions cuts are achieved totally based on GHGs pricing. We find that at the global level, the existence of PAMs could reduce the GDP in 2050 by 2.3% and 1.6% under *Paris Forever* and *Accelerated Actions*, respectively, compared with scenarios where PAMs are removed, reflecting the lack of flexibility caused by PAMs in pursuing the most efficient mitigation measures where the marginal abatement costs are lowest. Although due to trade linkages between regions, the GDP of each region might not always be reduced with the presence of PAMs.

We also analyze the sectoral value-added shares of each region under different scenarios (Appendix A14). Our focus here is on energy supply sectors. We find that even for USA and EUR, where the overall GDP impacts are relatively smaller, with more stringent mitigation targets, fossil fuel production sectors would suffer, and this is especially the case for the production of coal. Besides, in general, value added shares for the power generation sector will increase, reflecting an effort of low-carbon electrification in cutting GHGs emissions around the world.

4.3. Emissions

Under *Paris Forever*, projected global GHGs emissions (including those from land-use emissions) for 2030 and 2050 are lowered by around 18% and 20%, respectively, when compared with emissions under our projected reference run (**Figure 12**). In particular, at the global level, CO₂ emissions related to burning fossil fuels (i.e., combusted CO₂), which currently account for about two thirds of total GHGs emissions, would be cut by 20% in 2030 and 25% in 2050.

However, while globally the GHGs growth is slowed down, our results demonstrate that targets of this scenario are not enough to stop emissions from increasing in the long run—compared with the 2015 level, in 2030, while the overall GHGs (in CO₂ equivalent) are projected to be around 3% lower, they would be more than 8% higher in 2050, and the observation verifies the need for more aggressive measures in curbing anthropogenic emissions.

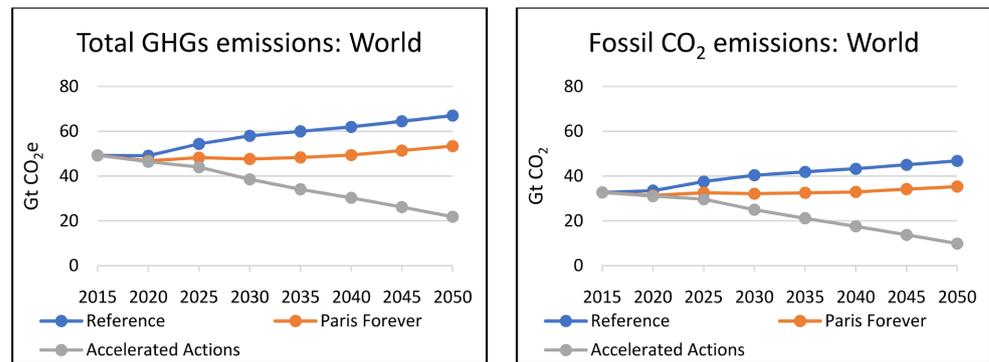


Figure 12. Projections for global GHGs and fossil CO₂ emissions.

In *Accelerated Actions*, which aims at targeting a 1.5°C scenario (see Section 4.2), global GHGs for 2030 and 2050 would be slashed by 34% and 67%, respectively, relative to the reference levels, which translates to about 22% and 56% cuts relative to the 2015 level. Besides, with *Accelerated Actions*, combusted CO₂ emissions are projected to be curtailed by 38% in 2030 and 79% in 2050, compared with the reference levels. When the benchmark for comparison is the global combusted CO₂ level in 2015, the reductions become 24% in 2030 and 70% in 2050.

We also present projections for regional emissions (**Figure 13**). For simplicity, our focus is on emissions from burning fossil fuels (i.e., combusted emissions), as they are closely related to the energy use projection that will be discussed in the following section. We find that using emissions for the reference run as the benchmark, USA, EUR, and CHN generally cut more emissions than other regions do in both policy scenarios, but that does not necessarily translate into higher negative GDP impacts for these regions. On the other hand, regardless of the fact MES and RUS have relatively smaller emissions reductions, their negative GDP impacts are more conspicuous due to reasons discussed before.

4.4. Energy Use

Under *Paris Forever*, global primary energy use in 2030 and 2050 will be lowered by around 12% and 13% relative to the reference run (**Figure 14**). In spite of that, if compared with the 2015 level, global primary energy use would still increase by 11% and 33%, respectively. Per the fossil fuel consumption, it is projected to be cut by 17% in 2030 and 20% in 2050 compared with those in the reference run, while non-fossil fuels would increase by 4% and 7%, reflecting a moderate trend of decarbonization.

Besides, at the global level, by the middle of the century, coal is projected to account for about 18% of energy use (down from 24% under the reference run), for oil the number is 26% (down from 28%), for gas it is 25% (up from 22%), for nuclear it is 3.4% (up from 3%), for hydro, renewables and bio-energy, the numbers are 6% (up from 5%), 15% (up from 12%), and 6% (up from 5%), respectively.

With *Accelerated Actions*, the projected global energy use in the aforemen-

tioned two time points will shrink by around 20% and 35%, fossil fuel use would be lessened by 31% and 71%, and non-fossil fuels would expand by about 18% and 72%, respectively. In particular, by the middle of the century, renewables and nuclear will grow by 127% and 81%, respectively, resulting from more aggressive emissions abatement efforts.

Since globally the total primary energy use under *Accelerated Actions* essentially remains flat over time, advances in energy efficiency, either through AEEI or through price induced improvements, would also play a key role in achieving a low-carbon growth path. In addition, for the structure of energy use with *Accelerated Actions*, it is projected that by the middle of the century, coal, oil, gas, and nuclear would account for around 4%, 19%, 12%, and 8% of energy use, while for hydro, renewables, and bio-energy the shares are 9%, 40%, and 9%, respectively.

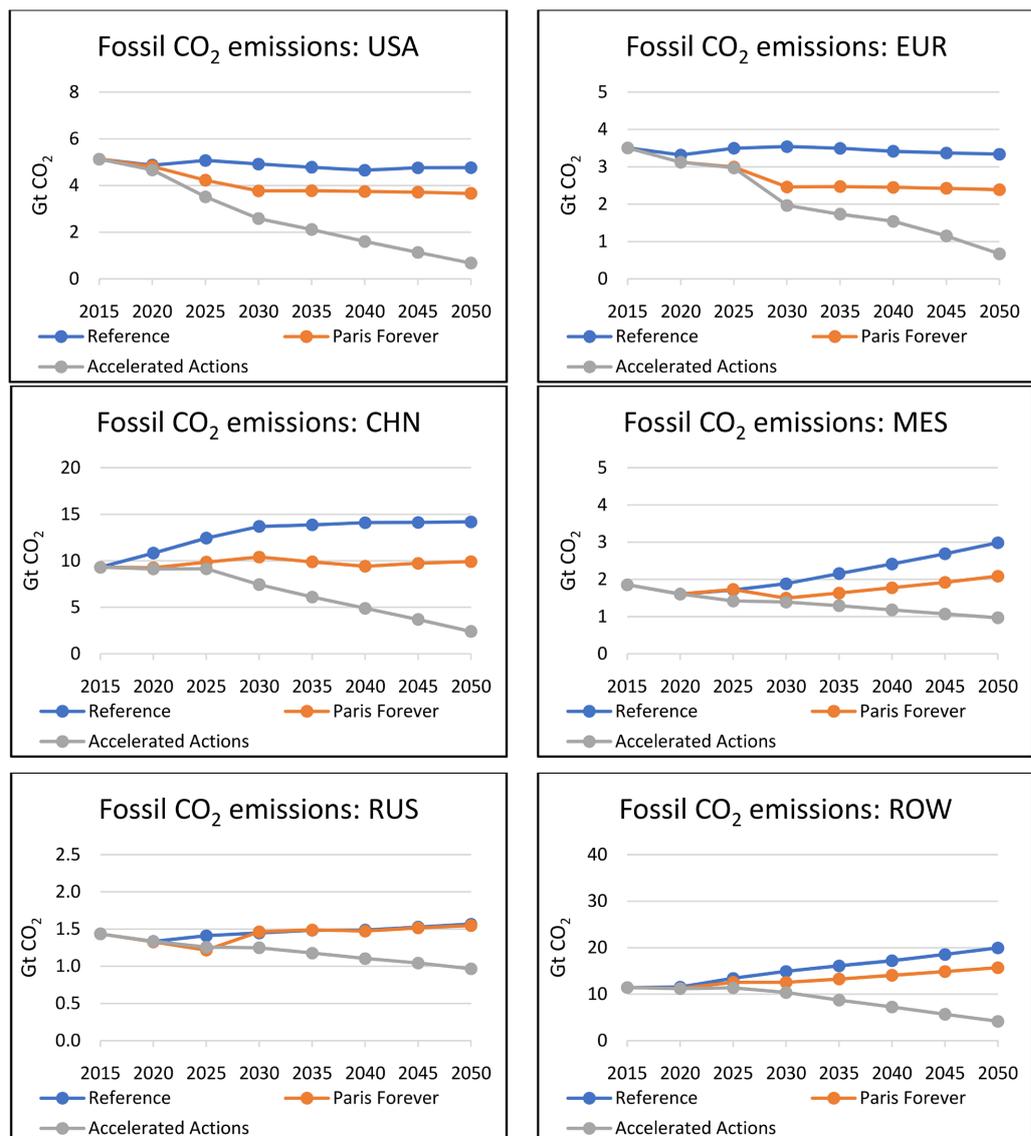


Figure 13. Projections for regional fossil CO₂ emissions.

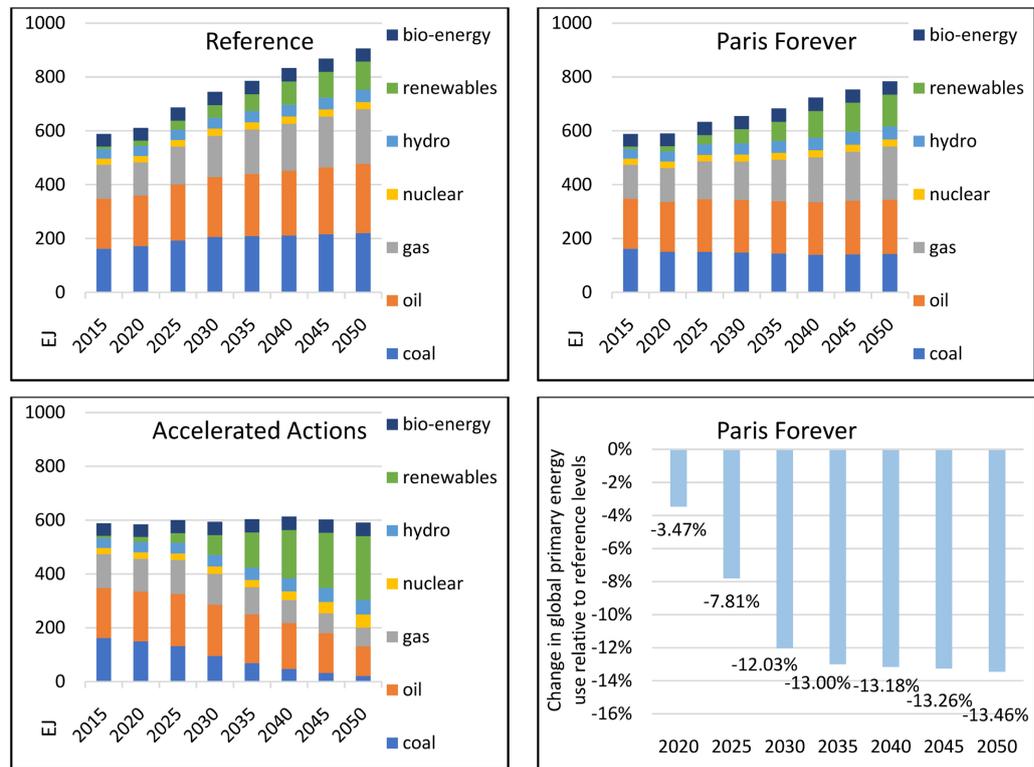


Figure 14. Projections for global primary energy use.

Similar to the global case, at the regional level, with *Paris Forever*, energy use is reduced to a certain extent across regions (Appendix A15). In particular, there is generally a moderate decrease in fossil fuel consumption accompanied with a modest increase in non-fossil fuel use. More dramatic changes would happen under *Accelerated Actions*, where renewables are projected to become a more dominant source to meet the energy demand, with the help of other forms of energy (fossil fuels, nuclear, hydro, bio-energy) as the backup options to tackle the intermittency issue, except for MES and RUS, where fossil fuels, although with reduced consumption levels, still continues to account for more than half of the energy use, due to the less stringent emissions targets considered in this scenario (Table 6).

4.5. Generation Mix

GHGs abatement efforts also have implications on power sector. Under *Paris Forever*, compared with those under the reference run, global electricity supply would be lowered by around 3% in 2030—much less than the projected reductions for primary energy use previously presented, and it will increase by about 2% in 2050—revealing a moderate trend of electrification. Still, global electricity supply would raise by about 30% and 87% in the aforementioned two years relative to the 2015 level, respectively (Figure 15). The most pronounced increase is in the rest of the world (Appendix A16), driven by a higher benchmark economic growth based on OECD (2020) (see Section 3.1). For instance, in India

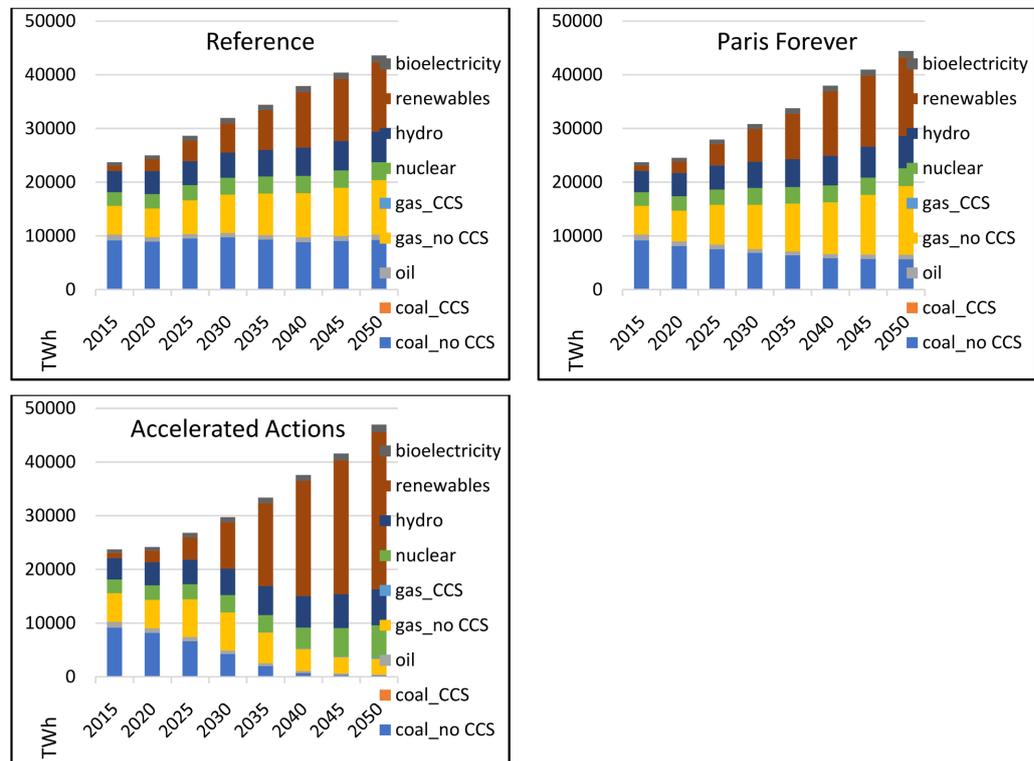


Figure 15. Projections for global generation mix.

(IND), the projected electricity supply in *Paris Forever* will increase by 348% relative to 2015 in 2050, and in Africa (AFR) the increase is 206%. On the other hand, the electricity supply in a more developed region (e.g., USA; EUR) generally has a much slower growth, or more or less remains flat for years beyond 2030.

As mentioned in Section 2.2, economic data for renewables (wind and solar) are now included in each region's input-output table in GTAP10-power, and so they are no longer backstop options of EPPA7. Two parameters that could affect the penetration of renewables are the substitution of elasticities for wind and solar, respectively (see [Figure 2](#) in Section 2.2). In our parameterization, for both elasticities, up to 2020 they are set to unity, and for later years they are gradually increased to a value up to 4, to reflect the technology improvement that could make integrating renewables into the grid easier. With this parameterization, our simulation shows that globally, renewables have the potential to account for about 17% in 2030, and 30% in 2050 under the reference run, and the shares can go up to 20% to 29% in 2030, and 33% to 62% in 2050 under the two policy runs.

Note that nuclear power in our model includes: 1) conventional (existing) nuclear, i.e., nuclear power with conventional light water reactors (LWRs); and 2) advanced nuclear, treated as a backstop technology and often referred as "Generation IV technologies" with new designs to improve safety and efficiency ([Congressional Research Service, 2019](#)). The expansion of conventional nuclear

is also governed by a resource factor (also referred to as a “fixed factor”) with a substitution elasticity derived from each region’s price elasticity of supply (Chen et al., 2016). We calibrate the resource factor (see Appendix A17) such that for each region, the nuclear outputs up to 2030 match IEA’s historical numbers or projections (IEA, 2019; IEA, 2017). Next, starting from 2035, the resource factor is gradually decreased and eventually matched that used in Reilly et al. (2018) around the middle of the century. On the other hand, advanced nuclear is assumed to be technically feasible in 2035 and may enter the market if it is economically competitive.⁹ With this consideration, we find that in 2050, the share of nuclear output may increase from around 7.5% (with an output level of approximately 3300 TWh) under the reference run or *Paris Forever* to about 13% (with an output level of roughly 6000 TWh) under the *Accelerated Actions*.

As expected, climate policies have significant implications on fossil-fuel-based generations. Our focus is on coal-fired and gas-fired generations, since in most regions oil-fired generation is used as a peak load option and remains to account for a tiny share of total electricity output. We find that while globally coal-fired generation output under the reference run remains more or less flat, it will be significantly reduced under *Paris Forever*, down from the reference run’s 9200 TWh to 5600 TWh in 2050, with the corresponding output share declining from 21% to 13% at that time. Global gas-fired output, on the other hand, is projected to raise over time even under the reference run, and *Paris Forever* would result in even more gas-to-coal switch and a higher gas-fired output. Therefore, in 2050, the share of gas-fired output would increase from the reference run’s 23% to 29%. Under *Paris Forever*, CCS as an option will not be applied on either coal-fired or gas-fired generation. At the global scale, there are no significant changes in output levels of nuclear, hydro, and bio-electricity under *Paris Forever*, when compared with the reference run.

With *Accelerated Actions*, at the beginning the global electricity supply would be somewhat lowered relative to the reference run up to 2040, due to more aggressive policies. But for years beyond 2040, the output is projected to surpass other two scenarios, because of the trend of low-carbon electrification observed worldwide. Under this scenario, the share of renewables in total electricity supply could raise from around 7.8% in 2019 (IEA, 2020) to 29% in 2030 and 62% in 2050.

At the regional level, we find that up to 2030, gas-fired power may play critical roles in cutting GHGs emissions in regions such as CHN and USA in both policy scenarios. However, under *Accelerated Actions* with higher carbon penalties per unit emissions in years beyond 2030, gas-fired power, even with its lowest carbon footprint among fossil generations, would still become harder to compete with other carbon free options, although in USA, gas with CCS may enter the

⁹As a result, while the nearer term nuclear output under the reference run is comparable to IEA’s projection, the output under a policy scenario or in the long run would be determined by the resource factor substitution possibility of conventional nuclear and the economics of advanced nuclear.

market starting from 2030 with a relatively small output share. Besides, under *Accelerated Actions*, outputs from renewables are projected to increase significantly in all regions but RUS, because of the less stringent targets for that region (see **Table 6** in Section 4.2).

4.6. Implications of EVs on Electricity Use

Boosting the use of EVs has been a measure of lowering anthropogenic GHGs, provided that the electricity comes from low-carbon sources. A related question that follows is the electricity use implications of EVs, especially under more aggressive policies aiming at having higher levels of EVs penetration.

Taking the worldwide use of light-duty EVs (henceforth EVs) as an example, we demonstrate that under *Paris Forever*, while the share of electricity use by EVs remains slightly less than 1% of total electricity use through 2030, it continues to raise as the fleet increases, and is projected to account for almost 4% of global electricity demand by 2050 (**Figure 16**). Under *Accelerated Actions*, with more aggressive EV targets, the share of electricity use by EVs may increase to almost 2% within a decade, and eventually reach roughly 6% by the middle of the century.

We also present projections of electricity demand structure from our model. It shows for either policy scenarios, electricity use by industry would remain to account for more than half of electricity supply through 2050, followed by electricity use of final demand (excluding electricity use by EVs), which accounts for about a quarter to one third of total electricity demand. We find that at the global level, while electricity use by EVs may increase significantly as the fleet grows, it remains a smaller share of total electricity demand (**Figure 17**).

A caveat to our finding is: we only consider the electrification of LDVs in this exercise. The stress of power demand would certainly increase if an extensive electrification on commercial transport is pursued as well.

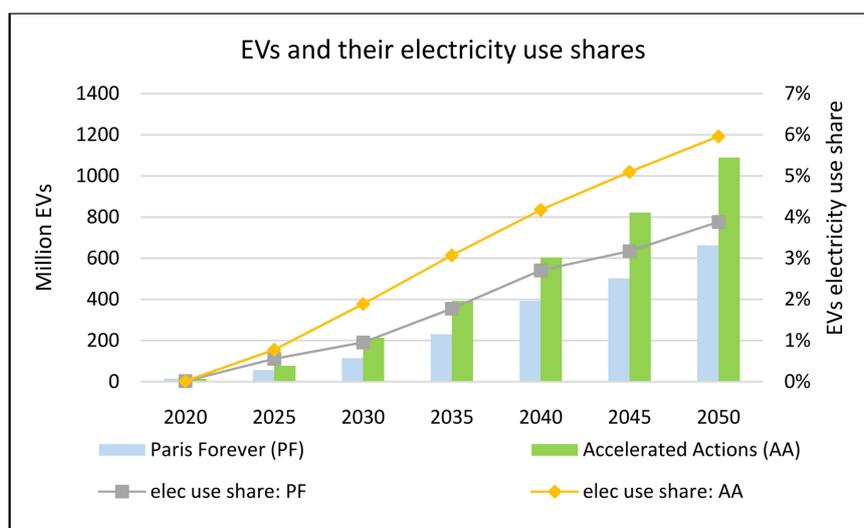


Figure 16. Global EVs and the projected electricity use shares.

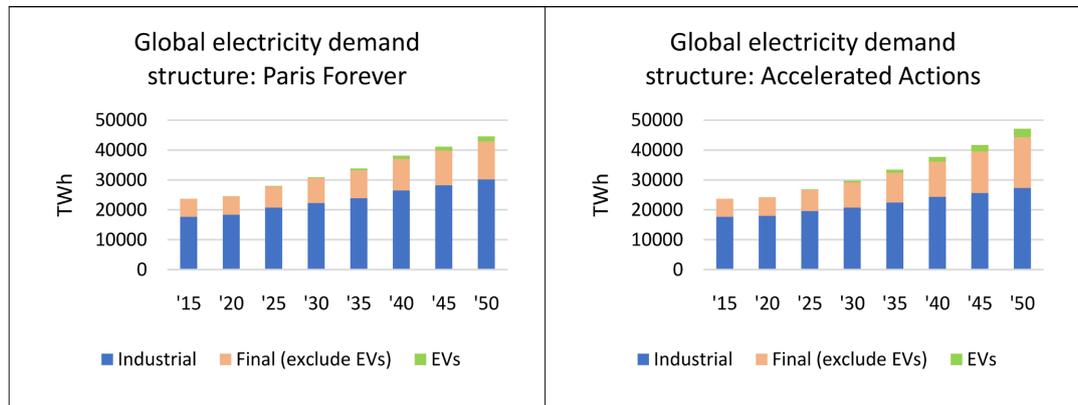


Figure 17. Global electricity demand structure.

4.7. Land-Use Changes

Future land use trajectories will be determined by several drivers, as increasing food demand due to population growth and changes in income, productivity gains and yield improvements, international trade, climate change and environmental policies. These forces vary by region of the world and development stage, as also as the current land use allocation. Figure 18 shows land use in 2015 and future projections under the reference scenario. While global agriculture area will expand in the future to accommodate increasing food demand, most of it will occur in developing countries/regions (AFR, ASI, BRA, CHN, IDZ, IND, LAM, MES, MEX, REA) replacing areas currently under natural vegetation. However, larger developing countries with low stocks of natural forests and grasslands, as CHN and IND, are already using most of their land suitable to agriculture and do not have room for much more conversion of natural areas to productive use. While in developed regions of the world (USA, CAN, EUR, JPN, ANZ), slowing population growth, higher income levels and increase in yields have favored agricultural land abandonment and regrowth of natural vegetation areas.

Decarbonization policies may affect future trajectories of land use through several ways (Figure 19). Some policies may constraint emissions from deforestation. Others may indirectly change the dynamics of land use changes by pricing CO₂ and other GHGs emissions, increasing costs of livestock production and use of fertilizer, as also as incentivizing bioenergy deployment. EPPA7 projects a strong intensification of livestock production at the global level under both *Paris Forever* and *Accelerated Actions* relative to the reference run, mostly due to the need to reduce methane emissions from livestock production and efforts to control deforestation. Lower economic growth also drives consumption down, which, together with yield improvements, prevent further increases in cropland. Higher prices on GHGs emissions under *Accelerated Actions* result in stronger conversion of pasture areas to other uses, including to bioenergy production on cropland areas. Managed forests expand strongly due to lower carbon intensity from forestry products.

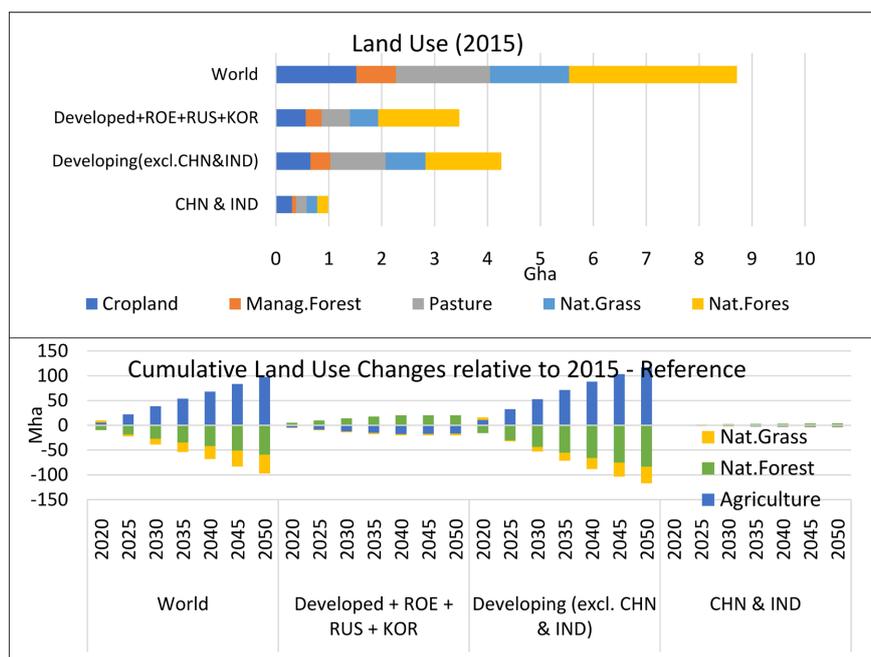


Figure 18. Land use in 2015 (top panel) and changes in land use relative to 2015 in the Reference (bottom).

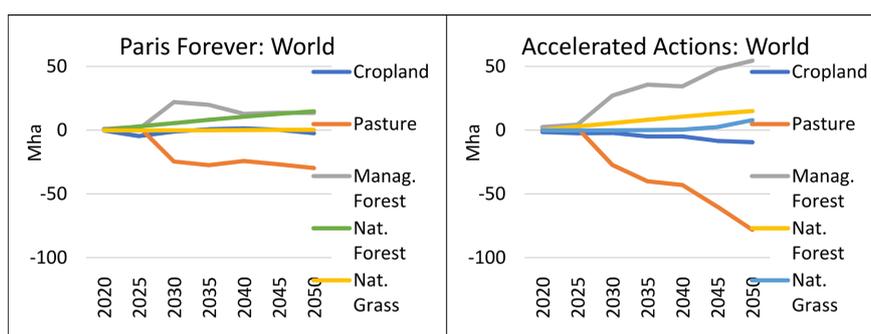


Figure 19. Global changes in land use in decarbonization scenarios relative to the reference run.

4.8. Stranded Assets

With efforts to cut GHGs emissions, especially under more aggressive policies, the shift from carrying on carbon-intensive activities to low-carbon or carbon-free ones gives rise to stranded assets across sectors that produce or use fossil fuels. As in Landry et al. (2019) and Chen et al. (2022), we delve into the stranded assets in two forms: the term *stranded value* is used to represent the loss of rents associated with fossil fuel resources. The stranded value estimation covers stranded equipment in the extraction sectors such as drilling rigs in the refined oil sector. On the other hand, the term *stranded capital* refers to lower returns to capital in fossil fuel consumption sectors. We only calculate and report the value of stranded coal-fired power plant capital, as coal-fired generation will be most affected by climate policies. Stranded assets are calculated relative to the reference scenario through 2050 and are reported as a Net Present Value

(NPV) assuming a discount rate of 4%. Details for the stranded assets calculation are presented in Appendix A18.

Our simulation shows that under *Paris Forever*, globally the stranded values resulted from the unproduced oil, gas, and coal are 16.4, 2.3, and 5.1 trillion US\$ (in 2015 price), respectively, and with *Accelerated Actions*, the stranded values become 22.0, 7.0, and 8.6 trillion US\$ (**Figure 20**). The stranded value of gas is much lower than those of oil and coal under *Paris Forever*, since the carbon footprint of gas—roughly half of the case for coal—is the lowest among fossil fuels, which suggests that switching from coal or oil to gas could be an avenue for carbon mitigation under a less aggressive scenario. However, gas is still not carbon free and therefore subject to carbon penalty when GHGs mitigation targets are enforced, even with the help of gas-fired power with CCS, which could significantly increase the cost of power generation. Therefore, under a more aggressive scenario such as *Accelerated Actions*, the use of gas (and so the production of gas) needs to be cut substantially, giving rise to a much higher stranded value compared with that under *Paris Forever*, although it is still the lowest among stranded values of fossil fuels.

At the regional level, MES has the highest stranded values for oil and gas among the considered regions (not including the rest of world) under both policy scenarios, reflecting the importance of crude oil and gas exports for this region. On the other hand, CHN has more stranded value in coal production than other regions under both policy scenarios, showing the current reliance of coal in powering its economy (**Figure 21**).

Our results also demonstrate that globally, the stranded capital estimations are 0.43 and 0.80 trillion US\$ under *Paris Forever* and *Accelerated Actions*, respectively (**Figure 22**). At the regional level, EUR has relatively higher stranded capital of coal-fired power under both policy scenarios, due to the more aggressive targets the region has. Compared with EUR and USA, although the targets of CHN are more lenient in both policy scenarios, the fact the electricity supply of CHN is highly dependent on coal-fired power still unavoidably make the stranded capital level of coal-fired power conspicuous (**Figure 23**).

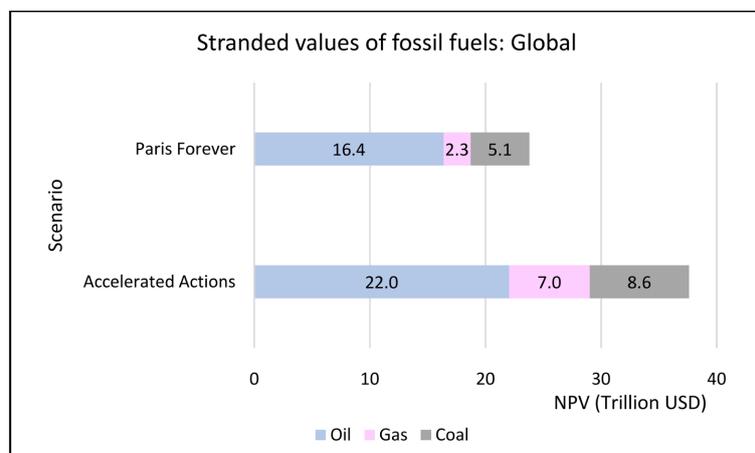


Figure 20. Stranded values of fossil fuels relative to the reference scenario.

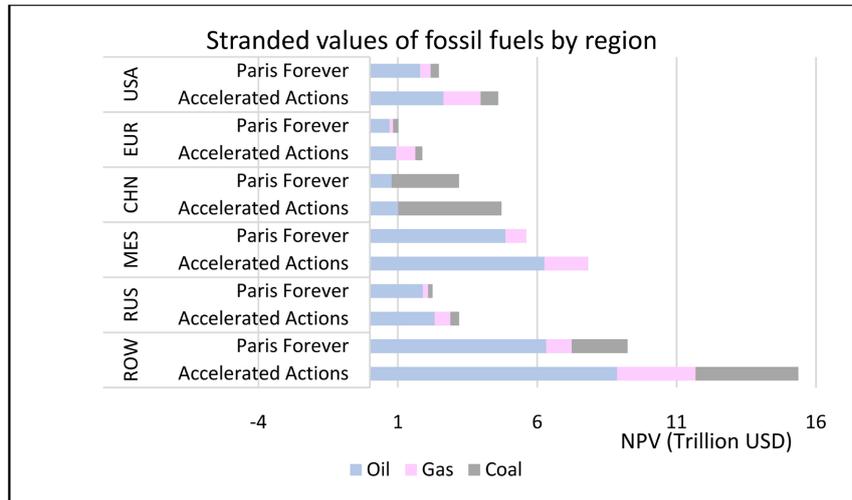


Figure 21. Stranded values of fossil fuels relative to the reference scenario by region.

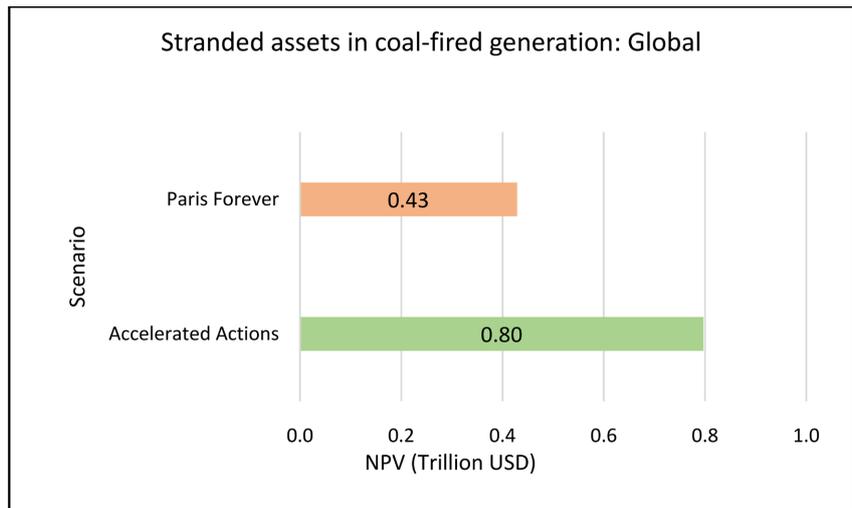


Figure 22. Stranded capital of coal-fired generation relative to the reference scenario.

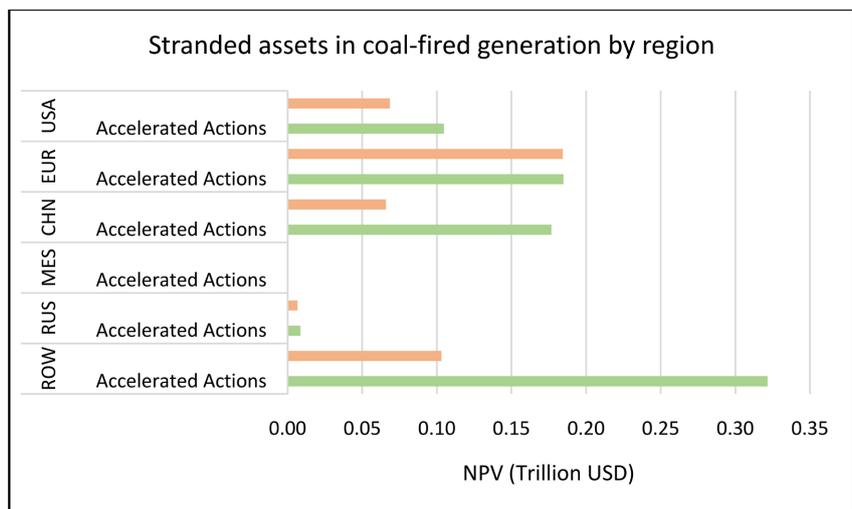


Figure 23. Stranded capital of coal-fired generation relative to the reference scenario by region.

It is worth noting that key factors affecting the stranded capital estimations include: 1) the projection for the coal-fired output in the reference run; and 2) how the forward-looking behaviors are considered in the modeling exercise. In EPPA7, the levelized cost of electricity generated by advanced coal is much higher than earlier data used in the previous version of EPPA (see **Table 5** in Section 3.3). As a result, unlike Landry et al. (2019) that uses an earlier version of EPPA, in our simulation advanced coal will not enter the market in any region even under the reference run, and consequently, under a policy scenario, there will be no stranded capital from idling the advanced coal built before policies are in place. Besides, with all the bells and whistles such as vintage dynamics and backstop technologies our model has, a recursive dynamic setting is adopted for computational reasons (Section 2.4). A caveat of this setting is the lack of forward-looking consideration. To address the concern, in EPPA7, each period covers five years, which can be viewed as decision makers have complete information for the entire five-year period and will make decisions accordingly. Nevertheless, longer-term considerations beyond five years are still out of reach under the recursive dynamic framework, which means that stranded assets could possibly be overestimated.

5. Conclusion

A multisectoral energy-economic model is the key component of an integrated assessment framework aiming at exploring climate change implications. In this study, we introduce our new edition of this class of models, EPPA, which is a recursive dynamic global CGE model with details in regions, sectors, low-carbon technology options, and emissions. Specifically, we provide updates and improvements done for the current model version, EPPA7, and conduct simulations with various scenarios to explore the policy implications on economic variables, emissions, energy use, power generation, land-use changes and stranded assets. The goal is to offer a clear documentation of EPPA7's model structure, parameterization, setting, and performance—all are critical in explaining and understanding simulation results. Our study contributes to the understanding of projections based on a large-scale energy-economic model. We believe similar efforts by other research groups would be beneficial for the modeling community, interested readers, policy makers, and shareholders.

A large-scale global multisectoral model such as EPPA7 that produces a vast amount of output with a decades-long time horizon is broadly used by researchers with various focuses. The task of developing and maintaining such a model is nontrivial, and a constant reexamination, either from comparing relevant research or from expert elicitation, is necessary to see if there is any room for improving the model projections, due to information not precisely reflected in the current parameterization or settings.

Another challenge in the modeling exercise is that usually implementing a more elaborate setting in the hope of better representing the real world could potentially pose numerical issues in finding the solution, and can make main-

taining and continued development of the model much trickier and more error-prone. As a result, balancing distinct and sometimes conflict goals is an inevitable consideration all modeling groups need to deal with, and decisions have to be made depending on the main focuses of the model and resources available. Therefore, while this study presents our best modeling effort at this moment, we remain unpretentious regarding our model's capability in producing a wide range of outputs as projections for the future or for a counterfactual, which are by all means subject to a great extent of uncertainties.

Acknowledgements

The financial support for this work is provided by the MIT Joint Program on the Science and Policy of Global Change through a consortium of industrial and foundation sponsors and Federal awards, including the U.S. Department of Energy, Office of Science. For a complete list of sponsors and the U.S. government funding sources, please visit <http://globalchange.mit.edu/sponsors/current>. The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this study. The authors are thankful for comments from three anonymous reviewers of the 25th Annual Conference on Global Economic Analysis, and suggestions from anonymous reviewers of this study. All remaining errors are our own.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

The Appendix is available upon request or from

<https://drive.google.com/file/d/1QOTZgOYY5PNV2ybyqXmOq9HDryMzy8kop/view>.