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The MIT EPPA7: A Multisectoral Dynamic Model for Energy, Economic, and Climate Scenario Analysis

Y.-H. Henry Chen, Sergey Paltsev, Angelo Gurgel, John M. Reilly, and Jennifer Morris

MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

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GLOBAL CHANGE

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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.

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. 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 (Karplus, 2011; Gurgel *et al.*, 2007; Choumert *et al.*, 2006; Ramberg and 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, where the solution algorithm is 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, 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. Key new features included non-homothetic preferences, a revised capital vintaging structure, and the potential for total factor productivity improvement.

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.

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 inputs 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 costminimizing 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:

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

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 and 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 A1 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

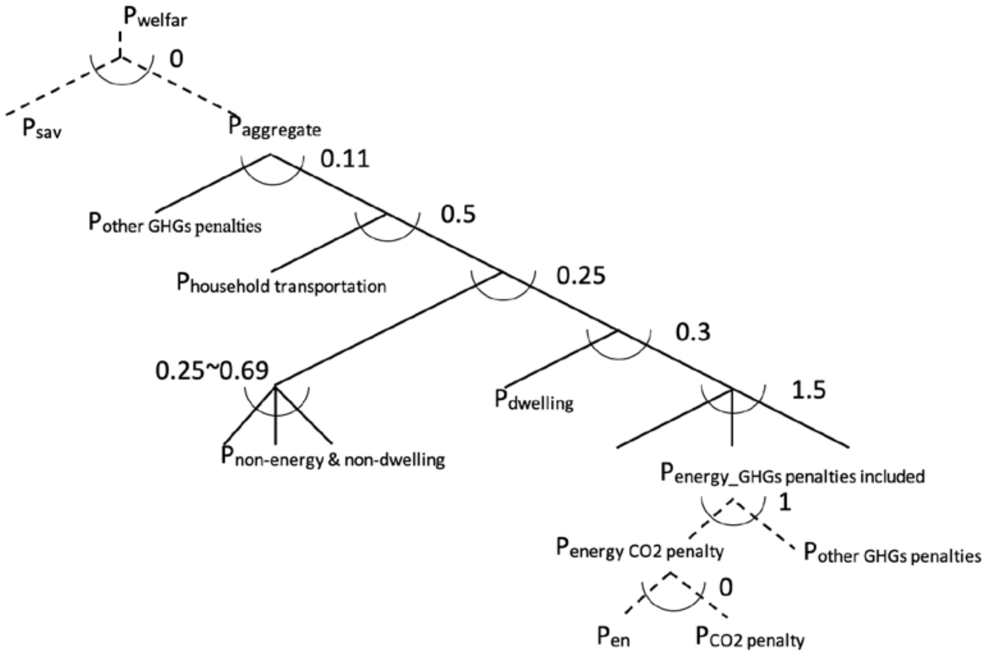


Figure 1. The expenditure function structure

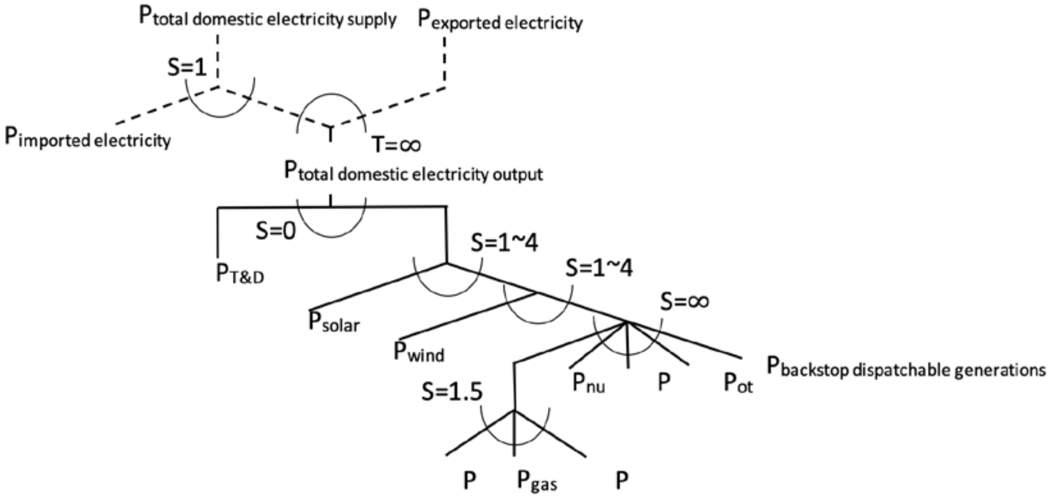


Figure 2. The cost function structure for power sector aggregation

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 explicitly in the current GTAP-power database, and therefore, they are 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 (Figure 2).

Another revision of the production technology is in household transportation, which is based on Ghandi and Paltsev (2019), where more elaborate modeling strategy and updated parameterization for the electric vehicles (EVs) were developed. 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 somewhat less likely to be electrified are called "necessary ICE LDVs" (Figure 3). Ghandi and Paltsev also considers part of EVs that are imperfect substitutes to the replaceable ICE LDVs (denoted by EV1s in Figure 3).

Minor departures of our setting 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 climate 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, depending on the focus, 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**. In addition, 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 A2. Note that while factor substitution in response to change in relative price is possible for production activities using malleable capital, input shares are fixed in the case

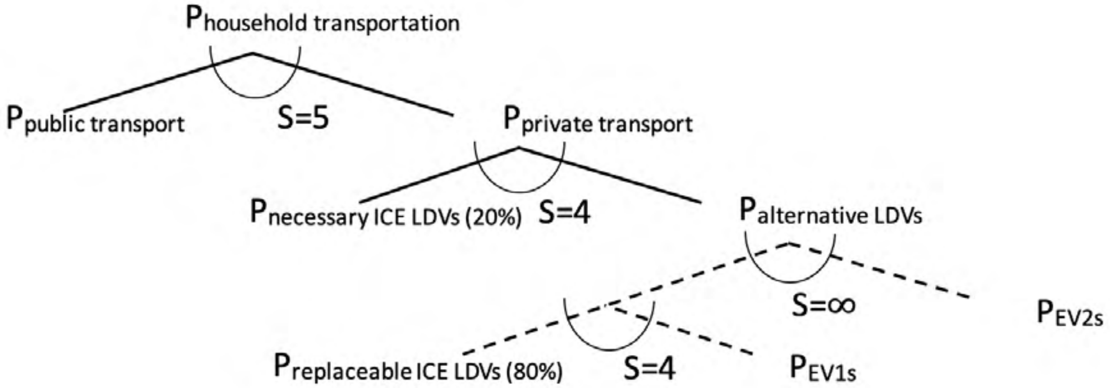


Figure 3. The cost function structure for household transportation aggregation

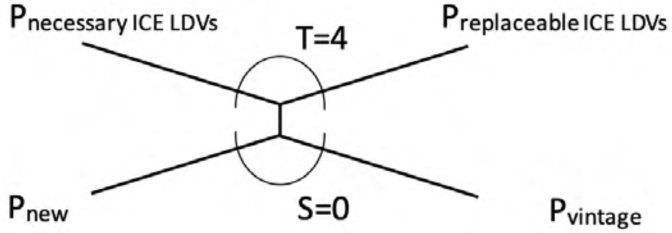


Figure 4. The cost function structure for ICE LDVs

of production activities using non-malleable capital. As in previous versions of the model, 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 the effect of dietary changes as incomes rise.

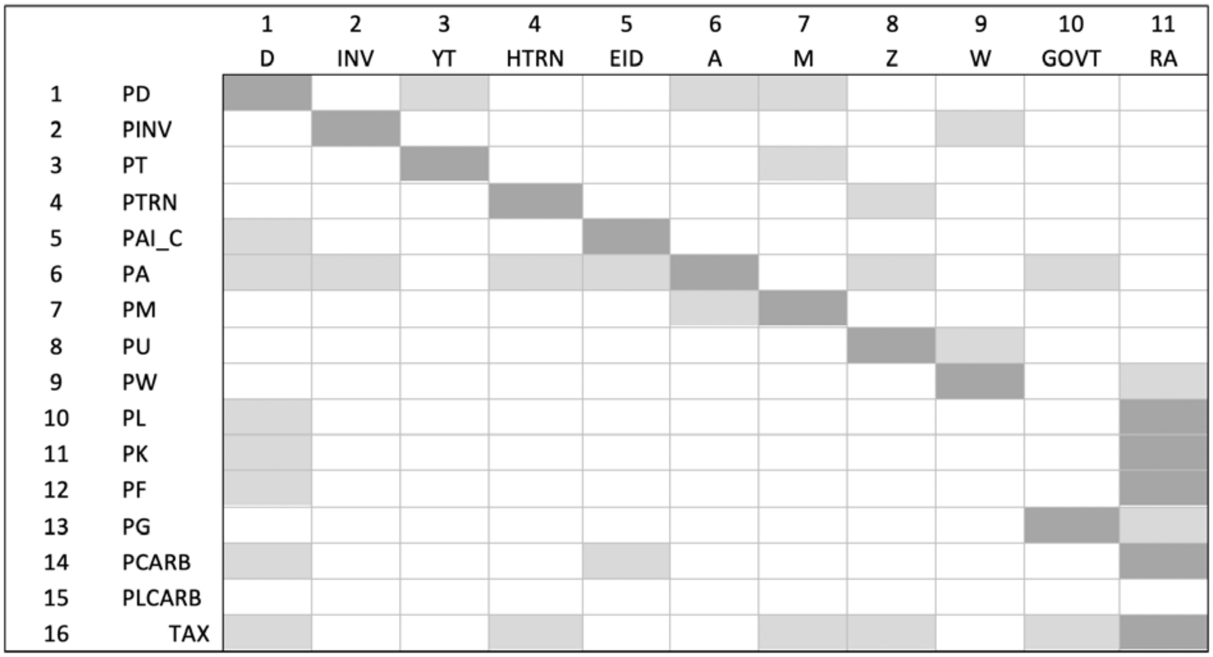
2.3 Social Accounting Matrix

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.

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 A3 for the SAM with greater details of price and activity variables.

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, CO_2 penalty (if CO_2 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.[1] 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.



		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	PAI_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

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

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

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 factoraugmented 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 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:

Table 2. Activity variables presented in the SAM

Notation	Definition
D	Activity level for domestic production
INV	Activity level for investment
YT	Activity level for international transport
HTRN	Activity level for aggregate household transport
EID	Activity level for energy input (w/ CO_2 penalty)
A	Activity level for Armington good production
M	Activity level for import
Z	Activity level for aggregate consumption
W	Activity level for welfare
GOVT	Activity level: total government expenditure
RA	Income of the representative consumer

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

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 (τ=5 from 2015 onward). The newly formed nonmalleable capital $V_{5,t}$ comes from a portion of the survived malleable capital from the previous period:

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

We consider the case where part of the vintage capital have 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. 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 $(1\text{-}\delta)^5\ V_{20,t+2}$, 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 , 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.

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 $F_{e,t}$ at period t. Values of $F_{e,t}$ are then multiplied by a factor of five to approximate depletion in intervening years, to align with the five-year time step:

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

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 $\gamma=(1\text{-}\delta)^5$, 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 in 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**).

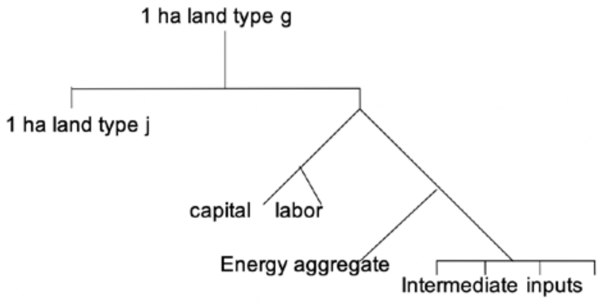

Figure 6. Structure of land transformation functions

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).

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.

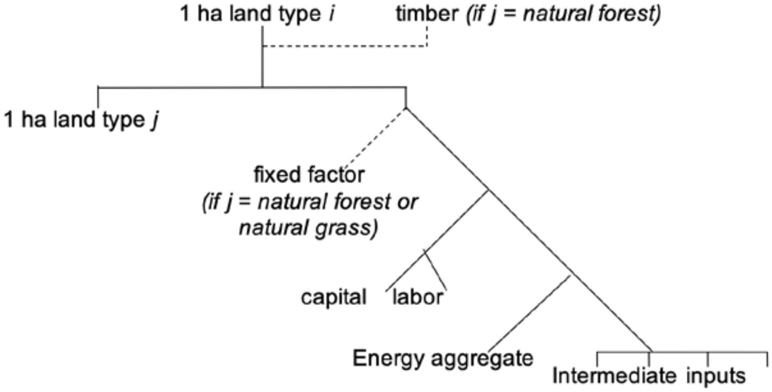

Figure 7. Structure of land transformation functions for conversion of natural forest

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), Schimtz *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 and 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 **Table 3**), 22 sectors (including 9 power subsectors; see **Table 4**), 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 A4 through A6.

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.

Table 3. Regions in EPPA7.

Region	EPPA7 notation
United States	USA
Canada	CAN
Mexico	MEX
Japan	JPN
Australia, New Zealand & Oceania	ANZ
European Union+[1]	EUR
Eastern Europe and Central Asia	ROE
Russia	RUS
East Asia	ASI
South Korea	KOR
Indonesia	IDZ
China	CHN
India	IND
Brazil	BRA
Africa	AFR
Middle East	MES
Latin America	LAM
Rest of Asia	REA

Table 4. Sectors in EPPA7.

Sector	EPPA7 notation
Agriculture - Crops	CROP
Agriculture - Livestock	LIVE
Agriculture - Forestry	FORS
Food Products	FOOD
Coal	COAL
Crude Oil	OIL
Refined Oil	ROIL
Gas	GAS
Electricity	ELEC
Coal-fired generation	cele
Gas-fired generation	gele
Hydro generation	hele
Nuclear generation	nele
Oil-fired generation	oele
Other generation	rele
Solar generation	sele
Wind generation	wele
Transmission and distribution	tele
Energy-Intensive Industries	EINT
Other Industries	OTHR
Ownership of Dwellings	DWE
Services	SERV
Transport	TRAN

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[1] The European Union (EU-27) plus U.K., Croatia, Norway, Switzerland, Iceland and Liechtenstein.

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 5**), 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 and electricity bundle) and non-energy (labor-capital bundle) inputs; and 2) electricity and fossil energy (see Table 5 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.[2] 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.[3] 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 capita 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 the 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

Table 5. 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

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[2] For 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.

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

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 is provided in **Table 6**, and that for electricity generation is presented in **Table 7**.

Table 6. Primary energy use in the base year.

Unit: EJ	coal	oil	gas	nuclear	hydro	renewables	bioenergy
AFR	4.698	7.086	4.558	0.125	1.108	0.066	0.002
ANZ	1.830	2.659	1.520	0.000	0.385	0.149	0.030
ASI	3.579	8.186	4.289	0.384	0.294	0.038	0.133
BRA	0.729	5.288	1.479	0.139	3.382	0.116	0.648
CAN	0.820	5.579	3.720	0.971	3.468	0.223	0.095
CHN	84.861	21.278	6.340	1.200	9.521	1.678	0.423
EUR	11.319	27.479	14.790	8.185	5.091	3.207	1.294
IDZ	1.585	3.997	1.538	0.000	0.137	0.004	0.062
IND	15.817	7.738	1.810	0.327	1.188	0.391	0.027
JPN	4.969	8.049	4.521	0.000	0.741	0.254	0.012
KOR	3.480	4.820	1.810	1.416	0.025	0.033	0.031
LAM	0.660	9.427	4.609	0.050	2.951	0.068	0.084
MES	0.130	14.290	15.339	0.038	0.182	0.015	0.001
MEX	0.540	5.100	2.540	0.088	0.353	0.060	0.002
REA	1.680	3.549	2.569	0.053	1.258	0.016	0.012
ROE	5.250	5.300	8.120	0.823	1.227	0.093	0.020
RUS	4.346	6.000	15.451	1.637	1.588	0.002	0.000
USA	18.070	32.749	26.130	7.523	2.368	1.899	1.688

Sources: IEA (2016); IEA (2020). Only the commercial bioenergy is included.

Table 7. Electricity generation in the base year.

Unit: TWh	coal	oil	gas	nuclear	hydro	renewables	bioelectricity & other
AFR	258.03	86.57	282.27	13.81	122.28	7.27	7.44
ANZ	156.95	4.97	62.46	0.00	42.56	16.50	11.47
ASI	257.53	19.61	334.12	42.39	32.42	4.17	23.47
BRA	26.69	35.34	80.91	15.39	373.43	12.80	46.38
CAN	67.27	7.86	59.36	107.25	382.92	24.64	14.92
CHN	4145.32	9.75	123.66	132.53	1051.14	185.30	57.58
EUR	847.76	67.83	468.90	903.64	562.06	354.05	209.64
IDZ	121.53	25.78	56.75	0.00	15.17	0.46	11.00
IND	966.35	22.69	62.91	36.11	131.20	43.19	25.42
JPN	349.81	116.80	422.01	0.00	81.81	28.03	51.06
KOR	236.23	17.20	132.66	156.36	2.75	3.69	3.64
LAM	41.77	123.88	167.99	5.54	325.77	7.50	20.97
MES	0.53	351.20	612.93	4.20	20.06	1.61	0.12
MEX	34.58	32.64	174.89	9.67	38.94	6.64	7.42
REA	51.63	59.79	129.71	5.81	138.89	1.75	0.00
ROE	274.11	4.28	287.95	90.83	135.50	10.22	4.31
RUS	158.03	8.79	527.19	180.75	175.28	0.25	3.56
USA	1712.58	39.89	1161.33	830.58	261.47	209.67	104.81

Sources: IEA (2016)

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 CO_2 emitting source at the global level, accounts for more than 40% of fossil-related and process CO_2 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 (**Table 8**). 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

Table 8. Engineering data of power sector backstop technologies for the U.S.

	Units	Adv. coal	Pulverized Coal w/CCS	Biomass plant	NGCC	NGCC w/CCS	Adv. Nuclear	Wind + Biomass Backup	Wind + Gas Turbine Backup	Biomass plant w/ CCS
Variable O&M	$/kWh	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01
Capacity Factor	%	0.85	0.85	0.80	0.85	0.85	0.85	0.42	0.42	0.80
(Capacity Factor Wind)								0.35	0.35	
(Capacity Factor Biomass/ NGCC)								0.07	0.07	
Operating Hours	hours	7446	7446	7008	7446	7446	7446	3679	3679	7008
Capital Recovery Required	$/kWh	0.05	0.09	0.06	0.01	0.03	0.11	0.17	0.07	0.17
Fixed O&M Recovery Required	$/kWh	0.00	0.01	0.02	0.00	0.00	0.01	0.04	0.01	0.03
Thermal efficiency		0.39	0.37	0.25	0.55	0.46	0.33			0.21
Fuel Cost per kWh	$/kWh	0.03	0.03	0.05	0.03	0.04	0.01	0.01	0.01	0.06
CO_2 capture rate			0.90			0.90				0.90
Cost of CO_2 Transport and Storage	$/t$CO_2$		10.00			10.00				10.00
CO_2 Transportation and Storage Cost	$/kWh		0.01			0.00				0.01
Levelized Cost of Electricity	$/kWh	0.09	0.15	0.13	0.04	0.08	0.13	0.22	0.09	0.28
Transmission and Distribution	$/kWh	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.03
Levelized Cost of Electricity incl. T&D	$/kWh	0.12	0.18	0.16	0.07	0.11	0.16	0.26	0.13	0.31
Markup		1.61	2.42	2.19	1.00	1.52	2.18	3.54	1.78	4.13

Source: EIA (2019); GTAP-power database (Chepeliev, 2020); the capacity factor is from Paltsev *et al.* (2010).

Earth System Model (MESM) study issues such as global mean temperature rise. The GHGs emissions considered in EPPA7 are: CO_2, CH_4, N_2O, PFCs, HFCs, SF_6, and the air pollutants included are: CO, VOCs, NO_X, SO_2, BC, OC, and NH_3.

As with the energy data, the base year combusted CO_2 emissions (i.e., emissions from burning fossil fuels) are calibrated to IEA (2016), which provides the base year data. The process-based CO_2 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 CO_2 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 CO_2 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 CO_2 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-CO_2 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 CH_4 and N_2O, 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, SF_6 and urban pollutants identified in EPPA from the Emission Database for Global Atmospheric Research (EDGAR) (Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency, 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 CO_2 as time goes by, for other emissions (process CO_2, non-CO_2 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 and Corong, 2020), the FAO data, and the Terrestrial Ecosystem Model (Felzer *et al.* 2004). **Table 9** presents the final land cover data at the base year in EPPA7.

Table 9. 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), Feltzer *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 Table A8-1 to Table A8-4 in Appendix A8). 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

Table 10. 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) 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. Alt. 2030 target (55% without offsets) 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	2.5-3.0b 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)

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 are presented in Appendix A8.

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 10**.

The goal of *Accelerated Actions* is to create a global emissions path that is consistent to the "1.5°C scenario.[4]" 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%.[5] For the rest of the world, AFR and REA achieve their 2015 GHGs levels in 2050, while other regions reduce their GHGs in 2050 by 50% relative to 2015 levels. Targets for emissions cuts relative to the 2015 levels are presented in **Table 11**.

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 A9). 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

Table 11. Emissions reductions relative to the 2015 levels for *Accelerated Actions*

Region	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%

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[4] It 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.

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

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 12**).

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 A11 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.

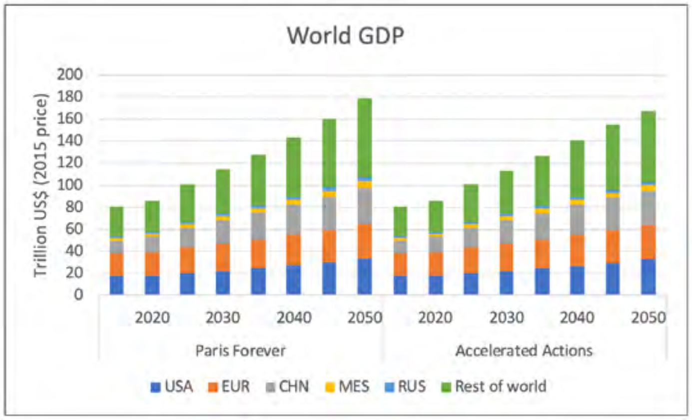

Figure 8. World GDP

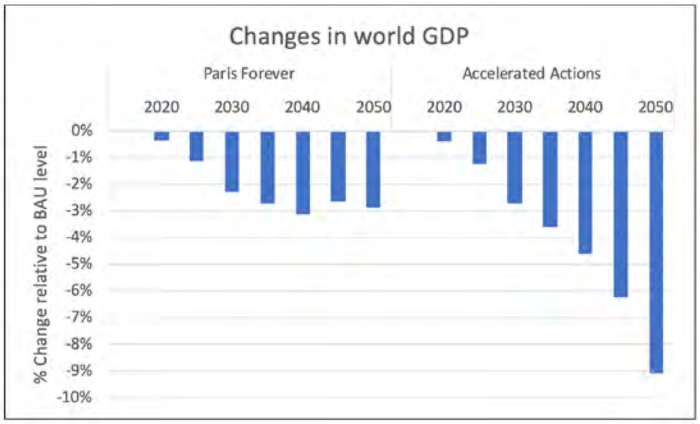

Figure 9. Changes in World GDP

Table 12. Regional GDP Shares

	2020	2030	2040	2050
Reference				
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				
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				
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 10. GDP Impacts under Different Scenarios

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.

The targets of *Accelerated Actions* dictate deeper emissions cuts than those of *Paris Forever*, and further decarboniza-

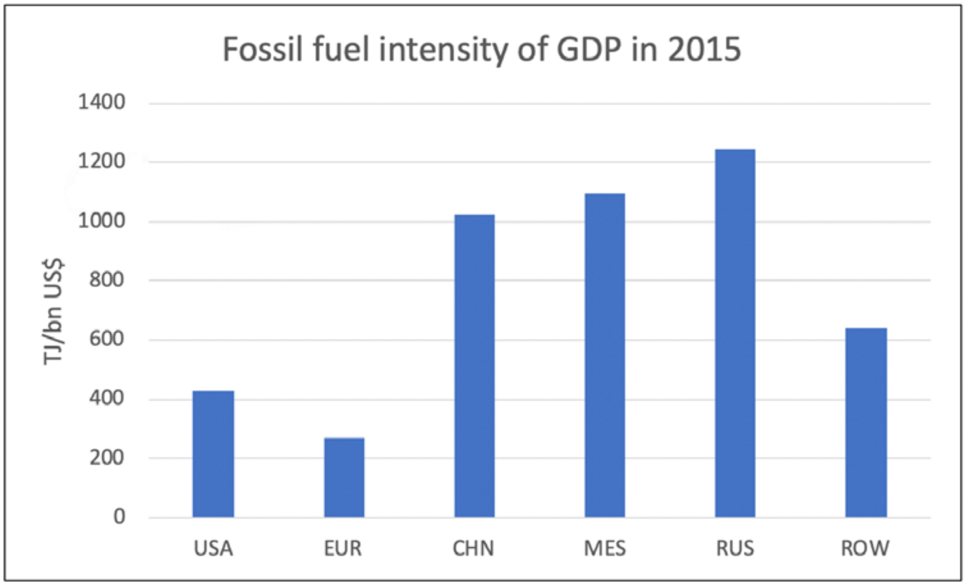

Figure 11. Fossil fuel intensity of GDP by region

tion 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 A10 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 present the sectoral value-added shares of each region under different scenarios (**Table 13**). 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, CO_2 emissions related to burning fossil fuels (i.e., combusted CO_2), 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 CO_2 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.

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 CO_2 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 CO_2 level in 2015, the reductions become 24% in 2030 and 70% in 2050.

Table 13. Sectoral Value-added Shares

		Reference			*Paris Forever*		*Accelerated Actions*	
		2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
USA	gas	0.45%	0.43%	0.40%	0.38%	0.31%	0.26%	0.04%
	coal	0.17%	0.12%	0.08%	0.04%	0.03%	0.01%	0.00%
	oil	1.45%	1.65%	1.52%	1.27%	0.74%	1.14%	0.26%
	roil	0.08%	0.07%	0.06%	0.05%	0.03%	0.05%	0.02%
	elec	0.11%	0.31%	0.39%	0.60%	0.54%	0.64%	0.41%
	other	97.73%	97.41%	97.54%	97.65%	98.36%	97.91%	99.28%
EUR	gas	0.39%	0.35%	0.32%	0.27%	0.27%	0.20%	0.06%
	coal	0.08%	0.05%	0.04%	0.02%	0.01%	0.00%	0.00%
	oil	0.54%	0.62%	0.61%	0.49%	0.33%	0.46%	0.13%
	roil	0.11%	0.09%	0.08%	0.07%	0.04%	0.06%	0.01%
	elec	0.13%	0.18%	0.19%	0.24%	0.37%	0.32%	0.53%
	other	98.76%	98.70%	98.76%	98.92%	98.98%	98.96%	99.26%
CHN	gas	0.01%	0.01%	0.01%	0.02%	0.02%	0.01%	0.01%
	coal	1.22%	1.15%	1.04%	0.71%	0.41%	0.38%	0.04%
	oil	0.65%	0.65%	0.58%	0.48%	0.27%	0.46%	0.10%
	roil	0.33%	0.29%	0.25%	0.19%	0.19%	0.19%	0.13%
	elec	0.18%	0.73%	0.69%	0.88%	1.07%	1.47%	2.38%
	other	97.61%	97.17%	97.42%	97.73%	98.03%	97.48%	97.34%
MES	gas	4.99%	4.62%	4.25%	3.80%	3.02%	3.28%	1.63%
	coal	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%
	oil	26.41%	27.57%	26.29%	24.36%	16.94%	24.34%	9.35%
	roil	1.88%	1.86%	1.65%	1.54%	1.06%	1.49%	0.60%
	elec	0.03%	0.05%	0.06%	0.04%	0.05%	0.05%	3.04%
	other	66.68%	65.90%	67.75%	70.25%	78.93%	70.84%	85.38%
RUS	gas	3.22%	2.89%	2.65%	2.81%	2.45%	2.45%	1.67%
	coal	0.79%	0.71%	0.63%	0.53%	0.42%	0.27%	0.12%
	oil	12.30%	13.39%	13.62%	11.51%	8.79%	11.87%	4.88%
	roil	0.91%	0.83%	0.74%	0.80%	0.63%	0.77%	0.38%
	elec	0.13%	0.22%	0.28%	0.26%	0.31%	0.23%	0.41%
	other	82.65%	81.96%	82.09%	84.09%	87.41%	84.41%	92.55%
Rest of World	gas	0.99%	0.94%	0.88%	0.83%	0.70%	0.73%	0.27%
	coal	0.61%	0.64%	0.60%	0.40%	0.27%	0.23%	0.02%
	oil	2.51%	2.74%	2.59%	2.06%	1.33%	2.00%	0.44%
	roil	0.41%	0.36%	0.30%	0.29%	0.26%	0.27%	0.23%
	elec	0.19%	0.47%	0.55%	0.54%	0.59%	0.66%	1.70%
	other	95.30%	94.84%	95.07%	95.88%	96.86%	96.11%	97.34%

Source: Our simulation.

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.

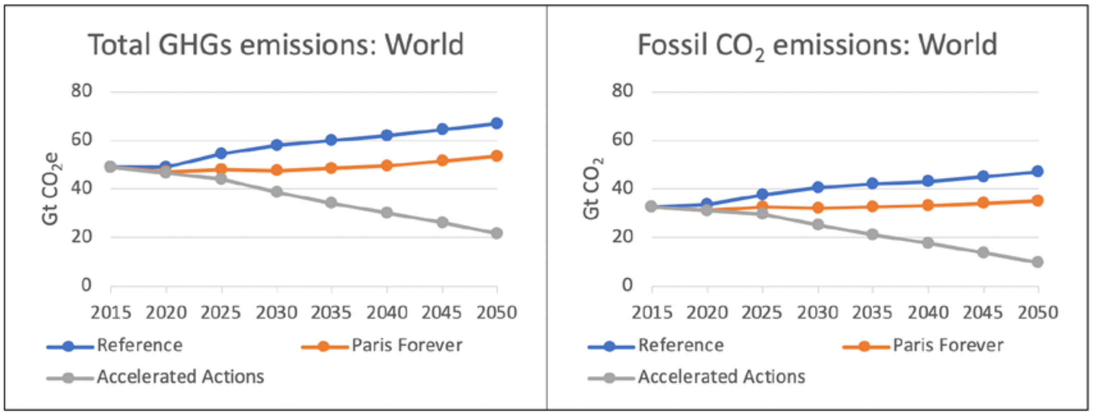

Figure 12. Projections for global GHGs and fossil CO_2 emissions

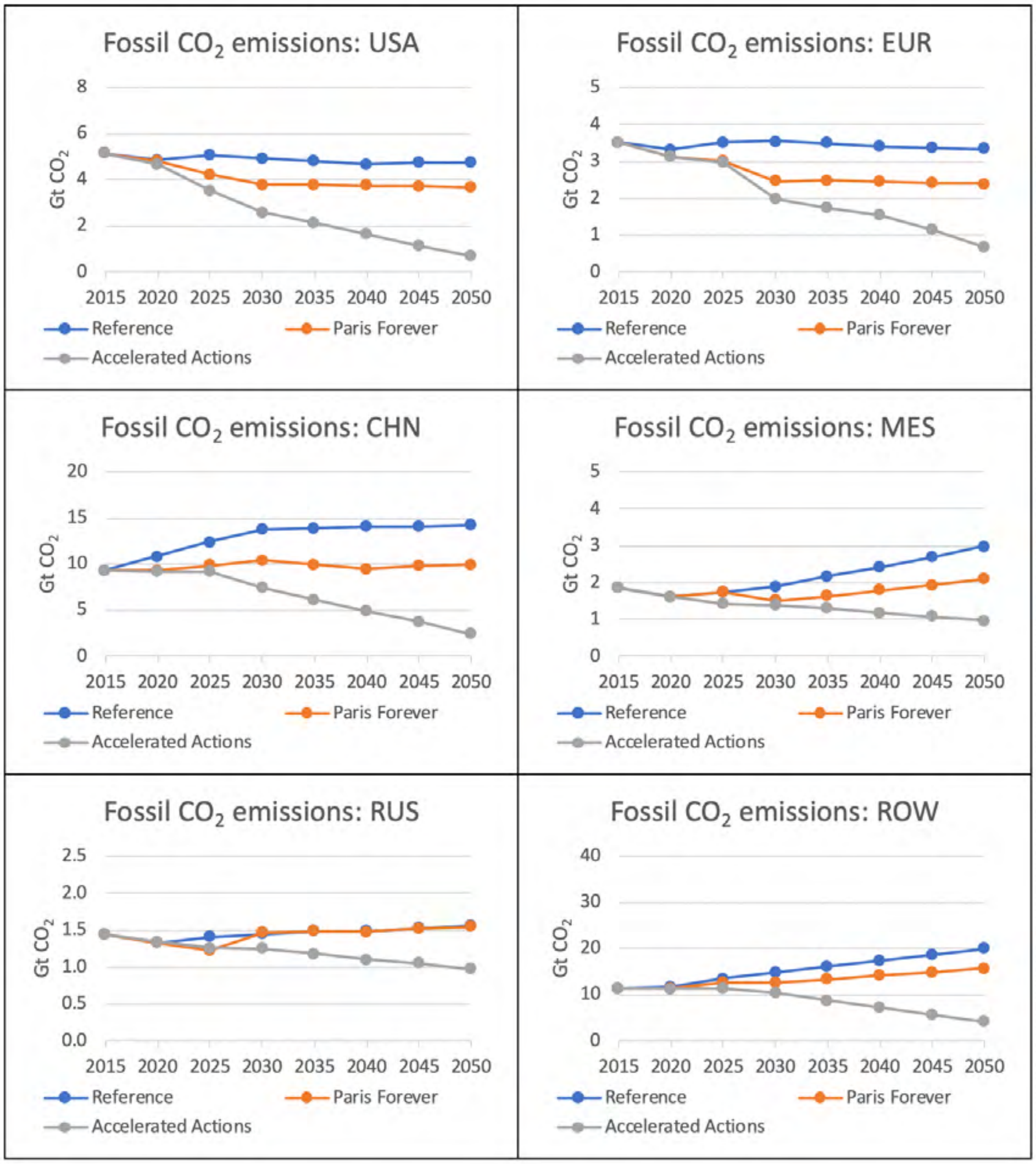

Figure 13. Projections for regional fossil CO_2 emissions

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.

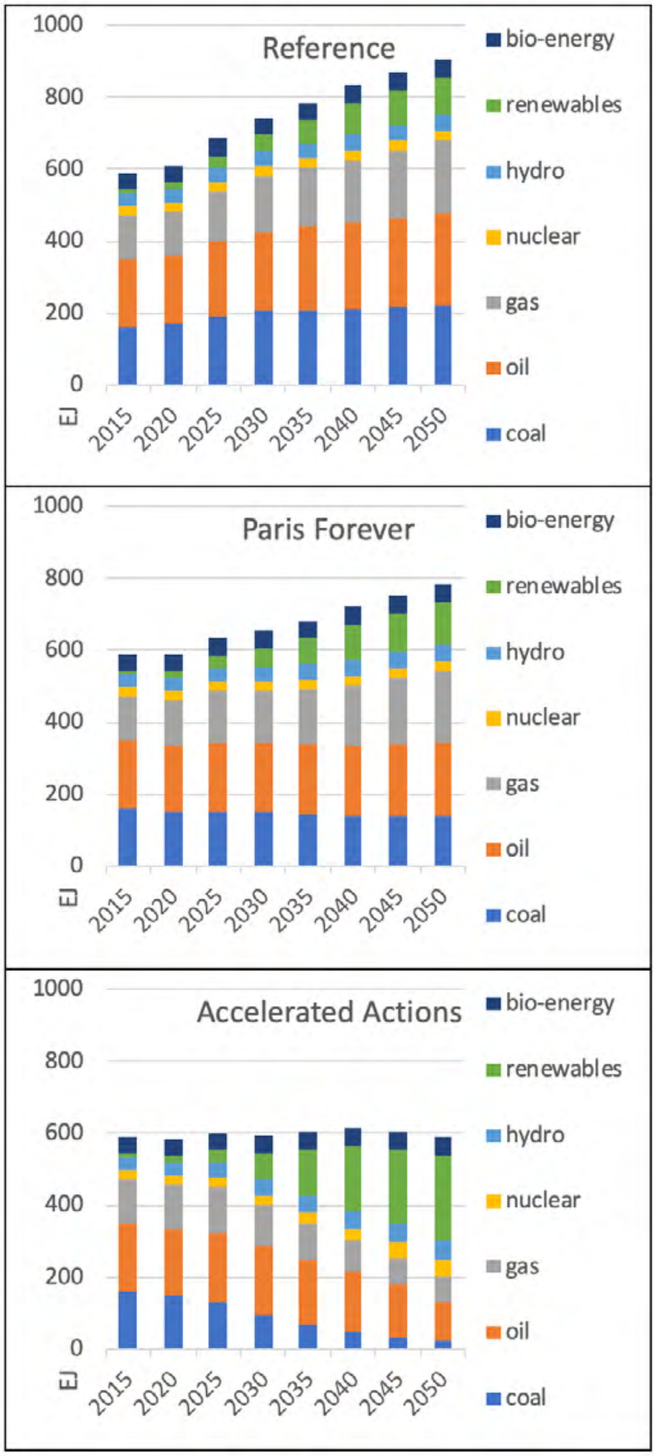

Figure 14. Projections for global primary energy use

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 aforementioned 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.

Similar to the global case, at the regional level, with *Paris Forever*, energy use is reduced to a certain extent across regions (Appendix A12). 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 11).

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 A13), driven by a higher benchmark economic growth based on OECD (2020) (see Section 3.1). For instance, in India (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.

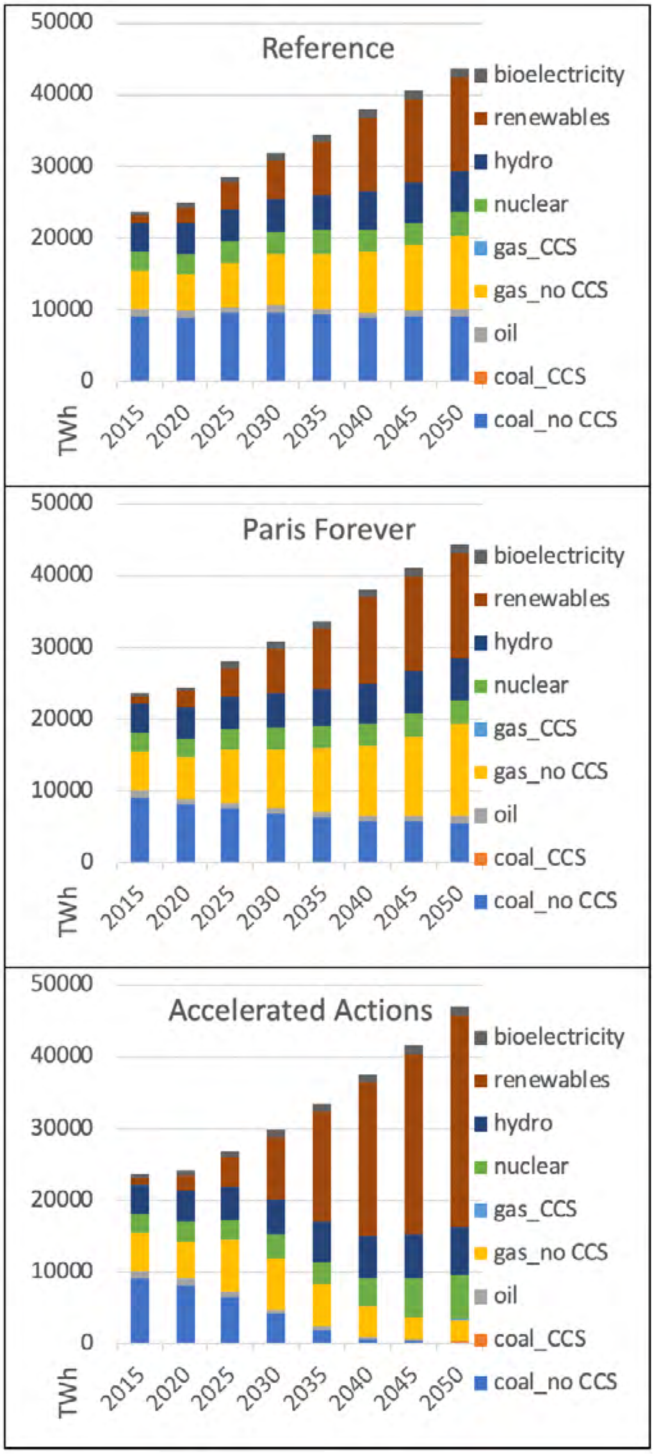

Figure 15. Projections for global generation mix

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.[6] 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 A14) 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

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[6] According to Congressional Research Service (2019), an advanced nuclear reactor is defined as '…*"a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors" or a reactor using nuclear fusion (P.L. 115-248). Such reactors include LWR designs that are far smaller than existing reactors, as well as concepts that would use different moderators, coolants, and types of fuel. Many of these advanced designs are considered to be small modular reactors (SMRs), which the Department of Energy (DOE) defines as reactors with electric generating capacity of 300 megawatts and below, in contrast to an average of about 1,000 megawatts for existing commercial reactors.*'

and may enter the market if it is economically competitive.[7] 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 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 11** 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.

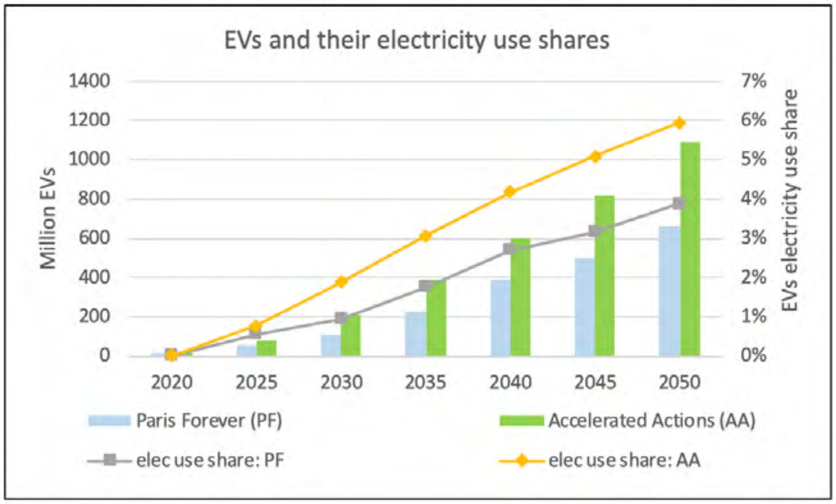

Figure 16. Global EVs and the projected electricity use shares

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[7] As 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.

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.

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

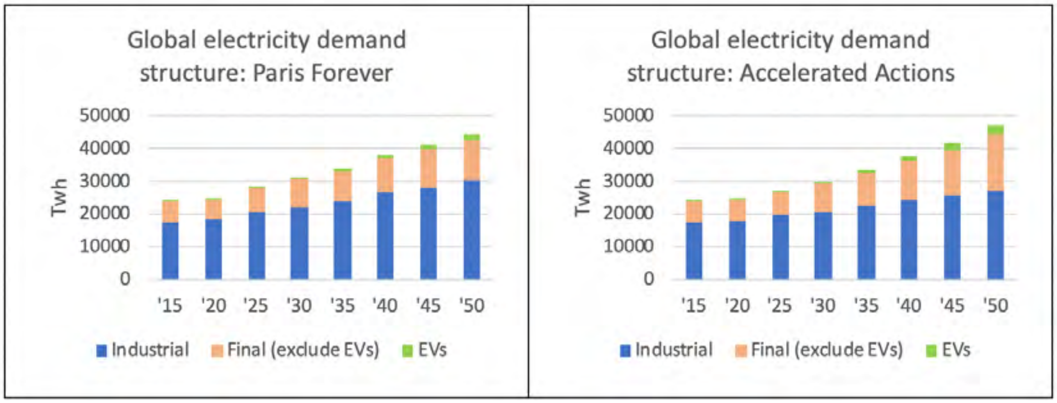

Figure 17. Global electricity demand structure

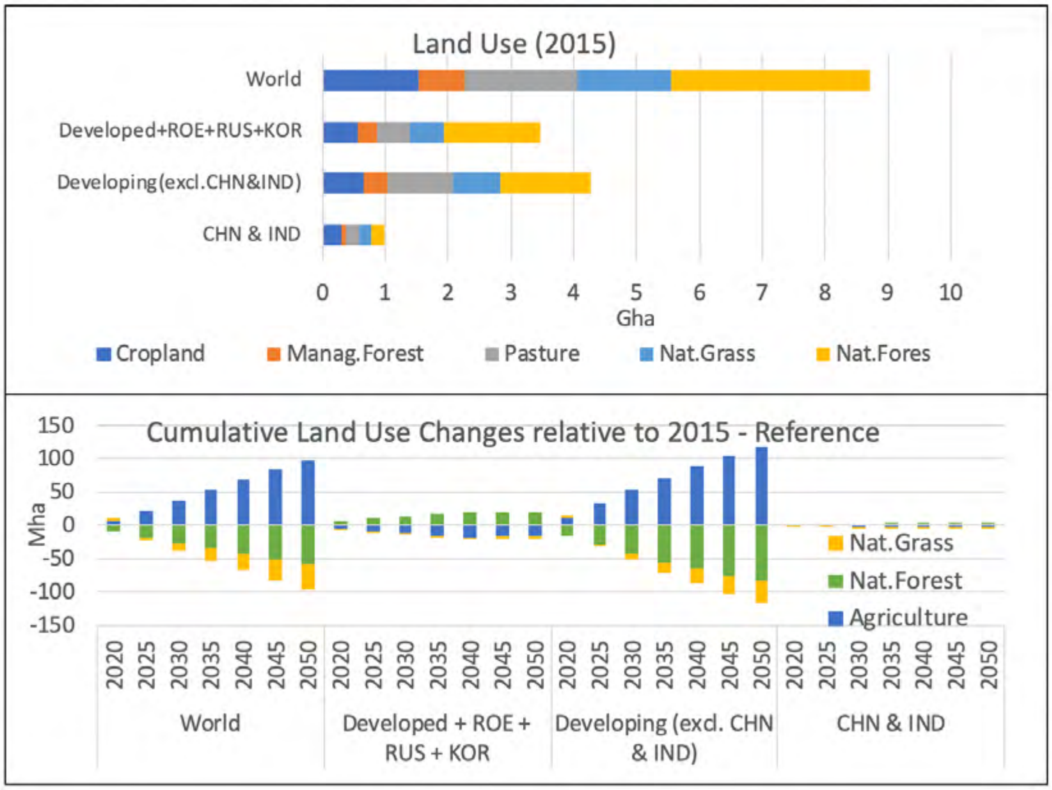

Figure 18. Land use in 2015 (top panel) and changes in land use relative to 2015 in the Reference (bottom).

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 CO_2 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.

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), 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 A15.

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.

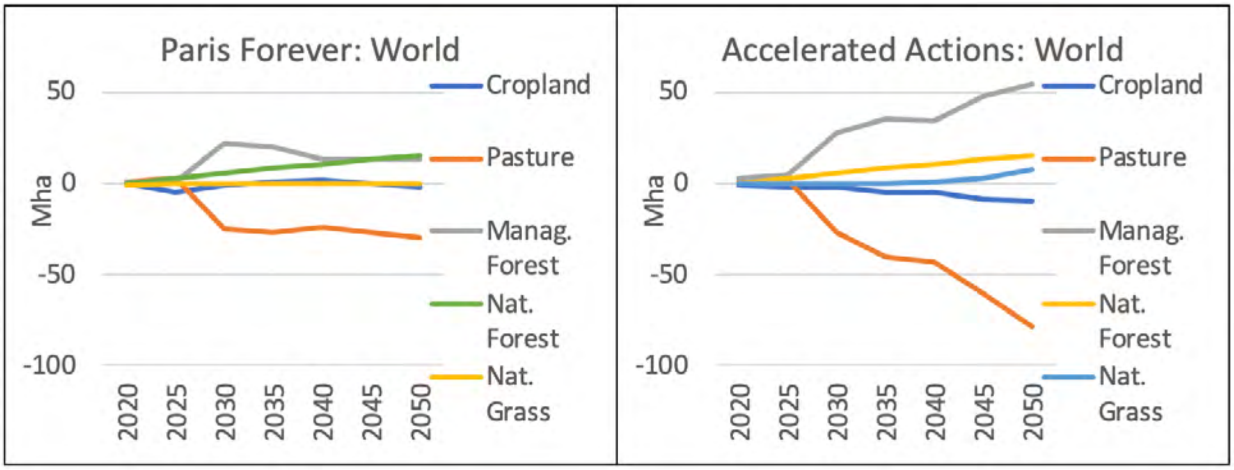

Figure 19. Global changes in land use in decarbonization scenarios relative to the reference run.

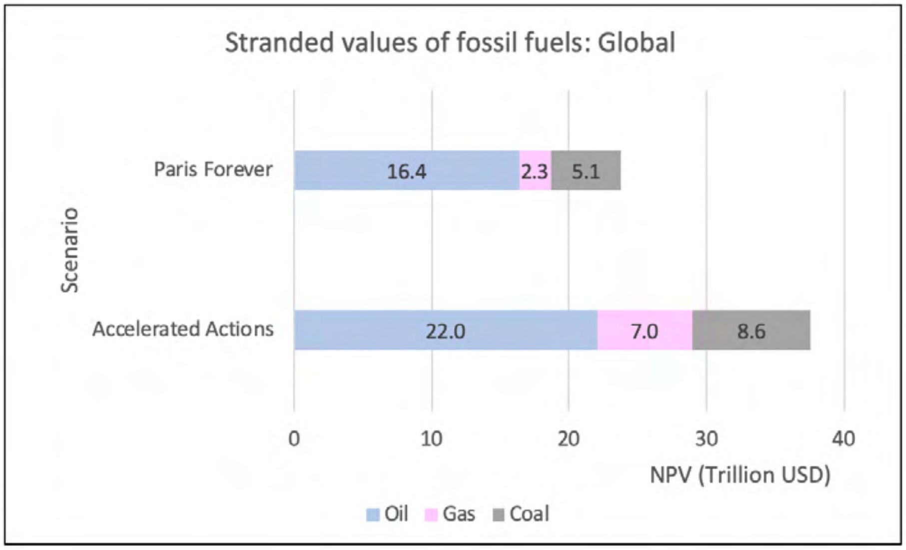

Figure 20. Stranded values of fossil fuels relative to the reference scenario.

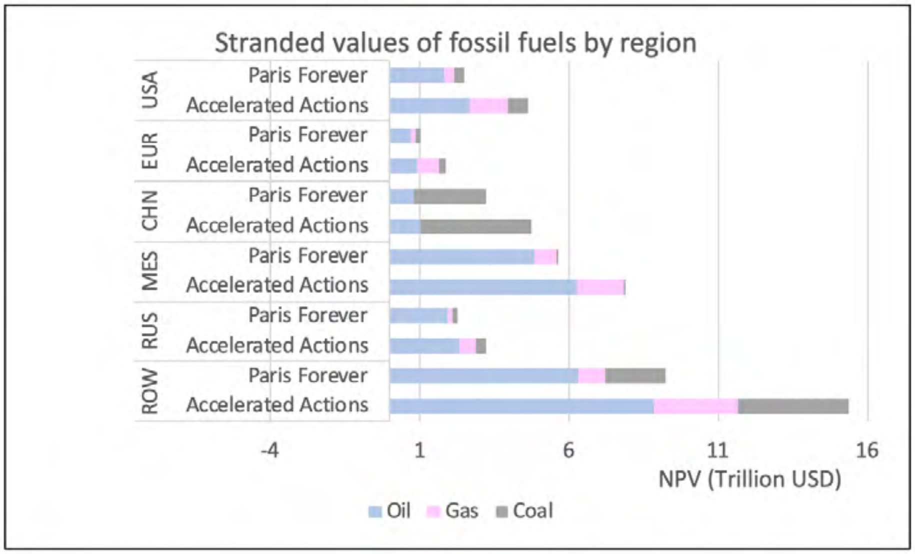

Figure 21. Stranded values of fossil fuels relative to the reference scenario by region.

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**).

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 8 in Section 3.3). As a result, unlike Landry *et al.* (2019) that uses an earlier version of EPPA, in our simulation advanced coal

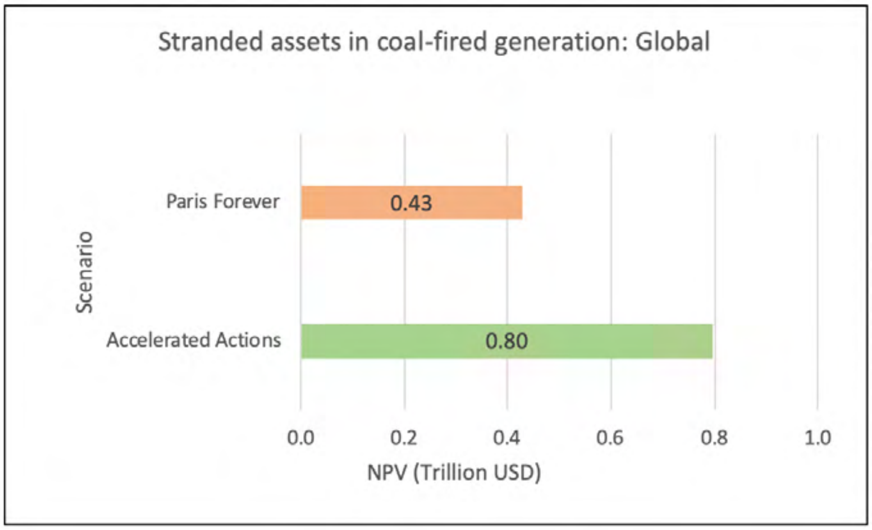

Figure 22. Stranded capital of coal-fired generation relative to the reference scenario.

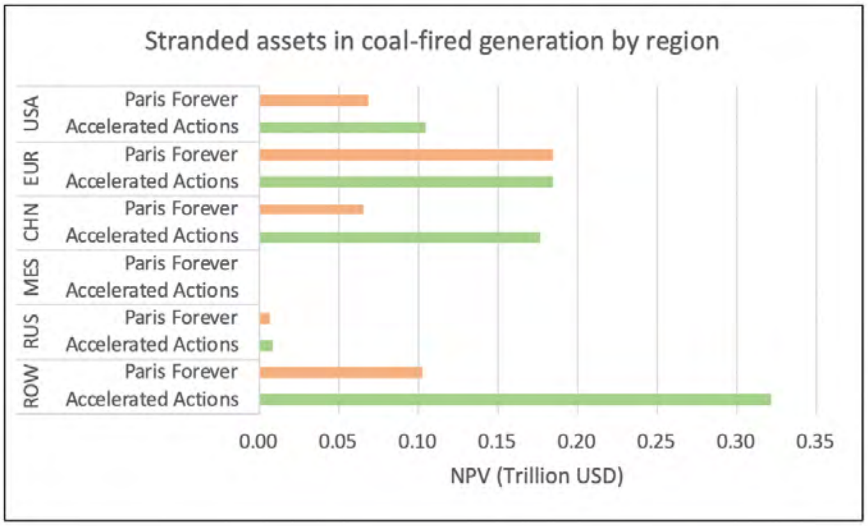

Figure 23. Stranded capital of coal-fired generation relative to the reference scenario by region.

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 polices 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. Conclusions

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. Our 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.

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 are 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 maintaining 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.

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Appendix A1: Stone-Geary preference with a time-varying subsistence consumption in EPPA7

Let us consider a utility function U with preference over commodities indexed by i, and use c_i, c_i^*, and w to represent consumption of commodity i, shift parameter for the consumption of commodity i, and the budget, respectively:

$$u = U(c_1 - c_1^*, c_2 - c_2^*, \ldots, c_N - c_N^*) \tag{A01}$$

The income elasticity for the consumption of commodity i is defined as:

$$\eta_i = \left(\frac{c_i - c_i^*}{c_i}\right) / \left(\frac{w - \sum_{i=1}^{N} c_i^*}{w}\right) \tag{A02}$$

Applying the Engel's Aggregation, Chen *et al.* (2016) shows that for a given η_i, the solution for c_i^* that satisfies Equation (A02) is:

$$c_i^* = (1 - \eta_i) c_i \tag{A03}$$

With Equation (A03), we can calculate c_i^* for the base year (i.e., the first period, denoted by $t=0$) such that the income elasticity of demand for commodity i is η_i. While the same c_i^* is used for the first two periods ($t=0,1$), for each later period is recalibrated to approximate . More specifically, from the third period onward ($t \geq 2$), information from both the adjacent previous period ($t-1$) and the first period ($t=0$) is used to update c_i^* based on Equation (A04):

$$c_{i,t}^* = x_{i,t-1}^T - y_{i,t-1}^T \cdot \frac{x_{i,t-1}^T - x_{i,0}}{y_{i,t-1}^T - y_{i,0}} \; ; t \geq 2 \tag{A04}$$

In Equation (A04), $(x_{i,0}, y_{i,0})$ is the base year consumption bundle, where y_i represents the aggregation of all commodities other than x_i, and $(x_{i,t-1}^T, y_{i,t-1}^T)$ is the imputed consumption bundle derived from the given income elasticities and the budget w_{t-1}, while using the base year relative price level (see Chen *et al.* for details). With this treatment, we can incorporate the existing income elasticity estimates for the final consumption of crop, livestock, food, and transportation products or services. For other EPPA sectors that cannot be directly mapped into sectors in the existing studies, we apply a uniform income elasticity level derived from the Engel's Aggregation.

Appendix A2: Cost function structures for other sectors

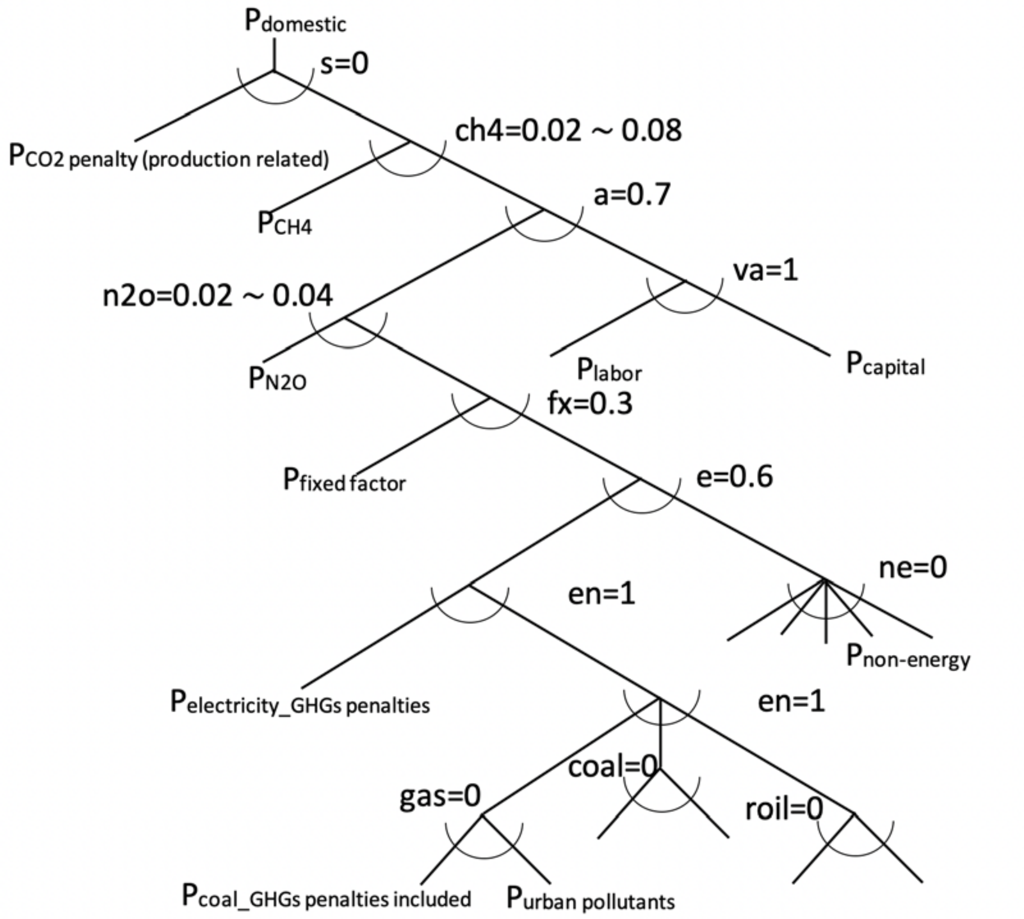
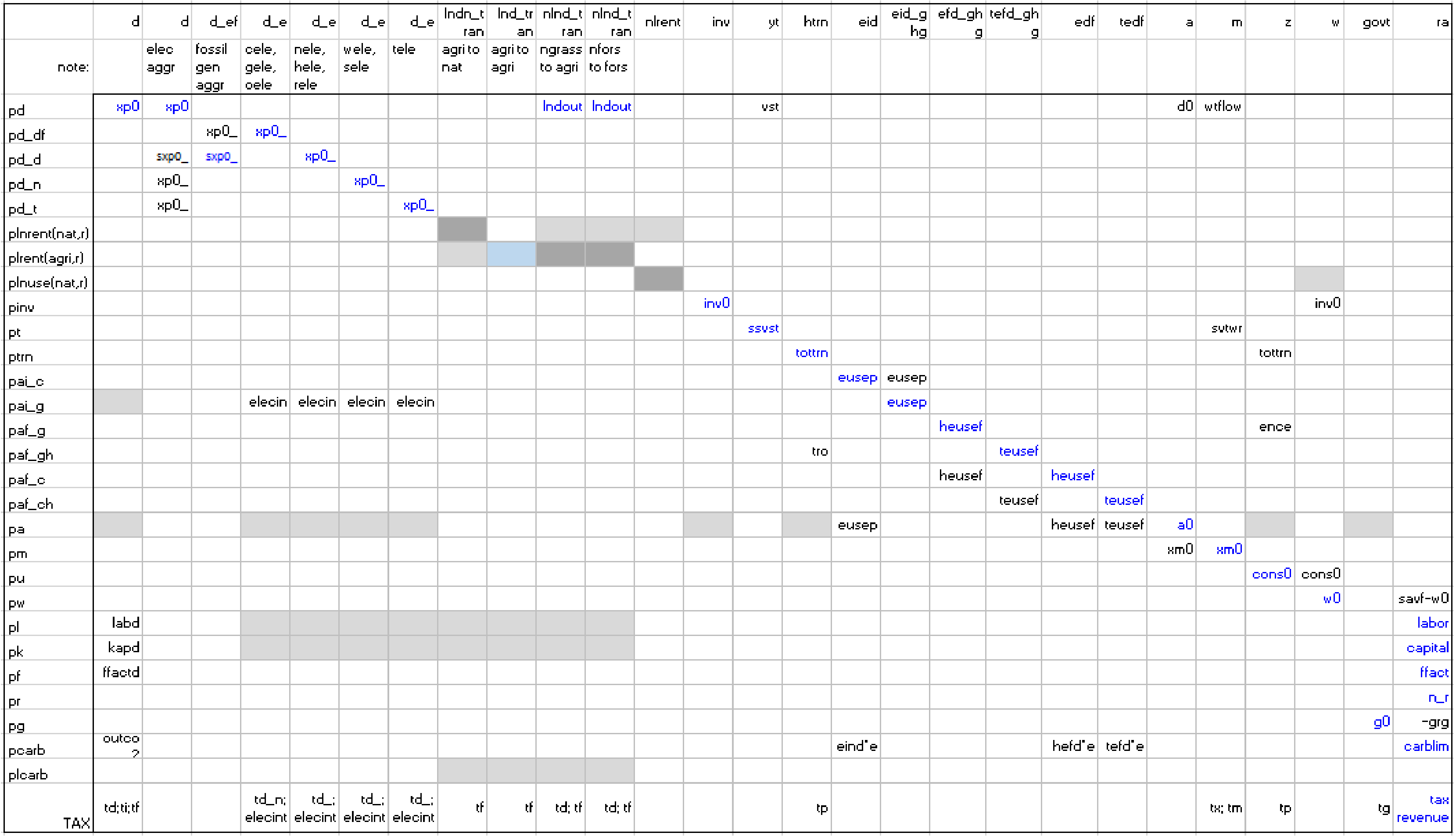


Figure A2-01. Sectoral cost function structure:

Appendix A3: EPPA7 SAM with details



	d	d	d_ef	d_e	d_e	d_e	d_e	lndn_tran	lnd_tran	nlnd_tran	nlnd_tran	nlrent	inv	yt	htrn	eid	eid_ghg	efd_ghg	tefd_ghg	edf	tedf	a	m	z	w	govt	ra
note:		elec aggr	fossil gen aggr	cele, gele, oele	nele, hele, rele	wele, sele	tele	agri to nat	agri to agri	ngrass to agri	nfors to fors																
pd	xp0	xp0								lndout	lndout			vst								d0	wtflow				
pd_df			xp0_	xp0_																							
pd_d		sxp0_	sxp0_		xp0_																						
pd_n		xp0_				xp0_																					
pd_t		xp0_					xp0_																				
plnrent(nat,r)																											
plrent(agri,r)																											
plnuse(nat,r)																											
pinv													inv0												inv0		
pt														ssvst									svtwr				
ptrn															tottrn									tottrn			
pai_c																eusep	eusep										
pai_g				elecin	elecin	elecin	elecin										eusep										
paf_g																		heusef						ence			
paf_gh															tro				teusef								
paf_c																		heusef		heusef							
paf_ch																			teusef		teusef						
pa																eusep				heusef	teusef	a0					
pm																						xm0	xm0				
pu																								cons0	cons0		
pw																									w0		savf-w0
pl	labd																										labor
pk	kapd																										capital
pf	ffactd																										ffact
pr																											n_r
pg																										g0	-grg
pcarb	outco?															eind*e				hefd*e	tefd*e						carblim
plcarb																											
TAX	td;ti;tf			td_n; elecint	td_; elecint	td_; elecint	td_; elecint	tf	tf	td; tf	td; tf				tp								tx; tm	tp		tg	tax revenue

Appendix A4: GTAP to EPPA regional mapping

GTAP region	GTAP region details	EPPA region
ALB	Albania	ROE
ARE	United Arab Emirates	MES
ARG	Argentina	LAM
ARM	Armenia	ROE
AUS	Australia	ANZ
AUT	Austria	EUR
AZE	Azerbaijan	ROE
BEL	Belgium	EUR
BEN	Benin	AFR
BFA	Burkina Faso	AFR
BGD	Bangladesh	REA
BGR	Bulgaria	EUR
BHR	Bahrain	MES
BLR	Belarus	ROE
BOL	Plurinational Republic of Bolivia	LAM
BRA	Brazil	BRA
BRN	Brunei	REA
BWA	Botswana	AFR
CAN	Canada	CAN
CHE	Switzerland	EUR
CHL	Chile	LAM
CHN	China	CHN
CIV	Cote d’Ivoire	AFR
CMR	Cameroon	AFR
COL	Colombia	LAM
CRI	Costa Rica	LAM
CYP	Cyprus	EUR
CZE	Czech Republic	EUR
DEU	Germany	EUR
DNK	Denmark	EUR
DOM	Dominican Republic	LAM
ECU	Ecuador	LAM
EGY	Egypt	AFR
ESP	Spain	EUR
EST	Estonia	EUR
ETH	Ethiopia	AFR
FIN	Finland	EUR
FRA	France	EUR
GBR	United Kingdom	EUR
GEO	Georgia	ROE
GHA	Ghana	AFR
GIN	Guinea	AFR
GRC	Greece	EUR
GTM	Guatemala	LAM
HKG	Hong Kong	CHN
HND	Honduras	LAM
HRV	Croatia	EUR
HUN	Hungary	EUR
IDN	Indonesia	IDZ
IND	India	IND
IRL	Ireland	EUR
IRN	Iran Islamic Republic of	MES
ISR	Israel	MES
ITA	Italy	EUR
JAM	Jamaica	LAM
JOR	Jordan	MES
JPN	Japan	JPN
KAZ	Kazakhstan	ROE
KEN	Kenya	AFR
KGZ	Kyrgyzstan	ROE
KHM	Cambodia	REA
KOR	Korea Republic of	KOR
KWT	Kuwait	MES
LAO	Lao People’s Democratic Republic	REA
LKA	Sri Lanka	REA
LTU	Lithuania	EUR
LUX	Luxembourg	EUR
LVA	Latvia	EUR
MAR	Morocco	AFR
MDG	Madagascar	AFR
MEX	Mexico	MEX
MLT	Malta	EUR
MNG	Mongolia	REA
MOZ	Mozambique	AFR
MUS	Mauritius	AFR
MWI	Malawi	AFR
MYS	Malaysia	ASI
NAM	Namibia	AFR
NGA	Nigeria	AFR
NIC	Nicaragua	LAM
NLD	Netherlands	EUR
NOR	Norway	EUR
NPL	Nepal	REA
NZL	New Zealand	ANZ
OMN	Oman	MES
PAK	Pakistan	REA
PAN	Panama	LAM
PER	Peru	LAM
PHL	Philippines	ASI
POL	Poland	EUR
PRI	Puerto Rico	LAM
PRT	Portugal	EUR
PRY	Paraguay	LAM
QAT	Qatar	MES
ROU	Romania	EUR
RUS	Russian Federation	RUS
RWA	Rwanda	AFR
SAU	Saudi Arabia	MES
SEN	Senegal	AFR
SGP	Singapore	ASI
SLV	El Salvador	LAM
SVK	Slovakia	EUR
SVN	Slovenia	EUR
SWE	Sweden	EUR
TGO	Togo	AFR
THA	Thailand	ASI
TTO	Trinidad and Tobago	LAM
TUN	Tunisia	AFR
TUR	Turkey	ROE
TWN	Taiwan	ASI
TZA	Tanzania United Republic of	AFR
UGA	Uganda	AFR
UKR	Ukraine	ROE
URY	Uruguay	LAM
USA	United States of America	USA
VEN	Venezuela	LAM
VNM	Viet Nam	REA
XAC	South Central Africa	AFR
XCA	Rest of Central America	LAM
XCB	Caribbean	LAM
XCF	Central Africa	AFR
XEA	Rest of East Asia	REA
XEC	Rest of Eastern Africa	AFR
XEE	Rest of Eastern Europe	ROE
XEF	Rest of EFTA	EUR
XER	Rest of Europe	ROE
XNA	Rest of North America	LAM
XNF	Rest of North Africa	AFR
XOC	Rest of Oceania	ANZ
XSA	Rest of South Asia	REA
XSC	Rest of South African Customs Union	AFR
XSE	Rest of Southeast Asia	REA
XSM	Rest of South America	LAM
XSU	Rest of Former Soviet Union	ROE
XTW	Rest of the World	ANZ
XWF	Rest of Western Africa	AFR
XWS	Rest of Western Asia	MES
ZAF	South Africa	AFR
ZMB	Zambia	AFR
ZWE	Zimbabwe	AFR

Appendix A5: GTAP to EPPA sectoral mapping

GTAP sector	GTAP sector details	EPPA sector
PDR	paddy rice	crop
WHT	wheat	crop
GRO	cereal grains nec	crop
V_F	vegetables - fruit - nuts	crop
OSD	oil seeds	crop
C_B	sugar cane - sugar beet	crop
PFB	plant-based fibers	crop
OCR	crops nec	crop
CTL	bo horses	live
OAP	animal products nec	live
RMK	raw milk	live
WOL	wool - silk-worm cocoons	live
FRS	forestry	fors
FSH	fishing	live
COA	coal	coal
OIL	oil	oil
GAS	gas	gas
OXT	minerals nec	othr
CMT	bo meat products	food
OMT	meat products	food
VOL	vegetable oils and fats	food
MIL	dairy products	food
PCR	processed rice	food
SGR	sugar	food
OFD	food products nec	food
B_T	beverages and tobacco	food
TEX	textiles	othr
WAP	wearing apparel	othr
LEA	leather products	othr
LUM	wood products	othr
PPP	paper products - publishing	eint
P_C	petroleum - coal products	roil
CHM	chemical products	eint
BPH	Basic pharmaceuticals	eint
RPP	Rubber and plastic products	eint
NMM	mineral products nec	eint
I_S	ferrous metals	eint
NFM	metals nec	eint
FMP	metal products	eint
ELE	electronic equipment	othr
EEQ	Electrical equipment	othr
OME	machinery and equipment nec	othr
MVH	motor vehicles and parts	othr
OTN	transport equipment nec	othr
OMF	manufactures nec	othr
TnD	transmission and distribution	tele
NuclearBL	nuclear: base load	nele
CoalBL	coal: base load	cele
GasBL	gas: base load	gele
WindBL	wind: base load	wele
HydroBL	hydro: base load	hele
OilBL	oil: base load	oele
OtherBL	other: base load	rele
GasP	gas: peak load	gele
HydroP	hydro: peak load	hele
OilP	oil: peak load	oele
SolarP	solar: peak load	sele
GDT	gas manufacture - distribution	gas
WTR	water	othr
CNS	construction	othr
TRD	trade	serv
AFS	Accommodation & food service	serv
OTP	Land transport & transport via pipelines	tran
WTP	water transport	tran
ATP	air transport	tran
WHS	Warehousing and support activities	tran
CMN	communication	serv
OFI	financial services nec	serv
INS	insurance	serv
RSA	Real estate activities	serv
OBS	Other business services	serv
ROS	recreational and other services	serv
OSG	Public administration and defense	serv
EDU	Education	serv
HHT	Human health and social work	serv
DWE	ownership of dwellings	dwe

Appendix A6: GTAP to EPPA factoral mapping

GTAP factor	GTAP factor details	EPPA factor
off_mgr_pros	Officials and Mangers legislators (ISCO-88 Major Groups 1-2)	lab
tech_aspros	Technicians technicians and associate professionals	lab
clerks	Clerks	lab
service_shop	Service and market sales workers	lab
ag_othlowsk	Agricultural and unskilled workers (Major Groups 6-9)	lab
Land	Land	lnd
Capital	Capital	cap
NatlRes	Natural resources	fix

Appendix A7: Income elasticities for the aggregated household transportation

	USA	CAN	MEX	JPN	ANZ	EUR	ROE	RUS	ASI	CHN	IND	BRA	AFR	MES	LAM	REA	KOR	IDZ
2014	0.996	0.986	1.512	0.984	1.024	1.012	1.385	1.353	1.122	2.351	1.991	1.504	1.156	1.588	1.427	1.795	1.150	1.543
2015	0.980	0.986	1.512	0.984	1.024	1.000	1.385	1.353	1.122	2.301	1.991	1.504	1.156	1.588	1.427	1.795	1.150	1.543
2020	0.917	0.938	1.415	0.950	0.975	0.930	1.293	1.300	1.070	2.037	1.813	1.450	1.096	1.481	1.339	1.650	1.089	1.418
2025	0.830	0.896	1.331	0.900	0.934	0.870	1.216	1.185	1.025	1.800	1.663	1.303	1.047	1.391	1.264	1.529	1.037	1.313
2030	0.760	0.861	1.261	0.850	0.898	0.830	1.152	1.121	0.988	1.609	1.537	1.224	1.006	1.315	1.200	1.428	0.993	1.225
2035	0.700	0.831	1.201	0.800	0.868	0.790	1.099	1.067	0.956	1.425	1.432	1.156	0.971	1.251	1.145	1.343	0.956	1.152
2040	0.650	0.805	1.149	0.750	0.843	0.750	1.054	1.021	0.929	1.264	1.343	1.097	0.943	1.198	1.098	1.271	0.924	1.090
2045	0.620	0.783	1.105	0.700	0.821	0.730	1.017	0.983	0.907	1.142	1.269	1.046	0.920	1.153	1.057	1.211	0.897	1.037
2050	0.600	0.696	0.928	0.700	0.732	0.650	0.832	0.807	0.809	0.990	0.919	0.853	0.799	0.946	0.900	0.928	0.782	0.794
2055	0.600	0.688	0.916	0.700	0.725	0.600	0.832	0.802	0.803	0.989	0.914	0.841	0.799	0.937	0.890	0.924	0.776	0.788
2060	0.550	0.684	0.908	0.700	0.721	0.550	0.832	0.799	0.801	0.983	0.910	0.828	0.800	0.935	0.880	0.920	0.773	0.785
2065	0.550	0.680	0.900	0.700	0.718	0.550	0.832	0.796	0.798	0.977	0.905	0.816	0.801	0.933	0.871	0.916	0.770	0.782
2070	0.550	0.676	0.892	0.700	0.714	0.550	0.832	0.794	0.795	0.972	0.901	0.804	0.802	0.931	0.861	0.912	0.767	0.780
2075	0.550	0.672	0.884	0.700	0.711	0.550	0.832	0.791	0.793	0.966	0.896	0.792	0.802	0.929	0.852	0.908	0.764	0.777
2080	0.550	0.668	0.876	0.700	0.707	0.550	0.832	0.788	0.790	0.960	0.892	0.779	0.803	0.926	0.842	0.904	0.761	0.774
2085	0.550	0.664	0.868	0.700	0.704	0.550	0.832	0.786	0.787	0.955	0.887	0.767	0.804	0.924	0.832	0.900	0.758	0.771
2090	0.550	0.662	0.864	0.700	0.702	0.550	0.832	0.784	0.786	0.952	0.885	0.761	0.804	0.923	0.828	0.898	0.756	0.769
2095	0.550	0.660	0.860	0.700	0.700	0.550	0.832	0.783	0.785	0.949	0.883	0.755	0.805	0.922	0.823	0.896	0.755	0.768
2100	0.550	0.658	0.856	0.700	0.698	0.550	0.832	0.782	0.784	0.946	0.880	0.749	0.806	0.921	0.818	0.894	0.753	0.767

Source: Ghandi and Paltsev (2019). 2014 numbers are interpolated based on that study.

Appendix A8: Policies and Measures (PAMs) in *Paris Forever*

Table A8-1. PAMs: Targets for Wind Power Share Out of Total Electricity Generation

	2015	2020	2025	2030	2035	2040	2045	2050
USA	4.5%	7.1%	9.8%	11.2%	12.7%	13.9%	13.9%	13.9%
CAN	4.3%	6.8%	9.3%	10.6%	11.8%	12.7%	12.7%	12.7%
MEX	4.3%	6.8%	9.3%	10.6%	11.8%	12.7%	12.7%	12.7%
JPN	0.5%	1.1%	1.7%	2.5%	3.0%	3.6%	3.6%	3.6%
ANZ	4.5%	4.5%	5.9%	7.2%	8.3%	8.9%	8.9%	8.9%
EUR	9.4%	14.0%	18.6%	21.4%	24.0%	26.0%	26.0%	26.0%
ROE	1.3%	2.7%	3.9%	5.1%	6.0%	6.6%	6.6%	6.6%
RUS	0.0%	0.2%	0.3%	0.3%	0.4%	0.7%	0.7%	0.7%
ASI	2.4%	4.2%	5.9%	7.2%	8.3%	8.9%	8.9%	8.9%
CHN	3.2%	5.4%	7.6%	8.9%	10.3%	11.4%	11.4%	11.4%
IND	3.1%	4.4%	5.7%	7.1%	8.0%	8.3%	8.3%	8.3%
BRA	3.7%	6.9%	10.1%	11.5%	11.6%	12.0%	12.0%	12.0%
AFR	0.9%	2.2%	3.5%	3.6%	3.8%	4.2%	4.2%	4.2%
LAM	1.0%	1.8%	2.7%	3.0%	3.1%	3.2%	3.2%	3.2%
REA	0.4%	0.5%	0.8%	1.0%	1.1%	1.2%	1.2%	1.2%
KOR	0.2%	0.5%	0.8%	1.0%	1.1%	1.2%	1.2%	1.2%
IDZ	0.0%	0.5%	0.8%	1.0%	1.1%	1.2%	1.2%	1.2%

Source: Current Policies Scenarios in IEA World Energy Outlook 2017/2019

Table A8-2: PAMs: Targets for Solar Power Share Out of Total Electricity Generation

	2015	2020	2025	2030	2035	2040	2045	2050
USA	0.8%	3.1%	5.4%	7.4%	9.2%	11.0%	11.0%	11.0%
CAN	0.7%	2.8%	4.9%	6.7%	8.2%	9.8%	9.8%	9.8%
MEX	0.7%	2.8%	4.9%	6.7%	8.2%	9.8%	9.8%	9.8%
JPN	3.5%	5.8%	8.1%	8.1%	8.1%	8.2%	8.2%	8.2%
ANZ	1.5%	3.7%	6.5%	8.1%	9.2%	10.4%	10.4%	10.4%
EUR	3.4%	5.0%	6.5%	6.9%	7.3%	7.8%	7.8%	7.8%
ROE	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
RUS	0.0%	0.1%	0.2%	0.2%	0.2%	0.3%	0.3%	0.3%
ASI	1.0%	3.7%	6.5%	8.1%	9.2%	10.4%	10.4%	10.4%
CHN	0.8%	3.9%	7.0%	8.8%	10.2%	11.3%	11.3%	11.3%
IND	0.5%	3.8%	7.2%	9.5%	11.3%	13.8%	13.8%	13.8%
BRA	0.0%	0.8%	1.6%	1.9%	2.3%	3.1%	3.1%	3.1%
AFR	0.3%	1.9%	3.4%	4.3%	5.2%	6.3%	6.3%	6.3%
MES	0.0%	1.2%	2.4%	4.3%	6.8%	9.2%	9.2%	9.2%
LAM	0.2%	1.2%	2.1%	2.4%	2.7%	3.4%	3.4%	3.4%
REA	0.1%	0.3%	0.6%	0.6%	0.7%	0.7%	0.7%	0.7%
KOR	0.5%	1.0%	1.6%	1.7%	1.9%	2.0%	2.0%	2.0%
IDZ	1.0%	3.7%	6.5%	8.1%	9.2%	10.4%	10.4%	10.4%

Source: Current Policies Scenarios in IEA World Energy Outlook 2017/2019

Table A8-3: PAMs: Targets for Bio-electricity Share Out of Total Electricity Generation

	2015	2020	2025	2030	2035	2040	2045	2050
USA	1.9%	1.9%	1.9%	2.0%	2.1%	2.2%	2.2%	2.2%
CAN	1.8%	1.8%	1.8%	1.9%	2.0%	2.1%	2.1%	2.1%
MEX	1.8%	1.8%	1.8%	1.9%	2.0%	2.1%	2.1%	2.1%
JPN	4.0%	4.5%	5.0%	5.2%	5.2%	5.2%	5.2%	5.2%
ANZ	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
EUR	6.3%	7.0%	7.7%	7.9%	8.1%	8.2%	8.2%	8.2%
ROE	0.5%	0.7%	1.0%	1.4%	1.8%	2.2%	2.2%	2.2%
ASI	1.5%	2.1%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%
CHN	1.1%	1.7%	2.3%	2.5%	2.5%	2.6%	2.6%	2.6%
IND	1.9%	2.6%	3.2%	2.7%	2.3%	2.0%	2.0%	2.0%
BRA	8.4%	8.6%	8.9%	8.1%	7.4%	6.8%	6.8%	6.8%
AFR	0.2%	0.4%	0.5%	1.0%	1.3%	1.4%	1.4%	1.4%
MES	0.0%	0.1%	0.2%	0.3%	0.5%	0.7%	0.7%	0.7%
LAM	2.9%	3.0%	3.1%	3.0%	2.9%	2.8%	2.8%	2.8%
KOR	0.7%	1.0%	1.3%	1.4%	1.5%	1.6%	1.6%	1.6%
IDZ	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%	4.6%

Source: Current Policies Scenarios in IEA World Energy Outlook 2017/2019

Table A8-4: PAMs: Targets for Nuclear Power Share Out of Total Electricity Generation

	2015	2020	2025	2030	2035	2040	2045	2050
USA	19.4%	17.8%	16.2%	15.1%	13.7%	12.4%	12.4%	12.4%
CAN	17.9%	16.3%	14.7%	13.6%	12.6%	11.5%	11.5%	11.5%
MEX	17.9%	16.3%	14.7%	13.6%	12.6%	11.5%	11.5%	11.5%
EUR	26.8%	24.0%	21.2%	19.2%	17.2%	17.4%	17.4%	17.4%
RUS	18.5%	17.4%	16.3%	16.6%	19.3%	19.4%	19.4%	19.4%
ASI	4.1%	4.8%	5.5%	6.4%	7.0%	7.0%	7.0%	7.0%
CHN	2.9%	4.0%	5.0%	6.3%	7.7%	8.3%	8.3%	8.3%
IND	2.7%	2.7%	2.7%	3.3%	4.1%	4.4%	4.4%	4.4%
BRA	2.5%	2.3%	2.1%	3.2%	4.3%	4.5%	4.5%	4.5%
AFR	1.5%	1.4%	1.3%	2.1%	2.1%	2.2%	2.2%	2.2%
MES	0.3%	1.8%	3.4%	3.1%	4.0%	3.8%	3.8%	3.8%
LAM	0.8%	0.8%	0.7%	0.9%	1.4%	1.5%	1.5%	1.5%

Source: Current Policies Scenarios in IEA World Energy Outlook 2017/2019

Table A8-5. PAMs: Targets for Coal-fired Power Output

	USA	CAN	MEX	JPN	EUR	CHN	IND	MES	IDZ
2015	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2020	-13.3%	-8.3%	-10.0%	-3.3%	-11.7%	0.0%	0.0%	0.0%	-10.0%
2025	-26.7%	-16.7%	-20.0%	-6.7%	-23.3%	0.0%	0.0%	0.0%	-20.0%
2030	-40.0%	-25.0%	-30.0%	-10.0%	-35.0%	0.0%	0.0%	0.0%	-30.0%
2035	-40.0%	-25.0%	-30.0%	-10.0%	-35.0%	0.0%	0.0%	0.0%	-30.0%
2040	-40.0%	-25.0%	-30.0%	-10.0%	-35.0%	0.0%	0.0%	0.0%	-30.0%
2045	-40.0%	-25.0%	-30.0%	-10.0%	-35.0%	0.0%	0.0%	0.0%	-30.0%
2050	-40.0%	-25.0%	-30.0%	-10.0%	-35.0%	0.0%	0.0%	0.0%	-30.0%

Source: Paltsev *et al.* (2021).

Table A8-6. PAMs: Targets for Refined Oil Consumption per Mile for LDVs

	USA	CAN	MEX	JPN	EUR	CHN	IND	MES	IDZ
2015	0%	0%	0%	0%	0%	0%	0%	0%	0%
2020	-9%	-9%	-6%	-12%	-10%	-6%	-6%	-9%	-6%
2025	-20%	-20%	-12%	-24%	-20%	-12%	-12%	-20%	-12%
2030	-30%	-30%	-20%	-35%	-30%	-20%	-20%	-30%	-20%
2035	-35%	-35%	-24%	-39%	-35%	-25%	-24%	-35%	-24%
2040	-40%	-40%	-28%	-43%	-40%	-30%	-28%	-40%	-28%
2045	-45%	-45%	-32%	-48%	-45%	-35%	-32%	-45%	-32%
2050	-50%	-50%	-36%	-52%	-50%	-40%	-36%	-50%	-36%

Source: Jacoby *et al.* (2017) and with our revisions to reflect updated prospects.

Table A8-7. PAMs: Targets for Economy-wide Fuel Consumption for Commercial Transport

	USA	CAN	MEX	JPN	EUR	CHN	IND	MES	IDZ
2015	0%	0%	0%	0%	0%	0%	0%	0%	0%
2020	-3%	-3%	-3%	-3%	-3%	-2%	-2%	-3%	-3%
2025	-6%	-6%	-6%	-6%	-6%	-3%	-3%	-6%	-6%
2030	-13%	-13%	-13%	-13%	-13%	-7%	-7%	-13%	-13%
2035	-19%	-19%	-19%	-19%	-19%	-12%	-12%	-19%	-19%
2040	-24%	-24%	-24%	-24%	-24%	-17%	-17%	-24%	-24%
2045	-30%	-30%	-30%	-30%	-30%	-23%	-23%	-30%	-30%
2050	-35%	-35%	-35%	-35%	-35%	-28%	-28%	-35%	-35%

Source: Jacoby *et al.* (2017).

Table A8-8. PAMs: Targets for Economy-wide Fossil fuel Consumption[1]

	Coal consumption			Refined oil consumption	
	EUR	**CHN**	**IND**	**JPN**	**CHN**
2015	0.0%	0.0%	0.0%	0.0%	0.0%
2020	-29.4%	-5.7%	-	-17.7%	10.6%
2025	-49.5%	-1.3%	-	-25.5%	15.8%
2030	-62.6%	3.6%	34.4%	-36.3%	18.9%
2035	-69.3%	-5.4%	38.7%	-44.3%	14.4%
2040	-76.3%	-13.5%	43.1%	-52.8%	8.4%
2045	-76.3%	-13.5%	47.4%	-55.7%	7.4%
2050	-76.3%	-13.5%	51.8%	-58.3%	5.4%

Source: Paltsev *et al.* (2021).

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[1] India's coal consumption and China's refined oil consumption are allowed to increase, but they are capped from above. India's coal consumption cap is assumed not in place until 2030.

Table A8-9. PAMs: Assumed EVs targets[1]

	2015	2020	2025	2030	2035	2040	2045	2050
Unit: million vehicles								
USA	0.404	1.781	17.015	29.584	44.132	59.025	88.839	106.229
CAN	0.014	0.150	0.270	0.501	1.400	2.863	8.023	12.231
MEX	0.003	0.022	0.590	1.067	2.723	6.779	13.766	23.191
JPN	0.126	0.321	0.662	1.167	2.603	7.634	19.304	27.052
ANZ	0.017	0.105	0.364	0.667	1.707	3.995	11.862	14.352
EUR	0.335	2.500	14.535	27.735	39.673	50.443	86.781	105.835
ROE	0.003	0.150	0.512	0.940	2.597	6.043	13.996	23.224
RUS	0.004	0.096	0.766	1.340	3.100	7.614	12.724	16.417
ASI	0.004	0.170	0.918	1.658	4.721	10.212	21.916	29.686
CHN	0.313	4.500	14.253	27.333	48.695	70.694	108.476	128.568
IND	0.012	0.037	1.295	3.146	8.888	21.563	35.406	46.118
BRA	0.002	0.085	0.461	0.877	2.040	4.049	11.072	20.006
AFR	0.002	0.100	0.345	0.638	1.880	5.116	14.254	23.079
MES	0.004	0.111	0.880	2.530	3.274	7.115	12.051	19.065
LAM	0.003	0.182	0.631	1.161	3.087	9.559	15.754	25.544
REA	0.001	0.026	0.332	0.574	1.292	3.055	5.307	9.721
KOR	0.016	0.141	0.523	2.065	3.521	6.246	11.618	15.013
IDZ	0.001	0.074	0.612	1.268	2.406	3.473	6.730	10.428

Source: MIT Energy Initiative (2019), Paltsev *et al.* (2022).

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[1] PAMs in the forms of subsidizing EVs and taxing ICEs are used to achieved these targets.

Appendix A9: Additional PAMs in Accelerated Actions

Table A9-1: Additional PAMs for EV targets in *Accelerated Actions*

Unit: million cars								
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
USA	0.404	4.850	20.064	48.618	80.584	113.413	145.401	183.036
CAN	0.014	0.130	1.729	4.606	8.180	12.296	16.642	21.513
MEX	0.003	0.020	0.799	3.156	7.358	13.245	20.063	29.339
JPN	0.126	0.280	3.986	9.389	15.432	21.338	26.817	32.332
ANZ	0.017	0.313	1.409	3.770	6.752	10.255	14.053	18.304
EUR	0.335	5.370	22.626	55.882	93.857	131.953	164.230	203.460
ROE	0.003	0.133	0.993	3.954	9.193	16.526	25.033	36.606
RUS	0.004	0.088	1.043	3.804	8.377	14.109	20.051	27.523
ASI	0.004	0.150	1.006	4.183	9.765	17.466	26.424	38.460
CHN	0.313	3.479	16.950	50.325	91.956	142.298	193.218	250.411
IND	0.012	0.032	1.094	4.859	11.739	22.077	33.989	50.848
BRA	0.002	0.074	0.837	3.361	7.751	13.624	20.460	29.525
AFR	0.002	0.089	0.768	3.253	8.128	15.639	25.237	38.822
MES	0.004	0.086	0.908	3.620	8.482	15.428	23.573	34.523
LAM	0.003	0.159	0.988	3.839	9.183	16.691	25.723	37.867
REA	0.001	0.023	0.300	1.241	3.005	5.598	8.666	12.857
KOR	0.016	0.317	1.418	3.885	6.919	10.452	14.246	18.713
IDZ	0.001	0.075	0.489	1.940	4.436	7.803	11.327	15.961

Source: Paltsev *et al.* (2022).

Appendix A10: Changes in welfare relative to the Reference scenario

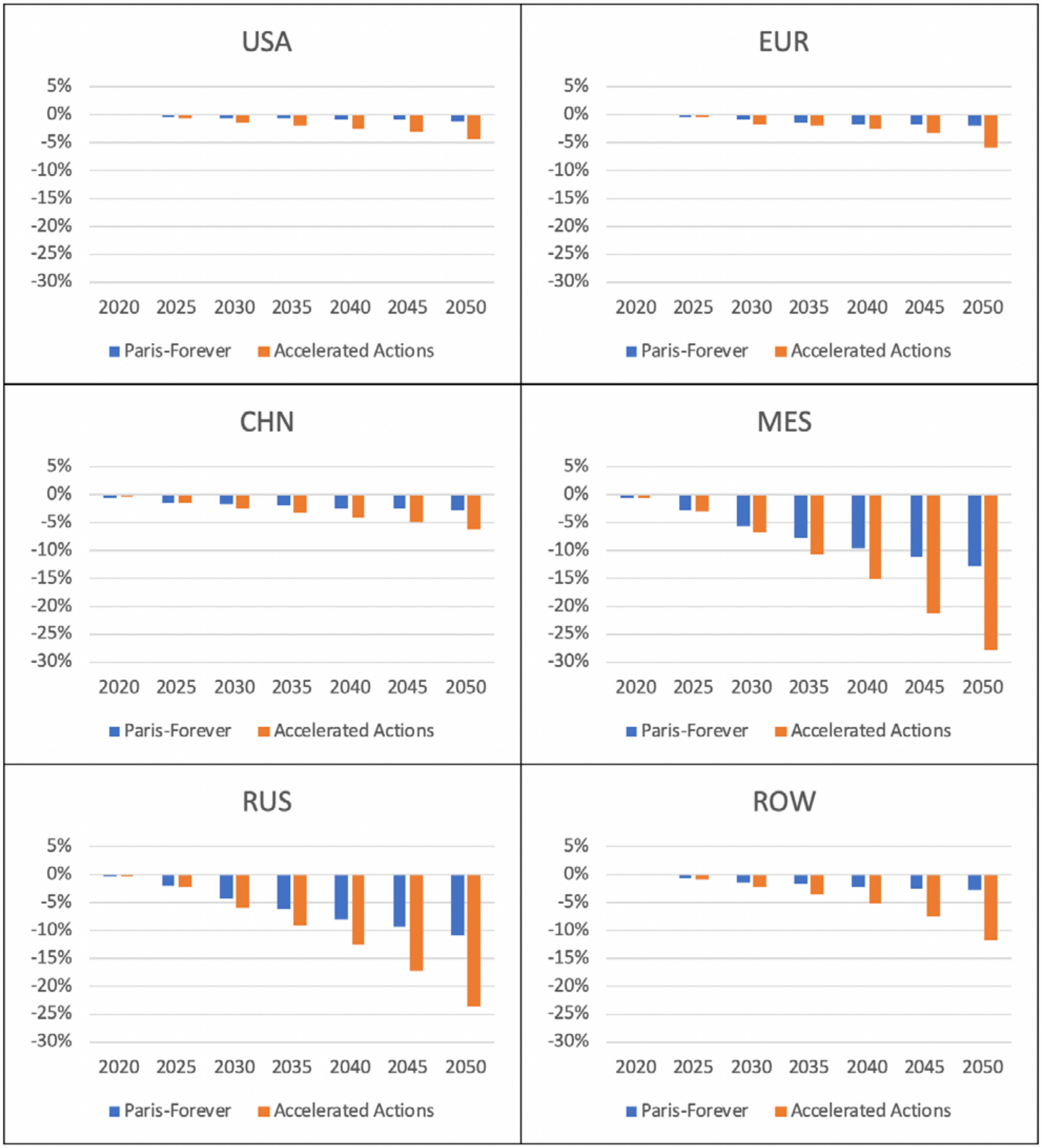

Figure A10-1. Changes in welfare (aggregate consumption)

Appendix A11: Sensitivity analysis

The sensitivity analysis considers a serious of GHGs mitigation targets applied on top of the reference run across regions with a timeframe up to 2050. In particular, starting from 2020, all regions are imposed with the same percentage of GHGs reduction for a given period. The reduction percentage increases linearly over time until 2050, when 10% to 80% emissions cut relative to 2015 levels are achieved. GHGs are assumed not being traded internationally, but they can be traded within a region.

We focus on the following five countries/regions to demonstrate the impact of GDP under distinct mitigation levels relative to the reference scenario: USA, EUR, CHN, MES, and RUS. For these regions, in general, the first three are net importers of fossil fuels while the last two are net fossil fuel exporters (**Table A11-1**). With efforts in cutting GHGs emissions related to the use of fossil fuels, GDP impacts on regions that are net importers of fossil fuels are generally much milder or even positive, due to the lower producer prices for fossil fuels, except for the gas prices in CHN (**Figure A11-1**).[8]

In terms of the base year fossil fuel import structures, USA, EUR, and CHN import 16.4% (15.9% crude oil and 0.5% gas), 44.3% (7.1% coal, 28.5% crude oil, and 8.7% gas), and 16.8% (5.3% coal, 10% crude oil, and 1.5% gas) of their primary energy supplies, respectively, which could explain why the positive GDP impact (up to a 70% mitigation) is highest in EUR.

As mitigation targets become more stringent, however, it becomes harder to capitalize the benefit of lower import prices for fossil fuels, since further decarbonization means that the domestic economy is required to substantially cut the fossil fuel consumption. This explains why GDP impacts of EUR and USA eventually turn negative.

The GDP impact is quite different for MES and RUS, two key fossil fuel exporting regions of the world. The mitigation efforts worldwide require cutting the fossil fuel usage globally, and therefore would suppress the producer prices of fossil fuels (**Figure A11-2**). As a result, both regions are projected to incur considerable GDP losses since their terms of trade become much worse.

Table A11-1. Fossil fuel net imports in the base year

billion US$ (2015 prices)	coal	oil	gas
USA	-20.74	145.26	4.79
EUR	51.31	205.89	62.70
CHN	67.42	126.09	18.81
MES	1.12	-342.44	-38.38
RUS	-34.15	-50.22	-55.01
ROW	-65.59	-167.98	20.73

Source: GTAP-Power 10 Database.

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[8] In our model, crude oil is treated as a homogenous good across the world and its price is determined internationally, while gas and coal are treated as differentiated goods across regions and their prices are more likely to be affected by regional supply-demand and trade patterns.

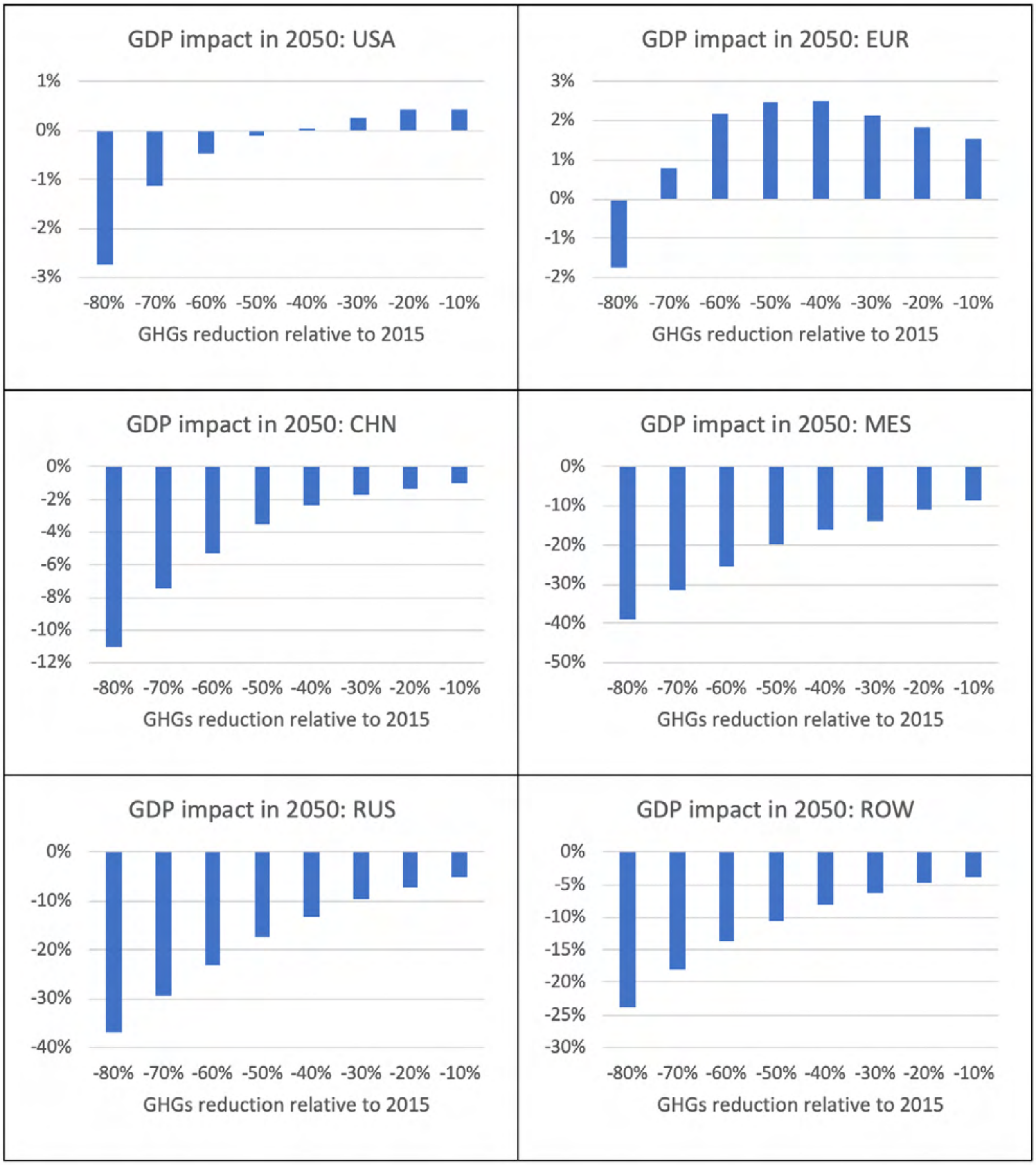


Figure A11-1. How GDP impact changes in response to different mitigation levels

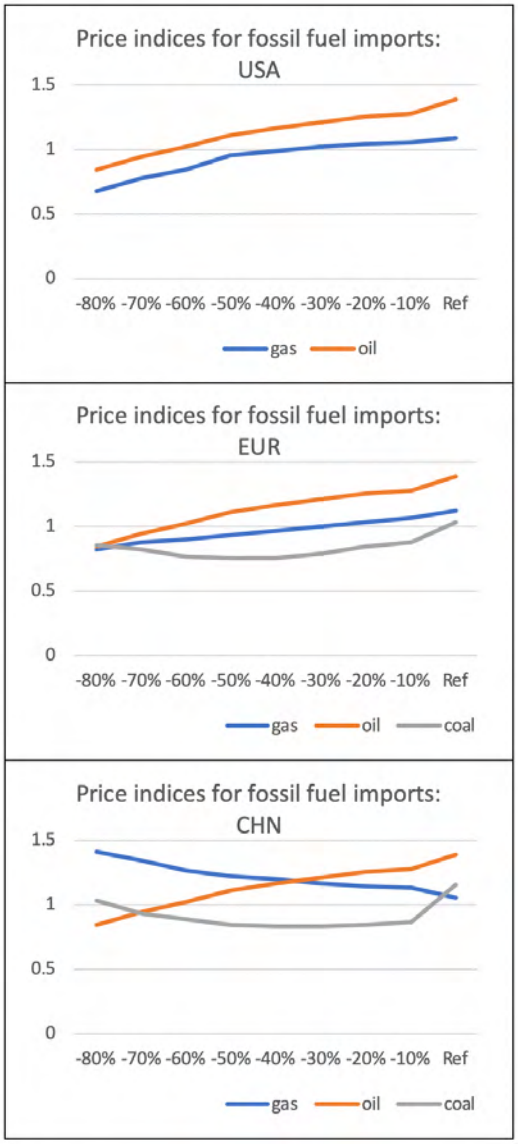


Figure A11-2. Prices for fossil fuel imports in USA, EUR, and CHN

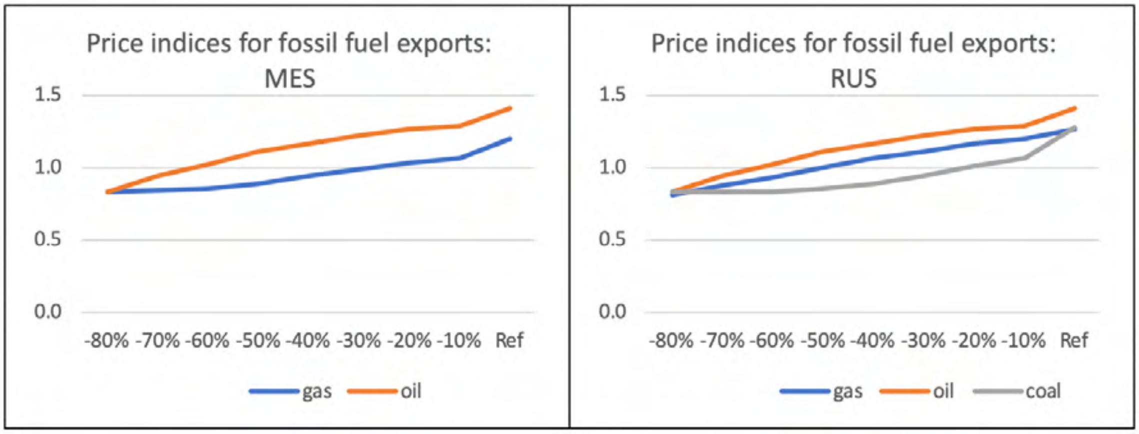


Figure A11-3. Prices for fossil fuel exports in MES and RUS

Appendix A12: Regional primary energy use projection under different scenarios

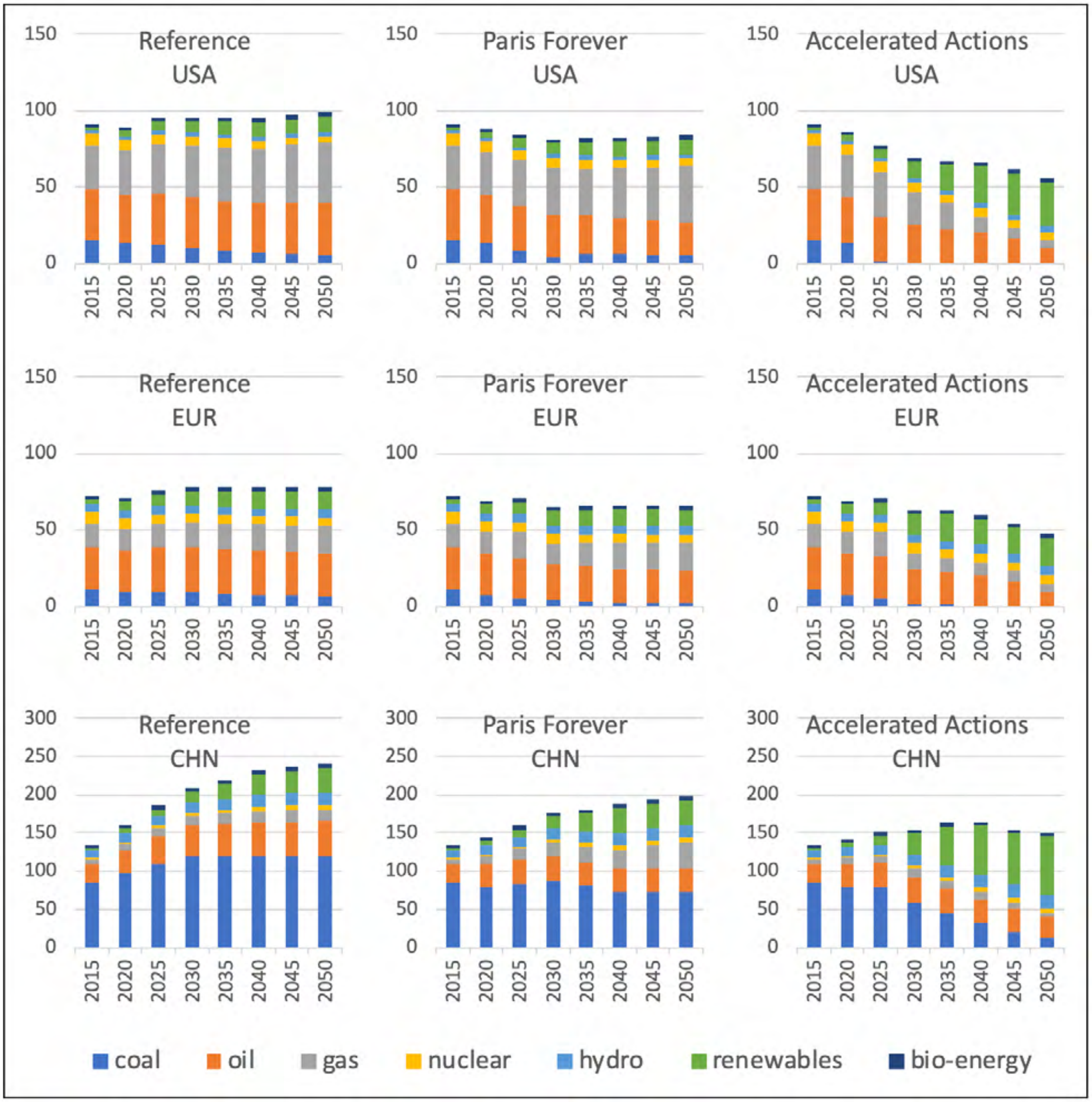


Figure A12-1. Projections for regional primary energy use

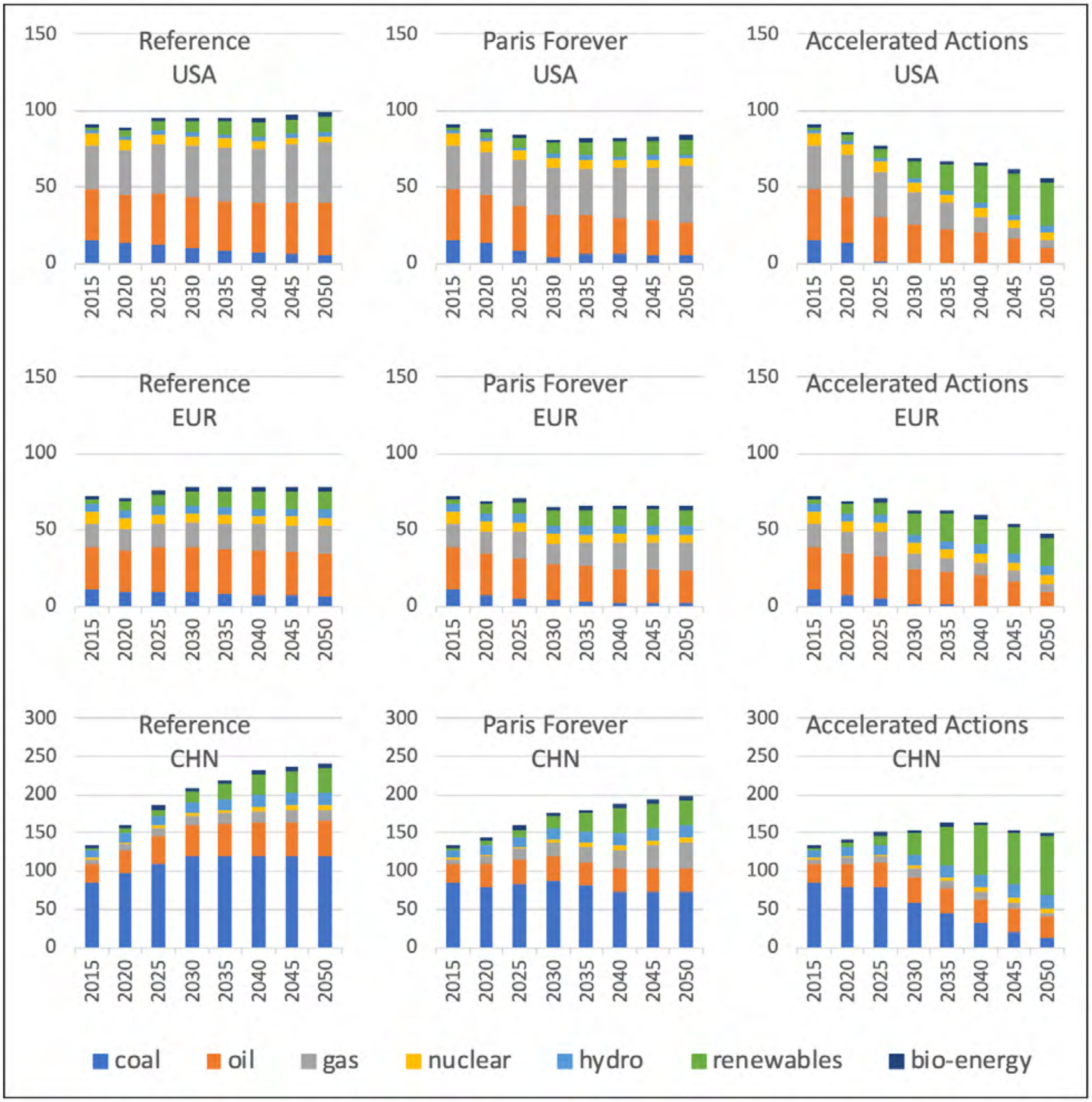


Figure A12-1 (continued). Projections for regional primary energy use

Appendix A13: Regional generation mix projection under different scenarios

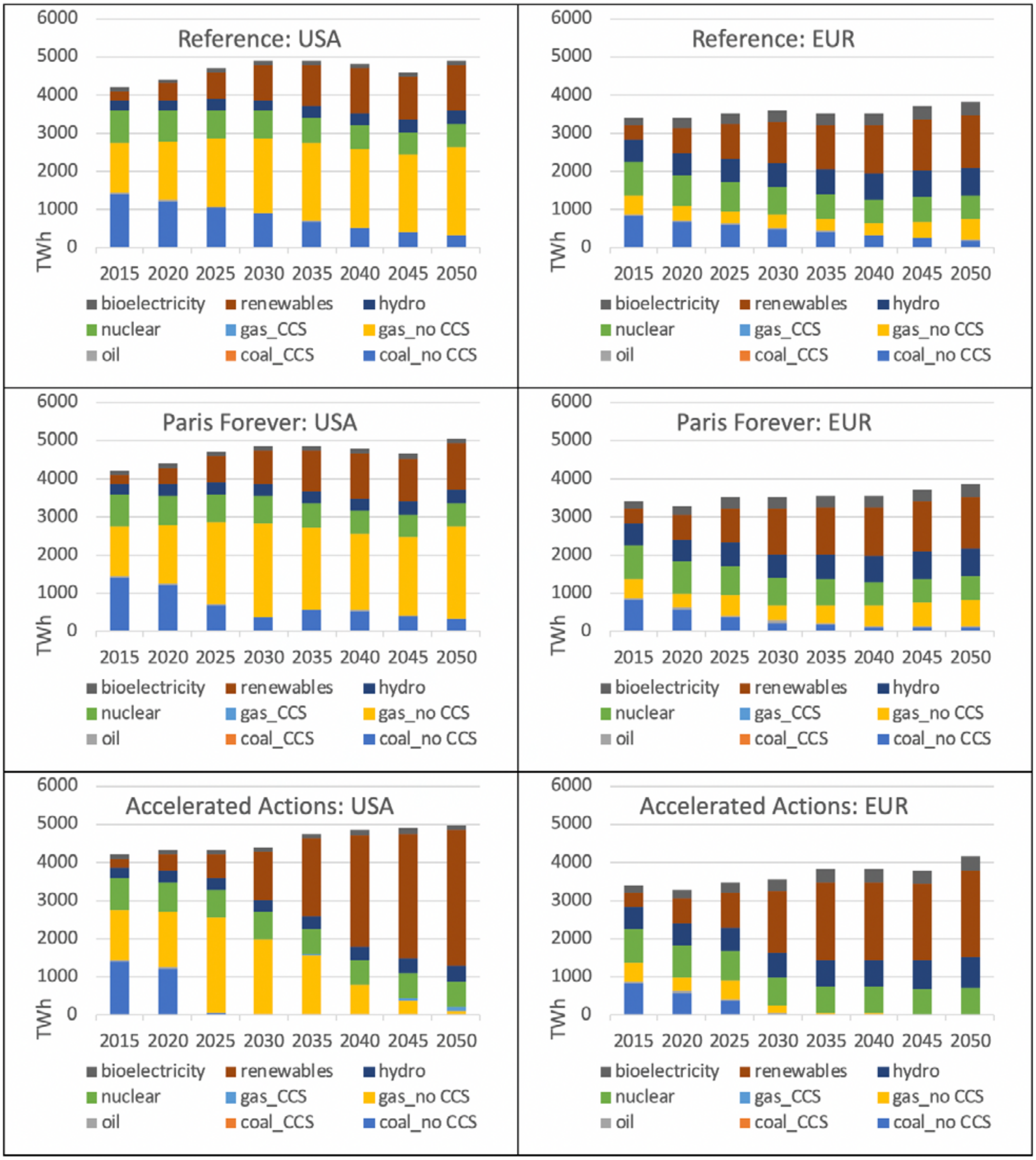


Figure A13-1. Projections for regional generation mix

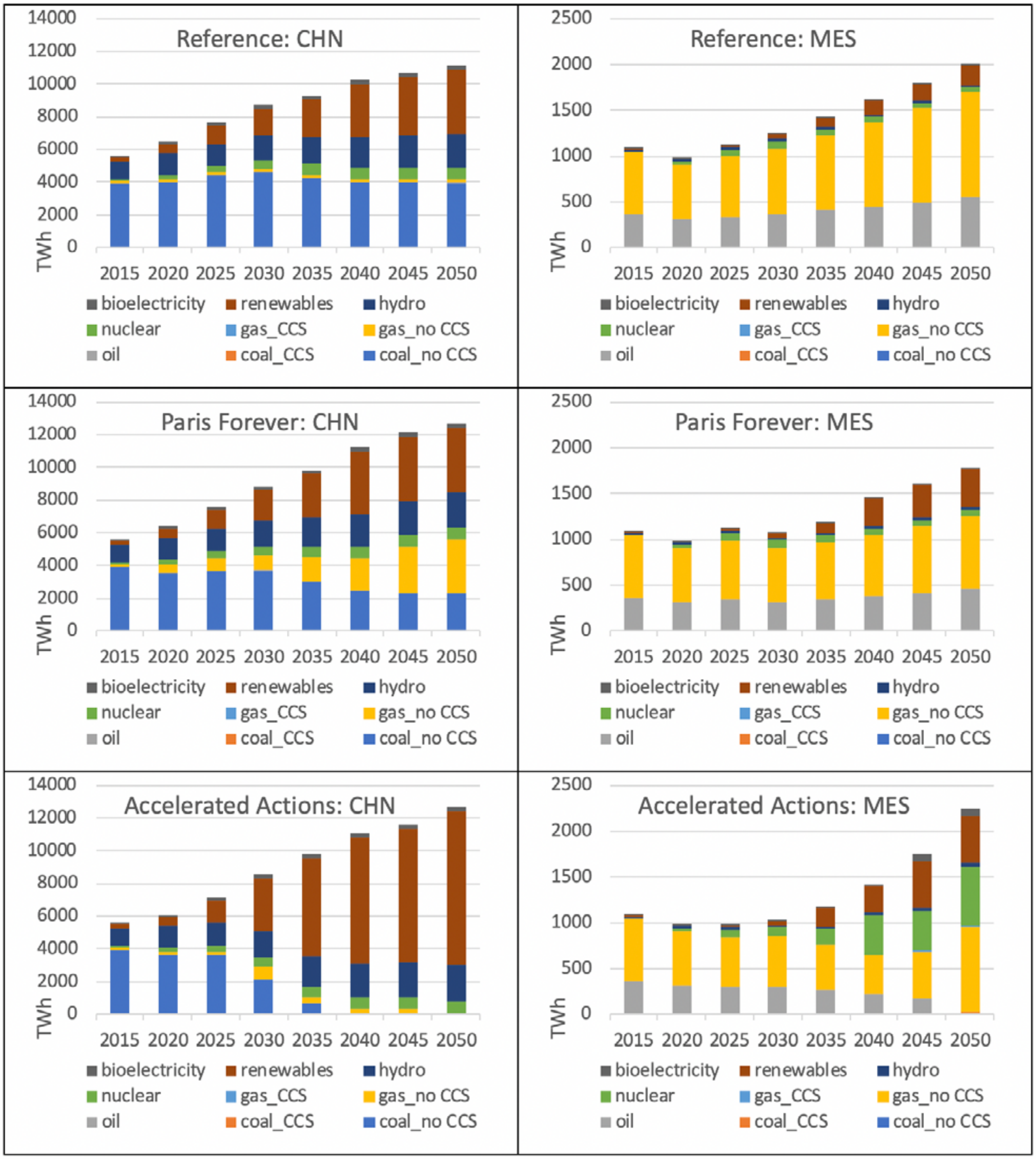
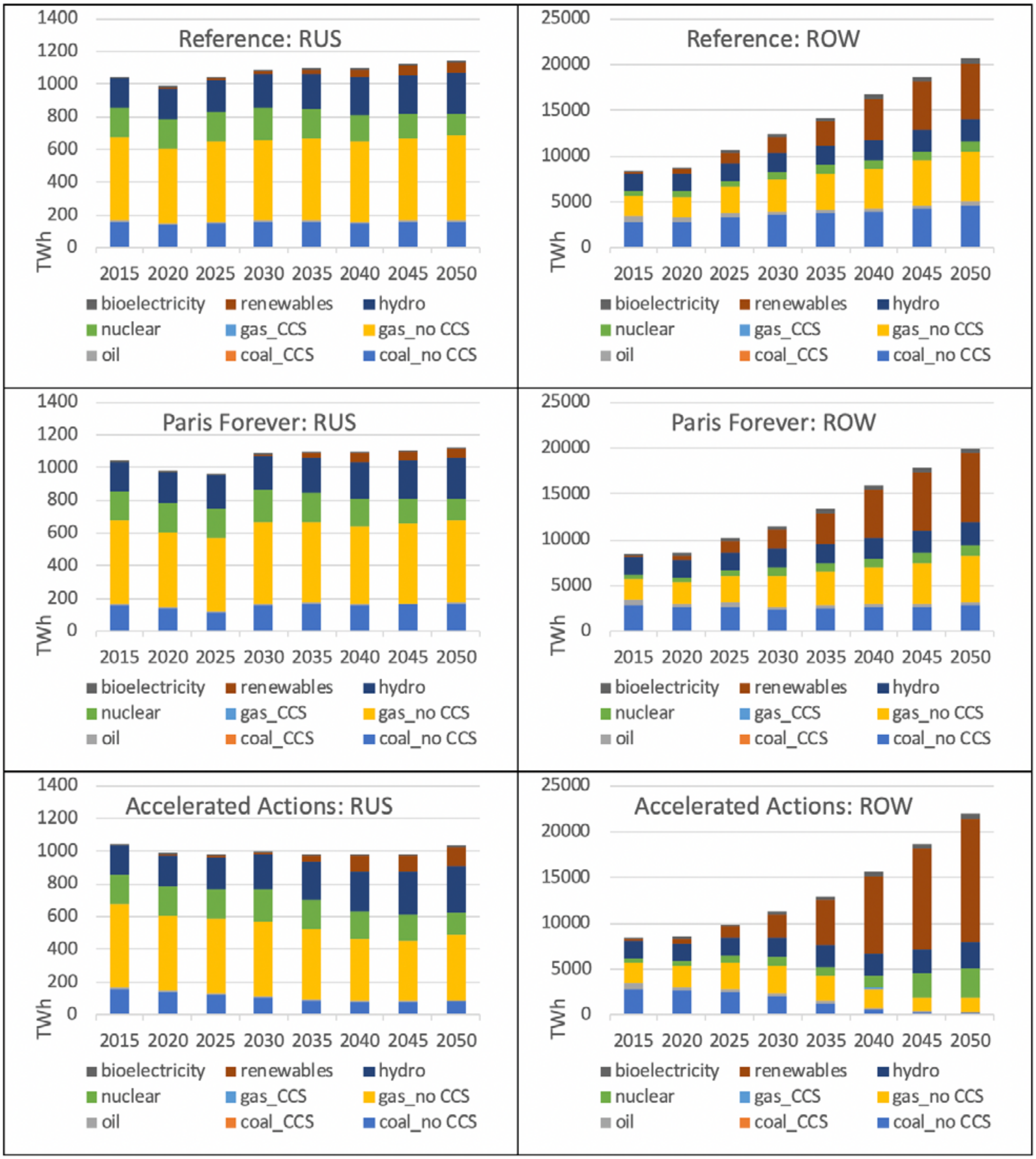


Figure A13-1 (continued). Projections for regional generation mix


Reference: RUS

Reference: ROW

Paris Forever: RUS

Paris Forever: ROW

Accelerated Actions: RUS

Accelerated Actions: ROW

Figure A13-1 (continued). Projections for regional generation mix

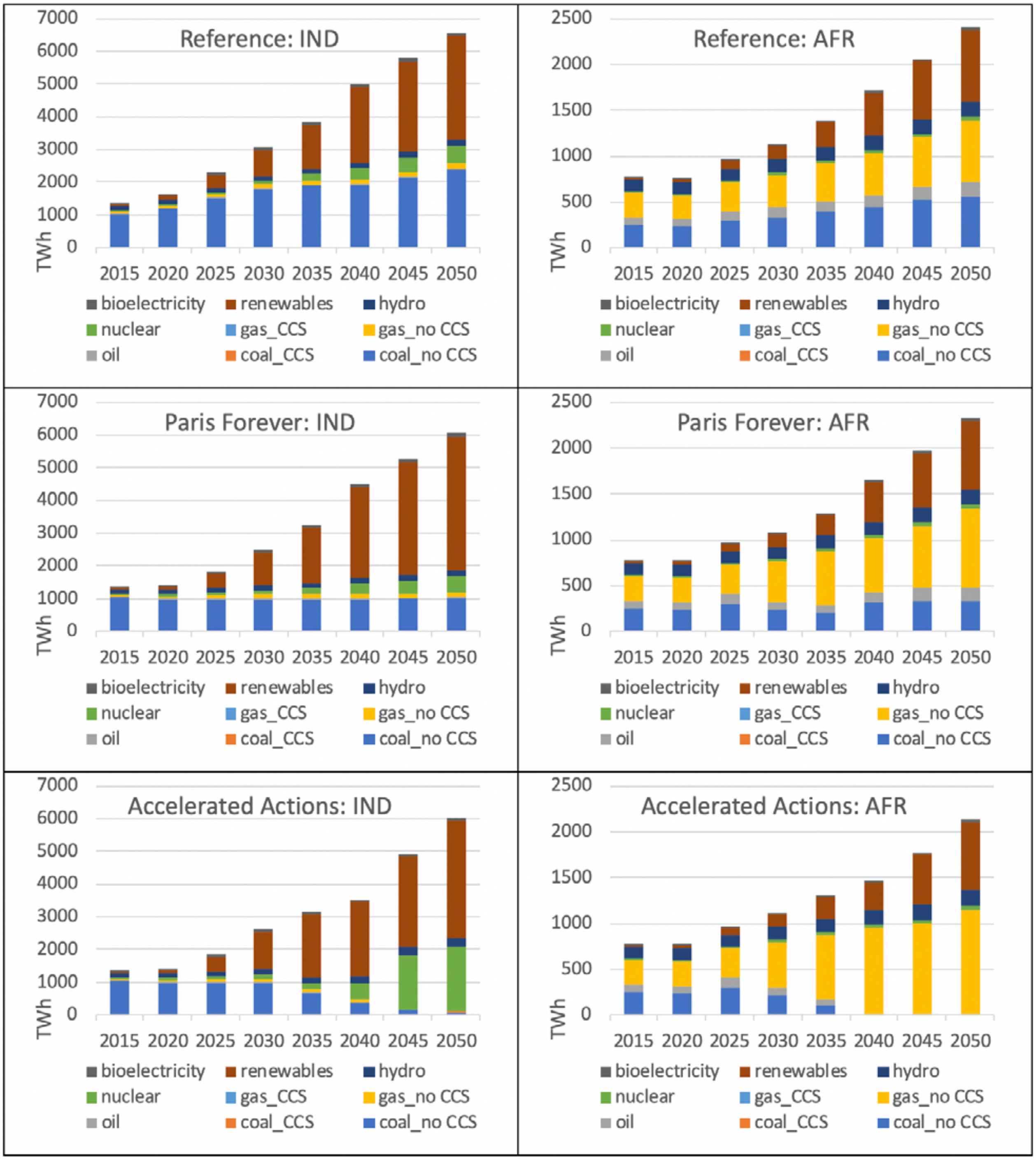


Figure A13-2. Projections for regional generation mix in two rest-of-the-world regions

Appendix A14 Conventional nuclear power resource factor trend

	2015	2020	2025	2030	2035	2040	2045	2050
USA	1.00	0.95	0.89	0.85	0.77	0.68	0.60	0.51
CAN	1.00	0.94	0.88	0.85	0.76	0.68	0.59	0.51
MEX	1.00	0.94	0.88	0.85	0.76	0.68	0.59	0.51
JPN	1.00	6.71	12.42	20.20	19.96	18.37	16.04	13.70
ANZ	1.00	1.52	2.03	2.73	2.46	2.19	1.91	1.64
EUR	1.00	0.93	0.85	0.79	0.71	0.63	0.55	0.47
ROE	1.00	0.94	0.89	0.85	0.77	0.68	0.60	0.51
RUS	1.00	1.00	1.00	1.08	0.97	0.86	0.76	0.65
ASI	1.00	1.52	2.03	2.73	2.46	2.19	1.91	1.64
CHN	1.00	1.84	2.67	3.78	3.41	3.03	2.65	2.27
IND	1.00	1.38	1.76	2.83	2.54	2.26	1.98	1.70
BRA	1.00	1.02	1.04	1.78	1.60	1.42	1.24	1.07
AFR	1.00	1.08	1.15	2.33	2.10	1.86	1.63	1.40
MES	1.00	9.06	17.11	18.69	16.82	14.95	13.08	11.22
LAM	1.00	1.05	1.10	1.61	1.45	1.29	1.13	0.96
REA	1.00	1.52	2.03	2.73	2.46	2.19	1.91	1.64
KOR	1.00	1.00	1.00	1.00	0.90	0.80	0.70	0.60
IDZ	1.00	1.52	2.03	2.73	2.46	2.19	1.91	1.64

Source: Our calibration and Reilly *et al.* (2018). See Section 4.5 for details.

Appendix A15 Stranded assets calculation

To provide an explanation for the stranded value calculation, in the following, we borrow freely from our earlier work documented in Landry *et al.* (2019) and Chen *et al.* (2021). Let us denote the domestic price index of fossil fuel f in period t under scenario s as $pd_{s,f,t}$, the domestic production index of f in t under s as $d_{s,f,t}$, and the base year domestic output level of f as $xp0_f$. Thus, $vout_{s,f,t}$,the economic value for the output of f in t under s, is:

$$vout_{s,f,t} = pd_{s,f,t} \cdot d_{s,f,t} \cdot xp0_f \qquad \text{(A05)}$$

The sum of stranded value over all fossil fuels in t under s can be written as:

$$sdvout_t = \sum_{f=\{coal,oil,gas\}} (vout_{vref,f,t} - vout_{policy,f,t}) \qquad \text{(A06)}$$

Therefore, our stranded value $psdvout$, which is the present value of the sum of reduced fossil fuels output with a discount rate of r (r=4%), can be expressed as:

$$psdvout = \sum_{t=1}^{t=T} sdvout_t/(1+r)^{t-1} \qquad \text{(A07)}$$

As the outputs are calculated at each five-year timestep, values for intermediate years were interpolated linearly. For the presentation of stranded value, values start at 2020, under the assumption that no pre-2020 action has been taken in any of the scenarios we consider.

To elaborate the calculation for the stranded capital, we first note that in EPPA, for each period, vintage capital stock is classified into four types: $v5$, $v10$, $v15$, and $v20$, which are vintage capital stocks of five, ten, fifteen, and twenty-year-old or older, respectively. Since they are sector specific, each type of vintage has its own price and quantity, which are endogenously determined. If it is not economic to operate a specific vintage, its price will be zero. For illustration purposes, let us denote the price and quantity of vintage capital in period t with type v (v = {$v5$, $v10$, $v15$, $v20$}) under scenario s as $pvk_{s,t,v}$ and $vk_{s,t,v}$, respectively (Figure 1). The stranded capital in t, $strv_{v,t}$, is the difference in the value of vintage under the no policy scenario and that under a policy scenario:

$$strv_{v,t} = pvk_{no\_policy,t,v} \cdot vk_{no\_policy,t,v} - pvk_{policy,t,v} \cdot vk_{policy,t,v} \qquad (A08)$$

Based on (A08), $strvb$, the present value of all stranded capital stocks with a discount rate of r (r=4%) is:

$$strv = \sum_{t=1}^{t=T} \sum_{v|v=\{v5,v10,v15,v20\}} strv_{v,t}/(1+r)^{t-1} \qquad (A09)$$

Similarly, since adjacent periods of EPPA are five years apart, values for intermediate years are interpolated linearly. For the presentation of stranded assets in coal-fired generation, values start at 2020, under the assumption that no pre-2020 action has been taken in any of the scenarios.

An important consideration to account for in these estimates is that the current valuation of assets, to the extent that investors already expect that the Paris agreement will be implemented or even more aggressive policy pursued, may already be partially discounted from the loss in value we estimate when compared with the no policy case.

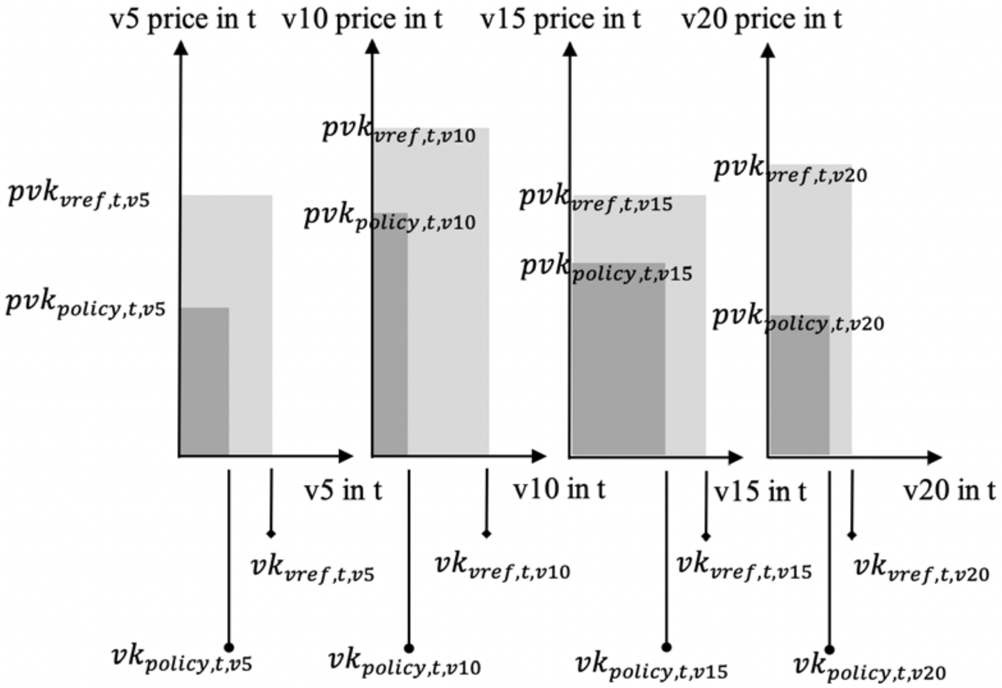


Figure A15-1. Estimation of stranded capital in coal-fired generation

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