An Economy-wide Framework for Assessing Global Transition Risk in the Energy Production Sector

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Abstract

Climate change mitigation efforts, which require the transition away from carbon-intensive activities, can pose financial risks for owners of fossil fuel assets and investors that finance companies engaged in greenhouse gas-emitting activities. For instance, fossil fuel extraction may be significantly scaled-back, and coal-power plants may be idled or even phased out prematurely, thus becoming stranded assets for the shareholders. Using a global general equilibrium model with detailed energy sector and capital stock structures, we estimate the corresponding stranded assets under various emissions mitigation scenarios. Our findings reveal that, depending on the policy scenario, the global net present value of unrealized fossil fuel output through 2040 relative to a "no policy" scenario is between 14.7 to 16.9 trillion US dollars, and that of stranded assets in coal power generation is between 1.0 to 1.4 trillion US dollars. The analytical framework presented in our study complements existing research, in which macroeconomic variables required for estimating the stranded assets are often derived from models with more simplified assumptions. Therefore, individual firms and financial institutions can combine our economy-wide analysis with details on their own investment portfolios to determine their climate-related transition risk exposure.

1. Introduction

Climate change is widely acknowledged to pose various threats to the financial sector. Transition risk, the focus of this paper, refers to those business risks associated with the global transition toward a low-carbon economy, which must take place in order to stabilize the rise in global temperature to "well below 2°C above preindustrial temperatures" — a goal that many nations have agreed upon in international climate negotiations. Thus, transition risk includes the risk inherent in a rapid shift away from greenhouse gas emitting activities such as the use of fossil fuels, which now account for approximately 85 percent of global primary energy supply. Such a rapid shift might entail a reduction in producer prices for fossil fuels, as well as a reduction in the value of fossil fuel reserves. It may also lead to the idling of coal power plants, fuel pipelines, and drilling rigs as these activities become uneconomical, creating "stranded assets."

There have been a variety of efforts aimed at reducing vulnerability of the financial industry to these climate-related risks, including the Task Force on Climate-related Financial Disclosures (TCFD, 2017), the Network for Greening the Financial System (NGFS, 2019), and efforts by the Bank of England to develop a "climate stress-test" for financial institutions (BOE, 2019).[1] Increasing attention is also being paid to climate risk when rating public and private bonds, as evidenced by Moody's recent purchase of the physical climate risk data provider, Four Twenty Seven. These efforts are bringing greater attention to climate-related risks across the financial system and the general economy. Evaluating these risks, however, is complex and resource intensive, and no existing models or studies provide a comprehensive risk assessment for all types of assets. In this study, we focus on estimating the potential loss of asset values when climate policies are enforced — a key element of transition risk — using a global general equilibrium model based on a worldwide input-output database, which provides comprehensive information for calibrating the consumption and production activities of various agents. The model is enhanced with details in the energy sector and leverages a dynamic capital stock structure. With

[1] All of these efforts involve parts of the financial system, but each takes a somewhat different approach. The TCFD is focused on companies' disclosure of their climate-related risks and opportunities to allow investors to take this information into account in their financial investment decisions. The NGFS is a group of Central Banks and Supervisors "willing, on a voluntary basis, to exchange experiences and share best practices in managing environment and climate risk in the financial sector and mobilizing finance to support the transition toward a sustainable economy." The BOE's efforts take the model of stress-testing financial institutions that came out of the 2008 financial crisis and is adapting it to climate risks.

representations for new energy supply technologies that may not be economic at the beginning but may play crucial roles as various emissions mitigation policies are introduced, such modeling details facilitate a more nuanced estimation of stranded assets. Our approach complements existing studies where, perhaps due to different research focuses, financial drivers required for the analyses (fossil fuel prices, demand levels, carbon prices, etc.) are often derived from models with simplified treatments of energy supply options or capital stock structure (Ansar et al., 2013; Leaton, 2013; UNEP FI, 2019; PRI, 2019).

Evaluations of transition risk at the level of an individual firm demands a much finer-grained assessment and is often conducted internally, as the company has access to detailed information about its assets. Nevertheless, such assessments, particularly those pertaining to the fossil-fuel extraction and power generation sectors, could benefit from extending our stylized analysis in which a theoretically consistent macroeconomic response to various policy scenarios is achieved. This internal consistency is attained by endogenously simulating variables, such as fuel and carbon prices, that can provide the foundation for a deeper evaluation in an economy-wide model. The rest of this study is organized as follows: Section 2 presents the modeling approach, our definition of stranded assets, and scenarios considered in our study; Section 3 analyzes our findings; and Section 4 provides conclusions and future research directions.

2. An Analytical Approach for Transition Risk Estimation

Because climate-related transition risks are closely dependent on how mitigation policies may affect economic activities, it is useful to have an analytical approach that can trace impacts through the entire economy. This section will give a brief introduction of our economy-wide model, define the stranded assets as explored in our research, and, finally, offer descriptions for each scenario. These scenarios are not predictions of what will occur, but rather consistent narratives of how the world could develop under a specific set of assumptions.

2.1 Model

We use the MIT Economic Projection and Policy Analysis (EPPA) model to simulate the response of economic, energy, and emissions behavior under various scenarios. The model is a multi-region and multi-sector recursive dynamic computable general equilibrium (CGE) model of the world economy, aggregated into 18 regions and 14 sectors (Chen et al., 2016).[2] The core database used is that compiled by the Global Trade Analysis Project (Aguiar, 2016). Additionally, engineering data are used to calibrate "backstop options" for new energy supply technologies that are not presented in the base year input-output data. The model is solved at 5-year intervals from 2010 onward to generate projections for variables such as GDP, sectoral outputs, price levels, and various types of energy use and greenhouse gases (GHGs) from human activities. The fact that each time period covers five years can be regarded as the assumption that agents will take into account their expectation for the coming five years (rather than a single year) when making various resource allocation decisions.

Key model agents of each region include household, producers, and government. The household owns primary factors (labor, capital, and natural resources), provides them to producers, and receives income in return. To maximize utility, consumers allocate income between consumption and savings. To maximize profit, producers (production sectors) use primary factors and intermediate inputs (outputs of other producers) to produce goods and services, and sell them to other domestic or foreign producers, households, or governments, as different regions are connected to each other via international trade. Governments, which are treated as passive entities, collects taxes from household and producers to finance their consumption and transfers.

The dynamics of the model is determined by calibrated exogenous factors and endogenous factors. The former includes projections for the business-as-usual (i.e., reference) GDP growth, labor endowment growth, factor-augmented productivity growth, autonomous energy efficiency improvement (AEEI), and natural resource assets. In the reference simulation, the factor-augmented productivity levels are adjusted proportionally to match that region's assumed reference GDP growth profile. With the calibrated productivity levels of the reference run, GDP projections, along with other economic, energy, and emissions variables, are endogenously determined under policy simulations, which means they will be affected by, for instance, the proposed climate policies.

The endogenous factors determining the model dynamics include savings, investment, and fossil fuel resource depletion. Savings provide funds for investment, and investment plus the

[2] To keep our study focused and succinct, readers are referred to Chen et al. (2016) for details of the model.

remaining capital from previous periods forms the capital for future production. A key model feature is that in the aforementioned capital formation process, part of the capital stock becomes vintage, and the vintage capital stock is sector specific. This means that a vintage capital stock cannot be freely allocated across sectors to seek higher returns—a setting that allows us to simulate, for example, the loss of idling coal-fired power plants to cut emissions. Furthermore, the depletion of fossil fuel resources is considered in the model in order to capture the long-run dynamics of fossil fuel prices, which themselves are important for evaluating stranded assets.

2.2 Stranded assets considered in this study

Under a more aggressive climate mitigation scenario, the rapid transition away from fossil fuels results in stranded assets across the fossil fuel sectors, explored here in two ways. We use the term *stranded value* to represent the loss of rents from fossil fuel resources (e.g., lower prices, more fuel left in the ground). Our stranded value calculation incorporates stranded equipment in the extraction sectors such as drilling rigs, which are inputs to the refined oil sector in the EPPA model. We use the term *stranded capital* to refer to lower returns to capital in fossil fuel consumption sectors. We only calculate and report the value of stranded coal power plant capital, as coal-fired generation will be most affected by climate policies. Stranded assets of both types are calculated through 2040 and are reported as a Net Present Value (NPV), relative to a no policy scenario, assuming a discount rate of 4%.

To provide an explanation for the stranded value calculation, let us denote the domestic price index of fossil fuel f in period t under scenario s as $\mathrm{pd}_{s,f,t}$, the domestic production index of f in t under s as $\mathrm{d}_{s,f,t}$, and the base year domestic output level of f as $\mathrm{xp0}_{f}$. Thus, $vout_{s,f,t}$, the economic value for the output of f in t under s, is:

$$vout_{s,f,t} = pd_{s,f,t} \cdot d_{s,f,t} \cdot xp0_{f} \tag{1}$$

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

$$sdvout_{t} = \sum_{f=\{coal,oil,gas\}}(vout_{vref,f,t} - vout_{policy,f,t}) \tag{2}$$

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:

$$psdvout = \sum_{t=1}^{t=T} sdvout_{t}/(1+r)^{t-1} \tag{3}$$

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, $\mathrm{strv}_{v,t}$, is the difference in the value of vintage under the no policy scenario and that under a policy scenario:

$$strv_{v,t} = pvk_{no\_policy,t,v} \cdot vk_{no\_policy,t,v} - pvk_{policy,t,v} \cdot vk_{policy,t,v} \quad (4)$$

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

$$strv = \sum_{t=1}^{t=T} \sum_{v|v=\{v5,v10,v15,v20\}} strv_{v,t}/(1+r)^{t-1} \quad (5)$$

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 power 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.

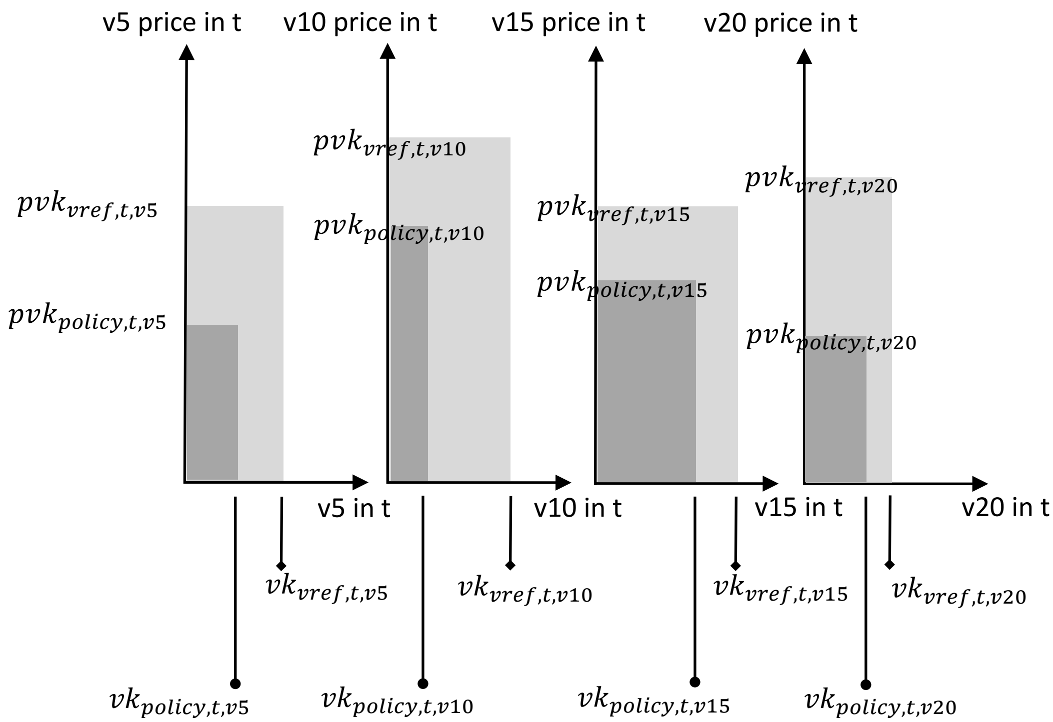

Figure 1. Estimation of stranded capital in coal power generation

2.3 Scenarios

A set of four scenarios are considered in this study. They were originally developed in conjunction with the 2018 Food, Energy, Water, and Climate Outlook produced by the MIT Joint Program on the Science and Policy of Global Change (Reilly et al., 2018). While all four scenarios use the same base growth in productivity and population, natural resource availabilities, and technology options that are major drivers or limits to GDP growth and energy and land-use patterns, they differ in the extent and timing of climate policies:

- *No Policy*: There are no explicit climate mitigation policies, but starting from 2025 it is assumed that all newly built coal power generation will be the advanced coal generation technology that is more efficient and cleaner (EIA, 2015). The scenario serves as a reference scenario for assessing the effects of the policy scenarios.
- *Paris Forever*: Following Jacoby et al. (2017), countries meet the targets presented in their Nationally Determined Contributions (NDCs) through a series of policies and measures (PAMs) on power and transportation sectors, including targets for phasing out some coal

power generation, vehicle efficiency standard on light duty vehicles, and cutting emissions from commercial transport (see Appendix A1 for details). Besides, countries are assumed to abide by the targets through the end of the century. If for a region the considered PAMs are not enough in achieving the NDC target, GHGs emissions will be priced on top of existing PAMs to close the gap.

- *Global Action Post-Paris*: Up to 2030 policy instruments to achieve the NDCs are the same as those in *Paris Forever*. For years beyond 2030, besides PAMs considered in *Paris Forever*, it is assumed that a globally coordinated GHGs pricing where trading between GHGs and among regions are allowed. The policy aims at the deep reductions needed to keep warming well below 2°C.
- *Deep Cuts Post-2070*: Most assumptions, including the 2°C target, are similar to *Global Action Post-Paris*, except in this scenario, it is also assumed that heretofore undeveloped negative emissions and emissions reduction options can be implemented late in the century, and the assumption allows for the emissions reduction efforts in the several decades following 2030 to be relaxed.

In addition, while the modeling approach simulates the world economy in 18 region/countries, they are aggregated for purposes of this study to the United States, Europe, China, India, Africa, the Middle East, and a single region called Rest of the World (See Appendix A2. for details).

Finally, although the timeframe of focus for our analysis is up to 2040, the emissions paths of each scenario are consistent to those of Reilly et al. (2018), where simulated emissions through 2100 are presented to ensure that the probability of achieving the temperature targets is achieved. Therefore, climate trajectories for the four scenarios fall into three types, broadly: *No Policy*, *Paris Forever*, and 2°C Likely. These climate trajectories result in median temperature rises by 2100 of approximately 3.4°C, 3°C, and 1.9°C, respectively as Reilly et al. Because cumulative emissions over the century are constrained to be identical in the two 2°C Likely scenarios (i.e., *Global Action Post-Paris*, and *Deep Cuts Post-2070*), there is no difference in the climate results across these scenarios; each represents a 66 percent chance that the temperature rise by 2100 will be limited to 2°C.

3. Findings and analyses

3.1 Primary energy use

Climate policies can have profound impact on primary energy use through emissions mitigation. The impact takes two major forms: (1) a reduction in the overall use of energy from what each policy scenario suggests, and (2) the reallocation of energy sources in the overall energy mix (Figure 1). The introduction of emissions mitigation can temporarily interrupt a trend of growth in overall energy demand if it is aggressive enough. In each scenario, primary energy use trends upwards through 2030 due to a growing population and rising living standards. The *Global Action Post-Paris* scenario experiences an initial drop in global primary energy upon the introduction of a global GHGs pricing after 2030. However, while a global GHGs pricing is also introduced at the same time in the *Deep Cuts Post-2070* scenario, it does not have a significant effect on global primary energy use until later on. While this hides some small tradeoffs that occur at a fuel-source level, a more aggressive GHGs pricing, only occurring in 2040, is required to disrupt the smooth upward trend of the aggregated energy use.

We also find that the share of non-fossil fuel sources in primary energy is projected to increase over time. Even in the *No Policy* scenario, non-fossil fuel use grows from 16% of the overall mix in 2015 to 19% in 2040. The grand majority of this growth stems from renewables (wind and solar) as opposed to hydro, nuclear, or bioenergy. The largest share of non-fossil energy in 2040 occurs in the *Global Action Post-Paris* scenario, with a doubling of the share at 32%.

On the other hand, coal is the most sensitive to the choice of scenario, exhibiting precipitous drops in usage with the introduction of a more aggressive climate policy such as the global GHGs pricing. This sensitivity is primarily driven by coal use in China and, to lesser degrees, India and the Rest of the World (Figure 2). The single largest source, oil, is almost exclusively used in the transportation sector. Climate policies affects the use of oil as expected, reducing its use from the trend under the *No Policy* scenario. However, the projected economic growth through 2040 even under the *Global Action Post-Paris* scenario will still lead to an increase in the use of oil worldwide.

The use of hydro energy is developed to its maximum under all scenarios due to its cost efficiency and limited resource. Nuclear generation at the global level is projected to be more or less stabilize up to 2040 except under the *Global Action Post-Paris* scenario, where a more aggressive decarbonization agenda is in place. The increase in nuclear in 2040 is due primarily to China's attempt to satisfy its electricity demand after a substantial jettison of coal (See Subsection

3.2). Bioenergy includes both biofuels (for transportation) and bioelectricity (for electric power generation). While there is a negligible difference in the use of bioelectricity between scenarios, the increased use of biofuels is suppressed in the *No Policy* relative to the other three scenarios. The use of renewable energy (wind and solar) rises in each scenario, only diverging after the completion of the NDCs through 2030. Even in the absence of climate policy, renewables compete on their own merit, increasing their share of primary energy use.

The world is slated to undergo further electrification, regardless of scenario. Both global primary energy use and electricity generation rise through 2040 for all scenarios. However, total primary energy use is much more susceptible to an overall reduction from climate policies through 2040 than is electricity generation (Figure 1; Figure 3). This is driven, in part, by the "electrification" of the global economy—e.g., shift from natural gas to electricity for heating/cooling buildings, greater growth rate in service sectors, displacement of internal combustion engine vehicles with electric vehicles.

Figure 1. Global primary energy use projection

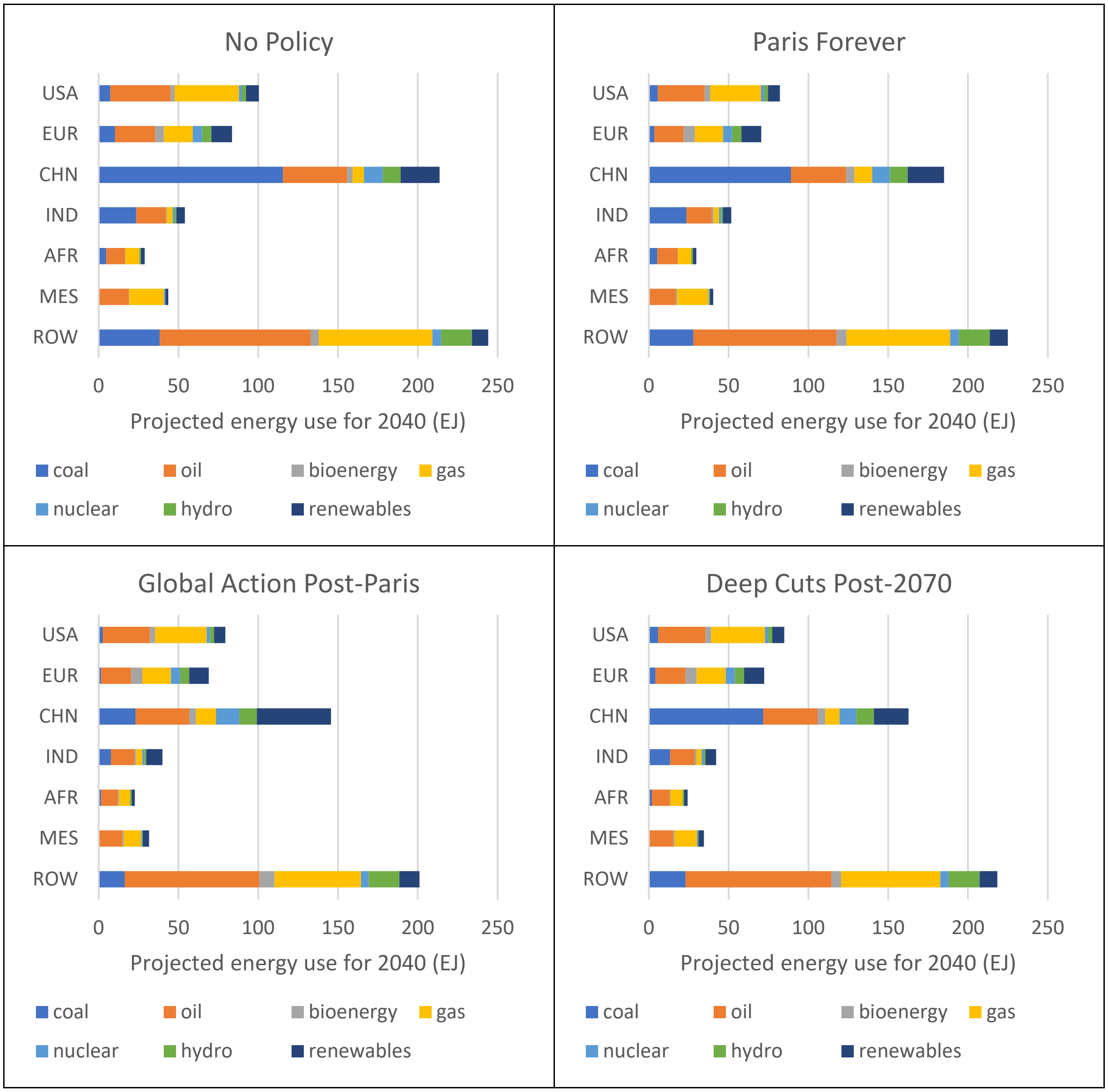

Figure 2. Global primary energy use projection for 2040 by region

3.2 Power generation

Electricity generation constitutes a larger proportion of primary energy use in the climate policy scenarios due to the greater reduction in primary energy use than the reduction in electricity generation. This could be due to a combination of three reasons: (1) efficiency gains in electricity production resulting from climate policies encourage a shift of energy use toward electricity, (2) the use of electricity is less elastic to the global consumer than is the use of energy in other industries, and (3) the greater share of non-fossil fueled electric power production makes the electric power sector more resilient to climate policies, allowing it to further increase its share of non-fossil-fueled power production in order to satisfy demand. This helps explain the growth in non-fossil-fueled power production in all scenarios, from 34% in 2015 to 43% and 61% in 2040 in the *No Policy* and *Global Action Post-Paris* scenarios, respectively (Figure 3).

Climate policies affect the use of natural gas differently in the electric power sector. The absolute use of natural gas rises by 2040 for primary energy production and electricity generation alike in all scenarios (Figure 1; Figure 3). However, while a more stringent climate policy also increases the relative use of natural gas for electricity production, it reduces its use relative to the *No Policy* scenario in other sectors (Figure 4). Natural gas is a very "flexible" electricity source, able to quickly ramp up and down given sharp increases or decreases in electricity demand. With the increasing penetration of intermittent energy sources (solar and wind) that occurs as a result of more stringent climate policies, natural gas is increasingly used as an effective method of handling increased variability in the net electricity demand profile. The falling use of natural gas in other sectors is driven by (1) the electrification of the economy as well as (2) the decline in overall primary energy use demanded with the climate policies.

The use of advanced coal is boosted by less aggressive climate policies. To a large degree, advanced coal will replace conventional coal energy production under all scenarios (Figure 5). The pattern of replacement, however, varies between scenarios and is primarily determined by two competing drivers: (1) more stringent climate policies such as GHGs pricing make the current efficiency of conventional coal-fueled energy production insufficient to retain energy production share, and (2) higher CO_2 prices makes even the higher efficiency of advanced coal-fueled energy production insufficient to retain energy production share. The individual structures of various NDCs, many of which contain goals to reduce emissions or emissions intensities by 2030, hold the growth of advanced coal just under that demonstrated by the *No Policy* scenario. However, upon completion of the NDCs, the relative CO_2 prices that the various scenarios introduce differ significantly. The *Deep Cuts Post-2070* global CO_2 price, introduced at \$21.2/ton-CO_2 after the NDCs, is low enough to accelerate use of advanced coal above that exhibited by *Paris Forever*, while still depressing overall coal use, if only slightly. Contrastingly, the *Global Action Post-Paris* global carbon price, introduced at \$68.0/ton-CO_2, reduces both overall coal use and advanced coal use.

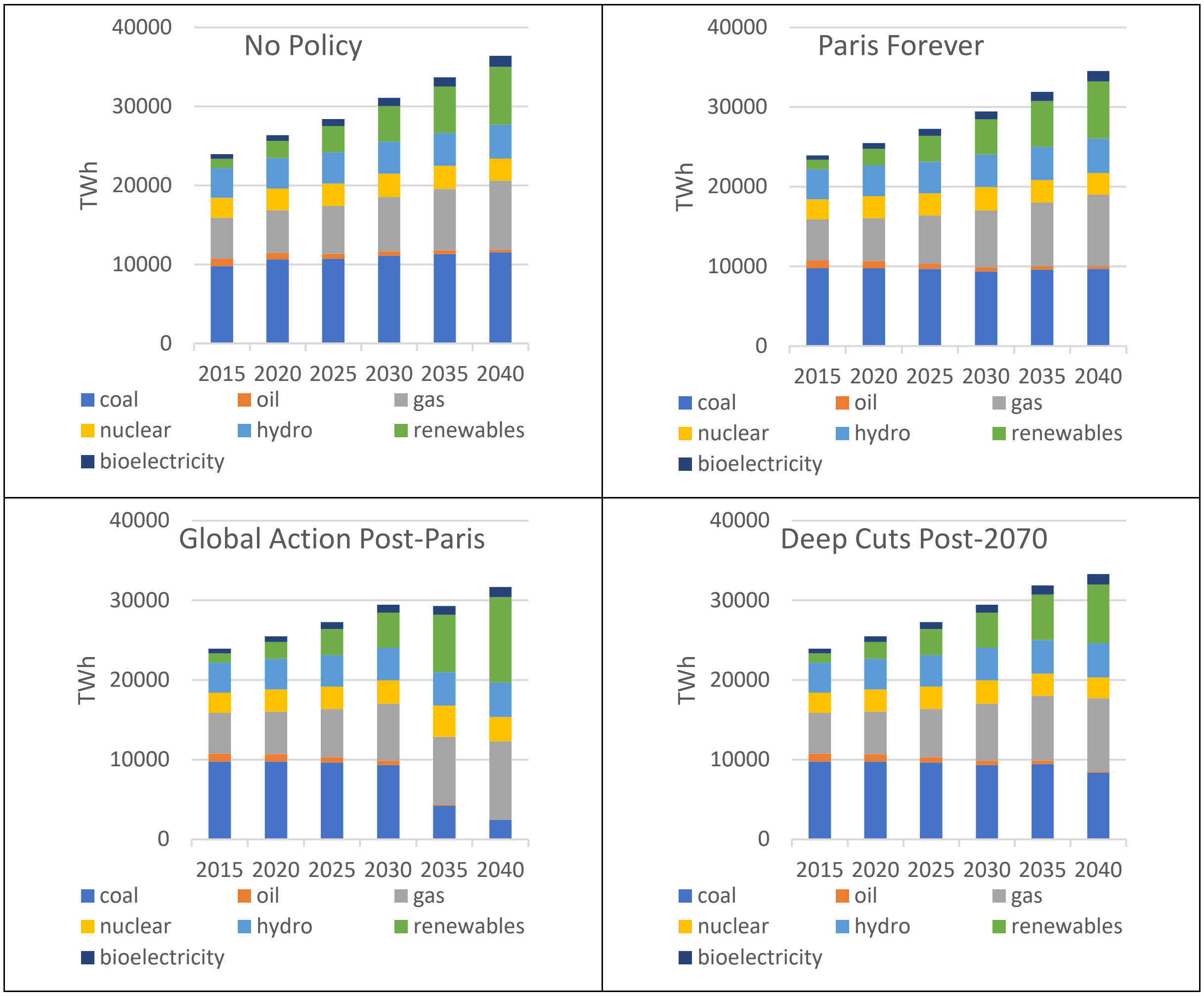

Figure 3. Global generation projection

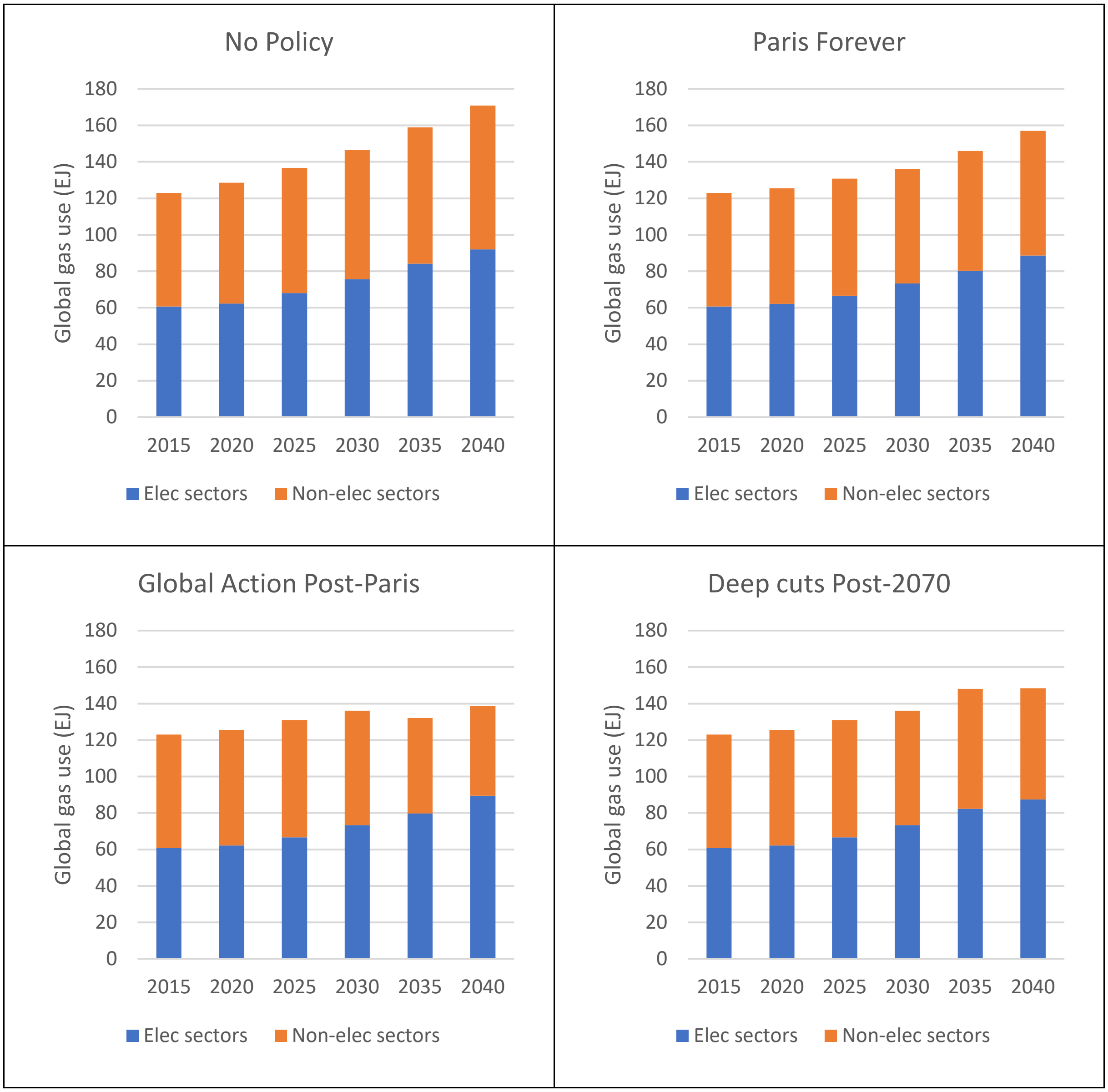

Figure 4. Global gas consumption projection by power and non-power sectors

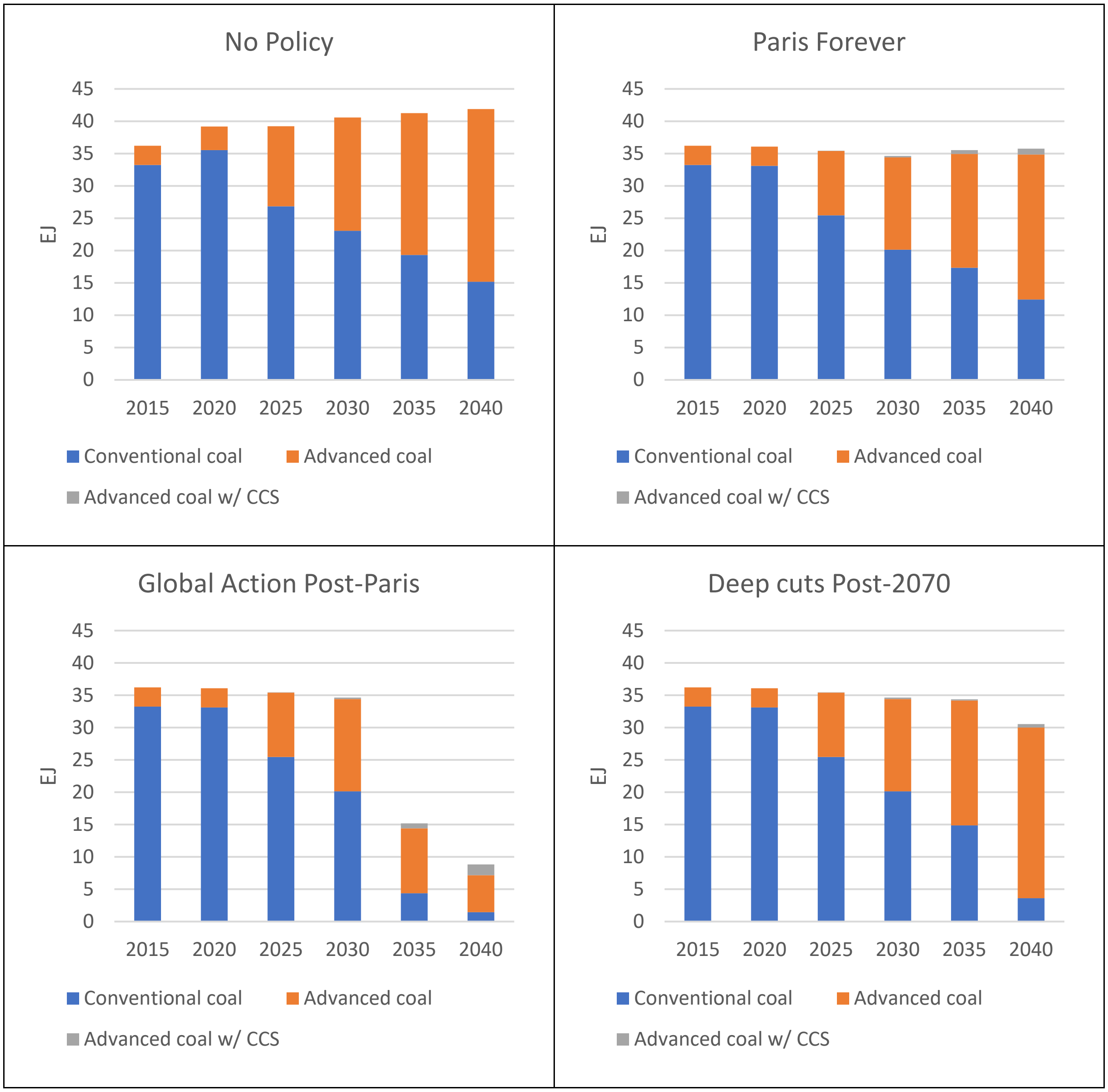

Figure 5. Global coal generation projection

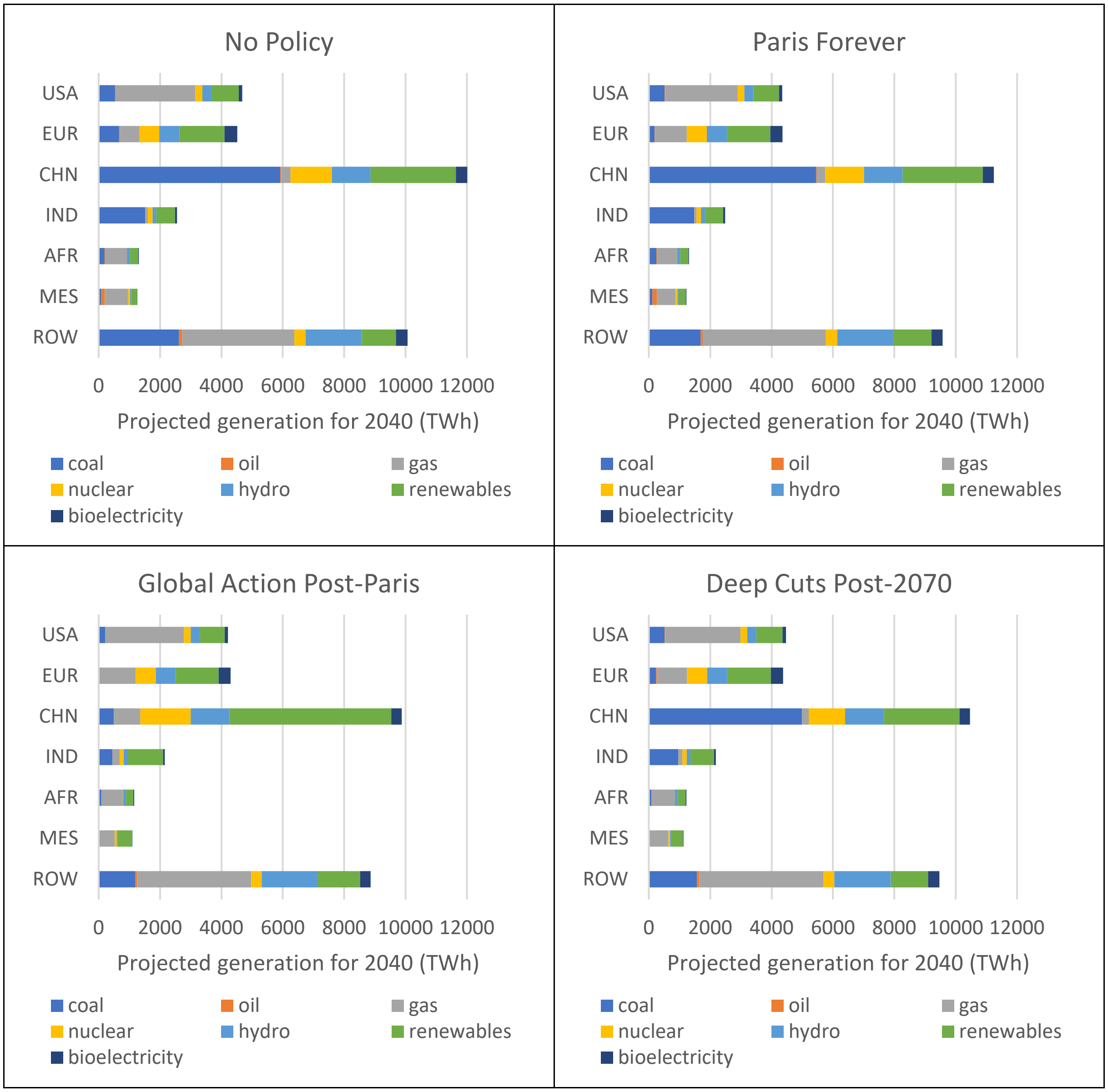

Figure 6. Global generation projection for 2040 by region

3.3 Stranded assets in oil, gas and coal sectors

Stranded assets in the fossil fuel sectors refer to the value of fossil fuel economic output that is not realized under a given scenario relative to the value of fossil fuel output under the *No Policy* scenario. The value of fossil fuel economic output in a given year is the product of the domestic price of fuel and the production output of that fuel for that year, which includes not only the value of the fossil fuel resource, but also that of the rents and production capital associated with the fossil fuel use (e.g. returns to drilling rigs). Refineries and transportation capital (e.g. pipelines) are not included in these estimates of stranded assets because they are included in other modeled sectors. Furthermore, the quantification of stranded assets is limited to the timeframe under exploration; that is, fossil fuels not produced through 2040 might be produced in later years. However, this is always the case, only to be rectified by simulating an infinite timeframe.

The NPV of stranded assets in fossil fuel production captures not only the volume of the overall production reduction under each scenario, but also the effect of early or delayed action. The earlier the reduction in fossil fuel output, the greater the value of that stranded output. Figure 7 illustrates the NPV of fossil fuels stranded values through 2040 under the policy scenarios.

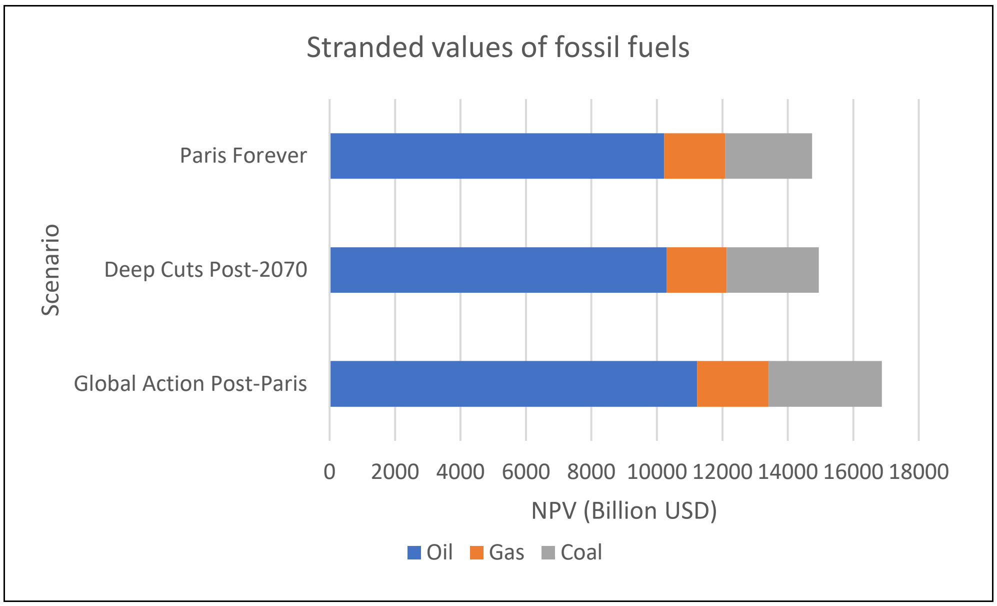

Figure 7. Economic output lost from unproduced fossil fuels through 2040 relative to *No Policy*.

3.4 Stranded assets in coal power generation

Stranded assets in coal power generation is the value of the portion of the coal-fired power plants that is not utilized under different scenarios relative to the *No Policy* scenario. While capital from different sectors might also be expected to be stranded to some degree, we focus on capital in coal power generation because it is, beyond the fossil fuel production sectors themselves, the most vulnerable sector to transition risk. Furthermore, the level of aggregation in the model limits the accuracy of estimates of stranded capital in other sectors. Figure 8 illustrates the NPV of stranded assets in coal power generation through 2040 under the policy scenarios.

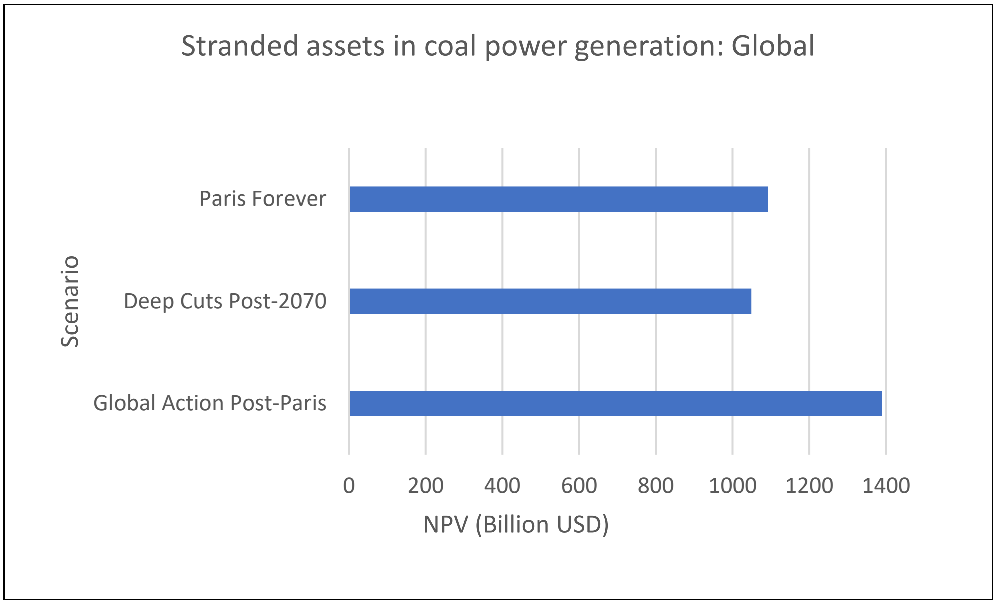

Figure 8. Stranded Assets in Coal Power Generation through 2040.

As might be expected, the scenario with the greatest amount of stranded assets in coal power generation is the *Global Action Post-Paris* scenario with a stranded NPV of capital of almost 1.4 trillion USD, due to the volume of coal plant capacity that goes unutilized. Figure 9 separates the cumulative data from Figure 8 into its regional components.

China has the most risk exposure of having stranded assets in coal power generation with NPV losses ranging from 268.6 billion USD to 410.8 billion USD in the *Paris Forever* and *Global Action Post-Paris* scenarios, respectively. This observation is corroborated by China's energy transition pathways (Figure A05). Not only do conventional coal assets become idled, but in the *Global Action Post-Paris* scenario, so in later years do the advanced coal assets that succeed them (Figure A06). The implicit assumption behind our modeling framework is that, if there is a new stringent policy going into place in 2035, or even a rise in the carbon price, it is not announced until after 2030, and therefore agents would continue to build the optimal power plant choice at the present time through 2030.[3] Conversely, the Middle East, which is primarily powered via oil and natural gas, has minimal exposure to stranded coal assets, with a maximum stranded NPV of

[3] The model is what is known as 'recursive,' in which agents make their decisions based on the information available to them. Thus, stringent policy actions of later years implemented in the model are not anticipated by the model agents. In actuality, if such policies were to take effect, there would be discussions leading up to the implementation of the policy, and the sooner serious policy discussions happen, the earlier impacts on asset valuation would precede the policy implementation.

about 6.5 billion USD. The developed regions of Canada, Europe, and the United States, each show relatively little sensitivity between scenarios. This suggests that the implementation of their Paris NDCs dictates the majority of their coal reduction (Figure 9).

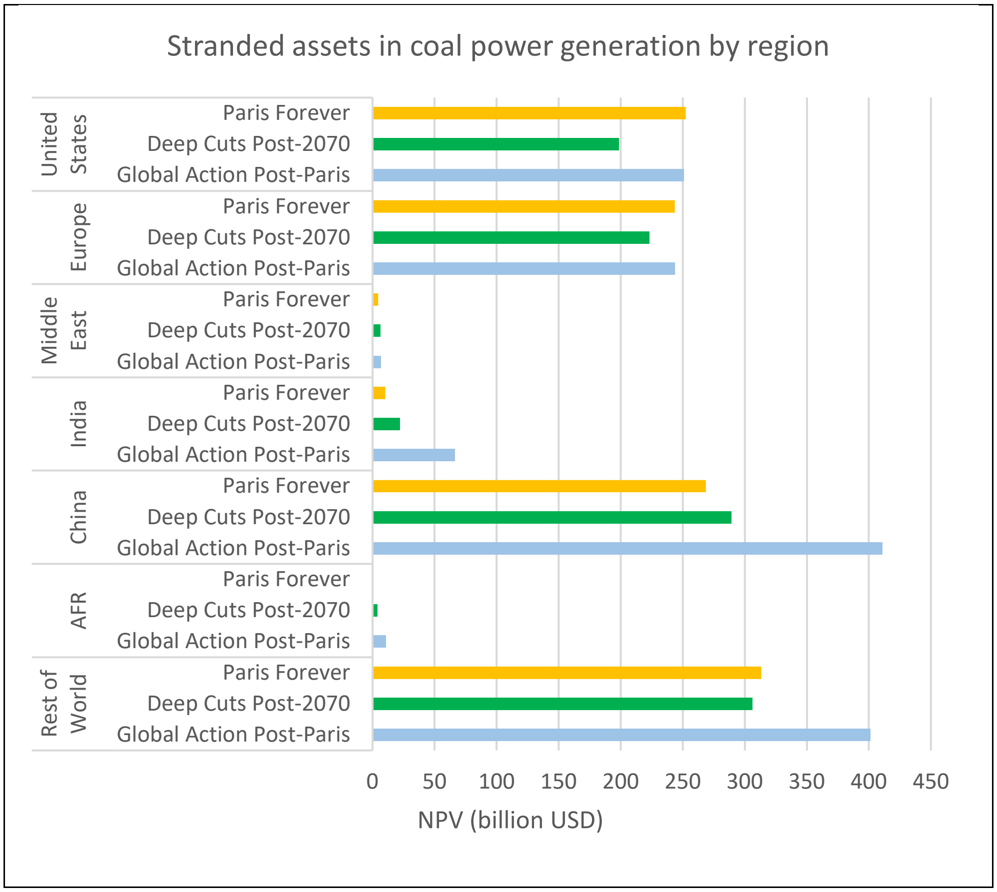

Figure 9. Stranded Assets in Coal Power Generation through 2040 by Region.

4. Conclusions

A key contribution of our study is to demonstrate that using a global general equilibrium model with more elaborate treatments on energy sectors and capital stock can offer valuable insights for assessing climate-related transition risk, since the model, which is parameterized based on empirical evidence and has been used extensively in policy analyses, takes into account a wide range of interactions between economic agents when simulating the economy-wide response to various climate policy scenarios, and therefore provides a more comprehensive foundation for estimating the value of stranded assets.

The next steps to advance the use of global climate scenarios in the assessment of financial portfolios must continue to hone in on the types of information needed by financial analysts to assess the vulnerability of specific assets. An effective path forward could take the form of a pilot study using the metrics presented in this study as a starting point for bridging the divide between climate scenarios and credit and loan assessment.

Additionally, the flexibility of scenario development and modeling offers plenty of room for exploring the transition risk. Are there additional metrics that could be provided from the existing modeling framework used here? Would greater disaggregation or reformulation of components of the model allow for reporting of metrics that are more useful in assessing financial risk? Would a more robust scenario design provide greater insight into transition risks, or uncover risks not revealed by the simple scenario designs used here, which were originally developed for purposes other than assessing financial risk? A pilot transition risk assessment using the metrics reported in this study would suggest answers to these questions, as well as future work on model and scenario development. Such a pilot study might best be carried out by financial institutions, with possible guidance on available data in the energy sectors.

Appendix A1. Nationally Determined Contributions (NDCs) and Policies and Measures (PAMs)

The 2030 emissions underlying the projection of the scenario *Paris Forever* are based on NDCs submitted to the Framework Convention website (UNFCCC, 2016) and summarized in Table A01. A series of PAMs on power and transportation sectors are considered in *Paris Forever* (see Figures A01 to A03). As mentioned in Section 2, in case PAMs alone are not enough to achieve the NDCs, taxes on GHGs are imposed to meet the targets. Behaviors under the first NDCs are extended to 2040. (Source: Jacoby et al. (2017)).

Table A01. NDCs and Assumed Performance in 2030

Region	NDCs		CO_2-e 2005 Mt or t/\$1000	Other Features	Expected CO_2-e
	Type/Base	Reduction			
USA	ABS 2005	26-28% by 2025	6220		25%
EUR	ABS 1990	40% by 2030	5370 (1990)	27% renewables in electricity by 2040	40%
CAN	ABS 2005	30% by 2030	789	Mainly land use & forestry with 18% reduction in industrial	25%
JPN	ABS 2005	25% by 2030	1260	2.5% LUCF. Nuclear = 20-22% of electric, solar/wind = 9%, also biomass. Assumes ITMOs. Target = 1.04b ton CO_2-e	20%
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	INDC is CO_2 only, discount to account for other gases. CO_2 peak by 2030, Non-fossil 20% of primary energy	55%
KOR	BAU	37% by 2030	NA	PAMs on renewables and autos (no detail)	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%

Source: Jacoby et al. (2017)

Table A02. Policy and measures (PAMs) applied to coal-fired electricity under *Paris Forever*

Country/Region	Capacity Reduction in 2030 (% of 2015)	Other Features
USA	40	
CAN	25	
EUR	35	
JPN	10	
CHN	NA	Cap 2035 & 2040 at the 2030 level
IND	NA	No coal constraint
MEX	30	
MES	NA	No coal constraint

Source: Jacoby et al. (2017)

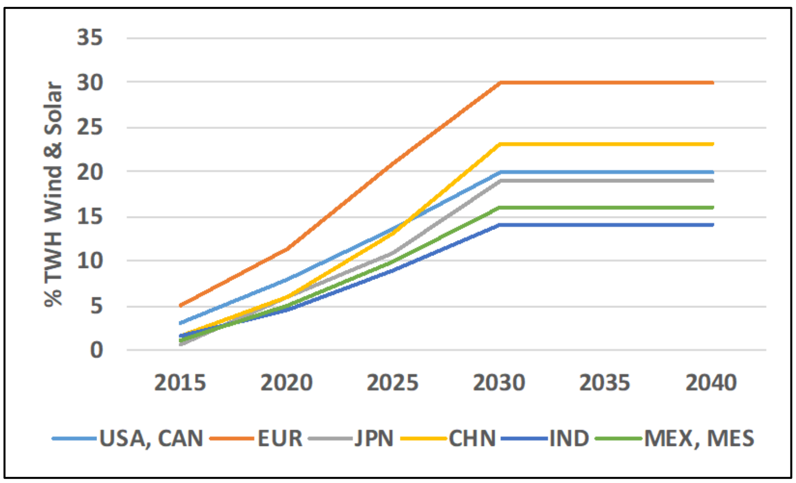

Figure A01. Minimum Levels of Wind and Solar Generation under *Paris Forever*

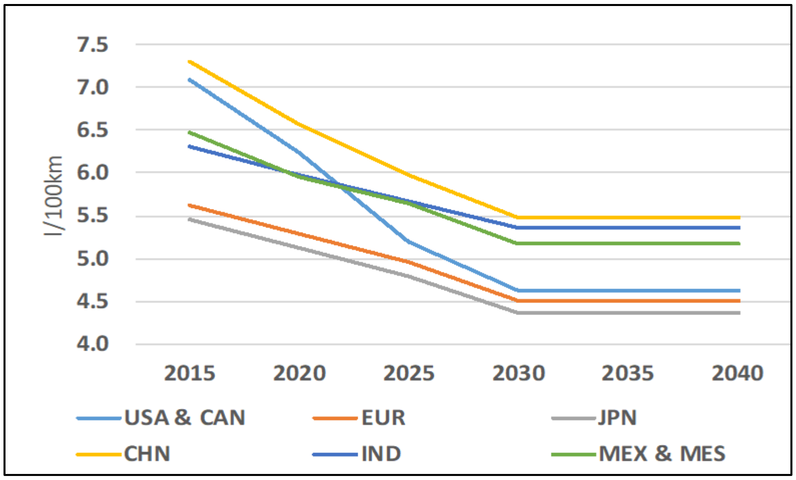

Figure A02. Efficiency Standards for Light Duty Vehicles under *Paris Forever*

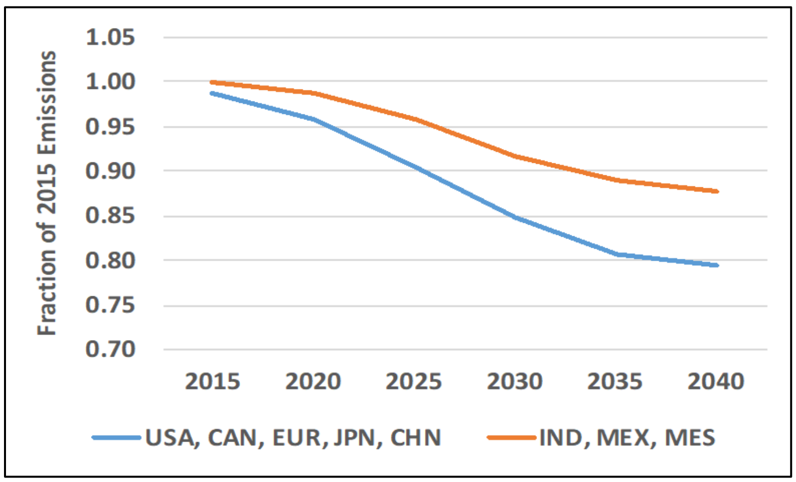

Figure A03. Reduction of emissions in commercial transport under *Paris Forever*

Appendix A2. Region Aggregation

Study Region	Region	Abbreviation
United States	United States	USA
Canada	Canada	CAN
China	China	CHN
Europe	Europe	EUR
India	India	IND
Middle East	Middle East	MES
Rest of World	Africa	AFR
	Australia & New Zealand	ANZ
	Dynamic Asia	ASI
	Brazil	BRA
	Indonesia	IDZ
	Japan	JPN
	South Korea	KOR
	Other Latin America	LAM
	Mexico	MEX
	Other East Asia	REA
	Other Eurasia	ROE
	Russia	RUS

Appendix A3. Energy use and electricity generation of China

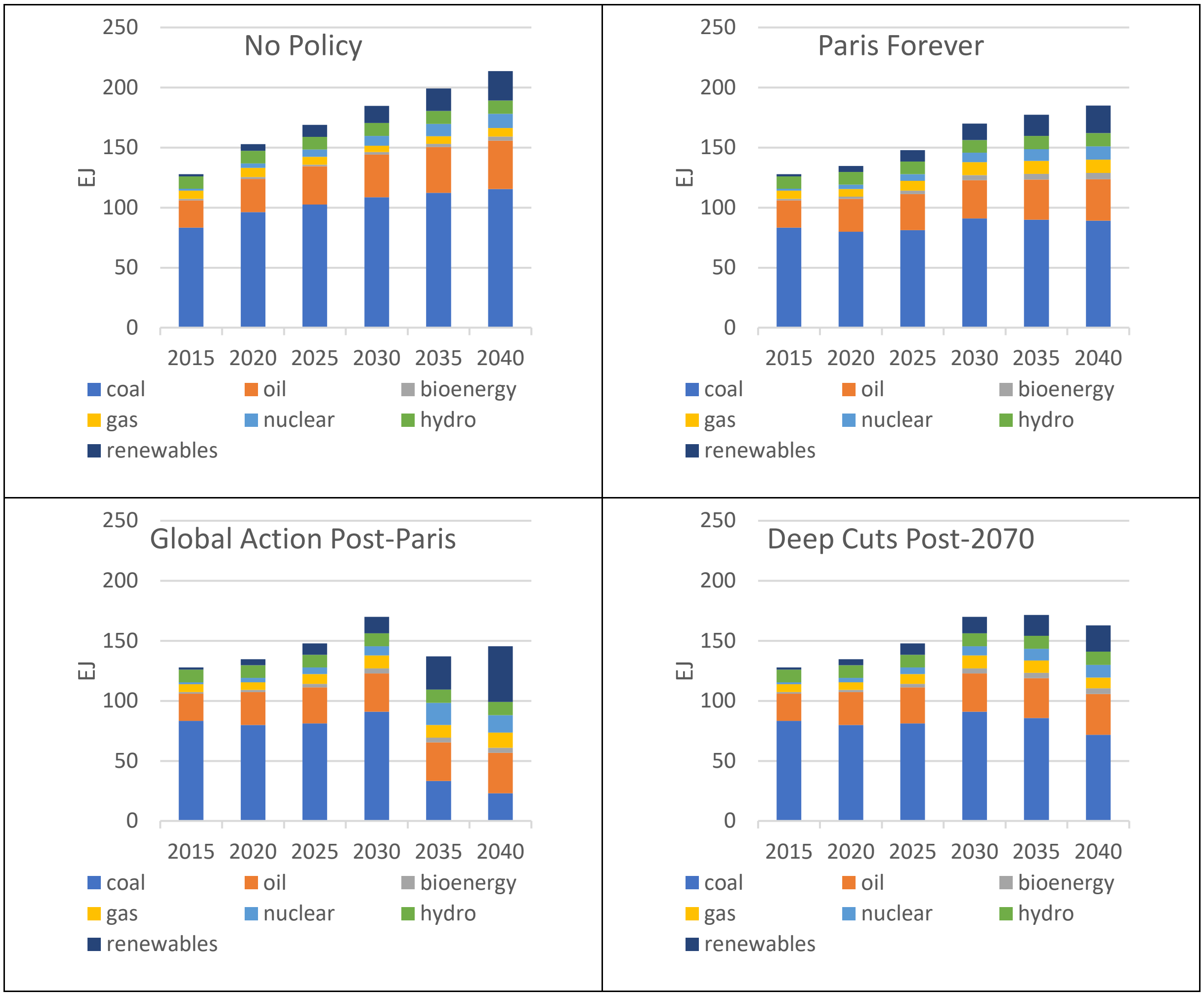

Figure A04. Primary energy use by scenario: China

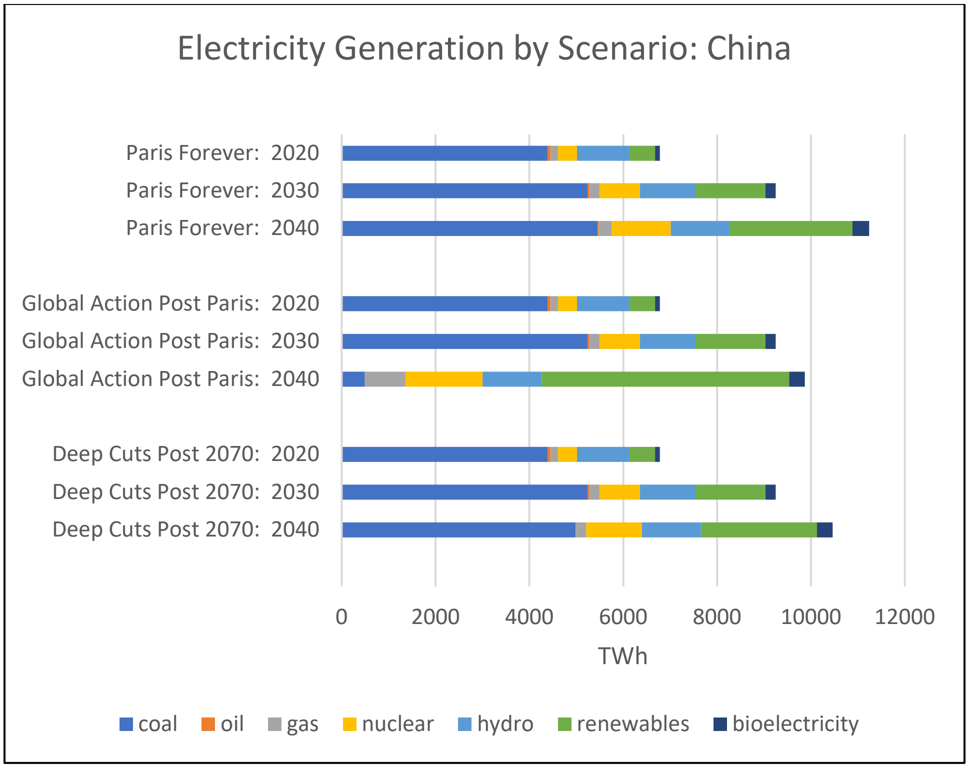

Figure A05. Electricity generation by scenario: China

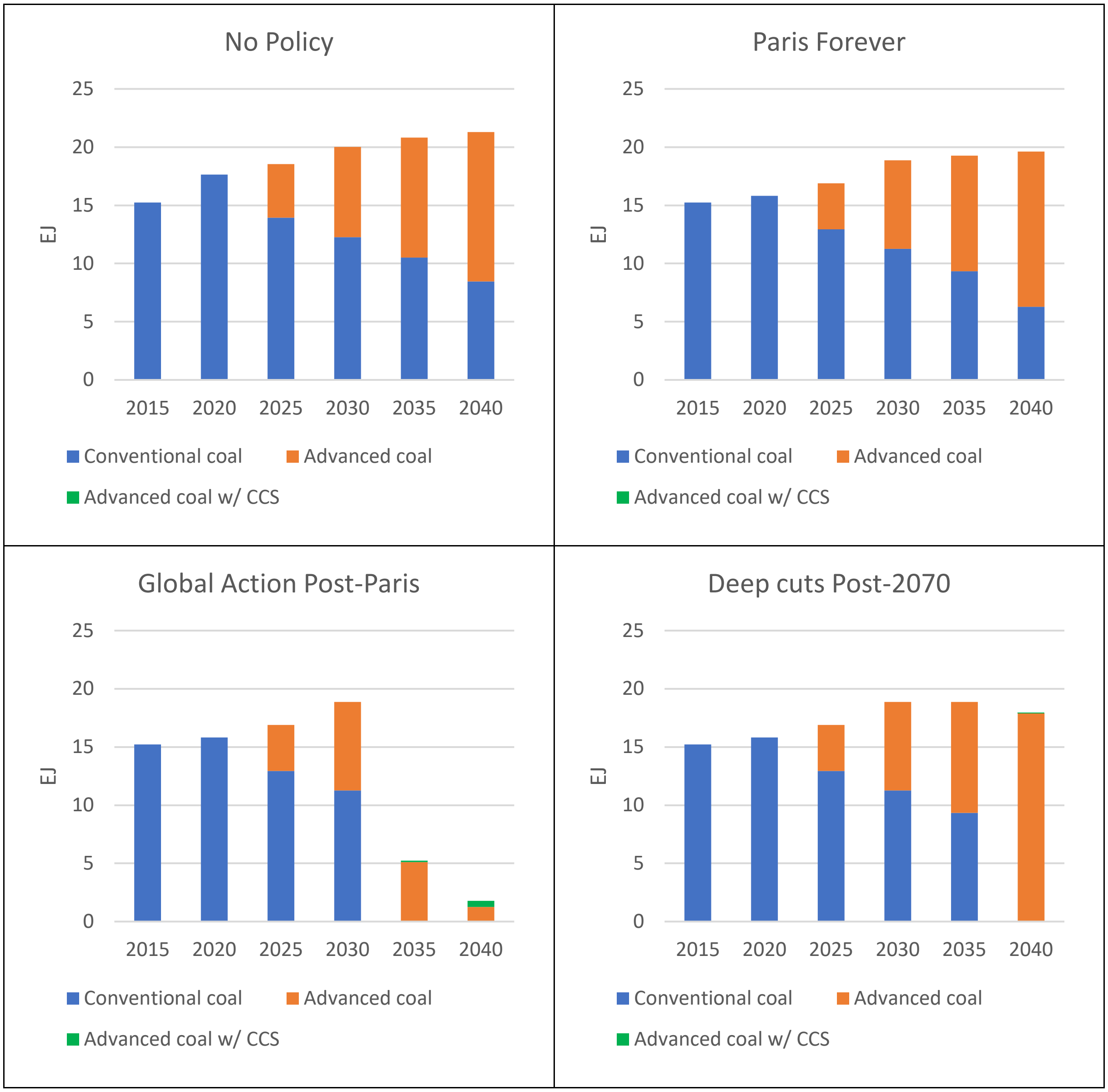

Figure A06. Coal power generation breakdown: China

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