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MIT Scenarios for Assessing Climate-Related Financial Risk

Erik Landry, C. Adam Schlosser, Y.-H. Henry Chen, John Reilly and Andrei Sokolov

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.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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1. Executive Summary

Climate change has been recognized as a source of risk for the financial sector. The nature of climate change, however, poses some challenges not traditionally encountered by general macro-economic and financial risk assessments. Climate-related risks are slowly evolving and span decades to centuries. This suggests the need for a different approach for evaluating climate-related financial risk than has been used for conventional stress testing of financial institutions. A goal of this paper is to investigate a range of climate policy scenarios to develop various metrics—such as carbon and fossil fuel prices, levels of sectoral production, and estimates of the value of stranded assets associated with a range of energy transitions—that can then be used in further analysis to help identify climate-related financial risk in the specific investment portfolios of individual financial institutions. A second goal is to lay out a set of methods appropriate for evaluating the physical risk of climate change, using an existing set of studies to illustrate challenges and necessary considerations.

Approach

Leveraging the results of a global, multi-region, multi-sector model of the economy, this report uses scenario analysis to provide a high-level narrative framing of potential climate-related risks across sectors of the economy. The scenarios are designed around future energy pathways that range from those with no climate policy to those likely to meet the long-term goal of international climate policy to keep the global temperature increase well below 2°C above preindustrial levels. The economic and emissions model is paired with a model of the global earth system to provide consistent projections of climate outcomes. This effort is *not* an attempt to provide a detailed financial risk assessment or to quantify the climate-related risk of a specific portfolio of investments held by an individual financial institution. Rather, it is intended to provide a basis for understanding the key characteristics of various climate-related scenarios, as well as to identify metrics that could then be used in such further analyses.

A set of five scenarios, 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, were extended for this exercise. The scenarios differ in the extent and timing of greenhouse gas mitigation policies. The mitigation policies result in different patterns of resource and energy use, different choices of technology, and drag on overall economic growth. All five 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. Results are reported for 7 regions: Canada, China, Europe, India, the Middle East, the United States, and the Rest of the World. The sectors examined include energy—itself broken down into coal, oil, gas, and a variety of other non-fossil sources—household transportation, crops, livestock, forestry, food, energy-intensive industry, other industry, services, commercial transportation, and dwelling ownership. Also, while the emissions profiles through 2100 are used to ensure that the scenarios meet their prescribed temperature targets, the period from 2015 to 2040 is used in this analysis to focus on the near-term transitions within the scenarios and their effects on the economy and financial risk.

The modeling approach is based on a representation of the real economy in 5-year time periods through the year 2040. With climate change, the potential loss of otherwise productive assets and the need to replace them with more expensive alternatives is expected to lead to a permanent reduction in economic growth (i.e. a lower potential GDP).

Scenarios			**No Policy:** No explicit climate mitigation policies anywhere in the world.
	Policy Scenarios		**Paris Forever:** Countries meet the mitigation targets in their Nationally Determined Contributions (NDCs) and continue to abide by them through the end of the century.
		2°C Likely Scenarios	**Global Action Post-Paris:** The Paris NDCs are met through 2030, with an agreement reached after 2030 to implement a global policy, in the form of a globally coordinated carbon price, aimed at the deep reductions needed to keep warming well below 2°C.
			2020 Global Action: The world recognizes that the Paris Agreement NDC's are not, by themselves, consistent with the level of emissions reductions needed to stabilize temperature at 2°C and that delaying those reductions will only raise the cost of meeting the target in the long-run, or worse, risk exceeding it. Thus, an accord is reached immediately, and a globally coordinated carbon price starting in 2020 puts the world on a path consistent with a 2°C outcome.
			Deep Cuts Post-2070: The Paris NDCs are met through 2030. Additionally, the assumption that heretofore undeveloped negative emissions and emissions reduction technology options can implemented late in the century allows for the emissions reduction efforts in the several decades following 2030 to be relaxed.

This is different than the short-term unemployment of resources typical of the severe economic recessions that are usually studied as a source of financial stress. The approach used here does not model the monetary system (inflation, interest rates), monetary policy, business cycles, unemployment, or short-run commodity price fluctuations.

Transition Risk

The carbon prices needed across the policy scenarios vary significantly depending on the goal of the policy, and if, how, and when an emissions path toward a 2°C outcome is initiated. For the *2°C Likely Scenarios* a global carbon price is layered on top of the mix of policies used in the *Paris Forever Scenario*. Should the world pursue a 2° C goal, it is likely that different countries will use a variety of policy instruments that lead to greater differentiation among regions, with different implications for investments and assets across sectors. Nevertheless, carbon pricing is useful proxy for level of commitment:

- *No Policy:* There are no explicit carbon prices but various energy policies currently in-place regarding vehicle fuel standards and renewable energy requirements shift energy-use patterns to some degree. The scenario serves as a business as usual (BAU) scenario comparison for assessing the effects of the policy scenarios.
- *Paris Forever:* Carbon prices vary widely across regions and time periods, ranging from $0 in India to $16.60 in Canada in 2020, with prices transitioning to $0 and $107.03 by 2040, respectively. Prices vary because of differing stringencies of countries' Nationally Determined Contributions (NDCs), the range of other measures used besides carbon pricing to achieve the NDCs, and the energy mixes, resource availabilities, and counterfactual emissions growth paths of their BAU scenarios.
- *Global Action Post-Paris:* Carbon prices in each region follow their individual Paris schemes until after the Paris term concludes in 2030. The world then converges on a price of $68.04 in 2035, rising to $84.52 in 2040, prices calculated to meet an emissions profile consistent with a 2°C-likely target.
- *2020 Global Action:* All regions conform to a $39.02 carbon price starting in 2020, gradually increasing to reach $77.65 by 2040, again calculated to meet an emissions profile consistent with a 2°C-likely target, but because the global action begins immediately, future prices are lower than in the *Global Action Post-Paris* scenario.
- *Deep Cuts Post-2070:* Carbon prices in each region follow their individual Paris schemes until after the Paris term concludes in 2030. The world then converges on a price of $21.19 in 2035, rising to $39.06 in 2040, calculated to meet an emissions profile consistent with a 2°C-likely target, but because of the assumption that the development of low-cost options occurs by the second half of the century, less mitigation is needed through 2040.

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), and, as calculated here, incorporates stranded equipment in the extraction sectors such as drilling rigs. 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 a stringent climate policy. The level of aggregation in the model limits ability to accurate estimate the value of stranded capital in other sectors. Stranded assets of both types are calculated through 2040 and are reported as a Net Present Value (NPV), relative to the *No Policy* scenario, assuming a discount rate of 4%:

- *Paris Forever:* The estimated stranded value is $14.7 trillion, with 69%, 13%, and 18% from oil, gas, and coal sectors, respectively, and stranded coal power plant capital is $1.1 trillion.
- *Deep Cuts Post-2070:* The estimated stranded value is $15.0 trillion, with 69%, 12%, and 19% from oil, gas, coal sectors, respectively, and stranded coal plant capital is $1.0 trillion.
- *Global Action Post-Paris:* The estimated stranded value is $16.9 trillion, with 67%, 13%, and 20% from oil, gas, coal sectors, respectively, and stranded coal plant capital is $1.4 trillion.
- *2020 Global Action:* The estimated stranded value is $20.2 trillion, with 65%, 13%, and 22% from oil, gas, coal sectors, respectively, and stranded coal plant capital is $2.0 trillion.
- China and the Rest of the World are at the greatest risk of stranded coal output value, exhibiting stranded coal values of $2.5 trillion and $1.4 trillion, respectively, under the *2020 Global Action* scenario, together making up 85.6% of the global total stranded coal value.
- The Middle East, the United States, and the Rest of the World are at the greatest risk of stranded gas output value, exhibiting stranded gas values of $527 billion, $713 billion, and $995 billion, respectively, under the *2020 Global Action* scenario, together making up 83.6% of the global total stranded gas value.
- The Middle East and the Rest of the World are at the greatest risk of stranded oil output value, exhibiting stranded oil values of $3.9 trillion and $5.8 trillion, respectively, under the *2020 Global Action* scenario, together making up 74.3% of the global total stranded oil value.

In the energy sector, the share of non-fossil fuel sources in primary energy continues to rise, and the world is slated to undergo further electrification, regardless of the scenario. Carbon prices are found to produce different effects on the same fuel used in either primary energy use or electric power production and boost advanced coal over conventional coal. As carbon prices rise, however, advanced coal too is phased out.

Other sectoral impacts include those on household transportation, crops, livestock, forestry, food, energy-intensive industry, other industry, services, commercial transportation, and dwelling ownership. In general, prematurely retired capital stock and the need to replace conventional energy sources with more expensive, low-carbon options, draws investment resources away from other sectors of the economy and, thus, reduce GDP growth in the policy scenarios. Globally, the sector most sensitive to the policy scenarios, second only to the energy sector, appears to be that of commercial transport. While sensitivities seem to be limited to differences of only a few percentage points, these global figures hide much of the variation present in the real output of regional sectors. Furthermore, a few percentage points in terms of global and regional economic output translates into differences of many billions of USD.

Physical Risks

No existing models or studies provide a comprehensive assessment of physical climate risks for all types of assets. Many studies investigate anticipated changes to specific climate variables or events in particular regions. However, these assessments are not easily or obviously transferable to other locations where the infrastructure, surrounding geomorphology, and formation of weather events are different.

Nevertheless, experience with efforts to estimate physical risk from climate change and associated extreme events suggests challenges and necessary considerations in estimating risk exposure and impact on asset valuation. Assessing physical risks of climate change involves four major scientific challenges:

1. Capturing the full range of possible climate responses to a specific time path of trace-gas forcing that encompasses the chaotic nature of weather and climate variability.
2. Providing projections of changing weather events and climate conditions relevant to the geographic scale of the assets at risk.
3. Improving projection of extreme events that inflict the most damage to specific assets.
4. Assessing the awareness of and adaptive responses that the owners of at-risk infrastructural assets take in light of changing conditions.

An appropriate set of steps for evaluating physical climate risk includes:

- Utilize a computationally efficient model of the Earth's systems (i.e. atmosphere, ocean, and land) to produce a large ensemble of scenarios that sample from a joint distribution of underlying uncertain climate responses (e.g. clouds, heat transfer, and carbon uptake). These scenario ensembles identify the likelihoods of more extreme climate change as opposed to the more central estimates typically projected by exhaustive, computationally expensive climate models.
- From the scenario ensembles, generate projections with the necessary spatial granularity to identify specific asset exposure to climate change. This approach has the advantage of incorporating both structural uncertainty stemming from differences across global climate models and parametric uncertainty that controls the climate's global temperature response to human activities.
- Apply "analogue" methods to refine projections of changes in extremes such as heat waves and precipitation. These methods utilize results from historical global weather and climate conditions, and use statistical approaches to identify large-scale patterns to the occurrence of particular extreme events at locations of interest.
- Evaluate the assets and their management to assess awareness and actions taken to reduce the chance of catastrophic loss. While the additional cost of reducing vulnerability to climate risk would likely diminish the value of exposed asset, catastrophic failure would likely have a much greater impact.

Large ensembles combined with downscaling approaches can produce regional results. Analogue methods and specific asset assessment require region-by-region and asset-by-asset analysis, as well as the identification of what large-scale climate features are predictors of particular extreme events in specific regions. Such assessments are relatively resource-intensive.

Summary of Implications and a Path Forward

Climate-related financial risks are of a much different nature than the traditional macro-economic risks that gave rise to financial stress tests and therefore require a different assessment approach. Financial institutions require bottom-up assessments of climate-related risks within their portfolios, identifying holdings in specific industries and geographies that are particularly vulnerable, to augment existing financial models.

Assessment of climate-related risk to financial institutions may need to focus as much on risk processes as on risk quantification. A process-based focus for evaluating climate-related risk might ask: what internal processes exist within a financial institution for assessing physical climate risk on new loans, new investments, and other financial operations? Are adequate methods being used to assess risk? This process could have the added advantage of encouraging consideration of physical risk by borrowers. It would also develop a demand for experts and methods for such assessment, leading to improvement in these methods.

In reporting economic impact on various industries, we find that the global impacts in percentage terms for most industries are relatively small through a 2040 horizon, but that the impacts on oil, gas, coal, and coal power generation sectors are much larger. While the percentage losses developed here could provide an initial estimate of transition risks in various energy sectors, many asset-specific factors would need to be considered to refine these estimates so they might be applied with confidence to specific investments.

Assessment of transition risks to specific companies and assets demands a much finer-grained assessment, but such assessments, particularly those pertaining to the fossil-fuel extraction and power generation sectors, could be based on metrics reported here. Metrics such as fuel prices and carbon prices could provide a foundation for a deeper evaluation.

Scenario analysis can provide a useful starting point in the assessment of transition risks, but one would need a more complete assessment of climate risk to assess physical risks. Extreme events are rare occurrences, by definition, and their appearance in a single climate simulation is largely a matter of chance. Large ensembles of simulations are needed to evaluate how the likelihood of extreme events may change.

There is a growing set of climate and weather event prediction tools for assessing physical risk, but there is no single model nor set of archived model simulations that is well suited to the task of accurately reflecting the physical risk for financial assets. Climate simulations provide a useful starting point, but complementary approaches are needed to better represent extreme events and downscale weather patterns to geographic scales relevant to specific assets.

An effective next step might take the form of pilot study on transition and physical risk that takes the metrics presented in this study as a starting point for bridging the divide between climate scenarios and credit and loan assessment. This would advance understanding between climate scientists, climate economists, and financial experts on the types of information needed to assess the vulnerability of specific assets.

A transition risk pilot could begin with the metrics presented in this report. This would likely need to be carried out within the financial institution where there is access to detailed information on the loan and investment portfolio of the institution. The pilot would help identify the utility of reported metrics and guide the advancement of models to become more relevant for this space.

A physical risk pilot study requires the selection of a specific site and vulnerable assets. This would mostly be done outside of the financial institution, with guidance from it on selecting an asset/geographic site. It requires considerable effort by climate scientists to develop a solid quantification of the future exposure of assets in the location to climate risk. It would also require information on the structural asset itself to assess vulnerability. One potentially promising approach is to develop simple climate metrics, that while insufficient to reliably estimate financial risk, could point to potential hot spots, triaging areas and assets that require a deeper analysis.

2. Introduction

Climate change poses risks for the financial sector. This recognition has led to a variety of efforts aimed at reducing vulnerability to these risks, including the Task Force on Climate-related Financial Disclosures (TCFD)[1], the Network for Greening the Financial System (NGFS)[2], an effort by the Bank of England (BOE) to develop a "climate stress-test" for financial institutions[3], and more attention to climate risk when rating public and private bonds, as evidenced by Moody's recent purchase of a climate data firm.[4] 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 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." [5] 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. All of these efforts are bringing greater attention to climate-related risks across the financial system and the general economy.

The existing capabilities at the MIT Joint Program on the Science and Policy of Global Change harnesses the ability to

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[1] Task Force on Climate-Related Financial Disclosure, https://www.fsb-tcfd.org/about/#

[2] Network for Greening the Financial System, https://www.mainstreamingclimate.org/ngfs/

[3] Bank of England, Prudential Regulation Authority, Life Insurance Stress Test 2019, June 2019 https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/letter/2019/life-insurance-stress-test-2019-scenario-specification-guidelines-and-instructions.pdf

[4] New York Times, Moody's buys climate data firm, signaling new scrutiny of climate risk, https://www.nytimes.com/2019/07/24/climate/moodys-ratings-climate-change-data.html

[5] https://www.banque-france.fr/en/financial-stability/international-role/network-greening-financial-system/about-us

examine risks to greenhouse gas emitting industries, such as the fossil energy industry, due to a rapid transition away from fossil fuels. This report demonstrates an approach to scenario development and analysis that can facilitate the exploration of climate-related risks to the economy and the financial system. Furthermore, a case study approach of the direct physical risks of climate change as information that could be used to assess impacts on asset values is presented. This approach adopts a global, economy-wide scope that, by its nature, coarsely resolves assets and industries. The aggregate information that results may then be interpreted by analysts in the context of rating or valuing specific assets or entities.

2.1 Climate-related Risk

Climate-related risk can be delineated into two broad types: transition risk and physical risk.

Transition risk refers to those business risks related to a transition away from fossil fuels and other greenhouse gas emitting activities. Nations have agreed that the goal of international climate negotiations is to stabilize the rise in global temperature well below 2°C above preindustrial temperatures and aim to keep the temperature rise below 1.5°C. Scientists conclude that to do so requires a very rapid global transition, especially of the energy sector, largely phasing out by mid-century the use of fossil fuels that now account for about 85 percent of global primary energy. A rapid transition away fossil fuels will reduce producer prices for fossil fuels, in turn reducing the value of fossil fuel reserves, and leaving some of these resources that would have been produced in the ground. A rapid transition may also strand assets such as coal power plants, fuel pipelines, and drilling rigs if these become uneconomic to operate or if returns to capital fall below those which were expected when the facilities were constructed.

Physical risk refers to risks due to climate change itself, including the effects of drought, forest fires, sea-level rise, increased intensity and/or frequency of tropical and extratropical storms, and other effects of a changing climate system. Such phenomena can damage homes, communities, and infrastructure and disrupt supply chains and business operations. These types of weather events have occurred in the past, but a changing climate system is predicted to increase the likelihood and intensity of these events, exposing infrastructure to risks for which they are ill-prepared, thus increasing the damage costs associated with these events. For example, more extreme precipitation will put at risk infrastructure that in the past was highly unlikely to flood. Alternatively, greater heat and drought will worsen forest fires or make areas that currently are not prone to fire more so. Sea level rise may lead to abandonment of structures regularly flooded, or the need to move entire communities.

2.2 What makes climate-related risk different?

The financial stress test approach to assessing resilience that was developed in response to the 2008 financial crisis will likely require some rethinking if it is to be used in the service of assessing climate-related risks.

One important consideration in accounting for climate-related risk is that, whereas conventional financial crises evolve rapidly, with hope of returning to normal economic conditions in a matter of months to a few years, climate change is a slowly evolving environmental problem spanning decades to centuries. Even a “rapid” energy transition is likely to take decades, and similarly, the climate will continue to change for decades, and may, only after hundreds or perhaps thousands of years, return to a “preindustrial” climate. This presents a challenge of how long-term, slowly evolving risk might be accurately accounted for in short-term financial operations. A global consultancy, Mercer, is one of the first to attempt this translation using a dividend discount modeling approach—viewing changes in market awareness of climate scenario probability as a market repricing event—to assess the impact on the valuation of different portfolio allocations.[6]

Another important consideration is that the type of long-term impact climate change threatens to have on the global economy is of a different type than the risk currently tracked by traditional macro-economic risk models. A global recession that might initiate a financial crisis often involves temporary under-utilization of capital and labor unemployment, leading to a situation where actual GDP is below “potential GDP” for a couple of years. It can have magnified effects by drying up of investment due to excess capacity across the economy, put highly leveraged assets under-water, and create relatively large losses. However, if managed well, these losses last for a short time.

In contrast, a rapid transition of the energy sector spurred by successful climate policy would likely lead to the permanent early retirement of fossil-related physical capital and permanent loss of value of fossil resources, simultaneously requiring new investment in alternative energy sources. Furthermore, the physical repercussions of climate change may lead to permanent damage to assets and infrastructure that require financial resources to repair, reinforce, replace, or rebuild, with the risk, even under the best of circumstances, of worsening conditions for decades.

Hence, the loss of otherwise productive assets and the need to replace them with more expensive alternatives is expected to lead to a permanent reduction in economic growth (i.e. a lower potential GDP). This can lead over decades to an economy that is 2 to 5 percent lower than it

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[6] https://www.mercer.com/our-thinking/wealth/climate-change-the-sequel.html

would have been without these effects. While this reduction is similar in magnitude to a major recession impact on GDP, integrating losses over decades leads to much greater net present value (NPV) loss to the economy than a short recession that lasts only a few years. Due to the only slightly slower growth, there need not be the disruption of economy-wide unemployment and excess industrial capacity. Nevertheless, under a rapid transition, there will be disruption in particularly sensitive sectors or regions.

3. An Analytical Approach to Evaluating Risks

Because climate-related risks have the potential to spread throughout the economy, it is useful to have an analytical approach that can trace impacts through the entire economy. It is also useful for that analytical approach to include all greenhouse gases and radiative forcing substances, as well as the ability to be linked to climate outcomes.

The general practice in this developing field of evaluating climate-related risks is to use scenario analysis to assess potential vulnerability. A scenario is not a prediction of what will occur, but a consistent picture of how the world would develop under a specific set of assumptions. This allows the analysis to remain agnostic about the relative likelihood of the different scenarios. By developing a range of scenarios that reasonably span the set of possibilities, one can identify risks to different classes of assets and industries. This, of course, is limited by the level of disaggregation in the chosen analytical framework.

3.1 MIT Scenario Development

The set of scenarios for this exercise was selected from the 2018 Food, Energy, Water, and Climate Outlook produced by the MIT Joint Program on the Science and Policy of Global Change.[7] The scenarios span a range of global emissions policies and are based on a regionally detailed, multi-sector, economy-wide model that includes pricing of fossil fuels, fossil resources, and vintage capital in capital intensive sectors.[8]

Given the long-term requirements of the climate issue, our focus is on the longer-term evolution of the economy and the implications of an energy transition over decades. The MIT Economic Projection and Policy Analysis (EPPA) model allows for this time frame, while maintaining a useful level of spatial, sectoral, and temporal disaggregation.

The modeling approach simulates the world economy in 18 region/countries, aggregated for purposes of this study to Europe, the United States of America, Canada, China, the Middle East, India, and a single region called Rest of the World.[9] See Appendix B for more detail.

The model solves in 5-year time steps, on the decade. As such, business cycles are not represented in the model and the economy is always at full employment. Additionally, commodity pricing swings are not captured. Rather, the focus remains on the long-term economic prospects for the continued relevance of specific energy sources. Additionally, the model deals with real goods and does not model monetary economics such as inflation, interest rates, liquidity, etc. A reasonable approach for estimating metrics between the 5-year time steps is to interpolate.

Overall economic growth is the near-term is benchmarked to the IMF economic outlook, population growth is from the UN's mid-range forecast, and GDP growth over the long term is driven in a reference case largely by long-term productivity growth assumptions.[10] An obvious limit of scenario analysis is that with a few scenarios it is not possible to capture differences in all possible drivers of economic development that may matter for assessment of financial risk. Differences in population growth, technology development, and other socio-demographic factors play a large role in the trajectory of GDP and energy use, but these are kept constant here in order to focus on the impact that various economic transitions, driven by climate policies, would produce.[11]

Under policy scenarios, prematurely retired capital stock and the need to replace conventional energy sources with more expensive, low-carbon options draw investment resources away from other sectors of the economy and, thus, have an impact on GDP growth in mitigation scenarios. The reduced GDP thereby reduces investment overall in the mitigation scenarios. However, it is reallocated toward those energy sources that meet the emissions reduction targets at least cost.[12] Savings is modeled as a fixed share of total income in the economy and determines the level

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[7] https://globalchange.mit.edu/sites/default/files/newsletters/files/2018-JP-Outlook.pdf

[8] More information on the MIT Economic Projection and Policy Analysis (EPPA) Model can be found at: https://globalchange.mit.edu/research/research-tools/eppa

[9] The UK is included in Europe. and is not split out separately.

[10] See GDP on page 13.

[11] The Shared Socio-economic Pathways (SSPs) provide an example of a suite of various demographic scenarios. See Riahi, K., *et al.* (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. https://www.sciencedirect.com/science/article/pii/S0959378016300681

[12] 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 implemented in the model are not anticipated by the model agents. In actuality, if such policies were to take effect there would be much discussion leading up to the implementation of the policy, and impacts on asset valuation would precede when the policy was implemented. We have discounted all of these back to 2019, and so the calculation, if applied to the value of assets today, is as if we know for certain that the policy would take effect as we have prescribed it.

of investment in each period. Financial market conditions and financial policy measures may work to either hasten or reduce the flow of capital into certain industries such as renewable energy, but financial markets and potential impact of policy on financial markets are not modelled.

Societal shifts in consumer sentiment (e.g., movements to buy electric cars or pay extra for carbon offsets) were not considered in these scenarios. Instead, changes in the consumption are driven by changes in relative prices.[13] For the most part, consumption goods are highly aggregated, and while income differences within a region do not lead to varying consumption patterns, income differences and the effect on consumption patterns among regions is represented. Additionally, social, geopolitical, and demographic impacts of climate change—food security, health, labor productivity in hot working conditions, migration, social unrest, migration, etc.— while perhaps representative of potential manifestations of financial risk, are not explicitly modelled. Smaller scale, specialized models would be better suited to assessing the financial risks of such phenomena. Nevertheless, an appropriately diversified set of transition scenarios can be designed to sufficiently cover a useful range of transition risks, at least in the energy sector, even without physical feedback built in.

3.2 Physical Risk Approach

When the Framework Convention on Climate Change was negotiated in the late 1980s and early 1990s the effects of climate change were widely seen as problems future generations would face. Thirty years later, those future generations are among us and the effects of climate change are manifesting themselves through changing average weather conditions and, more importantly, through an increase in the frequency of extreme events. Expansion and sustainability of society's infrastructures and resources are facing increased environmental and physical risks from a changing landscape of extreme events and conditions.

Infrastructure and assets have generally been developed to withstand variable weather by looking backward at the nature and frequency of extremes in the historical climate record. Resilience to the normal variation of weather means that just assessing a change in mean temperature or precipitation would make it appear that these assets are quite resilient to such changes. However, as panel (a) in **Figure 1** illustrates, a simple shift in the mean of a weather variable like temperature, with no change in the variance of the distribution will lead to new record high temperatures (red area) and a disproportionally (to the shift in mean) large increase in days that were considered extremely hot (pink + red). A shift in the variance alone can also increase extremes on both ends of the distribution as in panel (b). While most areas will warm with global climate change, for other weather variables such as precipitation, we may see trends for drier or wetter conditions in different areas, but some areas may see simply more variability and thus more chance of extreme heavy precipitation and extreme dry conditions. And, in some, and even many cases, we may see a shift in both mean and variance as in panel (c), further increasing the likelihood of record and extreme conditions. The likely disproportional increase in extremes, combined with the fact that unplanned-for extremes are the most damaging events, means that accurate assessment of physical risk must place a great emphasis on accurately predicting how extremes events—extreme heat, rainfall, tropical storms, etc.—will change.

Global climate models carry features that limit their usefulness for physical risk assessment. For instance, they do

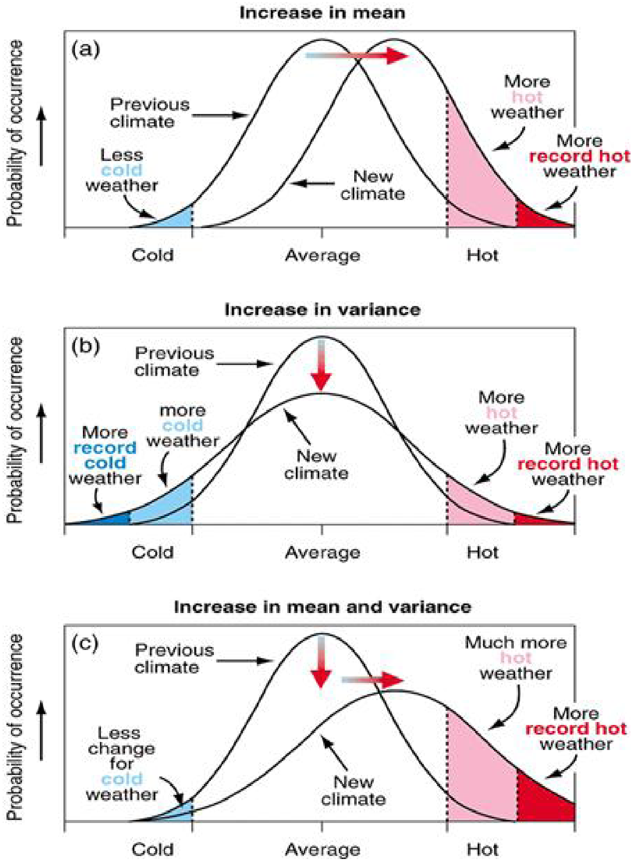

Figure 1. Climate Change: Means and Extremes. Source: IPCC (2001)

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[13] Consumers are formulated as a single representative agent for each region, and make choices among goods based on a specified utility function that includes elasticities of substitution based on econometric evidence. This formulation does not account explicitly for "early" or "late" adopters, although substitution elasticities will result in gradually greater substitution away from one good toward another as relative prices change. Choice among vehicle types is the one consumer choice that is not slowed by an elasticity of substitution. In this case, there are explicit vintages of vehicles, that slows adoption of e.g. electric vehicles, once they become economically competitive.

not simulate extremes for specific locations[14]. Moreover, they are generally designed to produce a 'best estimate' of future climate from increasing concentrations of trace gases. Hence, the various archived climate simulations–such as those from the Intergovernmental Panel on Climate Change (IPCC)–that are often used as starting points for assessment of physical risks are likely pre-conditioned around a central estimate of the future climate. A risk-based approach should investigate the full distribution of possible outcomes and in doing so consider the more extreme outcomes.

Additionally, efforts to use climate model information must carefully prioritize the types of events most relevant to the assets and location of interest. For example, heavy rainfall is damaging to flood-prone assets (e.g., buildings near rivers and streams), while extreme heat may be the biggest risk for other assets (e.g. large-scale power transformers). The risk for assets may also depend on compounding physical events (e.g., sea-level rise, storm surge, land subsidence, and inland flooding) that together dramatically increase the risk (e.g. flooding) to any one of these forces in isolation.

Assessing physical risks of climate change thus involves four major scientific challenges:

1. Capturing the full range of possible climate responses to a specific time path of trace-gas forcing that encompasses the chaotic nature of weather and climate variability.
2. Providing projections of changing weather events and climate conditions relevant to the geographic scale of the assets at risk.
3. Improving projections of extreme events that inflict the most damage to specific assets.
4. Assessing the awareness of and adaptive responses that the owners of at-risk infrastructural assets take in light of changing conditions.

As described above, the nature of physical risks makes its assessment a very different exercise, requiring different assessment tools than transition risks. The methodologies explored here with regard to physical risk address the issues outlined above to achieve more detailed and accurate "predictions" of historical weather events. The outperformance of these methodologies against other current efforts holds promise for a more sophisticated and useful assessment of physical risk to targeted assets and supply chain of a company/region/city/entity.

4. Scenarios

Five scenarios, developed to span a range of possible global actions to abate greenhouse gas emissions over the coming century, were used to explore the financial implications of climate-related transitions.

The main focus of the financial implications is on the period through 2040, and later sections of the report use the 2015–2040 period as the time horizon of interest. However, much of the longer-term focus of climate mitigation efforts involves the stabilization of global temperature. To assess the consistency of mitigation efforts in the next few decades with such long-term targets, the evolution of greenhouse gas concentrations and temperature over the rest of the century must be simulated to demonstrate that they stabilize. See Appendix A for more details.

All five 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. Given the need to focus on a limited set of scenarios, it was not possible to explore the financial ramifications of a wide range of possible disruptions in policy, technology, or prices, or to consider varying degrees of "global coordination" or "fragmented policy response." The scenarios differ in the extent and timing of greenhouse gas mitigation policies.[15] The 2°C Likely scenarios were achieved by implementing a globally coordinated, smoothly rising carbon price. The mitigation policies result in different patterns of resource and energy use, different choices of technology, and drag on overall economic growth. While the sudden increase in the carbon price when it is initially implemented creates a disruptive transition—resulting in stranded assets and some level of adjustment costs in the economy—it is implicitly assumed that reactions to the sudden policy change are rational and that financial markets are not disrupted. Similarly, the regional comparative economics that result are due only to the efficient economic actions of the actors in each region under consistent economic operations, not to destabilized financial reactions. Both disruptive transitions and fragmented responses provide substantial areas for future research.

The scenarios are *No Policy, Paris Forever, Global Action Post-Paris, Global Action 2020,* and *Deep Cuts Post-2070.*

4.1 No Policy

The *No Policy* scenario has no explicit climate mitigation policies anywhere in the world.

This represents a world in which there is no Paris Agreement and no alternative action towards reducing emissions for the sake of limiting climate change. However, it includes some

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[14] Extreme events such as intense summer thunderstorms that can lead to very large precipitation over a small area (i.e. 1 to 5 km2) are, at best, a rain event spread over the ~50 km by ~50km grid cell resolution of a global climate model.

[15] This differs from the approach taken with the Shared Socioeconomic Pathways, which explore a range of pathways with different demographic patterns and level of global coordination. See Riahi, *et al.* (2017). The Shared Socioeconomic Pathways and their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview. Global Environmental Change, 42, 153-168.

energy policies such as fuel economy standards, renewable electricity requirements, and the gradual phase-out of old coal power plants that are presently occurring with various motivations. These motivations include reducing imported oil dependence, using less of exhaustible resources, or to reducing conventional pollutants. Such efforts may in part reflect concerns about climate change, but the policies have no specific greenhouse gas emissions targets.

While the *No Policy* scenario paints a particularly bleak future in terms of its lack of global or regional action on climate change, it nonetheless serves as a baseline scenario because of its simplicity. Metrics from the other scenarios are often presented as the difference between another scenario and the *No Policy* scenario. It provides the upper assessment of our modeled physical risks.

4.2 Paris Forever

The *Paris Forever* scenario assumes countries meet the mitigation targets in their Nationally Determined Contributions (NDCs) and continue to abide by them through the end of the century.

The Paris Agreement includes NDCs submitted at the 2015 Paris Conference of the Parties (COP) of the Framework Convention on Climate Change (FCCC). These NDCs—aimed at the reduction of CO_2 and other GHG emissions—generally deepened and extended through 2030 those made at the 2009 Copenhagen COP through 2020.[16] These reductions are typically expressed as (1) an absolute emissions target (ABS), measured as an annual level of emissions measured in Mt), (2) a percentage reduction from a pre-determined baseline, which can easily be converted into an absolute emissions target, or (3) an emissions intensity target (INT), measured as emissions in relation to GDP. The various regional targets and measures are shown in **Table 1** on page 11.

For many of the world's richer countries (e.g., the United States and Canada), the Paris NDCs are absolute emissions targets, often submitted as percentage reduction below an historical base year such as 1990 or 2005.

For many other countries (e.g., China and India), emissions reduction goals were submitted as a percentage reduction from a "business as usual" (BAU) emissions projection,[17] or as an emissions intensity reduction percentage. In some cases, the submitted BAU is well above other analysts' projections. This can mean that even a relatively large percentage reduction commitment can mean little or no reduction from what is likely to happen anyway.

For countries with an absolute emissions target, emissions fall through 2030 and then remain flat at that level through the end of the century. If there is underlying growth in the economy with a tendency for BAU emissions growth, keeping emissions flat may require gradually more aggressive policies such as a rising carbon price.

Furthermore, if the projected growth in BAU emissions through 2030 is greater than the NDCs reduction commitment, then emissions will continue to grow through 2030 and beyond. Intensity targets leave even more room for different interpretations of what they mean for actual future emissions. If the economy grows very rapidly and the country meets its intensity target it will have higher emissions through 2030 and beyond than if GDP grows slowly. Moreover, due to structural change and improving technology emissions intensity of most economies has been falling by 1–2% per year for several decades or more. This means that emissions intensity reduction commitments would need to be greater than reductions already in progress in order to have a significant impact on future emissions.

Insofar as the remaining three scenarios each eventually result in some level of global coordination, the *Paris Forever* scenario might be akin to something like a "fragmented" or "uncoordinated" policy response. Rather than jettison its commitments after 2030, each region continues on the trajectories it had set for itself. For many regions, this means continued growth in energy use due to increases in population or income, while or others, like the US and Canada, it might mean stabilized or even declining energy use.

4.3 Global Action Post-Paris

The *Global Action Post-Paris* scenario assumes that the Paris NDCs are met through 2030. However, in upcoming COP meetings, through a process outlined in the Paris Agreement and in recognition of continuing deterioration of climate conditions, agreement is reached to implement a global policy aimed at the deep reductions needed to keep warming well below 2°C above preindustrial levels, essentially enacting the long-term goal of the Paris Agreement.[18]

This global policy is implemented as a coordinated global carbon tax, and starts after the Paris timeframe of 2030, with continued rise thereafter. As the modeling system used solves only every 5 years, the first year the global tax

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[16] In addition, many countries submitted NDCs with a second, deeper level of emissions cuts, conditional on either financial assistance or that other countries also make deeper cuts. Some countries have come forward with provisional plans to make deeper cuts in the post-2030 period. Some have focused only on CO_2, others have considered all greenhouse gases and black carbon, and emissions reductions or carbon uptake from avoided deforestation or reforestation is subject to different accounting practices. These various considerations leave a considerable interpretation of what the emissions level would be if the Paris agreement were fully implemented.

[17] If an NDC includes the projected BAU emissions and percentage reduction from it, then it can easily be translated into an absolute target for the NDC term.

[18] The Paris Agreement left "well below" undefined but for this purpose it is interpreted as an emissions path with a 66% likelihood of remaining below 2°C, recognizing that the climate response to radiative forcing is uncertain. In the language of the Intergovernmental Panel on Climate Change, something with a 66% chance is described as "likely".

Table 1. Nationally Determined Contributions under the Paris Agreement
(Translated to percent emissions cut for EPPA regions)

	NDC[b]				
Region[a]	**Metric Type[f] (Base Year)[g]**	**Target Reduction (Target Year)**	**Base CO_2e[c] Mt (ABS) or t-CO_2/$1000[d] (INT)**	**Other Features**	**Expected CO_2e reduction[e]**
USA	ABS (2005)	26–28% (2025)	6220 (ABS)		25%[h]
EUR	ABS (1990)	40% (2030)	5370 (ABS)	Electricity mix 27% renewables by 2040.	40%
CAN	ABS (2005)	30% (2030)	789 (ABS)	Mainly land use & forestry; 18% industrial reduction.	25%
JPN	ABS (2005)	25% (2030)	1260 (ABS)	2.5% LUCF. Electricity mix 20–22% nuclear, 9% solar/wind, also biomass. Assumes ITMOs. Target = 1.04b ton CO_2-e.	20%[i]
ANZ	ABS (2005)	26–28% (2030)	596 (ABS)		20%[j]
BRA	ABS (2005)	37% (2025)	2 (ABS)	Primary energy 45% renewable by 2030. LUCF down 41% 2005–12.	35%
CHN	INT (2005)	60–65% (2030)	2.00 (INT)	NDC 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% (2030)	NA	PAMs on renewables and autos (no detail).	25%
IND	INT (2005)	30–36% (2030)	1.17 (INT)	2.5–3.0b tons CO_2 from forests. 40% non-fossil electric. Assumes un-specified financial assistance.	30%
IDZ	BAU	29% (2030)	NA	Role of LUCF (63% of current emissions) not clear. Industrial emissions increase.	30%
MEX	BAU	25% (2030)	NA	22% of CO_2, 51% of BC. Int. reduction of 40% 2013–2030	25%
RUS	ABS (1990)	25–30% (2030)	3530 (ABS)	Reduction subject to “maximum accounting” from forests.	32%
ASI	BAU		NA	**Malaysia** 45% INT. **Philippines** 70% BAU. **Thailand** 20% BAU. **Singapore** 36% ABS.	10%
AFR	BAU		NA	**Nigeria** 45% BAU. **South Africa** 20–80% increase (ABS). Limited information on other regions	5%
MES	BAU		NA	**Iran** 15% BAU. **Saudi** & **Kuwait** actions only. **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. **Sri Lanka** 7% BAU. **Pakistan** reduction after unspecified peak. **Myanmar** & **Nepal** miscellaneous actions.	10%
ROE	BAU		NA	**Azerbaijan** 13% BAU. **Kazakhstan** 15% 1990. **Turkey** 21% BAU. **Ukraine** 40% BAU.	10%

a) Refer to Appendix B for regional abbreviations.

b) Sources include UNFCCC (2016) INDCs as communicated by parties. http://www4.unfccc.int/Submissions/INDC/Submission Pages/submissions.aspx, and CAT [Carbon Action Tracker], (2016) Climate Analytics. Ecofys & the NewClimate Institute. http://climateactiontracker.org

c) CO_2 equivalent

d) In 2007 US$.

e) Percentage reductions applied to the Base values in column 4, given the type of target in column 2.

f) ABS [absolute emissions]; INT [CO_2-e intensity]; BAU [relative to a business-as-usual projected value]

g) Base year of either absolute emissions or CO_2-e intensity to which the reduction goal refers.

h) Based on assessments by Greenblatt and Wei (2016), Larsen *et al.* (2016) and Vine (2016).

i) Discounts ITMOs and nuclear expectations.

j) Expectation discounted by political reversals in Australia.

is implemented in the model is 2035 with a price of 67.80 USD per tonne of CO_2-eq.[19] However, one can imagine this tax being phased in over the 5-year period of 2030 to 2035.

Having essentially delayed more aggressive global action until after 2030, the carbon price required in order to produce the emissions reductions needed to reach the well below 2°C target is rather aggressive, especially for China, India, the Middle East, and the Rest of the World, each of which have lower regional carbon prices in 2030 than the global price. As a result, the period between 2030 and 2035 in this scenario represents a substantial shock to many energy systems around the world, and is the closest

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[19] All prices are reported in 2015 USD unless otherwise noted.

representation of a "disruption" in the scenario selection. Market dislocations due to such rapid transitions take many forms including stranded capital, monopoly rents associated with the new technology, and adjustment costs related to expanding the new technology.[20]

4.4 2020 Global Action

The *2020 Global Action* scenario assumes the world recognizes that the Paris Agreement NDC's are not, by themselves, consistent with the level of emissions reductions needed to stabilize temperature at 2°C and that delaying those reductions will only raise the cost of meeting the target in the long-run, or worse, risk exceeding it. Thus, an accord is reached immediately, and a globally coordinated carbon price puts the world on a path consistent with a 2°C outcome starting in 2020 - essentially, immediately.

This scenario makes use of the widely recognized approximation that upon the determination of an emissions path consistent with a 2°C outcome, reallocating emissions over the course of the century will have little or no effect on the climate outcomes. Economic simulations were iterated with different carbon price starting points, starting in 2020 rather than 2035 in this case, until a carbon price was found that delivers the same level of total greenhouse gas emissions over the century.[21] Due to the earlier start date, a globally coordinated carbon price of 39.00 USD is enacted in 2020 and slowly ramps up thereafter, in contrast to the *Global Action Post-Paris* scenario where the carbon price increases to 67.80 USD in the five years following the Paris timeframe. As such, this scenario serves as a basis for exploring the effect of delays in policy action.

4.5 Deep Cuts Post-2070

The emissions path over time consistent with a 2°C outcome is completely dependent on technology and the economic structure of the economy. While there is more evidence and data on the costs and limits of technology in the near-term, the type and scale of new technology options to be developed in the distant future is highly uncertain. Nevertheless, these potential technologies have a large influence on how severe near-term cuts in emissions need to be. If there are options that can be effectively developed and applied at a reasonable cost, then deeper cuts in emissions in later years might allow for more "headroom" for emissions in the near term.

The *Deep Cuts Post-2070* scenario assumes that heretofore undeveloped negative emissions and emissions reduction technology options are taken advantage of late in the century, allowing for the emissions reduction efforts in the next several decades to be relaxed. Therefore, this scenario is optimistic about the development of low-cost technology to get deeper cuts, but risks not achieving the temperature goal (or a great escalation of costs sometime in the future) if those options don't appear. Furthermore, it reflects a greater risk of exceeding a climate "tipping point," in which non-linear earth system feedbacks make recovering to a 2°C stabilization point even more difficult, or even impossible, regardless of the assumption of the ability to make deep cuts in global emissions post-2070.

The 2018 Food, Energy, Water, and Climate Outlook stabilization scenarios include three different possible options that could lead to deep cuts in emissions in the latter part of the century. While these technology options are not formally modeled in EPPA, it refers to estimates in the literature on the potential cuts possible. Options considered include a very large reforestation program, carbon capture and storage (CCS) combined with bioenergy that can deliver net negative emissions[22], and the ability to eliminate carbon emissions from energy-intensive industry.

The technology to reforest or afforest is not difficult, or even particularly expensive on a small scale. However, at a scale needed to significantly draw down carbon, land requirements may begin to impinge on land needed for other purposes (e.g., crops), and can thus become costly.

There are CCS plants operating with coal plants on demonstration scales. However, CCS has so far proved costly, and using this technology with bioenergy would introduce additional issues and likely additional cost. Many of the IPCC scenarios, especially those achieving stabilization at 2°C or 1.5°C rely on biomass with CCS. In addition to the basic CCS technology being unproven at commercial scale, carbon storage underground may face resistance.

Then, while there are ambitious political calls to get to net zero emissions by as early as 2050, there are no obvious easy solutions for eliminating emissions of CO_2 from energy-intensive industry (or of nitrous oxide from the use of fertilizer and methane from ruminant livestock and rice). Therefore, a third option considered was a robust technology to completely eliminate emissions from energy-intensive industry.

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[20] See Morris J.F., Reilly, J.M., and Chen, Y.-H.H. (2019) Advanced technologies in energy-economy models for climate change assessment. Energy Economics. 80 (2019) 476-490.

[21] In principle, there can be very slight differences in the timing of warming and shifts among which greenhouse gases are abated, or how differences in abatement affect other substances such as sulfate aerosols could have effects on the amount warming and its timing. Once we determined a new emissions path starting with deep cuts in 2020, we verified that the climate simulation was essentially identical to the Global Action Post-Paris scenario.

[22] The biomass takes carbon out of the air when it grows, and then when the biomass is used to produce energy at least some of the carbon dioxide is captured and permanently stored—usually by pumping it deep underground. A CCS technology developed for capturing CO_2 from coal or gas power plants could be applied to bioenergy, or another option is to capture CO_2 gas from the fermentation process of producing ethanol, that can then be used as fuel.

The additional carbon emissions reduction from each of these options was fairly similar given the available literature, and any one of them would provide similar additional emissions headroom in the 2020–2050 period. In the *Deep Cuts Post-2070* scenario, we adopted the scenario which assumed emissions could be eliminated from energy-intensive industry; however, there remained emissions of methane and nitrous oxide from agricultural sources.[23]

5. Main Analysis

5.1 Population and GDP

The UN "Medium" projection from its 2017 revision provides the population profile used in all five scenarios, with the global population rising from just over 7.3 billion people in 2015, to just over 9.2 billion people in 2040, and to almost 11.2 billion people by 2100[24]. This allows for the analysis to focus on the policy and technological dynamics without being overshadowed by larger sociological ones. For most regions, the population has nearly stabilized (see **Figure 2**). The exception is the ROW region, which is shown to increase by almost 40% from 2015 to 2040, driven primarily by growth in Africa.

GDP

The IMF provides a regular estimate of current GDP across the world and an assessment of near-term growth prospects. To assure that the current economy as represented in the model is as close to that actual economy, we calibrate productivity growth through 2020 to the International Monetary Fund (IMF) short term projections.[25] After 2020, we allow productivity growth to return to long-term trends and expert judgement of likely future growth. For example, China has exhibited very rapid growth for the last couple of decades, but most analysts conclude that such growth rates cannot be sustained indefinitely. The GDPs that results from this calibration and long-term productivity assumptions for each region is shown in **Figure 3**.

The population and GDP projections imply a significant divergence in the GDP per capita patterns between devel-

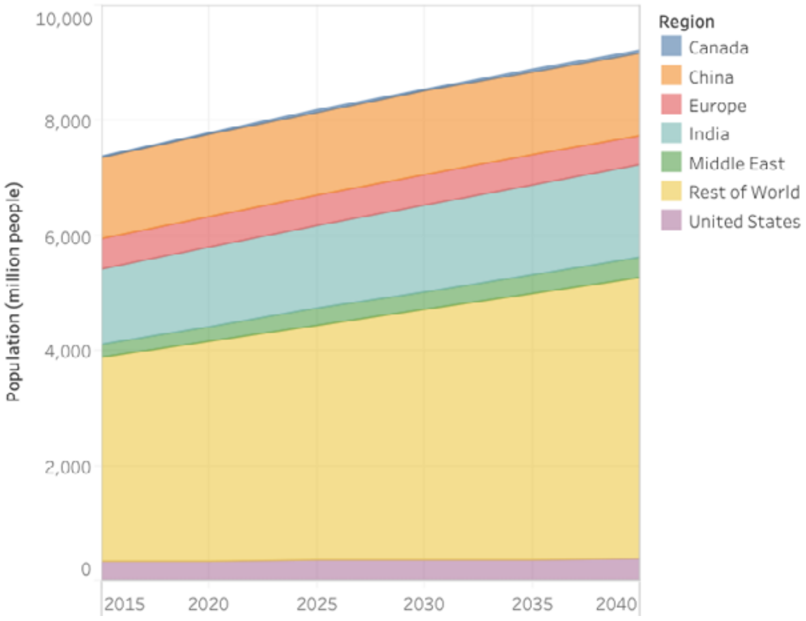

Figure 2. Global Population by Region

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[23] Within the EPPA model there is abatement of emissions in agriculture and energy-intensive industry consistent with estimates of possible abatement opportunities such as more judicious use of fertilizer so that less nitrous oxide is produced, substitution to less carbon-intensive energy in the energy-intensive sectors, and consumption shifts away from livestock and rice as carbon pricing of methane emissions raises the price of these commodities. However, there are no currently known options for completely eliminating these emissions short of eliminating ruminant livestock production and rice production. There are possible options within energy-intensive industry including CCS with steel, cement, and chemical production, possible shift to providing industrial heat with electricity or nuclear power, substitution of biomass-derived chemicals to replace petrochemicals that could, with CCS, be a net negative emissions source, or substitution to other materials, such as using lumber instead of steel or cement.

[24] United Nations (2013). World Population Prospect: The 2012 Revision. https://population.un.org/wpp/Publications/Files/WPP2012_HIGHLIGHTS.pdf

[25] IMF [International Monetary Fund], 2018: World Economic and Financial Surveys: World Economic Outlook Database. Washington, D.C., USA. (https://www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx).

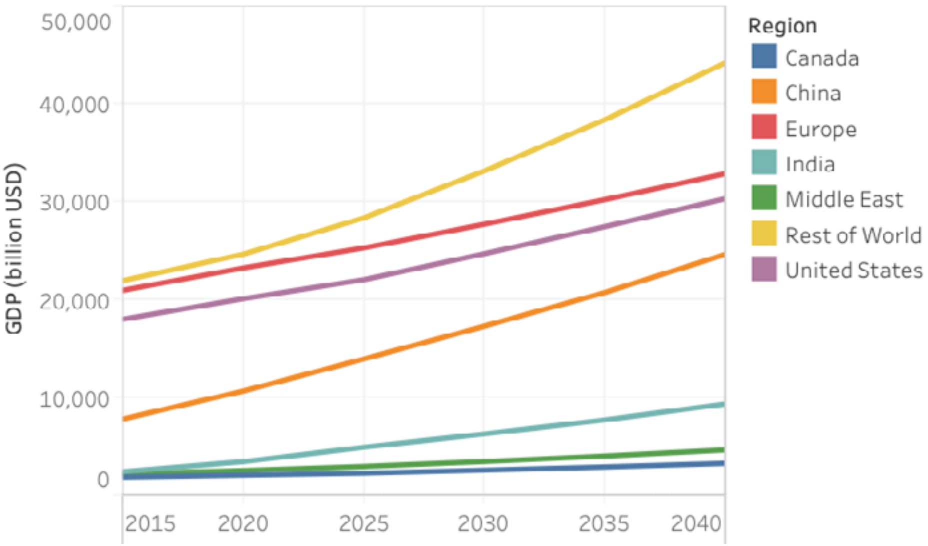

Figure 3. Regional GDPs in *No Policy* Scenario

oped and developing regions.[26] While the United States, Canada, and Europe demonstrated GDPs per capita between 40,000 and 60,000 in 2015, China, India, the Middle East and the Rest of the World demonstrated GDPs per capita under 10,000.

Absolute GDP growth in the US, Canada, China, and Europe is driven by growth in GDP per capita; absolute GDP growth in the Rest of the World is driven by population growth; absolute GDP growth in India is driven by both increases in population and GDP per capita; and absolute GDP growth in the Middle East is relatively small due to both population and GDP per capita.

5.2 The Paris Agreement and Carbon Prices

The Paris Agreement

Modeling the implementation of the Paris Agreement relies on several studies of what the NDCs entail for different countries, interpreted for the base regional aggregation of the EPPA model.[27] The approach was to first represent explicit policy measures such as vehicle fuel standards, renewable energy targets, and other measures where there was an indication of the measures countries were likely to use. Then, if the explicit policy measures were insufficient to meet the numerical targets, or no specific policy was described, a carbon cap was applied as a model constraint to generate the additional reductions required by the EPPA regions. Such caps result in a shadow price on carbon, which can be interpreted as the market price that would occur with a cap and trade system.[28]

Carbon Prices

As described above, regional carbon pricing during the implementation of the NDCs is layered on top of other explicitly modeled policy measures to achieve the remaining committed emissions reductions. During the 2020–2030 period, changes in energy mix, patterns of household transportation, and all other economic dynamics are due to a combination of both the explicitly modeled policies and carbon prices. For instance, China's energy sector transformation through 2030 is primarily driven by the NDCs rather than the carbon price for the *Paris Forever, Global Action Post-Paris,* and *Deep Cuts Post-2070* scenarios (see China on page 48).

Efficient pricing paths (i.e. carbon price trajectories that efficiently bring about the targeted emissions trajectories) were developed in which prices rise at the discount rate, with emissions reduced from a reference no policy case. We imposed this global emissions path on top of the Paris

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[26] GDP is reported in Market Exchange Rates (MER) because EPPA is formulated in MER and trade occurs at market exchange rates. Comparisons of per capita income are better reported in Purchasing Power Parity or a similar conversion, which better accounts for the domestic purchasing power of different currencies. Accordingly, we have limited the emphasis on GDP per capita.

[27] Greenblatt, J., and M. Wei, 2016: Assessment of the climate commitments and additional mitigation policies of the United States. Nature Climate Change, doi: 10.1038/NCLIMATE3125; Larsen, J. *et al.*, 2016: Taking Stock: Progress Toward Meeting US Climate Goals. The Rhodium Group. https://rhg.com/research/taking-stock-2016-us-greenhouse-gas-emissions; Vine, D., 2016: US can reach its Paris Agreement goal. Center for Climate and Energy Solutions, 26 March. https://www.c2es.org/2016/04/us-can-reach-its-paris-agreement-goal

[28] There was no provision for allowance trading among regions, in part, because there were no explicit suggestions that a cap and trade policy would be the instrument of choice. It is used because, in the absence of more information, it is the most straightforward way to ensure the emissions goal is met.

forever emissions trajectories. This helps delineate where and how the Paris NDCs diverge from this "efficient" path.

This result reflects an arbitrage condition in the context of time shifting (banking and borrowing) abatement. If the carbon price rises faster than the discount rate, abating more today would generate allowances whose value would rise faster than the rate of return one could earn on relatively risk-free financial assets. Hence, it would be economic to continue abating more today, until today's abatement cost was driven up, and the future price down through more supply of banked allowances, until arbitrage opportunities disappeared. Or if allowance prices rise more slowly, it would be economic to borrow future allowances to lower abatement costs today and raise them in later years, until arbitrage opportunities disappeared.[29]

For the *Climate Action Post-Paris* and *Deep Cuts Post-2070* scenarios, the various carbon pricing schemes implemented within the Paris timeframe transition into a single coordinated global carbon price for each scenario, 68.04 and 21.19 USD per tonne CO_2-eq, respectively (see **Figure 4**). The *No Policy* scenario has no carbon price (i.e. its global carbon price is consistently 0 USD per tonne CO_2-eq). The *2020 Global Action* scenario exhibits its coordinated global carbon price starting in 2020 at 39.02 USD per tonne CO_2-eq. The translucent lines represent the range of regional carbon prices implemented by the different study regions during the Paris NDC timeframe. Please refer to the regional appendices for further detail.

It is interesting to note that some of the regions, specifically the developed regions, exhibit higher carbon prices in 2030 than the globally coordinated carbon prices that succeed them. Specifically, Canada, Europe, and the United States exhibit carbon prices of 81.03, 84.99, and 74.72 USD per tonne CO_2-eq, respectively, in 2030. By contrast, China, India, and the Middle East exhibit carbon prices of 13.21, 0.00, and 11.95 USD per tonne CO_2-eq, respectively. It is important to consider that, due to the use of carbon prices as a method to achieve the remaining emissions reductions targeted by the NDCs (see page 14), high carbon prices could be due to either aggressive targets (see page 10), lack of specific policy plans, or combinations thereof.

5.3 Emissions Pathways and Climate Implications

Emissions Pathways

Although the model simulates the world economy and associated emissions through 2100, the timeframe of focus for this analysis is through 2040. Simulating emissions through 2100 ensures that the probability of achieving the temperature targets is achieved and is necessary to study the long-term consequences of the slowly-evolving climate system. Long-term simulations also provide insight into the required depth and timing of climate action in the first half of the century to achieve long-term targets. See Appendix A for more detail on the determination of emissions pathways consistent with the *2°C Likely* outcomes.

The emissions scenarios have been simulated through a flexible earth system model that represents underlying uncertainty in the climate system response to radiative forcing, thus creating probability distributions of future climate outcomes conditional on the emissions scenarios.

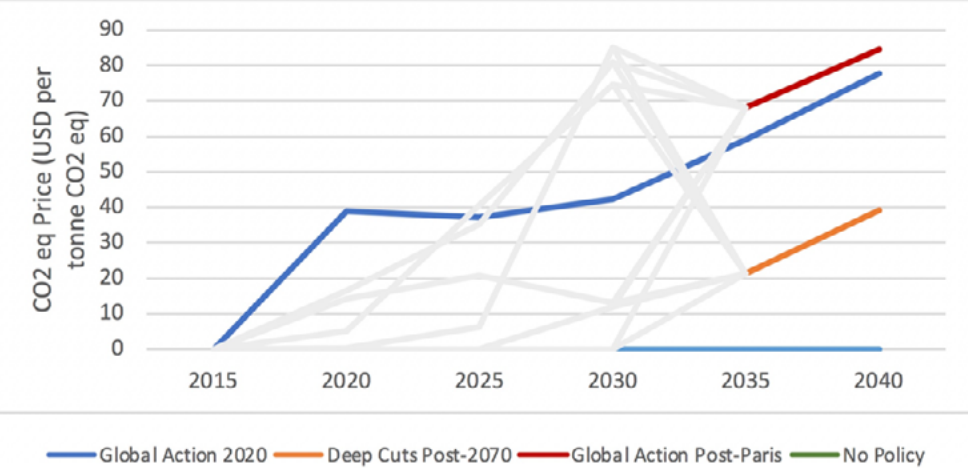

Figure 4. Globally Coordinated Carbon Prices

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[29] The cost of abating to different levels of emissions over time depends on the technology opportunities and overall structure of the economic system as described in the equations of the EPPA model. For example, abatement opportunities may be somewhat limited in the short term because of a large stock of carbon using capital (e.g. coal power plants) that would continue to operate if returns can cover variable operating costs even if they are not enough to fully cover the replacement cost of the capital. Furthermore, rising costs of fossil fuels due to depletion effects may make them costlier in the future, so switching to low-carbon fuels may be relatively less costly later than in the near term. Technological progress may differentially advantage different technologies over time, and consumption pattern shifts toward less energy-consumption goods may make for less costly abatement in the future.

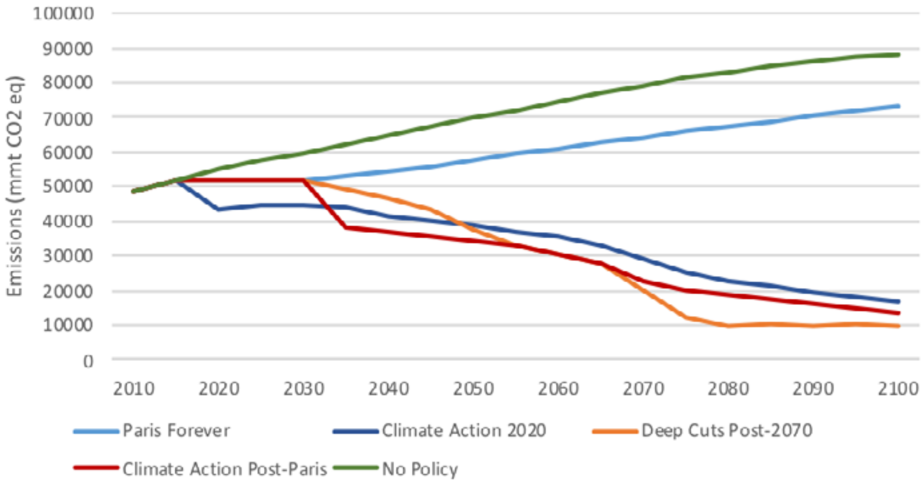

Figure 5. Global CO_2 Emissions Paths

Climate Implications

The climate trajectories for the five 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. Because cumulative emissions over the century are constrained to be identical in the three *2°C Likely* scenarios (i.e., *2020 Climate Action, Climate Action Post-Paris, and Deep Cuts Post-2070)*, there is no difference in the climate results across these three scenarios (see **Figure 6**); each represents a 66 percent chance that the temperature rise by 2100 will be limited to 2°C.

As illustrated above, regardless of the policy action across scenarios, average global temperatures (and their corresponding climate ramifications) do not diverge significantly until after 2040. Even if the long-run goals of staying well below 2°C or even 1.5°C of warming are met, physical risk will continue to increase for decades because of the inertia in the climate system (i.e., the significant concentration of GHGs and carbon dioxide already present in the atmosphere). Even fairly dramatic immediate cuts in global emissions will not significantly change the amount of warming we are likely to see for the next few decades. The recent Intergovernmental Panel on Climate Change (IPCC) special report on the impacts of warming above 1.5°C outlines some of the long-term dangers of failing to stabilize the climate system.[30]

Comparison with the IPCC Representative Concentration Pathways

The Representative Concentration Pathways (RCPs) adopted by the Intergovernmental Panel on Climate Change (IPCC) in their 2014 Fifth Assessment Report[31] are widely cited as reference points for climate studies.[32] They were developed over the period from 2006 to 2009 by various research groups using integrated assessment models to update previous scenarios used in the IPCC.[33] Intended to provide a set of concentration pathways that could be used to in climate model studies, the RCPs include energy and emissions pathways that kept radiative forcing in the atmosphere to 8.5, 6.0, 4.5, and 2.6 Watts per meter squared (Wm^{-2}) through 2100. We compare the RCP scenarios to the scenarios evaluated in this report in **Figure 7**.

First, the median radiative forcing at present (circa 2010–2020) in the scenarios used herein is slightly higher than that of the RCP scenarios, but the 90% range includes them.[34] Second, the range for a given scenario broadens slightly over time because of additional feedbacks from the earth system on natural sources and sinks of greenhouse gases. Note that radiative forcing calculations for

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[30] IPCC, 2018: Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.

[31] https://www.ipcc.ch/report/ar5/syr

[32] van Vuuren, D.P., Edmonds, J.A., Kainuma, M. *et al.* Climatic Change (2011) 109: 1. https://doi.org/10.1007/s10584-011-0157-y

[33] https://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/RCPs.html

[34] The range for radiative forcing at present is largely due to uncertainty in the aerosol forcing strength, as estimated jointly with climate sensitivity and ocean heat uptake parameters in the MIT IGSM. Because of the joint estimation, the lower cooling effect of the aerosols as estimated must be offset by climate sensitivity and ocean heat uptake, so that historical climate simulations are consistent with observations. The MIT IGSM simulations also have the advantage of another decade of observations.

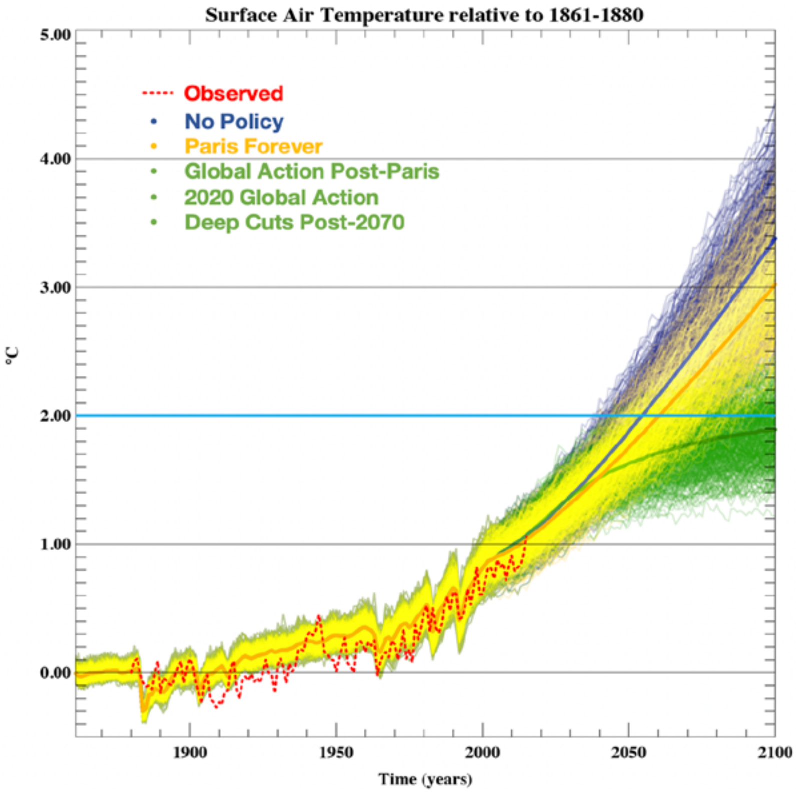

Figure 6. Average Global Surface Air Temperature Trajectories Relative to 1861–1880

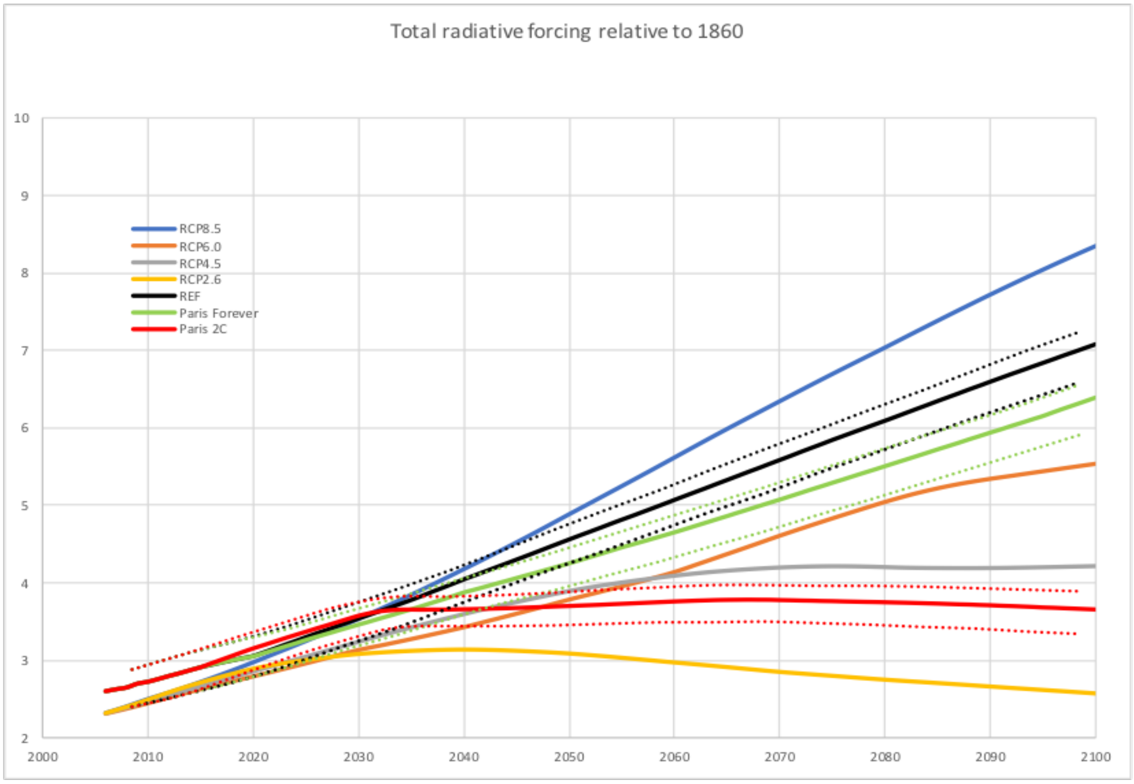

Figure 7. Total radiative forcing under IPCC RCP and MIT IGSM scenarios (Wm^{-2}) above pre-industrial (1860) levels. Solid lines represent median values. Dotted lines represent 90% confidence interval. The Paris 2°C line (red) represents any of the 2°C Likely scenarios.

the both the RCP and MIT IGSM scenarios use the same formulations.[35]

The MIT IGSM scenario range by 2100 (~4 Wm^{-2}) is narrower than that of the RCPs (~6 Wm^{-2}). Since uncertainty tends to widen further into the future, the elapse of more than a decade since the RCP scenarios were developed, during which emissions could be observed, narrows the 2100 range *ceteris paribus*. The RCP8.5 is now considered very high, in part because energy policy, technological development, and economic growth prospects have changed since the RCPs were developed. Reduced economic growth prospects for China, in combination with the desire to control conventional air pollution there, significantly lowers the likelihood of high emissions. It is important to note that the RCP process never intended to attach likelihood statements to any of the scenarios. RCP2.6 was designed to achieve a warming impact that centered around 1.5°C above preindustrial, recognizing that, given the range of earth system response, the actual temperature change could vary on either side of 1.5°C. This became the aspirational goal under the Paris Agreement so that additional scenario development could move toward emissions consistent with that target.

5.4 Energy System Transformations

The energy sector is by far the most susceptible sector to the various levels of low-carbon transition described by the scenarios. The impact of climate policy takes two major forms: (1) a reduction in the overall use of energy from what the counterfactual suggests (see **Figure 8**), and (2) the reallocation of energy sources in the overall energy mix (see **Figure 9**).

The introduction of global carbon policy can temporarily interrupt a trend of growth in overall energy demand if it is aggressive enough. In each of the five scenarios, primary energy use trends upwards through 2040 due to a growing population and rising living standards. The *Global Action Post-Paris* and *2020 Global Action* scenarios experience initial drops in global primary energy upon the introduction of a global carbon price after 2030. However, while a global carbon price is 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 carbon price, only occurring in 2040, is required to disrupt the smooth upward trend of the aggregated energy use.

The share of non-fossil fuel sources in primary energy continues to rise. Even in the *No Policy* scenario, non-fossil fuel generation grows from 16% of the overall mix in 2015 to 20% in 2040. The grand majority of this growth stems from renewables 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%.

As expected, coal is the most sensitive to the choice of scenario, exhibiting precipitous drops in usage with the introduction of a global carbon price. This sensitivity is primarily driven by coal use in China and, to lesser degrees, India and the Rest of the World. (See Figure G11, Figure G28, and Figure G44.) The single largest source, oil, is almost exclusively used in the transportation sector. Carbon pricing affects the use of oil as expected, reducing

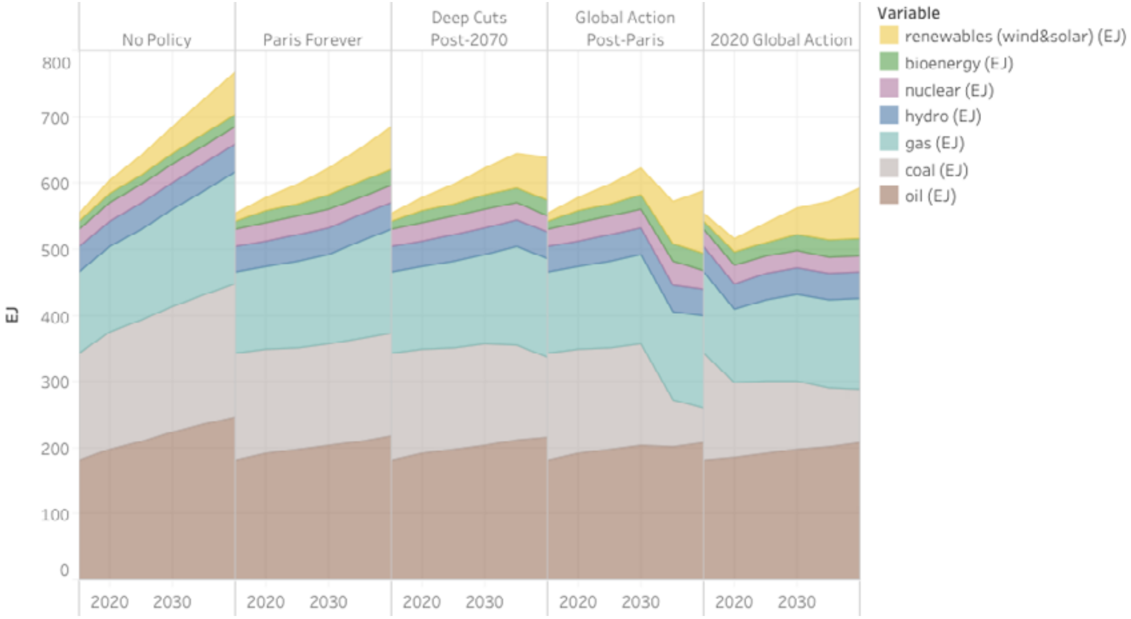

Figure 8. Global Primary Energy Use by Scenario

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[35] Myhre, G., E. Highwood, K. Shine, and F. Stordal (1998), New estimates of radiative forcing due to well mixed greenhouse gases, Geophys. Res. Lett., 25(14), 2715–2718, doi:10.1029/98GL01908.

Figure 9. Global Primary Energy Use by Source

its use from its counterfactual trend. However, increasing the use of fuel for transportation worldwide leads to projected growth through 2040 regardless of scenario, with the *No Policy* scenario predictably exhibiting the most growth. The use of pumped hydro energy is developed to its maximum under all scenarios due to its cost efficiency and limited resource. The bump in nuclear electricity generation in 2035 is due primarily to China's attempt to satisfy its electricity demand after a substantial jettison of coal. (See Figure G13.) India also contributes a small amount to the temporary increase. 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 four 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 (see **Figure 10**). 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.

Electrification of the economy is largely insensitive to climate policy scenario. Furthermore, 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) the efficiency gains in electricity production resulting from carbon pricing 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 carbon pricing, 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.

Carbon pricing affects 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. However, increasing carbon price increases the relative use of natural gas for electricity production (see **Figure 11**), but reduces its use relative to the *No Policy* scenario in other sectors (see Figure 9). Natural

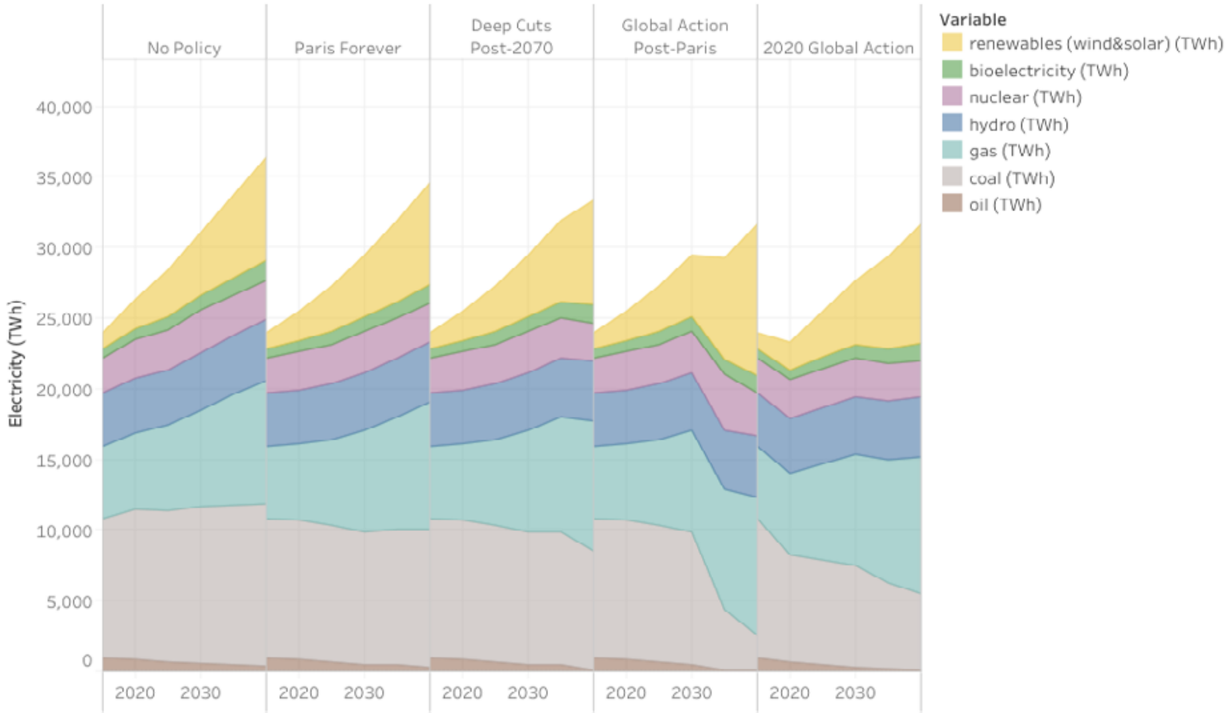

Figure 10. Global Electricity Generation by Scenario

Figure 11. Global Electricity Generation by Source

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 higher carbon prices, 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 increased carbon prices.

The use of advanced coal is boosted by less aggressive carbon prices. To a large degree, advanced coal will replace conventional coal energy production under all scenarios. The pattern of replacement, however, varies between scenarios and is primarily determined by two competing drivers: (1) carbon pricing makes the current efficiency of conventional coal-fueled energy production insufficient to retain energy production share, and (2) higher carbon prices makes even the higher efficiency of advanced coal-fueled energy production insufficient to retain energy production share. The fastest replacement occurs, unsurprisingly, under the *2020 Global Action* scenario, in which advanced coal grows to make up 73% of coal use by 2030. 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 carbon prices that the various scenarios introduce differ significantly. The *Deep Cuts Post-2070* global carbon price, introduced at 21.19 USD 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 68.04 USD, reduces both overall coal use and advanced coal use.

5.5 Stranded Assets

The term *stranded assets* can be used to refer to a variety of measurements used in a variety of contexts. The NGFS mentions a distinction between two broad types of stranded assets—stranded capital and stranded value. *Stranded capital* often refers to the upstream (i.e., exploration and development) infrastructure (e.g., wells, mines, refineries, etc.) whose upfront costs would not be able to be recouped given the market conditions brought about in a particular scenario. *Stranded value* has been used to refer to the value of the fuel that is no longer able to be extracted or used given the market conditions brought about in a particular scenario. However, even these definitions, let alone the methodologies for calculating them, vary depending on context and the user. This report explores specific varieties of each in the context of the energy and economic transitions that take place in the scenario simulations.

We report the value of stranded coal power generation assets and stranded assets in the fossil fuel production sectors (i.e., oil, coal, and gas). Stranded assets in the coal power generation sector are purely stranded capital, and are estimated as the reduced net present value (NPV) of the coal power plants due to idling or under-utilization through 2040. In the fossil fuel sectors, we use the NPV of reduced revenue through 2040 in for each producing region as an estimate of stranded assets.

There are several important considerations to account for in these estimates. First, 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. Second, a more conservative estimate of stranded value might consider lost value of only proved reserves because only proved reserves formally enter a company's balance sheet. For many oil and gas reserves, there are less than 10 years of supply at current production rates. We have included 20 years of reduced production and price, which necessarily involves further exploratory work to prove the resources.

There may be stranded capital in other sectors, however, given the aggregation of the EPPA model detecting that would be difficult, as it would likely be limited to facilities and sectors below the level of aggregation in the model. As will be shown later, the output reductions compared with the *No Policy* scenario in sectors other than those related to fossil fuels is on the order of one to two percent. At this level, changes in investment could lead to adjustment in the capital stock consistent with the new level of production, without premature retirement of existing capital.

Stranded Assets in Coal Power Generation

Stranded assets in coal power generation refers to the reduced value of coal power plants that, because of the climate policy, are idled or under-utilized over the course of what would have been the rest of their normal lifetime. Stated another way, it 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. (See Appendix C for more detail.) 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 12** illustrates the NPV of stranded assets in coal power generation through 2040 under the *Policy* scenarios.

As might be expected, the scenario with the greatest amount of stranded assets in coal power generation is the *2020 Global Action* scenario with a stranded NPV of capital of just over 2 trillion USD. This is due not only to the volume of coal plant capacity that goes unutilized, but also to the timing. The earlier the capital is idled, the greater the value lost because more years of potential full operation are lost (i.e., the output is reduced before physical depreciation of the plant efficiency declines). Moreover, the earlier the capital is idled, the less effect discounting has on the lost value in calculating the NPV. **Figure 13** separates the cumulative data from Figure 12 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 654.1 billion USD in the *Paris Forever* and *2020 Global Action* scenarios, respectively. This observation is corroborated by China's energy transition pathways (see Figure G10 and Figure G11). Not only do conventional coal assets become idled, but in the *2020 Global Action* and *Global Action Post-Paris* scenarios, so in later years do the advanced coal assets that succeed them (see Figure G14). Advanced coal would be used to replace conventional coal as a result of the recursive model nature (see footnote 12). For example, 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 agents would continue to build the optimal power plant choice at the present time through 2030, only to be hit with the "unanticipated" policy in 2035. 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 about 16 billion USD.

The developed regions of Canada, Europe, and the United States, each show relatively little sensitivity between scenarios, particularly the *Paris Forever, Deep Cuts Post-2070,* and *Global Action Post-Paris* scenarios. This suggests that the implementation of their Paris NDCs dictates the majority of their coal reduction.

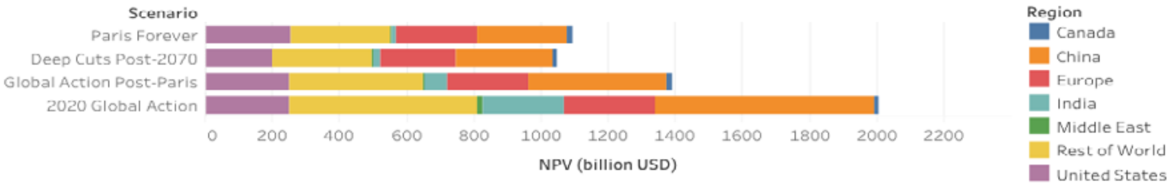

Figure 12. Stranded Assets in Coal Power Generation through 2040.

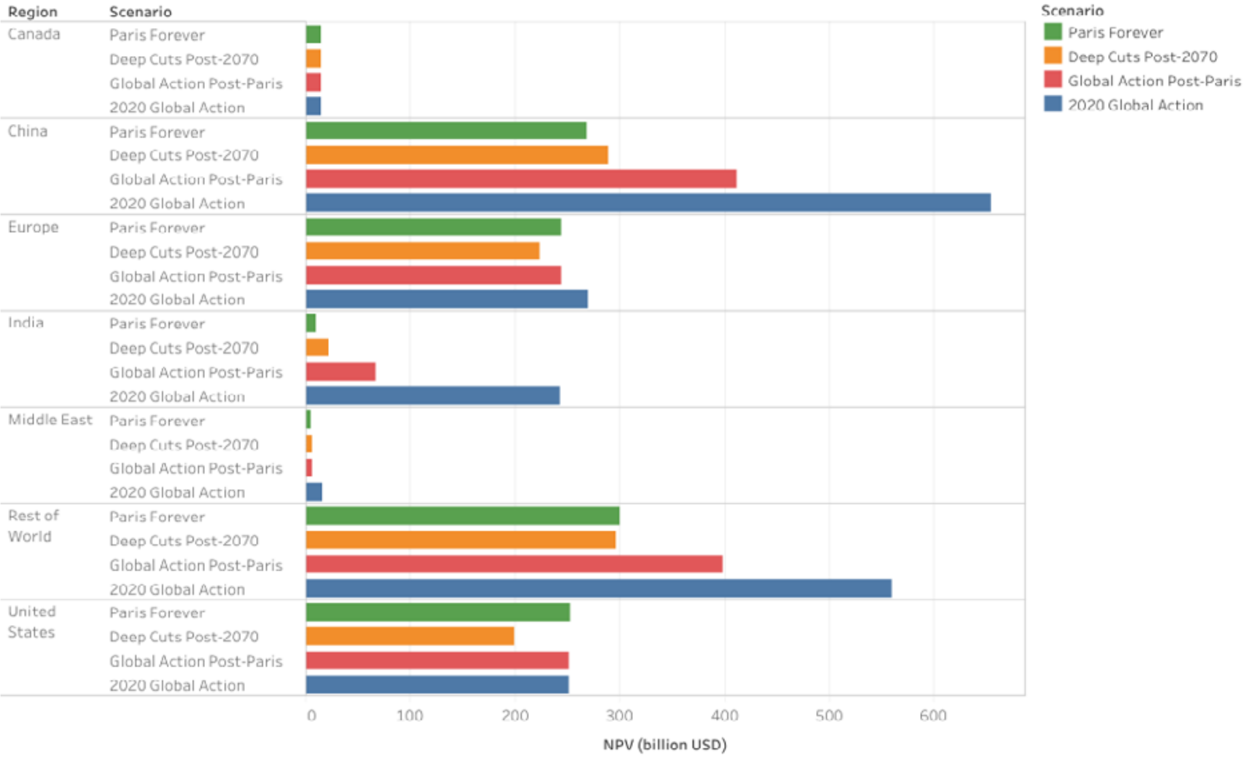

Figure 13. Stranded Assets in Coal Power Generation through 2040 by Region.

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. (See Appendix D for more detail.) 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 a simulating an infinite timeframe.

Similar to the NPV of stranded assets in coal power generation, 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 14** illustrates the NPV of stranded assets through 2040 under the four *Policy* scenarios.

The greatest value of global fossil fuel stranded assets occurs under the *2020 Global Action* scenario, with an NPV of over 20 trillion USD. **Figure 15** disaggregates stranded assets by fuel.

While the order of NPV of stranded assets is relatively constant across fuel types—*2020 Global Action* exhibiting the greatest amount, followed by *Global Action Post-Paris,* then *Deep Cuts Post-2070,* and finally *Paris Forever*—the regional exposure across fuel varies significantly. **Figure 16**, **Figure 17**, and **Figure 18** illustrate the regional variance of stranded asset value under each policy scenario for coal, gas, and oil, respectively.

China and the Rest of World regions are at the greatest risk of stranded coal assets, exhibiting NPV of stranded coal assets of over 2.4 trillion USD and 1.3 trillion USD, respectively, under the *2020 Global Action* scenario. By contrast, the combined NPV of stranded coal assets for the remaining regions (i.e., the Middle East, Canada, India, the United States, and Europe) falls below 646 billion USD.

The United States and the Rest of the World regions are at the greatest risk of stranded gas assets; the stranded gas asset NPV for the United States ranges from just over 609 billion USD in the *Deep Cuts Post*-2070 scenario to 724 billion USD in the *Paris Forever* scenario, and that of the Rest of the World ranges from 639 billion USD in the *Paris Forever* scenario to 995 billion USD in the *2020 Global Action* scenario. By contrast, China's stranded gas asset NPV falls below 1.4 billion in all policy scenarios. The Middle East exhibits 527 billion USD of stranded gas

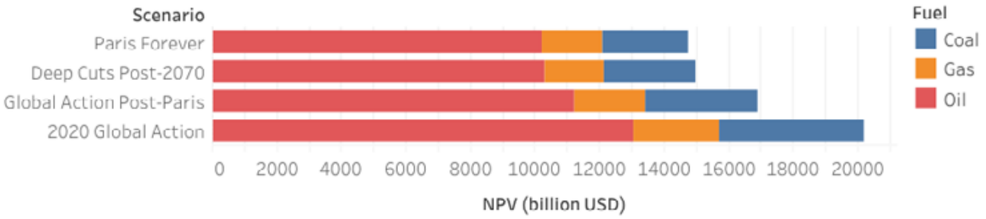

Figure 14. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy*.

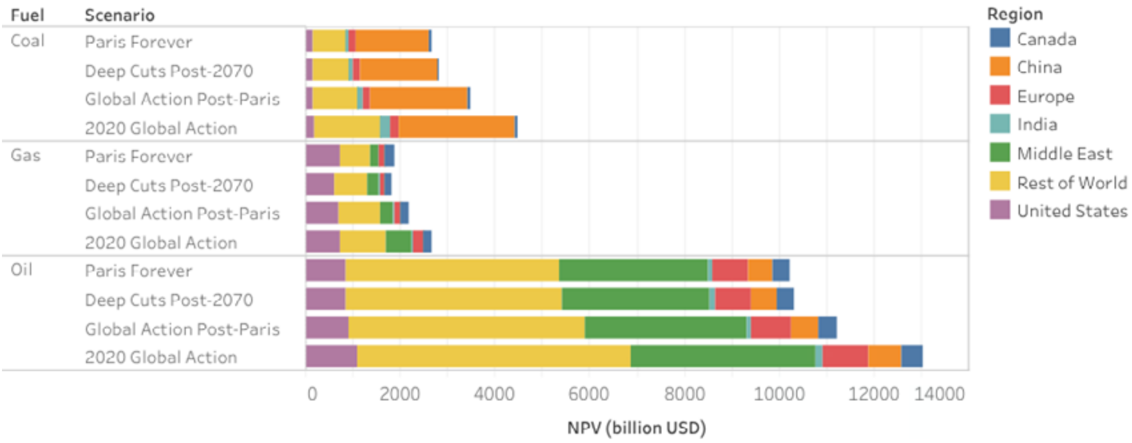

Figure 15. Stranded Value. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* by Fuel.

asset NPV loss under the *2020 Global Action* scenario, but significantly less—under 287 billion USD—in the rest of the policy scenarios, suggesting that the region has significant gas use, but its Paris NDCs can primarily be satisfied through reduction in oil use.

The Middle East and Rest of the World regions are at the greatest risk of stranded oil assets; the stranded oil asset NPV for the Middle East ranges from just over 3.1 trillion USD in the *Paris Forever* scenario to over 3.9 trillion USD in the *2020 Global Action* scenario, and that of the Rest of the World ranges from just over 4.5 trillion USD in the *Paris Forever* scenario to over 5.7 trillion USD in the *2020 Global Action* scenario.

In general, emerging market economies are particularly exposed to policy scenarios in absolute terms. Canada, Europe, and the United States exhibit cumulative stranded fossil fuel asset NPVs between approximately 3.1 trillion and 4.1 trillion USD depending on policy scenario. Con-

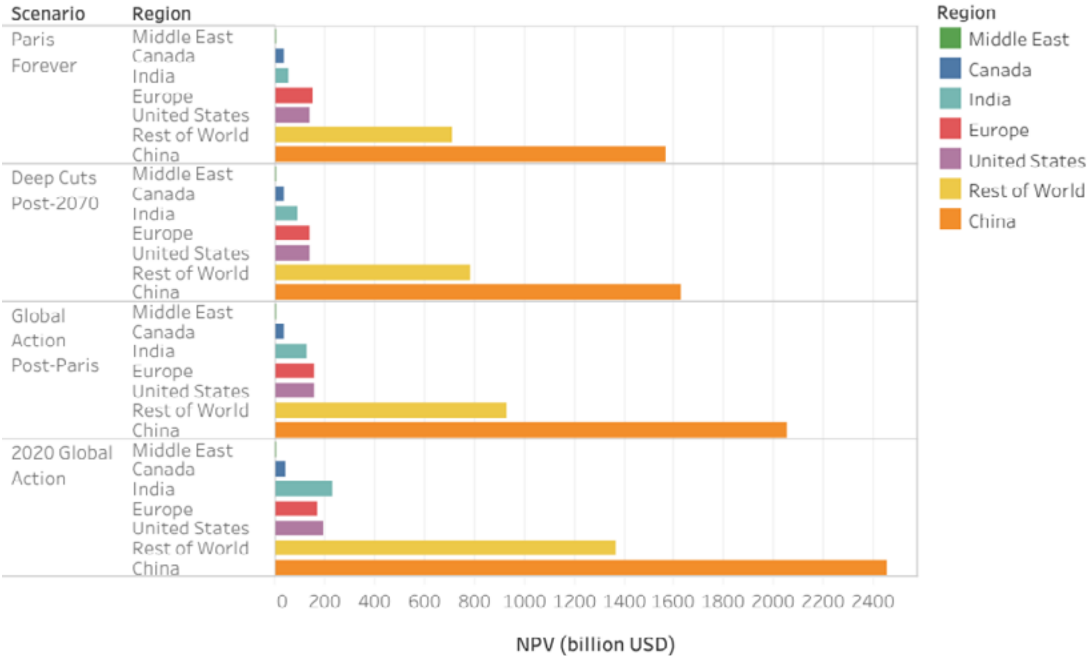

Figure 16. Coal Stranded Assets. NPV of Economic Output Lost from Coal Not Produced through 2040 Relative to *No Policy*.

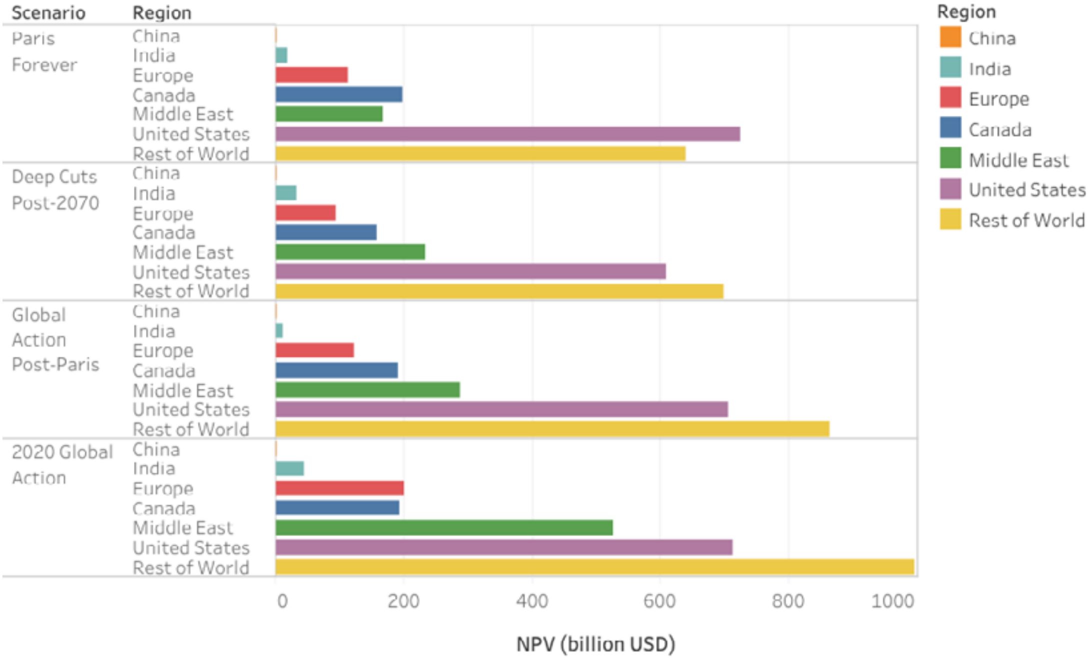

Figure 17. Gas Stranded Assets. NPV of Economic Output Lost from Gas Not Produced through 2040 Relative to *No Policy*.

trastingly, China, India, the Middle East, and the Rest of World exhibit cumulative stranded asset NPVs between approximately 11.4 trillion and 16.1 trillion USD depending on policy scenario.

These numbers represent a significant departure from the *No Policy* scenario, not only in trillions of dollars but also in NPV lost through 2040 as a percentage of economic output of the fossil fuels under the *No Policy* scenario. The order of relative loss remains the same, regardless of expression. The effects across regions, however, are surprising. While Canada, China, India, and the Rest of the World incur coal economic value losses above 64% in the *2020 Global Change* scenario relative to its *No Policy* scenario, the United States incurs approximately half of that percentage amount. This is, in part, due to wide variation in the evolution of coal price indices between regions.

Fuel Prices

As discussed on page 23, 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,

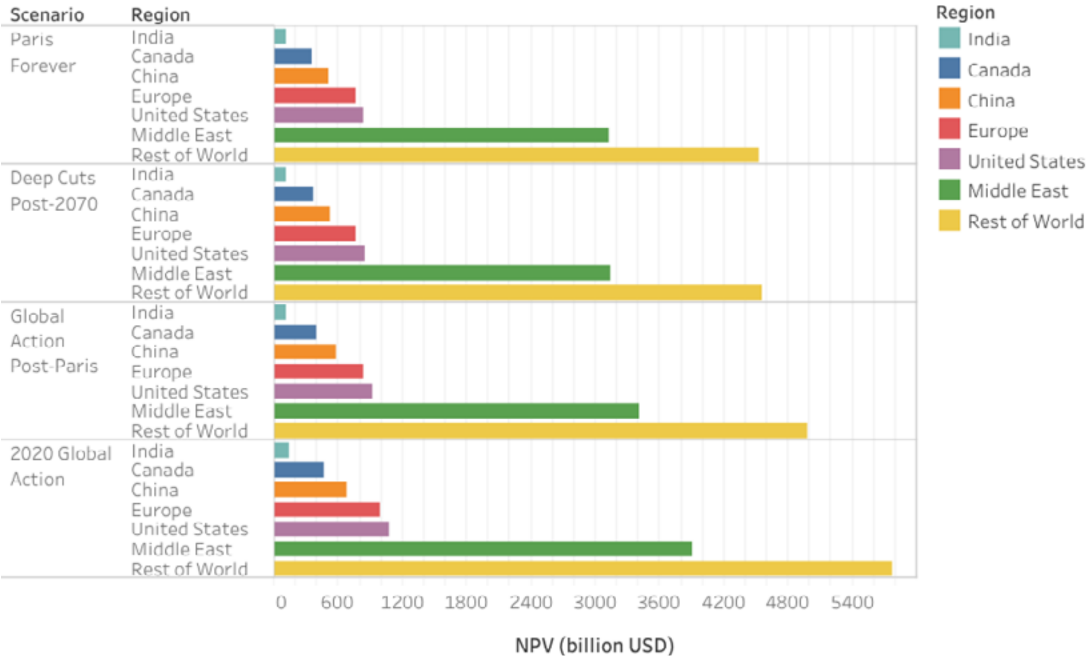

Figure 18. Oil Stranded Assets. NPV of Economic Output Lost from Oil Not Produced through 2040 Relative to *No Policy*.

Table 2. NPV through 2040 lost as a percentage of *No Policy* Fossil Fuel Economic Output Value

Fuel	Scenario	Canada	China	Europe	India	Middle East	Rest of World	USA
Coal	Paris Forever	50.56	42.37	48.87	15.07	8.01	33.37	24.60
	Deep Cuts Post-2070	49.82	44.11	46.28	25.94	23.00	36.79	24.69
	Global Action Post-Paris	56.13	55.64	50.56	35.24	28.73	43.87	27.80
	2020 Global Action	64.79	66.39	55.93	65.84	55.69	64.42	34.64
Gas	Paris Forever	23.34	14.11	7.26	6.70	10.47	10.29	24.24
	Deep Cuts Post-2070	18.45	13.65	6.05	12.51	14.75	11.25	20.41
	Global Action Post-Paris	22.51	16.07	7.82	4.85	18.08	13.90	23.64
	2020 Global Action	22.70	8.23	12.74	16.94	33.16	16.02	23.86
Oil	Paris Forever	20.90	18.45	21.25	18.51	18.75	20.59	20.93
	Deep Cuts Post-2070	21.36	18.73	21.45	18.75	18.80	20.73	21.23
	Global Action Post-Paris	23.18	20.75	23.41	20.42	20.42	22.62	23.05
	2020 Global Action	27.54	24.53	27.47	24.08	23.40	26.29	27.14

but also the rents and capital associated with the fossil fuel production. **Figure 19** illustrates the prices of coal and gas relative to an index of 1, representing a normalized price of fuel in that region in 2015. **Figure 20** illustrates the same for oil. In general, fossil fuel prices are greater in the *No Policy* scenario than in the other regions due, understandably, to greater demand. Of note is the rise in gas prices in China. However, this is due more to the fact there was so little gas infrastructure in China to begin with that even slight increases in the relatively small demand for gas creates

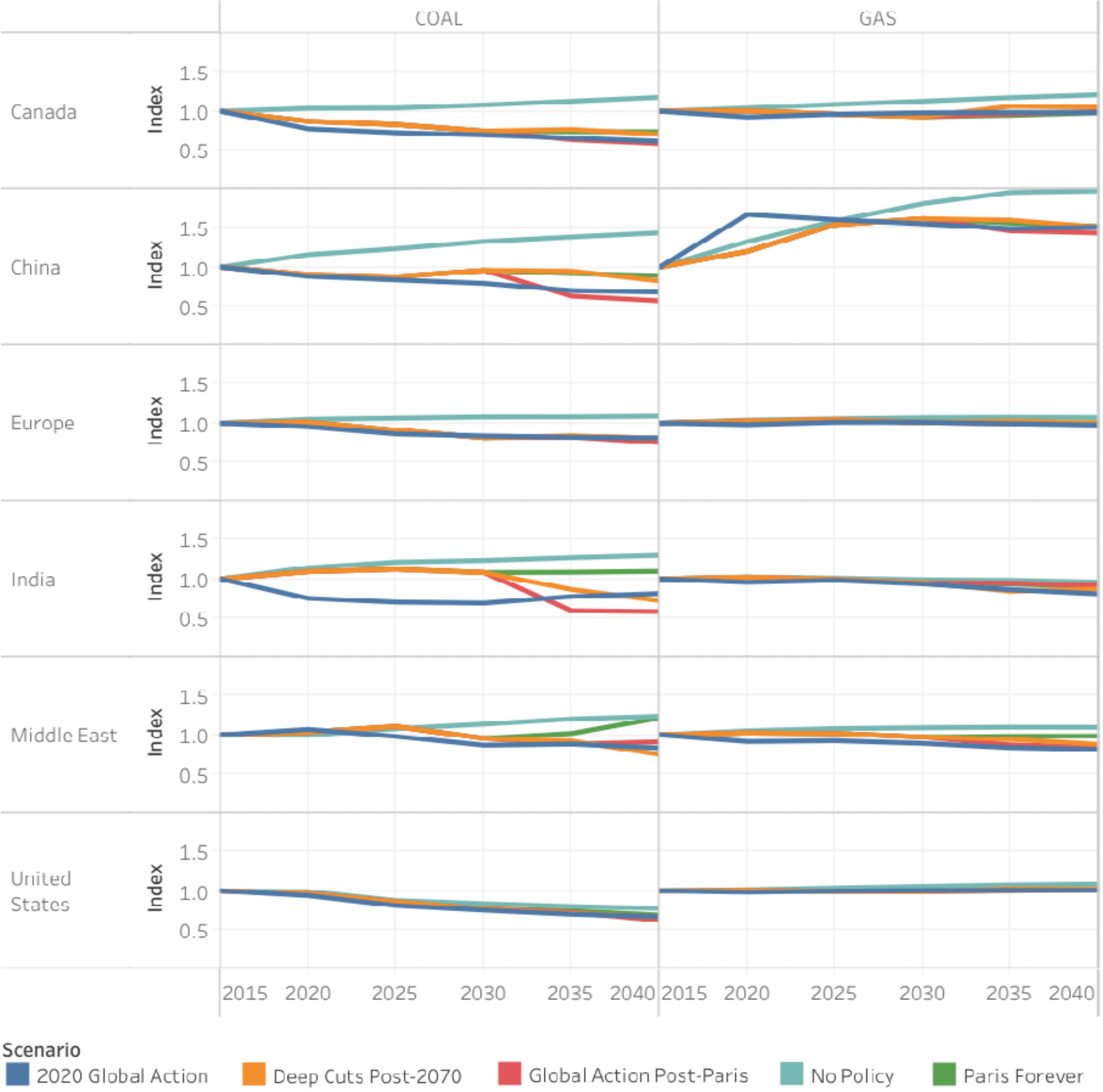

Figure 19. Coal and Gas Price Indices *(Normalized to a 2015 USD price index of 1)*

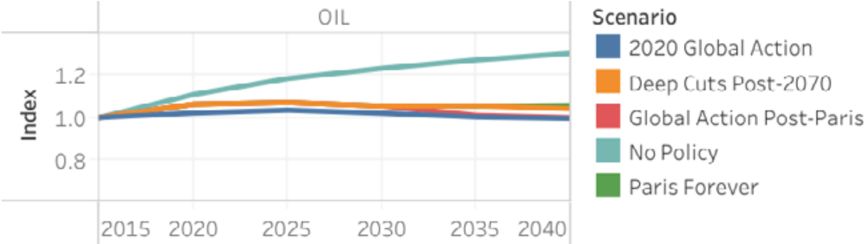

Figure 20. Oil Price Indices *(Normalized to a 2015 USD price index of 1)*
(Oil is modeled as a homogenous good. This keeps the price identical across regions.)

an outsized effect on its price (see Figure G10). In India, the *2020 Global Change* scenario produces a drop in coal prices, as coal goes from providing 78% of its electricity to 50% (see Figure G29).

Global oil prices, while significantly different under the *No Policy* scenario, exhibit less sensitivity to regional and global carbon prices than do, for example, coal prices. Oil, while already accounting for a minimal share of electricity production, is phased out of electricity production regardless of region or scenario, including the *No Policy* scenario. However, oil use for primary energy production continues to rise through 2040 in China, India, the Middle East, and the Rest of the World, regardless of scenario. This is somewhat offset by the reduction in oil use for primary energy production through 2040 in Canada, Europe, and the United States in the policy scenarios. Together, this amounts to the global demand patterns for oil illustrated in Figure 9 and reflected in the oil price indices. Although small, the price index for the *Global Action Post-Paris* scenario does drop away from the *Paris Forever* and *Deep Cuts Post-2070* scenarios between 2030 and 2035, reflecting the slightly greater impact of the more aggressive global carbon price in that scenario. Nonetheless, the impact in price is subdued in part due to the fact that oil is not easily substituted in the growing transportation sector, both retail and commercial.

5.6 Land Use

Land use is largely insensitive to the choice of scenario through 2040. The most significant scenario effect is produced by *2020 Global Action*, in which natural grassland is not used to contribute to managed forests. This is primarily driven by the Rest of the World region (see page 68). Managed forests decrease, possibly due to the increased cost of forestry and paper products, which is included in the energy-intensive industry sector.

Other trends illustrate the transformation of one land-use type to another. Pasture grows in all scenarios as a result of increased consumer income and preference for meat. Some of this land is taken from natural forest, some from cropland. Surprisingly, land use for bioenergy and renewables follows the same growth trajectory in each scenario.

There is no explicitly modeled climate-related land-use policy. As noted in the Deep Cuts Post-2070 section, one method of achieving such deep cuts might be to institute a global reforestation program. While the land requirements for such a program are not modeled, it is likely that the need for land would begin to impinge on other land uses (e.g., crops, pasture, etc.), eventually becoming costly.

5.7 Household Transportation

One contributor to the levels of household transportation is the price of refined oil. The average price of refined oil

Figure 21. Global Land Use

globally grows 30% from 2015 to 2040 in the *No Policy* scenario but only 0–6% for the remaining scenarios in the same time frame. This corresponds to an increase in global vehicle distance traveled from 1.38 trillion miles in 2015 to 3.39 trillion miles by 2040 in the *No Policy* scenario, and between 3.14 and 3.05 trillion miles by 2040 in the remaining scenarios. However, growth in vehicle distance traveled tends to follow the GDP of the region more than any other factor.

While scenarios are particularly good at identifying areas of risk, they can also be used to identify areas of opportunity. Investment in electric vehicles (EVs) could be one area in which opportunities might reside. Based on cost alone, and in the absence of explicitly modeled policy requirements related to the adoption of EVs or phasing out of internal combustion engine (ICE) vehicles, EVs are not projected to replace ICE vehicles in a disruptive way through 2040 (see **Figure 22**). While there is a minor increase in EVs and a decrease in ICE vehicle growth relative to the *No Policy* scenario, the patterns of growth remain relatively unchanged.

Regional breakdown of household vehicle ownership provides insight into the regions that might be best poised to take advantage of EV growth. **Table 3** illustrates that the Rest of the World and Middle East regions exhibit higher rates of EV adoption relative to the growth of total household vehicles in those regions, with the EVs representing 34% and 32% of total new household vehicles between 2015 and 2040 in the *No Policy* scenario. By contrast, Canada might not provide a relatively strong market for adoption of EVs.

5.8 Other Sectors

Globally, the sector most sensitive to the policy scenarios, second only to the energy sector, appears to be that of

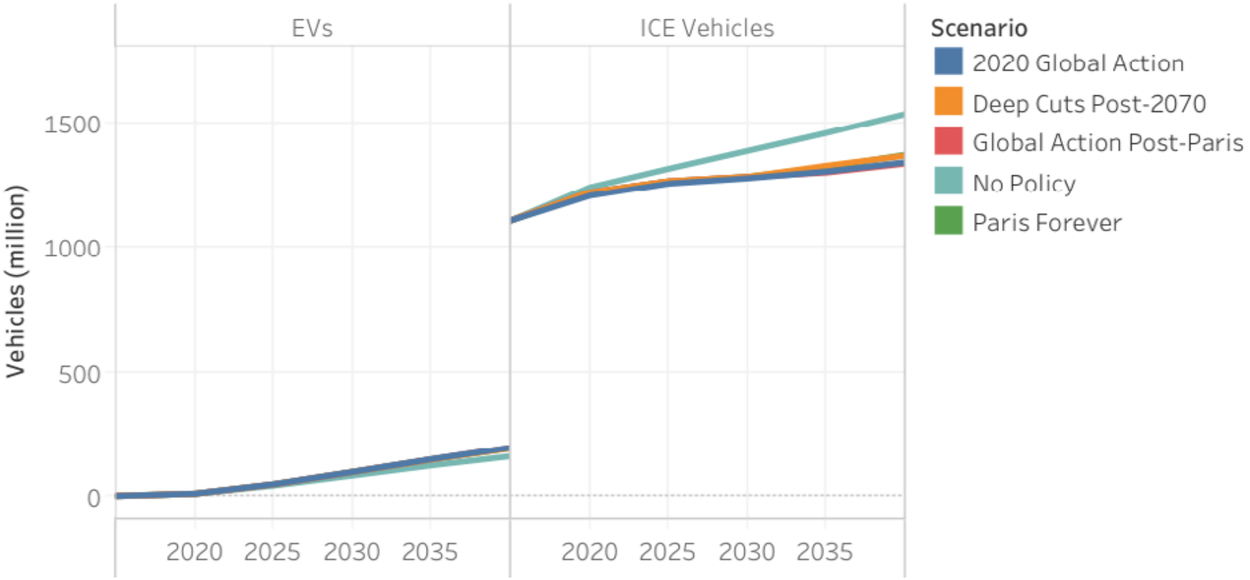

Figure 22. Global Household Vehicles. Breakdown of EVs and ICE Vehicles.

Table 3. Household Vehicle Growth in the *No Policy* Scenario

	EVs (million)		ICE Vehicles (million)		Percent of New Vehicles that are EVs
	2015	2040	2015	2040	
Canada	0.0	1.2	22.0	33.4	10%
China	0.1	30.9	143.9	228.6	27%
India	0.0	10.6	30.1	66.7	22%
Europe	0.2	19.7	261.4	343.8	19%
Middle East	0.0	8.0	39.9	57.1	32%
Rest of World	0.2	67.6	363.2	495.9	34%
United States	0.1	21.5	250.6	316.1	25%

commercial transport, which includes both air and water transport. Relative to the *No Policy* scenario, the other scenarios exhibit decreases in real output of the commercial transport sector from 2.1% to 3.1% in 2025 and from 3.7% to 5.4% in 2040. Most other sectors exhibit less of a percentage reduction in real output than that exhibited by GDP. This is due to the outsized negative impact on fossil fuels in the policy scenarios, skewing the GDP percentage of real output down. Real output from dwelling ownership increases relative to the *No Policy* scenario counterfactual in the four policy scenarios in the 2040 timeframe, except for later years in the *Global Action Post-Paris* scenario.

While these sensitivities seem to be limited to differences of only a few percentage points, the regional aggregation into global figures hides much of the variation present in the real output of regional sectors. For instance, Canada and the United States exhibit particularly sensitive crop sectors (see Table G2 and Table G8). Forestry in Europe benefits significantly from globally coordinated carbon prices; that is, in the *Global Action Post-Paris* scenario post-2030 and in the *2020 Global Action* scenario starting in 2020[36] (see Table G4). Meanwhile, forestry in the Rest of the World exhibits outsized negative sensitivity to globally coordinated carbon prices (see Table G7). Food output actually increases in Canada relative to the *No Policy* scenario and its real output from energy-intensive industry generally increases under global carbon prices because the energy transition under its own NDC is more aggressive than the global prices (see Table G2). India's energy-intensive industry real output illustrates the opposite, as its NDCs are non-binding and a global carbon price would be a significant step up (see Table G5). The Middle East demonstrates a substantial increase in real output in its energy-intensive industry in all policy scenarios, albeit slightly less with global carbon prices (see Table G6). Additionally, real output from services also rises in the Middle East under policy scenarios (see Table G6). Europe experiences a significant decrease in real output of its commercial transport sector as does India (see Table G4 and Table G5). The Middle East experiences significant decreases here as well in later years (when a globally coordinated carbon tax is in effect), but the percentage decreases are less significant in light of the percentage decreases of its GDP. Dwelling ownership under the policy scenarios does the best in China, increasing its real output by 1.1% to 1.9% by 2040 relative to the *No Policy* scenario.

A few percentage points in terms of global and regional economic output translates into differences of many billions of USD (see **Table 5**).

5.9 Physical Risk

The maintenance, expansion and sustainability of society's infrastructures and resources are facing increased environ-

Table 4. Scenario Sensitivity of Real Output Relative to *No Policy* Scenario | Global

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-1.0	-1.9	-1.0	-2.3	-1.0	-3.4	-1.5	-3.1
Commercial Transportation	-2.1	-3.7	-2.1	-4.1	-2.1	-5.4	-3.1	-5.1
Crops	-0.9	-0.8	-0.9	-1.0	-0.9	-1.9	-1.5	-2.0
Dwelling Ownership	0.3	0.2	0.3	0.3	0.3	-0.1	0.4	0.1
Energy Intensive Industry	-0.9	-1.4	-0.9	-2.0	-0.9	-3.6	-2.2	-3.5
Food	-0.4	-1.0	-0.4	-1.2	-0.4	-2.1	-1.0	-1.9
Forestry	-1.1	-0.9	-1.1	-3.3	-1.1	-5.3	-3.5	-4.0
Livestock	-0.7	-1.6	-0.7	-2.1	-0.7	-3.9	-2.5	-3.7
Other Industry	-0.8	-1.3	-0.8	-1.7	-0.8	-2.9	-1.7	-2.8
Services	-0.3	-0.6	-0.3	-0.7	-0.3	-1.1	-0.5	-0.9

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[36] Although the Deep Cuts Post-2070 scenario also introduces a globally coordinated carbon price post-2030, it is not aggressive enough to have a significant impact on the real sectoral output relative to the impact on GDP.

Table 5. Global Difference of Sectoral Economic Output of Scenarios Relative to *No Policy* Scenario using 2015 Prices (billion USD)

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-948	-2,913	-948	-3,372	-948	-5,089	-1,547	-4,707
Commercial Transportation	-226	-624	-226	-694	-226	-921	-331	-879
Crops	-29	-33	-29	-41	-29	-78	-48	-82
Dwelling Ownership	16	16	16	27	16	-12	26	10
Energy Intensive Industry	-224	-580	-224	-810	-224	-1,436	-553	-1,414
Food	-38	-123	-38	-152	-38	-265	-87	-249
Forestry	-6	-7	-6	-27	-6	-43	-17	-33
Livestock	-17	-54	-17	-72	-17	-134	-63	-128
Other Industry	-378	-978	-378	-1,282	-378	-2,246	-824	-2,117
Services	-240	-758	-240	-769	-240	-1,253	-360	-1,048

mental and physical risks from a changing landscape of extreme events and conditions. The nature of physical risks makes its assessment a very different exercise, requiring different assessment tools than transition risks. A key feature to many of these events is that they predominantly occur, and have their greatest impact, at more local spatial scales (e.g. from community/town/city to basin level), yet they are typically manifestations of much larger-scale atmospheric phenomenon. The methodologies explored here address the major challenges in the assessment of physical risk to local assets. The enhancement these methodologies represent to other current efforts holds promise for a more sophisticated and useful assessment of physical risk to targeted assets and supply chain of a company/region/city/entity.

Capturing the full range of possible climate responses to a specific time path of trace-gas forcing that encompasses the chaotic nature of weather and climate variability.

Capturing the full range of possible climate responses to a specific time path of trace-gas forcing that encompasses the chaotic nature of weather and climate variability is a significant challenge. Doing so requires large ensemble simulations such as in **Figure 23**, in which each simulation is based on joint distributions of underlying uncertainty in the climate response to increased atmospheric concentrations of greenhouse gases.[37] However, the simplified climate model needed to produce multiple large ensembles of runs does not provide the geographic detail needed to assess climate risks to particular regions and assets. In reality, even the most refined global-scale models require further downscaling of weather and climate projections to be relevant at the geographic scale of the assets at risk. We have developed two approaches that provide climate projections across a range of plausible trends and at sufficient spatial scale to explore physical risk.[38] (See Appendix F for further details.)

Figure 23 compares results from the two methods for temperature (panel a) and precipitation (panel b) over the United States for the coming century. The top panel is a simulation with a climate model developed by the MIT Joint Program for three different emissions paths featuring multiple values of climate sensitivity. The bottom figures are constructed using a method designed to capture the range in emerging trends' spatial features diagnosed across all climate models. While the MIT model is similar to the class of "general circulation models" (GCMs) that are used in the climate modeling community, it also boasts the capability to span the plausible range of climate sensitivity (based on empirical evidence). Temperature ranges begin to separate by about 2040, but precipitation—comparable to the variability in the historical data—is noisier.

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[37] See Libardoni, A.G., C.E. Forest, A.P. Sokolov and E. Monier (2018): Baseline evaluation of the impact of updates to the MIT Earth System Model on its model parameter estimates. Geoscientific Model Development, 11(8): 3313-3325 (doi: 10.5194/gmd-11-3313-2018) (https://www.geosci-model-dev.net/11/3313/2018/)

[38] Monier, E., X. Gao, J.R. Scott, A.P. Sokolov and C.A. Schlosser (2015): A framework for modeling uncertainty in regional climate change. Climatic Change, 131(1): 51-66 (doi:10.1007/s10584-014-1112-5) (http://dx.doi.org/10.1007/s10584-014-1112-5)

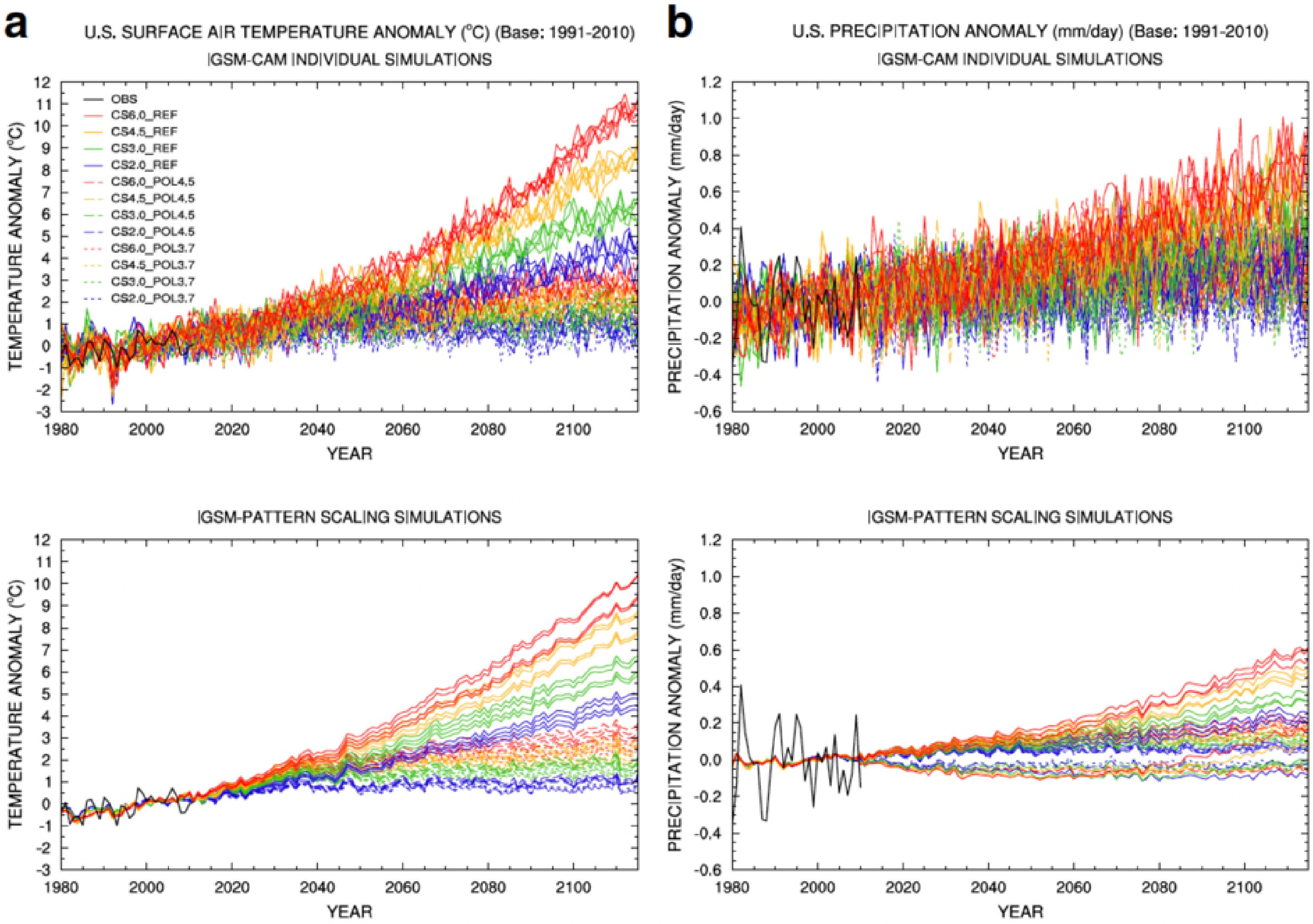

Figure 23. Comparing methods for different downscaling approaches from climate impacts assessment (Source: Monier *et al,* see footnote 34)

Providing projections of changing weather events and climate conditions relevant to the geographic scale of the assets at risk.

While the GCM simulations reasonably match the historical temperature and precipitation for the United States as a whole, they do not approximate well the climate in specific US regions. The topography of the land has strong effects on regional and local climates, and because such characteristics are smoothed out in simulations of larger areas, climates for finer geographic scales are not well approximated. The challenge, then, is to capture the range of uncertainty that exists in the climate system and our knowledge of the response of the system at reasonable costs and computational requirements so that apparent risks to assets in various locations reflect real differences rather than noise that appears from comparing only a few scenarios.

Methods have been developed that can better capture weather events and extremes not well captured in large scale climate models that can use large scale patterns and projections that are simulated. There are variants to these approaches, but they generally rely on the recognition that highly localized (e.g. from community/town/city to water basin level) weather events are typically a manifestation of a larger-scale atmospheric phenomenon that even coarsely resolved GCMs can simulate. This “analogue approach” identifies a specific weather variable (e.g. temperature, precipitation) and identifies a threshold considered extreme.[39] Researchers then seek to estimate a statistical relationship between the weather variable of interest in a particular region and a large-scale weather pattern simulated in the climate model.

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[39] The variable and the level considered “extreme” depends on the characteristic of the asset or system at risk and “normal” weather in the region of interest. For example, precipitation greater than x millimeters in 24 hours that would likely cause flooding, or extreme low precipitation over an extended period of time that would cause drought, etc.). Additionally, what might be considered extreme heat in London would be normal conditions in Hong Kong.

Figure 24[40] provides example results of how the analogue approach improves the forecast of the number of days of extreme precipitation in California and the Midwest (MWST) of the US, and temperature in the Northeast of the US for the historical period of 1979 to 2005. The dashed lines are based on the historical record during this period. The whisker plots are raw data from the GCMs (on the left in each figure) and the analogue results (right side of each figure). In each case, the mean for the analogue results is very close to the historically observed number of days, and the range is much narrower.

Several recent studies have emphasized that a multivariate analogue framework is beneficial for assessing not only the risk of extreme events that currently exists, but also under a warming global climate and associated changes in large-scale weather patterns.[41] **Figure 25** shows results for projected changes in heavy precipitation in California (panel a) and extreme heat in southeast Pennsylvania (panel b). The blue lines—representing ranges derived from 18 different GCM simulations—is wide and trends appears largely insignificant. By contrast, the whisker plots— resulting from the analogue approach—greatly narrows the range and shows a clearer signal of an increasing number of extreme events. The temperature extreme (panel b) was chosen to correspond to a temperature that would pose risks of large power transformers overheating and leading to large blackouts, and are shown for two climate stabilization scenarios. Both the GCM and analogue approach give a similar mean, but the distribution is narrower with the analogue approach. Insofar as the analogue method actually improves projections of weather extremes, it allows for a more accurate assessment of the resulting financial risk to vulnerable assets.

Improving projection of extreme events that inflict the most damage to specific assets.

The under-representation of extreme events in current climate modeling has led to a separate line of work in-

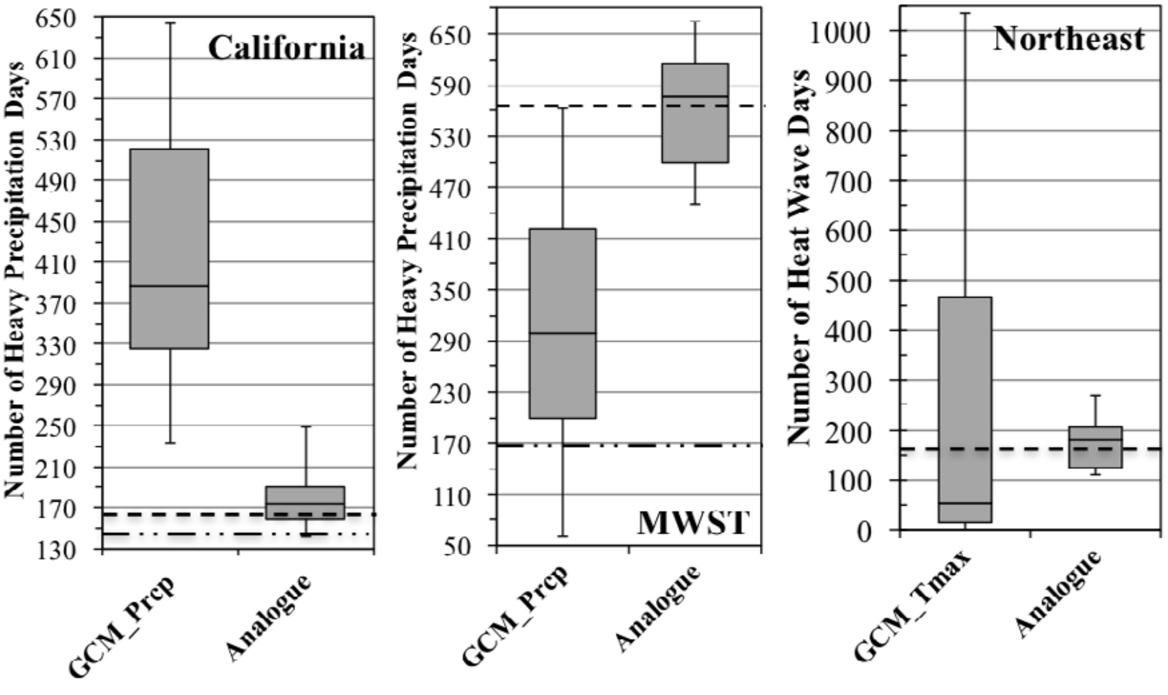

Figure 24. Examples of comparisons for a range of extreme events from model-simulated single-variable assessment (left whisker bar in each sub-frame) and an "analogue" multi-variate method. The whisker plot shows the minimum, the lower and upper quartile, median, and the maximum. The dash-dot lines in the precipitation frames show a result based on a blended product of models and observations.

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[40] Source: Gao, X. and Schlosser, C.A. (2018) Mid-Western US heavy summer-precipitation in regional and global climate models: the impact on model skill and consensus through an analogue lens. Clim. Dyn. https://doi.org/10.1007/s00382-018-4209-0; Gao X, Schlosser CA, Xie P, Monier E, Entekhabi D. (2014) An Analogue Approach to Identify Heavy Precipitation Events: Evaluation and Application to CMIP5 Climate Models in the United States. J Clim 27: 5941–5963; Gao X, Schlosser CA, O'Gorman PA, Monier E, Entekhabi D. (2017) Twenty-First-Century Changes in U.S. Regional Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. J Climate. 30: 2501–2521; Gao, X., Schlosser, C.A. and Morgan, E.R. (2018) Potential impacts of climate warming and increased summer heat stress on the electric grid: a case study for a large power transformer (LPT) in the Northeast United States, Climatic Change, 147, 107-118.

[41] Wahl *et al,* 2015; and Zscheischler *et al.* 2018 Wahl, T., Jain, S., Bender, J., Meyers, S. D. & Luther, M. E. (2015) Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nat. Clim. Change 5, 1093–1097; Zscheischler, J. *et al.* (2018) Future climate risk from compound events. Nat. Clim. Change 8, 469-477.

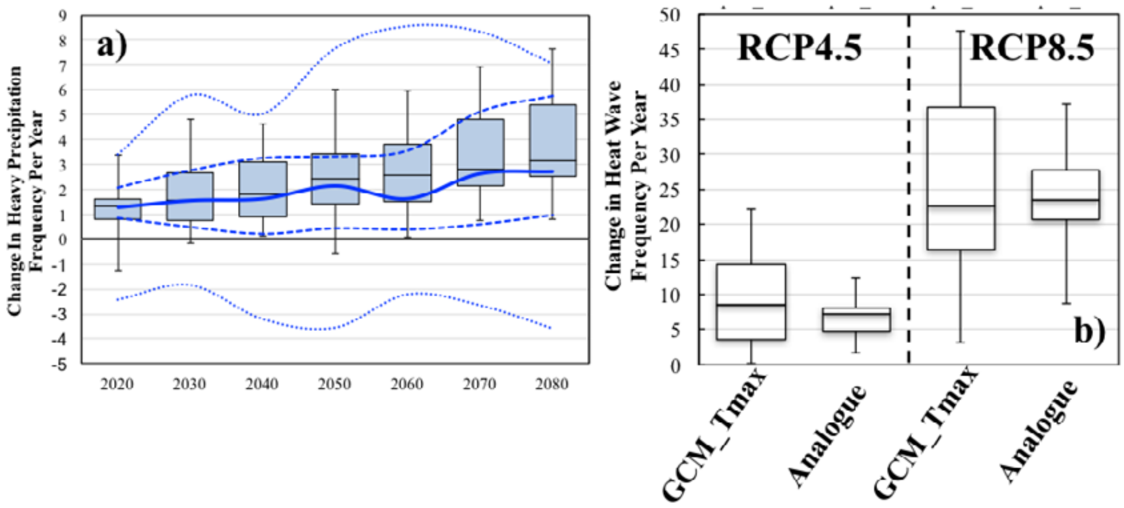

Figure 25. Changes in Weather Event Frequencies

a) Changes in California winter heavy precipitation frequency from the analogue (whisker) and from 18 CMIP5 GCM-simulated precipitation (solid-line: median, dashed: interquartile, and dotted: min/max) under a "business as usual"; b) Increases in "heat wave" frequency between the period of 2070–2090 and 2010–2030 for a large power transformer (LPT) located in southeast Pennsylvania from the analogue and from 20 CMIP5 GCM-simulated daily maximum air temperature under the IPCC RCP 4.5 (strong mitigation) and 8.5 scenarios (little or no mitigation actions). In both cases, the analogue notably improves the consensus among projected trends—particularly the interquartile range (boxed area).

tended to improve projections of extreme events that are the most damaging to specific assets. The challenge for evaluating physical risks for global companies and investment portfolios consisting of many different types of assets in many different regions of the world is that the specific weather variable and threshold will differ by asset and its location. Therefore, each combination of weather variable and region entails a research effort to connect the extreme to large scale weather patterns that affect that particular region. For example, in prior work looking at climate risks to developing nations in southern Africa, we identified that climate change and associated weather events that have the strongest effect on local productivity and prosperity are those that damage roads and transportation infrastructure. For this region, heavy precipitation events and periods of high river flow produce the greatest impact. In contrast, the climate risks associated with water resources and agriculture systems arise from extreme precipitation deficit and persistent dry events/periods. Further, the power grid and its transmission system can be damaged by extreme heat and cold/icing conditions – and the factors that control the occurrence of these events vary dramatically by location. The threat and resiliency and reliability of the power grid will be further complicated by the inclusion of renewable generation technologies, which are intimately reliant upon climate and weather variability (e.g., winds and clouds) – as well as extreme conditions (e.g., cut-in and cut-off windspeeds to turbine operation). In short, all these physical risks require targeted and detailed analysis that must be tailored to the specific region and asset.

Assessing the awareness of and adaptive responses that the owners of at-risk infrastructural assets take in light of changing conditions.

A final step in evaluating actual physical risk is assessing the awareness of and adaptive responses owners of assets have taken or are likely to take in light of future climate change. **Figure 26** is taken from a study that used a tropical storm simulation to investigate changing risks of flooding for an oil refinery located in the US Gulf of Mexico.[42] The study considered the height of the refinery above sea level, sea-level rise, and subsidence of the land in the region, an important determinate of relative sea level.[43] The study found these compounding stresses of storm intensity, sea-level rise, and subsidence combined in a multiplicative, rather than additive fashion, greatly increasing the risk of flooding when considered together.

The top panel shows the changing probability of surge height at the site based on climate information from one GCM. At the 1 meter mark on the x-axis, the cumulative distribution

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[42] See Lickley, M.J., N. Lin and H.D. Jacoby (2015): Analysis of coastal protection under rising flood risk. Climate Risk Management, 6 (2014): 18–26 (http://www.sciencedirect.com/science/article/pii/S2212096315000029)

[43] The Mississippi delta is the result of the geological process of river flooding that carries sediment from upriver into what were coastal waters, but with the constant addition of sediment became land. Flood control efforts along the river with the goal of preventing flooding eliminated the delivery of sediment to the delta, and as a result, the land is subject to considerable subsidence. In addition, extraction of oil and gas from reservoirs in the area may further contribute to subsidence.

function for the 2000 curve shows the annual chance of any floods remaining below 1 meter in 2000 is estimated to be approximately 98–99% (i.e., there is only a 1 to 2% risk of exceeding that level). By 2050, the annual risk of exceeding 1 meter has risen to over 40%, and by 2100 to over 90%. A 1-meter flood may be expected at the site almost every year by 2100. Even by circa today (2020), the annual flood risk of more than 1 meter is shown to be 7–8%, on the order of 4 or more times greater than it was just 20 years ago. The bottom panel then calculates the optimal height of a levee as it changes over time, given an estimate of the cost of disruption and the cost of the levee, for different GCM projections. The results suggest the facility should already have a levee height of at least 2 meters or more.

For purposes of assessing the impact of climate change on the value of this asset stemming from coastal inundation, there are a few possibilities. If no levee exists, there is already a substantial risk of inundation. An inundation event could interrupt operations for a lengthy amount of time, affecting the income flow and value of the refinery asset and the company who owns it. If the company is aware of this risk and undertakes efforts to build a levee adequate for the risks posed currently, then the value of the asset need not be reduced by disruption or early abandonment. Rather, with the recognition of the need to increase the levee height going forward, it may engage in the real options analysis of further levee extension in future decades. This analysis did not, however, consider how increasing flood risk would affect surrounding infrastructure that is needed to support operations of the refinery. If those are not supported, then the refinery may not be operable and further protection of it may not make sense. Thus, the effect of climate on the value of a particular asset may depend not only on what the private sector entity does to adapt, but also on the resilience of public infrastructure such as roads, ports, bridges, electrical grid, etc.

6. Implications and a Path Forward

The overarching goal of the effort described in this report was to leverage the results from an integrated human-earth system modeling framework to explore possible metrics that could assist in understanding climate-related financial risks to financial institutions. The framework, which includes a full representation of the global economy with regional and sectoral detail, provides a foundation to investigate both transition and physical risk. It was not an attempt to provide a detailed financial risk assessment that would identify the climate-related risk of a specific portfolio of investments held by an individual financial institution.

We then suggest some next steps in advancing modeling and data that could produce more targeted and refined analyses toward the application of assessing financial risk in banking.

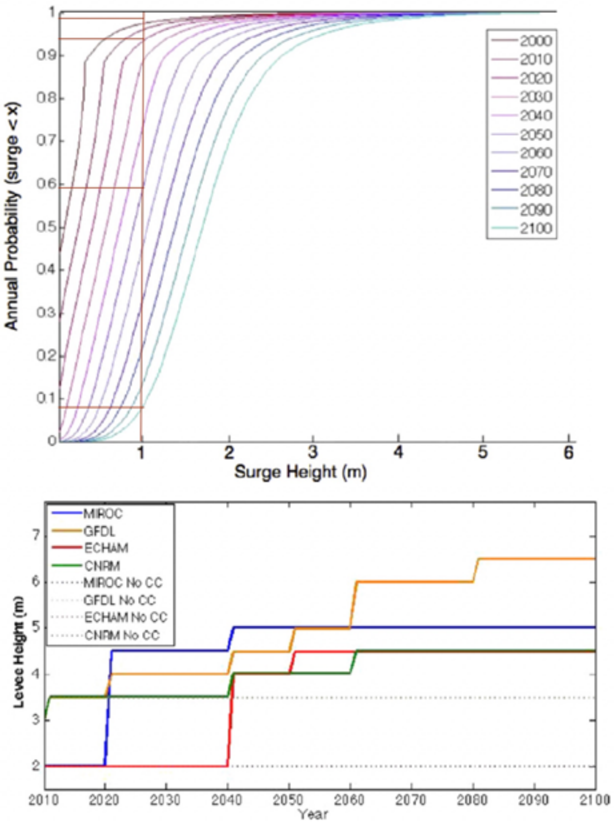

Figure 26. Flood risk and levee height.

Increasing probability of flood risk at a refinery site on US Gulf coast based on a GFDL GCM simulation (top panel) and optimal levee height over time in response to changing risks over time for several GCMs (bottom panel)

6.1 Main Conclusions and Implications

Climate change poses a systemic risk to the global economy, requiring banks to investigate different aspects of their resilience to climate risk factors. Banks must understand the implications for this systemic risk on their strategy and planning, loan impairment, capital adequacy and even their own operational resilience.

Many climate-related financial risks are of a much different nature than the traditional macro-economic risks that gave rise to financial stress tests and therefore require a different assessment approach. Compared with a financial crisis, climate-related risks are slowly evolving over decades, affect the long-term growth potential of the economy, and will produce significant differentiation in the consequences between sectors and geographies. As such, risks to financial institutions require bottom-up assessments of their portfolios, identifying holdings in specific industries and geographies that are particularly vulnerable, to augment existing financial models. Those that understand this are in a position to not only protect themselves from downside risks, but also to provide much needed financial services to the industries most affected by climate change. Both the transition and physical risks of climate change are likely to increase demand for financial services, whereas in the recession-driven financial crisis, the demand for investment and loans typically falls substantially. Banks in particular may gain substantially with the need to rebuild the world's energy infrastructure and invest in various adaptation measures meant to protect communities and facilities from more extreme weather events.

Assessment of climate-related risk to financial institutions may need to focus as much on risk processes as on risk quantification. A rough quantitative assessment of transition risk associated with fossil fuel holdings is possible, and likely could be conducted using metrics in this report. Likewise, as estimates of short-term physical risks improve for local scale properties, it should be possible to at least identify the extent of portfolio exposure to these properties. Assessing every separate loan or investment for physical risks would be a demanding exercise, requiring substantial science input to develop relevant risks of exposure to extreme events, and site-level assessment of vulnerability to this exposure. A process-based focus for evaluating climate-related risk might ask: what internal processes exist within a financial institution for assessing physical climate risk on new loans, new investments, and other financial exposure? And, what are adequate methods being used to assess risk? It also may be possible to identify particularly large exposures in the bank's existing portfolio that, based on a high-level assessment of climate risk, require a more detailed assessment. This process could have the added advantage of encouraging consideration of physical risk by borrowers, and taking measures to reduce vulnerability of investment in new assets. It would also develop a demand for experts and methods for such assessment, leading to improvement in these methods.

In reporting economic impact on various industries, we find that the global impacts in percentage terms for most industries are relatively small through a 2040 horizon, but that the impacts on oil, gas, coal, and coal power generation sectors are much larger. We calculated an approximation of stranded assets for these vulnerable energy sectors, and that Net Present Value (NPV), while varying by region, was generally between 30–60% of total revenue NPV for coal through 2040, between 5–25% for natural gas and between 18–28% for oil. The differences illustrated greater sensitivity to fuel type than to the policy scenarios themselves because the NPV approach discounts the more distant future where some of the bigger differences among scenarios exist. Our approach was to calculate NPV based on lost revenue to the sector over the period compared to the *No Policy* scenario. This may overstate stranded assets for a few reasons. First, since the *Paris Forever* scenario is based on commitments already made, if investors see those as credible, then the current valuation of fossil assets may already incorporate some of the reported losses. The extent of this is difficult or impossible to assess. Second, by comparing to a *No Policy* case through 2040, there are not strictly stranded assets, as additional investment in the sector would not occur in the *No Policy* scenario in the first place if these tighter policies came into place. Third, the books of fossil fuel companies only include valuation of proved reserves, which, for most oil and gas fields, would last less than 10 years. To take this into account, book risk might only measure that of proved reserves, whereas our modeling framework does not yet distinguish between proved reserves and resources yet to be proved. On the other hand, other produced assets such as drilling rigs have a much longer life and, with a sudden drop in oil production, would immediately lose much of their value. Our approach for stranded value aggregates losses of rents to resources and rents to produced capital assets in the sector. While the inclusion of only proved reserves can be made based on financial reporting requirements, the value of firms with expertise in oil, gas, and coal may include investor's expectations that these firms will continue to find and produce oil well beyond the exhaustion of existing reserves. If there is no longer much demand for fossil fuels, the value of the expertise these firms have developed will be diminished. With those caveats, the percentage losses developed here could provide an initial rough cut on transition risks in these various energy sectors.

Assessment of transition risks to specific companies and assets demands a much finer-grained assessment, but such assessments, particularly those pertaining to the fossil-fuel extraction and power generation sectors, could be based on metrics reported here. For example, with detailed data on production cost and reserve quantities, as well as the carbon footprint of production in different oil, gas, or coal fields, the projected fall in *fuel prices* could be directly converted into an estimate of loss in value of the reserve as it relates to different deposits and proved reserves. This, in turn, may be used to assess the risks embedded within loans to specific fossil developments. The vulnerability of the portfolios of entire firms could be assessed based on specific holdings. Similarly, with greater details on specific power plants, and likely power system operation, these *carbon prices* could provide a basis for better quantification of lost value in coal power plants under different possible mitigation policy paths.

Scenario analysis, considering a few scenarios in depth that bound alternative evolutions of the low-carbon energy transition, can provide a useful starting point in the assessment of transition risks, but one would need a more complete assessment of climate risk to assess physical risks. First, the emissions pathway the world chooses to pursue will have virtually no effect on the evolution of the climate over the next few decades, as average warming in this time period is largely pre-ordained due to inertia in the climate system. Second, the climate system is chaotic, and its response to increasing greenhouse gases, uncertain. Thus, information about its future behavior can only be prognosticated by simulating many potential evolutions of weather and possible weather events for the current year. However, the movement of climate response distributions over time make introduce challenges to quantifying "extreme" weather behavior, let alone the physical risks of such behavior when applied to infrastructural and financial assets. Many hundreds of years (large ensembles of simulations of the same period many times) are needed to evaluate how the likelihood of extreme events may have changed.

There is a growing set of climate and weather event prediction tools for assessing physical risk, but there is no single model nor set of archived model simulations that is well suited to the task of accurately reflecting the physical risk for financial assets. Large scale climate models do not resolve extreme events well and are not well-suited for sampling across the full distribution of earth response to increases in atmospheric greenhouse gas concentrations. Climate simulations provide a useful starting point, but additional complementary approaches are needed to better represent extreme events and downscale weather patterns to geographic scales relevant to specific assets.

6.2 A Path Forward

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 next step might take the form of a pilot study that takes the metrics presented in this study as a starting point for bridging the divide between climate scenarios and credit and loan assessment.

With regard to transition risk, the flexibility of scenario development and modeling offers ample room for exploration. 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. This would likely need to be carried out within the financial institution where there is access to detailed information on the loan and investment portfolio of the institution, with possible external guidance on energy sector dynamics.

With regard to physical risk, a pilot study requires the selection of a specific site and vulnerable assets, and further work by climate scientists who are expert in developing improved projections of weather events and outcomes that threaten critical infrastructure. It would be useful to contrast physical risk assessment based on a few global climate scenarios, with a more complete granular risk-based assessment framework. Documenting the extent of the error or imprecision in the former approach would provide a useful warning sign against putting much faith in such assessments. If it turns out there is more information in simpler scenario analysis, then that could point to an approach that is more feasible to apply at a large scale, potentially globally. And, one potentially promising approach is to develop some simpler climate metrics, that while insufficient to reliably estimate financial risk, could point to potential hot spots, triaging areas and assets that require a deeper analysis.

Appendix A. Scenario Modeling

To fully determine the emissions path under the *2°C Likely* scenarios, we further need to describe the uncertain response of the climate system to forcing and to describe the path of emissions reductions over time. The team of researchers running the MIT Integrated Global System Model[44] have over the years developed Monte Carlo methods for simulating likely future climate outcomes given joint distributions of underlying climate uncertainties that can be updated as more data is available using a statistical method known as optimal fingerprinting[45].

The determination of emissions scenarios consistent with remaining below 2°C was achieved through an iterative process, choosing a carbon price starting point, with the full carbon price then determined by the 4% increase assumption. This emissions path was simulated through the MIT climate model system using a Monte Carlo simulation approach to determine the probability distribution of global mean surface temperature outcomes in 2100.[46] With this distribution, the likelihood of remaining below 2°C was determined. If the likelihood was different from 66%, a different starting carbon price was chosen to move the likelihood in a direction closer to 66%. This was repeated until an emissions path that generated the 66% likelihood was found. We then have a full description of the global and regional economies' energy, industry, agriculture, and consumption patterns consistent with the emissions path.

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[44] Sokolov, A.P. *et al.*, 2018: Description and Evaluation of the MIT Earth System Model (MESM). J Adv Model Earth Sys,10 (8): 1759 -1789 (doi: 10.1029/2018MS001277)

[45] Libardoni, A.G., C.E. Forest, A.P. Sokolov and E. Monier (2018): Estimates of climate system properties incorporating recent climate change. Advances in Statistical Climatology, Meteorology and Oceanography, 4(1/2),19-36 (doi:10.5194/ascmo-4-19-2018) (https://www.adv-stat-clim-meteorol-oceanogr.net/4/19/2018/)

[46] The IPCC has popularized the idea of a global carbon budget that cannot be exceeded to remain below a given temperature. Some economic modeling efforts constrain total emissions of the economy over the century to be below that IPCC budget. The budget has seen significant revisions, and a problematic aspect of it is that it focuses only on carbon dioxide making assumptions about other greenhouse gases and substances in the background, yet policies directed at carbon dioxide emissions will have effects on other greenhouse gases, and these can also be targeted for control. Our approach includes all greenhouse gases and substances, captures policy interactions, includes control of other GHGs and with GWP weighted pricing, and simulates the full earth system model to assure that it is consistent with the targeted temperature goal, including an integrated assessment of uncertainty in climate response.

Appendix B. Region Aggregation

Study Region	Region	EPPA6 Abbr.
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
Rest of World (cont'd)	Indonesia	IDZ
	Japan	JPN
	South Korea	KOR
	Other Latin America	LAM
	Mexico	MEX
	Other East Asia	REA
	Other Eurasia	ROE
	Russia	RUS
United States	United States	USA

Country	Region
Afghanistan	REA
Albania	ROE
Algeria	AFR
American Samoa	ANZ
Andorra	ROE
Angola	AFR
Anguilla	LAM
Antigua & Barbuda	LAM
Argentina	LAM
Armenia	ROE
Aruba	LAM
Australia	ANZ
Austria	EUR
Azerbaijan	ROE
Bahamas	LAM
Bahrain	MES
Bangladesh	REA
Barbados	LAM
Belarus	ROE
Belgium	EUR
Belize	LAM
Benin	AFR
Bermuda	LAM
Bhutan	REA
Bolivia	LAM
Bosnia and Herzegovina	ROE
Botswana	AFR
Brazil	BRA
Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
Cameroon	AFR
Canada	CAN
Cape Verde	AFR
Cayman Islands	LAM
Central African Republic	AFR
Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR
Congo, Dem. Rep. (Zaire)	AFR
Cook Islands	ANZ
Costa Rica	LAM
Croatia	ROE
Cuba	LAM
Cyprus	EUR
Czech Republic	EUR
Denmark	EUR
Djibouti	AFR
Dominica	LAM
Dominican Republic	LAM
Ecuador	LAM
Egypt	AFR
El Salvador	LAM
Equatorial Guinea	AFR
Eritrea	AFR
Estonia	EUR
Ethiopia	AFR
Falkland Islands	LAM
Faroe Islands	ROE
Fiji	ANZ
Finland	EUR
France	EUR
French Guiana	LAM
French Polynesia	ANZ
Gabon	AFR
Gambia	AFR
Georgia	ROE
Germany	EUR
Ghana	AFR
Gibraltar	ROE
Greece	EUR
Greenland	LAM
Grenada	LAM
Guadeloupe	LAM
Guam	ANZ
Guatemala	LAM
Guinea	AFR
Guinea-Bissau	AFR
Guyana	LAM
Haiti	LAM
Honduras	LAM
Hong Kong	CHN
Hungary	EUR
Iceland	EUR
India	IND
Indonesia	IDZ
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
Kazakhstan	ROE
Kenya	AFR
Kiribati	ANZ
Korea	KOR
Korea, Dem. Ppl. Rep.	REA
Kuwait	MES
Kyrgyzstan	ROE
Laos	REA
Latvia	EUR
Lebanon	MES
Lesotho	AFR
Liberia	AFR
Liechtenstein	EUR
Lithuania	EUR
Luxembourg	EUR
Libya	AFR
Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
Malta	EUR
Marshall Islands	ANZ
Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
Mongolia	REA
Montserrat	LAM
Morocco	AFR
Mozambique	AFR
Myanmar	REA
Namibia	AFR
Nauru	ANZ
Nepal	REA
Netherlands	EUR
Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
Norway	EUR
Oman	MES
Pakistan	REA
Palestine	MES
Panama	LAM
Papua New Guinea	ANZ
Paraguay	LAM
Peru	LAM
Philippines	ASI
Poland	EUR
Portugal	EUR
Puerto Rico	LAM
Qatar	MES
Réunion	AFR
Romania	EUR
Russian Federation	RUS
Rwanda	AFR
Saint Helena	AFR
Saint Kitts and Nevis	LAM
Saint Lucia	LAM
Saint Pierre & Miquelon	LAM
Saint Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé and Príncipe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychelles	AFR
Sierra Leone	AFR
Singapore	ASI
Slovakia	EUR
Slovenia	EUR
Solomon Islands	ANZ
Somalia	AFR
South African Republic	AFR
Spain	EUR
Sri Lanka	REA
Sudan	AFR
Suriname	LAM
Swaziland	AFR
Sweden	EUR
Switzerland	EUR
Syria	MES
Taiwan	ASI
Tajikistan	ROE
Tanzania	AFR
Thailand	ASI
Timor-Leste	REA
Togo	AFR
Tokelau	ANZ
Tonga	ANZ
Trinidad and Tobago	LAM
Tunisia	AFR
Turkey	ROE
Turkmenistan	ROE
Turks and Caicos Islands	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
Venezuela	LAM
Vietnam	REA
Virgin Islands, British	LAM
Virgin Islands, U.S.	LAM
Wallis and Futuna	ANZ
Yemen	MES
Zambia	AFR
Zimbabwe	AFR

Appendix C. Estimating Stranded Assets in Coal Power Generation

Within the EPPA model, each capital vintage has an endogenously determined price, which can be zero if the vintage is not used at all. We take the difference for each price of each vintage in each region in a *Policy Scenario* and the comparable vintages price in the *No Policy Scenario* times the total amount of capital for each vintage to determine the stranded value in each region. We sum over all vintages in each period, interpolating values between the 5 year periods, and then calculate the net present discounted value for the period through 2040.

Figure C1 is a combination of four separate figures, each representing a different vintage of coal plant. The x-axes represent the quantity of capital of that particular vintage and the y-axes represent the prices of the vintage capital. The values of each are specific to each scenario.

The stranded asset v in t (see the gray area of each vintage v):

$$strvb_{v,t} = max(0, pvbk_{vref,t,v} \cdot bv\_k_{vref,t,v} - pvbk_{policy,t,v} \cdot bv\_k_{policy,t,v})$$

The present value of all stranded assets with a discount rate of r:

$$strvb\_ = \sum_{t=1}^{t=T} \sum_{v=\{v5,v10,v15,v20\}} strvb_{v,t}/(1+r)^{t-1}$$

As the outputs are calculated at each five-year timestep, values for intermediate years were 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.

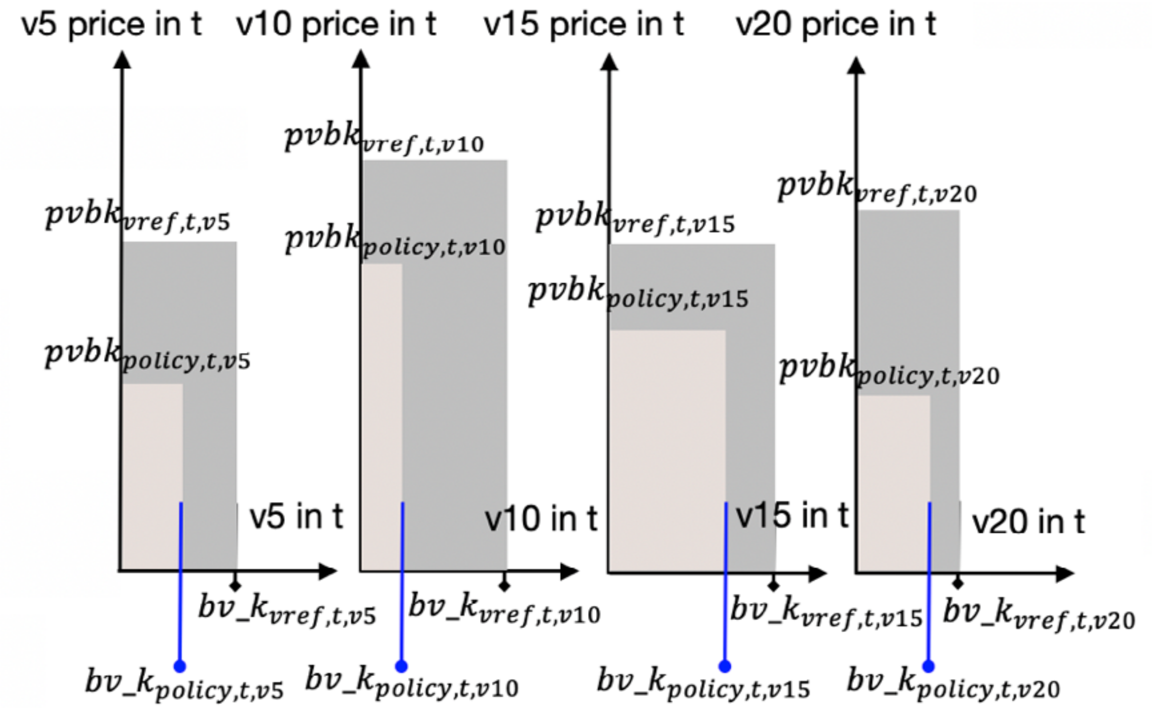

Figure C1. Estimation of Stranded Assets in Coal Power Generation

Appendix D. Estimating Stranded Assets in Fossil Fuel Production Sectors

$dpd_{s,f,t}$ = domestic price index of fossil fuel f in period t under scenario s

$d\_dv\_t_{s,f,t}$ = domestic production activity level of fossil fuel f in period t under scenario s

$xp0_f$ = base year domestic output level of fossil fuel f

$output\_{}_{s,f,t}$ = $dpd_{s,f,t} \cdot d\_dv\_t_{s,f,t} \cdot xp0_f$

$$sdoutput_t = \sum_{f=\{coal,oil,gas\}} (output_{vref,f,t} - output_{policy,f,t})$$

The present value of the sum of reduced fossil fuels output with a discount rate of r:

$$psdoutput\_ = \sum_{t=1}^{t=T} sdoutput_t/(1+r)^{t-1}$$

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.

Appendix E. Sector Aggregation

Table E1. Sector Aggregation

GTAP8 sectoral details	GTAP8 sector	EPPA6 sector
paddy rice	PDR	crop
wheat	WHT	crop
cereal grains nec	GRO	crop
vegetables, fruit, nuts	V_F	crop
oil seeds	OSD	crop
sugar cane, sugar beet	C_B	crop
plant-based fibers	PFB	crop
crops nec	OCR	crop
bovine cattle, sheep and goats, horses	CTL	live
animal products nec	OAP	live
raw milk	RMK	live
wool, silk-worm cocoons	WOL	live
forestry	FRS	fors
fishing	FSH	live
coal	COA	coal
oil	OIL	oil
gas	GAS	gas
minerals nec	OMN	othr
bovine meat products	CMT	food
meat products	OMT	food
vegetable oils & fats	VOL	food
dairy products	MIL	food
processed rice	PCR	food
sugar	SGR	food
food products nec	OFD	food
beverages and tobacco products	B_T	food
textiles	TEX	othr
wearing apparel	WAP	othr
leather products	LEA	othr
wood products	LUM	othr
paper products, publishing	PPP	eint
petroleum, coal products	P_C	roil
chemical, rubber, plastic products	CRP	eint
mineral products nec	NMM	eint
ferrous metals	I_S	eint
metals nec	NFM	eint
metal products	FMP	eint
motor vehicles and parts	MVH	othr
transport equipment nec	OTN	othr
electronic equipment	ELE	othr
machinery and equipment nec	OME	othr
manufactures nec	OMF	othr
electricity	ELY	elec
gas manufacture - distribution	GDT	gas
water	WTR	othr
construction	CNS	othr
trade	TRD	serv
transport nec	OTP	tran
water transport	WTP	tran
air transport	ATP	tran
communication	CMN	serv
financial services nec	OFI	serv
insurance	ISR	serv
business services nec	OBS	serv
recreational & other services	ROS	serv
public admin., defense, education, health	OSG	serv
ownership of dwellings	DWE	dwe

*nec = other

*for more detail, visit: https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

Appendix F. Physical Risk Methodology Details

Downscaling Approach Details

One approach is to use a full 3-D atmospheric model adjusted to capture the approximate range of uncertainty in climate outcomes simulated by the full ensemble of the simple 2-D climate model.[47] An advantage of this approach is that it can simulate the chaotic behavior in the climate system arising from uncertainty in initial conditions as well as uncertainty in the system response to increasing greenhouse gases. Results indicate that initial condition uncertainty is a major source of forecast uncertainty for the first few decades, and variation in responses to radiative forcing becomes a dominant driver of forecast uncertainty in the second half of the century.

A second approach is to use geographically detailed patterns of climate change from multiple 3-D climates models and scale them with the results from the simpler climate model.[48] By using multiple GCMs, this approach has the advantage of incorporating structural uncertainty reflected by different climate models while likely capturing the effects of different initial conditions as well.

The "gold standard" for downscaling is to use boundary conditions from a coarsely resolved GCM to drive a very detailed regional climate model for a specific region.[49] The advantage is that these can produce very realistic weather for a region on the order of the size of the US, but these models are extremely computationally intensive—so much so that only a few decades of simulations are feasible, and modeling would have to be repeated for each region of interest. Some intensive exercises have been conducted for the US and Europe to provide the community with results from regional climate models, albeit restricted to a specific set of boundary conditions.

Alternative to Analogue Method for Projecting Extreme Events

Similarly, colleagues at MIT have developed statistically based methods that assess the risk of land-falling tropical cyclones.[50] The method involves the generation of large numbers of synthetic hurricane tracks, along with each of which an analysis is conducted of storm intensity. The intensity increases with climate change because ocean surface temperature is one of the determinants of typhoon strength. The resulting statistical-physical results can then provide an analysis of the projected change in wind risk, or (combined with models of surge and wave generation) be applied to analysis of the future change in inundation risk. Similar to the analogue method, this technique has been evaluated by its skill in faithfully representing the statistics of conditions in the historical record.

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[47] This is computationally intensive—we have produced ensembles of 20 GCM simulations across 3 different emissions paths for a total of 60 simulations.

[48] Ongoing inter-model comparison efforts produce archived simulations on the order of 30 different climate models. Using each of those patterns with the 400-member 2-D climate simulations results in 12,000 simulated future climates. Here, the computational burden lies in assessing climate impacts for 12,000 simulations. Our approach is to sample from these 12,000 to get on order 600 simulations.

[49] See Komurcu, M., K.A. Emanuel, M. Huber and R.P. Acosta (2018): High Resolution Climate Projections for the Northeastern United States using Dynamical Downscaling at Convection Permitting Scales. Earth and Space Science, 5(11), 801-826 (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018EA000426)

[50] Emanuel, K., and S. Ravela. (2012) Synthetic Storm Simulation for Wind Risk Assessment. Storm Surge Barriers to Protect New York City, American Society of Civil Engineers, 15-36.; Ravela, S., and K. Emanuel. (2010) Statistical-deterministic approach to natural disaster prediction. US patent. US7734245 B2, CA2635686A1, EP1971883A2, EP1971883A4, US20070168155, WO2007084315A2, WO2007084315A3.; Emanuel, K., Ravela, S., Vivant, E. and Risi, C. (2006) A Statistical Deterministic Approach to Hurricane Risk Assessment. Bulletin of the American Meteorological Society 87(3): 299-314.

Appendix G. Regional Details

Canada

The primary component of Canada's NDC[51] is a commitment "to reduce greenhouse gas emissions by 30 percent below 2005 levels by 2030." This is translated into a carbon price growing from 16.60 USD in 2020 to 81.00 USD in 2030. As illustrated in **Figure G1**, the carbon price needed to achieve Canada's NDCs are higher than the globally coordinated carbon prices in the early years of the post-Paris term to likely reach a 2°C outcome by the end of the century.

In efforts to reach that commitment, Canada's Pan-Canadian Framework on Climate Change and Clean Growth with include "new regulations to accelerate the phase-out of traditional coal units by 2030."[52] This can be observed in its primary energy use, where coal is immediately slashed in the early years of the Paris timeframe, except for in the *No Policy* scenario (see **Figure G2** and **Figure G3**). This translates to the relatively small, yet consistent, stranding of an NPV of 14.7 billion USD in coal assets in each policy scenario through 2040 (see Figure 13, page 22). Additionally, the Canadian Framework includes performance standards for natural gas-fired electricity production, amplifying the natural gas electrification effect discussed on page 19.

Canada represents a case in which the *Paris Forever* scenario results in a greater sustained level of emissions reductions than if it transitioned to a globally coordinated carbon pricing scheme post-Paris.

Oil and gas in Canada demonstrate the same primary energy use dynamics under the range of scenarios. The *No Policy* scenario predictably sees the increase of oil and gas through 2040, with slight dips around 2025. The phase-out of nuclear represents the array of plants that are set to close, or whose licenses are set to expire, in the years between 2022 and 2037.[53]

As observed in Figure G3, oil primary energy use is moderately sensitive to the evolution of climate policy in Canada. While oil use increases in developing regions (i.e. China, India, Middle East, and the Rest of the World) regardless of scenario, it decreases in the other developed regions (i.e., Europe and the United States) regardless of scenario. It is possible that this is indicative of lower rent margins exhibited in the production of Canadian tar sands. Otherwise, the pattern of stranded oil assets across the policy scenarios mirrors that seen in the other regions, suggesting that the change in oil price—which is constant across regions—dictates the level of stranded oil assets in the region.

As a major crop producer and exporter, Canada is quite sensitive to transitions brought about by the policy scenarios. Similarly, its Livestock sector exhibits relative declines, albeit not as great as those exhibited by the Crop sector, to its output in the *No Policy* scenario.

Each of the policy scenarios produces a relative reduction in output from Canada's Energy Intensive Industry early in the transition (2025), but reverses to show a relative increase later on (2040), signifying that the Canadian NDCs would be more stringent on those industries than would a global carbon price.

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[51] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Canada%20First/Canada%20First%20NDC-Revised%20submission%202017-05-11.pdf

[52] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Canada%20First/Canada%20First%20NDC-Revised%20submission%202017-05-11.pdf

[53] https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/canada-nuclear-power.aspx

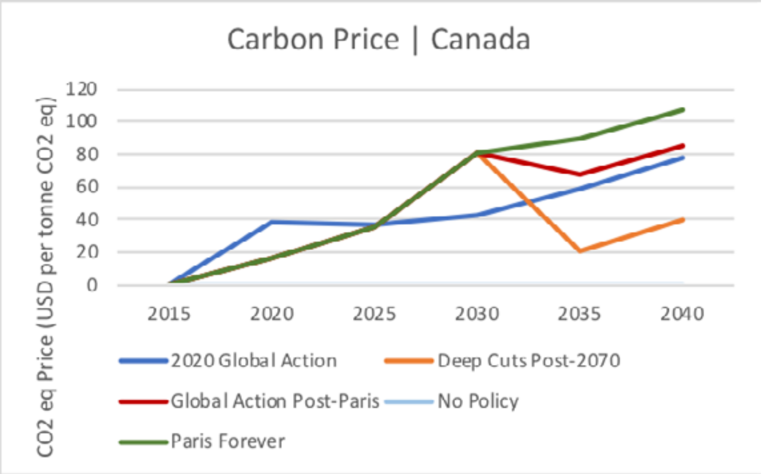

Figure G1. Modeled CO_2-eq Price | Canada

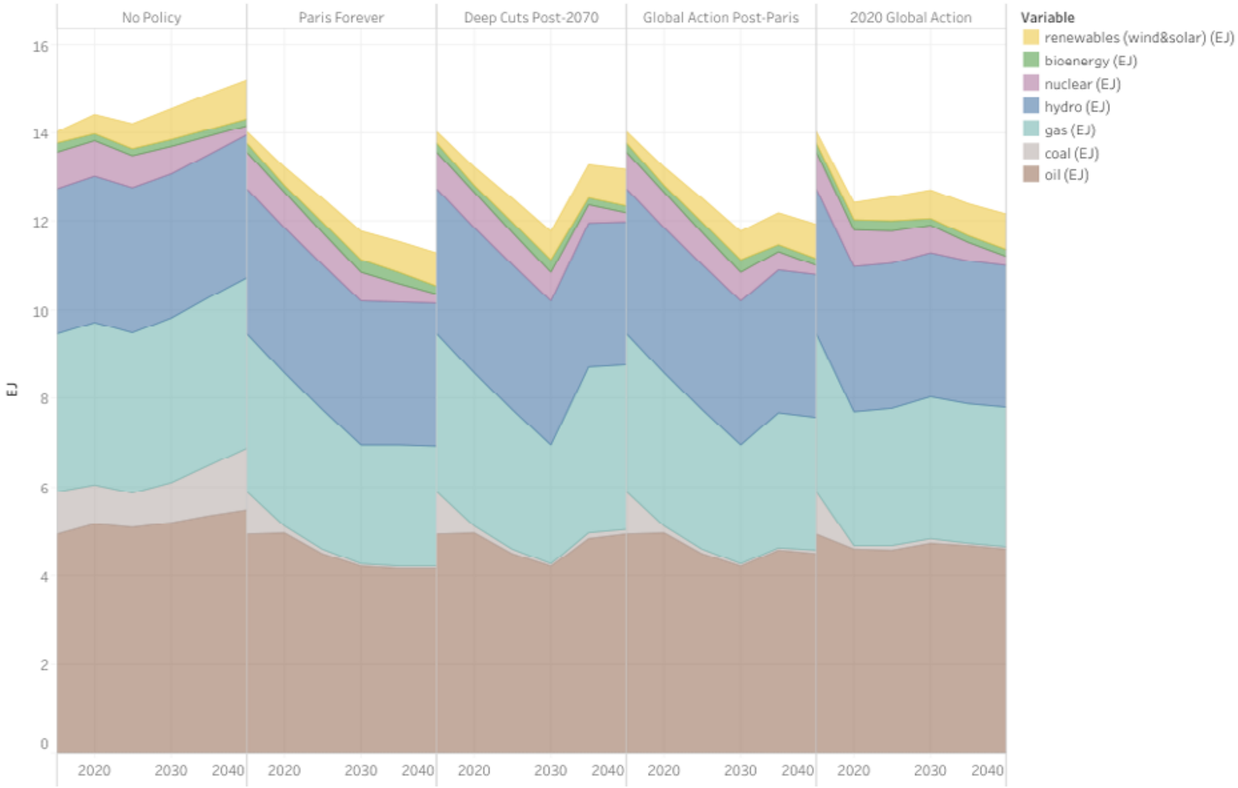

Figure G2. Primary Energy Use | Canada

Figure G3. Primary Energy Use | Canada

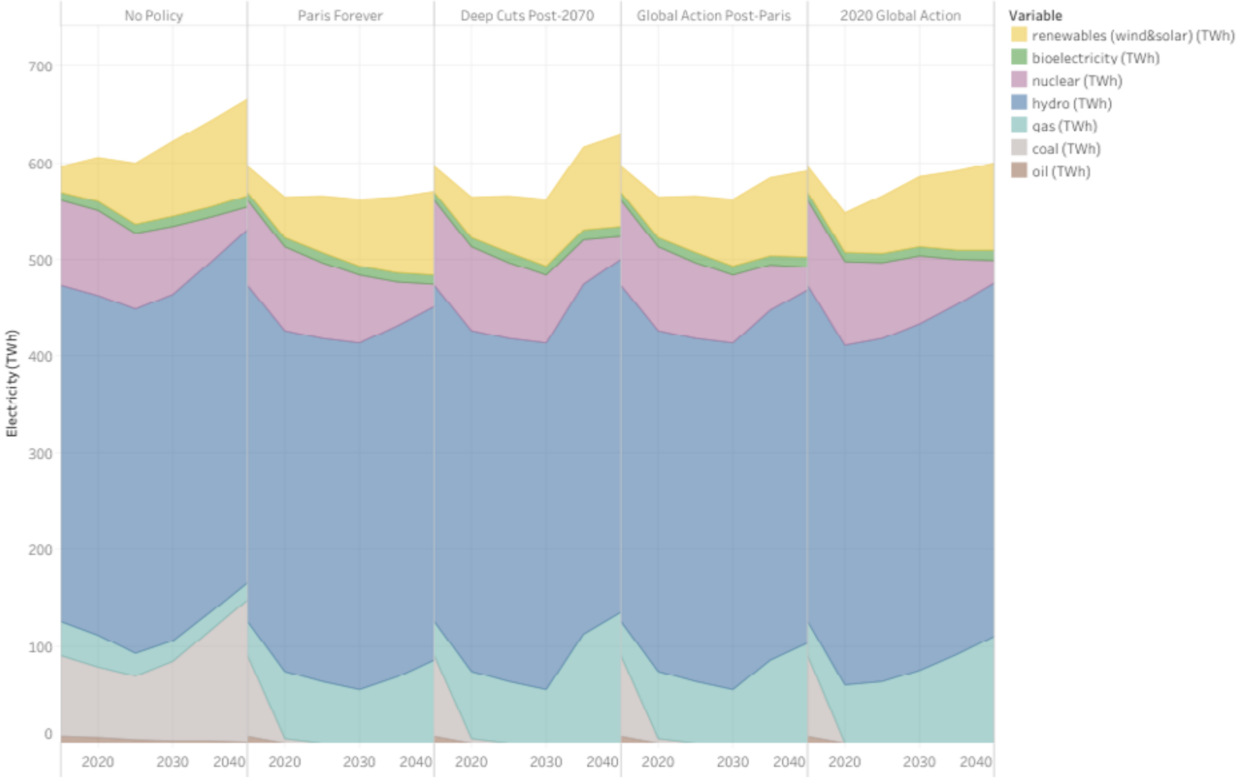

Figure G4. Electricity Generation | Canada

Figure G5. Electricity Generation | Canada

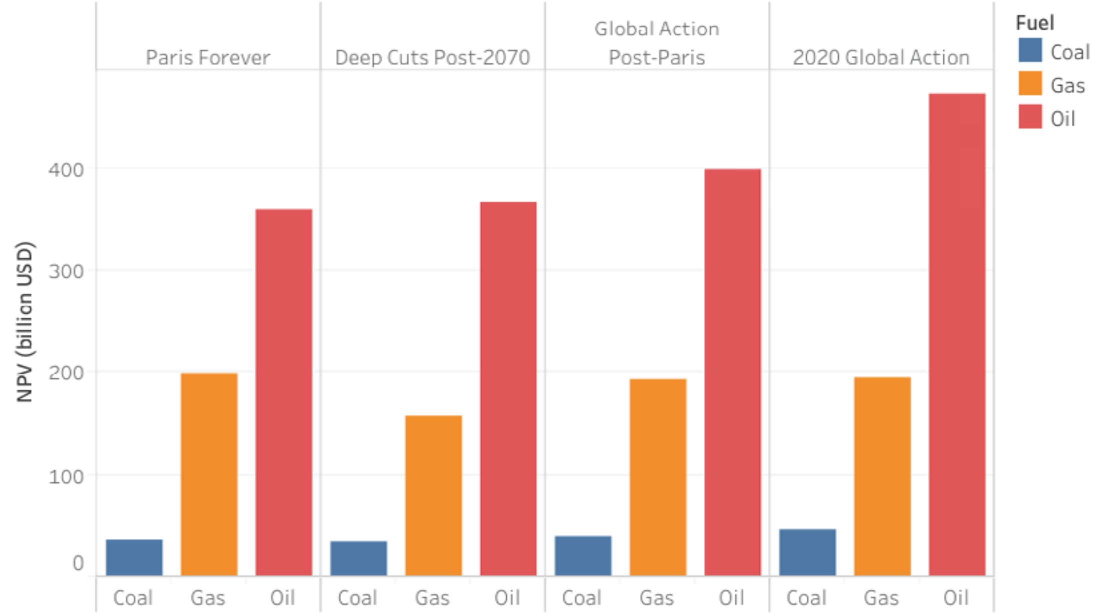

Figure G6. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* | Canada

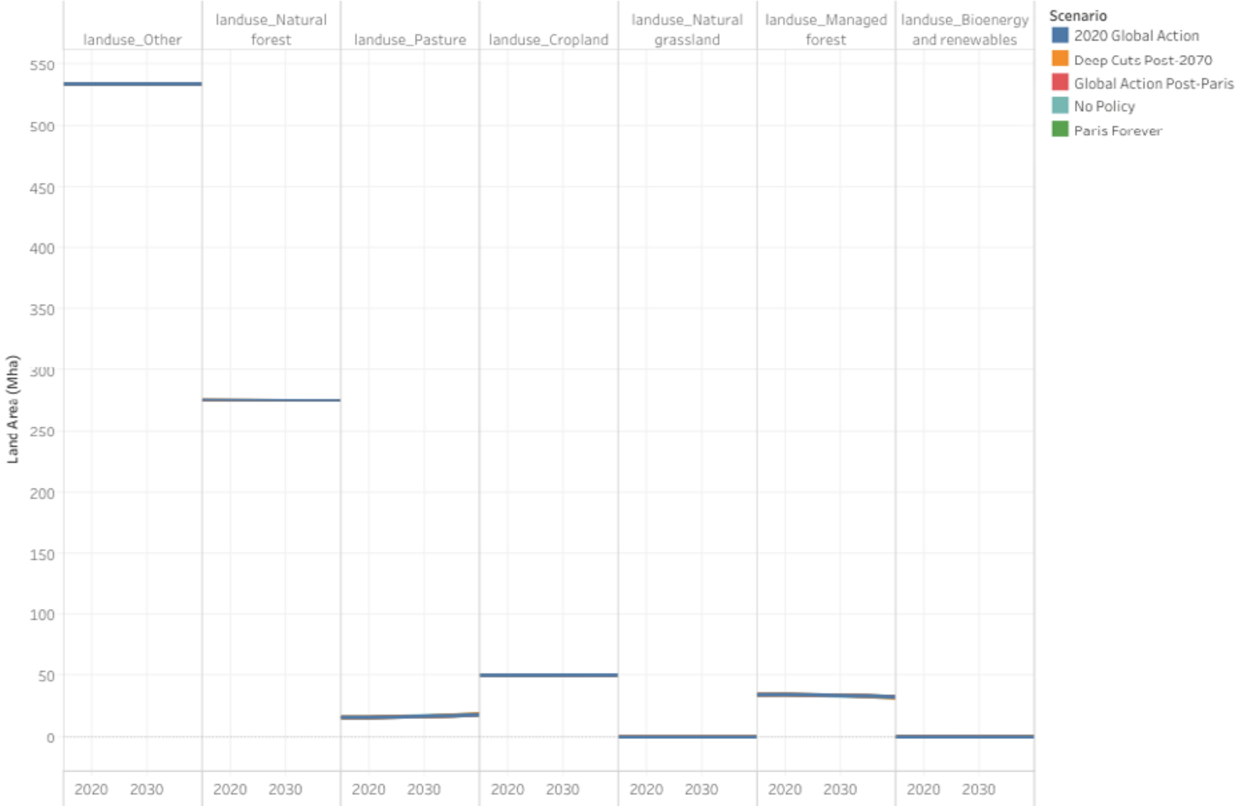

Figure G7. Land Use | Canada

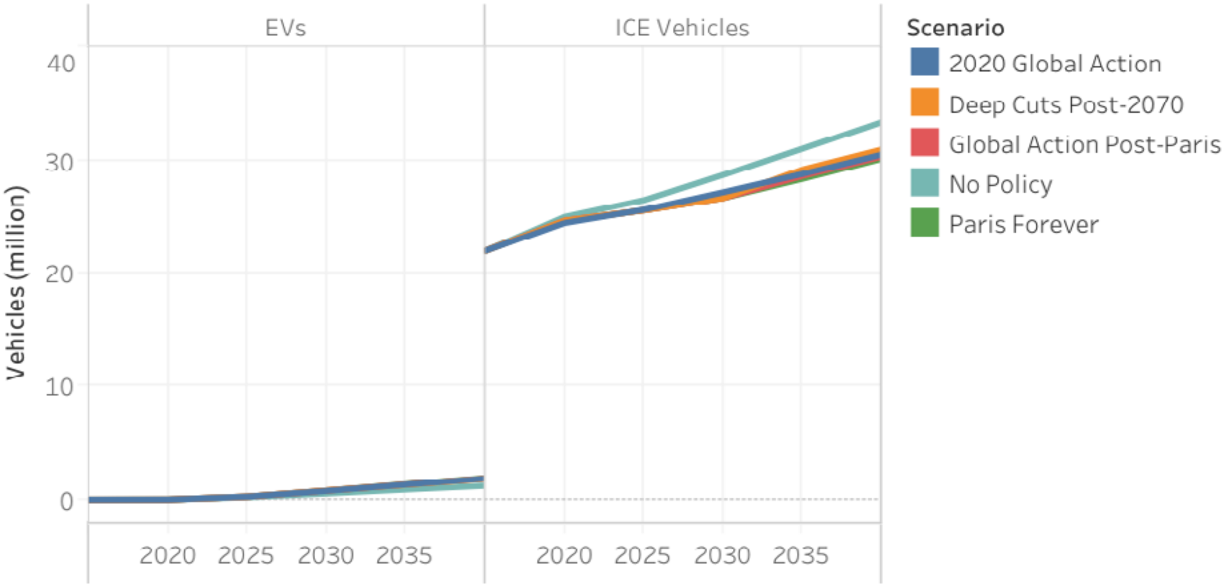

Figure G8. Household Vehicles | Canada

Table G2. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | Canada

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	**2040**	**2025**	**2040**	**2025**	**2040**	**2025**	**2040**
GDP	-0.6	-2.3	-0.6	-0.9	-0.6	-2.0	-0.5	-1.7
Commercial Transportation	-3.9	-9.3	-3.9	2.1	-3.9	-4.7	-3.5	-3.7
Crops	-9.2	-0.4	-9.2	3.0	-9.2	2.2	-7.0	2.5
Dwelling Ownership	-0.1	-0.5	-0.1	-0.4	-0.1	-0.7	0.1	-0.5
Energy Intensive Industry	-0.5	-2.7	-0.5	1.0	-0.5	0.8	0.7	1.3
Food	0.3	0.4	0.3	1.1	0.3	0.9	0.6	0.9
Forestry	0.8	1.2	0.8	1.8	0.8	3.2	1.6	2.6
Livestock	-2.1	-7.0	-2.1	-0.4	-2.1	-5.5	-3.0	-6.1
Other Industry	0.4	0.6	0.4	0.8	0.4	0.7	0.3	0.8
Services	0.0	-0.2	0.0	-0.2	0.0	-0.4	-0.1	-0.3

China

China presents a special case due to the construction of its Nationally Determined Contributions (NDCs) through 2030. These include having its carbon dioxide emissions peak by 2030 and to increase its share of non-fossil primary energy consumption to around 20%[54]. These two contributions can be seen clearly in the *Paris Forever* scenario in **Figure G10**. The use of renewables, bioenergy, nuclear, and hydro grow to 36.3 EJ out of the total primary energy usage of 169.9 EJ to make up just over 20% of the mix by 2030. Additionally, slight decreases in coal usage cancels out the emission increases from slight increases in the usage of oil and gas post-2030, holding overall carbon dioxide emissions constant.

China is in a unique position to be a driving force toward or away from a low-carbon future. In 2015, its use of coal constituted 52% of that of the world, which could grow to 58% by 2040 in the *No Policy* scenario. On the other hand, it could increase its primary energy use of renewables from 18% of the global share in 2015 to 49% by 2040 in the *Global Action Post-Paris* scenario.

China shows an aggressive switch to advanced coal. The *2020 Global Action* scenario has advanced coal completely replacing conventional coal by 2030 (see **Figure G14**). Even in the *Global Action Post-Paris* scenario, in which advanced coal develops less fully during the fulfillment of its NDCs, the introduction of the global carbon price of 68.04 USD quickly sheds conventional coal electricity generation to leave advanced coal supplying any of the remaining coal-fueled energy (~1,400 TWh). The switch takes until 2040 under the *Deep Cuts Post-2070* scenario, until 2045 under the *Paris Forever* scenario, and until 2050 under the *No Policy* scenario.

China exhibits growth in the real output of its dwelling ownership by 1.1% to 1.9% by 2040 relative to the *No Policy* scenario. This is the most significant growth in that sector out of any region.

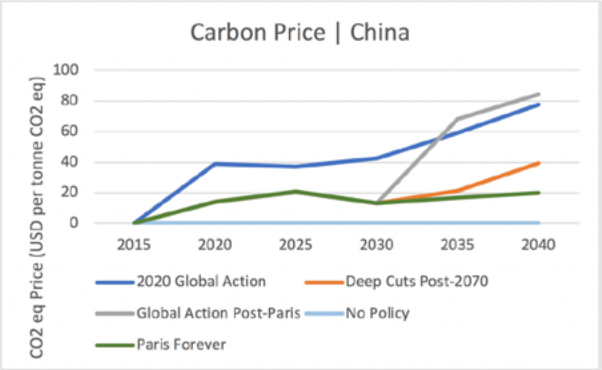

Figure G9. CO_2-eq Prices | China

Table G3. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | China

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-1.3	-2.1	-1.3	-3.5	-1.3	-6.0	-3.5	-5.6
Commercial Transportation	-1.5	-3.8	-1.5	-4.8	-1.5	-7.3	-3.1	-6.8
Crops	0.2	-1.6	0.2	-2.2	0.2	-3.3	-0.3	-1.9
Dwelling Ownership	1.6	1.5	1.6	1.9	1.6	1.0	2.1	1.1
Energy Intensive Industry	-2.1	-2.0	-2.1	-3.5	-2.1	-6.7	-4.8	-6.1
Food	-0.2	-1.0	-0.2	-1.7	-0.2	-3.2	-1.7	-2.9
Forestry	-1.0	-3.4	-1.0	-1.0	-1.0	-2.1	1.4	-1.3
Livestock	0.5	-0.7	0.5	-1.0	0.5	-1.3	-0.7	-0.8
Other Industry	-1.4	-1.8	-1.4	-2.8	-1.4	-5.6	-3.5	-5.2
Services	-0.3	-0.7	-0.3	-1.2	-0.3	-2.8	-1.5	-2.5

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[54] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%27s%20First%20NDC%20Submission.pdf

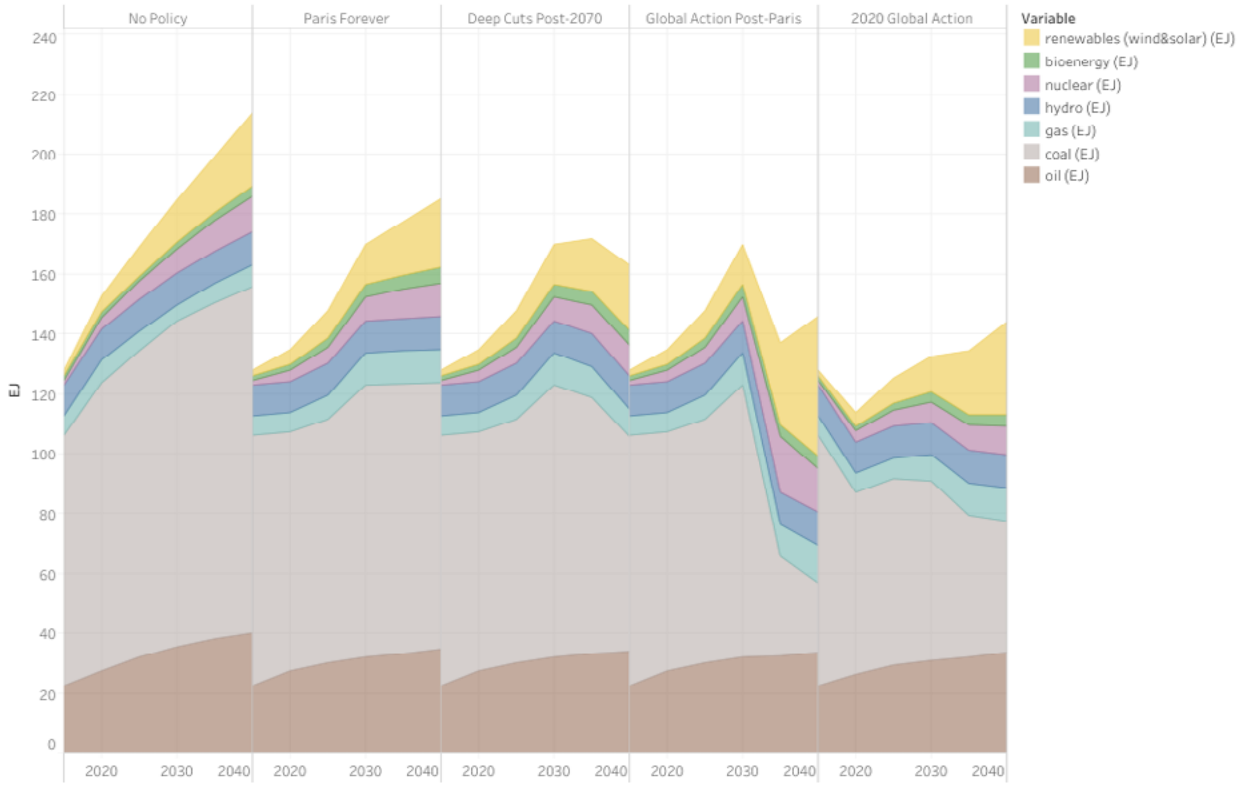

Figure G10. Primary Energy Use by Scenario | China

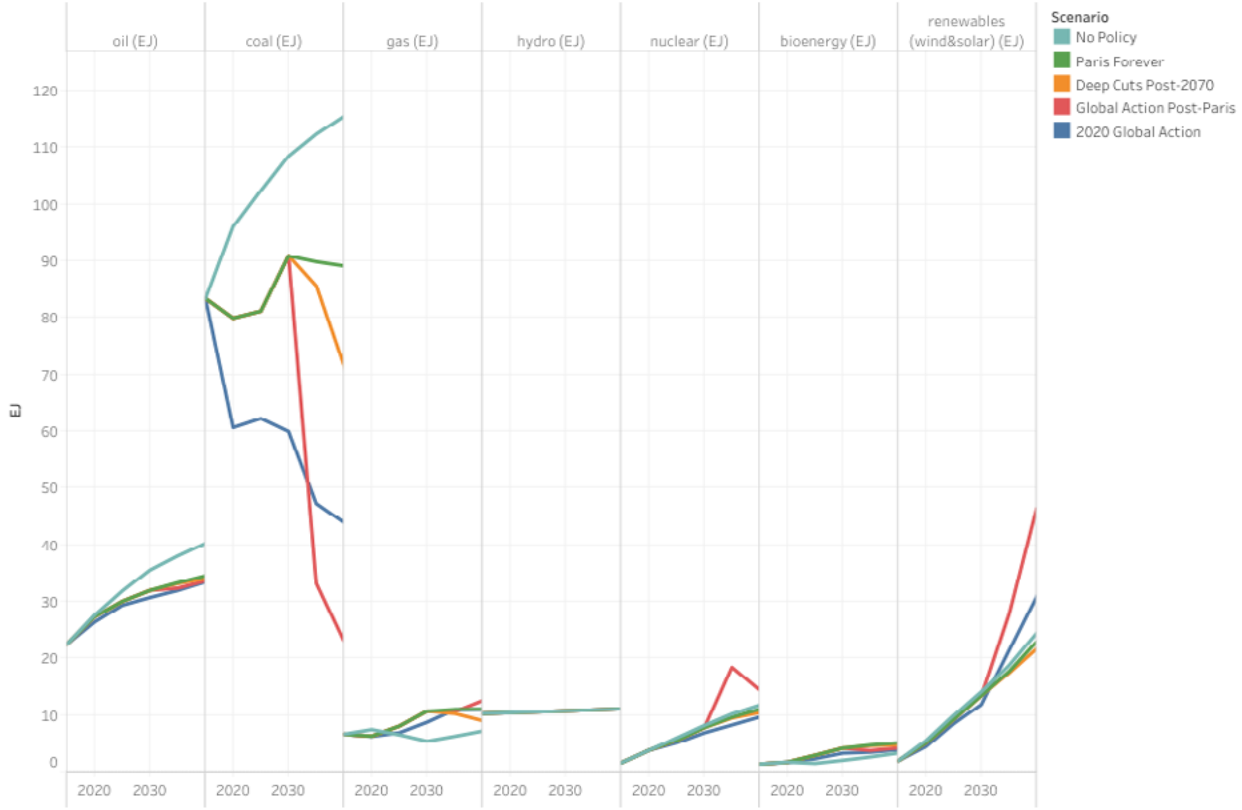

Figure G11. Primary Energy Use by Source | China

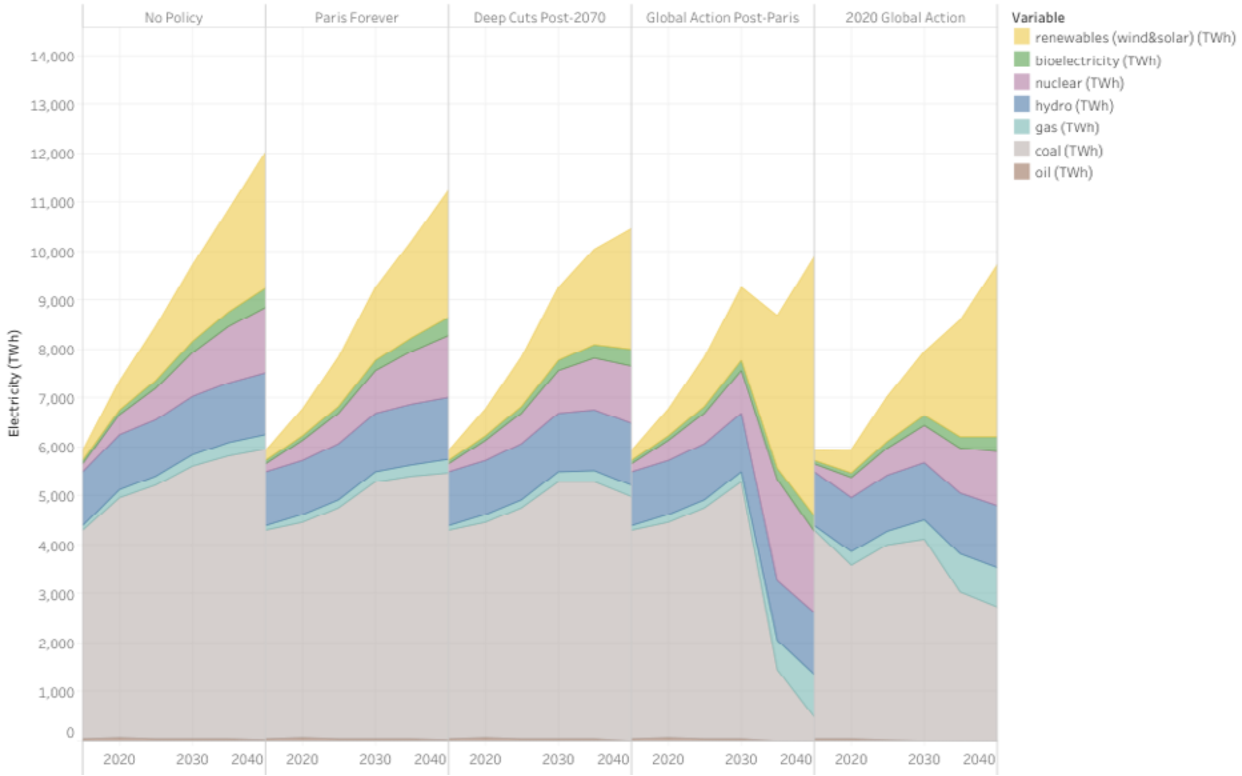

Figure G12. Electricity Generation by Scenario | China

Figure G13. Electricity Generation | China

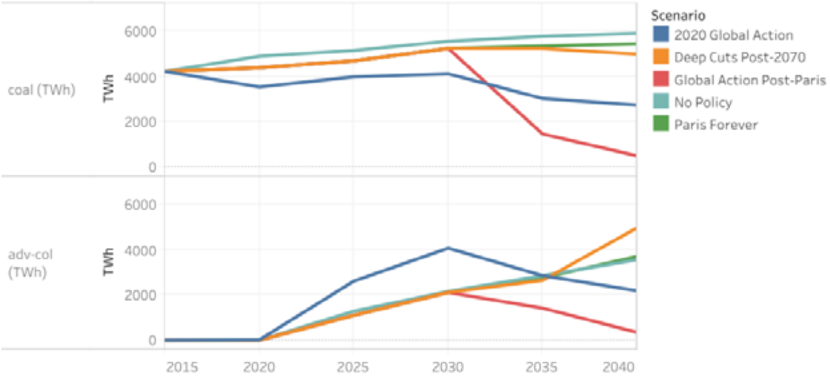

Figure G14. Coal Breakdown | China
Panel (a): cumulative conventional and advanced coal; Panel (b) advanced coal

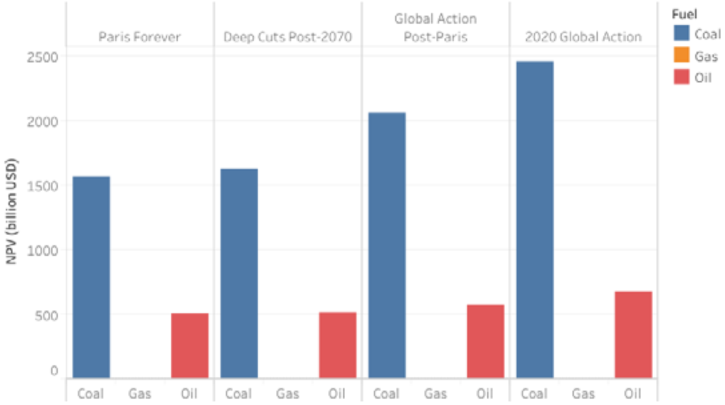

Figure G15. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* | China

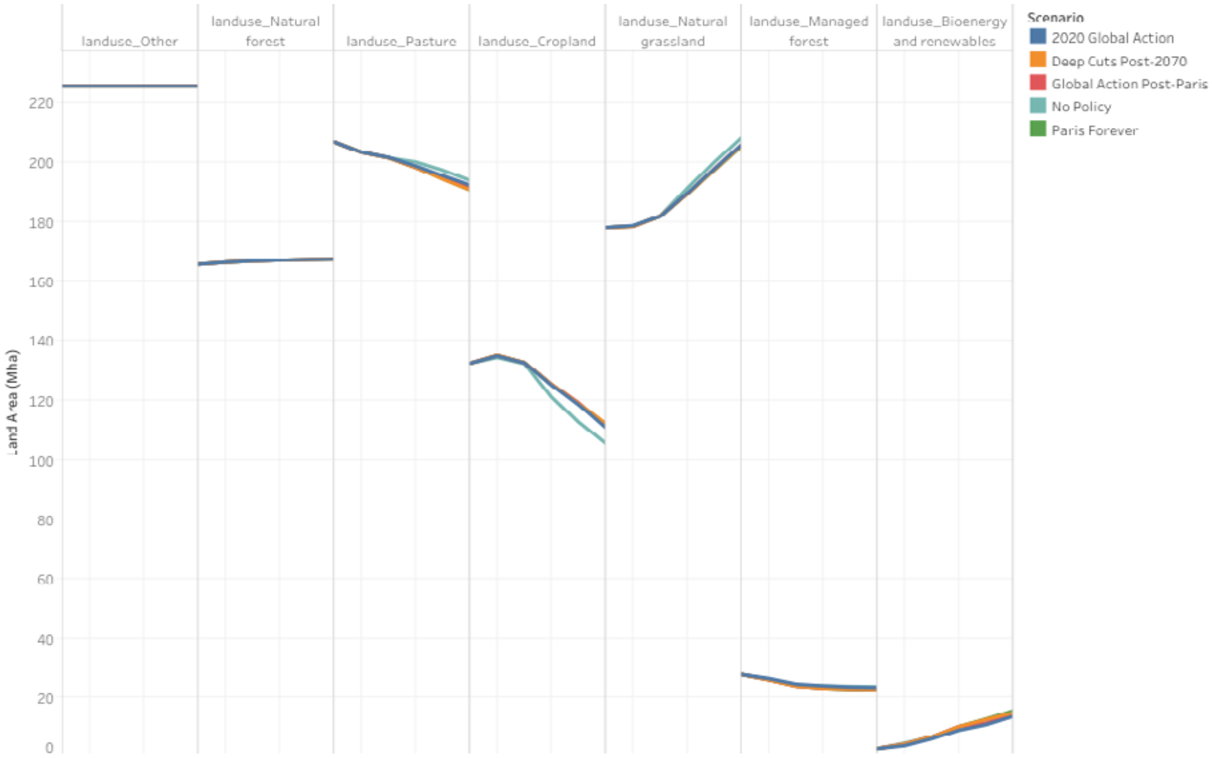

Figure G16. Land Use | China

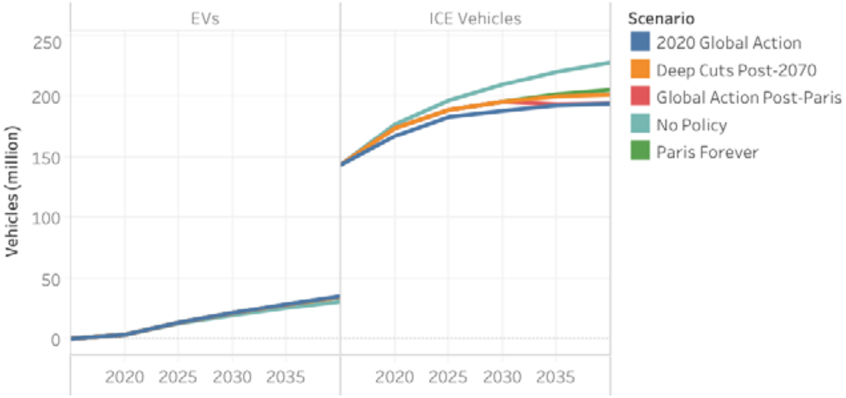

Figure G17. Household Vehicles | China

Europe

The combined NDCs of Europe are aggregated to amount to a 40% decrease in emissions by 2030. The method of emissions reduction is a goal of 27% renewable share in its electricity generation mix by 2040. As this is not sufficient to meet its 40% goal by 2030, a carbon price, rapidly ramping up through $6.22 in 2025 to $84.99 in 2030, makes up the difference. As this reduction is more aggressive than the globally coordinated carbon prices that follow in the *Global Action Post-Paris* and *Deep Cuts Post-2070* scenarios, there is a relaxation of the downward pressure on coal in the years immediately following the Paris timeframe. However, this downward pressure resumes by 2040.

The negligible difference in renewable growth among the scenarios suggests that such growth would happen regardless of specific policies put in place to support it. As a result, the carbon price, and its reduction in coal and oil energy production, have a direct impact on the cumulative energy profile of Europe.

Under the four policy scenarios, the reduction in coal-fired electricity is essentially replaced by natural gas.

Europe exhibits a higher than average sensitivity to policy scenarios in its Commercial Transport sector, even relative to that of other regions.

Interestingly, Europe's Crop sector exhibits a real output increase early on (2025) relative to a *No Policy* scenario, then reverses course to exhibit reductions by 2040 in each of its policy scenarios.

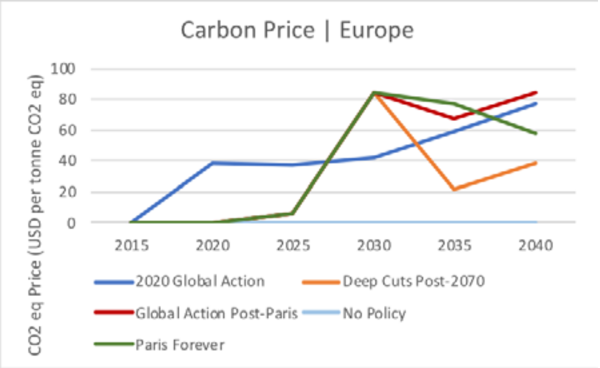

Figure G18. CO_2-eq Prices | Europe

Table G4. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | Europe

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-0.6	-1.5	-0.6	-1.0	-0.6	-0.9	-0.3	-0.8
Commercial Transportation	-5.4	-7.2	-5.4	-7.3	-5.4	-7.0	-5.4	-7.2
Crops	0.3	-4.1	0.3	-4.6	0.3	-4.7	0.9	-4.1
Dwelling Ownership	-0.3	-0.6	-0.3	-0.3	-0.3	-0.3	0.1	0.0
Energy Intensive Industry	-0.3	-1.4	-0.3	-0.7	-0.3	-0.3	0.4	0.3
Food	-0.4	-1.4	-0.4	-1.3	-0.4	-1.4	-0.5	-1.4
Forestry	-2.4	-0.5	-2.4	1.1	-2.4	4.7	2.2	7.0
Livestock	-0.1	-1.8	-0.1	-1.7	-0.1	-2.5	-1.3	-3.1
Other Industry	-0.7	-1.3	-0.7	-1.3	-0.7	-1.7	-1.0	-1.6
Services	-0.6	-1.0	-0.6	-1.0	-0.6	-1.2	-0.7	-1.1

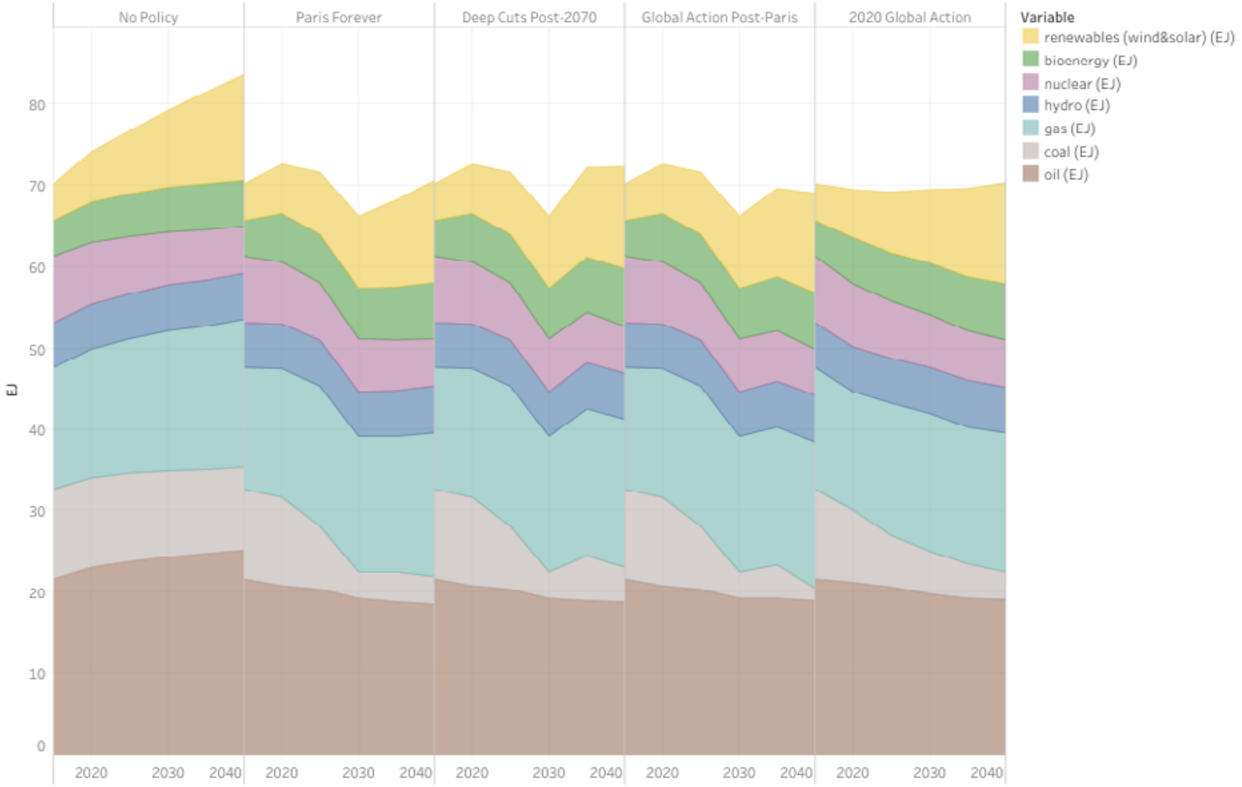

Figure G19. Primary Energy Use | Europe

Figure G20. Primary Energy Use | Europe

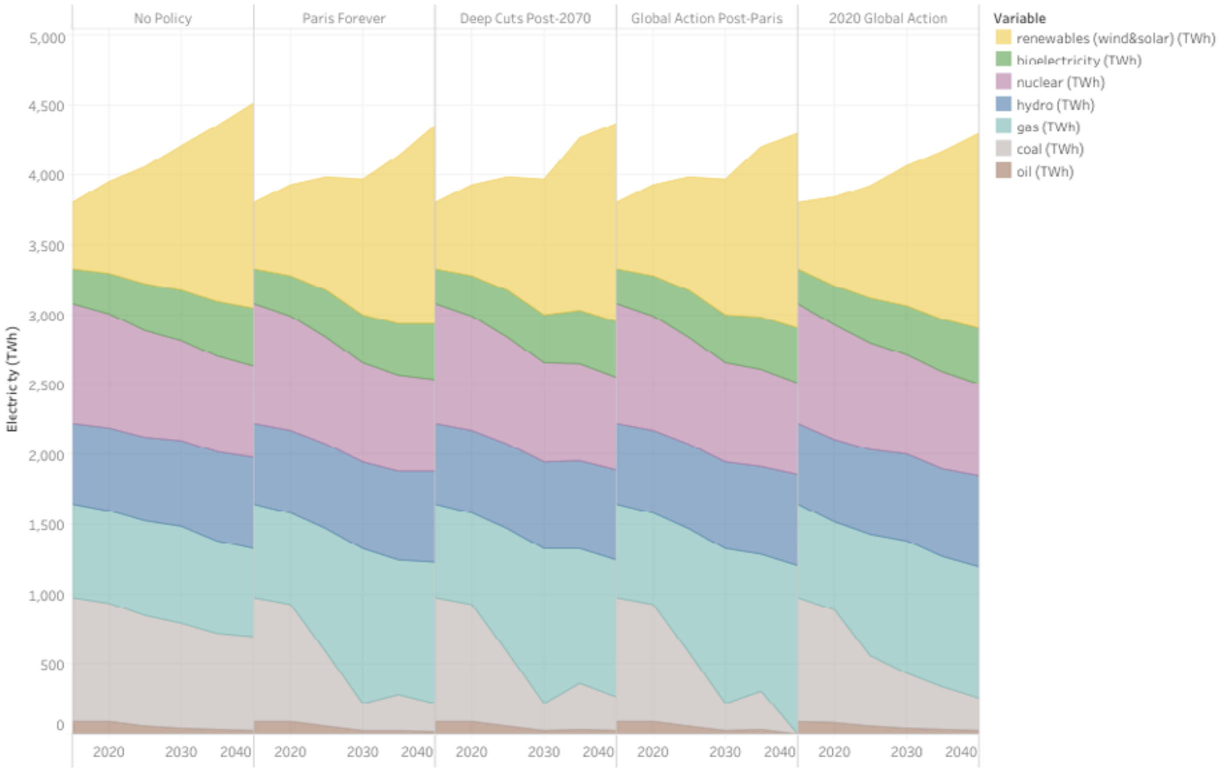

Figure G21. Electricity Generation | Europe

Figure G22. Electricity Energy | Europe

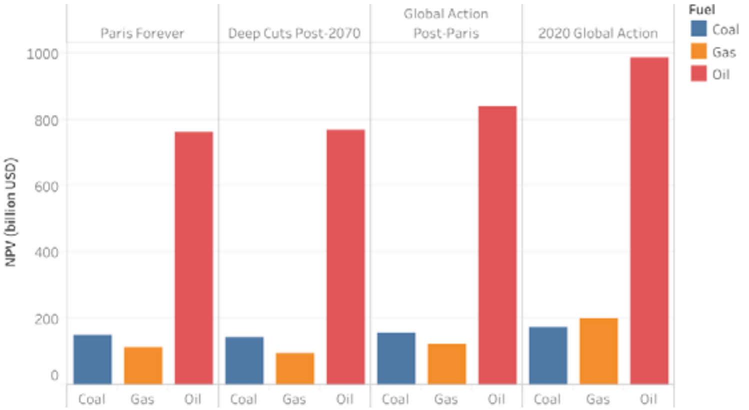

Figure G23. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No*

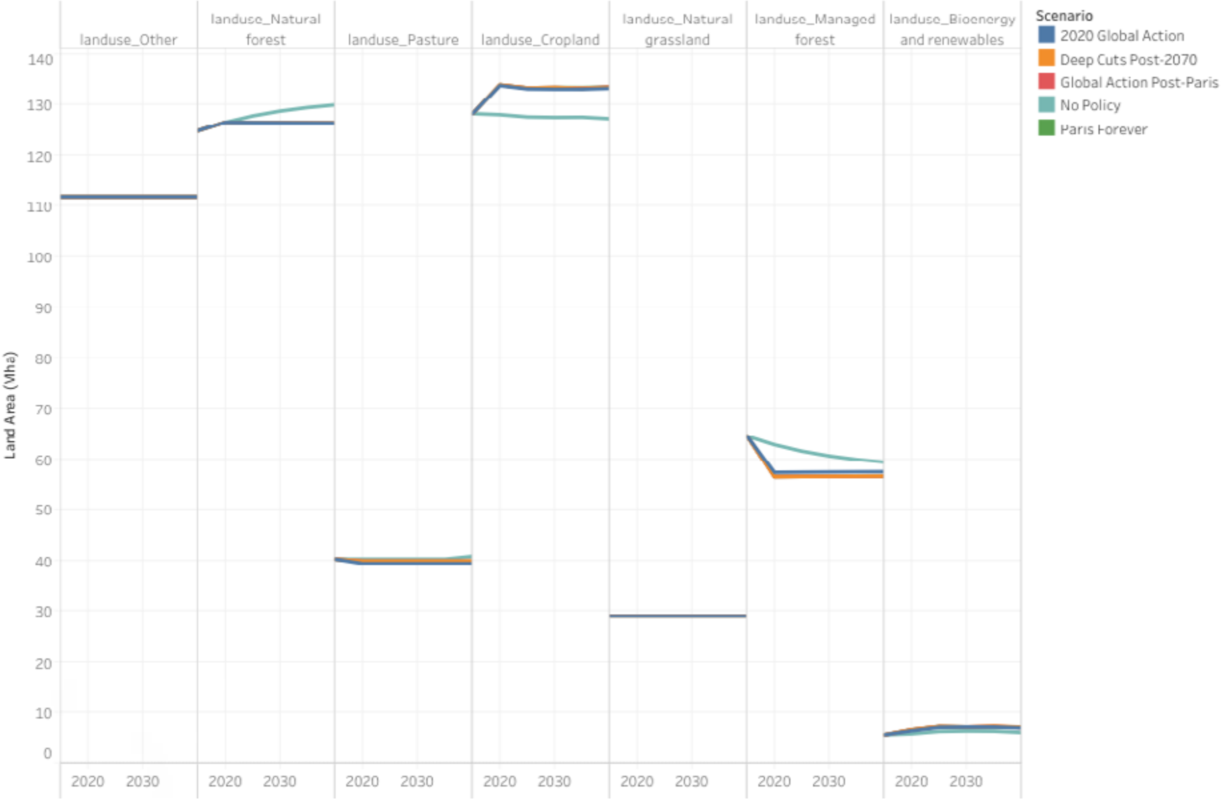

Figure G24. Land Use | Europe

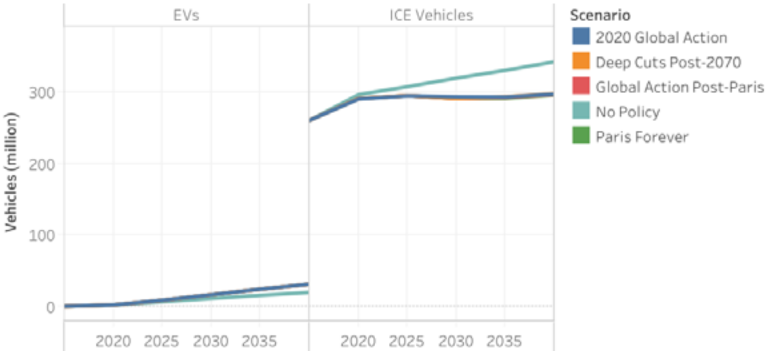

Figure G25. Household Vehicles | Europe

India

India's Intended National Determined Contribution (INDC) outlines a set of goals including the goals to reduce its GDP emissions intensity by 33 to 35% by 2030 from its 2005 level, to achieve about 40 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030 with the help of transfer of technology and low cost international finance including from Green Climate Fund (GCF), and to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.[55] However, since such contributions never manifested themselves into a final set of NDCs, it is modeled to continue on its *No Policy* pathway until globally coordinated carbon prices are enacted in the various *2°C Likely* scenarios.

As a result, even the relatively mild carbon price of $21.19 post-Paris in the *Deep Cuts Post*-2070 scenario is enough to significantly affect India's rapidly growing energy demand profile, primarily through severe cut-backs in its use of coal.

As the marginal cost fuel source in its electricity generation mix, conventional coal is replaced by advanced coal in all scenarios, albeit to different extents and on different timelines. Under the *2020 Global Action* scenario, advanced coal use grows to constitute 90% of its coal use by 2525. In the remaining scenarios, advance coal represents about 40% of total coal use in 2030, becoming approximately 64%, 64%, 100%, and 100% by 2040 in the *No Policy*, *Paris Forever*, *Global Action Post-Paris* and *Deep Cuts Post-2070* scenarios, respectively. The decline of advanced coal in the after 2025 in the *2020 Global Action* scenario is due to the rise in coal with CCS, which by 2040 constitutes 100% of India's coal use.

The outsized stranded value of coal in the *2020 Global Action* scenario is, in part, due to the stranding of advanced coal plants and associated economic output in the years between 2025 and 2040 as coal with CCS ramps up. Retrofitting the built advanced coal plants with CCS may decrease the amount of stranded assets and value incurred during that transition.

India's Commercial Transport sector suffers under policy scenarios, as does its Energy Intensive Industry, becoming more severe further in the future with globally coordinated carbon prices.

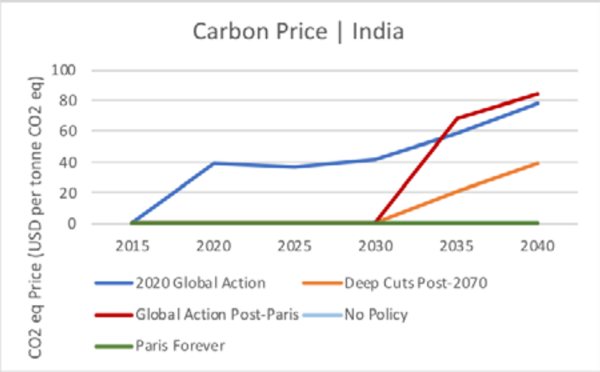

Figure G26. CO_2-eq Prices | India

Table G5. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | India

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	**2040**	**2025**	**2040**	**2025**	**2040**	**2025**	**2040**
GDP	-1.8	-2.9	-1.8	-5.1	-1.8	-6.8	-4.6	-6.2
Commercial Transportation	-5.9	-9.1	-5.9	-10.4	-5.9	-11.0	-8.5	-10.6
Crops	-3.8	-3.3	-3.8	-3.0	-3.8	-3.0	-3.1	-3.0
Dwelling Ownership	0.2	-0.8	0.2	-2.2	0.2	-3.3	-1.5	-3.0
Energy Intensive Industry	-1.0	-2.3	-1.0	-6.3	-1.0	-7.7	-8.9	-9.9
Food	0.6	-1.1	0.6	-2.6	0.6	-3.8	-2.3	-3.7
Forestry	0.8	-1.2	0.8	0.1	0.8	1.9	3.0	0.7
Livestock	-0.2	-1.0	-0.2	-2.6	-0.2	-4.3	-3.1	-3.7
Other Industry	-1.4	-2.4	-1.4	-3.8	-1.4	-4.7	-4.1	-4.7
Services	-1.2	-2.4	-1.2	-3.1	-1.2	-3.6	-2.8	-3.1

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[55] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/India%20First/INDIA%20INDC%20TO%20UNFCCC.pdf

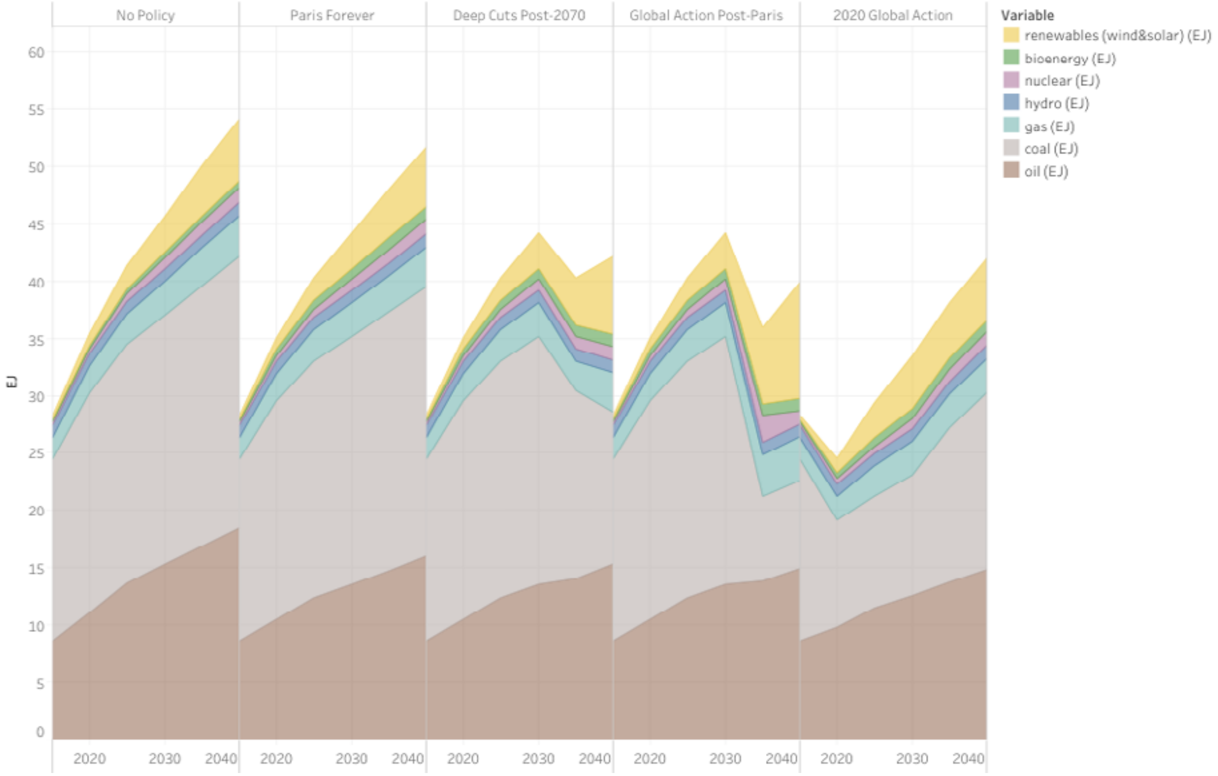

Figure G27. Primary Energy Use | India

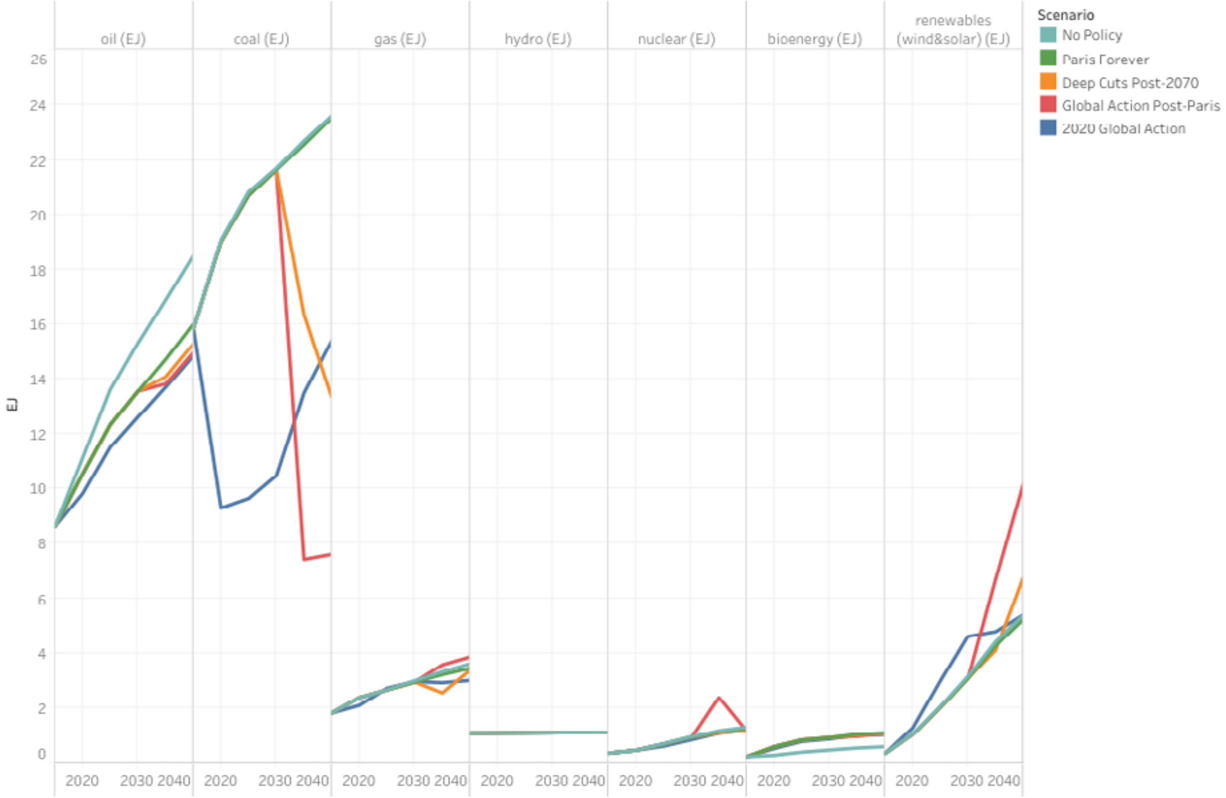

Figure G28. Primary Energy Use | India

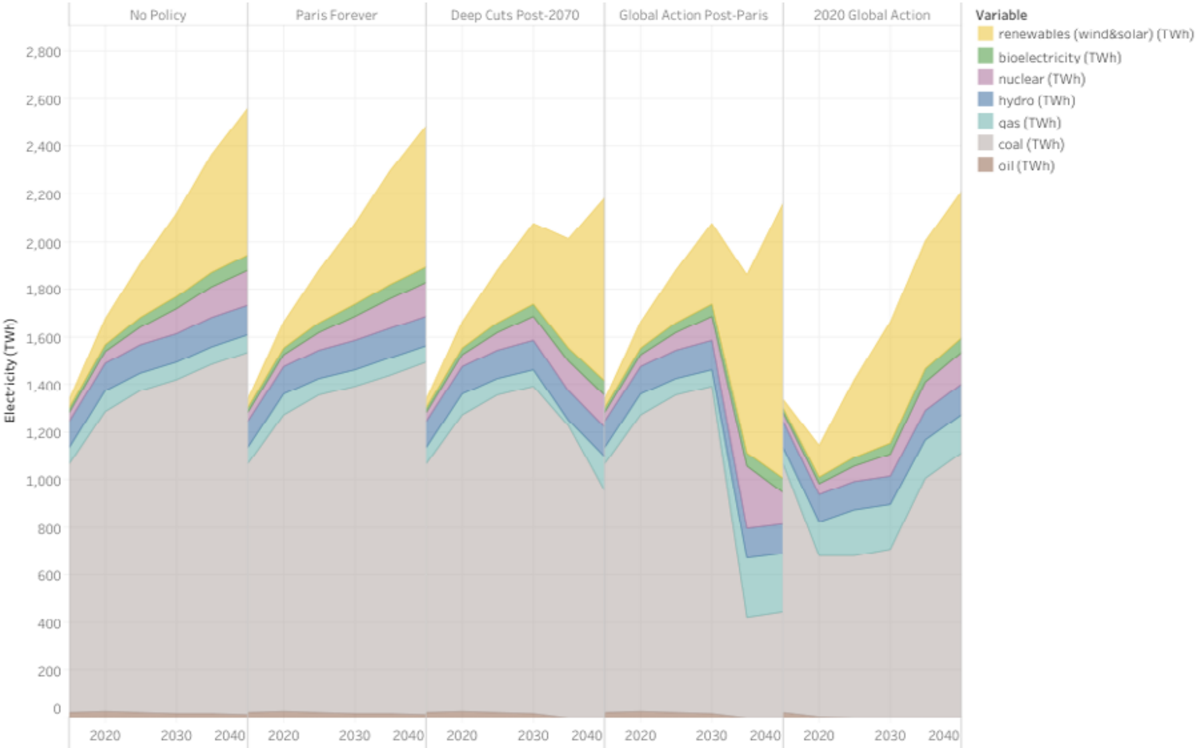

Figure G29. Electricity Generation | India

Figure G30. Electricity Generation | India

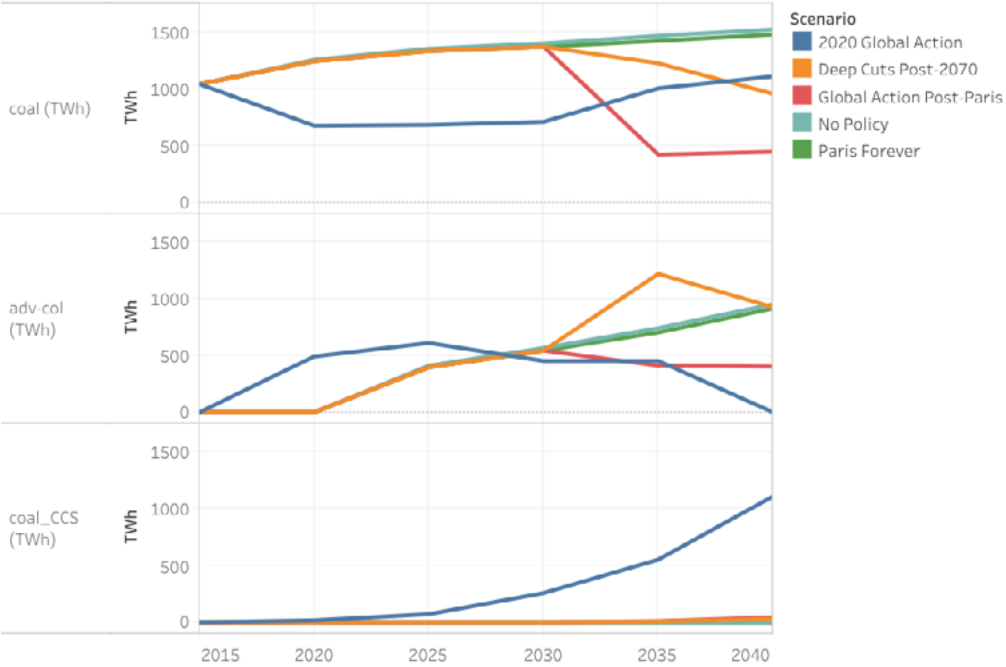

Figure G31. Coal Breakdown | India
Panel (a): cumulative conventional and advanced coal; Panel (b) advanced coal

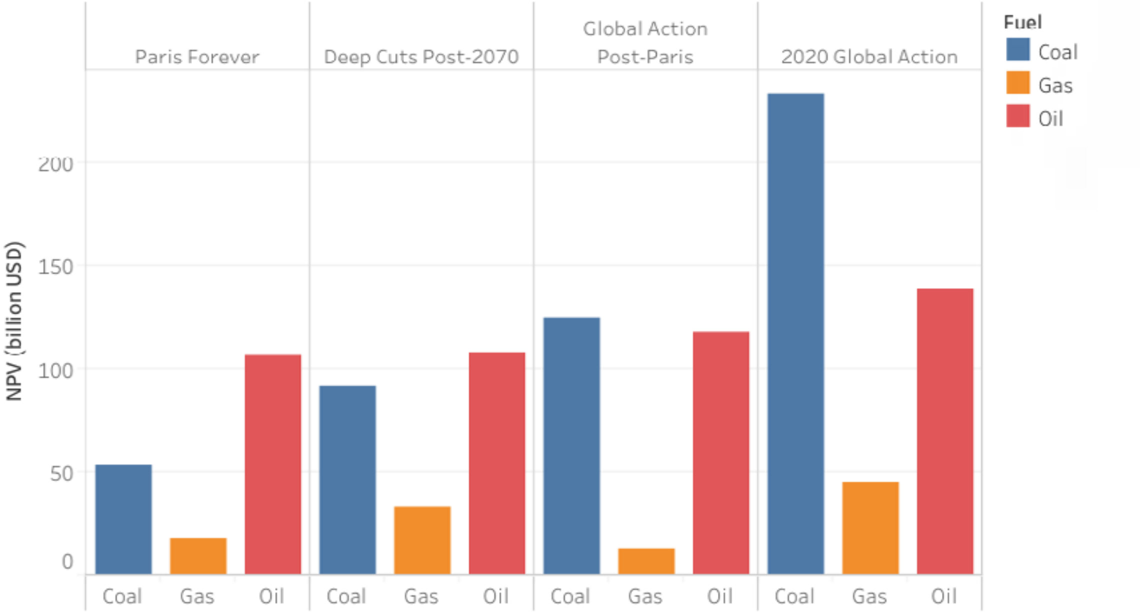

Figure G32. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* | India

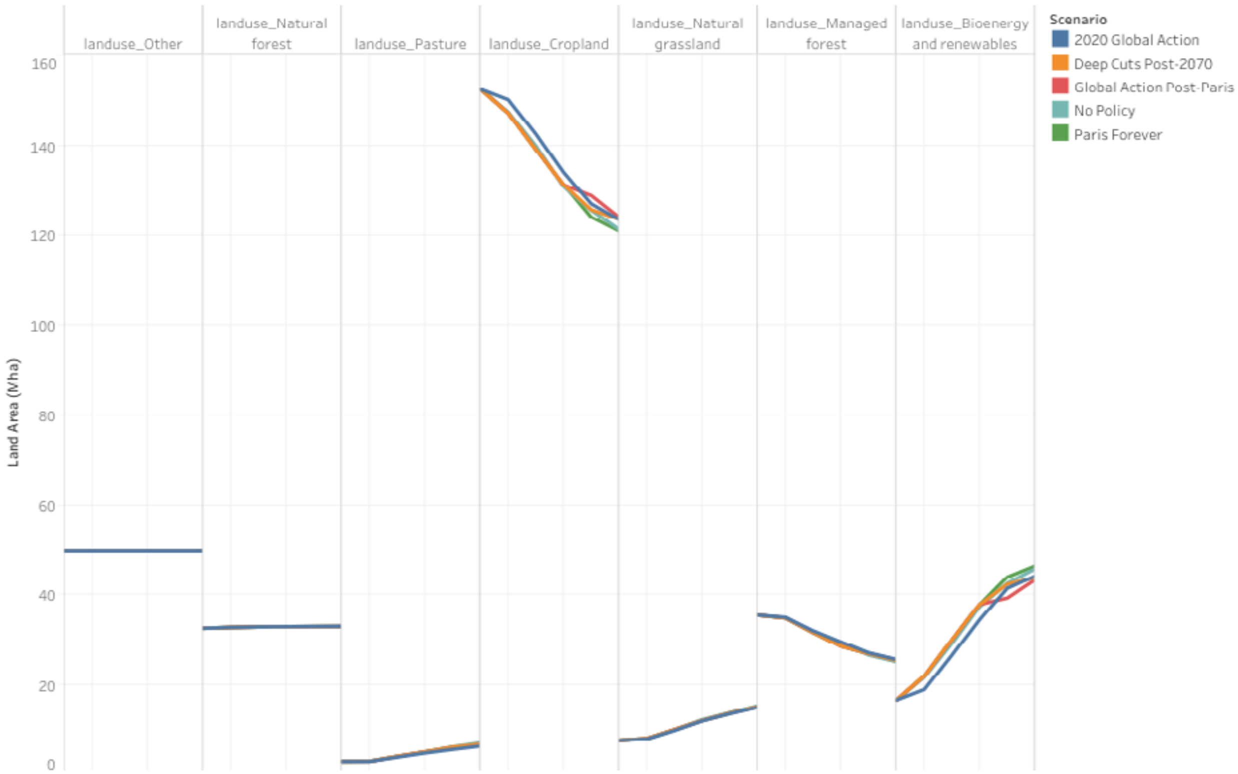

Figure G33. Land Use | India

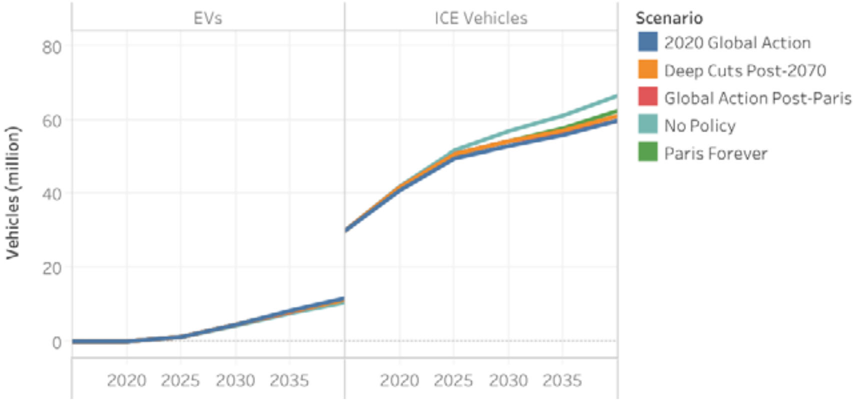

Figure G34. Household Vehicles | India

Middle East

The NDCs in the Middle East generally proposed actions instead of concrete emissions reductions targets. That of Iran is the exception, stating a 15% emissions intensity reduction target relative to its BAU projection. In aggregate, this is modeled as a 10% emissions intensity reduction goal to its BAU by 2030. This translates into a relatively low carbon price of $11.95 by 2030, and even then, only occurring close to the end of the Paris timeframe. As a result, while the 2030 carbon price helps to briefly halt the rise in fossil fuel energy use, real reductions occur only upon the implementation of globally coordinated carbon prices in the *2°C Likely* scenarios.

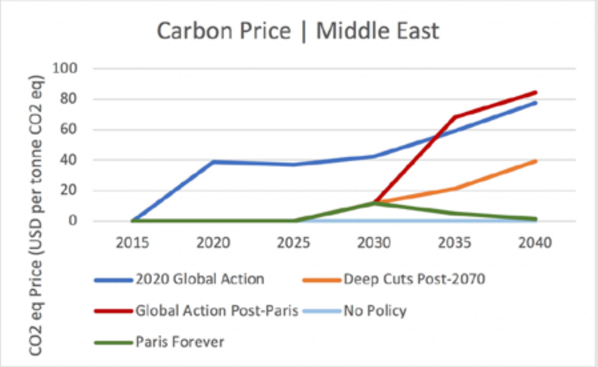

Figure G35. CO_2-eq Price | Middle East

Table G6. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | The Middle East

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-6.3	-13.0	-6.3	-14.2	-6.3	-16.9	-9.0	-17.1
Commercial Transportation	-6.3	-20.8	-6.3	-21.1	-6.3	-20.7	-5.6	-20.1
Crops	-3.1	0.0	-3.1	-3.4	-3.1	-3.2	-1.9	-0.9
Dwelling Ownership	-3.9	-9.9	-3.9	-9.8	-3.9	-11.4	-5.0	-12.1
Energy Intensive Industry	10.4	11.9	10.4	3.8	10.4	0.9	2.6	-2.9
Food	0.7	-1.5	0.7	-4.0	0.7	-5.1	-0.3	-4.8
Forestry	-6.9	-8.6	-6.9	-5.8	-6.9	8.4	4.5	4.9
Livestock	-0.7	-2.8	-0.7	-6.8	-0.7	-9.5	-3.7	-8.8
Other Industry	1.8	-0.6	1.8	-1.3	1.8	-1.5	1.6	-2.3
Services	1.8	0.4	1.8	0.5	1.8	1.4	3.0	1.2

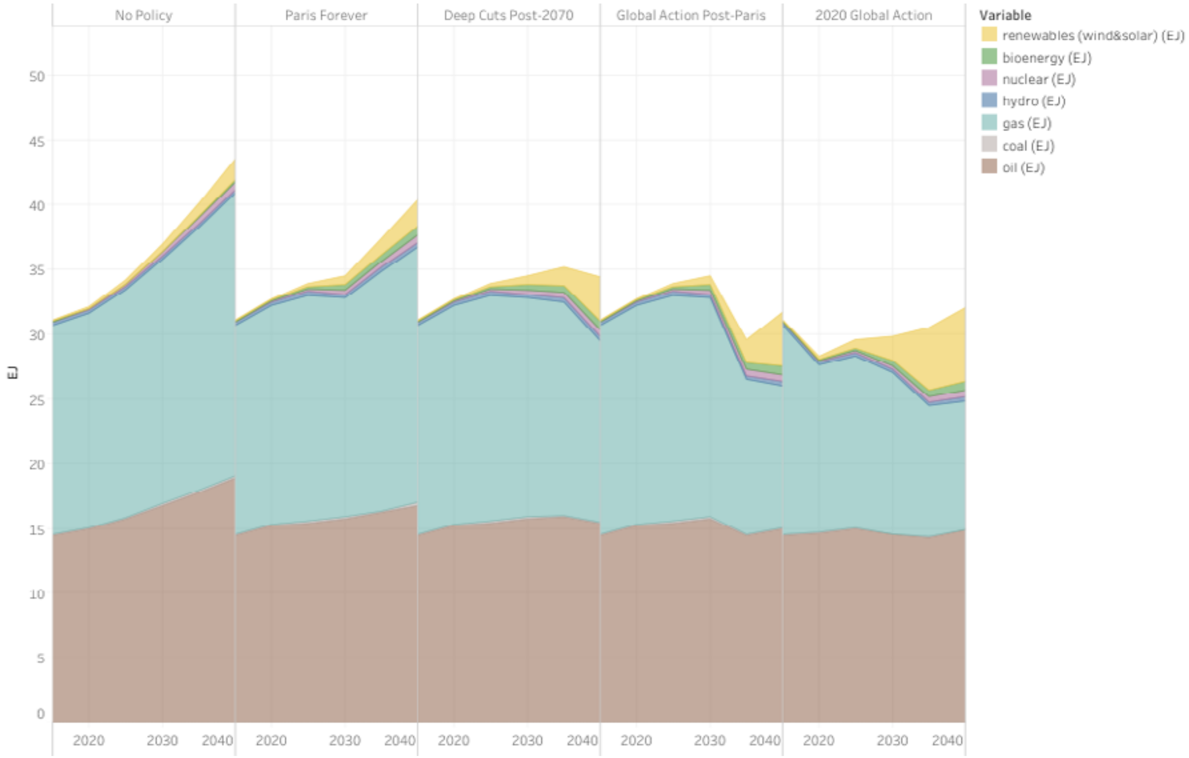

Figure G36. Primary Energy Use | Middle East

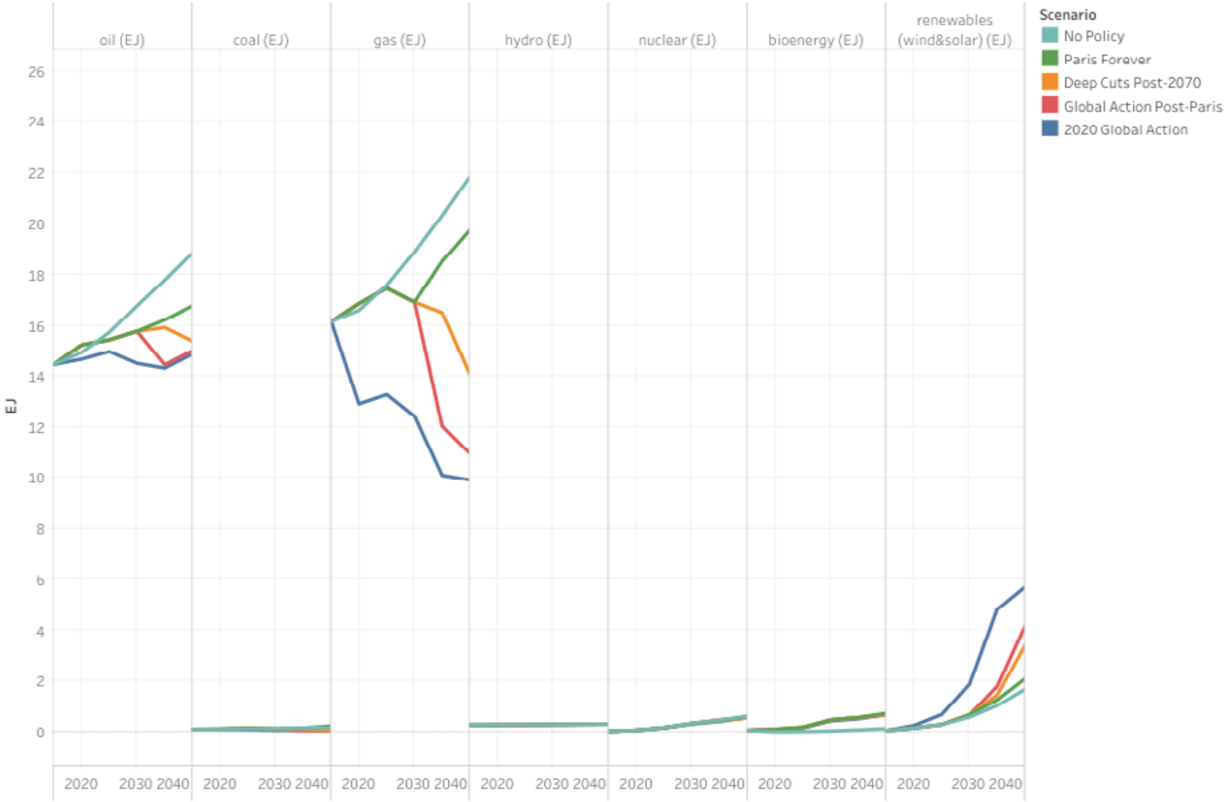

Figure G37. Primary Energy Use | Middle East

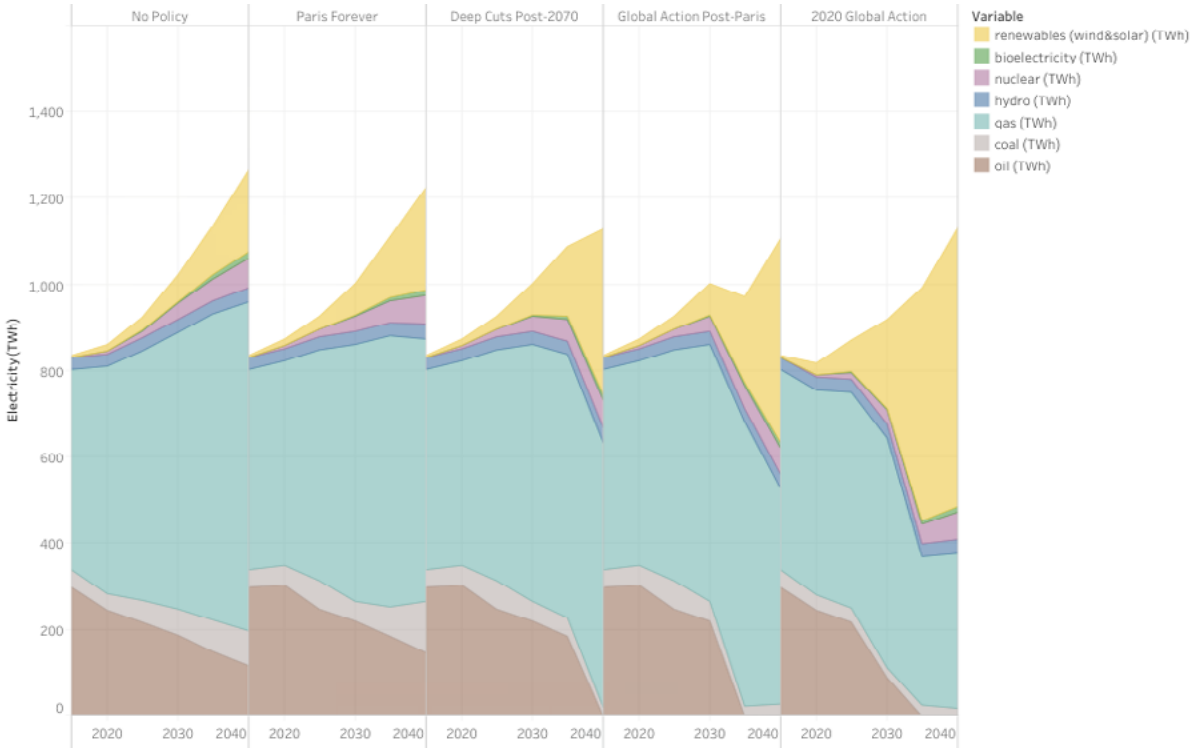

Figure G38. Electricity Generation | Middle East

Figure G39. Electricity Generation | Middle East

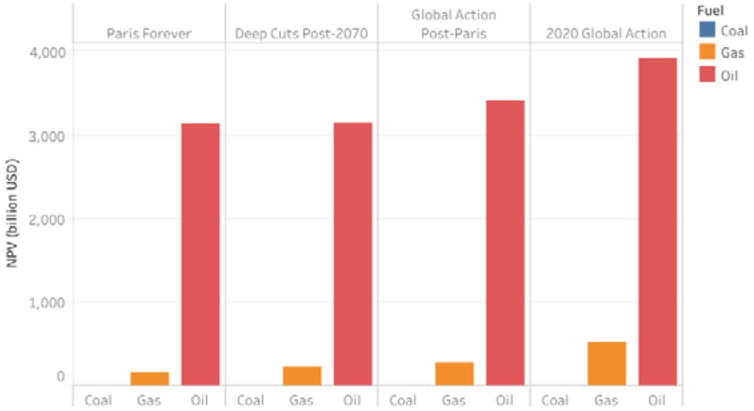

Figure G40. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* |

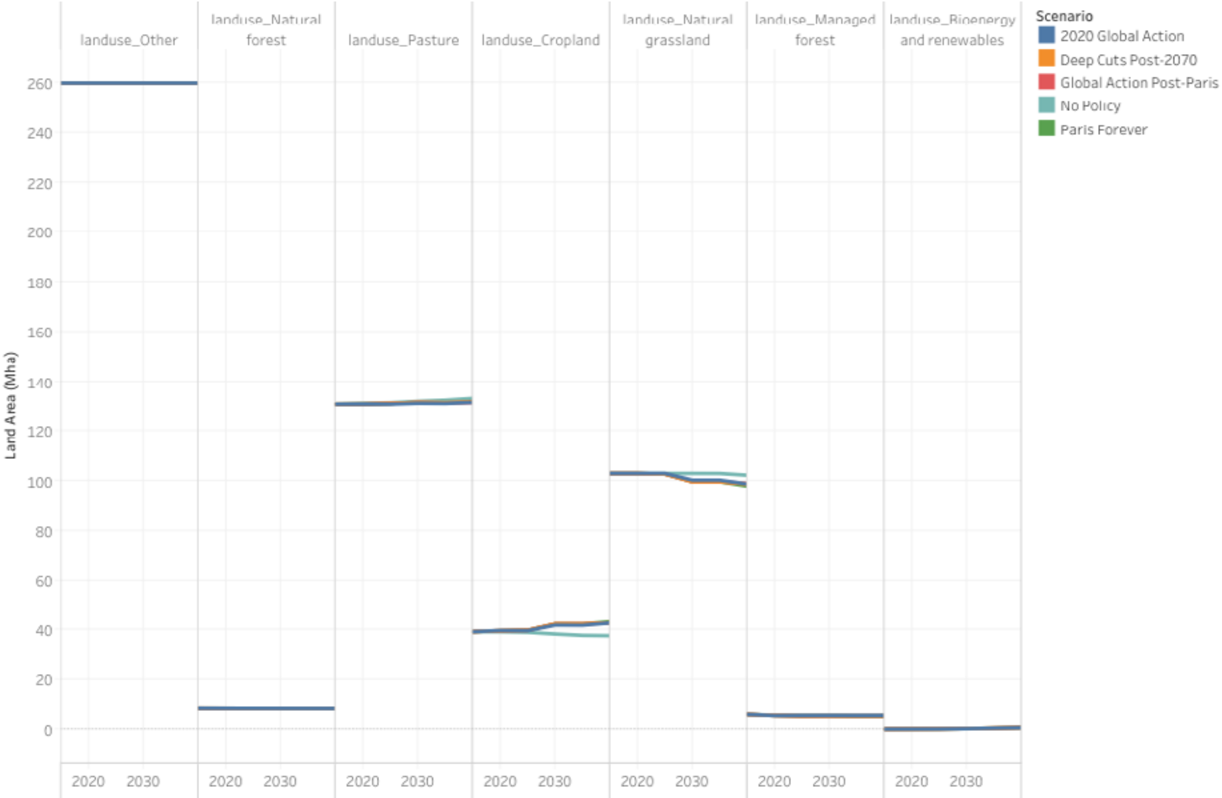

Figure G41. Land Use | Middle East

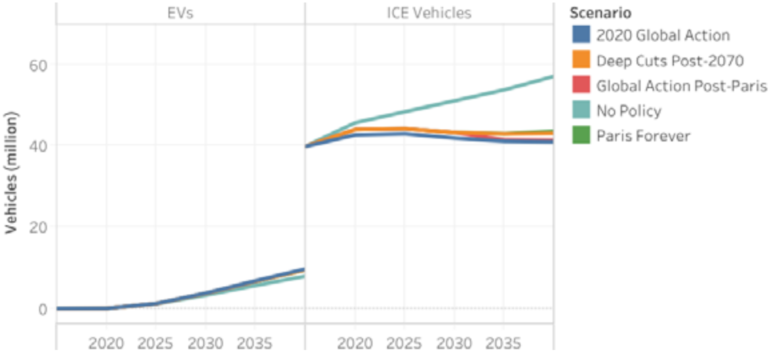

Figure G42. Household Vehicles | Middle East

Rest of the World

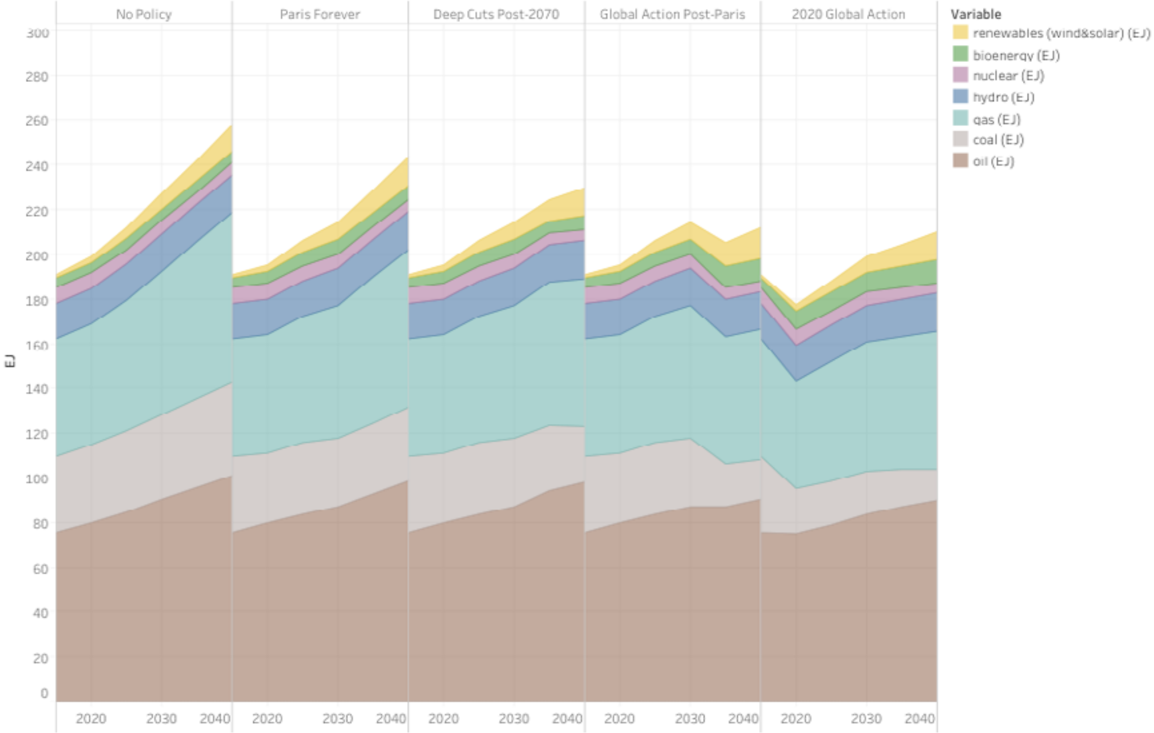

Figure G43. Primary Energy Use | Rest of the World

Figure G44. Primary Energy Use | Rest of the World

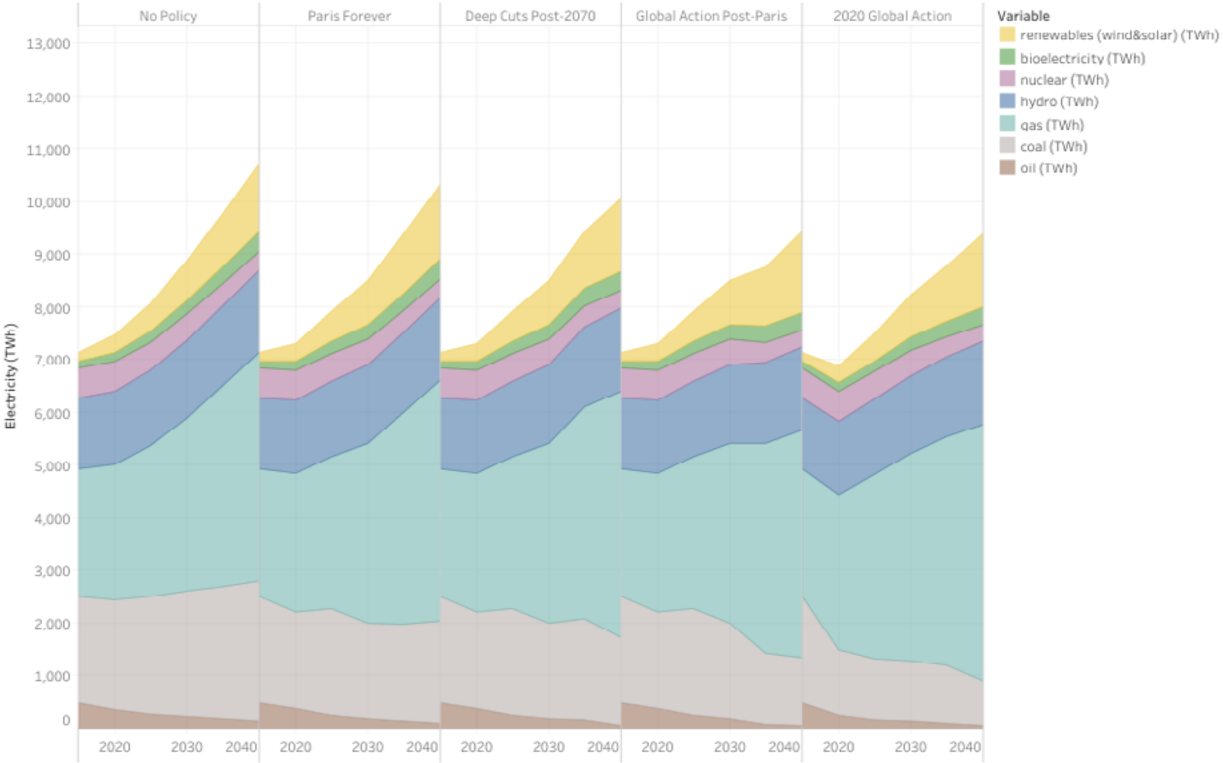

Figure G45. Electricity Generation | Rest of the World

Figure G46. Electricity Generation | Rest of the World

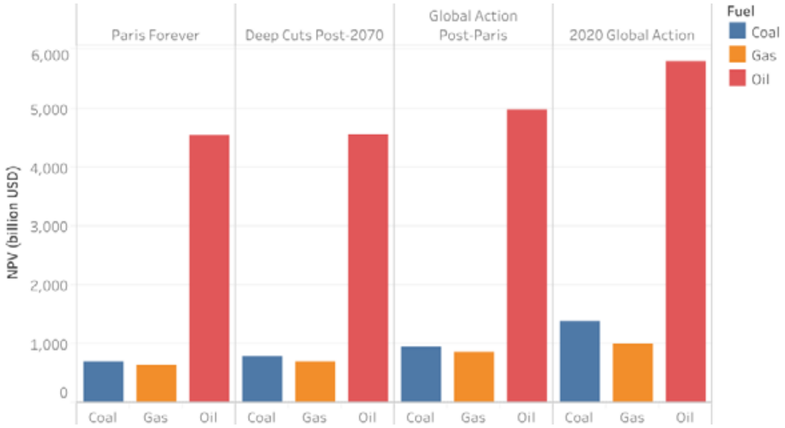

Figure G47. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* | Rest of the World

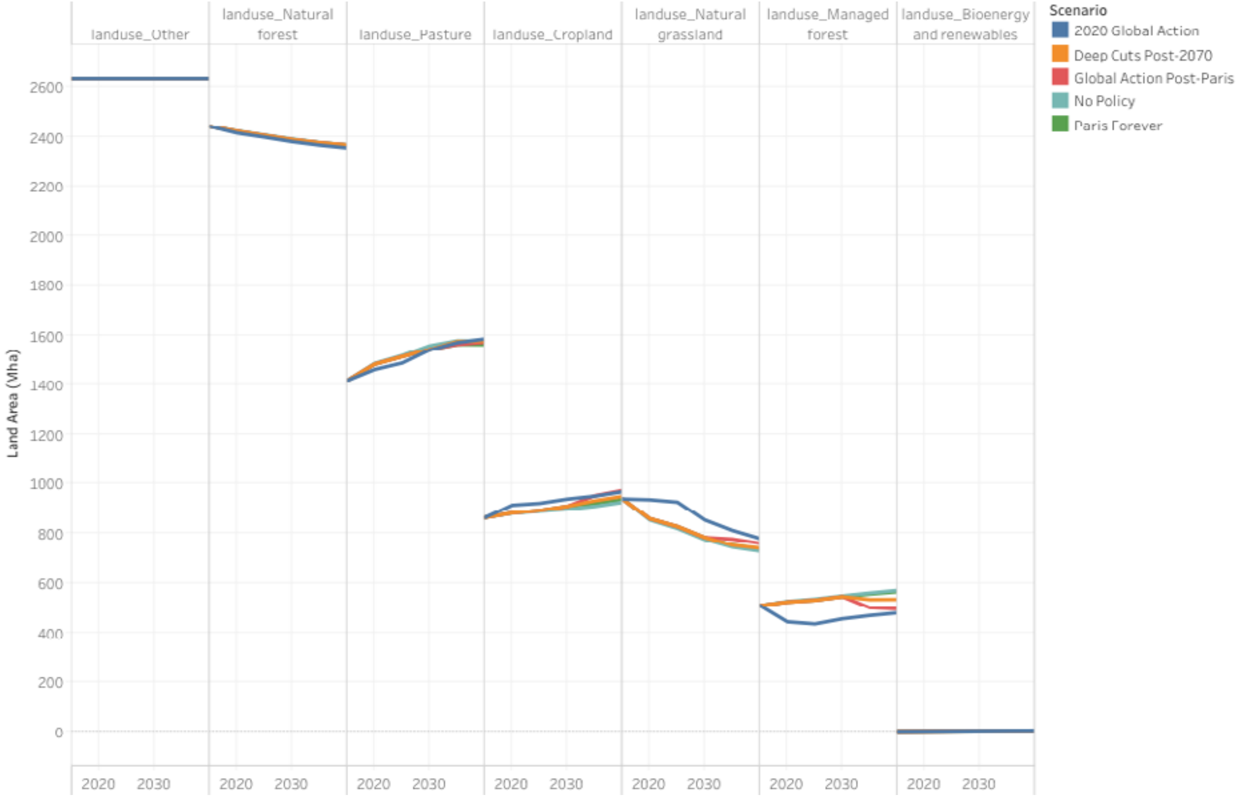

Figure G48. Land Use | Rest of World

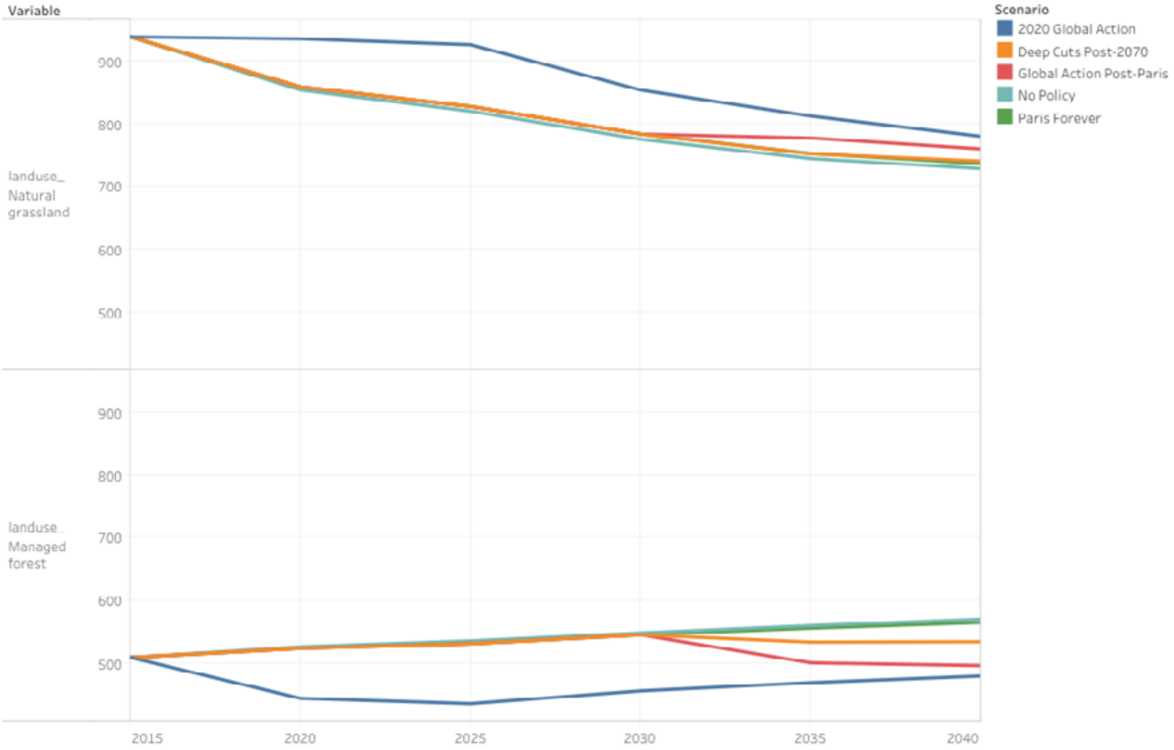

Figure G49. Land Use Transition | Rest of the World

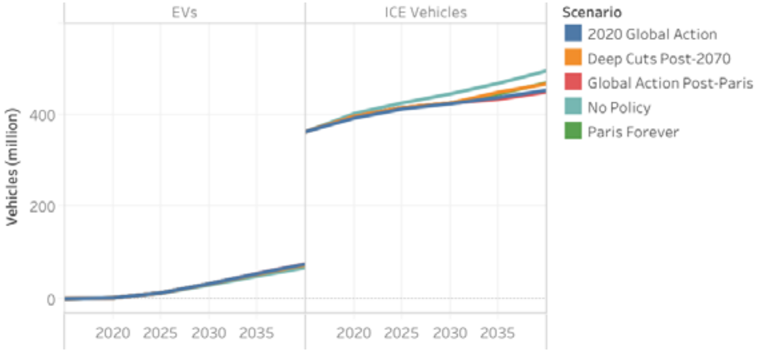

Figure G50. Household Vehicles | Rest of the World

Table G7. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | Rest of World

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-1.1	-1.9	-1.1	-2.2	-1.1	-3.9	-1.8	-3.7
Commercial Transportation	2.3	3.9	2.3	3.0	2.3	-0.1	0.2	0.5
Crops	0.8	1.9	0.8	2.0	0.8	0.4	-1.3	-0.7
Dwelling Ownership	0.0	-0.4	0.0	-0.4	0.0	-0.9	0.2	-0.6
Energy Intensive Industry	-0.1	-0.8	-0.1	-0.8	-0.1	-2.6	-1.4	-3.5
Food	-0.4	-0.7	-0.4	-0.7	-0.4	-1.9	-0.9	-1.7
Forestry	-1.7	-0.1	-1.7	-8.1	-1.7	-14.6	-12.0	-12.4
Livestock	-1.3	-1.6	-1.3	-2.5	-1.3	-5.5	-4.2	-5.3
Other Industry	-0.4	-0.8	-0.4	-0.9	-0.4	-1.7	-0.7	-1.7
Services	-0.2	-0.5	-0.2	-0.3	-0.2	-0.4	0.0	-0.3

United States of America

The first NDC of the United States offers its intention "to achieve an economy-wide target of reducing its greenhouse gas emissions by 26–28 percent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%."[56]

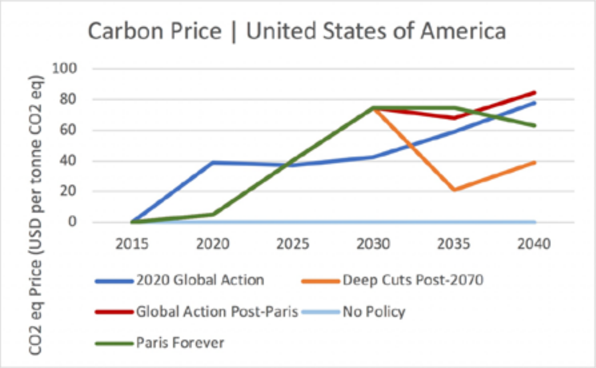

Figure G51. CO_2-eq Price | United States

Table G8. Sensitivity of Sectoral Real Output to Scenarios Relative to *No Policy* Scenario | United States

	Paris Forever		Deep Cuts Post-2070		Global Action Post-Paris		2020 Global Action	
	2025	2040	2025	2040	2025	2040	2025	2040
GDP	-0.1	-0.5	-0.1	-0.2	-0.1	-0.4	0.2	-0.1
Commercial Transportation	-1.3	-4.0	-1.3	-4.1	-1.3	-3.9	-1.1	-4.0
Crops	-8.1	-6.6	-8.1	-7.6	-8.1	-6.7	-6.1	-6.7
Dwelling Ownership	0.6	1.0	0.6	1.2	0.6	1.0	0.7	1.4
Energy Intensive Industry	-1.6	-1.8	-1.6	-1.4	-1.6	-1.3	-0.6	-0.7
Food	-1.3	-0.9	-1.3	-0.8	-1.3	-1.3	-1.0	-1.2
Forestry	1.4	0.6	1.4	0.7	1.4	1.8	2.2	1.9
Livestock	-3.6	-3.4	-3.6	-3.1	-3.6	-5.9	-3.9	-6.2
Other Industry	-0.6	-0.7	-0.6	-0.8	-0.6	-1.0	-0.9	-0.9
Services	-0.2	-0.2	-0.2	-0.2	-0.2	-0.4	-0.2	-0.2

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[56] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20States%20of%20America%20First/U.S.A.%20First%20NDC%20Submission.pdf

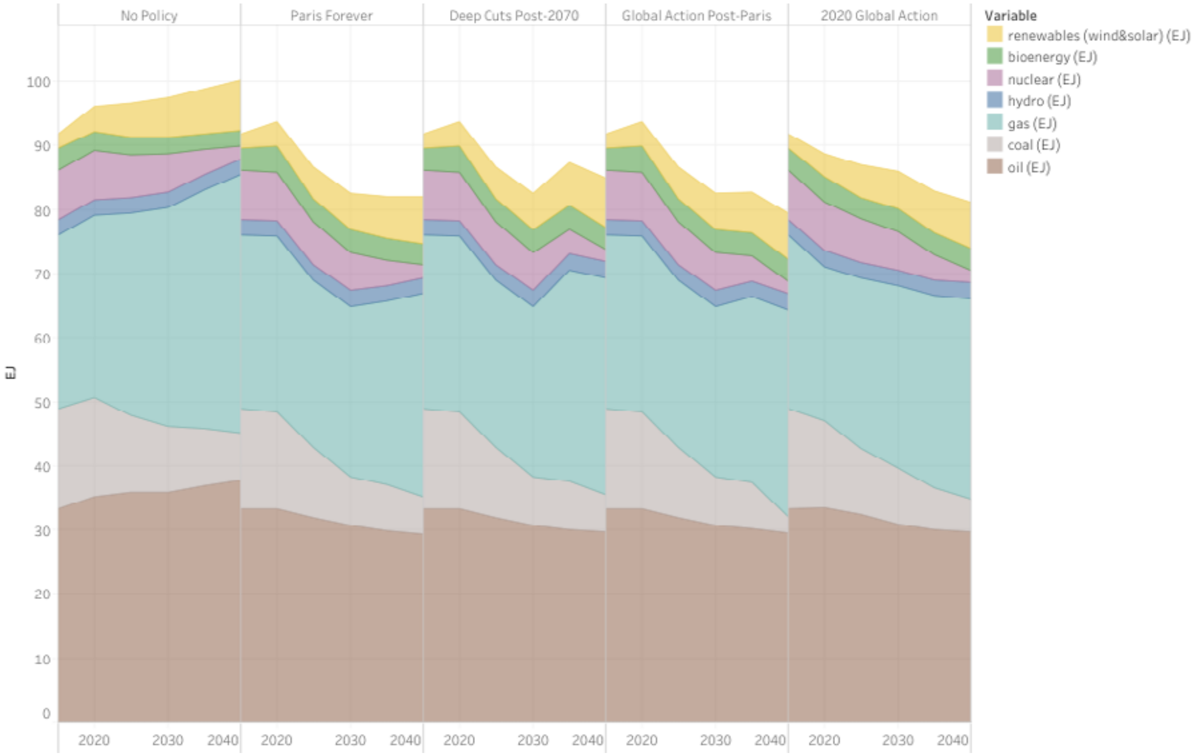

Figure G52. Primary Energy Use | United States

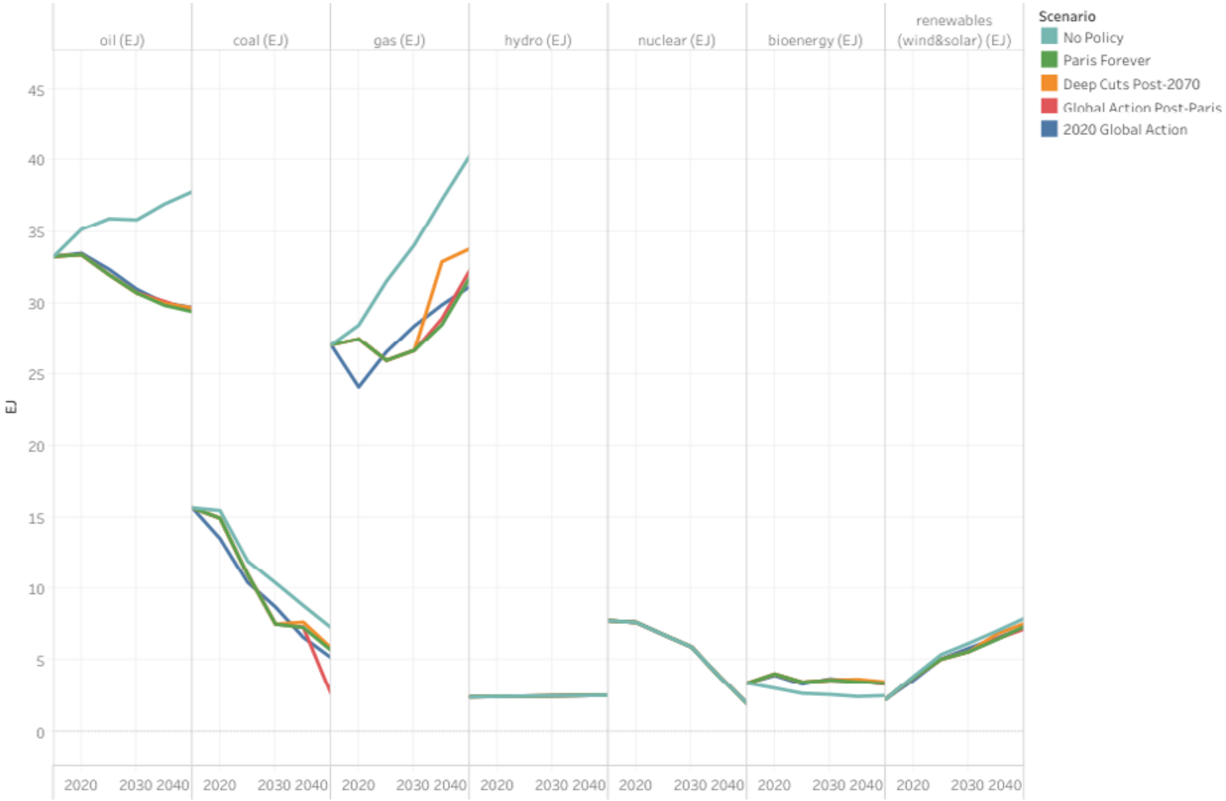

Figure G53. Primary Energy Use | United States

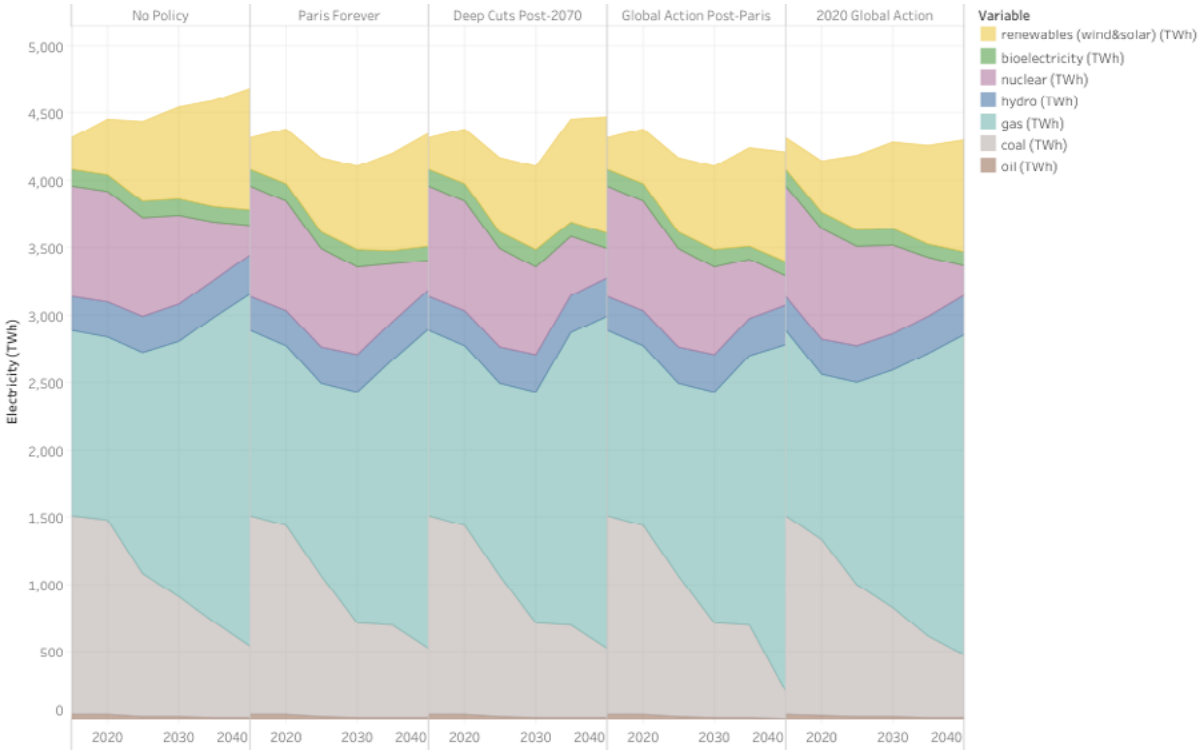

Figure G54. Electricity Generation | United States

Figure G55. Electricity Generation | United States

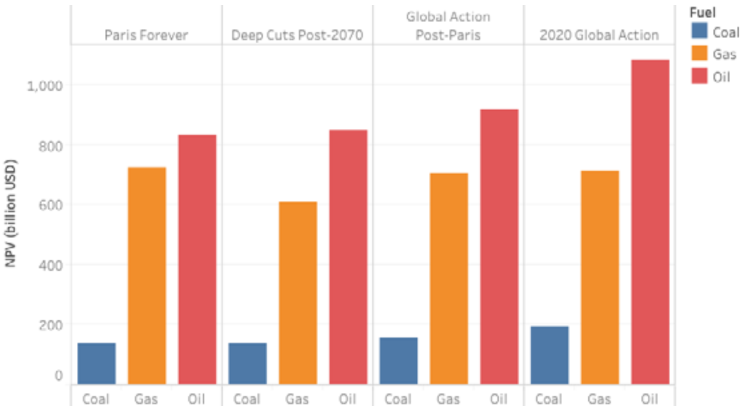

Figure G56. Stranded Assets. NPV of Economic Output Lost from Fossil Fuels Not Produced through 2040 Relative to *No Policy* | United States

Figure G57. Land Use | United States

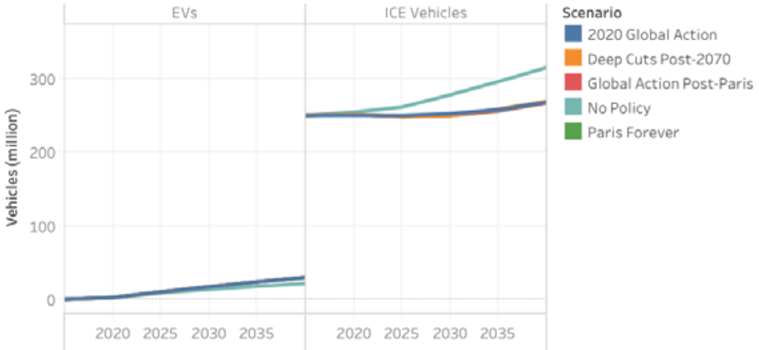

Figure G58. Household Vehicles | United States

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