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Low-Carbon Transition, Stranded Fossil Fuel Assets, Border Carbon Adjustments, and International Cooperation

**Grzegorz Peszko, Dominique van der Mensbrugghe,
Alexander Golub, and Maksym Chepeliev**

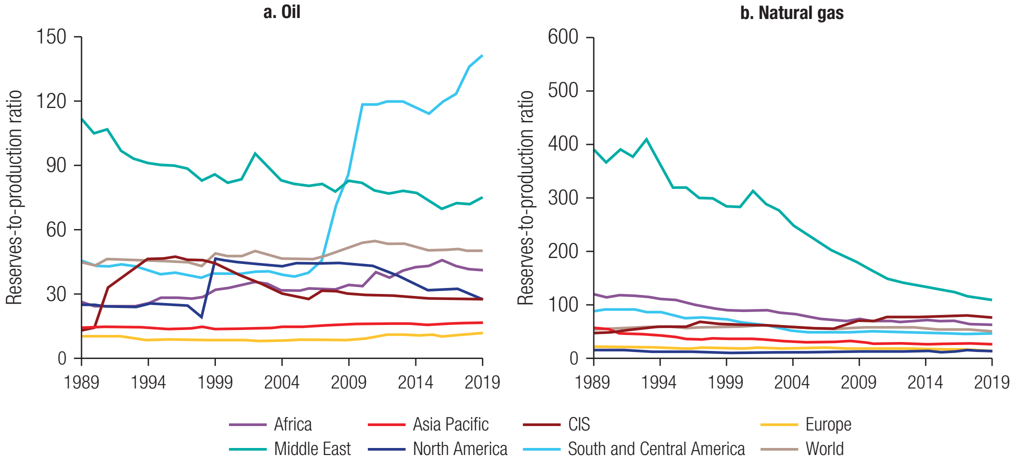
Main Messages

- A low-carbon transition represents a material risk to the value of all fossil fuel assets. In the 2018–50 period, global fossil fuel wealth may be US$4.4 trillion to US$6.2 trillion (13 to 18 percent) lower than in the reference scenario, depending on the ambition level of global climate policies.
- The distribution of risk across fuels, countries, and asset owners depends on initial conditions, such as the fuel type they depend on, costs of production, market power and exposure of the rest of the economy to this risk, and on policy pathways—whether they are cooperative or not and whether free riding will meet border carbon adjustment taxes (BCATs) or not.
- Net fuel importers have incentives to lead on climate policies and apply BCAT against fuel exporters to encourage their cooperation. Oil wealth benefits from cooperative climate action, while gas exporters may benefit from free riding and leakage, even facing BCATs. High carbon prices would significantly reduce the wealth of coal producers, whether they cooperate or not, but macrofiscal risk for coal-intensive countries is small—stranded power plants and people in mining regions are a bigger challenge.
- Lower-income, fragile, and conflict-affected fossil fuel producers may need assistance in the low-carbon transition if they have not yet converted underground energy wealth to produced capital in the manufacturing sector and have limited alternative assets (human and natural) to support growth.

Introduction

Fossil fuels will not run out anytime soon. During the past century, depletion of known oil, gas, and coal reserves has been compensated by new discoveries and progress in extraction technologies. Each time the expected scarcity pushed the resource prices up, the markets responded by accelerating technological innovation and exploration. New extraction technologies made production cheaper, bringing to markets new reserves that were previously commercially unrecoverable, such as shale oil and gas or deepwater oil fields. Over the past 30 years, the world's reserves-to-production ratios for oil and natural gas have remained fairly constant (figure 10.1).

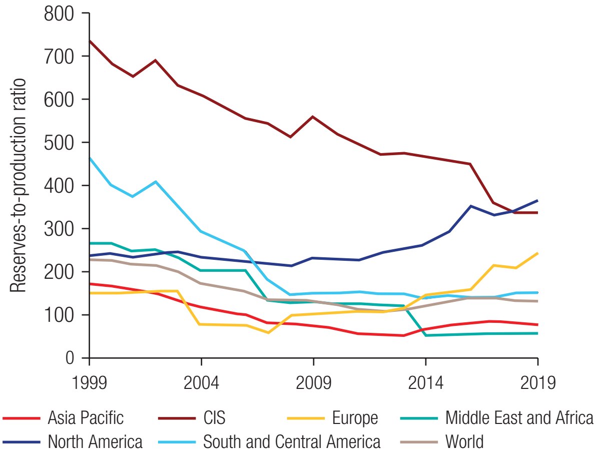
FIGURE 10.1 Reserves-to-Production Ratios for Oil, Gas, and Coal over the Past 30 Years



a. Oil

b. Natural gas

c. Coal



Source: BP 2020, 15, 33, 45. Used with permission; further permission required for reuse.

Note: BP uses the concept of "proved reserves" as "those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing conditions." CIS = Commonwealth of Independent States (Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyz Republic, Moldova, the Russian Federation, Tajikistan, Turkmenistan, and Uzbekistan).

But the planet is running out of space to burn fossil fuels. Using all known fuel reserves that can be commercially extracted under reference conditions would lead to the accumulation of greenhouse gasses in the atmosphere. There is a high probability that this would cause excessive climate-related risks (United Nations Framework Convention on Climate Change). Crucially, the world cannot rely on markets to self-correct economic activities when the concentration of greenhouse gasses in the atmosphere becomes too high in the same manner that fossil fuel prices inform investors and consumers when the fossil fuel reserves in the ground become too low. Climate change and other environmental impacts are "external" to markets. Global warming does not trigger an automatic increase in fossil fuel prices to inform economic agents that their consumption is excessive. Policies must do this job.

Government policies can put visible prices and other constraints on carbon embedded in fossil fuels and alter the market conditions for their extraction and use. Internalizing climate cost into the prices of fossil fuels would accelerate peak demand for them by encouraging substitution into alternative energy technologies. This in turn would render extraction of some reserves no longer commercially viable. Some oil, gas, and coal reserves that currently are commercially recoverable would no longer yield the expected economic benefits to their owners. Their value could drop, potentially reducing the contribution to national wealth reflected in *The Changing Wealth of Nations* (CWON).

Valuing assets is a forward-looking exercise. The value today of economic assets is an *expected* flow of future economic benefits to the owners and operators. The stranded assets literature has raised the alarm that low-carbon transition, whether induced by policies, technologies, or consumer preferences, may cut these economic benefits well short of expectations. If the goals of the Paris Agreement were to be achieved, future fossil fuel consumption would have to be much lower than in the past. But how exactly this future will unfold, when and where the policy and technology tipping points will materialize, is uncertain. This uncertainty is unfortunately deep, meaning that the probability distribution of different drivers of the value of fossil fuel assets is unknown or cannot be agreed upon among the key stakeholders who shape the future development pathways.

This chapter explores this uncertainty by stress testing the expected values of fossil fuel assets under alternative policy pathways to reach the goals of the Paris Agreement.[1] This question is not new in the literature and public debate. There are, however, a few novel contributions that this chapter aims to add to the existing knowledge. First, it explores risks to the valuation of fossil fuels in terms as closely related as possible to rigorous System of National Accounts (SNA) and System of Environmental-Economic Accounting (SEEA) accounting standards, rather than relying on assets as a metaphor. Second, it applies an economywide, global, recursive dynamic macroeconomic model rather than focusing on extractive sectors in isolation and assuming perfect foresight. Third, it applies a wider range of low-carbon transition policy scenarios than most models used in the stranded assets literature.[2] Fourth, it informs the political economy of international climate cooperation by exploring how the distribution of stranded assets across regions changes in alternative climate and trade policy scenarios.

Valuing Subsoil Fossil Fuel Assets in the CWON

Not all known and proven reserves qualify as economic assets. In the SNA, only the deposits that are commercially exploitable, given current technology and relative prices, are considered assets (EC et al. 2009). SEEA identifies three classes of known deposits, among which only "class A," commercially recoverable resources that come from on-production projects, projects approved for development, and projects justified for development, is recommended for inclusion in the balance sheets (United Nations 2019, 93). The CWON follows these recommendations in its valuation of fossil fuel reserves. In contrast, the stranded assets literature, especially the "gray" literature, often considers a much wider scope of reserves as being potentially "stranded assets," using the concept of asset as a metaphor rather than a balance sheet concept (Carbon Tracker Initiative 2011). Within the CWON/SNA approach, all known or proven recoverable reserves cannot be "stranded assets," because a large portion of them are not assets in the first place. It is uncertain whether they would be extracted and converted into economic wealth even in the reference scenario. Leaving resources in the ground is not new to extractive industries. For example, IEA (2013) shows that 60 percent of known coal reserves are left underground even in the business-as-usual scenario.

Expected returns determine asset value. The SNA and SEEA provide a recommended methodology for valuing commercially recoverable subsoil assets: the discounted sum of expected rents over the lifetime of an asset. In this approach, the asset value is determined by several factors, which can change resource rents in the future: the size of commercially recoverable reserves, the extraction path, prices, extraction costs, and interest rates. Since such forward estimates are not generally available for national accounts, the guidance from the SNA and SEEA is to assume that current or recent values for the factors that determine resource rents will remain constant into the future.[3]

The CWON core accounts apply the SNA and SEEA recommendations for the valuation of minerals and fossil fuels. Asset values are calculated with a five-year lagged average unit rent over the lifetime of the reserve of the resource or 100 years, whichever is less, and discounted with a constant 4 percent rate. For 2018, the last year for which annual resource rents were calculated, the five-year moving average covers the period of historically low fossil fuel prices following a significant drop in 2014. Therefore, constant future rents extrapolated from this five-year period are significantly lower than typically expected by resource owners. This implies that the traditional accounting methodology applied in the

CWON core accounts may lead to estimates of total fossil fuel wealth today that are somewhat conservative compared with what countries and companies are planning to realize. Even those conservative estimates help identify some fossil fuel wealth at risk across different fuels, regions, and countries. Furthermore, comparison of alternative policy scenarios with the reference policy pathway that is consistent with nationally determined contribution (NDC) commitments finds significant losses of fossil fuel wealth globally.

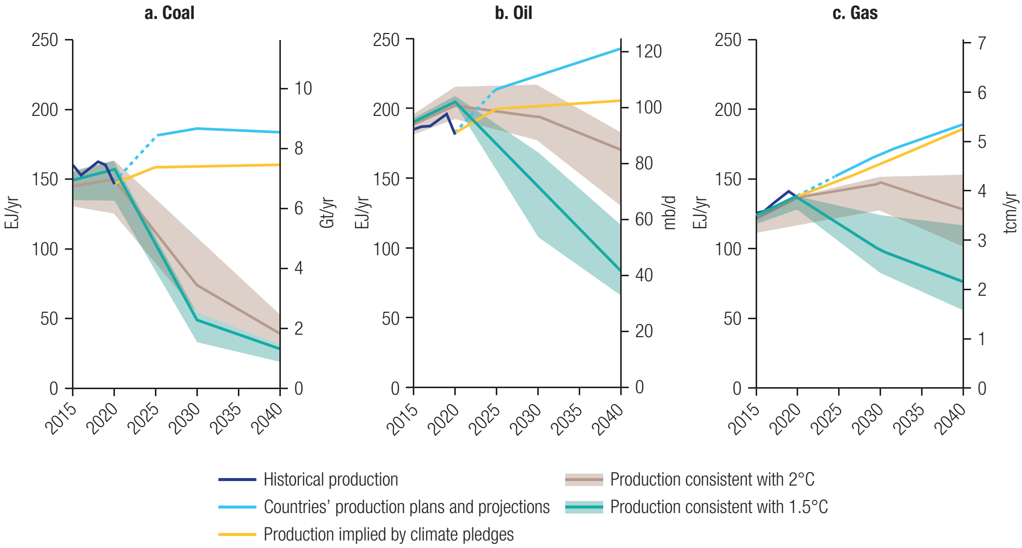
The historical values of oil, gas, and coal rents were calculated using multiple sources cross-checked for consistency. The value of national oil and gas reserves for 146 countries was compiled from the field-level data extracted from the Rystad database for production costs. Rystad was also used to calculate rental rates—unit price minus unit cost divided by unit price—with fossil fuel prices taken from the World Bank Commodities Price Data. Extraction data are from Rystad, the International Energy Agency (IEA), *BP Statistical Review of World Energy*, the US Energy Information Administration (EIA), and the United Nations *Monthly Bulletin of Statistics*. Proved reserves were taken from the *BP Statistical Review of World Energy* and the EIA.[4]

The CWON approach to valuing fossil fuel assets is a useful starting point for national balance sheets, but to understand the potential impacts of climate mitigation measures on the future of fossil fuel rents, it is not enough to assume that all the factors determining asset value remain constant. Therefore, this chapter complements the CWON core account estimates with model simulations of alternative profiles of future rents that may accrue to fossil fuel owners under the uncertain policy pathways of the low-carbon transition.

Valuation of Fossil Fuel Assets with the ENVISAGE v10 CGE Model

The uncertainty about the policy pathways to a carbon-neutral global economy and the tipping points for fossil fuels is *deep*. Expectations of different actors differ fundamentally, so—in technical terms—a probability distribution cannot be assigned to different future values of fossil fuel assets, because it is unknown or cannot be agreed by relevant stakeholders. The projections of production volumes, prices, and costs differ dramatically even for 2025 and 2030 (figure 10.2). Given the uncertainty about the future of fossil fuels, fewer and fewer organizations focus on projecting or forecasting future demand. Those who still do include the Organization of the Petroleum Exporting Countries and the EIA. Most, including the IEA and oil majors, have instead switched to foresights or scenarios for "exploring different possible futures, the levers that bring them about and the interactions that arise across a complex . . . system" (IEA 2018, 23). Developing several exploratory scenarios based on the plausible narratives about the future drivers of resource rent is the simplest way to inform decisions under such deep uncertainty (Ansari and Holz 2020; Peszko et al. 2020) and is applied in this study.

FIGURE 10.2 Fossil Fuel Production Gap: The Difference between National Production Plans and Low-Carbon (1.5°C and 2°C) Pathways, 2015–40



Source: SEI et al. 2020, 15.
Note: EJ = exajoules; Gt = gigatons (billion tons); mb/d = million barrels per day; tcm = trillion cubic meters; yr = year. Physical units are displayed on the secondary axes.

This chapter presents simulations of the values of oil, gas, and coal assets under alternative policy scenarios that can help reach the main goal of the Paris Agreement. The model is run in simulation and not optimization mode. This means that no particular emissions pathways or carbon budgets are assumed as constraints in the model. Instead, several cooperative and noncooperative carbon tax trajectories are run. The highest carbon taxes for which the model could find a solution for all policy scenarios produced cumulative carbon dioxide (CO_2) emissions (carbon budget) of 862 gigatons (Gt) of gross CO_2 emissions over 2018–50. Because (as expected from economic theory) the model could achieve deeper decarbonization with cooperative taxes only, next—as a sensitivity analysis—several iterations are run with higher cooperative carbon taxes. The cumulative gross emissions associated with the highest carbon tax trajectory for which the model could solve was 777 Gt CO_2 over 2018–50. Optimization approaches to scenarios that are dominant in the literature use a much wider variety of carbon budgets and emissions pathways (see Huppmann et al. 2019; Rogelj et al. 2019; Rogelj, Popp, et al. 2018; Rogelj, Shindell, et al. 2018 for more results).

The section on emissions results compares carbon budgets produced with the policy simulation approach to carbon budgets assumed or produced with the optimization approach available in the literature. It shows that the cumulative emissions produced by the scenarios are in line with the carbon budget used in the 2 degrees Celsius (°C)–consistent mitigation pathways and even some 1.5°C-consistent scenarios found in literature related to the Intergovernmental Panel on Climate Change (IPCC). The scenarios are simulated using the global, recursive, dynamic computable general equilibrium (CGE) model ENVISAGE v10 integrated with a dynamic and detailed resource depletion module calibrated to the global oil and gas extractive model Rystad UCube. The ENVISAGE model (van der Mensbrugghe 2019) is based on the Global Trade Analysis Project Power 10 database, containing a consistent set of social accounting matrices and energy balances for 141 world regions (Aguiar et al. 2019; Chepeliev 2020). The recursive and dynamic nature of the ENVISAGE v10 model used in this study represents decision-making in a dynamic setting under imperfect foresight. Such an approach allows accumulation of vulnerable capital stock based on the reference market conditions and expectations before the policy or technology shocks occur. Few stranded asset studies allow for myopic expectations and even fewer simulate dynamic, path-dependent processes (Mercure et al. 2018; Peszko, van der Mensbrugghe, and Golub 2020; Van der Ploeg and Rezai 2019).

The CGE perspective captures the economywide feedback loops and adjustments across sectors of the economy rather than just the direct impact in extractive industries and carbon-intensive sectors. Studies based on partial equilibrium or bottom-up models, prevailing in the stranded assets literature, do not capture these economywide spillover effects and feedbacks. They count capital released from industries affected by climate policy as fully stranded, while the general equilibrium framework more realistically allows a portion of this capital to be recycled into other sectors and still be productive.

For the purpose of this study, ENVISAGE was equipped with an endogenous oil, gas, and coal extraction module. This module includes three categories of oil, gas, and coal reserves: (1) unproven reserves, (2) proven reserves, and (3) the fraction of proven reserves that is brought to production if market conditions allow. The model mimics interactions between the fossil fuel supply and demand, which ultimately drives the production from fossil fuel reserves and market prices of fuel commodities. In unfavorable market conditions for a country (low demand and prices or high extraction costs), the extraction module suppresses production from its proven reserves, leaving some of them in the ground. When market conditions for this country become favorable, the module increases production of its previously underexploited proven reserves (if any) and converts some of its unproven reserves to proven ones. The supply and depletion functions have country-specific elasticities.

This model did not use induced technology progress through expenditures on research and development, as in Peszko, van der Mensbrugghe, and Golub (2020). As shown there, it could have a major impact on fossil fuel asset value in both directions, depending on how the public expenditure is targeted (to subsidize fuel use or innovation). Green technology policies are mimicked by the set of learning curves and preference parameters that were set in all scenarios (including the reference scenario) to accelerate the rates of penetration of clean technologies in the power, industry, and transport sectors.

The oil, natural gas, and coal rents are calculated endogenously in ENVISAGE. The resource rent is what is paid to the "flow" of the natural resource as it is transferred from the ground into the economy. In keeping with SEEA/SNA and CWON principles, unit resource rents are the difference between the market price and all variable costs—intermediate inputs, labor, and normal profits. Because ENVISAGE was calibrated to 2014, the asset values in 2018 that are calculated by the model deviate from those estimated in CWON for 2018. To facilitate comparison of results, the trajectory of rents attributed to oil, gas, and coal assets from ENVISAGE is normalized to the corresponding 2018 rent values estimated in the CWON and used to simulate the changes in resource rents over time. This method combines the comparative advantage of the CWON/SEEA methodology in estimating asset values in the past with the comparative advantage of the modeling approach to simulate alternative futures. Further details on ENVISAGE can be found in the underlying CWON technical report and online.[5]

Simulation of Subsoil Fuel Asset Values under Uncertainty

The goal of model simulation is not to predict the future value of the fossil fuel assets but to explore a range of alternative plausible policy futures. A set of exploratory scenarios represents uncertainty about how the key drivers of asset values will evolve. The simplest way to represent deep uncertainty is to build alternative scenarios from several combinations of a range of potential external impacts and strategic national policy choices. Constructing a range of future scenarios provides an opportunity to identify policy and asset management decisions that make the portfolio value robust to external shocks under the plausible worst-case futures. For clarity of argument, the range of scenarios has been limited and does not pretend to represent all plausible futures. A wider range of policy pathways to a low-carbon transition can be found in Mercure et al. (2018); Peszko, van der Mensbrugghe, and Golub (2020); and Van der Ploeg and Rezai (2019). The worst-case scenarios simulated were identified by ramping up the level of ambition of cooperative and noncooperative climate policies, respectively, until the CGE model could find an equilibrium solution. This can be interpreted as the numerical limit of the current model specification or the limits to the growth-focused neoclassical economics.

This study focuses on the distribution of risk to fossil fuel wealth across fuels and country groups and explores whether this distribution depends on the policy pathways to a low-carbon economy. Such a focus can inform the political economy of international cooperation on climate change. A set of unique narratives has been developed to underpin scenarios of alternative policy pathways toward the goals of the Paris Agreement. These narratives stress two critical dimensions of low-carbon transition: (1) whether it will be smooth and cooperative or disorderly and unilateral, and (2) whether noncooperation will be punished by border carbon adjustment measures or not. These narratives were first elaborated in Peszko et al. (2020) and were tailored specifically for this chapter to be simulated with the updated and enhanced ENVISAGE v10 and its new extraction module. The narratives are broadly consistent with the Network for Greening the Financial System scenarios for transition risk (NGFS 2020).

In the climate policy scenarios, the value of stranded assets (net present value of resource rents produced endogenously in the model) is calculated as the difference in the asset values against the reference scenario rather than against the CWON. Many investors and asset owners expect that future fossil fuel prices will be higher than those prevailing over 2014–18, which are used in the CWON for rent extrapolation. The more recent price shock caused by the COVID-19 lockdowns is not expected to keep fossil fuel prices low for too long. Therefore, asset owners often consider most of their economically proven but not yet commercially recoverable reserves as assets—more than could be put on the national balance sheet by conservative SNA standards. The asset owners expect that a large share of these proven reserves will be brought into production in the future and will generate rents. The reference scenario that assumes adherence to climate mitigation commitments officially pledged by countries through their NDC submissions better reflects such expectations than the CWON with its constant extraction and rent profile. It is common that national statistical offices assign lower values to national fossil fuel reserves in government balance sheets compared with the more wishful thinking of extractive companies and other agencies that exercise ownership rights over fossil fuel reserves. The policy scenarios simulated here represent surprise policy shocks that diverge fossil fuel prices and volumes away from those expected in the reference scenario and, hence, change the rent profiles compared with those expected by fuel owners. Sometimes the resulting rents (for example, for coal) are even below those that a conservative accountant would put into the national balance sheet from the CWON accounts.

Countries and Country Groups

For simulation purposes, the countries were aggregated into two stylized climate policy “clubs”: (1) *climate policy leaders (CPLs)*, the members of which are assumed to be the likely primary movers of climate mitigation policies, and (2) *fossil fuel–dependent countries* (FFDCs), which choose to cooperate with CPLs on climate mitigation or free ride on their policy effort, risking BCATs. The results are reported for eight subgroups (table 10.1). The full list of countries in each category can be found in the background technical paper (Peszko et al. 2021).

Fossil fuel wealth is highly concentrated. As much as 80 percent of the global fossil fuel wealth, reaching US$26 trillion in 2018, is in three country groups: Middle East and North Africa (MNA); Europe and Central Asia (ECA); and the coal-intensive middle-income fuel importers, including China and India (figure 10.3). MNA itself accounts for over 50 percent of the world’s total fossil fuel wealth.

Countries depend on fossil fuels in many ways. Countries are also differently prepared for the impacts of low-carbon transition (see Peszko

TABLE 10.1 Climate Clubs

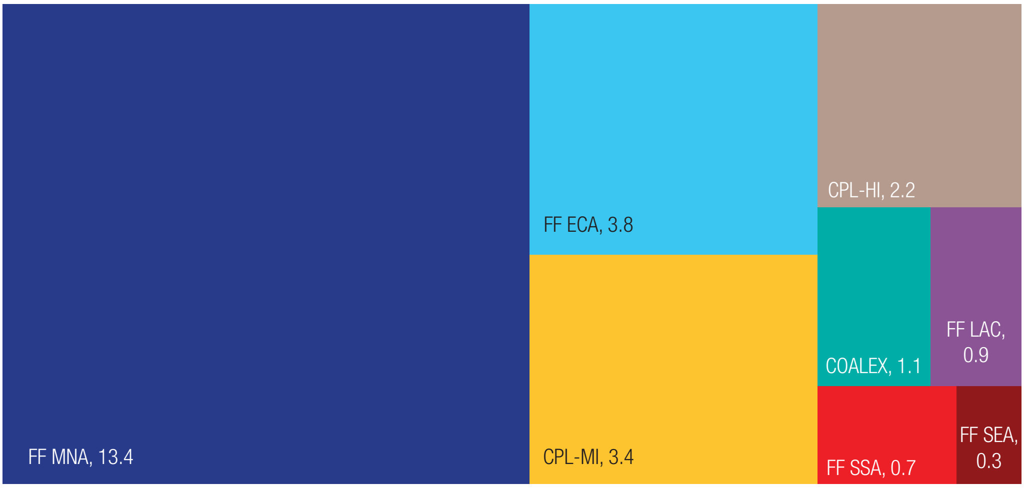
Climate policy leaders (CPLs)	Fossil fuel–dependent countries (FFDCs)
1. CPL-HI: high-income countries in the European Union, Canada, Norway, the United States, and other high-income fossil fuel importers 2. CPL-MI: low- and middle-income fossil fuel importers and often large coal users, including middle-income and lower-middle-income countries, such as Argentina, Brazil, Cambodia, China, India, the Lao People's Democratic Republic, Pakistan, the Philippines, Thailand, Turkey, Ukraine, and many others	3. FF MNA (Saudi Arabia + GCC + rest of oil and gas exporters in MNA) 4. FF ECA (Russian Federation + Caucasus and Central Asia) 5. FF SSA (Sub-Saharan Africa) 6. FF LAC (Latin America and the Caribbean) 7. FF SEA (Southeast Asia) 8. COALEX (coal exporters: Australia, Colombia, Indonesia, Mongolia, and South Africa)

Source: World Bank.

Note: ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); GCC = Gulf Cooperation Council; HI = high-income; LAC = Latin America and the Caribbean; MNA = Middle East and North Africa; SEA = Southeast Asia; SSA = Sub-Saharan Africa.

FIGURE 10.3 Value of Fossil Fuel Subsoil Assets, by Region, 2018

2018 US$ (trillions)

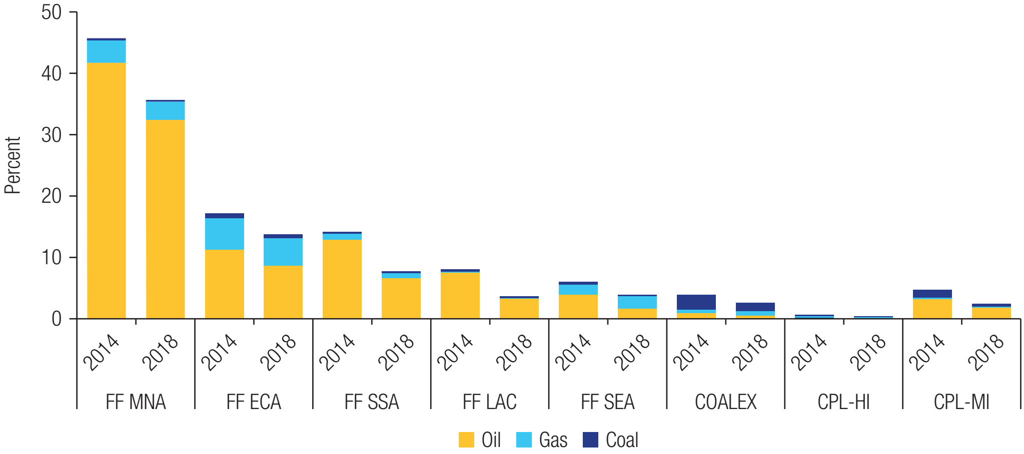


Source: World Bank staff calculations, http://www.worldbank.org/cwon/.

Note: COALEX = coal exporters; CPL = climate policy leaders; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income; LAC = Latin America and the Caribbean; MI = low- and middle-income; MNA = Middle East and North Africa; SEA = Southeast Asia; SSA = Sub-Saharan Africa.

et al. [2020] for the index of preparedness for low-carbon transition). Figure 10.4 uses the CWON database to illustrate that, in the eight country groups, the share of fossil fuel wealth in total wealth in the FFDCs is higher than in the net fuel importers that are assumed to be the global CPLs. Oil accounts for the lion's share of total fossil fuel wealth and is the major source of systemic risk in the most fossil fuel–dependent countries. Gas plays a disproportionate role in the wealth of ECA. Coal is always a small part of total wealth and accounts for the

FIGURE 10.4 Share of Fossil Fuel Assets in Total Wealth in the CWON Core Accounts, by Country Group, 2014 and 2018



Source: World Bank staff calculations, http://www.worldbank.org/cwon/.

Note: COALEX = coal exporters; CPL = climate policy leaders; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income; LAC = Latin America and the Caribbean; MI = low- and middle-income; MNA = Middle East and North Africa; SEA = Southeast Asia; SSA = Sub-Saharan Africa.

large share of total fossil fuel wealth in only two country groups—coal exporters and middle-income CPLs (mainly China and India). In all the country groups, the relative importance of fossil fuel wealth decreased after the 2014 fossil fuel price shock.

Scenario Analysis to Represent Risk and Uncertainty

The reference scenario assumes that countries will implement their unconditional NDCs, followed by four policy scenarios with assumptions about alternative climate and trade policy pathways to low-carbon transition (table 10.2). Climate policies are represented by economywide carbon taxes (shadow carbon prices) with rates calibrated to reach the goals of the Paris Agreement. The cumulative gross emissions of CO_2 in the modeling period calculated by the model are shown in the last column of table 10.2. They are gross, because they do not include unproven climate mitigation methods, such as carbon capture and storage (CCS) on fuel combustion installations, CO_2 removal (CDR) methods (so-called negative emissions), or geoengineering. Non-CO_2 gasses are also not included. After correcting for the impacts of these assumptions, the cumulative emissions produced by the core bundle of policy scenarios (numbers 1, 2, and 3 in table 10.2) are in line with the carbon budget used in the 2°C-consistent IPCC mitigation pathways and cooperative scenario number 4, even for some 1.5°C-consistent IPCC mitigation pathways.

TABLE 10.2 Structure of Low-Carbon Transition Scenarios

Scenario	Climate policies	Trade policies	Resulting carbon budget, 2018–50[a]
NDC (reference)	Reference with unconditional NDC pledges[b]	No border carbon taxes	1,362 Gt CO_2
1. COOP	Global cooperative carbon taxes	No border carbon adjustment	862 Gt CO_2
2. UNILAT	Unilateral carbon taxes in CPLs	No border carbon adjustment	
3. UNI-BCAT		Border carbon adjustment taxes levied by CPLs on carbon content of imports from FFDCs	
4. COOP<<2C	High global cooperative carbon taxes	No border carbon adjustment	777 Gt CO_2

Source: World Bank staff calculations.

Note: CO_2 = carbon dioxide; COOP = cooperative carbon tax implemented by all countries, including CPLs and FFDCs; COOP<<2C = a more ambitious cooperative sensitivity scenario; CPLs = climate policy leaders; FFDCs = fossil fuel–dependent countries; Gt = gigaton; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

a. Gross cumulative CO_2 emissions during 2018–50.

b. NDC commitments are assumed to continue at the current level of ambition until 2050.

In the cooperative scenarios (COOP), all countries, including FFDCs, implement domestic carbon prices with the same rates (figure 10.5, panel a). FFDCs' cooperation allows most CPLs to apply lower carbon tax rates than in unilateral scenarios (UNILATs). The standard cooperative scenario and both unilateral policy scenarios are calibrated to have the same cumulative CO_2 emissions.

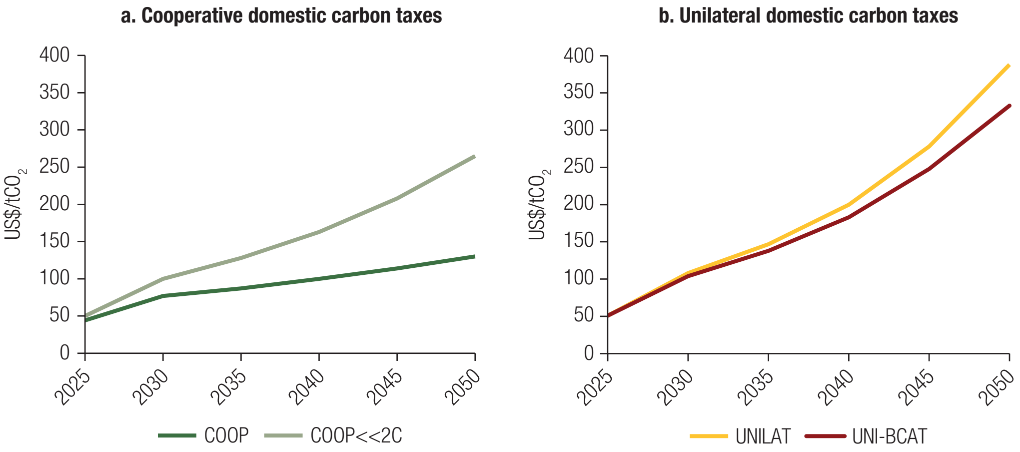
In unilateral policy scenarios, CPLs are assumed to implement unilateral carbon taxes on domestic CO_2 emissions, ramping them up steeply between 2025 and 2030 and at a slightly slower rate from 2030 to 2050. FFDCs are assumed not to increase their domestic carbon prices beyond their near-zero historical trends (figure 10.5, panel b), hence free ride on the ambitious climate action of CPLs.

In one unilateral policy scenario (UNI-BCAT), CPLs apply a BCAT on the carbon content of imports from noncooperating FFDCs. Border carbon taxes applied by CPLs have the same rates as their domestic carbon taxes. Producers try to pass through domestic carbon taxes and border carbon taxes to final consumers subject to competitive market conditions and price elasticities of intermediate and final demand for goods and services downstream in the fossil fuel value chains.

COOP, UNILAT, and UNI-BCAT scenarios are calibrated to result in cumulative gross CO_2 emissions of 862 Gt CO_2 between 2018 and 2050, which is in the range of the mitigation pathways consistent with the 2°C warming goal of the Paris Agreement.

Sensitivity analysis was conducted with a more ambitious cooperative scenario (COOP<<2C). The model was pushed to simulate as high carbon taxes as it was possible for ENVISAGE to find a cooperative equilibrium

FIGURE 10.5 Cooperative and Unilateral Domestic Carbon Taxes, 2025–50



Source: World Bank staff calculations.

Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders (CPLs) and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes; US$/t$CO_2$ = US dollars per metric ton of carbon dioxide.

solution. It resulted in cumulative gross CO_2 emissions of 777 Gt CO_2 in the period, consistent with the goal of limiting global warming to well below 2°C (even several IPCC 1.5°C scenarios). In unilateral scenarios, the model could not find equilibrium with higher carbon taxes and correspondingly lower carbon budget consistent with mitigation pathways well below 2°C. This may be the result of a limitation of the model or because the neoclassical economic theory, on which it is based, is not well suited to handle such policy shocks.

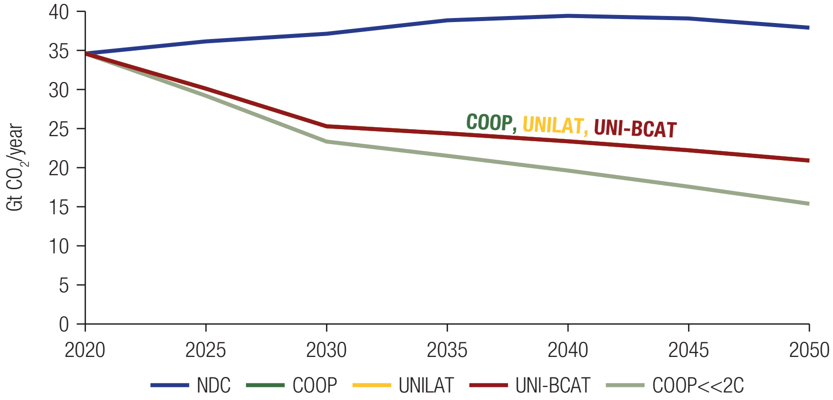
Simulation Results

Gross CO_2 Emissions

In all the climate policy scenarios consistent with limiting global warming to less than 2°C, cooperative or not, annual global gross CO_2 emissions have a similar downward trajectory (figure 10.6). They all reach cumulative gross emissions of 994 Gt of CO_2 between 2014 and 2050 (862 Gt in the 2018–50 period). In the more ambitious cooperative scenario, with higher carbon taxes, emissions drop at a faster rate, reaching a cumulative carbon budget of 909 Gt (777 Gt) of CO_2 in these periods, respectively.

This version of ENVISAGE calculates gross cumulative CO_2 emissions until 2050 and does not include CCS on fuel combustion installations or CDR methods. CDRs typically cover negative emissions from bioenergy with carbon capture and storage; the sequestration potential of

FIGURE 10.6 Profile of Global Gross CO_2 Emissions, 2020–50



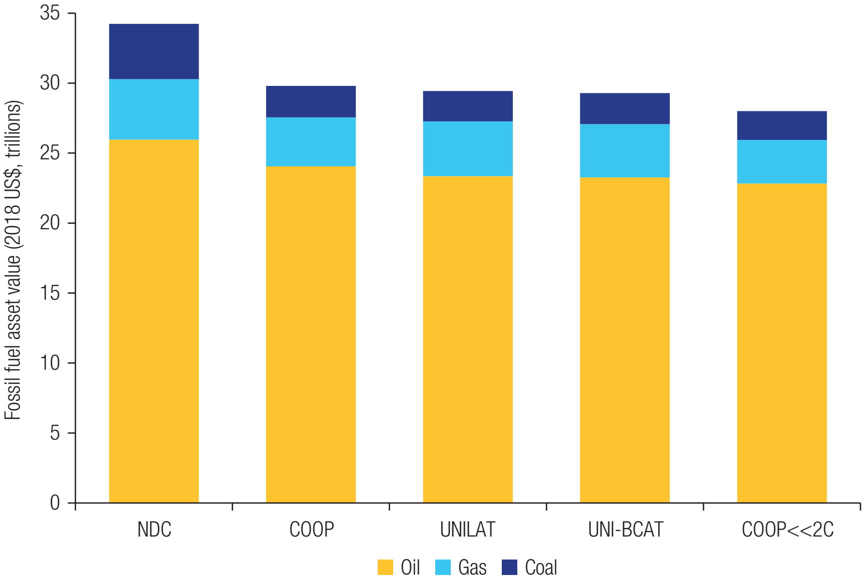
Source: World Bank simulations with ENVISAGE.
Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders (CPLs) and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; Gt CO_2 = gigatons of carbon dioxide; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

agriculture, forestry, and other land use sectors; or direct air capture. The IPCC says that overall CDR deployment over the 21st century is substantial in most of the 1.5°C-consistent mitigation pathways, ranging from 100 Gt CO_2 to more than 1,000 Gt CO_2, not counting CCS potential (Rogelj, Shindell, et al. 2018). Most of this potential is expected to be deployed in the second half of the century. Rogelj, Shindell, et al. (2018) provide a multimodel comparison of climate mitigation policies that are consistent with the 1.5°C goal. In the supplementary materials, they report lower and higher estimates of 2016–50 carbon budgets consistent with different shared socioeconomic pathways (minimum–maximum, all in Gt CO_2): SSP1 (525–1,025), SSP2 (625–850), and SSP5 (875–900). With total gross CO_2 emissions of around 840 Gt (over 2016–50) in the COOP<<2 scenario, this is below the maximum boundary of the 1.5C° target for all shared socioeconomic pathways. The model in this chapter does not have CCS/CDRs, while all the models reported in Rogelj, Shindell, et al. (2018) do have it. So, subtracting another 50–150 Gt CO_2 (a rough estimate that CCS/CDR would contribute by 2050) would bring the CO_2 budgets down to 775 Gt in COOP and 690 Gt in the COOP<<2C scenarios in the 2016–50 period–even closer to the lower, safer boundaries in the IPCC literature on the 1.5C° mitigation target. The same conclusions are derived from comparison with the scenarios in Rogelj et al. (2019) and Huppmann et al. (2019). Uncertainty about climate-forcing potential, feasibility, and costs of CCS and CDRs remains large because they are not yet commercially or even economically proven. Having said that, this study does not pretend to cover all plausible carbon pricing scenarios. A wider set of low-carbon transition scenarios can be found in Mercure et al. (2018), Peszko, van der Mensbrugghe, and Golub (2020), and Van der Ploeg and Rezai (2019). CPLs can apply an even higher level of climate policy ambition than the most ambitious scenarios, for which this model could find an equilibrium solution.

Risk to the Value of Fossil Fuel Assets

A range of low-carbon transition scenarios can reduce the value of fossil fuel assets by between US$4.4 trillion and US$6.2 trillion (in 2018 prices) over 2018–50, compared with what could be expected in the NDC scenario. The total value of all fuel assets does not materially differ between scenarios with the same CO_2 budget, although in the cooperative scenario, the value of oil is slightly greater than in the unilateral policy scenarios (figure 10.7). In the high carbon tax cooperative COOP<<2C scenario, the fossil fuel asset value (US$28 trillion) is US$6.2 trillion lower than the US$34.2 trillion in the NDC scenario. These results suggest that the total global value of fossil fuel assets is more sensitive to the level of ambition of climate policy than to the level of international cooperation in

FIGURE 10.7 Value of Subsoil Fossil Energy Assets, by Fuel, 2018–50



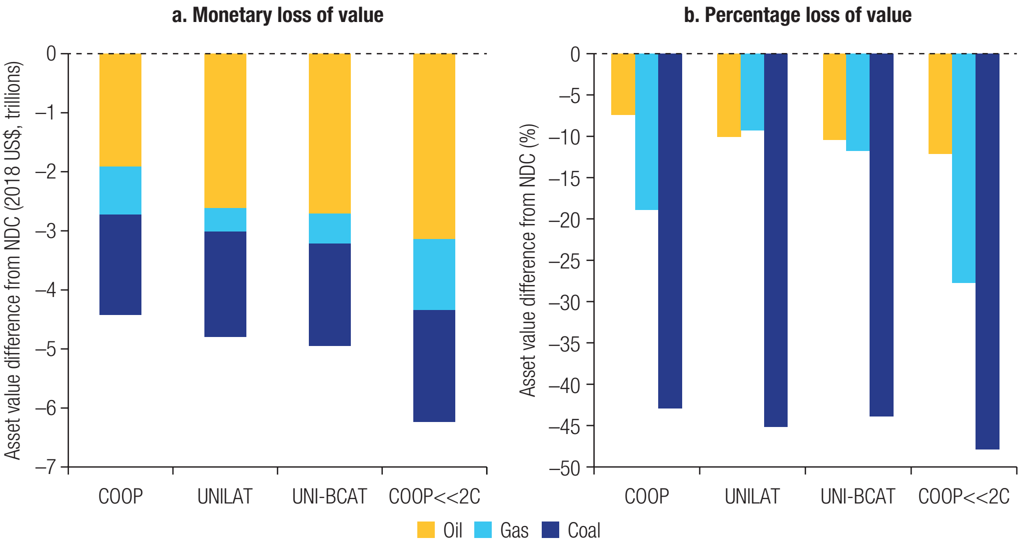
Source: World Bank staff simulations with ENVISAGE.
Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by climate policy leaders with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by climate policy leaders without border carbon adjustment taxes.

implementing this policy. Even in the most stringent climate policy scenario, however, the total fossil fuel wealth is higher than in the conservative estimates consistent with SNA standards based on the extrapolation of the low average price and fixed production level from 2014–18 until 2050 (as in the CWON core accounts).

In dollar terms, oil assets represent the largest value at risk and gas assets the lowest, but in percentage terms, the value of coal is most vulnerable to transition risk, while oil wealth is most resilient. In all scenarios, oil reserves left in the ground because of climate policies represent the largest value of the stranded fossil fuel assets, followed by coal and natural gas—US$3.1 trillion, US$1.9 trillion, and US$1.2 trillion, respectively—in the most ambitious climate policy scenario (figure 10.8, panel a). In percentage terms, across scenarios, coal reserves are valued 43 to 48 percent less than in the NDC scenario (figure 10.8, panel b). This is a big difference compared with natural gas and oil, which in no scenario are valued less than 28 and 13 percent, respectively, below NDC. Most of the coal is used in power generation which, under ambitious climate policies, is easier to replace with alternative inputs than oil in the transport sector and gas in industry, buildings, and transport.

Cooperative policies are better for global oil wealth with the same carbon budget. Lower carbon prices in oil-importing countries translate

FIGURE 10.8 Stranded Fossil Fuel Assets: Loss of Value against NDC, by Fuel, 2018–50



Source: World Bank staff simulations with ENVISAGE.

Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by climate policy leaders with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by climate policy leaders without border carbon adjustment taxes.

into lower fuel prices for consumers than in unilateral action scenarios, and hence slower penetration of electric vehicles in transport and prolonged external oil demand for FFDC producers. Oil importers, including Organisation for Economic Co-operation and Development (OECD) countries, China, and India, maintain the dominant share in the global vehicle fleet toward 2050.

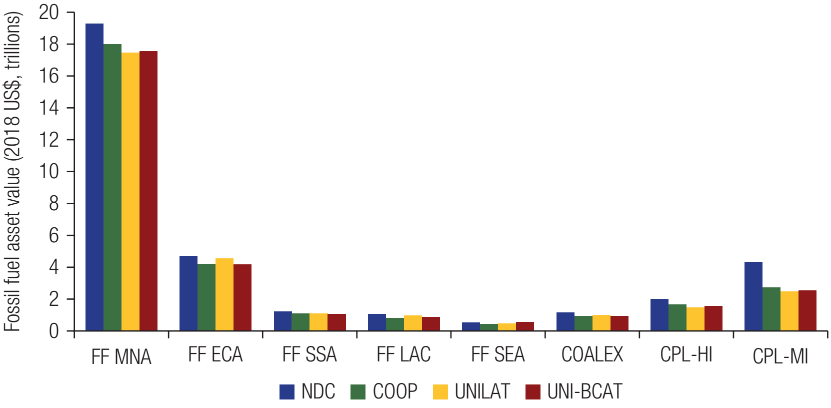
In contrast, natural gas has a higher global value in the noncooperative scenarios. Gas owners seem to benefit from asymmetric climate policies, in which gas exporters in FFDCs free ride on the increased level of climate policy ambition by CPLs and attract emission-intensive industries, even paying the price of BCAT. Coal value suffers similar large losses in all scenarios.

Risk Distribution across Regions

The countries that are the most generously endowed with fossil fuel wealth also face the highest value of fossil fuel assets exposed to transition risk. Three country groups—MNA, ECA, and the middle-income fuel importers (mainly China and India)—account not only for 83 percent of the global fossil fuel wealth in the NDC scenario but also for 77–80 percent of the global loss of fossil fuel wealth in the climate policy scenarios (figure 10.9).

MNA loses the highest dollar value of stranded oil assets but the smallest percentage of its total fossil fuel wealth (figure 10.10).

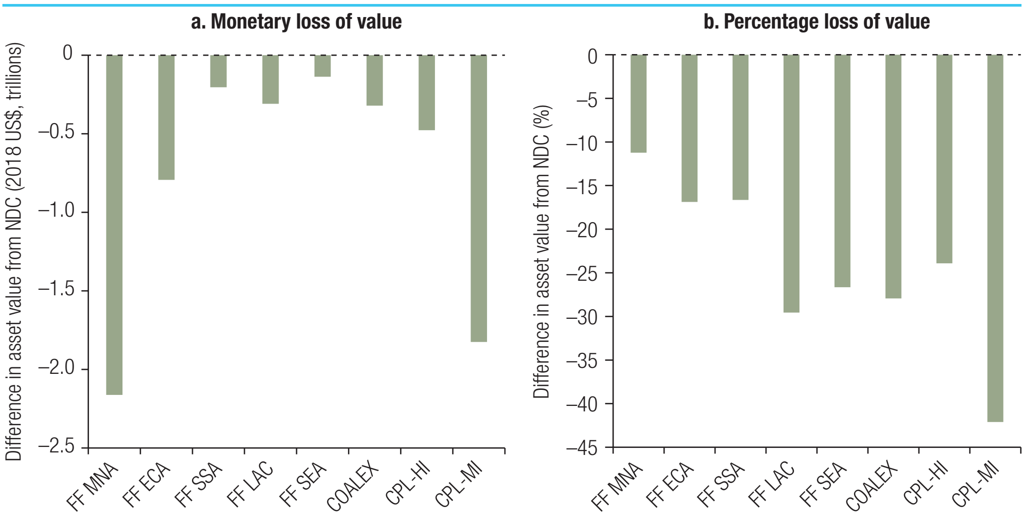
FIGURE 10.9 Value of Subsoil Fossil Fuel Assets, by Scenario and Region, 2018–50



Source: World Bank staff simulations with ENVISAGE.

Note: COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income fossil fuel importers; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

FIGURE 10.10 Risk to Fossil Fuel Wealth in the Most Ambitious (COOP<<2C) Climate Policy Scenario, by Region



Source: World Bank staff simulations with ENVISAGE.

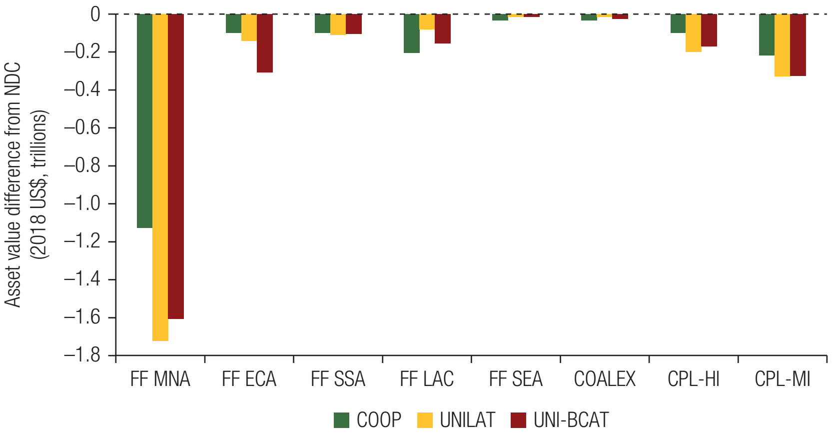
Note: Both panels show the impact only of the cooperative scenario with high carbon taxes. COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income fossil fuel importers; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa.

The second-largest foregone value of fossil fuel assets is experienced by the middle-income net fuel importers, especially China and India (US$1.8 trillion, compared with NDC), and it is mainly foregone coal wealth. These countries also lose a higher share of their fossil fuel asset value than any other region (up to 42 percent). ECA countries also have a large value (US$0.8 trillion) of fossil fuel assets at risk of low-carbon transition, but this value is a relatively smaller portion (17 percent) of their total fossil fuel wealth.

Risk Distribution across Regions and Fuels

The value of individual fuels foregone by different regions sheds light on the political economy of international cooperation toward the goals of the Paris Agreement (figure 10.11, figure 10.12, and figure 10.13). Cooperative climate policies benefit oil wealth, especially owners of low-extraction cost reserves. Most large oil producers (MNA, ECA, Sub-Saharan Africa, and both groups of net oil importers) forego less oil wealth in cooperative climate policy scenarios than in unilateral scenarios with the same carbon budget (figure 10.11). For example, compared to the NDC scenario, MNA oil producers extract US$1.1 trillion less of the oil asset value when they implement cooperative carbon prices, and US$1.7 trillion less when they free ride. MNA is

FIGURE 10.11 Potential Loss of Oil Asset Value, by Region

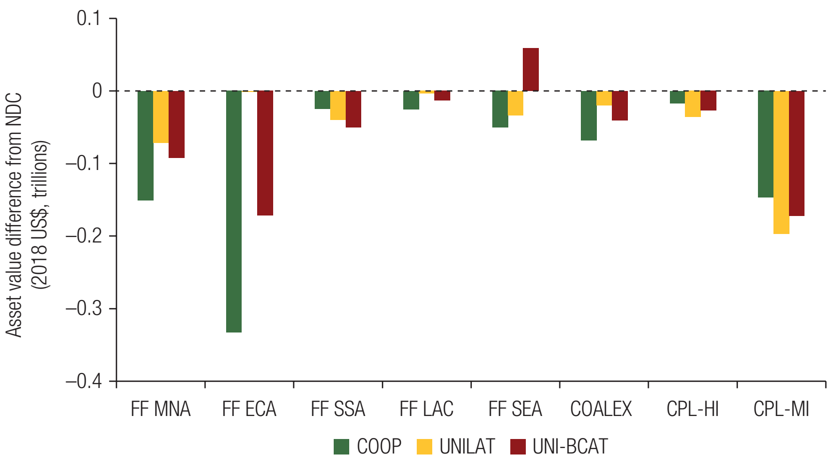


Source: World Bank staff simulations with ENVISAGE.
Note: COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income fossil fuel importers; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

disproportionally well endowed in large conventional oil and gas reserves, with one of the world's lowest extraction costs. The oil exporters in MNA increase their share of global oil asset value from 69 percent in NDC to 71 percent in all the climate policy scenarios, mainly at the expense of the CPLs. The cooperative scenarios allow CPLs (major oil importers and users) to keep their domestic carbon taxes lower, prolonging their transition away from internal combustion engines in transport and hence demand for oil, compared with the unilateral counterfactual. Oil producers in Latin America and the Caribbean seem to be the exception—cooperative scenarios destroy a higher value of their oil wealth than free riding because their extraction costs are high relative to other large producers and they are further from the major growing sources of demand in Asia. They are one of the first producers to be priced out of the declining global oil market, but without carbon pricing they maintain higher domestic demand for oil in transport and the petrochemical industry.

Natural gas owners in FFDCs seem to have opposite incentives to cooperate on climate action than gas owners in importing countries. In virtually all the FFDCs, the value of extracted natural gas is much lower when they cooperate on global climate action than when they free ride (figure 10.12). Contrary to oil, the gas wealth in FFDCs (except exporters in Sub-Saharan Africa) is higher when these countries free ride on

FIGURE 10.12 Potential Loss of Natural Gas Asset Value, by Region



Source: World Bank staff simulations with ENVISAGE.
Note: COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income fossil fuel importers; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

high carbon prices implemented by CPLs. This effect may be counterintuitive but follows from standard macroeconomic transmission mechanisms. The declines of export demand for gas suppress producer prices, lowering the opportunity costs of using gas at home. The value of exporters' currencies also falls, as a result reversing the Dutch disease and boosting the competitiveness of their other export sectors such as the manufacturing industry. In relatively advanced industrialized gas exporters, a large part of manufacturing output can be found downstream in the gas value chain. The foregone gas export revenues are offset by increased revenues from sales to domestic gas-intensive sectors (industry, households, and transport). Gas-fed manufacturing industries in FFDCs increase market share in globally declining brown sectors, especially when they can get away without facing BCAT. Border carbon adjustment taxes implemented by CPLs cause downward revaluation of gas wealth, reducing the benefits of free riding in all FFDC groups, but not enough to encourage gas owners to support cooperative climate policies. The genuine comparative advantage in emission-intensive industries using gas as input causes a leakage of gas-intensive industrial production and greenhouse gas emissions from net importers to net gas exporters even when a level playing field is established by imposing BCATs. The after-BCAT leakage would be "efficient" (Kossoy et al. 2015). Switching from coal to gas in the power sector plays some role only in cooperative scenarios, in which coal is hit even harder, but this advantage of gas is short-lived, because renewables quickly price gas out of the power sector. More discussion on why the wealth of gas and coal producers in FFDCs benefit from unilateral policies can be found in the "Political Economy of Global Cooperation on Climate Change" section later in the chapter.

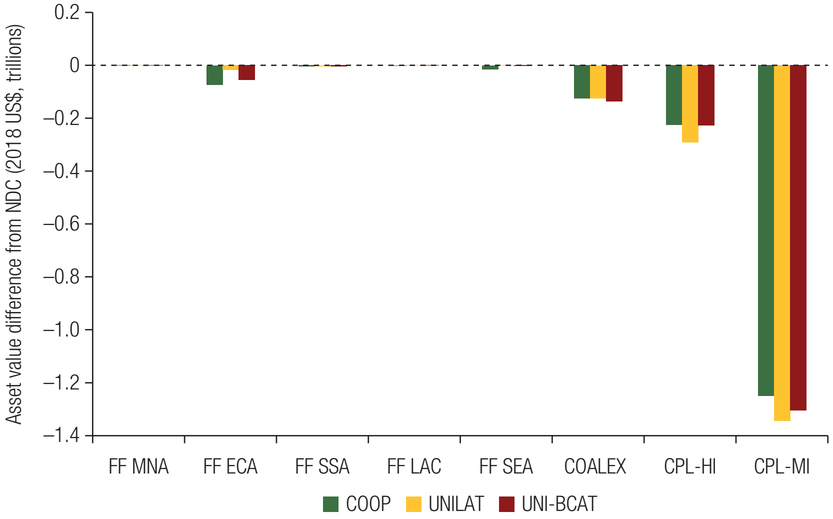
Nowhere are the incentives of gas producers to free ride on low-carbon transition stronger than in ECA and Southeast Asia. The ECA region, including Azerbaijan, Kazakhstan, the Russian Federation, Turkmenistan, and Uzbekistan, faces by far the highest value of natural gas assets at risk in the cooperative scenario, potentially leaving US$330 billion of gas wealth unexploited, compared to the NDC scenario. ECA gas producers also benefit the most from free riding by their countries. The value of ECA's gas wealth in the noncooperative scenario without border carbon adjustments is higher than in the NDC scenario. Even the BCAT does not encourage ECA gas producers to cooperate, since the loss of gas wealth in UNI-BCAT is only US$170 billion against NDC, still only half of the loss in the cooperative scenario. Oil and gas producers in Southeast Asia seem to even benefit from BCAT, which makes their gas wealth higher than in the NDC scenario. This may occur because BCAT accelerates premature retirement of the large coal power plant fleet in the region, increasing demand for gas as a transition fuel for electricity generation. Since the region also has limited variable renewable energy resources, substitution of gas for coal increases not only domestic gas demand but also prices.

Gas exporters in Sub-Saharan Africa are the exception among the FFDCs, as their gas wealth is higher in the cooperative scenarios. Their gas-intensive manufacturing industries are too small to attract any significant production leakage in the noncooperative scenarios. The falling exchange rates do not necessarily reverse the Dutch disease. This occurs only if the fossil fuel–exporting country already has well-developed export sectors such as manufacturing, which SSA countries do not have. Unless these economies diversify away from fuel exports, exchange rate depreciation arising from lower external demand as a result of climate policies implemented by large fuel importers worsens their economic performance. However, the nature of diversification matters. As discussed in Peszko et al. (2020), traditional diversification by branching out to downstream fuel-intensive manufacturing increases the exposure to transition risk.

Unsurprisingly, gas producers in both groups of net fuel importers benefit from cooperative policies, because carbon prices in FFDCs minimize the leakage of gas-intensive industries from CPLs.

Most of the coal wealth foregone in the climate policy scenarios is in the middle-income climate policy leaders (CPL-MI), especially China and India—around US$1.3 trillion or 57 percent less than in the NDC scenario (figure 10.13). The CPLs from the OECD countries and the group of major coal exporters (Australia, Colombia, Indonesia, Mongolia, and South Africa) can also write off significant value of coal assets compared

FIGURE 10.13 Potential Loss of Coal Asset Value, by Region



Source: World Bank staff simulations with ENVISAGE.
Note: COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); HI = high-income fossil fuel importers; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

with NDC policies, US$290 billion and US$140 billion, respectively. The ECA region also leaves some coal value in the ground, but much less than the other three regions. In contrast to the other regions, ECA's coal producers can benefit from the noncooperative behavior of their governments, because of further domestication of coal-intensive industries (power, steel, and cement), already well developed, internationally competitive, and close to the demand for heavy industry intermediate goods in Europe and Asia. BCATs significantly reduce the value of coal wealth in ECA countries because a relatively large share of their industrial exports is directed to Europe and China. However, BCAT does not leave as much of ECA's coal wealth in the ground as cooperative carbon prices do. Coal owners in Australia, Colombia, Indonesia, Mongolia, and South Africa seem to be indifferent to climate and trade policy. They enjoy relatively low coal extraction costs and are close to the premium coal-burning markets in East Asia and South Asia. As expected, all CPL coal producers benefit from global cooperation on climate policies and have self-interest in supporting BCAT against the FFDCs to encourage their cooperative climate policies.

Climate policies also induce shifts in the distribution of coal wealth across countries. China, India, and other middle-income CPLs reduce their share of the global coal asset value from 60 percent in the NDC scenario to 47–49 percent in the climate policy scenarios. Other coal producers, including the group of coal exporters, ECA, and high-income OECD countries, increase their shares of globally declining coal wealth.

Rent Profiles

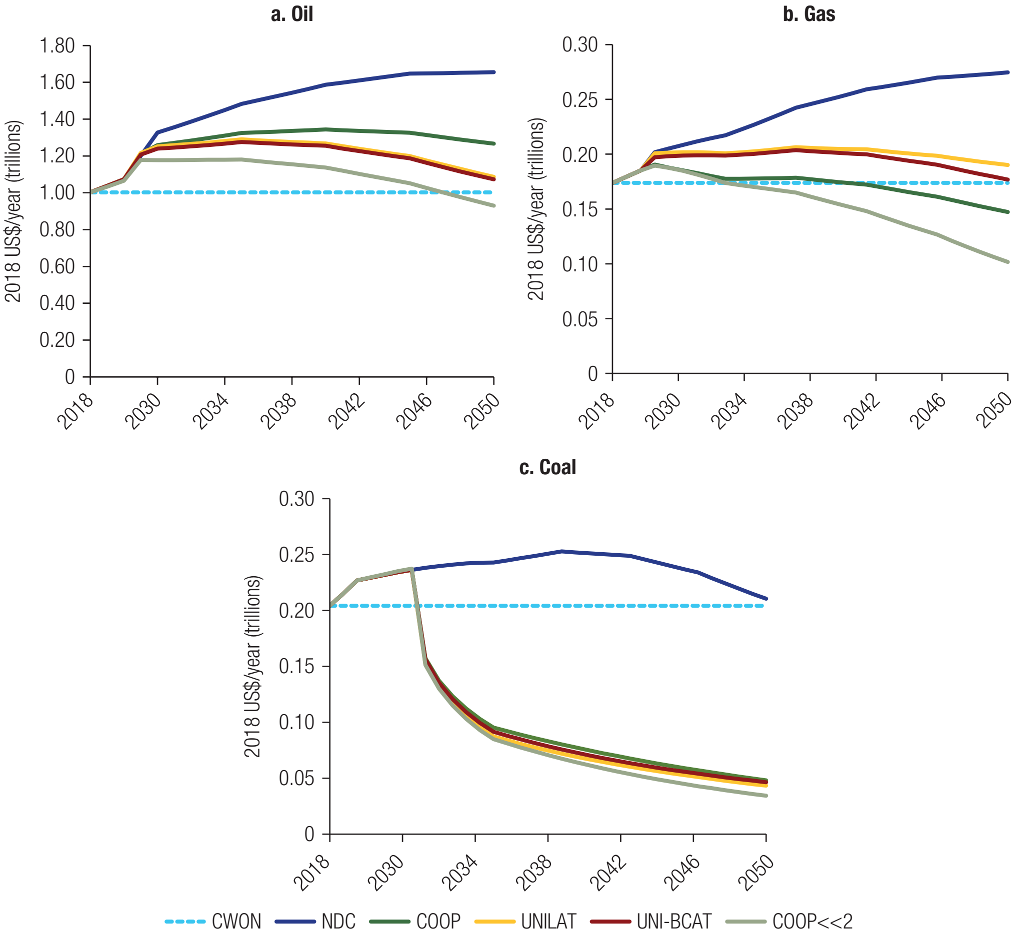
Climate policies can catch many owners of fossil fuel assets by surprise, either because they overlook the need for ambitious climate action or because—despite expecting it—they perceive a "prisoner's dilemma" and delay their own climate action, accumulating exposed assets instead. Therefore, a dynamic and recursive model specification is important to simulate path-dependent adjustments to surprising external changes in policy and the market environment. In ENVISAGE this specification was modified, so that economic agents learn to anticipate at least the near future over time. They make their investment decisions based on past trends until 2030 and with five years' foresight afterward. The specification mimics the myopic expectations of fossil fuel–related interest groups and avoids the pitfalls of static scenarios with long-term perfect foresight that dominate the stranded assets literature.

Owners of extractive companies expect resource rents to increase above average market rates of return, at least in the time frame relevant for shareholders (rarely longer than 10 years). The simulations suggest that NDC commitments do not materially alter these expectations. A steep rise in the ambition of the climate policies, however, abruptly breaks the trends in resource rents, causing potential shockwaves to their valuation (figure 10.14). This rapid adjustment of expectations in response to policy shock applied in 2025 indicates that the impact pathways of the low-carbon transition on fossil fuel asset values can be increasingly erratic.

The simulation results suggest that global oil rents are more resilient to climate policies and decline slower than gas and coal rents (figure 10.14, panel a). Ramping up the ambition level of climate policies in 2025–30 creates an immediate and major deviation from the NDC scenario. This notwithstanding, annual oil rents continue to grow, albeit much more slowly than in the NDC scenario (even slower in asymmetric climate policy scenarios) and begin to decline only after around 2035, by 2050 falling to 24 and 35 percent below rents expected in the NDC scenario in the cooperative and unilateral policy scenarios, respectively. Only in the sensitivity scenario with higher cooperative carbon prices (COOP<<2C) do the oil rents never recover from the 2025–30 policy shock and drop below the 2018 level by 2050 (44 percent below NDC).

Natural gas rents take a deeper dive than oil rents, but contrary to oil rents, natural gas rents lose value faster in the cooperative relative to asymmetric policy scenarios (figure 10.14, panel b). In the NDC scenario, natural gas rents grow after the 2025–30 carbon price shock. In the cooperative and asymmetric policy scenarios, gas rents by 2050 are 46 and 36 percent lower, respectively, than those expected with NDC policies (as much as 63 percent lower in the sensitivity scenario of higher cooperative carbon prices). Only cooperative climate policies suppress gas rents below the 2018 values before 2050. Unilateral climate policies allow for a slower

FIGURE 10.14 Global Rent Profiles for Oil, Natural Gas, and Coal Assets, 2018–50



Source: World Bank staff simulations with ENVISAGE.
Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders (CPLs) and fossil fuel–dependent countries; COOP<<2C = a more ambitious cooperative sensitivity scenario; CWON = Changing Wealth of Nations; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

decline in gas rents because of migration of some gas-intensive industries (for example, petrochemicals, fertilizers, and power) from CPLs to FFDCs, where they survive longer as the former implement steep carbon taxes alone. Even border carbon adjustments do not destroy the output of gas-intensive manufacturing in FFDCs. Cooperative climate policies reduce gas production and rents faster because they prevent emissions leakage, eliminating "pollution havens" for gas users.

Coal rents are the most vulnerable to climate policies, and rent destruction is similar in all climate policy scenarios (figure 10.14, panel c).

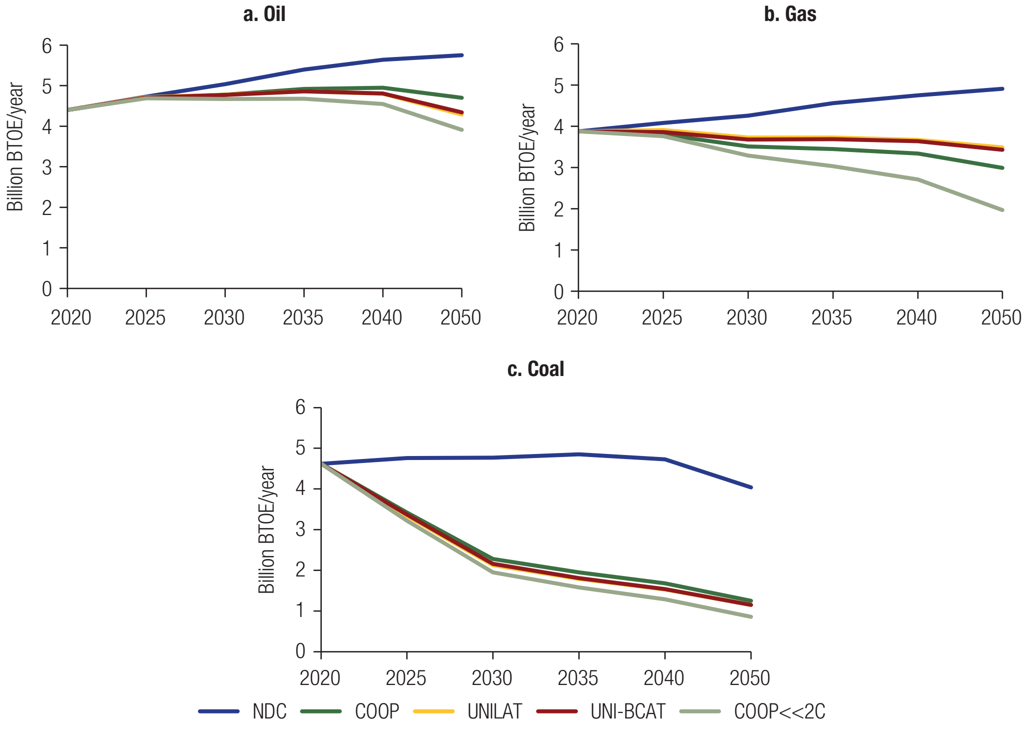
Climate policies assumed to be implemented in 2025 trigger an immediate freefall of global coal rents against the NDC expectations and even below the level in 2018. Within five years of implementation of carbon taxes, annual coal rents drop by 62 percent in real terms in the model, indicating a potentially dramatic impact on the coal industry in the real markets that do not have automatic equilibrium stabilizers as CGE models. By 2050, the annual coal rents collected by the mining countries is just 20 percent of what would have been collected in the NDC scenario and in 2018. To put it into perspective, in 2013–15 annual coal rents dropped by 40 percent globally, as an aftermath of the oil price drop, accompanied by climate and clean energy support policies in the European Union and North America (CWON core accounts). This caused a shockwave of bankruptcies of coal companies and accelerated mine closures in western countries, although coal rents fully rebounded by 2018. The deeper dive of coal rents simulated here, with no hope of rebound, could lead to a much more dramatic shock to the coal mining industry across the world, this time also in Asia and other coal-intensive developing countries.

Production Volumes of Fossil Fuels

The production volumes of fossil fuels are more sensitive to climate policy scenarios than their values are. Physical production volumes of oil and gas fall slightly faster than their rent profiles. Coal production falls slower initially and faster later in the modeling period (figure 10.15). The wedge between the production and rent profiles is attributed to resource prices, which are endogenously calculated by the model to clear the markets. Increasing prices of oil and gas partly offset the impact of the production losses on resource owners. This illustrates a significant difference between the perceptions of environmentalists and resource owners, which often creates avoidable tensions, counterproductive to cooperative climate action. Environmentalists are mainly concerned about volumes, because they determine climate impact, but climate advocacy narratives often attack the profits and rents of fossil fuel producers. Decoupling volumes from rents in the public dialogue could create a much-needed safe space for less confrontational dialogue about low-carbon transition. The resource-rich nations would find it easier to engage in the dialogue on climate policies if they could expect that their rents would be falling slower than their production volumes.

The production profiles of fossil fuels calculated endogenously by ENVISAGE are broadly aligned with the production trajectories taken as exogenous assumed constraints consistent with the 2°C scenarios in the integrated assessment models. There are significant differences across fuels, however. Comparison of figure 10.15 with figure 10.2 suggests that the production of coal and gas in this study is close to the 1.5°C scenarios in SEI et al. (2020), especially for the most comparable COOP<<2C scenario, but production of oil is higher than in most of the 2°C scenarios reported by SEI et al. The model finds more substitution opportunities for coal and gas in power generation and industrial uses and less for oil in transport. Researchers are encouraged to stress test these results with different models.

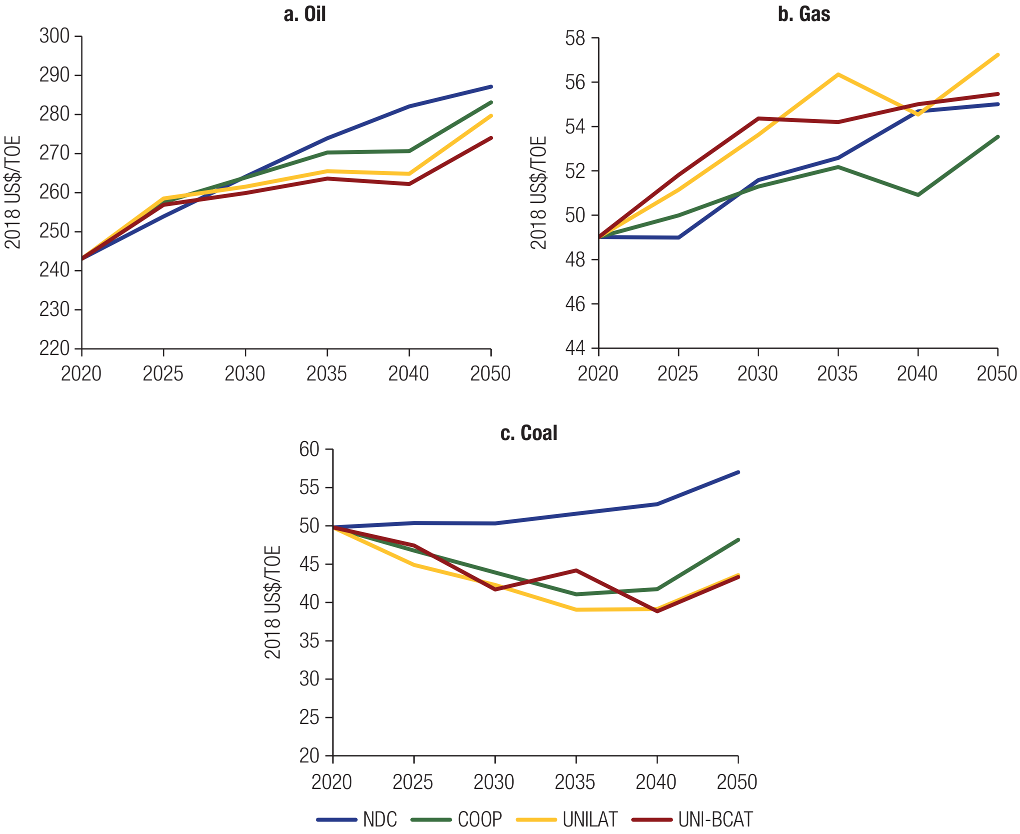
FIGURE 10.15 Production Volumes of Oil, Natural Gas, and Coal, 2020–50



Source: World Bank staff simulations with ENVISAGE.
Note: BTOE = billion tons of oil equivalent; COOP = cooperative carbon tax implemented by all countries, including climate policy leaders (CPLs) and fossil fuel–dependent countries; COOP<<2C = cooperative scenario with high carbon taxes; NDC = nationally determined contribution; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

This study suggests that oil- and gas-rich countries that survive the low-carbon transition can enjoy higher rents per unit of fuels extracted than current producers. The unit rents for the remaining oil and gas producers roughly follow the increasing NDC trends from 2018 onward, although with greater volatility. This means that resource prices increase slightly faster than extraction costs. Production volumes and unit rents for oil producers are higher in the cooperative scenarios than in unilateral policy scenarios with the same carbon budget (figure 10.16). BCATs have negligible impact on global oil production volumes but reduce producers' rents. This finding mitigates the concerns represented by the green paradox hypothesis, which suggests that expected low-carbon transition fossil will prompt fuel producers to accelerate current production and emissions. The hypothesis argues that producers who expect that low future demand will depress future prices will rationally try to extract as many resource rents as quickly as possible and dump extra fuels on the market. According to green paradox proponents, ambitious long-term NDC targets would

FIGURE 10.16 Profile of Average Unit Rents for Oil, Natural Gas, and Coal, 2020–50



Source: World Bank staff simulations with ENVISAGE.

Note: COOP = cooperative carbon tax implemented by all countries, including climate policy leaders (CPLs) and fossil fuel–dependent countries; NDC = nationally determined contribution; TOE = tons of oil equivalent; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

create incentives opposite to those intended (Sinn 2008). These simulations suggest that it is not realistic to expect that fuel demand and prices will smoothly decrease together and that at least some producers can capture significant resource rents in the future and hence can delay extraction. It also confirms an earlier hypothesis that some fossil fuel producers can successfully pursue risky *leadership strategies* (opposite to divestment) and try to increase their market share and market power in the globally declining fuel-intensive sectors through mergers and acquisitions (Peszko et al. 2020).

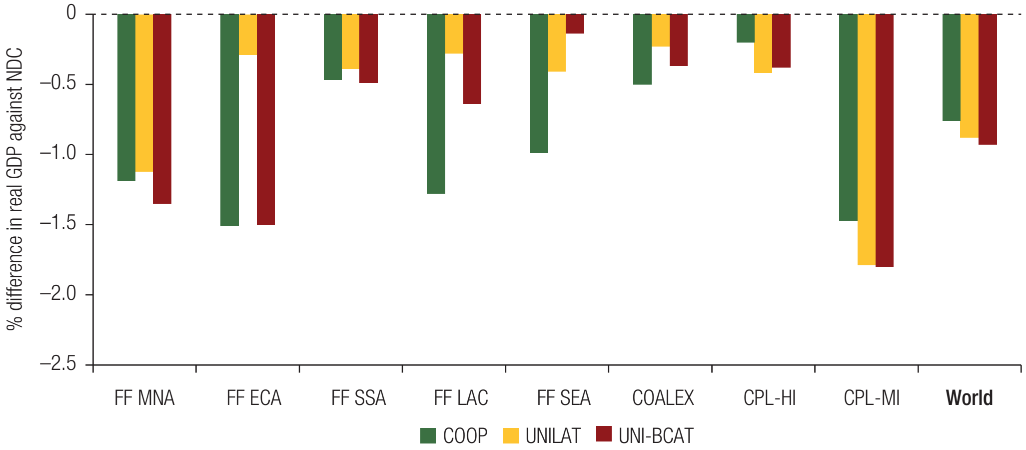
For the remaining coal producers, the unit rent outlook looks grim. In all the climate policy scenarios, even the most competitive coal producers find themselves with not only the total rents but also unit rents falling well below the NDC scenario and even below 2018 levels.

Gross Domestic Product

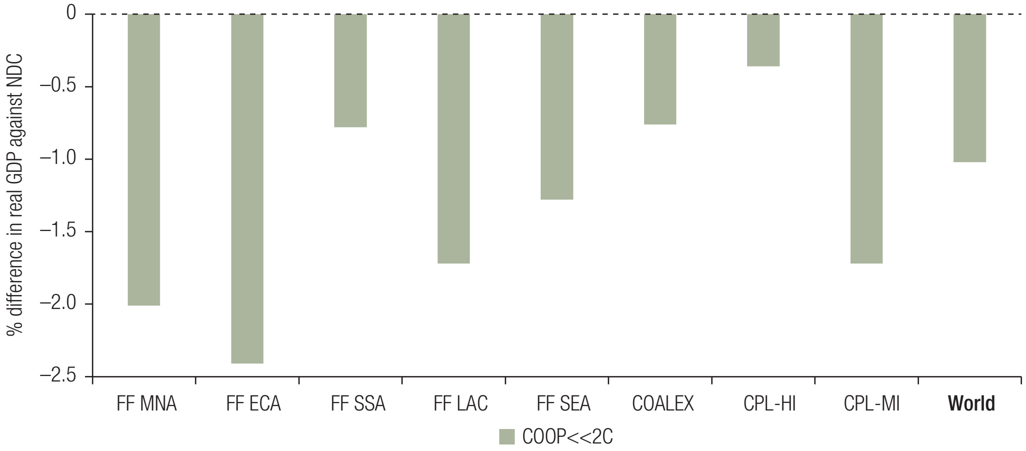
Figure 10.17 confirms what can already be observed: the low-carbon transition—especially a cooperative one—is least disruptive to high-income OECD net fuel importers (CPL-HI), which therefore have the strongest incentives to be the global CPLs. The low-carbon transition is more

FIGURE 10.17 Difference in Real GDP against the NDC Scenario

a. Scenarios with 862 Gt CO_2 cumulative gross emissions



b. Scenario with 777 Gt CO_2 cumulative gross emissions



Source: World Bank staff simulations with ENVISAGE.

Note: COALEX = coal exporters; COOP = cooperative carbon tax implemented by all countries, including CPLs and fossil fuel–dependent countries; COOP<<2C = cooperative scenario with high carbon taxes; CPL = climate policy leader; ECA = Europe and Central Asia; FF = fossil fuel(–dependent countries); GDP = gross domestic product; Gt CO_2 = gigatons of carbon dioxide; HI = high-income climate policy leaders; LAC = Latin America and the Caribbean; MI = low- and middle-income fossil fuel importers; MNA = Middle East and North Africa; NDC = nationally determined contribution; SEA = Southeast Asia; SSA = Sub-Saharan Africa; UNI-BCAT = unilateral carbon taxes applied by CPLs with border carbon adjustment taxes; UNILAT = unilateral carbon taxes applied by CPLs without border carbon adjustment taxes.

challenging for other countries, including coal-intensive fuel importers (CPL-MI), such as Cambodia, China, India, Morocco, Serbia, Turkey, and Ukraine, to say nothing of FFDCs, because of the higher carbon intensity of their economies. Among the FFDCs, the least negative impact on total economic output can be found among coal exporters. Although coal assets are the hardest hit by low-carbon transition, coal export revenues are a small share of total exports and GDP, even among the largest exporters.

The substantial difference between the net fuel importers (CPL-MI) and the FFDCs is that the former benefit from cooperative climate policies, while the latter benefit from industrial and emissions leakage when free riding on climate policies of CPLs (figure 10.17). This identifies probably the most important challenge to establishing a stable cooperation to implement the goals of the Paris Agreement. BCAT appears to be an important incentive for FFDCs to engage in cooperative climate policy, but unsurprisingly it is not necessarily a very attractive policy for CPL growth, unless it induces cooperative behavior by FFDCs.[6] The retaliation of FFDCs is not part of the simulated scenarios. It would make BCAT even less attractive to all countries. Therefore, the rational CPLs coalition would rather use BCAT as a credible threat rather than a long-term actual trade policy.

Comparison with Other Estimates of Stranded Assets

Approaches to measuring stranded assets vary considerably in the literature. They are difficult to compare across studies, reflecting the early stage of the field. Comparison between studies is complicated by the fact that different authors consider different metrics (what is stranded, and compared to what counterfactual), often loosely using the term assets as a metaphor rather than a balance sheet concept consistent with the SNA definition of assets. They compare "stranded" value to the different categories of reserves and use different scenarios, time horizons, discount rates, price levels, and so forth. Many studies measure unburnable reserves left in the ground in physical (volume) rather than in value terms (IEA 2012; McGlade and Ekins 2015). Some quantitative studies focus on produced assets, such as thermal power plants, rather than subsoil assets (Baldwin, Cai, and Kuralbayeva 2018; Bertram et al. 2015; Carbon Tracker Initiative 2013; Coulomb, Lecuyer, and Vogt-Schilb 2019; Guivarch and Hallegatte 2011; Koch and Bassen 2013; Löffler et al. 2019; Pfeiffer et al. 2018; Pfeiffer et al. 2016; and Rozenberg, Vogt-Schilb, and Hallegatte 2020). Several authors, financial institutions, and rating agencies employ the value-at-risk approach to calculate risk to financial assets that are invested in fossil fuel–dependent produced capital rather than measuring the risk to the value of subsoil assets themselves (for example, Dietz et al. 2016; Spedding, Mehta, and Robins 2013). The models and calculation methods chosen by researchers often involve inherent biases, which are rarely discussed explicitly. Only very few recent peer reviewed studies compare their results with other studies and explain the sources of differences (see Mercure et al. 2018; Peszko, van der Mensbrugghe, and Golub 2020; and Van der Ploeg and Rezai 2019. Table 10.3 compares the most relevant global studies.

TABLE 10.3 Comparative Assessment of Studies of Stranded Assets

Study	Metrics	Volume or value	Baseline reserves	Scenarios	Model or calculation method	Geographic breakdown	Discount rate	Price level
This study	*Fossil fuel asset value:* NPV of oil, gas, and coal resource rents against reference NDC scenario	*Value:* US$4.4 trillion to US$6.2 trillion globally (up to US$3.1 trillion for oil, US$1.9 trillion for coal, and US$1.2 trillion for gas), 2020–50	*Class A:* Producing under market conditions simulated by model	BAU (with NDC) plus cooperative and noncooperative carbon taxes with and without border carbon adjustment tax	Economywide global CGE (ENVISAGE) with endogenous resource exploration and extraction module	16 country groups: fuel exporters and importers	4%	2018
Carbon Tracker 2011	Unburnable reserves	*Volume:* 80% of proven reserves technically unburnable	All the proven reserves owned by private and public companies and governments	BAU, all proven reserves burned versus reserves that could be burned with 565 Gt CO_2 carbon budget	Bottom-up calculations	Global	n.a.	n.a.
IEA 2013	Reserves that cannot be used and foregone revenues	*Volume/value:* Oil and gas gross revenue 15% and coal 32% lower than in NPS (but three times higher than in previous period); less than 5% and 6% of new proven oil and gas reserves, respectively, to be developed	*Class A:* Producing under market conditions assumed by researchers	IEA NPS versus 450 ppm (2°C) scenarios (884 Gt CO_2 from the energy sector in 2012–50)	Bottom-up calculations supported by WEO model (partial equilibrium energy model)	Multiple countries (focus on owners of coal reserves)	n.a.	n.a.
Lewis et al. 2014	*Gross revenues:* Foregone by fossil fuel industry compared with IEA CPS scenarios	*Value:* US$28 trillion: US$19.3 trillion, US$4 trillion, and US$4.9 trillion, respectively, for oil, gas, and coal by 2035	n.a.	IEA scenarios from 2013 WEO (CPS, NPS, 450 ppm scenario)	Calculation based on IEA projections of fuel prices and demand by scenario	Global fossil fuel industry	n.a.	2012
Nelson et al. 2014	*Profits of extractive sectors:* Resource rents and returns on extractive capital	*Value:* US$15 trillion by 2035, of which oil, US$11.2 trillion; gas, US$1.7 trillion; and coal, US$2.2 trillion, 2015–35 (net of transfers)	*Class A:* Producing under IEA BAU scenario	Fuel demand under IEA 2C scenario	Supply (cost) curves for coal, oil, gas, and electricity	Multiple country groups	8%	2015
McGlade and Ekins 2015	Unused fossil fuels	*Volume:* 33% of oil reserves, 50% of gas reserves, and over 80% of current coal reserves should remain unused from 2010 to 2050 in 2C target	*Class A and partly B:* Proven and probable reserves	Technology-driven sensitivity scenarios	Linear optimization IAM: TIAM-UCL13 with supply cost curves for oil, gas, and coal	Multiple country groups	n.a.	n.a.

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TABLE 10.3 Comparative Assessment of Studies of Stranded Assets *(continued)*

Study	Metrics	Volume or value	Baseline reserves	Scenarios	Model or calculation method	Geographic breakdown	Discount rate	Price level
Carbon Tracker 2C of Separation 2017 with 2018 update	Unneeded upstream oil and gas capex to 2018–25	*Value:* US$4 trillion (2017), $2.3 trillion for 2C, and US$3.3 trillion for 1.75C	Potential supply from Rystad under EIA NPS	Company-by-company calculations	Carbon supply cost curves	Multiple companies	n.a.	2018
Carbon Tracker Mind the Gap 2018	Capex in upstream oil, gas, and thermal coal projects over 2018–25 above what is needed in EIA NPS	*Value:* US$1.6 trillion capex at risk in 1.75C scenario (33% of NPS); in 2C scenario, US$0.9 trillion (18% of NPS)	Fuel demand under the EIA NPS	EIA NPS (no policy scenario), and IEA B2DS (1.75C) and EIA SDS (2C) scenarios	Carbon supply cost curves	Multiple countries	n.a.	2018
Mercure et al. 2018	Loss of income on sales of fossil fuels	*Value:* US$1 trillion to US$4 trillion cumulative difference globally in the value of oil, gas, and coal to 2035	*Class A:* Produced in BAU and policy scenarios	Two BAUs: fuel use from IEA new policies and from technology diffusion trajectory; and policy scenarios based on combinations of carbon prices and trading strategies of producers	E3ME-FTT-GENIE dynamic simulation models (with macroeconometric core with imperfect foresight)	Multiple country groups (fuel exporters and importers)	10%	2016
Van der Ploeg and Rezai 2019	*Multiple:* market valuations, investments, and carbon resources and their scarcity rents belonging or accruing to international oil and gas companies	*Value:* Range of results stated as in line with US$2.3 trillion of unneeded capex from Carbon Tracker 2017.	*Class A and partly B:* Assumed produced under BAU (from proven reserves and new discoveries)	Unexpected stepping-up and abandoning announced climate policy scenario (carbon taxes versus RES subsidies)	Model of endogenous exploration in the global oil and gas industry	Global oil and gas industry	n.a.	n.a.
Carbon Tracker 2020	NPV of resource rents	*Value:* US$100 trillion gap between the assumed desired fossil fuel wealth of the petrostates and the assumed aspirations of the Paris Agreement	n.a.	Alternative combinations of two variables: (1) FF rents as a share of global GDP and (2) the discount rate	Back-of-the-envelope calculations based on selected studies	Global	Variable	2019

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TABLE 10.3 Comparative Assessment of Studies of Stranded Assets *(continued)*

Study	Metrics	Volume or value	Baseline reserves	Scenarios	Model or calculation method	Geographic breakdown	Discount rate	Price level
Peszko, van der Mensbrugghe, and Golub 2020	*Fossil fuel asset value:* NPV of oil, gas, and coal resource rents plus produced assets (value added attributed to capital across sectors against BAU in 2021–50)	*Value:* Asset value against BAU: coal minus US$0.5 trillion to US$1.2 trillion; gas from plus US$300 billion to minus US$2.8 trillion; oil minus US$5 trillion to US$17 trillion; produced assets shift values	*Class A:* Producing under market conditions simulated by model	BAU and combination of diversification and cooperation scenarios with and without border carbon adjustment taxes	Economywide global CGE (ENVISAGE) with endogenous resource extraction module (endogenous prices, demand, and supply cost curves)	15 country groups: fuel exporters and importers	6%	2013
Guivarch and Hallegatte 2011; Carbon Tracker Initiative 2013; Koch and Bassen 2013; Bertram et al. 2015; Pfeiffer et al. 2016; Pfeiffer et al. 2018; Baldwin, Cai, and Kuralbayeva 2018; Coulomb, Lecuyer, and Vogt-Schilb 2019; Rozenberg, Vogt-Schilb, and Hallegatte (2020; Löffler et al. 2019	Produced assets, no fossil fuel assets	Vary	n.a.	Vary	Vary	Vary	Vary	Vary

Source: World Bank.

Note: BAU = business as usual; capex = capital expenditure; CGE = computable general equilibrium; CO_2 = carbon dioxide; CPS = current policy scenario; EIA = US Energy Information Administration; FF = fossil fuel; GDP = gross domestic product; Gt = gigaton; IAM = integrated assessment model; IEA = International Energy Agency; n.a. = not applicable; NDC = nationally determined contribution; NPS = new policy scenario; NPV = net present value; ppm = parts per million; RES = renewable energy sources; WEO = World Energy Outlook.

A problem with the physical and monetary estimates is that the authors use different concepts of reserves, some of them not being economic assets. In other words, the authors often count those reserves as stranded that would have zero balance sheet value even in the baseline without low-carbon transition. This confusion was introduced with the first Carbon Tracker report (2011), which popularized the concept of stranded assets. In the SNA/SEEA, standard proven reserves include three distinct categories, class A, B, and C deposits. Only category A deposits (defined as producing or commercially recoverable under the current market conditions) are considered assets. IEA (2013, 2015) stressed that most known fossil fuel reserves (for example, 60 percent of known coal reserves) would stay in the ground even in the business-as-usual scenario. McGlade and Ekins (2015) define business-as-usual reserves more narrowly, as those reserves that are recoverable under current economic conditions and have a specific probability of being produced. These include class A and part of class B deposits. This is closer to but still broader than the definition of economic assets in the SNA/SEEA/CWON methodology (that is, class A deposits). Such choices may exaggerate the volume and/or value of stranded assets because some class B and C deposits would likely be left in the ground even without low-carbon transition (IEA 2018) and would never enter the balance sheets of the extractive companies or governments. This analysis follows those few forward-looking models (such as Mercure et al. 2018; Peszko, van der Mensbrugghe, and Golub 2020; and Van der Ploeg and Rezai 2019) that allow only some known reserves to be commercially recoverable and producing (hence becoming SNA assets) under the market conditions simulated endogenously in the business-as-usual scenario. Policy scenarios alter these market conditions; hence, they cause shifts in asset values by changing the production volumes, time profiles, and prices of fossil fuels. Only the difference in the present values of such assets between business-as-usual and policy scenarios is a measure of "stranded assets."

The stranded assets literature rarely measures economic assets as defined in the SNA/SEEA. The gray literature, such as the Carbon Tracker, usually measures financial indicators that are relevant to the listed international extractive companies rather than the rental value of subsoil assets. For example, the Carbon Tracker (2015) estimates that fossil fuel firms could risk around US$2.2 trillion in capex on projects that could be "uneconomic" with a 2°C carbon budget constraint. Another Carbon Tracker study (2017, with 2018 update) uses bottom-up extractive industry supply cost curves to estimate that one-third of the capex from new oil development projects approved by the major listed and state-owned oil companies is "unneeded" in a 2°C scenario (25 percent from new gas projects). The capex of committed fossil fuel development projects or production volume is a different economic category than the asset value in the SNA/SEEA (that is, the discounted value of resource rents). On the one hand, the capex of committed fossil fuel development projects is a conservative estimate of the subsoil asset value, since rational economic agents should expect the value of assets created by a project to be larger than the initial capital investment. On the other hand, the capex exaggerates the value of foregone returns to owners, since many projects that are "unneeded" in the long term will generate net returns in the short term, until some external market or regulatory event ceases their operation. A portion of the initial capex will be recovered before the remaining asset value becomes stranded. It also conflates the value of subsoil assets with the value of produced capital involved in their extraction. On the other side of the spectrum, Lewis et al. (2014) use EIA projections of demand for and prices of fossil fuels to calculate the gross revenue (not of rents or assets) of the fossil fuel companies under alternative EIA scenarios.

Nelson et al. (2014) are more closely aligned with the SNA/SEEA definition of assets than most stranded asset studies available so far. They explore the impact of low-carbon transition on the value of investor portfolios with the supply (cost) curves for coal, oil, gas, and electricity and exogenous assumptions of demand. Like many other later studies, however, the rental value of subsoil assets—oil, gas, and coal—is merged with returns to and depreciation of produced capital in extractive industries. This rich and, in many respects, pioneering analysis provides several important policy-relevant insights, one of them being that not all value at risk would be lost in the low-carbon transition—a portion would be transferred from one economic actor to another, or from one country to another, and would find other sometimes less, sometimes more productive economic uses. The authors estimate that governments would bear close to 80 percent of the US$25 trillion value difference for producers. The study also emphasizes the role of transfers within countries (taxes and subsidies) that should be excluded from asset valuation by the SNA/SEEA/CWON standards. After correcting for transfers, the total value at risk falls from US$25 trillion to US$15 trillion by 2035, of which US$11.2 trillion accounts for oil, US$1.7 trillion for gas, and US$2.2 trillion for coal (including resource rents and returns on extractive capital). After correcting for produced capital, time periods, and discount rates, the value given to stranded fuel reserves is comparable to this study's.

Another common problem in the stranded assets literature is that, until recently, almost all studies have simulated impacts of emission pathways rather than policy pathways. Authors stress tested the fossil fuel sectors with exogenous emission caps applied and "enforced" by a modeler rather than shocking them with policy instruments that can be implemented by legislators. Stranded assets are created by reverse engineering of how much fossil fuels can be burned under the binding carbon budget imposed by *deus ex machina* on the energy sector models. This approach makes it difficult to address policy-relevant questions about stranded assets, such as what the key transmission mechanisms of transition risk are, and how to most effectively and efficiently manage asset portfolios to mitigate this risk. This study belongs to the emerging modeling literature that shows that the risk of stranded assets varies by country and fuel and depends significantly on policy instruments and strategies applied by actors of the global low-carbon transition.

Recent studies increasingly use macroeconomic models instead of simple energy models, in which extractive sectors do not interact with the rest of the economy. Mercure et al. (2018) applied a suite of

E3ME-FTT-GENIE dynamic simulation models (including macroeconometric models) relying on empirical data on socioeconomic and technology diffusion trajectories to capture the impact of imperfect foresight by economic agents and alternative strategies of fossil fuel producers. They compare five scenarios built around different expectations of the future demand for fossil fuels, different technology diffusion trajectories, energy and carbon prices, and trading strategies of major producers. They come up with US$1 trillion to US$4 trillion in stranded oil, gas, and coal assets to 2035 as the differences between the baseline scenario and alternative low-carbon transition scenarios. The authors find significant differences between the winners (net importers such as China and the European Union) and the losers (Canada, the Russian Federation, and the United States). The analysis of Mercure et al. (2018) is the closest to this study in terms of metrics, approach, and rigor. The results are in a similar range when corrected for different discount rates, price levels, and time periods, despite using two different macroeconomic cores of the modeling suites, the neo-Keynesian macroeconometric model by Mercure et al. (2018) and the CGE model based on neoclassical economic theory used here.

In another study, Jin and Zhang (2019) show that under some conditions, environmental regulations, by directing investment toward clean capital, do not have to lead to any significant value loss resulting from stranded fossil fuel assets. Van der Ploeg and Rezai (2019) conduct another policy-driven simulation using a model of the global oil and gas extractive industry (without a macroeconomic model). They find that as soon as climate policy is unexpectedly stepped up, exploration capital and fossil reserves suffer a sudden loss in value. The opposite happens when previously announced climate policy is abruptly abandoned. The value of stranded assets is also higher with carbon taxes than with renewable subsidies.

Peszko, van der Mensbrugghe, and Golub (2020) apply an earlier version of the models used in this study to run a wider range of scenarios. They find that fossil fuel exporters can protect the value of their fossil fuel assets by free riding and subsidizing domestic fuel-intensive industries, as this accelerates industrial and emissions leakage (traditional, *emission-intensive diversification* of fuel exporters). This comes at a price, however, of lower long-term consumption and growth and higher exposure to external transition shocks. A flat import fee imposed by fuel importers against nonparticipating FFDCs, as proposed by Nordhaus (2015), represents the worst-case scenario for fuel asset owners in exporting countries. As shown by Peszko, van der Mensbrugghe, and Golub (2020), its credible threat should encourage FFDCs to pursue *asset diversification* beyond fossil fuel value chains and cooperative carbon policies. Both coping strategies would benefit their societies at large but harm the extractive fuel wealth. That study also illustrated that values and composition of nations' wealth will depend on how low-carbon transition unfolds and how countries choose to diversify. Asset diversification would help FFDCs accumulate capital that is more productive and resilient in a decarbonizing world and discover new sources of global comparative advantage outside of the comfort zone of the fossil fuel value chains.

Political Economy of Global Cooperation on Climate Change

From the policy perspective, the question of who loses the most value in what fuel and under what scenario matters much more than any global value of stranded assets. Two country groups stand out with the highest fossil fuel assets value at risk in dollar terms (figure 10.9). The first is MNA, which is heavily dependent on fossil fuel wealth for growth and export revenue. The most exposed fuel in MNA is oil, which is also the most valuable fuel per unit of energy and the most tradable. The second group consists of middle-income fuel importers including China and India. These countries have a large value of coal reserves exposed to low-carbon transition risk, although their growth and export revenues are not dependent on coal (figure 10.4). Potentially stranded coal assets are not a source of systemic macrofiscal risk, although they pose a challenge for low-carbon transition in the electricity sector and social and political risk because of potentially *stranded labor* in coal mining. These two most exposed regions differ in many respects but have one surprising common interest—they both benefit from cooperative low-carbon transition. MNA benefits because lower CPL carbon taxes in the cooperative scenarios prolong the transition away from oil in transport in CPLs, which are the major oil importers. China and India also benefit from cooperation because lower domestic carbon taxes in the cooperative scenarios prevent industrial leakage to FFDCs and delay early retirement of some of the most efficient coal power plants. None of these increase global CO_2 emissions. Total emission trajectories are the same as in the unilateral policy scenarios (figure 10.6). Emissions just shift between countries.

Ambitious unilateral climate policies implemented by large net fuel importers can trigger significant industrial and emissions leakage to fossil fuel–dependent countries. In the unilateral policy scenarios, the OECD countries and middle-income net fuel importers, including China and India, implement much higher domestic carbon taxes to maintain the same global emissions as in the cooperative scenarios. FFDCs continue domestic climate policies just to meet their initial NDC goals. This triggers a chain of macroeconomic pressures on fuel producers and exporters. First, by imposing carbon taxes, fuel importers capture a portion of exporters' resource rents and collect them as their own fiscal revenue. High carbon taxes in major fossil fuel importers increase fuel prices to their consumers, suppressing external fuel demand. The declines of export demand and/or producer prices reduce the exporters' opportunity costs of using fuels at home. Exchange rates of exporters' currencies also fall, reversing the Dutch disease and boosting the export competitiveness of their manufacturing industry (if it is sufficiently developed and competitive). In industrialized fuel-producing countries, a bulk of manufacturing output is concentrated downstream in the value chain of the extractive sectors. In the meantime, foreign competitors in energy-intensive industries are being prematurely retired at home by high unilateral carbon prices. Therefore, the emission- and energy-intensive industries in fuel-producing countries expand their market shares in the globally declining emission-intensive sectors, at the expense of the CPLs. Such traditional diversification away from reliance on fuel exports and toward reliance on downstream, fuel-intensive tradable products can be successful in the short to medium term. But it leads to accumulation of carbon-intensive produced capital, which is increasingly exposed to external technology and policy shocks of low-carbon transition and eventually to the tragedy of the horizon (Carney 2015; Peszko et al. 2020). Relatively new fuel exporters in Africa and Latin America or conflict-affected countries in MNA may not be able to cushion the external shock to fossil fuel wealth by reversing the Dutch disease, because they have not yet converted fossil fuel rents to well-developed manufacturing sectors. Unless these economies diversify their exports away from fuels, exchange rate depreciation arising from lower external demand by large fuel importers may push these countries back to dependence on mining, agricultural commodities, or timber, increasing environmental pressures on sustainable development.

Already industrialized natural gas and coal producers have stronger incentives to free ride and fall into the trap of traditional, emission-intensive diversification. Gas has multiple industrial uses, including in process heating, chemicals, fertilizers, hydrogen, and space heating. It can substitute for coal in power and for oil in transport. In contrast, oil is used mainly in transport and much less in petrochemicals and power. The simulations suggest that the comparative advantage of gas-intensive industries in FFDCs seems to persist in the noncooperative scenarios despite BCATs. Coal is mainly used in power generation where it faces competitive pressure from natural gas and renewables. Smaller quantities are used in steel and cement production, where coal is more difficult to substitute.

These findings paint a more complex picture of the vulnerability of different fossil fuel producers than simple divestment narratives often found in stranded assets literature. The multisectoral and dynamic nature of ENVISAGE, coupled with a detailed extractive sector model, illustrates that low-carbon transition poses additional challenges, not just for high-cost producers, but also for those that are further from the remaining demand, less diversified, and with limited access to resources. The ability to redirect fossil fuels from exports to domestic use by increasing the output of energy- and emission-intensive industries also makes a difference to sovereign risk and risk management strategies. Many fuel-producing and -exporting countries in Sub-Saharan Africa and Latin America and the Caribbean, as well as conflict-affected countries in MNA and the rest of Africa, may have limited capabilities to mitigate transition risk in this way. In contrast, fuel exporters that have already developed a heavy industrial base and value chains, such as the Gulf Cooperation Council countries, Mexico, or the Russian Federation, may be tempted to give their heavy industries a "free ride" on the global effort to mitigate climate change and try to continue generating wealth from fossil fuel reserves by stimulating domestic demand by downstream fuel-intensive industries and becoming "emissions havens." The simulations show that a credible threat of BCATs can be a sufficient deterrent to discourage such free riding for MNA and ECA, but only if policy makers were concerned more about the wealth of the entire society (figure 10.17) than about the wealth of gas and coal producers. For the countries that are captured by their extractive institutions (Acemoglu and Robinson 2012), BCAT may not be enough to encourage cooperation without additional incentives, such as financial and technology transfers, preferential trade and policy agreements, or stricter trade sanctions (Peszko, Golub, and van der Mensbrugghe 2019; Peszko, van der Mensbrugghe, and Golub 2020).

Dynamic analysis of resource rents suggests that the steep ramping-up of climate action in 2025 may be a much larger shock to resource owners and shareholders than a CGE model can simulate. For the oil and gas markets, it could be a shock comparable to the value destruction in 2014 and 2020, although some significant differences must be noted. First, the 2014 shock was an unexpected market price drop with no impact on demand. In contrast, the COVID-19 shock to fossil fuel rents in 2020 was driven by an equally unexpected and sudden drop but in demand because of pandemic lockdowns. In both historical cases, the impact was "external" and surprising, but once it happened it was expected to be temporary. Indeed, demand and prices rebounded after the shocks, restoring the future value of fossil fuel assets. In contrast, the shocks of low-carbon transition are driven by dedicated policy efforts; hence, the markets are more likely to lose hope for a future rebound of rents and returns. The future loss of fossil fuel asset value can be secular and permanent rather than just cyclical as in the past.

Competition and fights for market shares in declining industries are much more volatile and irrational than simulated in the CGE model, which assumes rational behavior of all economic agents and always pushes them to new equilibria after the shock. For coal owners and shareholders in coal companies, the impact can be unprecedented. The milder and short-term drop of global coal rents by 40 percent globally in 2013–15 caused a shockwave of mine closures in Europe and bankruptcies in the US coal mining industry, starting with the world's largest private coal company, Peabody Energy. The policy-induced annual drop in coal rents of 62 percent in five years simulated here suggests the possibility of a much deeper impact on the coal industry. With no hope for a future rebound of coal rents, which always happened in the past, the future shock to coal mining may be very serious. And this time it would also affect the coal mines in developing countries, including China and India, where mining communities are often more vulnerable than those in the Appalachian region in the United States or Silesia in Poland. The good news is that the policy-induced shocks are anticipated at least by those who want to believe they will prevail; hence, countries can better prepare to hedge the transition risks. The challenge for policy makers will be to give mining communities honest early warning and help them through a smooth *just transition* and facilitate the accumulation of a broader wealth base for their development.

The lower-income, fragile, and conflict-affected fossil fuel producers may need international assistance in the low-carbon transition. They have few alternative sources of short-term revenue that could be reinvested in a diversified portfolio of national wealth to create a more resilient and greener asset base for long-term resilient, sustainable, and equitable prosperity. As discussed earlier, reversing the Dutch disease may not help them in the absence of well-developed internationally competitive manufacturing sectors.

Conclusion

Low-carbon transition represents a material risk to the value of all fossil fuel assets. In 2018–50, under ambitious climate policies, global fossil fuel wealth may be US$4.4 trillion to US$6.2 trillion (13–18 percent) lower than in the reference scenario that reflects the expectations of fossil fuel owners. Globally, this amounts to only 13–18 percent less value than with the NDC-oriented reference scenario. In real life, however, without the gentle safeguards of the equilibrium conditions and perfect rationality of all agents assumed in the CGE model, the shocks can be much stronger. This could be especially true for the least prepared asset owners and those countries that have not developed internationally competitive manufacturing. Once extractive industries become widely perceived by investors as declining industries, the transition may be much more volatile and erratic than even past experience suggests. Competition between asset owners will intensify as demand shrinks and disruptive clean technologies capture more markets. Producers with low extraction costs, already sunk capital costs, lower upfront capital needs, better access to investors and developers, higher accumulated financial strength, lower leverage, and more highly developed export infrastructure will be in a more privileged position to maintain and even increase their fossil fuel wealth than others. Countries that are less dependent on fuel export revenues and have more diversified asset bases with which to compete internationally in terms of manufacturing goods and knowledge-intensive services will find it easier to navigate a low-carbon transition toward new sources of growth and comparative advantage.

The risk of low-carbon transition is unevenly distributed across fuels, countries, and asset owners. By fuel, oil assets represent the largest value at risk and gas the lowest, but in percentage terms, coal reserves are likely to lose the largest share of value and oil the least. By region, the highest fuel assets value at risk is in the MNA region, because of oil.

Rapid ratcheting up of carbon pricing may have very serious implications for coal wealth worldwide. In percentage terms, coal-intensive middle-income fuel importers and coal exporters risk the most. Cambodia, China, India, Indonesia, Mongolia, and several other coal-intensive countries will also need to prepare for downstream shocks in coal-intensive electricity generation. A policy-driven low-carbon transition can cause almost total collapse of coal mining industries. Coal-producing developing countries could experience a similar but faster collapse of coal mining than those experienced in the past by the European Union and the United States. The collapse of coal mining is not likely to cause systemic macrofiscal risk in any country because, unlike the case of oil and gas, even the largest coal producers do not depend on coal rents for tax and export revenues or as a growth driver. The largest risk of economic, social, and political disruptions is related to stranded workers in coal mining regions and coal-dominated power systems.

Exploratory policy scenarios can help understand the risks and uncertainties of low-carbon transition. They can also identify policy pathways to cooperation on climate change between fuel importers and exporters. The scenarios simulated here shed new light on the political economy of low-carbon transition and climate cooperation between countries with different path dependencies. Despite the likelihood that a noncooperative low-carbon transition would destroy more fossil fuel asset value, especially with BCAT, the self-interest to be a leader or a follower of climate action varies by country and fuel.

Fuel importers have economic incentives and capabilities to lead climate policies. They also have collective self-interest and market power to encourage fuel exporters to overcome their free-riding incentives with policies including BCATs, although for some gas and coal exporters this may not be enough to cooperate. The gains that CPLs would enjoy from global climate cooperation are more than enough to compensate for their loss of coal wealth, including in coal-intensive net fuel importers, like China and India.

Interestingly, large oil exporters, especially in MNA, also benefit from cooperative climate policies, especially if the counterfactual is an ambitious unilateral climate action by a large club of major oil importers with BCATs. The fundamental incentives of large oil exporters in cooperative climate policies still goes largely unnoticed in the literature and in public debates, although recent more proactive engagement of the Gulf Cooperation Council countries in cooperative climate initiatives suggests that their leaders begin to see that the risks of cooperation are lower than the risks of free riding.

Many gas and coal exporters may have relatively strong incentives to free ride on the unilateral climate policies of fuel importers. They benefit from domestication of emission-intensive heavy industry (emissions leakage) under the asymmetric climate policies. A credible threat of a BCAT imposed by importers could erase the benefits of free riding for many, although not necessarily all, large gas and coal producers. Low international fuel prices combined with high carbon taxes abroad encourage most industrialized gas and coal exporters to increase their market share in globally declining emission-intensive manufacturing and services. Additional incentives may be needed to encourage and enable cooperative climate policies by countries having strong comparative advantage in heavy industrial products (Peszko, Golub, and van der Mensbrugghe 2019; Peszko, van der Mensbrugghe, and Golub 2020). Pollution havens may be consistent with mitigation pathways toward 2°C and even some 1.5°C goals. Policy-driven yet still uncertain technology breakthroughs, for example in production and distribution of green and blue hydrogen, could eliminate the benefits of pollution havens, however.

The lower-income, fragile, and conflict-affected fossil fuel producers will need international assistance in the low-carbon transition. They have few alternative sources of short-term revenue that could be reinvested in a diversified portfolio of national wealth to create a more resilient and greener asset base for long-term resilient, sustainable, and equitable prosperity.

The CWON core accounts represent a conservative approach to the valuation of fossil fuel wealth, consistent with SNA-compatible standards of government balance sheets. In the climate policy scenarios, the value of oil and gas assets remains higher than in the CWON, although coal wealth in the CWON does not pass the low-carbon transition stress test. The reason is that the CWON uses rigorous, albeit conservative, SNA accounting principles and considers as assets only class A deposits that come from projects that were producing, those approved for development, and those justified for development (United Nations 2019) under market conditions prevailing in 2014–18, which were characterized by historically low fossil fuel prices. Furthermore, following the SNA/SEEA recommendations, the CWON valuation assumes that the average rents from 2014–18 will remain constant until 2050. In contrast, ENVISAGE, with its resource extraction module and endogenous formation of prices, production, and rents, also converts some proven, class B reserves to class A reserves and brings them into production when simulated market conditions allow. Future market conditions in the business-as-usual scenario (even with NDC pledges) are more conducive to fossil fuel wealth than on average in 2014–18; therefore, total fossil fuel asset value increases to US$34.2 trillion (compared to US$25.9 trillion in the CWON).

The values of the stranded fuel assets simulated here are broadly in line with the stranded assets literature, although comparison is difficult because of the literature's wide variety of approaches and rigor. This study contributes to a nascent literature that stress tests fossil fuel wealth with alternative policy pathways rather than emissions pathways (that is, carbon budgets on paper).

As the low-carbon transition drives down volumes of fossil fuel use, the noncompetitive producers will also be leaving market, inducing additional volatility in the global commodity prices. The last remaining fuel producers will increase their market power and may well be able to secure higher prices and extract higher rents and profits from the last producing reserves. Decoupling volumes from rents in the public discourse could create a much-needed space for less confrontational dialogue about low-carbon transition. The resource-rich nations would find it less threatening to engage in the dialogue on climate policies if they could expect that their total rents would be falling slower than their production volumes.

Notes

1. The key goal of the Paris Agreement is to limit global warming to well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, compared with preindustrial levels.
2. By far, most scenarios available in the mitigation pathways literature assume alternative environmental constraints as inputs to the models (stabilize greenhouse gas concentrations over the 21st century, limit end-of-century radiative forcing to specific levels, or prescribe an overall limit on total cumulative carbon dioxide [CO_2] or greenhouse gas emissions over the 21st century, as a proxy for global-mean temperature rise over the year). Models are then optimized to achieve these objectives in a cost-effective manner (Rogelj, Shindell, et al. 2018;

Rogelj et al. 2019). In this chapter, the modeling approach applies a rarer logic. It assumes alternative policy instruments applied by certain country groups as explicit inputs to the model. The model produces an emissions pathway as an output of model simulations. The approach produces scenarios that may be more realistic and policy relevant but are neither globally nor intertemporally optimal. Nor do they guarantee the same stringency of carbon budgets or temperature outcomes as in scenarios in which these environmental variables are assumed to be constraints. Nonetheless, as explained later in the text, comparison with Intergovernmental Panel on Climate Change (IPCC) scenarios on the same terms (gross emissions of CO_2 in the same period) shows that the cumulative emissions calculated in the scenarios are in line with the carbon budget used in the 2 degrees Celsius–consistent mitigation pathways and even some 1.5 degrees Celsius–consistent scenarios found in the IPCC-related literature.

3. Except for unit rent, which is often smoothed over five or six years for asset valuation.
4. Detailed descriptions of the methodology and data sources are provided on the CWON website, http://www.worldbank.org/cwon/.
5. These can be accessed at the Global Trade Analysis Project databank, https://mygeohub.org/groups/gtap/envisage-docs.
6. For this study, ENVISAGE was not run in its integrated assessment mode, so avoided damages from climate change are not endogenously calculated and the impact of climate policy on GDP is by design negative compared with the baseline. It is also worth stressing that in the CGE models it is not the absolute figures but differences between countries, fuels, and policy scenarios that provide the most important insights.

References

Acemoglu, D., and J. Robinson. 2012. “Why Nations Fail: The Origins of Power, Prosperity, and Poverty.” New York: Crown.

Aguiar, A., M. Chepeliev, E. Corong, R. McDougall, and D. van der Mensbrugghe. 2019. “The GTAP Data Base: Version 10.” *Journal of Global Economic Analysis* 4 (1): 1–27. https://jgea.org/ojs/index.php/jgea/article/view/77.

Ansari, D., and F. Holz. 2020. “Between Stranded Assets and Green Transformation: Fossil-Fuel-Producing Developing Countries towards 2055.” *World Development* 130: 104947. https://doi.org/10.1016/j.worlddev.2020.104947.

Baldwin, E., Y. Cai, and K. Kuralbayeva. 2018. “To Build or Not to Build? Capital Stocks and Climate Policy.” The Grantham Research Institute on Climate Change and the Environment, Centre for Climate Change Economics and Policy, London. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2018/01/Working-Paper-290-Baldwin-et-al-1.pdf.

Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac, and J. Eom. 2015. “Carbon Lock-In through Capital Stock Inertia Associated with Weak Near-Term Climate Policies.” *Technological Forecasting and Social Change* 90 (A): 62–72.

BP. 2020. *Statistical Review of World Energy 2020*. London: BP. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf.

Carbon Tracker Initiative. 2011. “Unburnable Carbon: Are the World’s Financial Markets Carrying a Carbon Bubble?” https://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-Full-rev2-1.pdf.

Carbon Tracker Initiative. 2013. “Unburnable Carbon 2013: Wasted Capital and Stranded Assets.” http://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-2-Web-Version.pdf.

Carbon Tracker Initiative. 2015. “The $2 Trillion Stranded Assets Danger Zone: How Fossil Fuel Firms Risk Destroying Investor Returns.” http://www.carbontracker.org/wp-content/uploads/2015/11/CAR3817_Synthesis_Report_24.11.15_WEB2.pdf.

Carbon Tracker Initiative. 2017 (with 2018 update). “2 Degrees of Separation: Transition Risk for Oil and Gas in a Low Carbon World.” https://www.carbontracker.org/reports/2-degrees-of-separation-transition-risk-for-oil-and-gas-in-a-low-carbon-world-2/.

Carbon Tracker Initiative. 2018. “Mind the Gap: The $1.6 Trillion Energy Transition Risk.” https://carbontracker.org/reports/mind-the-gap/.

Carbon Tracker Initiative. 2020. “Decline and Fall: The Size and Vulnerability of the Fossil Fuel System.” https://carbontracker.org/reports/decline-and-fall/.

Carney, M. 2015. “Breaking the Tragedy of the Horizon: Climate Change and Financial Stability.” Speech by the Governor of the Bank of England, September 29, London.

Chepeliev, M. 2020. “GTAP-Power Data Base: Version 10.” *Journal of Global Economic Analysis* 5 (2). http://dx.doi.org/10.21642/JGEA.050203AF.

Coulomb, R., O. Lecuyer, and A. Vogt-Schilb. 2019. “Optimal Transition from Coal to Gas and Renewable Power under Capacity Constraints and Adjustment Costs.” *Environmental and Resource Economics* 73 (2): 557–90.

Dietz, S., A. Bowen, C. Dixon, and P. Gradwell. 2016. “ ‘Climate Value at Risk’ of Global Financial Assets.” *Nature Climate Change* 6: 676–79.

EC (European Commission), IMF (International Monetary Fund), OECD (Organisation for Economic Co-operation and Development), UN (United Nations), and World Bank. 2009. *System of National Accounts 2008*. New York: United Nations.

Guivarch, C., and S. Hallegatte. 2011. “Existing Infrastructure and the 2C Target.” *Climatic Change* 109 (3): 801–05.

Huppmann, D., E. Kriegler, V. Krey, K. Riahi, J. Rogelj, K. Calvin, F. Humpenoeder, et al. 2019. “IAMC 1.5°C Scenario Explorer and Data Hosted by IIASA.” Integrated Assessment Modeling Consortium and International Institute for Applied Systems Analysis. https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.

IEA (International Energy Agency). 2012. *World Energy Outlook 2012*. Paris: IEA.

IEA (International Energy Agency). 2013. *Redrawing the Energy-Climate Map*. World Energy Outlook Special Report. Paris: Organisation for Economic Co-operation and Development/IEA.

IEA (International Energy Agency). 2015. *World Energy Outlook 2015*. Paris: IEA.

IEA (International Energy Agency). 2018. *World Energy Outlook 2018*. Paris: IEA.

Jin, W., and Z. Zhang. 2019. “Capital Accumulation, Green Paradox, and Stranded Assets: An Endogenous Growth Perspective.” FEEM Working Paper No. 33.2018, Fondazione Eni Enrico Mattei, Milan, Italy. https://ssrn.com/abstract=3313337 or http://dx.doi.org/10.2139/ssrn.3313337.

Koch, N., and A. Bassen. 2013. “Valuing the Carbon Exposure of European Utilities: The Role of Fuel Mix, Permit Allocation, and Replacement Investments.” *Energy Economics* 36: 431–43.

Kossoy, A., G. Peszko, K. Oppermann, N. Prytz, N. Klein, K. Blok, L. Lam, et al. 2015. *State and Trends of Carbon Pricing 2015*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/22630.

Lewis, M. C., S. Voisin, S. Hazra, S. Mary, and R. Walker. 2014. "Stranded Assets, Fossilised Revenues." *Energy Transition and Climate Change*, April 24. Kepler Cheuvreux, Paris.

Löffler, K., T. Burandt, K. Hainsch, and P.-Y. Oei. 2019. "Modeling the Low-Carbon Transition of the European Energy System: A Quantitative Assessment of the Stranded Assets Problem." *Energy Strategy Reviews* 26: 100422.

McGlade, C., and P. Ekins. 2015. "The Geographical Distribution of Fossil Fuels Unused When Limiting Global Warming to 2°C." *Nature* 517: 187–90. https://doi.org/10.1038/nature14016.

Mercure, J.-F., H. Pollitt, J. E. Viñuales, N. R. Edwards, P. B. Holden, U. Chewpreecha, P. Salas, et al. 2018. "Macroeconomic Impact of Stranded Fossil Fuel Assets." *Nature Climate Change* 8: 588–93. https://doi.org/10.1038/s41558-018-0182-1.

Nelson, D., M. Hervé-Mignucci, A. Goggins, S. J. Szambelan, T. Vladeck, and J. Zuckerman. 2014. "Moving to a Low-Carbon Economy: The Impact of Policy Pathways on Fossil Fuel Asset Values." CPI Energy Transition Series, Climate Policy Initiative, San Francisco.

NGFS (Network for Greening the Financial System). 2020. "Guide to Climate Scenario Analysis for Central Banks and Supervisors." NGFS, Paris. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_guide_scenario_analysis_final.pdf.

Nordhaus, W. 2015. "Climate Clubs: Overcoming Free-Riding in International Climate Policy." *American Economic Review* 105 (4): 1339–70.

Peszko, G., A. Golub, and D. van der Mensbrugghe. 2019. "Cooperative Carbon Taxes under the Paris Agreement that Even Fuel Exporters Could Like." World Bank Working Paper Series. First International Conference on Carbon Pricing, 131–55, World Bank, Washington, DC.

Peszko, G., D. van der Mensbrugghe, and A. Golub. 2020. "Diversification and Cooperation Strategies in a Decarbonizing World." Policy Research Working Paper 9315, World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/34056.

Peszko, G., D. van der Mensbrugghe, A. Golub, and M. Chepeliev. 2021. "Low-Carbon Transition, Stranded Fossil Fuel Assets, Border Carbon Adjustments, and International Cooperation-Macroeconomic Analysis." CWON 2021 background paper, World Bank, Washington, DC.

Peszko, G., D. van der Mensbrugghe, A. Golub, J. Ward, D. Zenghelis, C. Marijs, A. Schopp, et al. 2020. *Diversification and Cooperation in a Decarbonizing World: Climate Strategies for Fossil Fuel-Dependent Countries*. Climate Change and Development. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/34011.

Pfeiffer, A., C. Hepburn, A. Vogt-Schilb, and B. Caldecott. 2018. "Committed Emissions from Existing and Planned Power Plants and Asset Stranding Required to Meet the Paris Agreement." *Environmental Research Letters* 13 (5). https://doi.org/10.1088/1748-9326/aabc5f.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker. 2016. "The '2°C Capital Stock' for Electricity Generation: Committed Cumulative Carbon Emissions from Electricity Generation Sector and the Transition to a Green Economy." *Applied Energy* 196: 1395–1408.

Rogelj, J., D. Huppmann, V. Krey, K. Riahi, L. Clarke, M. Gidden, Z. Nicholls, and M. Meinshausen. 2019. "A New Scenario Logic for the Paris Agreement Long-Term Temperature Goal." *Nature* 573: 357–63. https://doi.org/10.1038/s41586-019-1541-4.

Rogelj, J., A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, et al. 2018. "Scenarios towards Limiting Global Mean Temperature Increase below 1.5°C." *Nature Climate Change* 8: 325–32. https://doi.org/10.1038/s41558-018-0091-3, with supplementary materials at https://static-content.springer.com/esm/art%3A10.1038%2Fs41558-018-0091-3/MediaObjects/41558_2018_91_MOESM1_ESM.pdf.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development." In *Global Warming of 1.5°C*, an IPCC Special Report, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, et al. Geneva: Intergovernmental Panel on Climate Change.

Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte. 2020. "Instrument Choice and Stranded Assets in the Transition to Clean Capital." *Journal of Environmental Economics and Management* 100: 102183.

SEI (Stockholm Environment Institute), IISD (International Institute for Sustainable Development), ODI (Overseas Development Institute), E3G (Third Generation Environmentalism), and UNEP (United Nations Environment Programme). 2020. *The Production Gap Report: 2020 Special Report*. Nairobi, Kenya: UNEP. http://productiongap.org/2020report.

Sinn, H.-W. 2008. "Public Policies against Global Warming: A Supply Side Approach." *International Tax and Public Finance* 15 (4): 360–94.

Spedding, P., K. Mehta, and N. Robins. 2013. "Oil and Carbon Revisited: Value at Risk From 'Unburnable' Reserves." HSBC Oil and Gas/Climate Change Europe. https://www.longfinance.net/media/documents/hsbc_oilcarbon_2013.pdf.

United Nations. 2019. "The System of Environmental-Economic Accounting for Energy (SEEA-Energy)." New York: Department of Economic and Social Affairs, United Nations. https://seea.un.org/sites/seea.un.org/files/documents/seea-energy_final_web.pdf.

van der Mensbrugghe, D. 2019. "The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model Version 10.01." Center for Global Trade Analysis, Purdue University, West Lafayette, IN. https://mygeohub.org/groups/gtap/envisage-docs.

Van der Ploeg, F., and A. Rezai. 2019. "The Risk of Policy Tipping and Stranded Carbon Assets." Working Paper No. 7769, CESifo Economic Studies, Oxford University, Oxford, UK.