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Diversification and Cooperation Strategies in a Decarbonizing World

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Abstract

Fossil fuel importers can apply various climate and trade taxes to encourage fossil fuel–dependent countries to cooperate on climate mitigation, and fossil fuel–dependent countries can respond with alternative diversification and cooperation strategies. This paper runs macroeconomic model simulations of alternative strategies that the global community and fossil fuel–dependent countries can pursue to encourage and enable their participation in a global low-carbon transition. The following are the findings from the simulations. (i) Fuel importers' unilateral carbon taxes capture fossil fuel–dependent countries' resource rents and accelerate their emission-intensive diversification. (ii) Border taxes on the carbon content of imports from fossil fuel–dependent countries do not induce comprehensive cooperation, but broader trade sanctions do. (iii) Cooperative wellhead carbon taxes can achieve cooperation without trade wars. (iv) Lower-income fossil fuel–dependent countries with large untapped reserves need additional incentives and enablers to cooperate and diversify into low-carbon assets. (v) Incentives to cooperate are misaligned between different fossil fuel–dependent countries and between owners of different fuels. (vi) The strategies that maximize consumption and growth in fossil fuel–dependent countries reduce the value of assets in extractive and heavy industries. (vii) Asset diversification is a robust, long-term strategy but faces the tragedy of the horizon.

JEL:
O44: Environment and Growth
Q32: Exhaustible Resources and Economic Development
Q43: Energy and the Macroeconomy
Q56: Environment and Development • Environment and Trade • Sustainability • Environmental Accounts and Accounting • Environmental Equity • Population Growth

Keywords: Low-carbon transition, Climate clubs, Climate cooperation, Diversification, Fossil Fuel–Dependent Countries, Stranded Assets

1. Background and the Problem

Fossil fuel–dependent countries (FFDCs) face the conundrum of being both vulnerable to climate change and exposed to the global efforts to mitigate it. The FFDCs that rely on oil, gas, and coal are at greatest risk of upheaval from a low carbon transition (LCT), which may cause a global decline in fossil fuel industries and related value chains on which their economies depend (Carney 2015, IMF 2019, Bolton et al. 2020). But they find themselves at a crossroads due to the uncertainty of whether and when tipping points will come. Hence many have delayed preparations to adequately manage the impacts of low carbon transition (Manley, Cust and Cecchinato 2017, Mirzoev et al. 2020).

FFDCs face the challenges of poverty and limited options for development opportunities beyond the fossil fuel value chain. The poorest FFDCs in Africa and Latin America are concerned that their discovered but not yet exploited fuel reserves will become worthless before they can be converted into the productive infrastructure, industry and educated people that can pull them out of poverty and allow them to successfully compete in the knowledge-intensive, low-carbon global economy of the future. The more advanced emerging fossil fuel–dependent economies are concerned about the economic and social disruption of suddenly shifting away from foundational infrastructure and systems they relied on for decades and that pulled them out of poverty on the back of fossil fuels and related industries. The 2014 oil price dive and the Covid-19 crisis have demonstrated that the poorest fuel exporters are more vulnerable compared to the largest and the richest oil producers with large market power, such as the United States, Gulf countries and the Russian Federation.

The literature on international climate cooperation is dominated by the old developed-developing countries divide (Gollier and Tirole 2015; MacKay et al. 2015; and Cramton et al. 2017, Stiglitz 2015). Recently, however, several low-income countries that are vulnerable to climate change change—such as the Alliance of Small Island States (AOSIS group)—are becoming global leaders of climate mitigation, although their ability to act is constrained by a lack of resources. China and India have also realized their potential strengths in the global low-carbon economy and are shifting their gears towards knowledge-, rather than energy-intensive growth drivers. It proves that the willingness to cooperate on climate action varies among developing countries and cannot be explained by the income level alone. The path dependency on fossil fuels also shapes national incentives.

The perspective of fossil fuel exporters on traditional demand-side climate policies is not new to the economic literature. Already in 1982 Bergstrom showed that if the main oil consuming nations cooperated with each other they could extract significant rents from oil producing nations through national excise taxes, counterbalancing the OPEC cartel goals. Liski and Tahvonen (2004), Jonansson et al. (2009), Dong and Whalley (2009) or Bauer et al. (2016) also show that demand-side climate policies of OECD countries would capture rents from fossil fuel exporters, and Strand (2008; 2013) and Karp et al (2015) proposed that a carbon tax extracts higher rents from exporters than a cap-and-trade scheme. Franks et al. (2015) and Edenhofer and Ockenfels (2015) moved the debate further by demonstrating with a theoretical model that for fuel importers carbon taxes are a superior alternative to capital taxes because they capture part of the resource rent that is held initially by the owners and exporters of fossil fuels. They showed that this result holds regardless of whether fuel importers cooperate, and that fuel exporters lose on international carbon taxes even if they can influence price strategically with an export tax. Erickson et al. 2015; Erickson and Lazarus 2015; Elliott et al 2010 and Seto et al. 2016 explored further why carbon lock-in makes fossil fuel producers reluctant to undertake climate action. Therefore, Stiglitz (2015) noted that fossil fuel exporters may not have the incentive to implement traditional demand-side domestic carbon pricing just under the pressure of moral suasion.

Relatively fewer authors explore the coping strategies that the fossil fuel–dependent countries can pursue amid the international climate mitigation action. Already in 1995 Wirl argued that the best strategy for oil exporters is to pre-empt importers' carbon tax at the wellhead. Dullieux et al 2014 suggested that in anticipation of consumers' carbon tax, OPEC could respond by increasing the producer price to postpone extraction and reduce consumption, rendering the carbon tax useless and capturing (a part of) the "climate rent". Similarly, Bohringer et al (2018) argued that OPEC may increase the oil price as a response to EU climate policy, thereby reversing leakage while retaining resource rents, but the coalition or cartel size critically affects the effectiveness of such strategy. The unusual joint effort of OPEC+ (including Russia) and the United States to defend the oil price hit by coronavirus pandemic in April 2020 shows that the size of such coalition can grow under stress, at least temporarily.

Supply-side climate policies in the major fossil fuel producers (mainly coal) are proposed to overcome the "green paradox". The green paradox is the observation first made by Sinn (2008, 2012 and 2015) that the owners of polluting assets (such as fossil fuels), when anticipating tightening of environmental policies, would accelerate extraction and consumption of fossil fuels for fear of their becoming worthless (stranded), hence accelerating global warming. Papers like Asheim 2012; Lazarus et al. 2015; Gerarden et al.2016; Muttitt et al. 2016; Richter et al. 2018; Collier and Venables 2014; Fæhn et al. 2017; Day and Day 2017; Eichner and Pethig 2017, Lazarus and van Asselt 2018, or Piggot et al., 2018 explore different variations of coal production taxes or output quotas that coal producers could initiate to ensure that as demand for coal drops their revenues do not fall correspondingly, thus relieving the pressure to accelerate fuel consumption and reversing the green paradox. Most recently Asheim et al (2019) called for a supply-side climate treaty, based on coordinated agreement to limit global fossil fuel supply by major producers. Harstad 2012 proposed that the coalition of climate leaders could simply buy out foreign fossil fuel reserves and keep them in the ground. In this paper we explore the options for a combination of supply and demand side carbon tax and trade policies that could be negotiated between fuel exporters and importers in their mutual interest (see Peszko et al 2019).

In this context, this paper contributes to the World Bank report "Diversification and Cooperation in a Decarbonizing World" with macroeconomic model simulations of the alternative strategies that the global community and fossil fuel–dependent countries' (FFDCs) can pursue to encourage and enable their participation in a global low carbon transition (LCT). Without FFDCs, an international coalition of climate action may not be comprehensive and stable enough to achieve the climate mitigation goals of the Paris Agreement.

This analysis also contributes to the debate on stranded assets but transcends the conventional narrative with a broader perspective. The stranded assets literature originated from the observation of the quantitative mismatch between the volume of carbon embedded in the size of proven reserves of fossil fuels and the volume of future emissions consistent with different global temperature increase constraints, or "carbon budget" (Carbon Tracker and Grantham Institute

2013, Helm 2015, Meinshausen et al. 2009, Allen et al., 2009; McGlade and Ekins, 2015; van der Ploeg, 2018). The distributional estimates of whose reserves are "unburnable" are usually based on the calculations using global extraction cost curves and break-even prices. For example McGlade and Ekins 2015 used a large ensemble of models to estimate that about a third of global oil reserves, half of global gas reserves and over four-fifths of global coal reserves are "unburnable" for a 66 percent probability of achieving the 2°C goal, mostly in China, Russia and the United States in the Arctic, and Canadian tar sands. The Carbon Tracker (2017) used a bottom-up extractive industries model to estimate that one-third of the potential supply from new oil projects in the pipeline of major listed and state-owned oil companies is "unneeded" and 25% of potential supply from new gas projects is "unneeded" in a 2°C scenario. This implies that two-thirds of new oil, and three-quarters of new gas development projects were considered compatible with the 2°C constraint. Ansari and Holz (2020) use a partial equilibrium model of the global energy system to argue that China has less carbon assets at risk than Latin America and much less than the Middle East, and hence is more likely to engage in a green transformation.

The stranded asset studies using more complex macroeconomic models are scarce. Mercure et al. (2018), with a suite of models based on the macroeconomic model E3ME, estimated a discounted global wealth loss of $1 trillion to $4 trillion in stranded fossil-fuel assets as a result of (1) ongoing technological progress; (2) amplified by new climate policies to reach the 2°C target; and/or (3) 'sell-out' strategies of low-cost producers (some OPEC countries) to maintain their level of production despite declining demand. The authors found a small impact on aggregate global GDP but significant differences between the winners (e.g. net importers such as China or the European Union) and the losers such as Russia, the United States or Canada, which could see their fossil-fuel industries nearly shut down. Van der Ploeg and Rezai (2016) applied a macroeconomic model to calculate the value of stranded assets that varies with different policy scenarios. Wei Jin and ZhongXiang Zhang (2018) showed that under some conditions, environmental regulations, through directing investment towards clean capital, do not have to lead to stranding of fossil fuel assets or the Green Paradox.

This study goes beyond the narrow focus of the literature on individual assets at risk, whether oil, gas or oil or thermal power plants. We explore how alternative scenarios of low-carbon transition can trigger structural transformation and diversification of national wealth and related drivers of growth and welfare in the fossil fuel–dependent nations. We also quantify impacts of alternative coping diversification and climate cooperation strategies that these countries can pursue to overcome the resource curse and navigate towards sustainable long-term growth in a decarbonizing world. Our approach aligns more with authors like Zenghelis, Fouquet, and Hippe (2018) and Lange et al (2018), who see stranded assets as an opportunity to refresh and rebalance the wealth of nations.

2. Methodology

This section summarizes the methodological approach chosen for this study. A more technical description can be found in GTAP (2018).

2.1. The Models

This study explores multiple scenarios of the plausible impacts of external policy events on the FFDCs and their domestic policy choices to cope with these impacts. Exploratory scenarios are simulated with the GTAP-based global, dynamic, recursive computable general equilibrium

(CGE) ENVISAGE model of the Center for Global Trade Analysis (GTAP) at Purdue University and the World Bank.[1] The macroeconomic model is linked with the fossil fuel depletion models from Rystad (oil and gas) and Wood Mackenzie (coal).

2.2. Climate Clubs

For this study, ENVISAGE's 141 countries and regions were aggregated into 15 regions, further grouped into two stylized and hypothetical climate policy "clubs," the members of which are assumed to apply similar policies:

- *Low Carbon-Transition (LCT) pioneers*, which are assumed to be the first movers of climate policies. They include almost all member countries of the Organisation for Economic Co-operation and Development (OECD) and several middle-income net importers of fossil fuels, most notably China and India. LCT Pioneers have a revealed comparative advantage in low-carbon, knowledge-intensive sectors, even if they are large producers of fossil fuels (such as Canada, Norway, Australia, the United Kingdom, or the United States).
- *Fossil Fuel–Dependent Countries (FFDCs)*, which can cope with an LCT through various diversification and cooperation choices. FFDCs are divided into five subgroups with distinct patterns of fuel dependency and income levels: (i) Gulf Cooperation Countries; (ii) other large middle-income oil and gas exporters; (iii) Russian Federation; (iv) low- and middle-income countries with large discovered, but not yet fully exploited reserves; and (v) middle-income coal exporters (Indonesia, Mongolia, South Africa, Colombia).

The assignment of countries to a category (LCT pioneers or FFDCs) is based on similarities in their fossil fuel–dependency structure, stage of industrialization and diversification, expected exposure to climate policy impacts, and income level, as well as observed pledges, strategies, and behavior (for example, level of ambition of their nationally determined contribution). Each country's assignment to one of the two clubs also includes a subjective element—the judgment of the authors—and is not necessarily consistent with its ranking based on the index of preparedness for an LCT (Peszko et al 2020).

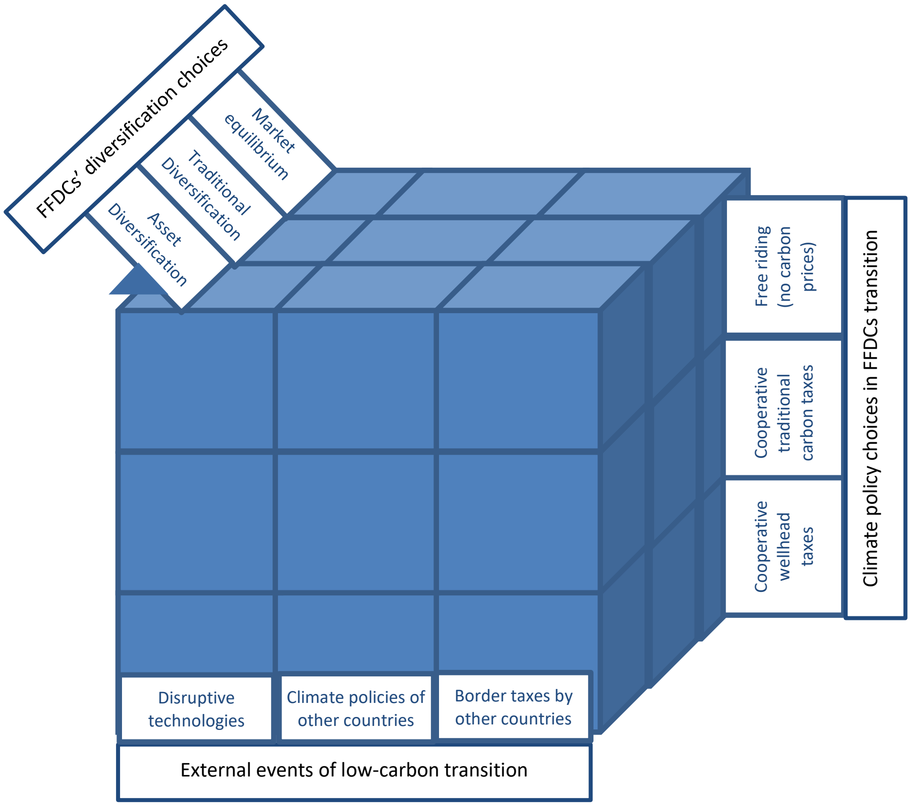
2.3. Scenarios

The robustness of different diversification and climate policy strategies available to FFDCs is stress-tested by simulating multiple exploratory policy scenarios. These scenarios are designed as combinations of plausible (not necessarily probable) alternative external LCT impacts on FFDCs (over which they have little control) as well as the strategic choices that FFDCs can make to prepare for these impacts (figure 1):

- LCT Pioneers choices of climate policies (unilateral carbon taxes);
- LCT Pioneers choices of trade measures (border adjustment taxes);
- The FFDCs choices how to diversify their economies; and
- The FFDCs choices whether and how to cooperate on global climate action.

[1] Recursive, dynamic CGE models are useful tools with which to understand both the relative scale of the shock and the subsequent economy—with adjustments of prices, wages, profits, outputs and trade flows. The recursive nature of the model simulates decision making under uncertainty and with myopic behavior of decision makers. For example, it allows for accumulation of vulnerable capital stock before the policy or technology shock occurs, even if some economic actors divest in response to preannounced or expected policies. Such models also have well-documented limitations.

Figure 1: Scenario Design: Mapping Uncertain External Events and Alternative Domestic Policy Choices for FFDCs



The large number of exploratory scenarios represents the uncertainty about the impact channels and timing of low carbon transition as well as the uncertainty about the policy choices the FFDCs themselves will make. No probabilities or normative judgments are assigned to any scenario. Instead, scenarios are purely alternative versions of plausible futures. For simplicity of presentation, only 10 selected exploratory scenarios are presented in this paper (box 1).

The model is run in annual recursive steps for the period 2011–2050 and generates a broad set of economic output indicators. We focus on two headline indicators – real adjusted consumption[2] and gross domestic product (GDP) as well as the value of underground and produced assets used by the economies to generate income.

[2] Adjusted consumption includes households' consumption and a portion of government consumption that directly benefits households. This is an approximation of a welfare measure.

BOX 1: Structure of Simulated Scenarios

TABLE 1 Ten Policy Scenarios simulated (except BAU)

Climate policies applied by LCT Pioneers	Climate policies Applied by the FFDCs	Trade policies applied by LCT pioneers	Diversification strategies of FFDCs
Unilateral carbon taxes to stabilize climate at 2-degree Celsius target (baseline carbon prices in LCT pioneer countries until 2025 and a rapid ramp-up until 2030 and beyond;	Baseline carbon prices in FFDCs	No border adjustment	1. Traditional diversification
			2. Asset diversification
		Border adjustment tax based on carbon content of imports	3. Traditional diversification
			4. Asset diversification
		Flat 10 percent import tariff (ala Nordhaus)	5. Traditional diversification
			6. Asset diversification
Cooperative climate policies to stabilize climate at 2-degree Celsius target (smoothly increasing uniform carbon prices in all countries since 2015)	Cooperative carbon tax on CO_2 emissions	No border adjustment	7. Traditional diversification
			8. Asset diversification
	Cooperative wellhead carbon tax on fuel production		9. Traditional diversification
			10. Asset diversification

Note: FFDC = fossil fuel–dependent country; LCT = low-carbon transition; n.a. = not applicable.

For convenience, color and line style coding are used for different scenario subsets in all figures in this paper:

- **Orange**: Unilateral climate response measures *without any border adjustment taxes*
- **Grey:** Unilateral climate response measures with traditional border carbon adjustment tax based on *carbon content of imports*
- **Red:** Unilateral climate response measures with *Nordhaus border tariffs* (ad valorem 10 percent import duty on all imports from nonparticipating FFDCs)
- **Green:** Cooperative *traditional carbon taxes* on carbon dioxide emissions within the national borders
- **Blue:** Cooperative *wellhead carbon taxes* on carbon content of fuels produced

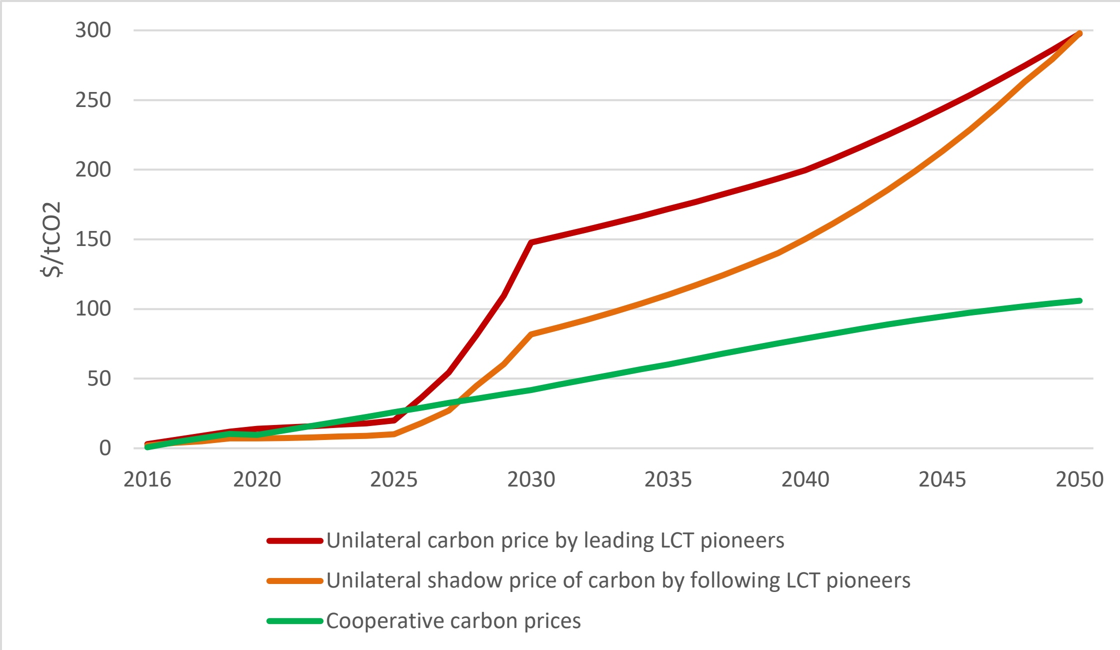
To distinguish between diversification options, in all dynamic figures illustrating changes of parameter values over time, the following apply:

- Solid lines (………) = traditional diversification (TD)
- Dashed lines (- - - - -) = asset diversification (AD)

Design of the Climate and Trade Policy Scenarios

In several possible cooperative and noncooperative versions of the future, different "climate clubs" implement different levels of ambition of domestic climate policies, represented by economy-wide carbon taxes (figure 2). Some LCT pioneers, mainly high-income OECD countries, are assumed to ramp-up their unilateral carbon taxes faster and steeper than other LCT pioneers (middle income fuel importers, including China and India), although they all converge their carbon price trajectories by 2050.

Figure 2: Assumed Timing and Level of Ambition of Unilateral and Cooperative Domestic Climate Policies (Inputs to ENVISAGE)



Source: World Bank and Purdue University (ENVISAGE).

Note: $/tCO$_2$ = U.S. dollars per ton of carbon dioxide; LCT = low-carbon transition. The level of ambition of climate policy in each club is represented in GTAP-ENVISAGE as an economy-wide carbon tax with revenues returned as lump-sum transfers to households. The red and orange lines show the domestic carbon prices that the modeling suggests the respective LCT pioneers would need to impose to stabilize global warming at 2 degrees Celsius (with respect to the preindustrial era), given lack of cooperation from fossil fuel–dependent countries. The green line is the uniform carbon price that would achieve the same purpose through harmonized cooperative climate policies.

In subsets of unilateral policy scenarios, LCT pioneers apply alternative types of border adjustment taxes against noncooperating FFDCs. All climate policies are calibrated to result in a similar 2015-2050 carbon budget within the IPCC AR5 and other IAMs range consistent with 66 percent probability of meeting the 2°C goal of the Paris Agreement (IPCC 2014).[3]

The following three versions of the unilateral policies of LCT pioneers are simulated:

- *Unilateral carbon taxes without any trade measures*. In all unilateral climate policy scenarios FFDCs apply only the carbon prices that were already in place in 2017.
- *Unilateral carbon taxes with traditional border carbon adjustment (BCA)* in the form of an import tax based on the carbon content of goods and services imported from nonparticipating FFDCs. Border tax rates are aligned with domestic prices of carbon applied by the LCT Pioneers.
- *Unilateral carbon taxes with a 10 percent ad valorem import tariff on all goods and services from non-cooperating FFDCs*, irrespective of their carbon content, including imports of manufactured products and services, as well as energy commodities. Such form of a border tax was proposed by Nordhaus (2015).

Two cooperative (internationally harmonized) carbon taxes are simulated:

- *Cooperative traditional emissions- or consumption-based domestic carbon taxes*, covering

[3] As with all IPCC AR5 emission pathways (IPCC 2014b), the consistency of our scenarios with the 2°C goal ultimately depends upon continued and amplified policies beyond 2050, including negative net emissions at the global scale. Like most policy simulation models, we do not run our policy scenarios beyond 2050, because it would be too speculative. We also have not calibrated out the scenario for consistency with the 1.5°C goal.

a country scope 1 CO_2 emissions.[4] In these scenarios, all countries (LCT pioneers and FFDCs alike) undertake similar levels of mitigation effort, allowing the LCT pioneers to apply lower domestic carbon prices than under their unilateral policy scenarios. Carbon tax revenue from combustion of fuels exported by FFDCs is collected by importing countries.

- *Cooperative production-based (wellhead) carbon taxes*. In these scenarios, LCT pioneers apply the traditional cooperative carbon tax on scope 1 emissions. The FFDCs, however, apply the same uniform tax rate, but on the carbon embedded in the fossil fuels and collect revenues from producers at the point of extraction, that is, at the mine mouth or oil or gas wellhead, regardless of whether the fuels are consumed domestically or exported (thus covering scope 1 and 2 emissions). LCT pioneers, through cooperative trade agreement, allow a pass-through of this carbon tax to their consumers and waive domestic carbon prices on their scope 1 emissions from the combustion of fuels imported from FFDCs where wellhead taxes were applied, so final consumers face the same after-tax price as with traditional carbon taxes. At the same time, fuel importers continue taxing emissions from fuels produced domestically and imported from countries without a comparable tax regime to prevent trade distortion.

Diversification Scenarios

Traditional approaches to diversification in fossil fuel–dependent countries still focus on diversifying beyond reliance on export of hydrocarbons (Arezki and Matsumoto 2018; Cherif, Hasanov, Zhu 2016). Through scenario design we test whether this is enough to manage the impacts of an LCT. FFDCs have long grappled with commodity price volatility, Dutch disease and resource curse using countercyclical macro-fiscal policies and measures. The traditional diversification through vertical, energy-intensive industrialization branches out from fossil fuel extraction to add value in downstream domestic fuel processing and fuel-intensive manufacturing. Such diversification, subject to several other policy and institutional conditions (Acemoglu, Robinson 2012), can help hedge against cyclical risks in commodity markets (Cherif, Hasanov, Pande 2017). However, it also increases the FFDCs' exposure to the structural impacts of an LCT by deepening economic dependence on downstream emissions-intensive industries (Ollero et al 2019).

In this analysis we simulate the opportunities and risks of traditional diversification into emission-intensive industries. We also simulate the impact of the broader *diversification of assets*. Rather than focusing on diversifying tradable products in the traditional fossil fuel product space (Hidalgo et al 2007), an asset diversification strategy focuses more on diversifying the underlying wealth—the portfolio of assets used by an economy, including human capital and renewable natural capital, along with underground assets and produced capital (Gill et al. 2014). It is expected to pave the way for the productive and competitive knowledge economies that are also flexible and resilient to external shocks, especially if supported by strong institutions and good governance.

In the model simulations we explore two broad diversification options as alternative ways of reinvesting resource rents in the economy:

- In traditional diversification scenarios, FFDCs allocate a share of their rents from fuel extraction to subsidize energy-intensive industrial production activities.
- In asset diversification scenarios, FFDCs invest the same amount of resource rents into

[4] Scope 1 emissions are direct emissions from the activities within national borders.

education and research and development (R&D). These investments gradually, and with a lag, increase labor productivity across sectors (see ENVISAGE documentation in GTAP 2018 for details of how the functional relations were estimated). These impacts of investments in R&D and human capital are introduced into the ENVISAGE model to partially endogenize the impact of policy-induced technology change.

In both diversification scenarios the level of subsidies and investments of resource rents is calibrated to match 1 percent of GDP of the baseline scenario. In this way, the two alternative diversification strategies are calibrated to have a similar fiscal burden. The direct effects of subsidizing energy-intensive industries are different from the indirect effects of a productivity boost through asset diversification: the former increase the margins of heavy industries, while the latter boost economy-wide productivity.

Technology Scenarios

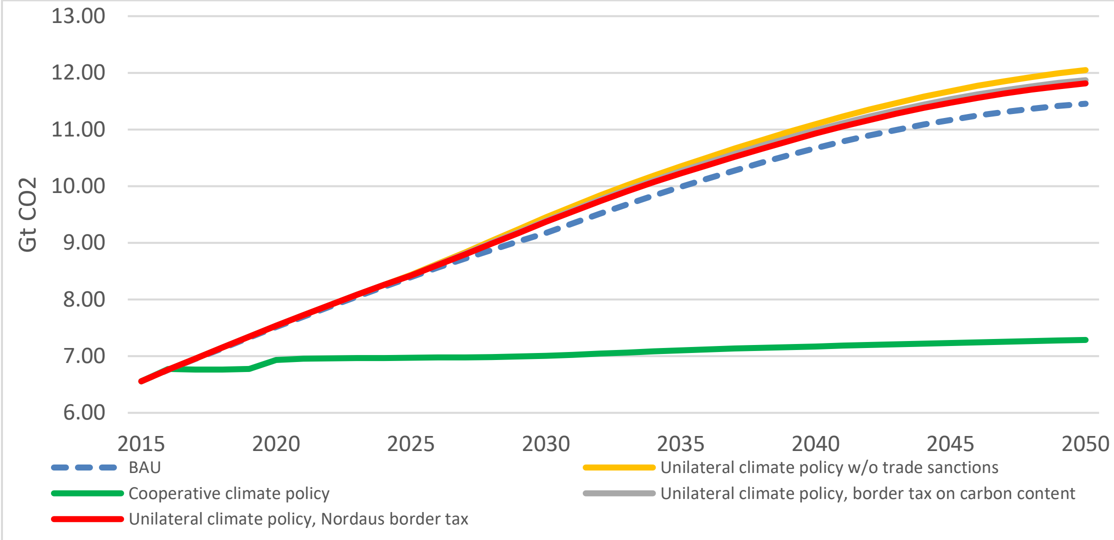
We run the models with two alternative assumptions about the development of green technologies – one when the progress on renewable energy, electric cars, and power storage follows recent (historical) trends, and another in which it is significantly accelerated in the future. However, to avoid confusion with too many scenarios, only those with accelerated technology development are presented here. So, the impact of the clean technology revolution is embedded in the baseline (or business-as-usual, BAU) presented here.

3. Results: Incentives to Cooperate and Diversify

The FFDCs' domestic climate mitigation policies are crucial to stabilize global climate. Cooperative climate policies combined with asset diversification is the only scenario that stabilizes domestic emissions in FFDCs (figure 3). Unilateral climate actions by LCT pioneers result in an increase of FFDCs' carbon dioxide emissions compared with the baseline, even if they face border carbon adjustment taxes, because carbon-intensive industrial production and emissions reallocate ("leak") from LCT Pioneers. Only cooperative domestic climate policies and asset diversification combined can stabilize fossil fuel–dependent countries' carbon emissions and prevent carbon leakage.

Figure 3: CO2 Emissions of Fossil Fuel–Dependent Countries' Emissions under Noncooperative and

Cooperative Scenarios

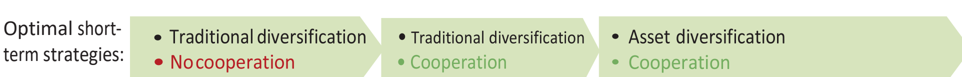


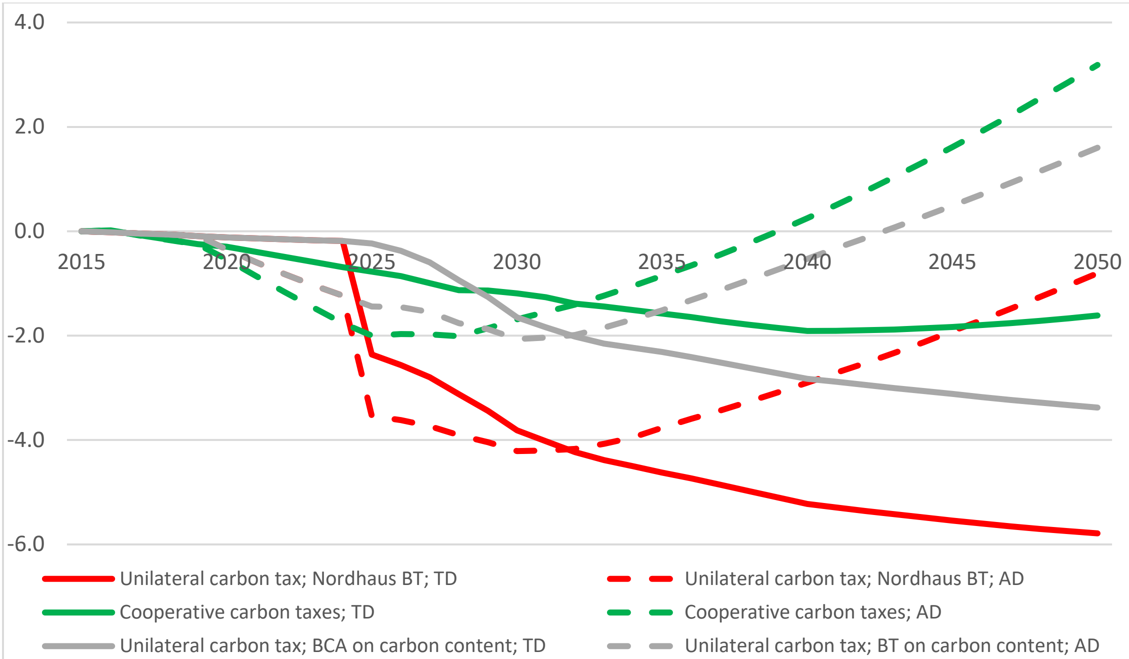
Below we first discuss the FFDCs' incentives to implement cooperative carbon prices, and then their incentives to diversify not only beyond fossil fuel exports but also beyond fuel-intensive industries. In each sub-subsection we first present results from a commonly observed myopic perspective, in which governments and economic agents make their decisions with the expectation that past trends will continue in future. Such backward-looking representation of decision making offers a conservative view on the incentives that would encourage FFDCs to diversify their wealth and cooperate on climate action. Second, we present the cumulative results over the period 2021-2050. We also identify scenarios that reconcile myopic and long-term perspectives and break the tragedy of the horizon.

3.1. Incentives to Cooperate on Climate Action

"Tragedy of the Horizon" weakens FFDCs' incentives to diversify early and cooperate on climate policies. Before LCT pioneers implement climate and trade policies, traditional diversification and noncooperative policies look like the most attractive strategies for FFDCs (figures 4 and 5). Both asset diversification and cooperation require upfront investments, which in the CGE framework crowd-out households' disposable income in the short term, and yield delayed returns, hence initially decelerate growth of households' consumption (figure 4) and economic output (figure 5). In this initial period the rates of growth of consumption and GDP with climate-friendly domestic policy choices are below those of BAU and below non-cooperative alternatives. Therefore, in the absence of external policy impacts the FFDCs would rather diversify into familiar heavy industries and delay cooperative climate policies. These results replicate observed behavior of most FFDCs thus far.

Figure 4: Year-to-Year Consumption versus BAU in Fossil Fuel–Dependent Countries



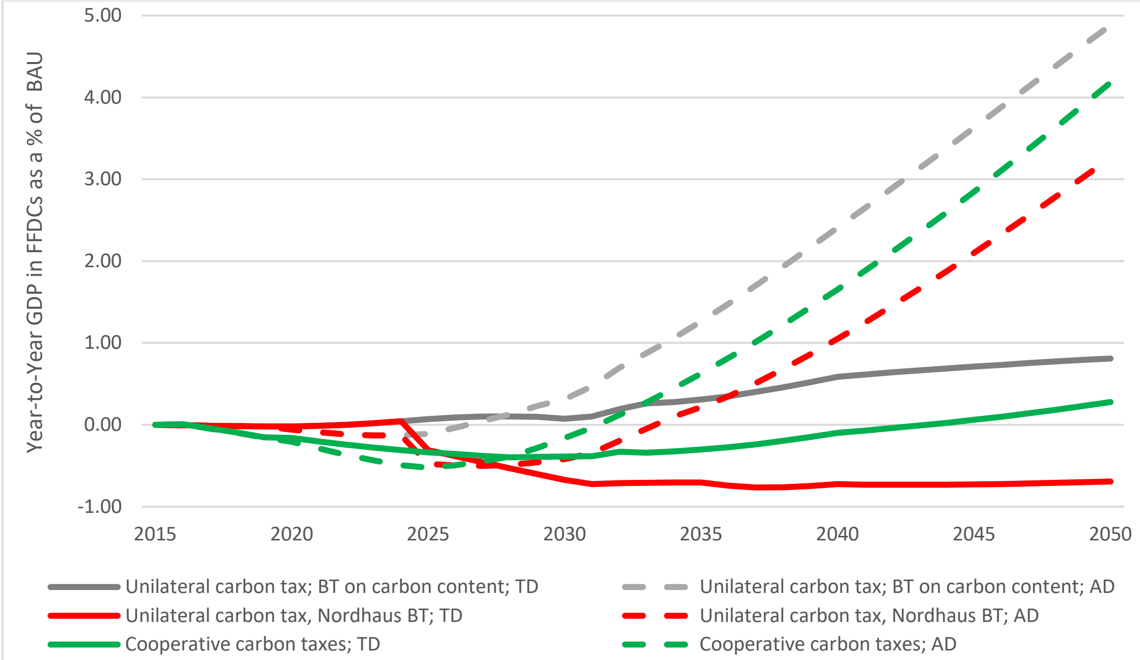


Source: World Bank and Purdue University (ENVISAGE).

Note: BAU = business as usual; TD = traditional diversification; AD = asset diversification. Red lines represent unilateral (noncooperative) climate policies involving the imposition of a Nordhaus tax in 2025; green lines represent cooperative climate polices based on traditional carbon prices. The colored lines represent the difference between consumption under a specific scenario with respect to consumption under the BAU scenario in a given year, expressed as a percentage of BAU.

High unilateral carbon taxes imposed by LCT pioneers and the traditional border taxes on the carbon content of imports initially do not encourage most FFDCs to cooperate. For a few years after the external impact occurs, free riding allows higher household consumption than putting domestic carbon taxes (figure 4) and higher growth for the entire modeling period (figure 5). Therefore, traditional border adjustment taxes may not be enough to tilt FFDCs' incentives towards cooperation no matter what diversification strategy they choose. The analysis of general equilibrium effects sheds light on the macroeconomic adjustments to such external conditions. On one hand, unilateral steep carbon taxes in fuel importing countries squeeze import demand and prices for fossil fuels, hence transferring a portion of resource rents to fossil fuel importers as carbon tax revenues. On the other hand, however, the FFDCs' industries using fuel as an important input benefit from stringent and asymmetric climate policies implemented by LCT pioneers. The drop of prices and revenue from fossil fuel exports reverses the resource curse and the Dutch disease, increasing export competitiveness of FFDCs' manufacturing industry that in addition enjoys lower domestic prices of fuels, favorable exchange rates and weak foreign competitors squeezed by high carbon taxes in LCT pioneer countries. Therefore, the FFDCs industries maintain and even strengthen their comparative advantage in energy intensive products despite traditional border carbon adjustments. They increase global market share along with domestic fuel use and carbon emissions (carbon leakage).

Figure 5: Year-to-Year GDP versus BAU in Fossil Fuel–Dependent Countries under Different Cooperation and Diversification Scenarios



Source: World Bank and Purdue University (ENVISAGE).

Note: BAU = business as usual; GDP = gross domestic product; TD = traditional diversification; AD = asset diversification. Red lines represent unilateral (noncooperative) climate policies with a Nordhaus import tax introduced in 2025; Grey lines represent unilateral (noncooperative) climate policies with border tax on carbon content of imports introduced in 2025; green lines represent cooperative climate polices based on traditional carbon prices. The colored lines represent the difference between GDP under a given scenario and GDP under the BAU scenario in a given year, expressed as a percentage of BAU. GDP figures represent real GDP calculated at market prices.

The incentives for FFDCs to cooperate change rapidly when LCT pioneers implement Nordhaus-type import taxes, here assumed in the years 2025–30. Ad valorem 10 percent import duties on all FFDCs exports quickly erode their terms of trade and export competitiveness, harming consumption and output (figures 4 and 5). Therefore, traditional border adjustment taxes may not be enough to overcome free-riding incentives of FFDCs, but a credible threat of Nordhaus import taxes may.

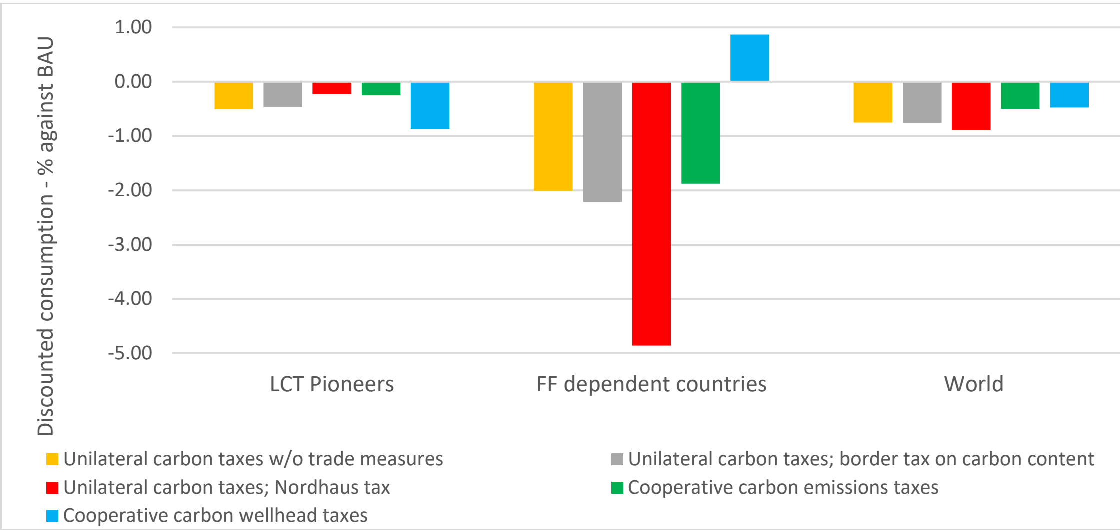
The long-term incentives to cooperate on climate action towards the 2°C goal of the Paris Agreement are not aligned between LCT pioneers and FFDCs (figures 6 and 7). This study confirms the standard literature's finding that global cooperation would be a cost-effective outcome for the world and for many LCT pioneers.[5] The LCT pioneers enjoy higher consumption (figure 6) and GDP (figure 7) when FFDCs share the burden of climate mitigation efforts through cooperative domestic carbon prices. The alternative of unilateral climate action toward the 2°C goal without protection against carbon leakage, or with just traditional border carbon adjustment taxes (orange and grey bars in figures 6 and 7), erodes the growth and consumption of LCT pioneers, more than unilateral 2°C compatible carbon prices.

For consumers in both groups of countries, the incentives to globally cooperate on climate action can be easily aligned. Consumers in FFDCs are slightly better-off in cooperative scenarios compared to any unilateral scenario simulated here (figure 6). Therefore FFDCs' households may be supportive of domestic carbon taxes, even without a credible threat of Nordhaus taxes, because they transfer wealth from producers', to consumers' surplus, especially in our modeling setting. Obviously if the alternative is a trade war with Nordhaus import taxes, consumers' self-interest to

[5] Most macro-economic models calculate the results of cooperative and non-cooperative climate policies for the entire world only, usually to demonstrate that cooperative scenarios are more efficient for the global economy. Some distinguish between the impacts of non-cooperative climate policies on developed and developing countries, but so far very few studies have distinguished between the fossil fuel–dependent countries and the rest of the world.

cooperate increases dramatically. Cooperation on climate action is particularly attractive if it is implemented through cooperative wellhead carbon taxes and trade agreements with major importers of fossil fuels. The windfall tax revenues (now also from carbon embodied in exported oil and gas) boost households' welfare above BAU (we discuss this scenario in more detail below).

Figure 6: Percentage Changes in Discounted Adjusted Household Consumption over the Period 2021–50 against BAU



Source: World Bank and Purdue University (ENVISAGE).

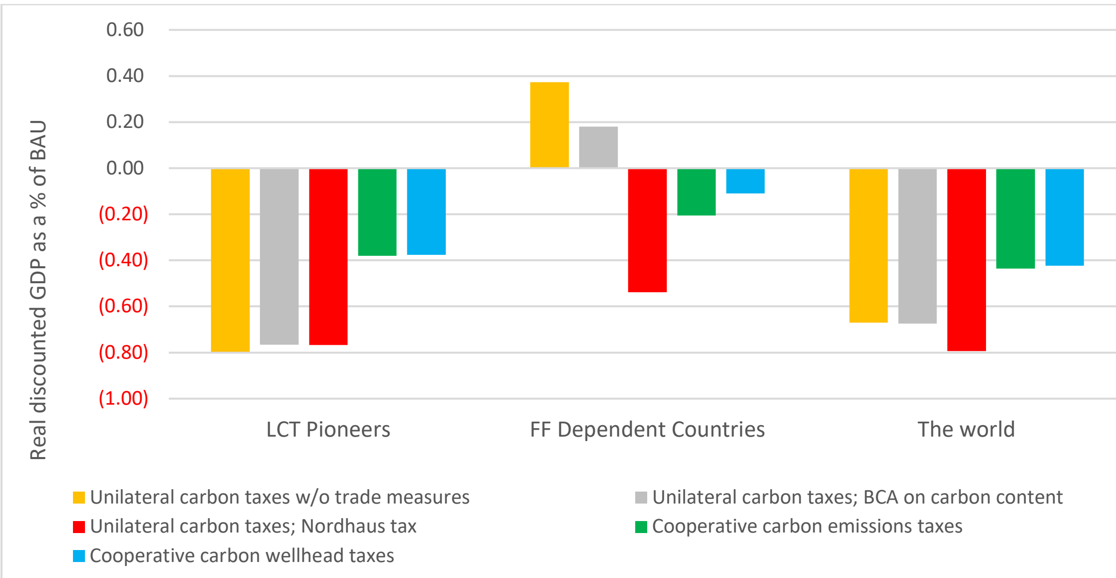
Note: BAU = business as usual; FFDCs = fossil fuel–dependent countries; LCT = low-carbon transition. Figure is calculated in market prices, using a 6 percent discount rate. All scenarios presented here assume traditional diversification in the FFDCs.

Free-riding on the unilateral climate action by LCT Pioneers is the long-term economically optimum strategy, unless they face a credible threat of Nordhaus-type import taxes (figure 7). Economic output in the two unilateral policy scenarios–with no border adjustment and with border taxes based on carbon content of imports–is robustly higher than in any cooperative scenario and even in BAU. These results hold regardless of the diversification strategy chosen by FFDCs. As discussed above, the ambitious unilateral climate policies implemented by LCT pioneers to stabilize climate at 2°C strengthen the pre-existing competitive advantage of FFDCs' industries in carbon-intensive products and lead to production and emissions leakage. Unilateral action increases the (after tax) costs of energy-intensive industries in LCT Pioneers and depresses global pre-tax fuel prices, reducing the opportunity cost of fossil fuels used by industry in FFDCs. Therefore, so long as consumers in LCT pioneer countries continue to purchase carbon-intensive goods and services, producers in FFDCs expand market share in the globally declining emissions-intensive products, at the expense of producers in LCT pioneer countries. Traditional border adjustment taxes on carbon content on imports may not be enough to prevent this leakage. It is worth stressing that with traditional border carbon adjustments carbon leakage would be "efficient" in economic terms (Kossoy et al 2015). These scenarios are unstable, however, because they represent the worst-case scenario for LCT pioneers, hence they are likely to try to avoid it, for example by threatening to apply Nordhaus taxes.

The combination of unilateral carbon taxes and Nordhaus border taxes applied by LCT Pioneers is an effective and credible nudge for FFDCs to cooperate on climate action. This combined external policy shock represents the worst-case scenario for welfare and growth in the FFDCs, worth avoiding through climate policy cooperation. Nordhaus import taxes reduce international competitiveness of all goods and services of FFDCs, including crude fuels and derivatives, depressing FFDCs terms of trade across the board and contracting economic growth more than domestic carbon taxes do in cooperative scenarios.

The threat of Nordhaus taxes also looks credible, as LCT Pioneers seem to have an incentive to apply it in order to encourage cooperative behavior of FFDCs. Consumers in LCT Pioneer countries are better-off with Nordhaus-type import taxes compared to all other unilateral scenarios (figure 6), due to the windfall tax revenue and households' income benefits. For producers in LCT pioneer countries, Nordhaus import taxes do not make much difference compared to other unilateral scenarios (figure 7). While some firms suffer from the increased costs of imported supply chains, others benefit from import substitution. However, on aggregate their output is significantly higher when FFDCs cooperate. Therefore, from the producers' perspective in the LCT pioneers', the value of Nordhaus tax lies primarily in its power to induce global cooperation on climate change.

Figure 7: Percentage Differences in Discounted Real GDP over the Period 2021–50 against BAU



Source: World Bank and Purdue University (ENVISAGE).

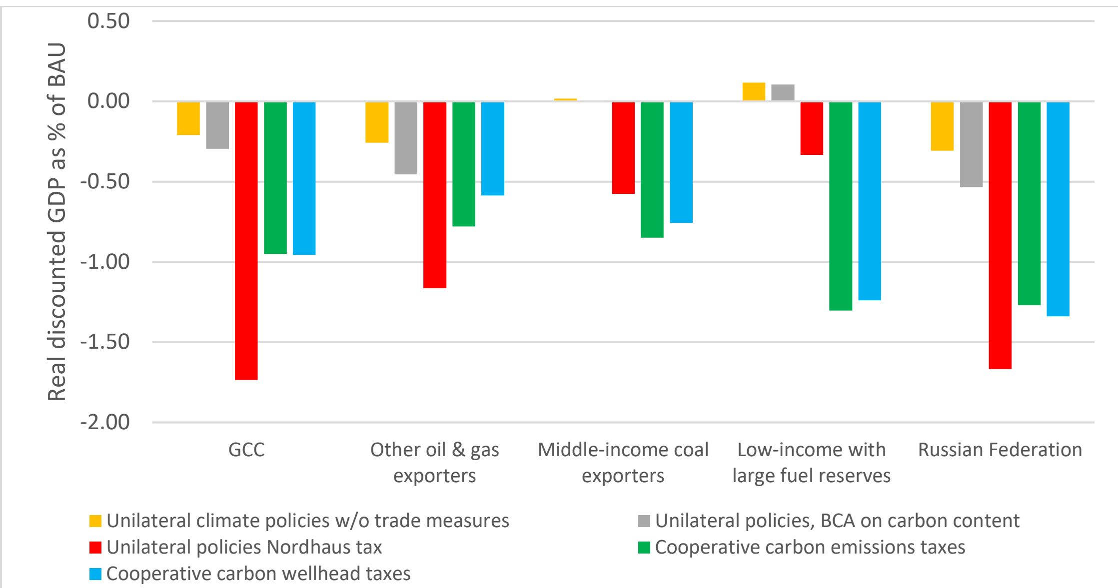
Note: BAU = business as usual; FFDCs = fossil fuel–dependent countries; GDP = gross domestic product; LCT = low-carbon transition. BAU is defined here as the absence of new climate policies and a slow increase in the carbon price of different climate clubs following historical trends, no additional diversification efforts, and no trade measures. The colored bars show percentage differences in discounted real GDP over the period 2021–50 against BAU (at a 6 percent discount rate), calculated at market prices. All scenarios presented here assume traditional diversification in FFDCs.

In contrast to LCT pioneers, the FFDCs have lower accumulated GDP in cooperative scenarios (figure 7) than with unilateral ones, except when they are faced with Nordhaus-type trade sanctions. While fossil fuel extractive sectors suffer from lower demand and prices induced by the unilateral carbon taxes in importing countries, the tradable products of heavy manufacturing and services are better off. By 2050, FFDCs' heavy manufacturing exports increase, especially in oil and gas exporting countries, such as GCC countries and Russia (see figure 12). Lower exports of oil and gas entails depreciation (compared to the reference scenario) of the real exchange rate, improving the international competitiveness of tradable products, especially in heavy industry. Through this mechanism, referred to as the "reverse Dutch Disease," stringent climate response measures in major fuel-importing economies additionally facilitate traditional diversification of FFDCs economy away from reliance on fossil fuels, but into the downstream industries relying on the fuel value chain. This does not help modern manufacturing industries not related to fossil fuels. These knowledge-intensive sectors are crowded out by heavy industry incumbents that enjoy not only lower domestic prices of oil, but also subsidies for energy intensive sectors assumed in the traditional diversification scenarios, and so are able to absorb most of the cheaper labor and capital released from oil and gas extraction.

Domestic carbon taxes in FFDCs increase domestic fuel prices, reducing the cost-competitiveness of FFDCs manufacturing relying on oil, gas and coal as inputs. Because those downstream heavy industries and services (besides oil and gas) are currently key drivers of GDP in FFDCs, the output growth of the entire economy slows down more than in all unilateral policy scenarios except with Nordhaus taxes.

FFDC countries are heterogenous and the incentives to implement cooperative domestic climate policies vary by country group (figure 8). For all FFDCs, the GDP is higher in non-cooperative scenarios with or without traditional border adjustment taxes. Nordhaus taxes depress output, but not everywhere enough to make cooperation attractive. The Gulf Cooperation Council [GCC] countries, Russian Federation, and other large oil and gas exporters have stronger incentives to cooperate in climate action if the alternative is a credible threat of Nordhaus taxes. These wealthier FFDCs have higher-value assets already locked in emissions-intensive industry exposed to trade sanctions and are strongly integrated into the world economy. Besides, Nordhaus taxes destroy the large value of their oil export revenues, which are much higher than any other FFDCs' group. Therefore, they experience higher GDP losses under a Nordhaus border tax scenario than other FFDCs.

Figure 8: Incentives to Cooperate for Different Fossil Fuel–Dependent Countries Vary by Country Group



Source: World Bank and Purdue University (ENVISAGE).

Note: BAU = business as usual; GDP = gross domestic product; GCC = Gulf Cooperation Council. The colored bars show percentage changes in discounted real GDP over the period 2021–50 against BAU (at a 6 percent discount rate), calculated in market prices. All scenarios presented here assume baseline diversification in FFDCs. Negative values indicate gain relative to BAU.

Among coal exporters and low-income countries with large oil and gas reserves, even Nordhaus trade sanctions may not encourage cooperation (figure 8). Countries such as Colombia, Indonesia, Mongolia, and South Africa grow faster in all noncooperative scenarios, capitalizing on their source of comparative advantage in coal-intensive industries in a carbon-constrained rest of the world. However, their consumers are better-off with cooperative carbon taxes. Also, for the least developed countries with large, unexploited fuel reserves, domestic carbon taxes suppress output by more than trade sanctions.

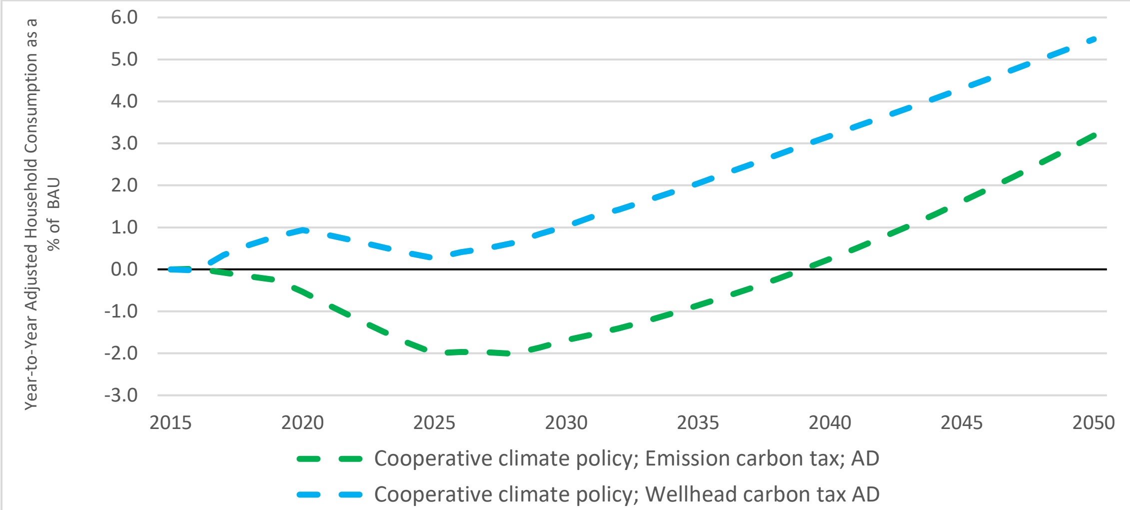
3.2. Breaking the Tragedy of the Horizon

FFDCs' incentives to cooperate on climate action increase when LCT pioneers agree to share a portion of carbon tax revenues with FFDCs through wellhead carbon tax agreements (blue bars in figures 6, 7, and 9). International climate cooperation based on wellhead carbon taxes alleviates short-term regrets of cooperative low-carbon transition in FFDCs. This scenario assumes a cooperative carbon tax and trade treaties between fuel exporters and importers, under which FFDCs put a tax on the carbon content of a fuel at the point where it is first extracted from the ground (covering scope 1 and scope 2 emissions). Importers of this fuel agree not to tax the same carbon again when it is emitted to the atmosphere, while taxing carbon emitted from other fuels, whether domestically produced or imported from countries without wellhead carbon taxes. Wellhead carbon taxes cover domestic emissions in fossil fuel–dependent countries but allow them to retain carbon tax revenues also from exported fuels that in other cooperative scenarios are collected abroad. Since the CGE model requires a balanced budget as one of the equilibrium conditions, these windfall carbon tax revenues reduce income taxes and boost disposable income of FFDC households.[6] Therefore, it leads to immediate increase of household welfare due to increased income linked to growth, recycling of carbon tax revenues, and lower income taxes, all of which outweigh the effect of higher consumption prices due to a carbon tax. For FFDCs' households, it is a no-regret strategy towards a low-carbon transition, preventing consumption from ever falling below BAU levels throughout the period to 2050, notwithstanding the domestic carbon pricing regime. Hence, wellhead carbon taxes can effectively break the tragedy of the horizon and offer FFDCs a continuous and sustainable rise in welfare, while encouraging and enabling them to engage in international efforts to stabilize the climate.

Within FFDCs the benefits of wellhead taxes are not evenly distributed – consumers benefit much more than producers (compare figures 6 and 7). The cooperative climate policy based on wellhead taxes seems to be less favorable to their trade than the traditional cooperative strategy. Shifting the carbon taxation of fossil fuels from importers to exporters would deepen the reduction in LCT pioneers' import demand induced by the low-carbon transition. Passing the carbon tax burden through the border to final fuel users in importing countries reduces their disposable income. Furthermore, their governments forego tax revenues. This translates into a decline in import demand as part of a general deterioration of household consumption in LCT pioneers' economies, as the carbon tax revenue under the wellhead assumption is transferred to FFDCs' households instead. Furthermore, the increase in FFDCs household revenue would lead to an increase in domestic private savings, demand, prices, and real exchange rates, resulting in the deterioration of the international competitiveness of their producers (symptoms of a Dutch disease). More detailed discussion of cooperative wellhead carbon taxes can be found in Peszko et al. (2019).

Figure 9: Wellhead Carbon Taxes Break the Tragedy of the Horizon for Consumers in Fossil Fuel–

[6] This is the default closure of the model and the most logical in a long-term context. In the near term, countries could decide to increase domestic expenditures and/or reduce deficit financing or some combination of all three fiscal options.



3.3. Incentives to Diversify

Incentives to diversify assets are also affected by the tragedy of the horizon. GDP and household consumption become higher than in traditional diversification scenarios only at around 2027 and 2032 respectively (figures 5 and 4). So, for the first few years in the aftermath of external policy impact, some FFDCs may want to implement contradictory polices, namely carbon pricing to avoid trade sanctions and fossil fuel subsidies to maintain comparative advantage in heavy industry. GDP (figure 5) rebounds earlier than consumption (figure 4) because upfront investments needed for asset diversification initially crowd-out household consumption.

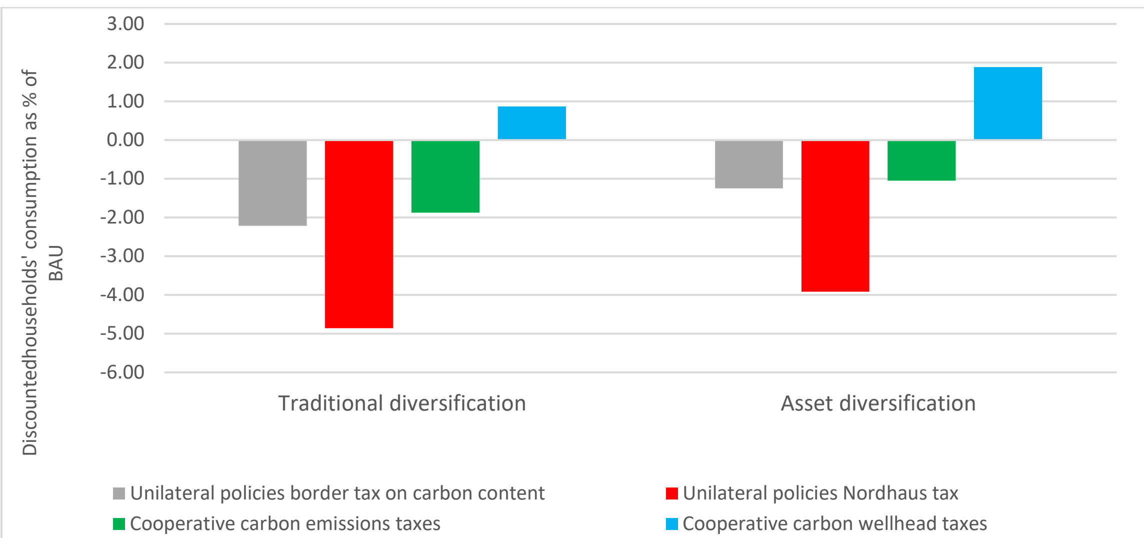
But asset diversification is a sustainable long-term growth and welfare strategy for the FFDCs. Following the initial decline, both consumption and GDP increase at a more rapid rate than in traditional diversification scenarios. Consumption grows faster due to accelerated growth, higher productivity (wages) and reduced prices. Over time, higher output accumulates into new high-return-yielding asset classes, which also increase household income and consumption. Asset diversification also gives a competitive boost to the consumer goods industries and services, as opposed to traditional diversification that diverts investments to intermediate goods produced by heavy industry.

Asset diversification policies strengthen FFDCs' long-term export competitiveness and increase resilience to low-carbon transition. Under these scenarios the overall exports of FFDCs in the period until 2050 are higher than in the traditional diversification scenarios. This increase in trade is attributed to competitiveness gains related to higher productivity in response to higher expenditures on R&D assumed in the asset diversification scenario, which more than offsets any export competitiveness loss after removal of energy price subsidies (applied in traditional diversification scenarios). Even though investments, consumption, and exports are all contributing to GDP growth under asset diversification scenarios, the main underlying driver of higher growth is the productivity increase related to redirecting fiscal resources from fossil fuel subsidies to innovation and education.

In the long-term, cooperative climate action works in synergy with asset diversification for FFDCs. Asset diversification alone (without cooperative climate policies) offers no immediate hedge against the Nordhaus border taxes. The drop of GDP and consumption as a result of external trade sanctions is similar no matter what diversification path they were on (figure 5). Gradually, however, these strategies combined ensure the fastest increase in the rate of growth of GDP and consumption compared with alternatives. By 2050, the combination of asset diversification and cooperation results in households' consumption and GDP being around 9 and 5 percent higher respectively than under free-riding and traditional diversification scenarios. Asset diversification reduces GHG emissions slightly below traditional diversification for any cooperative policy choices, but only together with domestic cooperative carbon taxes, asset diversification also reduces emissions against BAU (figure 3).

Asset diversification is also a robust economic strategy. "Robust" means that in the long run, asset diversification outperforms traditional diversification by all macro-economic indicators and under all external policies that have been simulated here. With or without cooperation, it robustly offers higher long-term consumption and GDP for the FFDCs as the world moves more rapidly toward decarbonization. It performs better than alternative economic strategies by two decision criteria. By the *minimax (least-regret)* criterion, asset diversification minimizes the possible losses of consumption in the worst-case scenario, although it does not prevent consumption from being lower than in BAU. Asset diversification also maximizes possible consumption gains in the best-case scenario, in which FFDCs implement cooperative domestic climate policies through wellhead taxes, meeting the *maximax (highest gain)* criterion. The only no-regret long-term strategy for FFDC consumers is cooperative climate action with internationally agreed-upon wellhead taxes.

Figure 10: Long-Term Consumption in Fossil Fuel–Dependent Countries (% difference from BAU)

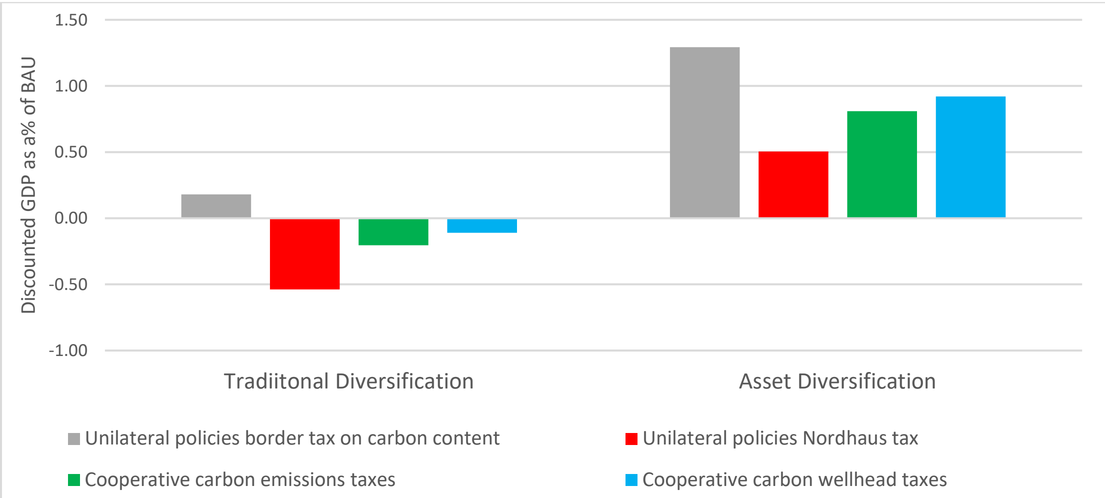


Source: World Bank and Purdue University (ENVISAGE).

Note: BAU = business as usual; FFDCs = fossil fuel–dependent countries. The colored bars denote the cumulative difference between discounted real adjusted consumption under different scenarios and the corresponding figures under the BAU scenario (at a 6 percent discount rate) in FFDCs (over the 2021–50 period), expressed as a percentage of BAU

Asset diversification is also robustly better for long-term GDP in FFDCs. Under any configuration of external events, it yields higher discounted GDP than any alternative diversification strategy (figure 11). It also meets the *minimax (least-regret)* criterion, by minimizing possible GDP losses for FFDCs in the worst-case scenario (unilateral climate policies with Nordhaus taxes imposed by LCT pioneers on imports from FFDCs). In fact, it is the only economic strategy that results in long-term GDP gains relative to BAU regardless of the external policy events considered here. Asset diversification should therefore be particularly appealing to loss-averse decision makers if they are also very patient. Asset diversification also maximizes the possible gains in the best-case scenario for FFDCs (unilateral climate policies without border taxes), meeting the *maximax (highest gain)* criterion. Even in the worst-case scenario (unilateral climate policies in the rest of the world with Nordhaus trade taxes), asset diversification is the only growth strategy that puts FFDCs back on a sustainable development path and pulls them out of what some economists call "the development trap" (Collier 2007).

Figure 11: Discounted GDP over 2021-2050 in FFDCs as a percentage deviation from BAU



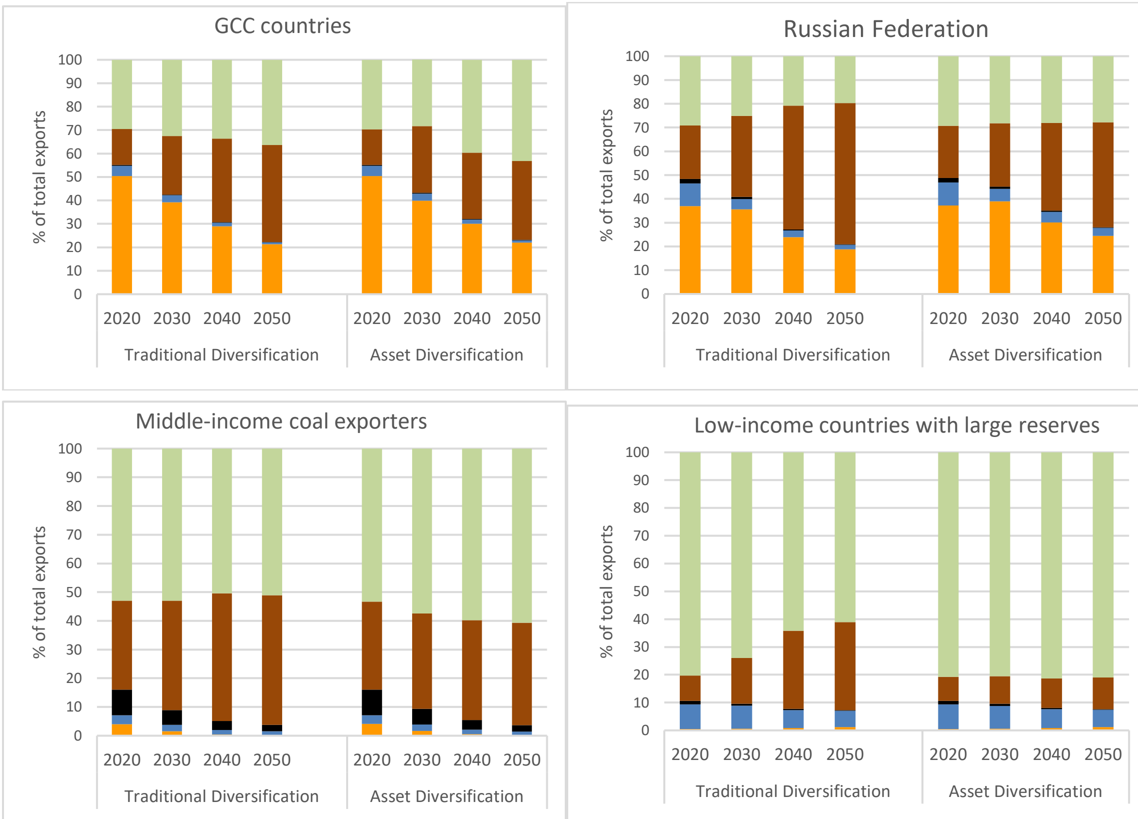
Source: World Bank and Purdue University (ENVISAGE).

Note: BAU = business as usual; FFDCs = fossil fuel–dependent countries; GDP = gross domestic product. The colored bars denote the difference between the cumulative discounted (with 6 percent discount rate) real GDP in FFDCs under different scenarios (over the period 2021–50) and the corresponding figures under the BAU scenario, expressed as a percentage of the BAU figures.

Even successful asset diversification and cooperative carbon taxes do not induce a major shift in FFDCs' economic structures (figure 12). In none of the simulated scenarios could asset diversification significantly shift the comparative advantage of FFDCs away from fuel-related products and services. In cooperative scenarios shown in figure 12 the value added of services, consumer goods industry, and agriculture ("rest of the economy") increase because the additional revenue generated by domestic carbon taxes increase households' consumption and savings. This helps less carbon-intensive sectors producing final consumers' goods (e.g. agriculture) and services. Higher households' consumption does not help heavy industry which is producing mainly capital and energy intensive intermediate goods. Yet, despite helping the relatively knowledge-intensive "rest of the economy", asset diversification in our simulations does not change the core specialization of FFDCs in the oil, gas, and coal product space. In three of the four FFDCs sub-groups in figure 12, fuel extractive sectors and carbon intensive heavy industry dominate exports even in 2050. The decline of the share of commodity exports is offset by the increase of the exports share of carbon intensive manufacturing, especially in traditional diversification scenarios. Only for the low-income countries with large unexploited fuel reserves (figure 12d), the two diversification strategy choices have a significant bearing on the future economic structure, because their "rest of the economy" sectors have played a major role already in the base year's exports. Many of these countries are currently more dependent on exports of agricultural commodities than fossil fuels.[7]

[7] These results can be partly attributed to the nature of the CGE models, which are not very good in simulating the rapid growth of new sectors, which are insignificant in the economy in the base year, for which the BAU was calibrated with input-output data for 2011.

Figure 12: Sector Export Shares in Cooperative Scenarios

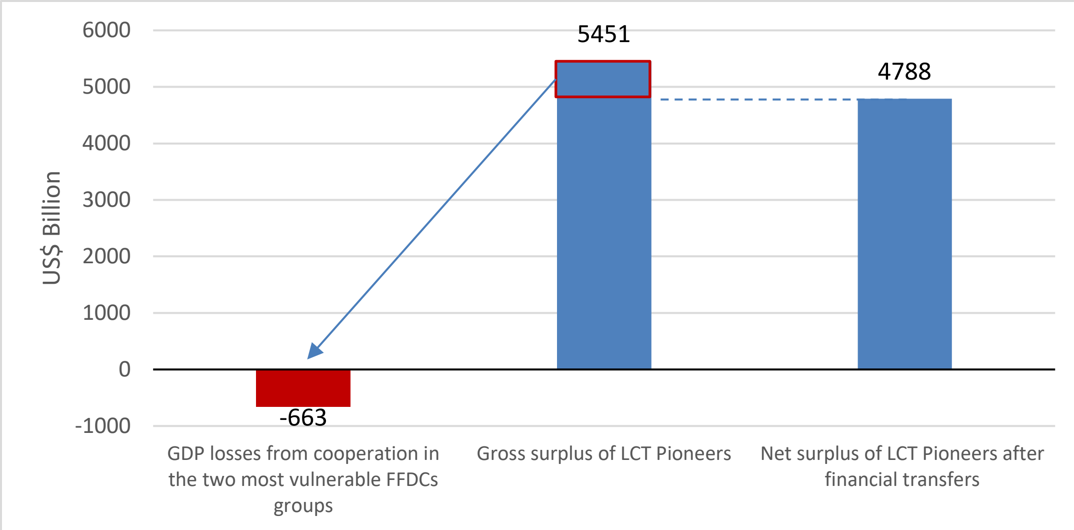


Source: World Bank and Purdue University (ENVISAGE)

3.4. Helping Those Who Are Less Able to Diversify and Cooperate

Additional nudges to cooperate may be needed for the two country groups that have low incentives to implement domestic carbon taxes even under the threat of Nordhaus import duties, namely (i) lower-middle income countries with large proven, but not yet extracted, fossil fuel reserves; and (ii) the middle-income coal-exporting countries (see figure 8). In order to bridge the gap between consumption in cooperative and non-cooperative scenarios, the LCT pioneers can provide strategic financial, technology, and knowledge transfers worth $663 billion until 2050 (approximately $22 billion per year). This is one-eighth of the $5.5 trillion savings they would derive if all FFDCs cooperated (avoided incremental costs of unilateral climate action). These transfers would allow these vulnerable countries to implement domestic cooperative carbon prices. The former ones could use international assistance to overcome shortage of capital needed to invest in asset diversification. The latter, to address social challenges of transition away from coal in the mining regions. The key challenge of financial transfers is political feasibility, where historically it has been difficult to ensure credible international climate finance transfers (OECD et al. 2015, CPI 2019).

Figure 13: Financial Transfers from LCT Pioneers to Less Developed Countries with Large, Untapped Fuel Reserves

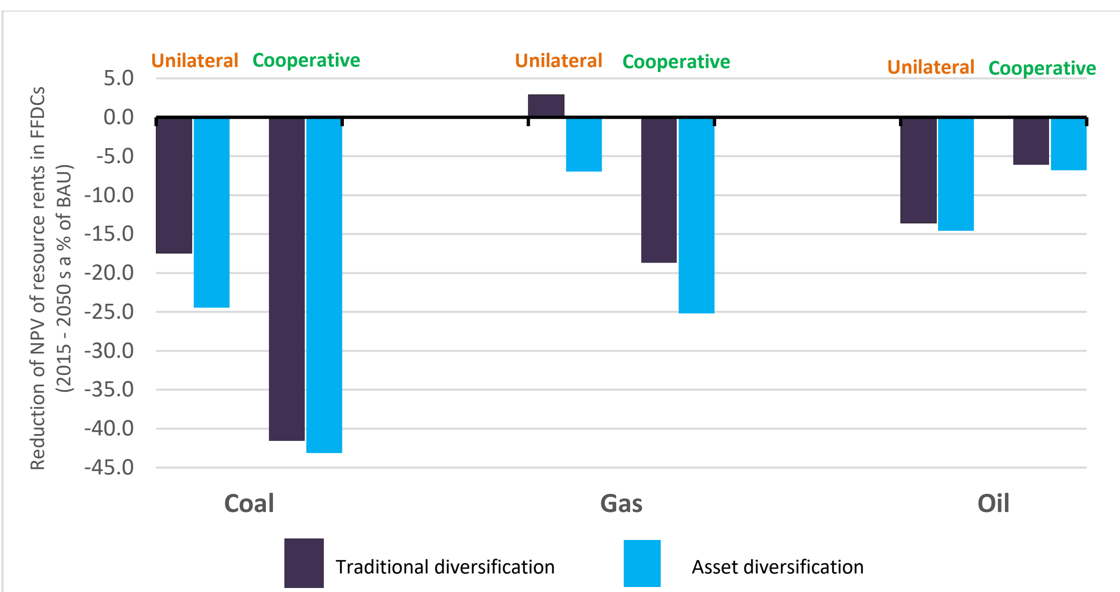


Source: World Bank and Purdue University (ENVISAGE).
Notes: LCT = low-carbon transition. Surplus to the pioneers (large emitters) is calculated as the difference between the net present value of GDP under a cooperative scenario and the net present value of GDP under the unilateral (noncooperative) scenario with Nordhaus taxes. Losses are calculated as the total discounted GDP lost under cooperation to low-income countries with large unexploited fuel reserves and middle income coal exporters.

3.5. Political Economy of Low-Carbon Transition

Low carbon transition represses the value of almost all fossil fuel reserves in FFDCs below BAU in almost all scenarios (figure 14). Accumulated rents decrease even in the scenarios that increase GDP and consumption. This suggests that economic growth and welfare in FFDCs can be decoupled from the declining value of fossil fuel assets. But, long-term interests of individual extractive sectors in FFDCs are not always aligned.

Figure 14: Cumulative Losses of Discounted Resource Rents in FFDCs as a percentage of BAU



Source: World Bank and Purdue University (ENVISAGE).
Note: BAU = business as usual; FFDCs = fossil fuel–dependent countries; NPV = net present value. The bars indicate the difference between the cumulative absolute losses of discounted resource rents (value of underground assets) for different fossil fuel reserves over the period 2021–50 under various climate scenarios and the corresponding values under the BAU scenario, expressed as a percentage of the BAU figures (discounted at 6 percent). Cooperative scenario

is compared with unilateral carbon taxes applied by LCT pioneers without border adjustment taxes (the best-case scenario for both coal and gas rents).

What unites all fossil fuel owners is their preference for traditional diversification. All benefit from fossil fuel subsidies, though at the expense of consumers and the rest of the economy as we have seen before. This is not surprising: subsidies to the fuel input costs of the extractive sectors' clients increase domestic sales and revenues of extractive sectors, partly compensating for the shrinking export markets due to the high carbon taxes in export markets. Traditional diversification partly mitigates the negative impact of low carbon transition on asset value in all extractive sectors, with coal and gas benefitting more than oil. Asset diversification, in turn, threatens all fuel extractive industries because it transfers resource rents from energy-intensive to knowledge-intensive sectors.

However, the impact of carbon pricing varies by extractive sector – cooperative strategies preserve value of oil, while destroying value of gas and coal rents. We will break down these and other political economy findings below.[8]

For gas and coal owners, cooperative carbon prices reduce the present value of rents more than any unilateral scenario. When LCT pioneers introduce very high unilateral carbon prices in non-cooperative scenarios, they squeeze the margins of their heavy industry, leading to accelerated mines' and plants' closures followed by the leakage of output and emissions to FFDCs, which do not internalize carbon cost for domestic industries.

Coal reserves in FFDCs are the most affected by the low carbon transition in percentage terms (figure 14), but the least in value terms (figure 15). The worst-case scenario for coal rents in in FFDCs consists of cooperative domestic carbon taxes and asset diversification. It reduces the coal rents by more than 43 percent, or by US$1.2 trillion, compared with BAU between 2021 and 2050. Even in the best-case scenario for FFDCs' coal rents – non-cooperation without border carbon adjustment and traditional diversification – they lose about 17 percent of value, or US$0.5 trillion over the period. The decline in coal asset value has only a negligible macroeconomic effect on most coal-mining nations, because coal rents are very small compared with oil and gas rents. However, mining regions in countries like Colombia, Indonesia, Mongolia, Mozambique, and South Africa could experience economic decline and social distress.

Gas rents are moderately affected by an LCT, both in value and percentage terms, compared with coal and oil, and even increase above BAU in unilateral scenarios without border taxes and traditional diversification. The domestic industrial use of gas in this best-case scenario increases much faster and discounted rents are even 3 percent ($300 billion) higher than in BAU. The worst-case scenario for gas is the same as for coal producers – cooperative climate action with asset diversification. It results in lowering the present value of rents by $2.8 trillion compared with BAU in the period 2021–50. This is 25 percent less than in BAU. Gas is not making major headway in power generation. It is not competitive with coal before an LCT impact, and with renewables afterwards. Faster growth of industrial use of gas partly offsets sluggish demand in the power sector, and the use of gas in transport never scales up in our simulations, being

[8] The absolute values of resource rents critically depend on the future international resource prices, which here are computed endogenously by the linked Rystad and Envisage models. Assumptions of extraction costs and available reserves in Rystad linked to demand trajectories computed by ENVISAGE give smoothly increasing fuel prices. Also, the short-term fluctuations in fuel prices such as in 2014 and 2020 are not captured by the simulations. Therefore, the reader is advised to draw policy conclusions from the difference between the scenario results and their relative scales, rather than from absolute dollar values of resource rents and other asset values.

overwhelmed by the uptake of electric vehicles.

Losses of oil rents dwarf those of coal and gas in value terms in all scenarios (figure 15) but represent the smallest drop in percentage terms (figure 14). Interestingly, the best-case scenario for oil owners in FFDCs is different than for other fuels, namely cooperation and traditional diversification. In this scenario, the discounted oil rents in FFDCs are only 6 percent lower than in BAU, but it entails the loss of $5 trillion over the 2012-2050 period. The LCT pioneer countries import more fossil fuels from FFDCs than in unilateral policy scenarios, because cooperative taxes in FFDCs allow them to lower carbon taxes on their fuel users and achieve the same climate outcomes. Lower carbon taxes extend the life of oil-consuming industries (e.g. petrochemicals and plastics) in LCT pioneers and delay a phase out of internal combustion engines in cars, prolonging stronger export demand for FFDCs oil. It does not increase global emissions over the period, however, because FFDCs join international emission reduction efforts. The worst-case LCT scenario for FFDCs' oil rents – unilateral climate policies in other countries combined with Nordhaus-type taxes on imports from FFDCs and domestic asset diversification – is also different than for coal and gas producers. This scenario reduces the discounted value of oil rents in FFDCs by more than $17 trillion (21 percent) compared with BAU over 2021-2050. In the unilateral scenario with none, or traditional border taxes, the oil rents in FDCs are almost 15 percent lower than in BAU (figure 14).

3.6. Can Low-Carbon Transition Diversify Assets in FFDCs?

The impacts of low carbon transition shift asset values[9] across all sectors, not only extractives. Therefore, the importance of asset value to the economy can be better understood in the broader context of redistribution of wealth across sectors and countries, rather than through the narrower concept of asset stranding. Multisectoral, dynamic macroeconomic CGE models are particularly well suited to capture the impacts of external and internal policy shocks on structural shifts in the economy. As capital in some sectors no longer yields sufficient returns it is gradually reallocated to other, more productive uses in other sectors, allowing to trace potential winners and losers of the structural transformation. Such modeling approach also illustrates more realistically that the assets released by the worst affected sectors are stranded to their owners but not necessarily to the economy. Some capital is picked up by other sectors (even if with lower returns), reducing the economy-wide costs associated with structural transformation.[10]

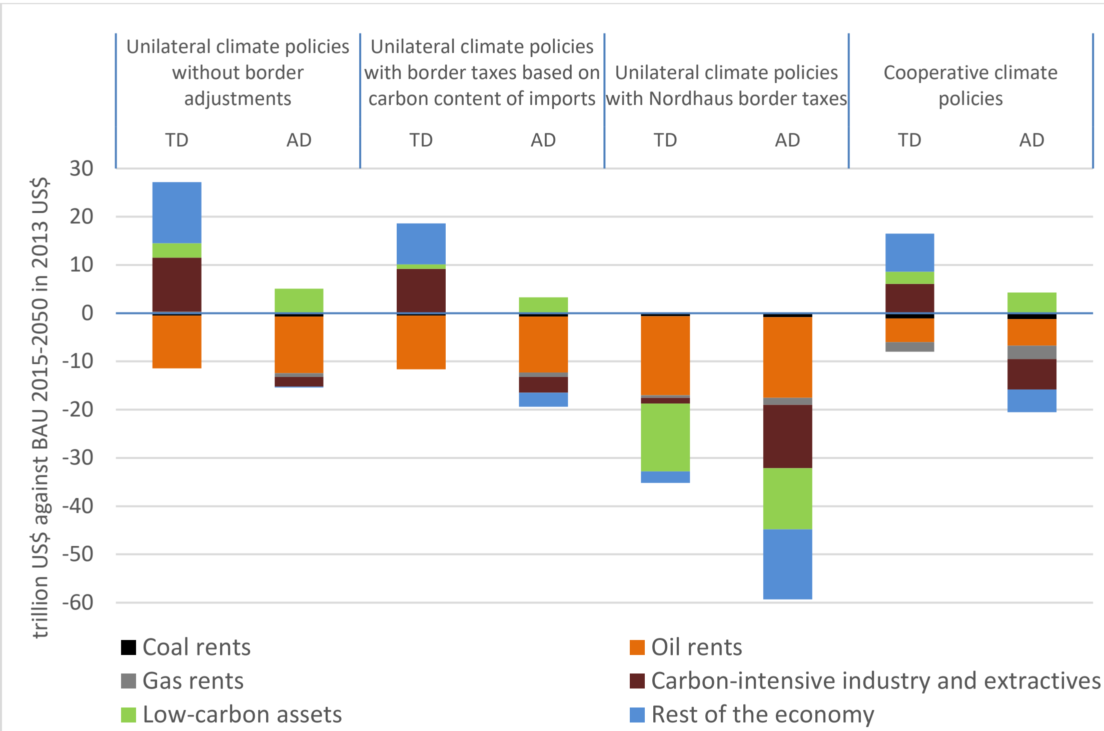
The FFDCs' strategies that preserve the value of fossil fuel assets destroy the value of low-carbon assets. Of all the external events simulated in this study, only Nordhaus taxes against noncooperating FFDCs always knock down the value of all assets in the FFDCs, whether they are fossil fuel–

[9] The value of assets is measured here as the discounted value of net income that an asset is expected to generate over its economic lifetime. The total value of assets in the fuel extractive sectors is the sum of (1) the value of fossil fuel reserves in situ (NPV of the expected resource rents) and (2) the equity value of capital invested in fossil fuel–dependent sectors (among others, the machines and pipelines used for the extraction and transport of fossil fuel commodities to markets). The latter component is measured by the difference in the NPV of economic value added related to capital in a sector between a given scenario and the BAU scenario. The loss of value of extractive assets that can be attributed to an LCT is the difference between the value of assets under BAU trends and after the policy shock occurs.

[10] In addition to general equilibrium effects, the dynamic view on economic decision making is another important perspective on the impact of policy shocks on asset value. It allows a realistic adjustment to be made of capital investments and economic structures after the shocks occur. In the climate policy scenarios designed in this study, investors respond to these shocks by gradually shifting their capital investments away from carbon-intensive assets toward asset classes that have not been negatively affected by climate policies and that become more productive as clean technologies become established, cheaper, and more acceptable. That is this study's main difference compared with the more static and partial equilibrium models used in the stranded assets debate so far.

dependent on not (figure 15). But the impacts of other climate and trade policies and diversification strategies are not the same in size and direction across asset classes. For example, traditional diversification preserves asset value mainly in the fossil fuel-intensive sectors, which have been the important drivers of these countries' growth and exports so far. Yet, traditional diversification restrains the growth of productive low-carbon assets although the final sectoral incidence is not clear-cut, because in FFDCs low-carbon, knowledge intensive sectors are often integrated into the fossil fuel value chains (figure 15).

Figure 15: Impact of Climate Policies and Diversification Strategies on Asset Value in FFDCs by Sector (trillion US$ against BAU)



Source: World Bank and Purdue University (ENVISAGE).

Note: AD = asset diversification; BAU = business as usual; FFDCs = fossil fuel–dependent countries; ND = no diversification; TD = traditional diversification; units = nominal value added. The table illustrates the impact of external policies and domestic coping strategies on long-term asset value in fossil fuel–dependent countries by sector. All figures are in trillions of 2013 US$, difference against BAU, over the period 2021-2050, discounted at 6 percent from 2015. BAU is defined here as a slow increase in the carbon price of different climate clubs following historical trends, which de facto implies a lack of new climate policies, no additional diversification efforts, and no trade measures. For oil, coal, and gas extraction, asset value comprises resource rents and the value of built (produced) capital and is expressed as the difference in discounted trillion US$ from BAU at a 6 percent discount rate. For all other sectors, asset value represents the value of built (produced) capital and is represented in the same units. The asset value in the rest of the economy also includes the rental value of resources in the non–fossil fuel extractive sectors. This table covers only the assets whose value is represented in the standard economic (computable general equilibrium) model used for this study. The values of human capital, renewable natural capital, and land in agriculture or forestry are not accounted for here.

Diversification strategies that preserve the value of traditional economic assets slow down economic growth and welfare. The best-case scenario for the total value of economic assets consists of unilateral climate policies without trade sanctions and traditional diversification. The total value of FFDCs' underground and produced wealth in this scenario increases by $16 trillion above BAU over the 2021-2050 period, despite knocking $11 trillion off the value of oil rents. This is because fossil fuel subsidies increase the value of produced assets in domestic heavy industries (using large volumes of coal and gas as inputs), that are also benefitting from asymmetric carbon prices and production leakage from LCT pioneers. The rest of the FFDC economies also enjoys higher value of produced capital thanks to forward and backward linkages with heavy industry. In the knowledge-intensive asset-diversification scenarios, the total value of tangible physical assets is lower relative to traditional diversification scenarios (figure 15) But the long-term consumption and output are higher (compare with figures 10 and 11 respectively). An economy that uses a broader set of inputs (more renewable natural assets, more knowledge, more intangible produced assets, and more efficient institutions) requires less traditional capital—needs fewer underground reserves and less bulky produced assets—to achieve the same output. This "dematerialized" growth model relies more on assets that are not well represented in economic models or in the systems of national accounts, such as renewable natural and human capital as well as intangible institutional and social capital. Their impact on macroeconomic outcomes is captured in our simulations by higher labor productivity associated with human capital and R&D investments in asset diversification scenarios.

4. Conclusions and Policy Implications

4.1. Incentives to Cooperate

Domestic climate mitigation policies in FFDCs are crucial to stabilize the global climate. Without their participation in cooperative climate policies, the rest of the world (in our simulations the pioneers of the low carbon transition or LCT pioneers) would need to very steeply ramp up their unilateral carbon prices to stabilize climate below the 2°C temperature threshold.

Without external policy incentives, the FFDCs may not have self-interest to cooperate on climate policies and diversify away from fossil fuel–dependent economic activities. Both asset diversification and cooperation require repurposing of the investment flows from sectors and products that are their current comparative advantages to the areas that are comparative advantages of LCT pioneers. This initially decelerates growth of households' consumption and slows output growth.

High unilateral carbon taxes imposed by LCT pioneers strengthen FFDCs' comparative advantage in heavy fuel-intensive industries benefitting from output and emissions leakage. Unilateral policy action of LCT pioneers decreases their demand for and import of coal, oil and gas. As the global fuel prices decrease as a result, so do the opportunity costs of using these fuels by domestic industries in FFDCs. Thus, loss of export revenues from coal and gas is offset by the increase of domestic sales to the coal- and gas-intensive industries in FFDCs. Heavy industries benefit from asymmetric carbon prices by increasing production and exports of carbon-intensive products (refined products, heavy chemicals, metals, etc.), capturing a portion of the now-unserved markets, including in LCT pioneer countries. Only radical shift in consumers' habits in LCT pioneers could change that.

The production (and emissions) leakage occurs in unilateral scenarios even if the LCT pioneers introduce traditional border carbon adjustments on the carbon content of imports. This leakage is "efficient" as it continues even when the LCT pioneers fully protect the international competitiveness of their producers with WTO-compliant border taxes on carbon embedded in imported products.

Free-riding on the unilateral climate action by the LCT Pioneers is no longer an economically optimum strategy for the FFDCs when they face a credible threat of Nordhaus-type import taxes. This external policy shock represents the worst-case scenario for welfare and growth in the FFDCs, worth avoiding through climate policy cooperation. Nordhaus import taxes reduce international competitiveness of all goods and services of FFDCs, including crude fuels and derivatives, depressing FFDCs' terms of trade across the board and contracting economic growth more than domestic carbon taxes do in cooperative scenarios.

The threat of Nordhaus taxes also looks credible, as LCT Pioneers have an incentive to apply it in order to encourage cooperative behavior of FFDCs. Despite the attractiveness to the FFDCs, the unilateral climate policy scenarios are unstable, because they represent the worst-case scenario for the LCT pioneers. Consumers in LCT Pioneer countries are better-off with Nordhaus-type import taxes compared to all other unilateral scenarios, due to the windfall tax revenue. Producers in LCT pioneer countries are indifferent between various unilateral scenarios with or without Nordhaus import taxes but are significantly better off when the FFDCs cooperate. Therefore, the value of Nordhaus tax for LCT pioneers' producers lies primarily in its power to induce global cooperation on climate change. LCT pioneers also have sufficient market power to induce change of FFDCs' behavior.

The incentives to implement cooperative domestic climate policies vary among the FFDCs. The Gulf Cooperation Council countries, Russian Federation, and other large oil and gas exporters are much better off cooperating in climate action than facing Nordhaus taxes. They have higher baseline oil and gas export revenue exposed to Nordhaus taxes than any other FFDCs. They are also more strongly integrated into the world economy and have high value of assets in emissions-intensive industries exposed to trade sanctions. These countries also find it easier to cooperate, as they have already extracted a large share of their fuel resources and accumulated relatively larger value of wealth and skills in more complex sectors.

The lower-income countries with large proven but not yet extracted fossil fuel reserves are least willing and able to price carbon. Many of them are conflict-affected countries in Africa, posing development challenges to an LCT. They are often dependent on agricultural commodities and just beginning their transition to a dependence on fossil fuels, hoping it will allow them to accumulate capital to invest in other tradable industries in the future. Hence, they are less capable of generating revenues quickly enough to leapfrog to competitive, knowledge-based economies. The markets they are entering are dominated by large established players who have better access to investors, capital and markets as global demand for fossil fuels declines. Imposing trade sanctions against these countries would lead to deepening the global poverty gap and fuel local conflicts without achieving the intended results because their emissions are low in the baseline scenario. Some middle-income coal-exporting countries may also encounter economic and social disruptions in the coal-mining regions. Additional financial, technology, or knowledge transfers from LCT pioneers to encourage and enable asset diversification and domestic low-carbon transition in these two country groups would amount to $663 billion until 2050 (approximately $22 billion per year). This is one-eighth of the $5.5 trillion savings that the LCT pioneers would derive from international cooperation by all FFDCs.

Wellhead tax agreements could break the tragedy of the horizon for the FFDCs but would be politically challenging for the LCT Pioneers. In traditional cooperative carbon prices on scope 1 emissions, LCT pioneers capture (a portion of) resource rents from FFDCs and collect them as their carbon tax revenue, thus reducing the means available for FFDCs to diversify. Shifting the carbon tax base from consumption (or emissions) to production of fossil fuels and allowing full pass-through to consumer prices in importing countries would allow FFDCs to retain a higher share of fossil fuel rents and reinvest them in low-carbon assets. Yet, this would leave LCT pioneers with high retail prices and lower carbon tax revenues, worsening the welfare of their consumers, despite gains from climate cooperation by the FFDCs. Nonetheless, this concept opens the room for the mutually beneficial carbon pricing and trade agreements between fuel exporters and importers (Peszko 2019).

4.2. Incentives to Diversify

The traditional way for fossil fuel exporters to diversify is to branch out from fuel extraction and add more value to fuels through domestication of the downstream energy-intensive industries.

Traditional diversification builds on abundant domestic resources, often available at subsidized prices, accumulated capital, capabilities, skills and established value chains. If supported by strong institutions, it has been a successful, although energy-, and emission-intensive pathway to break the resource curse for many resource rich economies. Yet, amid the looming global low-carbon transition such a diversification route is risky, because it exposes the emission intensive industries to the adverse impacts of global changes in policies, technologies as well as investors and consumers' preferences.

Asset diversification is an alternative long-term growth and welfare strategy for the FFDCs, sustainable and robustly resilient to external policy shocks. It implies phasing out of fossil fuel subsidies and redirecting this fiscal stimulus to education and innovation that boosts labor productivity across sectors. Higher productivity translates into higher wages and households' income, hence increased consumption and savings. Households invest their savings in a broader range of productive assets, giving a competitive edge to more knowledge-intensive tradable consumer goods industries and services, as opposed to traditional diversification that diverts investments to intermediate goods produced by heavy industry. In the long run, asset diversification outperforms its traditional alternative by all macro-economic indicators and under all external policy impacts that have been simulated here. The broader asset base from which the economy derives income strengthens economic flexibility, hence resilience to external shocks, although in our scenarios asset diversification alone does shield the FFDCs' economies from the short-term aftershock of Nordhaus import taxes.

But asset diversification falls victim to the tragedy of the horizon. Initially, traditional diversification provides higher and more predictable revenue, output, and consumption compared to asset diversification. For FFDCs asset diversification implies abandoning the comfort zone of historic comparative advantage and core strengths in the fossil fuel-based product space. It requires massive upfront investments in new sectors that yield delayed and uncertain returns on products that are other countries' revealed comparative advantage. Productivity improvements and international competitiveness in new low-carbon sectors need time to materialize. Discovering new sources of global comparative advantage requires developing new capabilities and skills and building new national and sectoral innovation systems often from scratch.

During transition the FFDCs need access to revenues to finance diversification and decarbonization. There is a risk that a low carbon transition drains FFDCs of revenues from the fossil fuel–dependent assets before they accumulate a critical mass of new, "clean" assets and the capabilities to innovate and shift to new sources of sustainable income. This could make asset diversification impossible and get the FFDCs stuck in the emission-intensive economic structure, despite associated risks. The ability of fossil fuel–dependent sectors to produce (even declining) rents and generate a return on equity during transition is one of the necessary (though not sufficient) enabling conditions of diversification often overlooked in the "divestment" and the "stranded assets" debate. Under all scenarios of low carbon transition simulated here, the FFDCs see the reduction of their oil, gas and especially coal production in absolute terms, but not as much as producers in LCT pioneering countries. The rate of growth of fossil fuel revenues is substantially lower than expected under BAU, but higher than in the base year (as increasing fuel prices more than offset the impact of lower demand), allowing FFDCs to finance asset diversification and low-carbon investments.

FFDCs' economic structures are resistant to change. Despite helping the relatively knowledge-intensive sectors, asset diversification in our simulations does not change the core specialization of FFDCs in fuel extractive sectors and carbon intensive heavy industry, which dominate exports until 2050 in all scenarios and for most of the FFDCs country groups. The declining share of fuel commodity exports is more than offset by the increase of the exports of carbon intensive manufacturing products, especially in scenarios with fossil fuel subsidies. Many existing cleaner sectors are also integrated into the value chains of carbon intensive industries, benefitting indirectly from traditional diversification. Only for the low-income countries with large unexploited fuel reserves, the two diversification strategy choices make a big difference for the future economic structure, because many of them are currently more dependent on exports of agricultural commodities than fossil fuels.

Asset diversification and climate policies work in synergy. In one direction, asset diversification favors more productive and innovative firms and products that can more successfully compete in the knowledge-intensive global economy. These new entrepreneurs would more swiftly discover new sources of comparative advantage beyond fossil fuels and related fuel-intensive industries under increasing costs of carbon emissions. The other side is also true: cooperative domestic policies stabilize the long-term benefits of asset diversification strategies by avoiding the surprising external policy shocks and the risk of trade wars.

4.3. Political Economy of Low-Carbon Transition

Owners of all fossil fuel assets in FFDCs benefit from traditional diversification scenarios at the expense of consumers and the rest of the economy. The strategies narrowly targeted at maximizing the value of fossil fuel assets limit the long-term growth and consumption opportunities.

The impacts of climate and trade policies and diversification strategies are not the same in size and direction across asset classes. For example, traditional diversification preserves asset value mainly in the fossil fuel-intensive sectors, which have been the increasingly important drivers of these countries' growth and exports so far, but it restrains the growth of productive low-carbon assets. Fossil fuel subsidies help domestic sales and revenues of extractive sectors, partly compensating for the shrinking export markets. Coal and gas benefit more than oil, because there are more opportunities for their domestic industrial uses. Asset diversification, in turn, threatens all fuel extractive industries because it transfers resource rents from energy-intensive to knowledge-intensive sectors. The final sectoral incidence of wealth is not clear-cut, because in FFDCs low-carbon, knowledge intensive sectors are often integrated into the fossil fuel value chains. Of all the external events simulated in this study, only Nordhaus taxes against noncooperating FFDCs always knock down the value of all assets in the FFDCs, whether they are fossil fuel–dependent on not.

Interests in cooperation are misaligned between extractive sectors in the FFDCs. Cooperative domestic carbon pricing benefitting oil producers, while destroying the value of gas and coal rents. Our simulations underpin a hypothesis that unlike coal and gas rents, the oil rents in FFDCs can benefit from cooperative carbon taxes if the counterfactual is a rapid ramp-up of unilateral climate policies in fossil fuel importing countries. Climate cooperation by FFDCs allows LCT pioneers to follow the slower rate of growth of carbon taxes on their own fossil fuel consumption, delaying a phase-out of internal combustion engines in cars and extending export demand for oil imported from FFDCs (without detrimental impact on accumulated CO_2 budgets). For coal and gas rents in FFDCs, cooperative domestic carbon taxes and asset diversification represent the worst-case scenario, however. It gives them a double blow. First, they reduce export demand and prices. Second, they slash domestic demand for gas and coal because of much lower leakage. Despite these differences, cooperative behavior of FFDCs benefit all fuel–dependent sectors in a sense that it makes the policy environment less uncertain, preventing demand and price volatility and trade wars, hence sharp changes in asset values, observed for example during the 2014 oil price slump and the Covid-19 crisis.

Coal reserves in FFDCs are the most affected by the low carbon transition in percentage terms, but the least in value terms. In the worst-case scenario the FFDCs forego 43 percent of the coal rents expected under BAU (or US$1.2 trillion). This has negligible macroeconomic effect on most coal-mining nations, however because coal rents are very small compared with oil and gas rents and account for small shares of national GDP and exports. However, mining regions could experience economic decline and social distress (stranded labor) that will require support of "just transition".

The worst-case scenario for gas is the same as for coal producers – cooperative climate action with asset diversification. It results in lowering the present value of rents by 25 percent ($2.8 trillion) compared to BAU. The best-case scenario for gas is also the same as for coal – unilateral carbon taxes by LCT pioneers without any trade measures and traditional diversification. It increases the discounted gas rents 3 percent above BAU.

The best- and worst-case scenarios for oil rents are different than for other fuels. The worst-case scenario (Nordhaus taxes) reduces the discounted value of oil rents in FFDCs by more than US$17 trillion (21 percent) compared with BAU. The best-case scenario for oil owners in FFDCs (cooperation and traditional diversification) reduces oil rents in FFDCs by 6 percent below BAU (US$5 trillion). Losses of oil rents dwarf those of coal and gas in value terms but are smaller in percentage terms.

The real-life impacts of an LCT may be harder for FFDCs to manage than the scenarios this study suggests. Amid declining demand, investments in fossil fuel–dependent assets can become increasingly risky during an LCT. Competition between fuel producers could become more aggressive. Sharp dips and spikes in asset values can lead to investor panic and tipping points. Therefore, extractive industries could end up paying a higher price for noncooperation by their host countries than calculated by the economic models in this study, which always assume smooth adjustments to shocks. As demand shrinks and disruptive clean technologies capture market share, suppliers would likely seek to improve production efficiency and reduce their margins (Behar and Ritz 2017; Bornstein, Krusell, and Rebelo 2017). Market shares of different producing regions will shift, mainly benefitting the FFDCs producers with low production costs, low volumes of capex requirements, larger market power and access to low-cost finance. This is good news for FFDCs that are low on the global oil and gas supply curve and whose costs of developing new fields are largely sunk (for example, most GCC countries). For these FFDCs, increasing oil and gas revenues in the next 20 to 30 years will give them an opportunity to invest in diversification without having to rely on international financial assistance. However, those FFDCs that have not yet had a chance to bring their reserves to production may find it more difficult to finance economic transformation. Price wars would create short-term winners and losers, bankruptcies and mergers as seen in 2014 and 2020. Access to low-cost, long-term capital may become a limiting factor for many new development projects. Several investors and financial institutions are already revising expectations regarding maturity and the cost of financing, depending on a project's exposure to LCT risks (Mercer 2015; Lloyd's 2017, Bolton et al 2020). Financing coal projects is already becoming a challenge in the European Union and the United States. Europe's biggest insurance companies, such as Allianz and Axa, have policies designed to make it harder for coal companies to buy insurance cover (Ralph and Storbeck 2018). New fossil fuel development projects with low upfront capital needs, short development times, and flexible production schedules may have a competitive advantage (Kleinberg et al. 2018). All these challenges would amplify if the external policy shocks were consistent with the high probability of achieving the aspirational 1.5°C goal of the Paris Agreement.

The important insight from our simulations is that the low carbon transition redistributes wealth across sectors and countries, rather than just stranding the assets. The assets that no longer yield returns expected by owners in the worst affected sectors are stranded to them, but not necessarily to the economy. Some capital is gradually reallocated to other, more productive uses in other sectors, reducing the economy-wide costs associated with structural transformation and creating winners and losers during a transition. Produced (material and intangible) assets can be easier to reallocate to other productive uses than can underground reserves. Most fossil fuel assets are used in combustion processes to produce energy. Smaller quantities of fossil fuels are used in industrial processes as feedstocks to produce synthetic materials, plastics, fertilizers, and so on. Therefore, unless new, noncombustible uses for fossil fuels are found at the scale comparable with energy generation, they cannot easily be reallocated to other economic activities. The obverse of the stranded asset risk is the upside that technology developments combined with climate and diversification policies may increase the value of produced assets in the non-fuel-dependent sectors. The structural transformation can increase the profits of knowledge-intensive, clean economic activities. It also implies substitution of human and natural renewable capital as well as intangibles for produced material and natural exhaustible assets. These effects cannot be captured well by the economic models. But if these low-carbon asset classes are underdeveloped in a country, as is the case in some developing FFDCs, significant investment and policy effort will be required before new assets can generate the flow of welfare and income that would match the profits lost from the old, fossil fuel–intensive asset classes. Eventually, this leads to a structural and systemic transition to a “dematerialized” long-term sustainable growth model, where fewer material inputs generate higher economic output and welfare. It is a shift from a capital-intensive growth model to a more labor- and knowledge-intensive growth model. A low-carbon future is its co-benefit.

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