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Cross-Border Risks of a Global Economy in Mid-Transition

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ABSTRACT: This paper analyzes the cross-border risks that could result from a decarbonization of the world economy. We develop a typology of cross-border risks and their respective channels. Our qualitative and quantitative scenario analysis suggests that the mid-transition – a period during which fossil-fuel and low-carbon energy systems co-exist and transform at a rapid pace – could have profound stability and resilience implications for global trade and the international financial system.

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Contents

I. Introduction

To limit global warming to 1.5°C or even 2°C above pre-industrial levels, the world economy must decarbonize very rapidly, which it is currently failing to do. As the recent IPCC synthesis report (IPCC, 2023) reaffirms, the 1.5°C target requires global greenhouse gas (GHG) emissions to peak before 2025 and to decline by 43 percent before 2030 compared to 2019 levels. The 2°C target also requires global emissions to peak before 2025 and then to be reduced by 21 percent before 2030 and 64 percent before 2050 compared to 2019 levels. These objectives imply net zero emissions reached around 2050 and 2070, respectively. Ahead of the first global review of climate action due at COP28 in Dubai, most objectives announced by countries for 2030 fail to credibly align with a neutrality horizon (Black et al. 2022).[1]

A large-scale transformation of the global economy is still underway in the technological, trade and financial domains, and will incur important yet still largely unknown cross-border risks. Even if ambitious climate goals are not met, the technological change that is already underway and already committed by past climate policies – with, most notably, a switch to renewable energy and electrical vehicles – can be expected to profoundly alter the global economy (Mercure et al., 2021). The implications of decarbonization for economies have so far been mostly assessed at the domestic or global aggregate levels. With a few exceptions in the production networks field (See Blackburn and Moreno-Cruz, 2021; Chepeliev et al., 2021; Devulder and Lisack, 2020; Frankovic, 2022; King et al., 2019), much less attention has been paid to the cross-border channels of risk and opportunity transmission. Recent political developments, including the European Union's (EU) Carbon Border Adjustment Mechanism, the U.S. Inflation Reduction Act, and China's decision to stop financing coal power plants under the Belt and Road Initiative, have put cross-border impacts of climate policy in the spotlight (Magacho et al., 2023a).

This paper aims at improving our understanding of some of the main potential cross-border impacts of such a deep structural transformation. Structural differences between countries in relation to the degree of fossil dependence, the penetration of renewables and their underlying supply-chains may have important cross-border macroeconomic implications. Changing patterns of trade in energy commodities (fuel, technologies, materials) may have substantial impacts, negative or positive, on the balance of payments of both exporting and importing countries, as well as on international financial flows. At the country level these changes can be large, even if opposite effects nearly cancel out at the global level (Mercure et al., 2018a; 2021). Likewise, cross-country differences in the stringency and pace of climate policies (Dubash, 2021) and the degree of regional or international policy coordination may have cross-border implications (IMF, 2022a).

During the "mid-transition" period, when the economic transformation is most rapid, cross-border risks could generate or exacerbate instability in the economic, political, and financial spheres, which may become detrimental to the global transition process itself. We define the transition as the transformation of energy, industrial, transport and agricultural socio-technical regimes, together with the associated transformation of dependent systems (Geels, 2002; Turnheim et al., 2015), with the goal of reducing greenhouse gas emissions in time to avoid a global average temperature increase beyond the limits agreed in the Paris Agreement (UNFCCC, 2016). Following Grubert and Hastings-Simon (2022), we then define the "mid-transition" period as the time span during which low-carbon and fossil-based energy and industrial socio-technical regimes are both undergoing rapid transformation, co-exist on a large scale, and operate in a highly

[1] Per the Paris Agreement (UNFCCC, 2016), the temperature goal of keeping global warming to well below 2°C "will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (Article 2), and "Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (Article 4).

contested space, which causes new or exacerbates existing instabilities and volatility of global energy markets, with knock-on effects on the global economy.[2]

A consistent analytical framework for the cross-border economic and financial risks associated with a world economy in this critical mid-transition period is needed.[3] The existing literature on the macroeconomic effects of climate mitigation policies often simplifies nation-level challenges and policy contexts with the goal of seeking simple narratives that apply at the global level (Riahi et al., 2022; Masson-Delmotte et al., 2018; Van Vuuren et al., 2020; Rogelj et al., 2018; Grubler et al., 2018). Developed as general basis scenarios of globally coordinated decision-making and cost-effective economic evolution, this literature sheds little light on the links between the transition and the structural transformation of the global economy. While a growing body of literature examines the cross-border effects of the physical impacts of climate change, we are unaware of any systematic analysis of the cross-border impacts of decarbonization in a mid-transition context.[4]

The paper's three main contributions are as follows. First, we draw on a range of stylized facts to show that global decarbonization will very likely change the structure of international trade and capital flows. Second, we propose an analytical framework to analyze these effects that is based on a system dynamics approach. Third, we assess a subset of the likely impacts of global decarbonization that we outline, notably those on output and trade, under specific global decarbonization assumptions. Our analysis suggests that, among the world's largest economies, China, India and Japan are likely to benefit the most from the transition, while Russia, Saudi Arabia the U.S. could be negatively affected relative to a hypothetical baseline of baseline GDP growth.

While this paper seeks to draw the attention of the research and policy communities to cross-border transition risks, it does not imply any minimization of the major opportunities associated with the transition – and the counterfactual of an absence of transition implies far greater risks than those we analyze here. Opportunities include economic growth, notably in the short run as low-carbon infrastructure is developed, as well as job creation, innovation, and many environmental and health co-benefits (see, e.g., Bhattacharya et al., 2021). A counterfactual "no (or failed) transition" scenario, where fossil production and consumption are not significantly reduced would imply a host of major cross-border risks, in particular those stemming from the economic and financial consequences of an accelerated deregulation and destabilization of the Earth system.

The rest of this paper is organized as follows. Section 2 highlights several stylized facts that are relevant for assessing cross-border risks during the mid-transition period. Section 3 proposes a taxonomy of country-level cross-border risks. Section 4 analyzes potential cross-border impacts that result from shifting trade, energy, and employment patterns, quantifying some of them using the E3ME-FTT global macroeconomic model. Section 5 explores the potential international macroeconomic and financial spillovers that cross-border mid-

[2] As documented by Fressoz (2022), the concept of "energy transition" first appeared in 1967 in response to the threat of energy resource shortages, and in 1982 to make the case for the need to invest in nuclear energy as a contingency option to rapidly decarbonize the global energy system if a climate catastrophe were to appear likely. Geels and Turnheim (2022), meanwhile, use the term "transition" to refer to a technological transformation that may not necessarily be entirely driven by a climate goal, making use of a historical perspective looking at where transitions have occurred before and the conducing factors. Here, the mid-transition that we describe does not necessarily imply a sufficiently rapid decarbonization of the world economy to avoid climate change of 2°C or more.
[3] The paper essentially abstracts from the macroeconomic effects of physical risks of climate change, including those that could adversely impact the global low-carbon transition.
[4] See the recent study by Carter et al. (2021) for a conceptual framework for cross-border impacts of the physical effects of climate change. On cross-border impacts of physical climate change, see also Adams et al. (2021), Benzie et al. (2019), Bailey and Wellesley (2017), Challinor et al. (2017, 2018), Hedlund et al. (2018), Otto et al. (2017), Schenker (2012), Smith et al. (2018), Volz et al. (2020), and Feng and Li (2021). Laybourn et al. (2023) argue that societal reactions to worsening physical climate impacts could create destructive dynamics whereby societies are increasingly distracted by the symptoms of the crisis, deepening its consequences and generating a doom loop.

transition risks could cause. Section 6 provides a summary of the findings and concludes with reflections on the scope for future research.

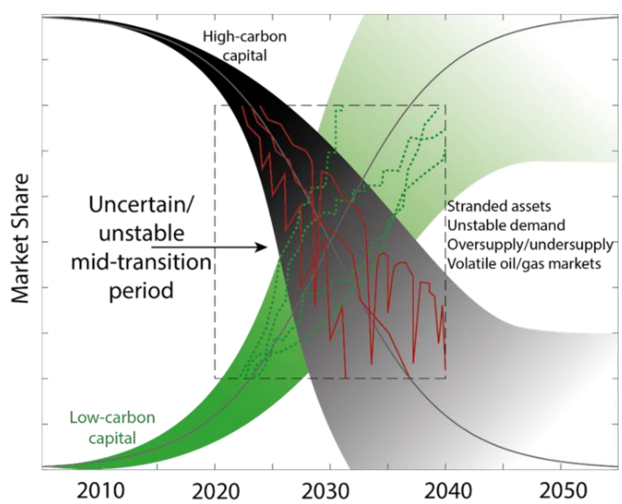
2. Stylized Facts to Inform Mid-Transition Cross-Border Risk Analysis

This section covers current technological and structural transformation trends, global macroeconomic and financial patterns observed in the recent past, and specific price dynamics that arise with mid-transition cross-border risk scenarios.

2.1. Stylized Facts for a Mid-transition Period

The world economy could become exposed to higher uncertainty and instability as a result of the parallel emergence of low-carbon technologies and persistence of fossil-based infrastructures. These parallel and contradictory trends open a potentially lengthy mid-transition period, when the fossil-based energy system will coexist with the emerging low-carbon energy system, while being increasingly impacted by increasing climate damages. As noted in the introduction, we borrow the “mid-transition” term from Grubert and Hastings-Simon (2022). As these authors note, each energy system – the old and the emerging – imposes operational constraints on the other. This coexistence means that the emerging low-carbon energy system will face fossil system constraints. This “mid-transition” will therefore require “decision-making under dynamic and uncertain conditions.” There is a substantial low-carbon energy investment shortfall for reaching global average temperature objectives, with some estimates putting the clean energy shortfall at nearly US$3 trillion per year (IEA, 2022a), alongside a potential investment excess or shortfall in fossil systems (reflecting increasing market uncertainty and uncoordinated expectations). The potential for instability could therefore become considerable. During that period, as shown in Figure 1, different sources of instability and uncertainty are likely to materialize, with opposite effects on the transition.

Figure 1. Stylized Representation of the Unstable Mid-Transition Period



Note: Stylized view of the possible volatility and instability of paths for market shares of high- and low-carbon capital through the middle phase of a low-carbon economic transformation, as low-carbon industries rise rapidly concurrently to a high-carbon industry decline.

The first key trend is that low-carbon technological change is underway, affecting conventional fossil markets. Technology data show that decarbonization is well underway in several key sectors and countries (power, transport in the EU and China) but only nascent in others (industry, heat; see IEA 2022b; Mercure et al., 2021). Established high-carbon systems and economic structures may be disrupted by ongoing low-carbon technological change and innovation (Tong et al., 2019). The transition towards low-carbon energy generation and use is a self-reinforcing process, in which deployment decreases costs, which facilitates further deployment (Way et al., 2022, Mercure 2012, Mercure et al., 2014, Arthur, 1994; Unruh, 2000). Tipping points past which diffusion becomes irreversible could be near or already past (Sharpe and Lenton, 2020), notably towards solar energy (Nijsse et al., 2023) and electric vehicles (Lam and Mercure, 2022). The prospect of a dominance of solar energy and electric vehicles has stark implications for the value of high-carbon assets (Semieniuk et al., 2022).

Emerging market and developing economies (EMDEs) could become markets for low-carbon technologies even with limited government capacity to implement climate policies. Diminishing cost through broader adoption of these technologies could in turn mitigate the potentially negative current account effects for EMDEs of importing low-carbon technologies. In the longer run, the main cross-border risk from increasing renewables installation globally is a declining demand for and trade in fossil fuels, and the potential for stranded fossil assets and related capital and infrastructure, concurrent with increased trade in and declining costs of low-carbon technology.[5]

At the same time, the emergence of uncoordinated low-carbon industrial policies by the world's largest economies highlights the importance of resilient low-carbon supply chains as a key policy objective. China has a long-standing national planning strategy, based on Five-Year Plans, while the U.S. has turned to explicit, climate-oriented industrial policy through the Inflation Reduction Act. In contrast to the U.S. and China, the EU's approach to industrial policy – with the "Fit for 55" climate transition plan, REPowerEU, and EU Green Deal Industrial Plan and Net Zero Industry Act – emphasizes the principle of free trade and the need to abide by WTO rules, maintain competitive markets, and deepen the EU's internal market. These industrial policies interact with geoeconomic fragmentation, and could either amplify or mitigate it.

In parallel to these decarbonization trends, investment in unabated fossil generation remains high, on a par with its 2016 level (IEA, 2023; IMF, forthcoming), with significant volatility in prices. If and when the transition gains momentum, a large amount of assets – notably fossil assets – could become stranded if investment exceeds perceived future needs (Pfeiffer et al., 2018; Mercure et al., 2018a, 2021; Semieniuk et al., 2022, van der Ploeg and Rezai, 2020).[6] However, price spikes could occur in the opposite scenario if stranded assets are excessively anticipated and investment collapses prematurely. Hence, this points to a case for international coordination and regulation policies within climate policy frameworks (CFMCA, 2023; Krogstrup and Oman, 2019). Supply-demand imbalances could lead to significant volatility in oil and gas markets, in part generated by instability in market regimes motivated by geopolitics (Van der Graaf and Bradshaw, 2018), affecting a wide range of activities and assets, from manufacturing to services. In 2022, short term supply shocks such as the Russian reduction of gas exports to Europe and the G7 sanctions hitting Russian oil exports were complemented by a shift in oil producer strategy to maximize shareholder value rather than production and speculation (Weber and Wasner, 2023; Breman and Storm, 2023). Such volatility can be expected to persist as the market declines and investment and demand coordination becomes harder. However, until the oil market is firmly in decline, stranded assets are likely to be invested in as the high profits in a shortage period induce oil companies to expand investment in order to partake in the short-term profit boom. But since the resulting assets are long-lived, they are vulnerable to subsequent stranding. The European

[5] Broadly speaking, stranded assets can be defined as investments that stop returning a profit before the end of their life cycle.
[6] Current expectations, as shown by the limited pricing of climate risk in the banking sector (Beyene et al., 2021), are clearly not aligned with the Paris Agreement, particularly in the banking sector.

oil majors' recent adjustment of their transition plans, and OPEC's upward revision of its 2045 global oil demand projection upward from 100.6 to 110 million barrel per day in an interval of only 9 months (OPEC, 2022; Reuters, 2023), suggest this dynamic is at play.

Furthermore, the value of fossil exports and imports may not necessarily be replaced by trade in other commodities, which could determine the stance of countries on climate action. In particular, the prospect of declining demand for oil and gas and resulting disproportionate macroeconomic impacts on producing countries could drive geopolitical conflict or political maneuvers aiming to capture larger shares of declining markets at the expense of other producers. Electricity is not an easily traded commodity since long-distance transport requires expensive interconnectors and transmission lines (which can be exposed to weather and climate extreme events), whereas most countries have substantial renewable energy potential over their territory that enable local electricity production (Mercure and Salas, 2012). International trade in green hydrogen is emerging but will unlikely match today's volumes of trade in fossil, given that it is not used in as many applications nor with volumes of the same size (IRENA, 2022). Moreover, net exporters of fossil and hydrogen and other renewable electricity-based energy carriers need not be the same (Berrada and Laasmi, 2021; Hank et al., 2020). Perhaps more importantly than trade in renewable energy itself, the world economy is projected to experience growth in trade in low-carbon technology/capital goods and critical minerals (Boer et al., 2021), as well as the intermediate goods and industrial equipment required to produce or refine them.

Hard-to-predict binding constraints on resources needed for the transition could emerge, generating potential non-linearities in the transition from one energy system to another. Physical constraints on the reduction in production costs of low-carbon technology may emerge. Although geological reserves are likely sufficient through 2050 (Wang et al., 2023), the demand growth for many materials needed to make low-carbon products (critical materials) currently far exceeds the rate of expansion of their supply (Miller et al., 2023). The costs of critical materials have recently increased noticeably, which could lead to a stop or even a reversal in some (though not all) of the long trends of decline in the costs of low-carbon technologies (IEA 2021a). Second, there could be physical and other obstacles to material substitution aimed at overcoming these constraints. For instance, widely available metals such as aluminum could in principle substitute for cobalt and lithium in the production of batteries, the key component of electric vehicles. However, creating a battery free of critical materials currently remains a major technological challenge and is riddled with uncertainties. Lastly, geopolitical confrontations linked to critical materials could emerge, whereby, for reasons linked to national security or strategic competition, key commodity-producing countries adopt quantitative restrictions on exports.[7]

The duration and volatility of the mid-transition period will largely depend on countries' cross-border characteristics and policy coordination modalities. We now turn to these emerging cross-border risks of the mid-transition period.

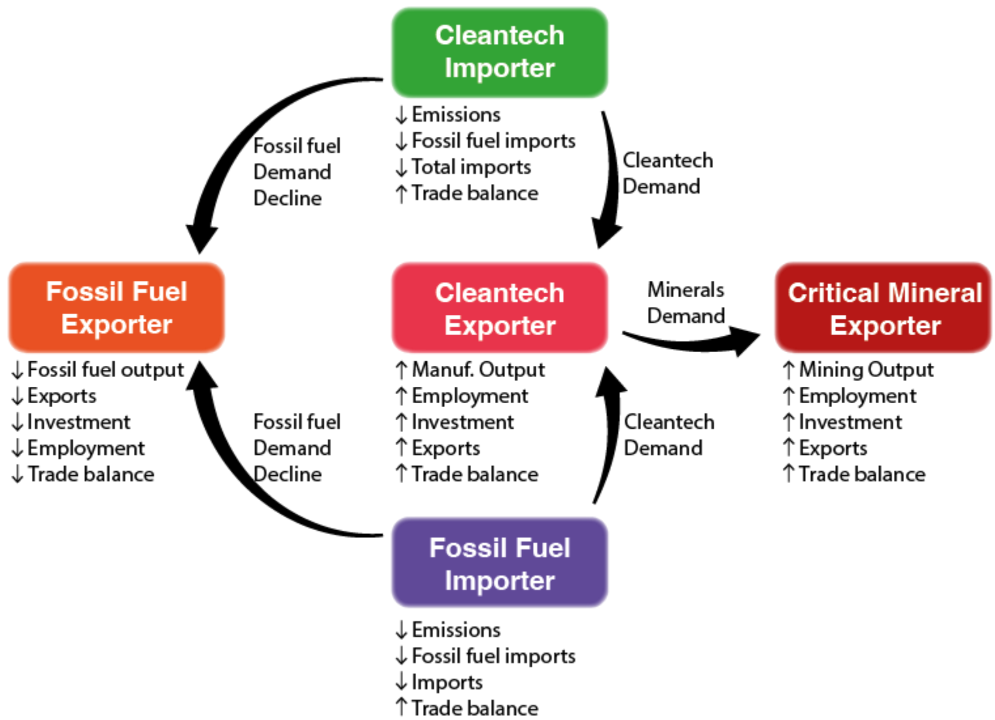
2.2. Emerging Cross-Border Risks of the Mid-Transition Period

Five country archetypes can be defined to characterize cross-border feedbacks through the transition (Figure 2). Obviously, actual countries are positioned (or exposed) heterogeneously with regards to these feedbacks. Few countries correspond exactly to any of the individual archetypes, as most countries have the characteristics of two or more (e.g., a fossil and cleantech importer, and critical mineral exporter). The

[7] Highlighting the links between the economic and national security dimensions of TCMs, a US Executive Order in September 2020 stressed that "[the United States'] undue reliance on critical minerals, in processed or unprocessed form, from foreign adversaries constitutes an unusual and extraordinary threat, which has its source in substantial part outside the United States, to the national security, foreign policy, and economy of the United States." The Executive Order then declared a "national emergency to deal with that threat." In 2020, Indonesia introduced an export ban on unprocessed nickel, which led to claims against Indonesia at the World Trade Organization by the European Union, as well as criticism by key steelmaking countries like China and South Korea.

proposed framework is meant to be used to decompose the upwards and downwards pressures on various variables that result from their exposure to one or more of these archetypes. Although we illustrate this taxonomy with G20 countries, these archetypes are not explicitly connected to the list of G20 countries. The reason is that the archetypes are not intended to apply only to G20 countries, but potentially to all economies, including low-, middle- and high-income countries. While some G20 countries fall relatively neatly into one of the archetypes (e.g., Saudi Arabia into the "fossil exporter" archetype), several do not.

Figure 2. Archetypes of Countries in the Transition



Note: Archetypes of country roles in the transition from a cross-border perspective. Thick arrows indicate the direction of specific cross-border impacts on financial flows. Up and down arrows in the captions indicate whether a quantity increases/improves or decreases/worsens. For simplicity purposes, we consider cleantech exporters as implicitly being also critical mineral exporters.

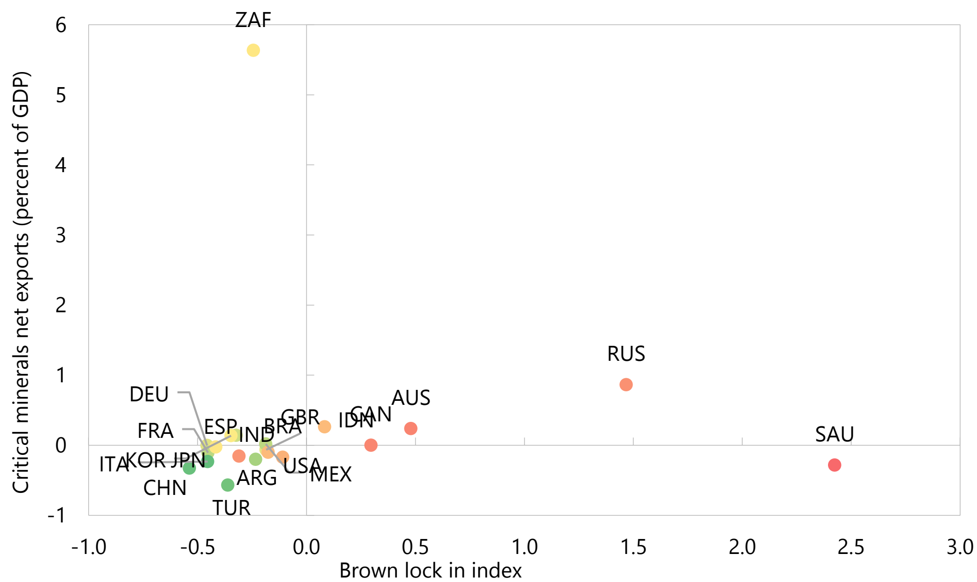
The five country archetypes illustrate the external pressures that affect countries according to whether they are net importers or exporters (or more generally large producers) of fossil related technologies, critical materials for the transition, and/or low-carbon-related technology. The framework assumes that decarbonization occurs in at least the fossil and cleantech importers, and that only cleantech producers make use of critical materials. Fossil importers will generally also be cleantech importers since few, if any, countries produce all the cleantech that they need for decarbonization. Decarbonizing countries generate a cross-border impact on fossil exporting countries through volumes, and on fossil producers more generally through both volumes and prices. They impose a cross-border impact on cleantech producers through increased demand for such exports. Cleantech producers generate a cross-border effect on critical material producers through the demand for such exports.[8] The critical lesson is that cross-border impacts critically depend on these (simplified) structural country characteristics. Countries will be affected differently across borders, depending on several factors such as their own endowment with fossil fuels, their fossil production and consumption patterns, their

[8] It should be noted that, strictly speaking, no technology is clean in the sense that material production processes always involve environmental and social impacts. Cleantech here means technologies considered to be low carbon.

technological capabilities to develop and produce low-carbon technologies that will substitute for fossil-based technologies, their endowment with critical minerals and other commodities needed to manufacture the capital goods required for the low-carbon economy, and their ability to produce renewable energy.

The direction of cross-border effects could be different from the directions outlined in Figure 2 in the case of policy coordination across countries. Cross-border impacts are also affected by the domestic and international policy setting, as well as the degree of international policy coordination. Furthermore, trade effects could materialize in hard-to-anticipate directions. A fossil importing country could increase fossil imports in a global decarbonization scenario, as global demand for fossil fuels declines and puts downward pressure on international fossil prices. By contrast, a fossil exporting country's trade balance could improve through the domestic economy's diversification to low-carbon manufacturing sectors, through both price and non-price policy levers. Its imports could also fall more than its exports in response to a deterioration in terms of trade combined with a need to stabilize the country's net foreign asset position. Indirect emissions upstream (emissions embodied in intermediate inputs) and downstream (emissions after production until final consumption) are another essential component of this structural cross-border exposure to transitions (Magacho et al., 2023b). The higher the dependence on these intermediary industries, the higher the country's external exposure. However, countries with higher productive and technological capabilities are likely to have a higher adaptive capacity to climate policy shocks than undiversified economies (Mealy and Teytelboym, 2020; Andres et al., 2023).

Figure 3. G20 Countries' Fossil Fuel, Critical Minerals Net Exports, and Green Complexity Potential



Sources: World Bank; UN Comtrade Database; World Economic Outlook Database; Andres et al., 2023; and authors' calculations.
Note: The countries are colored by gradation of transition outlook index. The axes place countries along the critical mineral exporter/importer archetypes (y axis) and brown lock in index (x axis), while the color characterizes the capacity of countries to export green technology.

The country archetypes and their cross-border risks can also be mapped quantitatively using proxy indicators. The carbon lock-in index developed by Andres et al. (2023) makes it possible capture not only fossil fuel exporters/importers but also the technical dependencies to fossils. The exports/imports of critical materials relative to GDP measure the current situation of countries with respect to this dimension. Finally, the transition outlook index shows how countries could benefits from exporting green technologies based on their current productive structure. It measures in particular the proximity of each declining activity to other, climate compatible activities. While some of the risks stemming from the mid-transition can be larger, from a domestic perspective, for smaller economies, we focus on G20 countries because they collectively represent about 85 percent of global GDP and 75 percent of international trade. The transition outlook index characterizes the ability of countries to expand exports to new types of cleantech on the basis of existing national manufacturing capabilities (Andres et al., 2023). The five country archetypes are visible in the scatterplot chart, which focuses on G20 countries. First, the high-carbon locked-in countries, with high net fossil exports and a low transition outlook index, include Saudi Arabia, Russia, Australia, Canada, and to a lesser extent Indonesia. Second, fossil importer countries include the EU, Japan, Korea, India, and China. Third, critical mineral exporter countries, with low fossil net exports but critical mineral net exports, and low green transition outlook, include South Africa, Australia, and Brazil within the G20, but also many more countries outside the G20. Fourth, critical mineral importer countries, characterized by a low brown lock-in index, critical minerals net imports (reflecting the building up on low-carbon infrastructure systems), and a high green transition outlook, includes China, Korea, Japan, and the EU, and these are also the cleantech exporters. India could also be included in this group, although with a relatively lower green transition outlook. The U.S. falls somewhere between the five clusters, with a relatively high green transition outlook, seemingly small dependency on critical minerals, and relatively low dependency on fossil imports, but being a relatively large fossil producer and a moderate critical mineral producer.

The duration of the mid-transition period may depend heavily on the dynamic relations between these five country archetypes. Several factors stand out. The emerging geoeconomic fragmentation could both fracture the relations between these groups but also incentivize resilience policies that mitigate the need for these interactions. This manifests as reversals in trade, capital flows, international labor mobility, international payments, and multilateral cooperation on the provision of global public goods (Aiyar et al., 2023). Since 1990, there has been a large increase in trade and cross-border capital flows. From 1990 to 2008 there was significant trade – world goods exports roughly doubled from 10 percent to 20 percent of world GDP (Shin, 2023) – and increasing cross-border capital flows, consisting of FDI, bank lending and portfolio flows (Aiyar et al., 2023). On the one hand, geoeconomic and geopolitical rivalry amplify supply shortage risks and could slow some countries' low-carbon transition. On the other hand, a move to reshore or regionalize certain activities could reduce some cross-border transition risks while amplifying others, by increasing local manufacturing capabilities and shortening value chains and the potential for bottlenecks and supply disruptions, at the expense of existing global value chains.[9]

The high degree of interdependence of global productive structures makes them vulnerable to the shocks to prices and output that could occur during a geopolitical rivalry period. Several interrelated phenomena may explain these fragilities: extractivism, i.e. a concentration of production of key inputs to global supply chains in a small number of – mainly developing – countries (Althouse and Svartzman, 2022; Aiyar et al., 2023); complex extended value chains and just-in-time production (Baldwin, 2016); financialized management of companies (Cordonnier et al., 2013; Rachel and Summers, 2019; Christophers 2020, 2023). In

[9] Copeland et al. (2022) and Shapiro (2021) document stylized facts on the relationship between trade and the environment (polluting industries are more exposed to trade, there is a negative environmental bias in trade policy, polluting industries tend to be located upstream in value chains, carbon emissions embedded in products that are internationally traded account for a fourth to a third of global emissions, advanced economies are increasingly outsourcing greenhouse gas emissions) that, taken together, suggest that global decarbonization inevitably involves decarbonizing or reducing trade, while conversely trade policy can also affect the effectiveness of climate action.

complex and globalized supply structures, sudden supply-demand imbalances can lead to large price volatility and shortages, which may intensify and occur at increasingly short intervals during the mid-transition (Weber et al., 2022). Shocks could lead to price increases if they hit systemically significant upstream sectors, ultimately generating inflation through further price increases (Weber and Wasner, 2023). The extent to which discrete relative price shifts lead to general price increases will depend on the monetary policy regime.

Ultimately, there is also a link between scarce resources needed for the transition and conflicts, especially in fragile states, generating potential cross-border conflict risks. Furthermore, political instability could emerge within fossil exporting countries, for example if the government faces fiscal pressures induced by a deteriorating current account balance and must reform its domestic fossil price regime, in turn leading to social unrest. Such political instability could have regional or global consequences. Given still insufficient investment in renewable energy relative to fossil projects, there is high uncertainty around the potential for stranded fossil assets and related capital and infrastructure. Pricing of climate risk in the banking sector remains limited (Ongena and al. 2021), and expectations of stranded assets also depend on the type of financial market participant and market being considered. Regional fragmentation could occur, and decarbonization of global supply chains could materialize in a "too little, too late" scenario. All these risks constitute additional potential sources of non-linearities.

These factors would interact with the global inflation regime. As argued in BIS (2022) and Borio et al. (2023), we may have entered a high-inflation regime that could reduce certainty, deter productive and foreign direct investment (FDI), and be detrimental to price signals given that large price swings in key commodities (such as oil) could swamp policy-related price signals (e.g., carbon pricing). In the longer run, higher levels of inflation could however help absorb economic and financial rents and rebalance the labor and capital shares of income while incentivizing the control of "transition-critical" prices and "systemically significant prices" (Hockett and Omarova, 2016; Weber et al., 2022).

The mounting physical impacts of climate change as well as other planetary boundaries contribute to a higher inflation regime. There is evidence of persistent inflationary pressure from higher average temperatures (Kotz et al., 2023). Domestic and imported inflation could become more volatile because of the impact of extreme weather events and gradual warming on agricultural crops, housing, and energy prices. Other planetary boundaries such as biodiversity could lead to similar effects (Svartzman et al., 2021; Maurin et al., 2022; Calice et al., 2023). At the country level, this risk is presumably proportional to the share of energy and food in total imports, and ultimately in the consumer price index, which is typically significant in EMDEs. Moreover, price changes related to climate events could become persistent, and measures to address energy supply risks driven by climate events (e.g., measures aimed at ensuring sufficient inventories or technological diversification in either production or trading partners' supplies) will affect how strongly shocks impact the economy – and thus inflation (Bandera et al., 2023). A switch to a new inflation regime (as a result of climate or other factors) will impact low-carbon investment costs specifically (as they tend to be more capital intensive). In turn, this will have ripple effects across borders.

Given possibly binding balance of payment constraints, some countries may face a dilemma between sufficiently rapid decarbonization and raising income per capita. Valdecantos (2023) argues that South American economies face a green transition dilemma, whereby attempts to maintain external sustainability to enable the financing of investments to raise the level of income per capita require sustained exploitation of natural resources, while decarbonization requires lower or negative growth of exports (given the latter's reliance on the exploitation of natural resources), which would make the external constraint more binding.

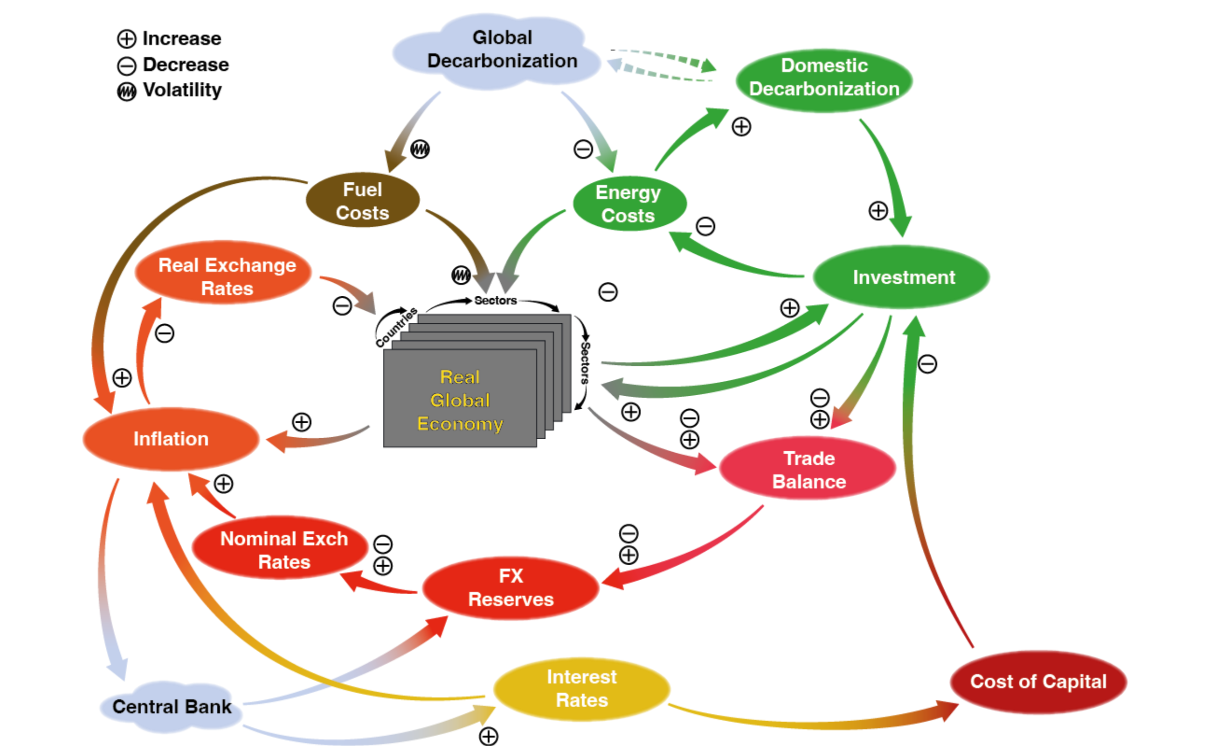
Separately, countries could choose or be forced into sufficiency strategies that could affect cross-border risks and opportunities (IPCC, 2022). The IPCC (2022) defines sufficiency policies as a "set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human wellbeing for all within planetary boundaries."[10] Sufficiency strategies could emerge at the national level because they may be necessary to meet mitigation goals, because they could yield strategic advantages in a world of geoeconomic fragmentation, more frequent shortages, growing energy instability, and possibly structurally higher inflation, or simply as a consequence of shortages that would have not been properly anticipated. Indeed, sufficiency strategies could potentially help countries improve their energy and material security, trade balances, and strategic autonomy. The economic impacts of the war in Ukraine show the huge costs of dependence on key resources, highlighting the role that sufficiency strategies could play.

3. Real-Economy Cross-Border Effects in the Mid-transition Period

Building on the taxonomy described in section 2, this section provides an analytical mapping of the real-economy channels of cross-border impacts during the mid-transition period. It then uses the E3ME-FTT macroeconometric model to help quantify some of the key channels of risk transmission for G20 countries.

3.1 Trade, Energy, and Employment Feedback Loops

Figure 4. Linkages Between Decarbonization, Trade Balances, Exchange Rates, and Inflation



Note: Systems map of the dynamic cross-border feedbacks between domestic decarbonization, investment and cost reductions for low-carbon technology, and their impact on the economy, trade balances, exchange rates, and inflation. The color scheme is used for clarity of exposition.

[10] On one definition, the aim of sufficiency is to optimally link infrastructures and equipment to citizens' real needs. Sufficiency is thus a societal vision that aims to satisfy better consumption behavior adapted to the climate emergency (Hache, 2022).

The deployment of green technology globally involves strong increasing returns to scale at the national level, causing decreasing energy costs, higher investment levels and possibly technological tipping points (Figure 4). The costs of low-carbon technologies decline rapidly with cumulative investment, enabling further deployment (Way et al., 2022; Weiss et al., 2010; McDonald, 2001; Arthur 1994), reinforced by deployment in other countries. Similarly, financing costs tend to decline with the adoption rate – Egli et al. (2018) find that costs related to access to finance decline as financial actors gain experience in green technologies and markets. This expansion decreases energy costs in the economy, but also puts pressure on fossil markets. The lack of coordination in production across countries in fossil markets could lead to either insufficient or excessive capacity, or both in alternation, potentially causing price and volume volatility (Mercure et al., 2021). These transformations occur heterogeneously across countries, which implies cross-border risks and opportunities.

A decline in global demand for fossil fuels and an associated volatility in fossil prices is likely to have adverse economic implications for the fossil exporting countries. The prospect of a decline in fossil demand reduces investment in fossil extraction, adversely impacting aggregate investment, employment, and GDP. It also prompts a revaluation of fossil related assets. This affects international investors who own such assets, and thus creates risks of cross-border contagion in cases of corporate insolvencies or debt distress. All else equal, lower exports lead to a deterioration of current account balances and puts devaluation pressure on the exchange rate, which the central bank might only partially counter. A deterioration in a country's international investment position implies fewer investment of petrodollars in international financial centers.

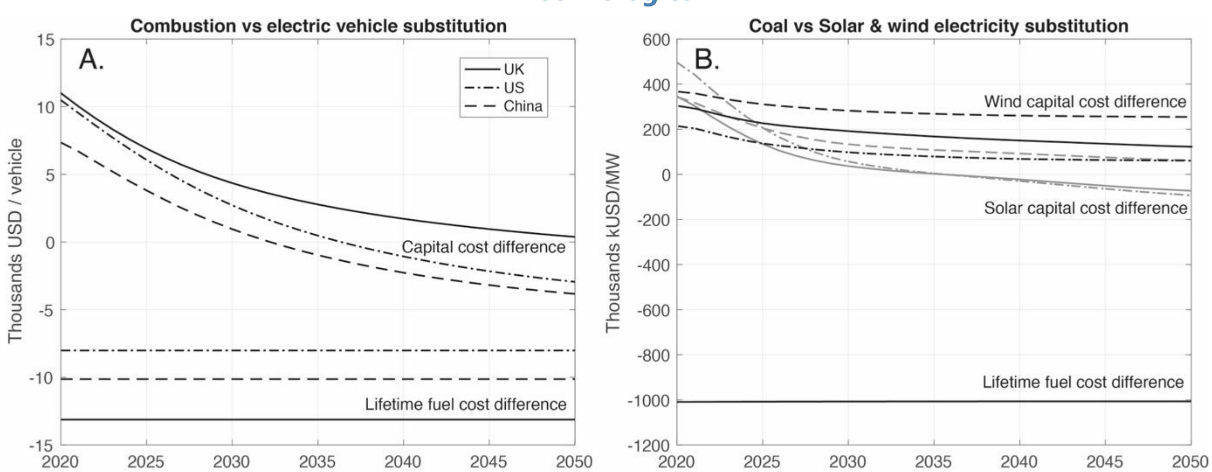
The effects in cleantech-exporting countries point in the opposite direction. International demand for cleantech capital goods increases and boosts investment and production of cleantech, with positive effects on output and employment. The boom in cleantech benefits domestic and international investors with direct and indirect exposure to these assets. An improvement in the current account leads to appreciation pressure on the exchange rate. An improvement in a country's international investment position triggers more investment in international financial centers, which may or may not be the same international financial centers as in the last decades. The effects are analogous for critical minerals-exporting countries.

There is significant uncertainty around where low-carbon value chains could emerge. Uncertainties related to low-carbon supply chains are much larger than those related to the size and location of stranded high-carbon assets. Whereas the location of fossil assets that will eventually need to be retired is well known, the location of the development of low-carbon supply chains is more difficult to anticipate. The transition outlook index helps identify in which existing manufacturing ecosystems cleantech production could arise, based on current national capabilities, even in brown sectors. According to Andres et al. (2023), countries exporting technologically sophisticated brown products could find it relatively easy to transition. Conversely, countries with exports highly concentrated in a few, low-complexity brown products would have much fewer diversification opportunities. The proximity between brown and green products is greater, all things equal, when products are more complex.

Future trade in green technology is unlikely to compensate for losses in the trade of fossil fuels. Given that fossil resources are geographically concentrated, a large share of fossil fuels produced are traded, while renewable energy is available in all countries. To understand the impact of decarbonization at the macroeconomic and global trade level, a key question is whether the loss of cross-border expenditure on fossil because of decarbonization is offset by cross-border expenditure on low-carbon capital between the same countries. However, the overall lifetime costs of cleantech are often lower than those of fossil fuels for the equivalent energy service and declining rapidly (Figure 5). Since countries producing fossil fuels are generally not the same as those producing cleantech, the two flows are unlikely to compensate each other. Instead, a complex picture of evolving and declining global trade patterns emerges.

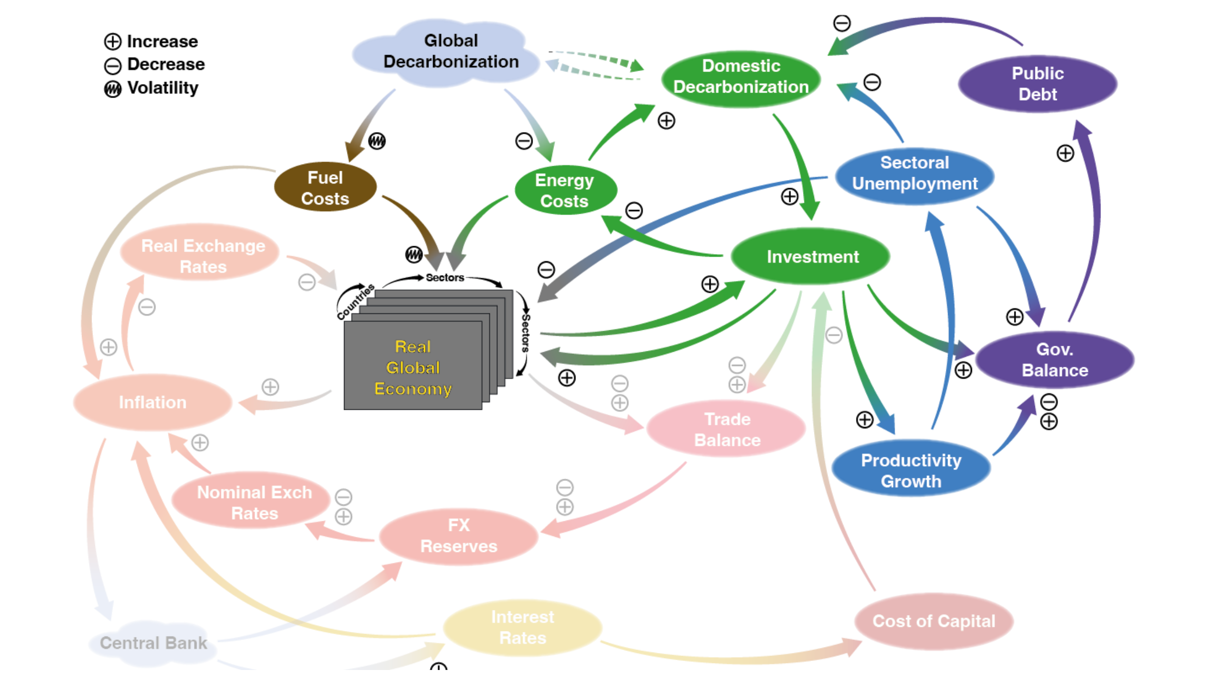
Adopting cleantech almost universally reduces net imports for EMDEs that produce neither fossil fuels nor cleantech domestically and improves their current account balance. Over the lifetime of high-carbon technologies, the expenditure on fossil fuels is usually comparable to their capital costs. Clean technologies have instead no fuel costs and rapidly declining capital costs, with many of them close to cost parity with fossil counterparts (IEA 2010b, 2015, 2020a, 2020b). Simple projections of the capital cost difference between equivalent high- and low-carbon technologies following learning curves and investment trajectories suggest an approach to and – for some technologies and geographies – achievement of cost parity even on capital cost before 2040 (Figure 5). When switching from high- to low-carbon, the saving on fossil over the technologies' lifetimes far exceeds the capital cost difference almost universally across technologies (power generation, transport, heating, and some industries). This means that, for a country that imports both fossil and technology, as the costs of cleantech decline at a growing pace, the net impact on imports of technology switching is increasingly negative, all else equal. This long run positive effect may be counterbalanced by specific structural financing issues. Fossil investments still show much higher profitability levels than renewables (Christophers, 2022). But even more importantly EMDEs are facing much higher cost of capital in general compared to developed economies. This difference in the cost of capital between developed and developing economies can be worsened whenever policy rates are raised in large advanced economies, precipitating a flight to safety and to higher-return dollar assets, such as in the current global monetary tightening environment.

Figure 5. Per unit CAPEX and OPEX Difference Between High- and Low-Carbon Cornerstone Technologies



Note: Average present and projected per unit CAPEX and OPEX difference between high-carbon and low-carbon cornerstone technologies. The projections were made based on existing trends using the FTT models. The historical data were gathered by the authors online from manufacturer websites over a wide range of technologies (Mercure et al., 2021).

Figure 6. Linkages Between Decarbonization, Employment, Fiscal Balances, and Public Debt



Note: Systems map of the dynamic feedbacks connecting decarbonization, productivity, employment, fiscal balances, and public debt. The cross-border impacts of decarbonization affect productivity, sectoral employment, fiscal balances, and public debt in different ways, depending on the context. The color scheme is used for clarity of exposition.

The aggregate employment implications of the low-carbon transition are uncertain (Figure 6). Low-carbon investment generally increases employment in the domestic manufacturing, construction, electricity and transport sectors in the short to medium run, as the new technologies are deployed, and decreases employment correspondingly in the high-carbon energy and manufacturing sectors. However, employment is also affected by climate policy in other countries if it reduces domestic high-carbon activity through declines in exports. Renewables currently require fewer operational and maintenance jobs per unit of output than fossil fuels, while they require comparable numbers in construction. In the longer run, productivity increases, as capital costs decrease following learning curves, may imply fewer workers per unit of energy service produced overall. The overall aggregate impact on employment strongly depends on a country's industrial structure, and whether more low-carbon activity is created than high-carbon activity is lost.[11]

The economic process of decarbonization can boost or dampen public acceptance of climate policies, potentially reinforcing or undermining itself (Figure 6). The potential reallocation of employment and other real or perceived distributional impacts resulting from decarbonization can have a negative impact on its public acceptance (Dechezlepretre et al., 2022). However, investment in cleantech could create jobs and generate in this case the opposite political economy effect. Cleantech investment can also lower fiscal balances, as the total upfront investment required to reach climate targets is substantially higher than the no-transition counterfactuals, since cleantech is capital intensive. Temporarily higher public debt could then affect countries' fiscal space and/or the political acceptability of climate policy. But these higher investments in the low-carbon transition are generally self-sustaining in the medium to long run. A debt issue might arise in the case of debt issued in foreign currency, when the transition leads to increased foreign exchange risk.

[11] On the possible implications of the low-carbon transition for employment, see also IMF (2022b).

3.2 Modelling Trade Impacts of Decarbonization

To empirically simulate the potential impacts of a decarbonization of the world economy on trade, we employ E3ME-FTT, a global macro-econometric model that integrates a range of social and environmental processes (Cambridge Econometrics, 2022; Mercure et al., 2018a, 2018b, 2019). E3ME is a widely used global macroeconometric model disaggregated over 70 regions and 43 industrial sectors. Its core is a demand-led input-output and econometric-driven accounting system. The demand for final goods and services is first estimated based on domestic and import prices and disposable household income. This drives the demand for intermediate products and investment goods (production capital) through the input-output framework and through investment equations. Disposable income is determined econometrically from employment and wages, while investment is determined based on the needs of industry to expand and the prices of capital goods. The allocation of finance is demand-driven, which implies that loans are created based on the creditworthiness of projects, where new investment ventures do not necessarily crowd out other investment elsewhere in the economy (see Pollitt and Mercure, 2017; Mercure et al., 2019). Behavioral relationships for consumption, investment, employment, imports and exports are estimated through multivariate linear cointegration methods by sector and region on data since 1970. More details are given in Annex I.

Crucially, trade relationships are established on a bilateral basis between each country or region. Existing bilateral and multilateral trade agreements are not considered explicitly but are taken into account implicitly through the data themselves (trade in the model will be greater within zones of free trade where this is the case in the data reflecting existing trends). The foreign or domestic origin of investment is not currently differentiated, nor are stocks of currencies or other assets.

The demand for all energy carriers is estimated in physical units, according to 22 energy-using sectors. For fossil fuels, three global pools are assumed to exist (coal, oil, gas), and a database covering more than 40,000 oil and gas wells (from Rystad, 2021) is used to determine which assets are economically viable to produce at each time step, the marginal cost of which determine an endogenous oil price in the model. We note that this approach excludes emerging trade barriers related to the conflict in Ukraine, which may be drastically redefining global energy markets (see Annex I).

E3ME does not specifically define countries as importers or exporters of fossils or critical minerals. Such aspects emerge from their economic structure through the national accounts data used to parameterize the model. Lastly, while sectoral disaggregation in E3ME is among the highest in existing global economic models, it is nevertheless not sufficiently detailed to analyze some aspects of the low-carbon transition.[12] Notably, the standard industrial sectors used in the model cannot always separate high- and low- carbon production, and mining is not split between critical materials and other materials.

The evolution of technology follows a different, evolutionary methodology that is grounded in the theory of the diffusion of innovations. Technology diffusion follows S-shaped diffusion curves, where the initial evolution is slow, followed by a rapid deployment, and a slow process of market saturation (Rogers, 2010). Meanwhile, technology costs follow endogenous learning-by-doing relationships that are a function of cumulative deployment, where cost reductions attract more deployment, which cause more cost reductions, in self-reinforcing patterns typically observed with innovations. The “Future Technology Transformations” (FTT) family of models apply this methodology (Mercure, 2012) to a total of 88 technologies in power generation, road transport, household heating and steelmaking, covering over 60 percent of global CO_2 emissions. Technology trajectories are calibrated against the current diffusion rates of existing technologies (see Annex I).

[12] For a comparison of E3ME and other climate-energy-economy models, see Council of Economic Advisers and Office of Management and Budget (2023).

The use of a demand-driven and technology forecasting approach is important when assessing cross-border impacts, since these impacts primarily stem from changes in demand patterns for both high- and low-carbon products, and those patterns in turn stem from behavioral, technology diffusion and innovation processes driving technological change. Many technology and macro models are based on whole-system cost or utility optimization, which is suitable for many types of questions. However, in the case of cross-border risks, the global objective functions typically used in general equilibrium models are likely not to be adequate since the interests of countries are heterogenous and policies are uncoordinated (Pottier et al., 2014). Global optimization may therefore overlook important second- or third-best processes by focusing on first-best global allocation of resources, as opposed to the structure of the implied economic transformation.

Scenarios of global energy demand and low-carbon transition until 2070 were developed to better understand future energy-related economic transformation and impacts on trade, against a current trajectory counterfactual. Two scenario variations are explored in this paper in the cross-border risk context, building on earlier work (Mercure et al., 2021). This includes a baseline for energy use based on existing observed technological trajectories, and a hypothetical scenario that achieves net-zero emissions worldwide shortly after 2050. In the baseline, all key current trends of global decarbonization occurring through ongoing technological change are reproduced, but not those related to land-use nor non-energy use of fossil fuels. For example, the diffusion of solar panels and electric vehicles is occurring rapidly in many countries including the EU and China, trends that the FTT model ensures are maintained in the early years of the simulation. Current policies are implicitly assumed to be maintained through this process.

Meanwhile, in the decarbonization scenario, additional policies are assumed (subsidies on technologies, investment programs, energy efficiency regulations and a carbon price), designed in all regions according to national circumstances, energy system configurations, and following where possible existing policy frameworks. The policies impact fuel use in the model through either the investment decision-making modeling in FTT impacting the technological stock in each country, or the econometric consumption relationships in E3ME.

The model reproduces the key features of an orderly rapid transition by assumption, and does not explicitly include endogenous processes of instability through the mid-transition period. The aim is to model some of the main economic imbalances that could give rise to cross-border risks in a global decarbonization scenario. Electric vehicles and solar energy diffusion trends make fossil use peak and decline by 2035 or before in all scenarios, including the baseline. Using any alternate baseline in which fossil fuels do not peak would intensify all the cross-border impacts discussed below, but this is something that our modeling suggests is unlikely (Mercure et al. 2021, Semieniuk et al., 2022). The impacts discussed in this paper are those that stem from accelerating the transition from current trends sufficiently to meet climate targets, in a scenario that assumes that financial, fossil and other markets do not see price instability. In other words, we do not model instability in the mid-transition, but we model various processes that could give rise to such instability, notably large changes in trade balances.

3.3 Discussion of Results

We focus here on the key results of the mid-transition period for the G20 countries, with focus on external macroeconomic variables.

Figures 7-9 show changes in energy exports, trade balance and GDP for G20 countries. Figure 7 shows specific reductions in energy-related exports relative to total baseline exports for G20 countries, the primary driver of changes in their trade balances through decarbonization, in the net-zero scenario against the current trajectory. Changes are highly concentrated in the large fossil fuel exporters: Canada, Russia, Saudi Arabia the

U.S. (for oil), and South Africa (for coal). Impacts on Saudi Arabia are delayed while those on Canada, Russia and the U.S. are accelerated, reflecting their relative competitiveness in oil and gas markets, a result that stems from our modeling individual oil and gas assets worldwide. Figure 8 shows the overall impacts of the transition on the trade balances of G20 countries through all sectors, relative to GDP. We see that most countries improve their trade balances, except the large fossil producers, which see a worsening trade balance. Figure 9 shows the impacts on GDP of the transition relative to the baseline. In our results, fossil exporters are negatively affected, while fossil importers largely benefit. For aggregate model results at the global level on GDP, employment, exports, and emissions, see Figure A.3 in Annex II.

Our results point to a complex story of decline in fossil exports and related manufacturing for the large fossil producing countries, linked to reductions in imports and expansion in manufacturing and construction in large energy importers. Importantly, since renewable resources are widely distributed across the globe, solar energy costs are breaking parity with the lowest cost fossil-based electricity generation (Nijsse et al., 2023), and since the transport of electricity requires substantial and expensive transmission infrastructure, electricity is not expected to be traded widely across borders in a low-carbon world. Therefore, while global use of energy services continues to grow through the low-carbon transition, the loss of fossil exports and imports is not offset by the trade of electricity or any other low-carbon energy carriers.[13] Lastly, because of a retreat from relatively inefficient fossil combustion technology towards more efficient non-thermal options, total primary energy demand growth largely stabilizes in absolute energy units, without the growth of energy services becoming compromised (Mercure et al., 2021).[14]

In a low-carbon world, volumes of fossil demanded until 2050 become limited, and compare relatively closely with available reserves in OPEC countries, where they are on average most competitive to extract. Available reserves exceed the range of possible total demand for oil and gas in scenarios achieving a 2°C target (McGlade and Ekins, 2015; Meinshausen et al., 2009), and sufficient oil and gas reserves exist at low cost in OPEC countries to displace substantial amounts of production elsewhere. Geopolitical analysis suggests it is possible and perhaps even likely that, to maximize the value of their existing fossil assets, OPEC producers maintain or increase current oil and gas output between now and 2050 as global demand peaks and declines, thereby increasing even more their market share at the expense of that of non-OPEC producers (Van de Graaf and Bradshaw, 2018; IRENA, 2019). This could push products originating from less competitive extraction sites such as deep offshore, arctic, shale oil/gas and tar sands out of global oil and gas markets. In the present simulation, this is not assumed to occur, where OPEC is assumed to continue its present role as market makers preserving price stability using production quotas. In a scenario in which OPEC increases production to increase its market share at the expense of lower international oil and gas prices, all impacts shown in Figures 7-9 are intensified by an order of 10 percent (Mercure et al., 2021).

Many economies in the model evolve to some small or large degree away from primary and secondary industries towards services going towards 2050, which could be accelerated by the transition. In fossil producing countries, substantial levies on fossil production typically finance sizable fractions of government expenditure, in areas covering most sectors of these economies (Mercure et al., 2018; 2021). The loss of these royalties potentially implies large reductions in public spending, affecting disposable income spent on final goods and services (we assume for clarity no compensatory deficit spending by governments, something that could not be maintained indefinitely). Wage income from fossil fuel workers also supports a wide range of often

[13] The International Solar Alliance's One Sun One World One Grid initiative, aims to connect different regional grids through a common grid that will be used to transfer renewable energy power.

[14] This is largely due to accounting convention, where renewables in primary energy are accounted already in the form of electricity with, by definition, no conversion loss, whereas fossil fuels incur a conversion loss. This conversion loss disappears through decarbonization.

regional economic activities, notably in the services, which could be significantly affected by the transition. Hence the transition and related trade impacts affect not only Industry but also services.

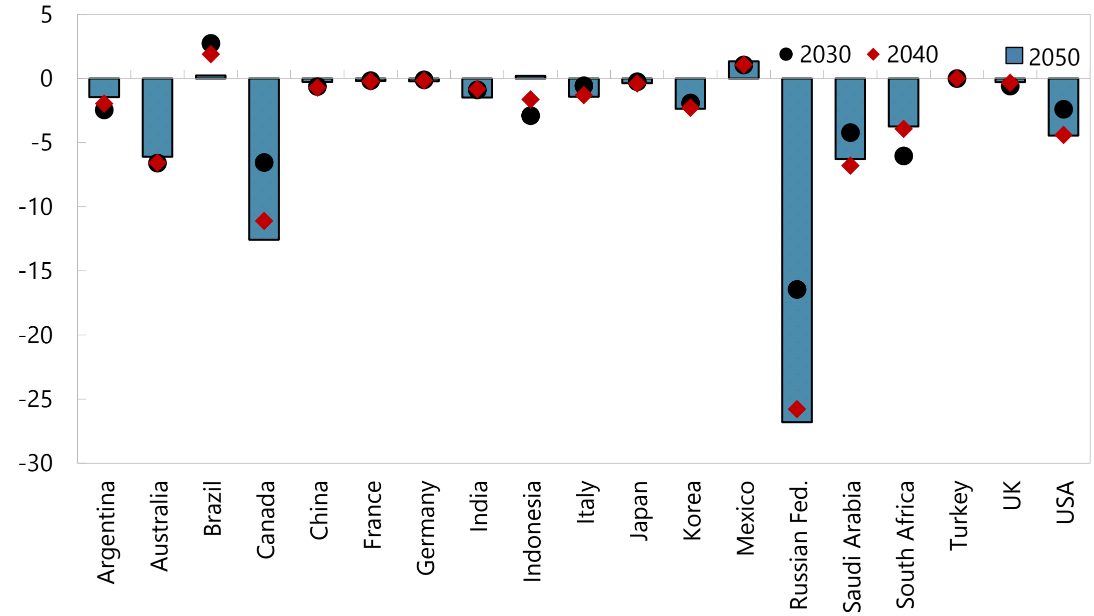
Our estimates suggest that, assuming a return to global geopolitics comparable to the situation prior to the conflict in Ukraine, Canada, Russia and the U.S. would see their fossil exports decline very rapidly, as OPEC countries seek to maintain fossil exports, enabled by their competitiveness. Canada, Russia, and the U.S. could see their trade balance deteriorate within a decade from now, whereas OPEC countries may not begin to see a deterioration of theirs until after 2035. China, the EU and India, by contrast, could see their trade balances improve. India stands to benefit the most, relative to GDP. These three economies are also likely to benefit from the low-carbon transition in terms of output growth.

However, a return to the pre-Ukraine war situation may well become ever more unlikely, and instead become unpredictable. Trends in energy demand in the model are relatively robust against assumptions made over global energy market instability, whereas modeled energy supply trends are not necessarily as robust, since unpredictable emerging trade restrictions, conflict, fossil production decisions, and use of strategic reserves, could all have impacts on prices and volumes.

Large uncertainties arise regarding the impact of a new primary commodity price cycle in the global economy. Specifically, the IEA (2022b) suggests that current price increases for critical materials for manufacturing low-carbon technologies may be currently overcompensating innovation learning-by-doing cost reductions. We are therefore implicitly assuming in the model that this effect is temporary and that new supplies of critical materials release these existing constraints in the near future. Lastly, changes in existing trade agreements (WTO, various bilateral treaties) are difficult to model and may constrain changes in trade patterns observed in our modeled scenarios. This could primarily affect the ease with which we assume that new technologies can be traded worldwide, but would not likely change modeled losses of trade in fossil fuels, as long as they originate from losses in demand.

Figure 7. Energy Exports Change Relative to Total Baseline Exports

(In Percent)

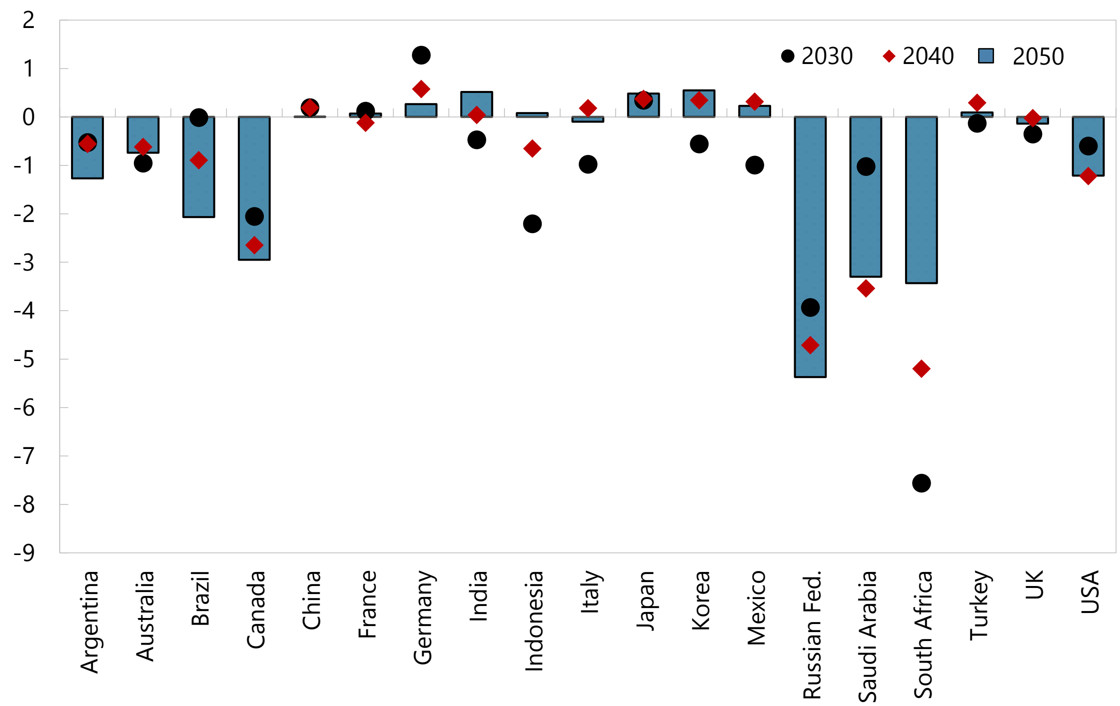


Sources: Authors' calculations.

Note: Fossil export balances of G20 countries relative to total baseline exports, estimated using E3ME-FTT.

Figure 8. Trade Balance Change Relative to Baseline GDP

(In Percent)

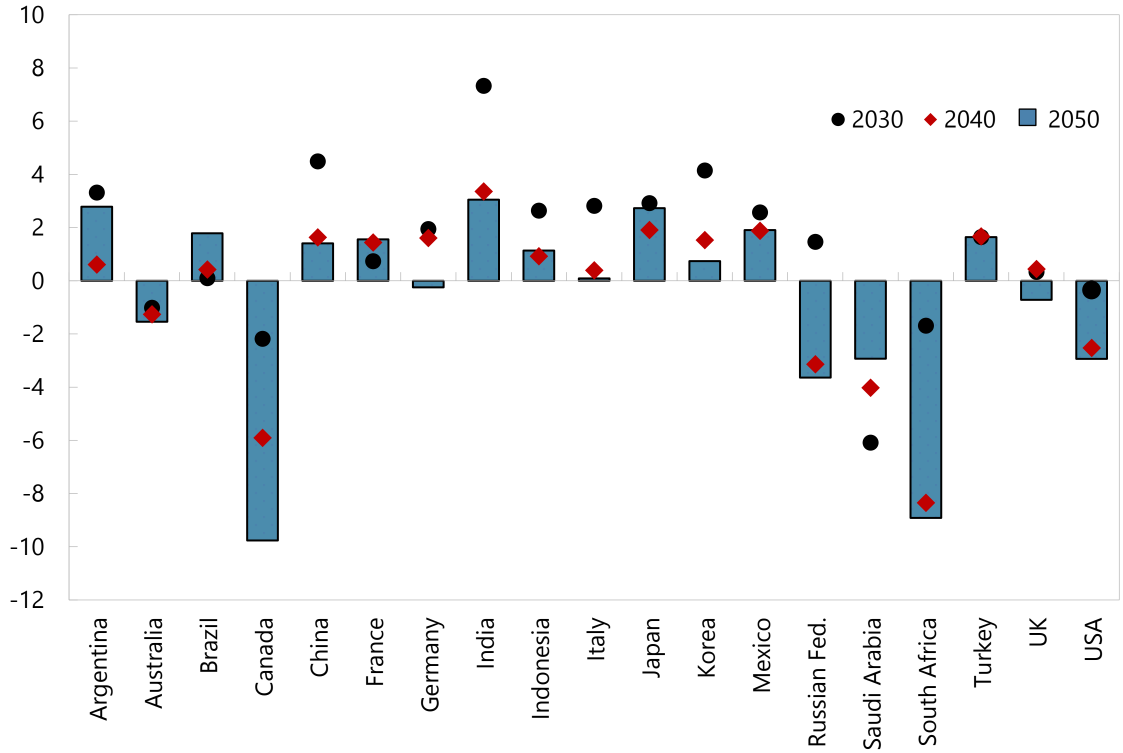


Sources: Authors' calculations.

Note: Change in trade balances of G20 countries relative to GDP, estimated using E3ME-FTT.

Figure 9. Change in GDP Relative to Baseline

(In percent change)



Sources: Authors' calculations.

Note: Change in real GDP of G20 countries relative to baseline, estimated using E3ME-FTT.

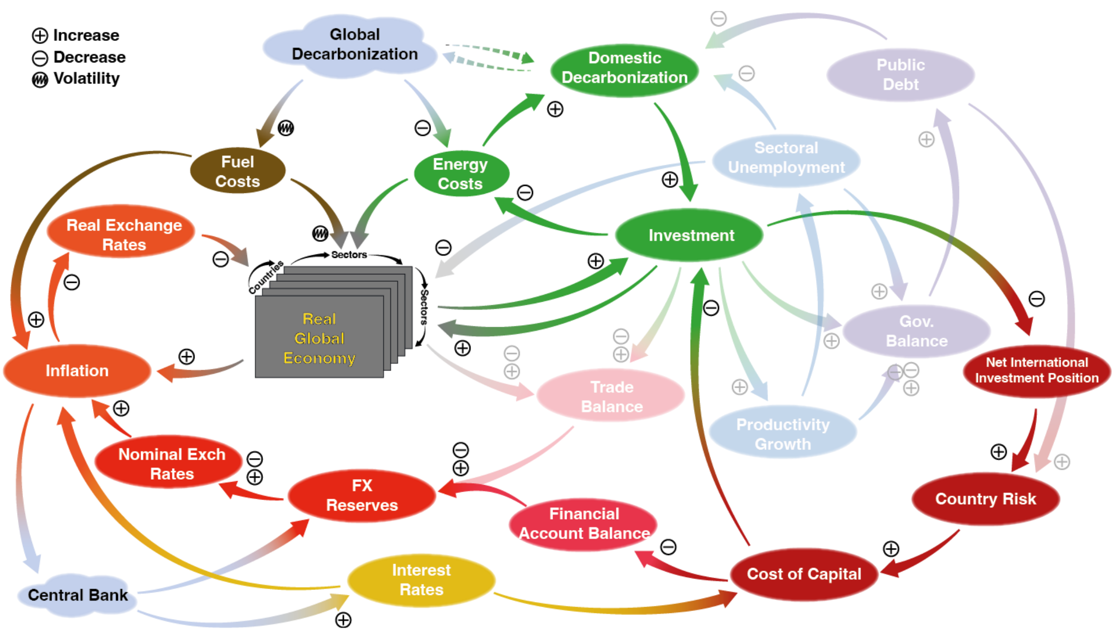
4. International Macroeconomic and Financial Spillovers

This section identifies the main sources of financial cross-border risks, stemming from stranded assets, sovereign risks, and certain types of financial climate mitigation and adaptation instruments.

Changing patterns of global trade caused by a decarbonization of the world economy can have consequences for global financial flows, financial stability, and the international financial architecture. The current account balance is often a poor indicator of the scale and direction of financial flows (Borio and Disyatat, 2015). In today's financially integrated system, financing sources are tied to the location of banks, (almost) independently of the direction of associated flows of goods. Following the process of capital-account liberalization of the last four decades, developing economies have gone through episodes of capital inflows and outflows closely related to powerful global financial cycles. Rey (2015) suggests that monetary policy from high-income economies (mainly the U.S.) is transmitted through leverage and cross-border gross capital flows (particularly credit flows) to the rest of the world, even under floating exchange rate regimes. In this perspective, high growth prospects and low public debt have low significance in explaining cross-border flows, while interest rate differentials are critical (Nier et al., 2014).[15]

The cross-border effects of the emergence of new low-carbon sectors and fossil-related asset stranding have a financial dimension that is not captured by the evolution of trade relations. This stems from the fact that the global geography of ownership of productive assets does not generally match the geography of those assets themselves, where for instance the ownership of fossil-related assets frequently crosses borders (Semieniuk et al., 2022). Building on these insights, we further expand the conceptual representation proposed in section 3 by adding a set of key financial variables and linkages' (Figure 10), complementary to the real economy effects explored earlier (Figures 4-5). The diagram attempts to capture the linkages between global decarbonization as a structural force and macroeconomic and financial effects, including of a cross-border nature.

Figure 10. Linkages Between Decarbonization, Financial Balances, and Inflation



Note: Systems map for the dynamic financial feedbacks connecting decarbonization, foreign investment, country risk, financial balances, and inflation. The color scheme is used for clarity of exposition.

The dynamic and combined role of private and public finance is currently not well understood in climate-related macroeconomic models, reflecting the lack of explicit representation of finance (Espagne, 2018). The same financing tool might lead to exchange rate depreciation and increased indebtedness if it leads to an unexpected increase in the import propensity of the country to achieve a low-carbon transition (Godin et al., 2023). Conversely, it could attract private finance in the low-carbon sector and limit macro-financial destabilization if the public sector has done its share of initial investment in strategic parts of the green supply chain (Rickman et al., 2022).

There is thus a need to explicitly model endogenous financial flows in the form of loans, portfolio investment and cross-border lending in order to carefully assess balance of payments problems (Espagne et al., 2021; Godin and Yilmaz, 2020), especially for EMDEs in the face of climate policies. Various attempts at

[15] See Godin and Yilmaz (2020) for an integrated modeling framework of this dynamic relation between the global policy rate and appreciation-induced boom-bust episodes in small open economies.

building such a framework have recently been applied to the energy transition in Colombia (Godin et al., 2023), climate change-related losses in agricultural output in Tunisia (Yilmaz et al. 2023), broader climate change impacts and adaptation in Vietnam (Espagne et al., 2021), climate stress-testing of the financial sector in the Philippines (Hallegatte et al., 2022), and compound mitigation and climate impact risks in Indonesia (Gourdel et al., 2022). The explicit consideration of finance in climate-related macroeconomic modeling would therefore allow for a more contingent risk and opportunity assessment of the global climate finance architecture (Svartzman et al., 2019). The international macrofinancial spillovers could notably imply heterogeneous effects across the four archetypes of countries described in section 2. The next three subsections describe in more detail key linkages highlighted in Figure 10.

4.1 Stranded Assets and Cross-Border Financial Risks

The inconsistency between committed emissions from invested capital and carbon budgets suggests that an increasing share of the global fossil infrastructure is at risk of premature decommissioning. The inconsistency between estimates of remaining carbon budgets (Rogelj et al., 2019, Millar et al., 2017) and those of fossil fuel reserves and resources suggest that large amounts of fossil must remain underground to achieve international climate goals (Meinshausen et al., 2009; Heede and Oreskes, 2016; Welsby et al., 2021). Trillions of U.S. dollars of investments in fossil assets could be at risk of stranding if investors' expectations do not align with scenarios consistent with a low-carbon world (Pfeiffer et al., 2018; Semieniuk et al., 2020). Some physical capital operable only with fossil fuels (e.g., certain steel and concrete manufacturing methods, airplanes) or focused on fossil-dependent final products (e.g., internal combustion engine supply chains, gas turbine manufacturing) is directly at risk.[16] Other industries that depend on carbon-intensive technologies could become indirectly at risk from changing policies and regulations (Caldecott, 2018; Bank of England, 2015).

The systemic and cross-border risk that stranded assets impose is considerable, although difficult to estimate. The immediate owners of assets at risk of stranding (e.g., fossil companies, local subsidiaries of international banks) frequently have parent organizations or shareholders abroad, which may in turn be owned by other firms, governments or pension funds domiciled in other countries (Semieniuk et al., 2021, 2022). Investment funds have large exposures to sectors that are most sensitive to the low-carbon transition (IMF, 2021; ECB, 2021; ESMA, 2021), implying the existence of global financial stability risks. Debt networks are equally internationalized (Dungey et al., 2019; Nardo et al., 2017) and interlinked with equity networks. Cahen-Fourot et al. (2021) analyze how supply-side constraints on fossil production can create under-utilization of capital stocks in downstream sectors via multi-regional production networks. Manych et al. (2021) find that, since 2015, most coal-fired power plants have been constructed in Asia, but many financing sources are located abroad, raising the finance-based (as opposed to territorial) emissions of many advanced economies by up to 10 percent (17 percent) in the U.S. (Japan). Semieniuk et al. (2022) show, for scenarios of asset stranding in the global oil and gas sector, that the loss of OECD companies and ultimate owners is much larger than the physical asset loss in these countries as a consequence of cross-border equity ownership. In their medium scenario, OECD country corporate shareholders are exposed to 55 percent of losses even though only 36 percent of physical assets are likely to be stranded in OECD countries.

Second-round effects can occur through a liquidity channel if assets becoming stranded have previously been used as collateral for cross-border loans. A sell-off could occur because of widespread efforts to offset emerging risks stemming from such collateral (BCBS, 2021). Financial institutions that have cross-border exposures to firms that have not abated their carbon emissions could also suffer credit-related losses, as carbon pricing, regulations, or changes to demand patterns and consumer behavior or market

[16] Meanwhile, physical risks from changed weather patterns, temperature changes and flooding threaten vast swaths of invested productive capital, and land and real estate assets (IPCC, 2018; Mandel et al., 2021; Dafermos et al., 2018).

sentiment toward carbon-intensive products or investments could dent these firms' competitiveness and hit their current and expected profitability (BCBS, 2021).

Another channel could materialize through the exposure to transition-related credit, market and liquidity risks of large cross-border financial players, in particular asset managers and public actors. Asset managers could be exposed to large transition-induced financial losses given that, since the GFC, their profitability has increasingly relied on "real(-economy) assets" exposed to transition risks in a scenario of global decarbonization, including energy, transportation and water supply infrastructure, farmland, and housing (Christophers, 2023). Similarly, the decarbonization strategies of states that are "global owners" through their state-owned enterprises (SOEs) and/or sovereign wealth funds (SWFs) (e.g., China, Norway, Qatar, Russia, UAE) could have cross-border financial impacts, notably through changes in SWFs' "carbon portfolios" (Babić, 2023). Uncoordinated and/or sudden divestment decisions could in turn generate second-round effects such as widespread carbon asset selloffs.[17]

Further amplification could arise through an exchange rate channel, as current approaches to risk diversification and management may not take climate risk (sufficiently) into account, such that they may be inadequate to the task in the event of a shock induced by transition risk. Renewables projects supported by international investors are generally financed in foreign currency, whereas they generate income in domestic currency. This exposes international investors in low-carbon projects to currency risk, in addition to regulatory risks given the dependence of their revenues on domestic policy frameworks (Ameli et al., 2021; Prasad et al., 2022). This could generate an adverse feedback loop between contracting bank lending and insurance provision (FSB, 2020).

Fossil asset retirement obligations could create new cross-border financial risks. Premature decommissioning could accelerate – although fossil investment data for 2022 point in the opposite direction (IEA, 2023). So far, however, little attention has been paid to either the financing or the legal aspects of fossil decommissioning plans (but see Tienhaara et al., 2022, on investor treaties). Environmental and legal risks are set to increase in economies implementing climate policies, with potential impacts on the development of low-carbon value chains – notably the impact on the valuation and competitiveness of major oil and gas companies in a decarbonizing economy. An illustration of this is the EU's likely exit from the Energy Charter Treaty (Hancock and Hodgson, 2023), which is legally binding and protects fossil investments (Prasad et al., 2022). National oil companies (NOCs) may also have more limited decarbonization ambitions than (at least some) international oil companies given their role in securing domestic energy security. This is consistent with evidence that NOCs remain cautious on the financial returns on low-carbon investments and mindful of their host governments' dependence on oil and gas revenues (S&P Global, 2022; IEA, 2020).

4.2 Sovereign Risk and The International Financial System

Credit ratings

Markets have begun partially pricing physical and transition risks, increasing the cost of debt in climate vulnerable countries. Volz et al. (2020) identify transition risks as a potential source of sovereign risk, with potential implications on the investibility of sovereign bonds and the cost of debt. Transition impacts can

[17] As noted by Babić (2023), the relative liquidity of some SWFs' portfolio investment implies greater decarbonization potential. In contrast to such financialized strategies based on aligning investment strategies with widely-used indices, more "controlling strategies" of states as global owners have lower liquidity and flexibility as they rely on investing in majority stakes of cross-border-owned corporates and often aim to capture cross-border assets, acquire know-how, or control critical parts of value chains rather than to achieve pure profitability objectives. "Controlling strategies" are therefore more constrained in terms of their ability to rapidly switch from high- to low-carbon investments.

cause fundamental and enduring structural changes to the economy that erode sources of fiscal revenue and require large-scale government spending to alleviate impacts on affected workers and communities (Semieniuk et al., 2021a). The fiscal impact of transition risk materialization could be extremely large, with, for example, oil exporters in Latin American and the Caribbean standing to lose up to US$3 trillion in royalties by 2035 (Solano-Rodríguez et al., 2021). This could feed back to sovereign debt markets, with potential adverse consequences for transition dynamics.

Potential downgrades by credit rating agencies could make it costlier for sovereigns to tap international debt markets. Tiftik and Mahmood (2021) suggest that a failure to reduce reliance on carbon-intensive activities could raise pressures on EMDE sovereign borrowing costs by lowering investor appetite for EMDE assets. The willingness of international investors to provide funding to governments facing high transition risks could worsen precisely when declining exports and current account balances increase a country's need for (and dependence on) external finance. More generally, countries that depend heavily on the fossil economy may experience a sovereign debt crisis, which itself could have contagious effects internationally. For instance, climate-vulnerable sovereigns' ability to backstop domestic banks could be compromised because of a sudden loss of access to international debt markets or central bank swap lines. This could lead to multifaceted crises that are directly or indirectly related to cross-border transition risks, including financial, fiscal and balance of payments crises. The extent to which such crises could occur simultaneously across countries, and the implications of such dynamics for global economic and financial stability, remains an open question.

International investment position and foreign exchange reserves

Fossil exporting countries may experience a deterioration of their current account balances and a worsening of their international investment position. Historically, fossil exporting countries have been among the largest contributors to global macroeconomic imbalances (Arezki and Hasanov, 2013; Obstfeld, 2018). With a potential rapid diffusion of electric vehicles, oil revenues could peak and decline, and various countries' macro-financial position could turn from current account surpluses to current account deficits. Fossil producers may not only lose export revenues, but also see a decline in foreign direct investment in the fossil sector. Some may subsequently be forced to liquidate international assets to finance their deficits. The extent to which this may prove disruptive to international financial markets depends on the speed and scale of this mechanism. Fossil-dependent economies diversifying away from oil, coal and gas (e.g., Hendrix, 2019; Peszko et al., 2020) could mitigate this risk. However, few countries have undertaken such a process.

A deterioration of the international investment position of fossil exporting countries could affect flows of petrodollars into international financial centers, notably the U.S. (Higgins et al., 2006). Warnock and Warnock (2009) suggest that without the substantial foreign inflows into U.S. government bonds, the 10-year Treasury yield could be 80 basis points higher. As noted by Nsouli (2006), investment of oil exporter petrodollars in the U.S. may have helped keep U.S. long-term interest rates low.

New international investment flows may emerge towards cleantech and critical mineral exporters. These investments could notably be substantial in an initial phase of the transition while new infrastructures build up. Given that the geography of cleantech and critical mineral production is not the same as that of fossil fuels, sunrise financial flows may not replace sunset ones or even use the same currencies, something that may also depend on geopolitical factors. All this could also have wider implications for the international reserve system and the status of the dollar as the global lead currency (Svartzman and Althouse, 2020).[18]

There are cross-border links between sovereign debt crises, extractivism, and transition risks. According to the IMF, about 15 percent of low-income countries are currently in debt distress, and 45 percent are at high risk of debt distress, whereas among emerging economies, 25 percent are at high risk and facing "default-like" borrowing spreads (Georgieva, 2023). The widespread lack of fiscal space and public and external debt pressures in developing economies create significant needs for foreign exchange. In turn, this puts pressure on many developing countries to open up to FDI, in particular in profitable extractive sectors such as fossil fuels or mining (Osborn, 2022). Such dynamics illustrate the cross-border connection between macroeconomic and sovereign debt crises, particularly those that lead to external debt problems in developing economies, and the build-up of transition risks.

Monetary policy and cross-border mid-transition risks

Monetary tightening in response to inflation shocks could generate cross-border transition risks by slowing investment in renewables and favoring fossil fuels. Higher interest rates, in response to inflation shocks or persistent inflation, as occurred with the global monetary policy tightening cycle in 2022, raise the so-called hurdle rate for investors in renewables, which have high upfront capital costs. The reason is that tighter financial conditions and higher interest rates increase risk aversion, and the yields of safer assets, respectively. This means that riskier projects, such as renewables, need to provide a higher rate of return to remain attractive.

Crucially, the relative profitability of low- versus high-carbon technologies is affected by policy rates since low-carbon technologies have a higher ratio of capital expenditure to operational expenditure. With falling government bond yields having helped bring down the cost of capital across countries in recent years (IEA, 2021d), low-carbon technologies face financial headwinds as yields rise. Higher funding costs driven by tightening in large AEs could be particularly detrimental in EMDEs, as – according to the IEA – transitions require a shift in the capital structure of investments toward debt (IEA, 2021d). The levelized cost of electricity (LCOE) is higher in EMDEs, and the cost of capital is a major component of renewables' LCOE in EMDEs, where for instance financing costs accounted for around half of the LCOEs of a solar PV plant in EMDEs in 2021, compared to only 25-30 percent in AEs and China (IEA, 2022b). Monetary tightening in AEs could also cause capital outflows from EMDEs, which could delay their transition and raise their transition risks.

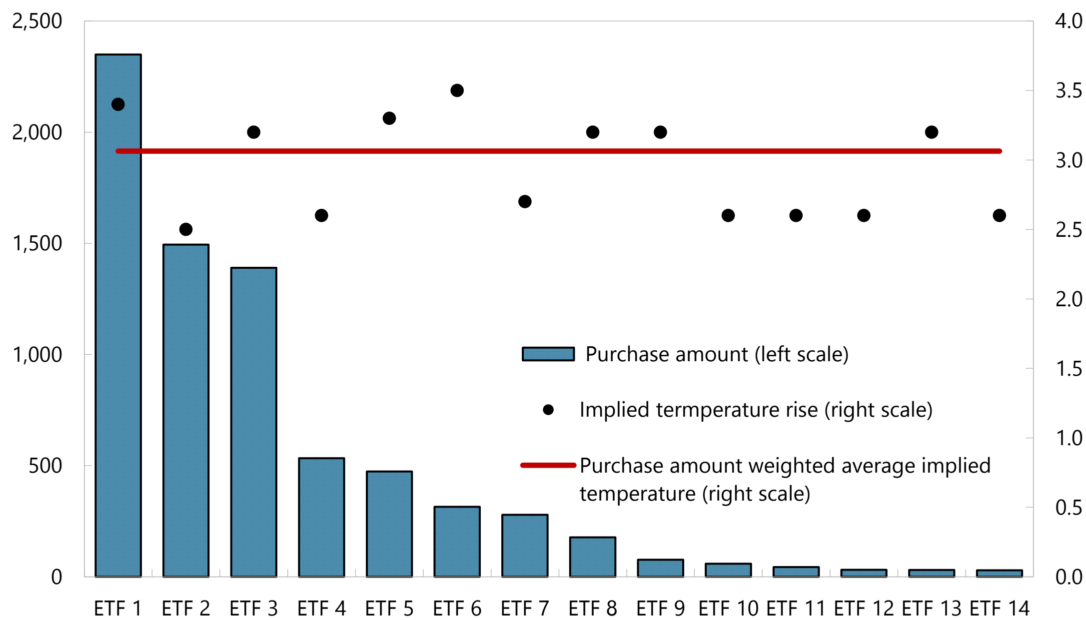
Expectation of bailouts by major central banks could play a role in indirectly generating cross-border risks in the mid-transition period. Bailouts by central banks can impact cross-border transition risks when they occur in major economies. Given that a large share of the market risk of stranded assets falls on private investors in OECD countries (Semieniuk et al., 2022), the bail-out signal sent by major central banks implies a bailout of fossil activities in the rest of the world.

There are both price and signaling channels through which major central banks' actions to support the economy during crises can affect cross-border transition risks. First, by acting as a price-insensitive buyer and supporting companies with low creditworthiness, major central banks change the structure of market prices, notably the debt of fossil companies. They do this by backstopping their profitability and socializing their losses both within their jurisdiction and in other countries, since assets purchased often include those of foreign

[18] Article 2 of the Paris Agreement (UNFCCC, 2016) emphasizes that the agreement "aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty," including by "[m]aking finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (Article 2, paragraph 1.c). According to the Agreement, developed countries must therefore prioritize equitable access to sustainable development and the eradication of poverty.

companies. Second, by bailing out companies that may not be creditworthy, major central banks send a signal to foreign investors and asset managers whereby high-carbon activities are a good bet, because profits are privatized while losses are socialized.[19] As Stern and Stiglitz (2021) note, in the short term the social losses of not bailing out unsustainable firms are greater than those associated with a bailout. Under those expectations, firms may engage in excessively correlated behavior, and excessive investment in fossil fuels.[20] For a preliminary analysis of this channel, see Annex III, where we estimate that the implied temperature rise (ITR) of purchases made under the Fed's Secondary Market Asset Purchase Program (SMCCF, specifically its exchange-traded fund portfolio) and the ECB's Corporate Sector Purchase Program (CSPP) during the COVID-19 crisis stood at 3.1°C and 2.3°C, respectively (see Figure 11 for the implied temperature rise of Fed asset purchases of Exchange-Traded Funds under the SMCCF).

Figure 11. Implied Temperature Rise of Federal Reserve Asset Purchases during COVID-19 Crisis



Sources: Federal Reserve; MSCI ESG Manager; and authors' calculations.

Note: There are 16 ETFs under SMCCF and 14 of them have implied temperature rise data in MSCI dataset.

4.3 Global Climate Finance Architecture and Related Policies

The financial sector at large is expected to play a significant role in enabling the funding required to make the transition possible. Recent research on the role of green financial sector initiatives in the low-carbon transition has identified four main types of policy actions that may shape the financial sector in that direction (Monasterolo et al., 2022): green regulatory policies (including green supporting factors and dirty

[19] This is consistent with the language used by the Fed to justify its crisis measures. Indeed, in a speech delivered on April 9, 2022, Fed Chair Jerome Powell noted that the Fed "will put these emergency tools away […] when the economy is well on its way back to recovery, and private markets and institutions are once again able to perform their vital functions of channeling credit and supporting economic growth." These justifications do not mention the need for the recovery to be sustainable nor the need to take into account the impact that the economic activities being supported will have on the U.S.'s future emissions. See Powell (2020).

[20] Blinder (2022) stresses that the Fed's support for corporate bonds in the secondary market – including for "fallen angels" (i.e., formerly investment-grade issues that had been downgraded to high yield by credit rating agencies) – during the COVID-19 crisis was unprecedented and had never been attempted during the 2008-2009 financial crisis.

penalizing factors), green portfolio rewards (or penalties) for financial institutions as a function of the share of lending to low-carbon activities in their portfolio, green monetary policies consisting of orienting the conventional (and more recently unconventional) daily operations of central banks according to their impact on environmental sustainability, and public co-financing of green investment. The prevailing view is that to remain effective, prudential regulation should remain risk focused and not attempt to drive investments. Using prudential regulation as a substitute for effective government policy on climate is likely to be ineffective and generate unintended consequences. More importantly, the mobilization of finance from developed countries to support country-driven strategies in the developing world involves the wider mobilization of financial instruments like grants, concessional loans and guarantees (Hourcade et al., 2021).

Such policies target primarily the domestic financial sector and could generate balance of payments sustainability issues. The import intensity of the investments associated with the transition is a key potenal cause of trade deficits, depending on the import elasticities of different economies. The exchange rate could be affected if domestic savings are channeled towards the acquisition of foreign assets instead of domestic assets. Other risks stemming from policies to mobilize private climate financing in EMDEs include liquidity and market risks, contingent liabilities, and leverage risks. Higher financial risks associated with climate-related investments with regard to fossil investments imply greater reliance on financial leverage to raise expected returns. This exposes the domestic financial sector to a sudden tightening in global financial conditions (Prasad et al., 2022).

Some proposals have been made for financing the green transition without affecting the external debt sustainability of EMDEs. Among these initiatives, green Special Drawing Rights (SDR) allocation, just as standard SDR allocations, could increase recipient countries' stock of foreign exchange reserves, thereby extending their room for deploying green financial sector interventions without necessarily augmenting external vulnerability (Aglietta and Espagne, 2018). The Resilience and Sustainability Trust launched by the IMF partly reflects that approach (Steele et al., 2021). Debt for climate swaps also seek to free up fiscal resources so that governments can improve resilience without triggering a fiscal crisis or sacrificing spending on other development priorities (Chamon et al., 2022). Creditors provide debt relief in return for a government commitment to decarbonize the economy, invest in climate-resilient infrastructure, or protect biodiverse forests or reefs (Kraemer and Volz, 2022). Contingent debt instruments such as the climate resilient debt clauses (ICMA, 2022) institutionalize this setting by automatically suspending the payment of interests for a given period after a climate shock has reached a pre-defined threshold. Broader coordinated public sovereign guarantee mechanisms have been proposed, based on the social value of mitigation action (Hourcade et al., 2018; Dasgupta et al., 2019). Scaling up these instruments comes with many technical, financial, and governance-related challenges (Paul et al., 2023).

5. Conclusion

In this paper, we explore the cross-border dimension of risks associated with an uncoordinated decarbonization of the global economy during the mid-transition period. A mid-transition period of instability is possible in the short to medium run, whether or not countries align themselves with the Paris Agreement, because of ongoing changes occurring in the global energy system committed by past climate policies. However, there is also a risk that mid-transition instability lasts longer if endogenous processes of instability interfere with decarbonization and lock the global economy into a form of "mid-transition trap." This could occur if international coordination and national policy instruments fail to address the specific instability risks that rapid transformation entails. The paper proposes a research agenda on cross-border transition risks through four main contributions.

First, we describe the characteristics of mid-transition cross-border risks at the global scale, focusing on the technological, trade and financial domains. We emphasize three characteristics of mid-transition risks. First, ongoing technological change is path-dependent and possibly irreversible; as such, it will likely disrupt high-carbon economic structures, although with ambiguous aggregate effects in the absence of accompanying financial policies. Second, the scale, pace and unprecedented nature of the transition challenge imply a period when the fossil-based energy system coexists with the emerging low-carbon energy system. The duration of this mid-transition can be shortened by targeted policies aiming at reducing cross-border risks in social, economic, and financial terms. Third, in a mid-transition period, hard-to-predict binding constraints on resources could emerge, notably with respect to materials that are critical to the transition, generating disruptions or bottlenecks that could hinder the deployment of low-carbon technologies. Global macroeconomic factors could make the mid-transition a lasting unstable regime, most notably with the concomitant geoeconomic fragmentation, rise of renewables dominance and rapid depreciation of high-carbon capital, the emergence of trade rivalries between the largest economies, and a possible shift to a high inflation regime.

Second, **we propose a taxonomy of the cross-border risks that economies could face during the mid-transition period.** The taxonomy captures five dimensions: exports/imports of fossil fuels; transition outlook (including imports/exports of clean tech), and exports of raw critical minerals. This taxonomy is observed based on clusters of G20 countries' brown lock-in index and critical minerals exports/imports, and their transition outlook index.

Third, we outline a general framework for analyzing channels of transmission of cross-border risks during the mid-transition period. By "mid-transition," following Grubert and Hastings-Simon (2022), we refer to a period when low-carbon and fossil fuel-based energy and industrial socio-technical regimes are simultaneously undergoing rapid transformation, co-exist on a large scale, and operate in a highly contested space. The framework we outline includes energy, trade, employment, and sovereign and financial risk feedback loops. It suggests that the world faces a pathway on a razor's edge amid energy, trade, sovereign and financial cross-border risks. We provide a first attempt at quantifying a subset of cross-border transition risks for G20 countries using the global disaggregated E3ME-FTT macroeconomic and technology model, including technological, energy, trade, and employment feedback loops. The results in terms of energy exports, trade balances and GDP indicate vary large cross-border changes by 2050 among the members of the G20 and Spain. This is notably the case for Argentina, Brazil, the Russian Federation, Saudi Arabia, South Africa, and the U.S. However, the macroeconomic effects on these fossil exporters are also heterogenous, depending on their individual transition outlook and production capacity of green products. We further review the literature on several assessments related to sovereign and financial feedback loops.

Our findings point to several key policy implications. The significance of the cross-border transition risk channels that we identify implies the need for international I on economic, climate and development policies (notably the G20 and the climate COPs) to emphasize the specific cross-border dimensions of transition dynamics. There is a need for further developing indicators of cross-border risks and opportunities beyond the simplified taxonomy highlighted in this paper. Finally, there is a need for policy agendas in all countries to include a focus on mitigating cross-border transition risks at the regional and international levels. Further research is required on the linkages between macroeconomic and financial channels of cross-border risk, including the linkages between external debt, monetary policy and tightening global financial conditions, and systemic cross-border transition financial risks (for instance, the buildup in fossil infrastructure and assets in many EMDEs).

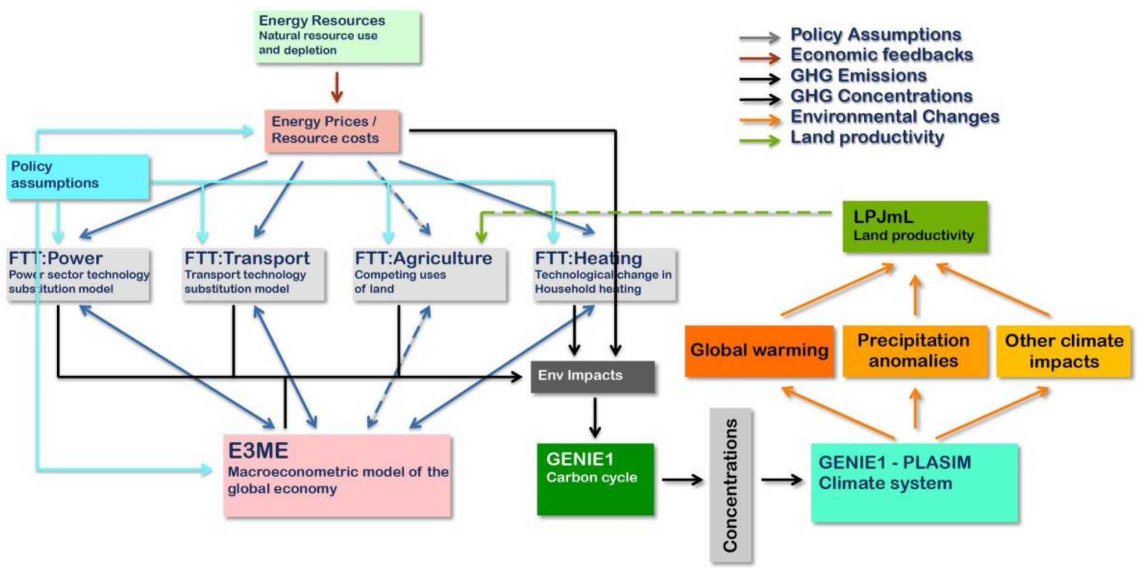
Our research leads to several critical questions. First, what role should financial regulation (encompassing the role of capital requirements, prudential regulation, and risk management), climate information architecture (IMF, World Bank, OECD, and BIS, forthcoming) and the global financial safety net (including both the IMF and regional financial arrangements) play in mitigating cross-border transition risks (Volz, 2022)? In this area, the

Network for Greening the Financial System, the Financial Stability Board and the Basel Committee on Banking Supervision are working on the role of prudential transition plans (NGFS, 2023). It would be useful for the NGFS to incorporate into its scenario analysis cross-border risks such as those analyzed in this paper. Indeed, the findings in this paper highlight the importance of countries' macrofinancial resilience to the low-carbon transition. Second, do EMDE exporters face the risk of a "critical materials resource curse" – and related macrofinancial risks – in the mid-transition period (Miller et al., 2023)? Third, what role is there for international policy cooperation on critical issues, such as the stabilization of key commodity, or "systemically significant," prices and organizing critical metals markets (Weber et al., 2022)? By contrast, if the world economy continues to fragment, what could this imply during the mid-transition? The mid-transition period could see the low-carbon transition generate sufficient instability that it eventually comes to destabilize and stop the transition itself. This could occur if one or several of the real economy and financial processes discussed in this paper generate instability that ultimately hamper the ability to move forward in the decarbonization process. These questions thus open the door to a broader question of decarbonization dynamics falling into a potential "mid-transition trap."

Annex I. The E3ME-FTT-GENIE Integrated Assessment Model

1. Overview

Figure A.1. Components of E3ME-FTT-GENIE and their Interactions



Source: http://www.E3ME.com

E3ME-FTT-GENIE is an integrated energy-technology-economy-climate simulation model used to assess the impacts of various types of policies, for various types of stakeholders including governments (EU Commission, national governments). The model specializes in, but is not exclusively used for, environmental, energy and climate policy, as well as labor markets. The model joins up an analysis of detailed technology diffusion dynamics for carbon-intensive sectors in FTT (Future Technology Transformations) with detailed and highly disaggregated macroeconomics in E3ME (Energy-Economy-Environment MacroEconometric model), and a fully-fledged climate and carbon cycle simulation of intermediate complexity in GENIE (Grid Enabled Integrated Earth system model). Of interest here are E3ME and FTT and the underlying detailed global energy system model. For a complete description of the model equations and dynamics, we refer the reader to Mercure et al.(2018a), including for a description of the climate simulation integration, which we omit here.

2. Macroeconomic evolution in E3ME

E3ME is a demand-driven macroeconometric model, based on a standard social accounting matrix with input-output relationships, bilateral trade relationships, and econometric equations describing the economic behavior of agents parameterized on time series from 1970 to the present. The model is disaggregated into 70 regions (including all G20 nations) and 43 (70) sectors of industry, for countries outside of the EU (inside of the EU). Econometric relationships are used to project the evolution of econometric variables up to 2070. The model manual (Cambridge Econometrics, 2022) is available online. A detailed list of all equations in E3ME is given in Mercure et al.(2018a).

The model Is demand-driven, which means that it does not operate on the basis of production functions nor utility optimization. The model does not assume full employment of labor, physical and financial capital, but instead, assumes the existence of levels of resource use below full capacity (measured as unemployment and the output gap).

In contrast to standard general equilibrium models, the consumption of agents by product type is first determined econometrically on the basis of prices, disposable income, population, and patterns of expenditure. The input-output relationships are then used to determine final and intermediate production as well as the demand for investment goods. Investment is determined econometrically on the basis of past economic activity, prices of capital assets and levels of capacity use. Employment and hours worked is determined on the basis of economic activity. Imports and exports are determined on the basis of price differentials between domestic and foreign goods by sector.

Innovation is represented across the model through technology progress factors determined on the basis of cumulated past investment by sector. These indicators are integrated through various econometric equations, in particular domestic and export prices. The accumulation of capital in every sector is assumed to lead to production cost reductions, where the regression parameter is related to an effective sector-wide rate of learning-by-doing. Resulting price reductions determine the relative competitiveness of every sector-region.

GDP is calculated on the basis of the sum of value added across the economy, where intermediate and final production in every sector is endogenously determined from levels of consumption. However, for consistency with other models, sectoral output is calibrated in the baseline scenario to match OECD and national economic projections.

3. Energy sector module in E3ME

Particular focus is adopted in E3ME towards estimating energy demand in physical units, by type of energy carrier, for all sectors and types of fuel users, on the basis of energy balance time series from the International Energy Agency. The final demand for energy carriers is determined for 22 types of final energy users (including industrial users, transport and non-energy types of use) for 12 types of fuels (incl. oil, coal, gas, electricity, biofuels). This allows to accurately estimate greenhouse gas emissions in all scenarios. Econometric estimations of energy use are made on the basis of sectoral economic activity and substitution between sectors.

4. Technology diffusion in FTT

While the above approach for modeling total energy demand by energy carrier is comprehensive, which ensures matching known greenhouse emission levels, the use of elasticities of substitution is less than accurate for fuel users in which technological change is the major driver of substitution. Instead, it is well known that an approach involving technological diffusion processes is much more satisfactory and allows to reproduce observed data. Furthermore, for technological changes, while price differentials incentivize substitutions of technologies across fuels, the use of fuel is not just simply related to price differentials but depends on a complex process of technology adoption by agents and the survival of technological stocks and fleets.

The FTT model was created to represent the technological diffusion process in detail, on the basis of individual technologies currently available on the market, currently for power generation (Mercure et al., 2014), road transport (Lam and Mercure, 2021), heat (Knobloch et al., 2018) in buildings and steelmaking. This includes for example coal plants and solar panels for power generation, petrol and electric vehicles for road transport, gas boilers and heat pumps for household heating and so on. A current total of 88 technologies are represented (24 in power generation, 30 in road transport, 10 in household heating, 24 routes in steelmaking).

The model is a vintage capital model that essentially represents fleets of technological items that agents purchase or invest in, each of which age and depreciate over time, with a turnover determined by technology-specific survival functions (or rates of life expectancy). For instance, cars survive on average for 11 years while coal plants survive for 40 years. This suggests that over 25 years, the vehicle fleet turns over entirely, while technological change is slower in power generation.

Technological choice is represented on the basis of heterogeneous agents making comparisons between available technologies. The explicit assumption is made that the availability of technologies to agents is proportional to their prevalence in markets (the proportion of agents having access to technology A is proportional to the market share of that technology in markets). It is well known in sociology that agent investment or purchasing decisions are strongly determined by visual influence. This visual or peer influence effect is a way that agents have to reduce uncertainty when facing decisions to adopt new practices, and leads to the widely observed S-shaped profile of technological diffusion (Rogers 2010). Rates of technological uptake in FTT are calibrated against historically observed diffusion rates, ensuring consistency between history and projections.

The agent choice representation in FTT involves a comparison of a relevant levelized cost metric for each market (e.g., $/MWh in power generation, $ per km driven in road transport). Each technology is characterized by its particular learning-by-doing rate, which drives its cost down with cumulative investment. However, exogenous policies also influence rates of technological uptake, including technology-specific subsidies, the carbon price/tax, other taxes, bans and regulations as well as public/private procurement/investment.

Fuel use is determined on the basis of technological compositions in each FTT sector. E3ME supplies FTT with total demand by FTT sector (power, transport, heat and steelmaking currently), and in return, FTT supplies E3ME with prices, investment, fuel use by fuel type and public income or expenditure through policy initiatives.

The power model however does not model in detail the structure of electricity markets. The model has a representation of electricity storage, capacity factors, load bands and output allocation between different producing technologies according to auction by the network regulator. However, we have not carried out systematic studies of the different possible market clearing rules that could conceivably be adopted by regulators in different countries. We assume that electricity prices approximately reflect average costs of electricity production across the technology fleet in each country.

5. Fossil fuel asset module

Economic activity in fossil fuel production is strongly dependent on regional competitiveness in those sectors. This level of competitiveness is not straightforward to determine accurately from national accounts data. It is more effectively determined by using data on fossil fuel production by region. The model uses a detailed database of stocks of fossil fuels by region specified as distributed along a production cost variable. For oil and gas, this was determined using the Rystad database, which documents over 40,000 oil and gas assets worldwide. Coal reserves are determined similarly but given the ubiquity of coal resources worldwide at low extraction costs, the model uses less detailed data collected from various sources.

Rystad provides 2P reserves and resources for each asset along with a breakeven cost value. The model assumes that each asset produces if and only if it is profitable at each time period (this may or may not always be accurate, as stopping production when it is unprofitable poses challenges in some contexts). The model uses the Rystad data to determine which asset produces and which asset is idle according to the price of oil and gas, and thus searches through the database to determine the prices of oil and gas that clear the demand each simulated year. This means that for instance, in scenarios of peaking and declining oil demand, some oil wells stop production and become stranded where the breakeven cost is high (e.g., tar sands in Canada), while others remain in production until they are depleted where the breakeven cost is low (e.g., conventional oil in OPEC countries).

This calculation makes it possible to determine in detail production profiles for each E3ME country in each scenario, and these output profiles strongly affect economic activity for oil producers as it affects their exports and balance of trade. Conversely, this calculation indirectly influences oil importing countries as it redresses their trade balance through reduced imports. Thus, this model is a major source of structural change in the economy.

6. Climate policies and scenarios

In this paper, we make use of a number of policy instruments to simulate decarbonization to limit climate change to well below 2˚C.The policies are exclusively instruments that are common and used by governments worldwide, including: carbon taxes, fuel taxes, technology subsidies, public investments, fuel blend mandates, vehicle mandates, scrappage schemes.

In earlier work, we showed that in a model simulating non-linear technology diffusion processes such as in FTT, policies can produce complementarity effects where the overall outcome is more than the sum of the effects of the individual policies. Notably, carbon taxes and technology subsidies tend to work well with mandate policies (where manufacturers are required to market a proportion of low-carbon technologies), since mandates expand the choice options that consumers face, while the taxes or subsidies stabilize choices towards these new options. Taxes on their own work less well if choice is limited in which case consumers may be forced by circumstances to pay the taxes without changing their behavior. Mandates on their own work less well if the technologies pushed into the market fail to become cost competitive (Lam and Mercure, 2022; Mercure et al. 2014; Knobloch et al., 2019).

It is also noteworthy that technology compositions in different countries are generally completely different, which often means that effective policy mixes tend to vary depending on circumstances. Some countries are endowed with largely low-carbon electricity sectors, while other countries find themselves well ahead of others in terms of low-carbon technology compositions as a result of past policies.

Taking advantage of synergies explored in earlier work, and building on the policy mixes used in Mercure et al. (2021) and Nijsse et al. (2023), we constructed independent policy mixes in each of the 71 countries represented in the model. While they differ in each case, they build upon the following approach:

Cross-sectoral policies:

- Carbon price that gradually increases over time to around \$200/tCO_2 in 2050 and covers the power sector and industrial activities, but not personal transport nor residential heat (as is currently the case in most countries).
- Energy efficiency regulations for curbing energy use in sectors not modelled in FTT

Power sector:

- Feed-in tariffs (or contracts for difference) for wind power, but no policy usually needed for solar
- Capital cost subsidies for technologies such as geothermal, hydro, carbon capture, nuclear and other low-carbon options
- We assume implicitly that market regulations change to allow renewables to receive fair remuneration (e.g., reforming marginal cost pricing where it exists)
- Ban on building new coal plants by 2030, and for gas plants by 2040.

Road transport:

- Ownership/purchase taxes for conventional vehicles

- Subsidies on electric vehicles (we are not currently modelling hydrogen vehicles)
- Electric vehicle mandates in the early years to increase numbers on roads
- Biofuel blends
- Bans on conventional vehicles in 2030 or on dates announced in various countries
- We assume that charging infrastructure diffuses at the same pace as electric vehicles

Household heating

- Heating fuel taxes
- Subsidies on heat pumps, solar heaters and other low-carbon options
- Mandates on heat pumps and other low-carbon options

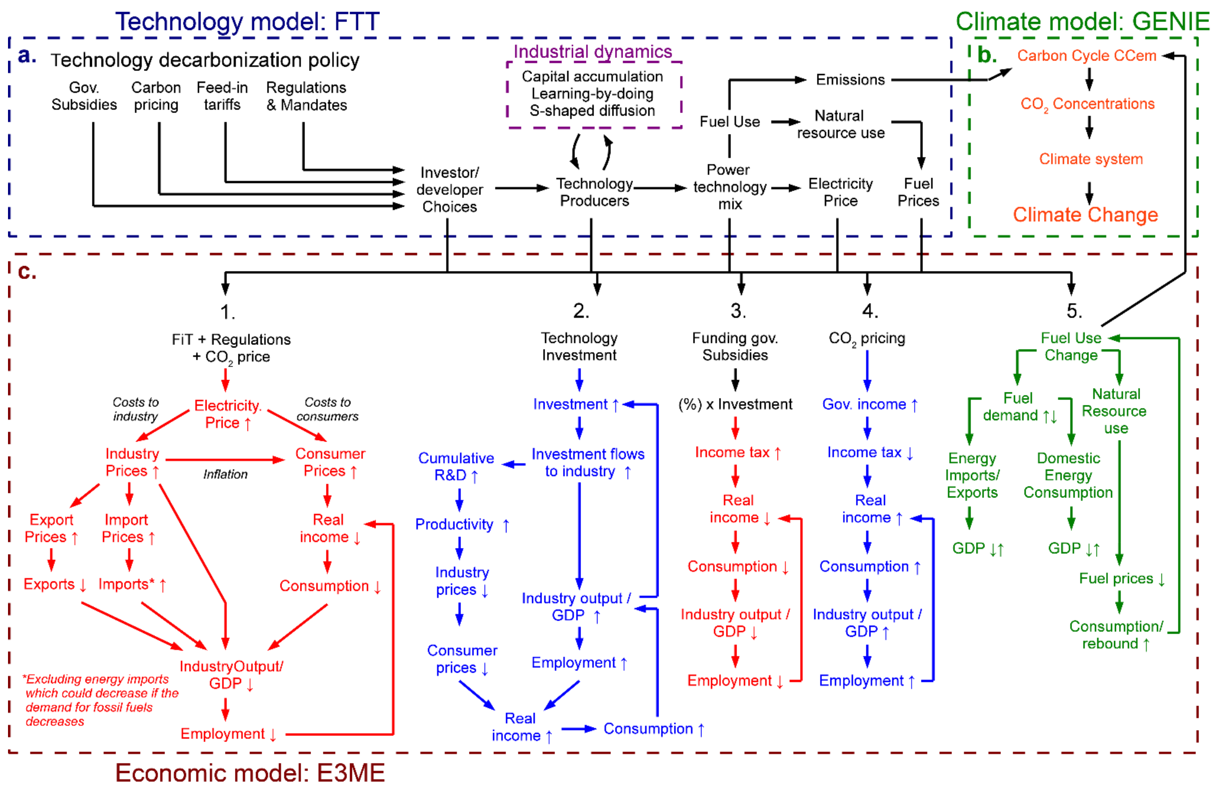
Steelmaking

- Public investment in hydrogen steel demonstration plants to attract private investment. This is modelled similarly to a mandate, in which industry is required to build capacity for low-carbon steel, part-funded by the public sector
- Capital cost subsidies
- We assume declining costs for hydrogen as inputs.

To generate a scenario of global decarbonization, we searched policy space and adjusted the stringency of the policies to achieve net-zero in countries in which such a pledge has been made (2050 for the EU, Japan and Korea, 2060 for China, 2070 for India), and adjusted the policy stringency for the rest of the world to achieve net-zero by between 2050 and 2060. We note that there are very large numbers of equivalent policy mixes with which such emission reductions could be achieved in the model, but that carbon pricing on its own does not achieve those targets.

7. Composition of macroeconomic changes

Figure A.2. Relevant feedbacks E3ME-FTT-GENIE



Source: Authors.

GDP changes in different countries originate from various sources depending on circumstances. Figure A.2 shows diagrammatically the relevant five feedbacks from policy instruments to changes in output in the E3ME-FTT model.

1. Changes in energy prices, which may increase due to the use of carbon pricing, which may initially be passed on into the price of electricity and other energy carriers. This reduces industry output and consumption.
2. The investment feedback originates since low-carbon technologies are capital-intensive while they often also increase productivity (in those cases in which cost parity has been achieved). The additional investment, relative to the baseline, increases employment in construction and manufacturing, and increases output. Meanwhile, capacity expansion increases sectoral productivity which also increases output. This feedback however also includes losses of investment in high-carbon sectors.
3. Subsidies are taken into account into government balances, and are ultimately financed by changes in other taxes such as on employment. To achieve balanced budgets, this implies reducing expenditure in other domains, reducing employment and output.
4. Carbon pricing raises substantial resources domestically, which has an effect opposite to the previous feedback. This feedback however also includes losses of tax income, notably from royalties in fossil fuel extraction, where they exist.
5. Large changes occur in trade of carbon-intensive and low-carbon products, which become reflected in domestic employment and output. In particular, fossil fuel producers are severely affected by

reductions of demand from importing countries. This reduces outputs for the countries at the losing end and increases output for the countries at the winning end. The assumption is made that resources not used for importing products are spent domestically (not on other imports). For fossil fuels, this is reasonable since electricity is not widely traded across borders.

The above feedbacks are not of equal magnitude. The dominant feedbacks, however, depend on context. In some countries, the investment feedback dominates (typically the middle-income fossil fuel importers such as India and China). In other countries, trade effects dominate (typically for fossil fuel exporters).

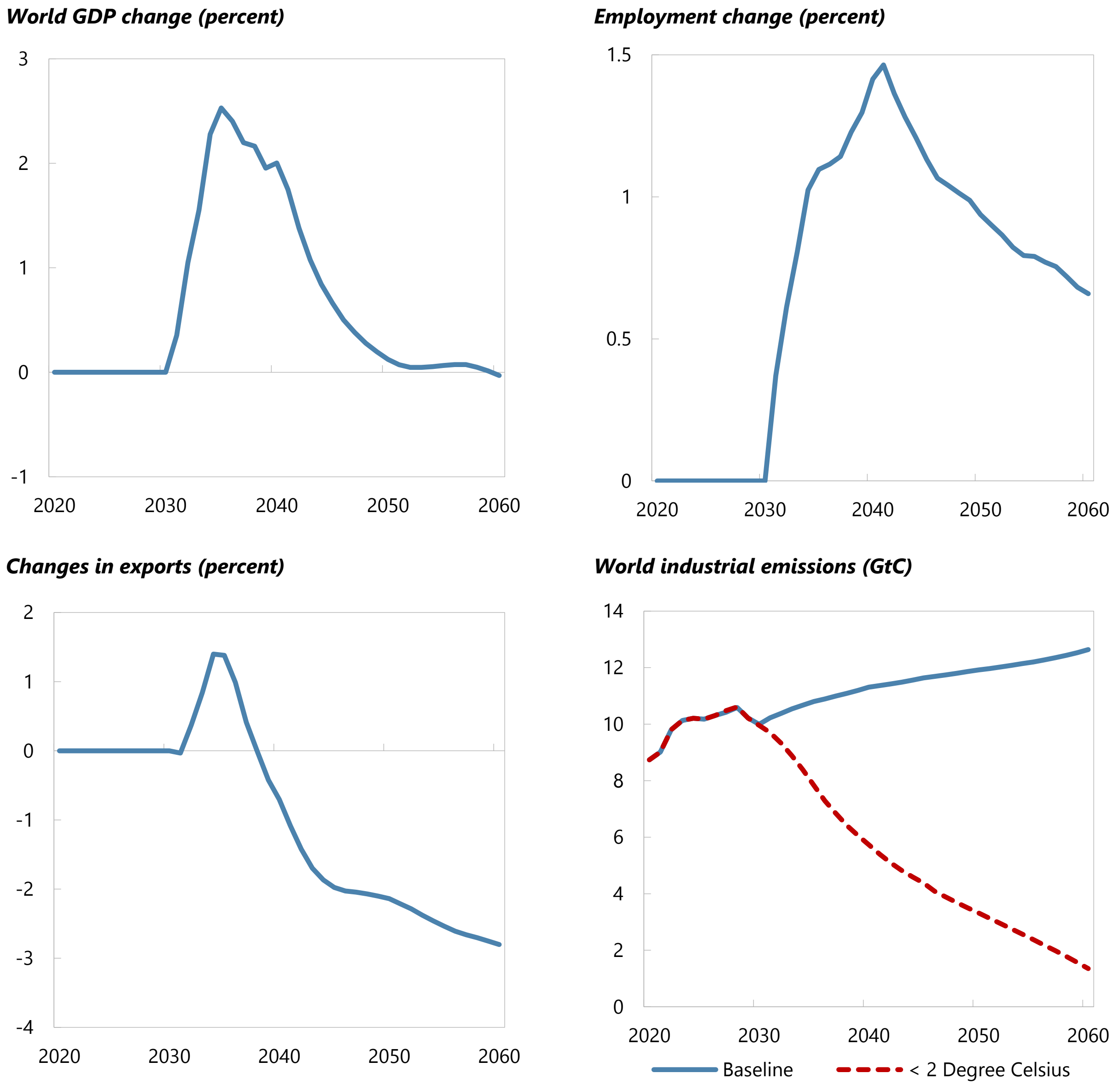
For countries such as the EU, China, India, a double dividend effect is seen in which an investment-led construction boom occurs alongside reductions in imports that are large with respect to the overall economy, money that is assumed spent domestically.

For countries such as Canada, Russia, OPEC and to some degree the US, a double loss occurs. The investment feedback is low or negative since the balance of investment not occurring in high-carbon sectors, with respect to the baseline, is in many cases higher than the green investment stimulus. The feedback effect is high and negative, as export driven income is lost. The loss of royalty income from fossil fuel extraction can also be substantial relative to overall government expenditure, and assuming balanced budgets, results in reductions in government expenditure.

We note that for clarity of analysis, we only model effects of decarbonization processes on the economy, and not the impacts of climate change. This means that the baseline does not include losses of output due to climate impacts. Were we to include such effects, we would observe systematically large increases in aggregate output in the decarbonization scenario relative to the baseline.

Annex II. Aggregate Model Results

Figure A.3. GDP, Employment, Exports, World Industrial Emissions



Source: Authors' calculations.

Annex III. Estimating the Implied Temperature Rise of Fed and ECB Corporate Asset Purchases During the COVID-19 Crisis

The Fed Board authorized two facilities to support large employers during the crisis: the Primary Market Corporate Credit Facility (PMCCF) and the Secondary Market Corporate Credit Facility (SMCCF), with the CARES Act allocating US$25 billion to the SMCCF and US$50 billion to the PMCCF (Federal Reserve Bank of New York, 2021). SMCCF purchases of outstanding corporate bonds of Eligible Issuers and ETFs in the secondary market were based on the Broad Market Index, which mirrors the structure of the corporate bond market. The SMCCF's ETFs holdings accounted for over half of the SMCCF portfolio. The Fed also established the Main Street Lending Program (MSLP) to support lending to small and medium-sized for-profit firms and non-profit organizations, however we did not assess this program because of data limitations.

To estimate emission features of corporate asset purchases by two major central banks in response to the COVID-19 crisis, we focus on two facilities: the Fed's SMCFF, and the ECB's Corporate Sector Purchase Programme (CSPP).

We use MSCI's "Implied Temperature Rise" (ITR) metric, which provides an indication of "how companies and investment portfolios align to global climate targets" (MSCI, 2022).

The (ITR) methodology is based on the concept of carbon budgets (i.e., how much the world can emit in order to limit global warming to 2°C by 2100, and how much a company can therefore emit for its fair share of global decarbonization). The ITR methodology extrapolates the global implied temperature rise at a 2100 horizon "as if the whole economy 'overshot/undershot' its budget in the same way as the given company (or portfolio) 'overshoots/undershoot[s]' its specific company-specific carbon budget" (MSCI, 2022).

A caveat on ITR metrics is in order. As noted in Raynaud et al. (2020, 60), ITR metrics rely on certain key assumptions, including the measurement of the climate performance of companies and portfolio, the estimation of their future climate performance, when a forward-looking assessment is used, uncertainties embedded in the scenarios themselves, assumptions to disaggregate the macro trajectories to micro benchmarks, assumptions on the calculation of temperature alignment, and calculation of the temperature metric.

Our methodology to estimate the ITR of asset purchases under the SMCCF consists in two steps. First, we match the list of indexes and firms whose bonds were purchased under the SMCCF with the ITR estimated for them by MSCI. Second, we plot a density histogram to represent the distribution of ITRs, weighted by the amount of asset purchased, for both the ETFs and corporate bonds purchased under the SMCCF.

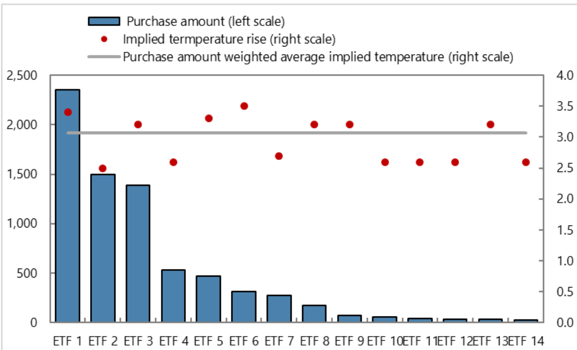
For the ECB's CSPP, the methodology is slightly different. Reflecting the fact that the ECB does not provide publicly-available data on the amounts of corporate bonds purchased by the ECB under the CSPP, we obtain the list of corporate bonds eligible for the CSPP at the beginning and the end of the increase in asset purchases associated with the response to the COVID-19 crisis, based on data provided by the ECB on the history of cumulative net asset purchases under the ECB's Asset Purchase Programme (which are provided at the following URL: https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html). Second, we concatenate these firm names to obtain as comprehensive as possible a list of CSPP-eligible bonds. Third, we plot a histogram of the ITRs of these bonds and we compute the simple average of these ITRs.

In line with the literature on this subject (Matikainen et al., 2017; Dafermos et al., 2020), we find that Fed and ECB corporate bond purchases during the COVID-19 crisis implied a high temperature rise. We estimate the Implied Temperature Rise (ITR) of purchases made under both the Fed's SMCCF and the ECB's Corporate Sector Purchase Program (CSPP). Figure 1 shows that the purchase-mount-weighted ITR is 3.1°C. For corporate bonds, the purchase amount-weighted ITR is 2.5°C. While the ECB does not provide data on asset purchases amounts, data on CSPP-eligible bonds paint a broadly similar picture, although with somewhat lower ITRs. The simple average ITR of firms whose bonds are CSPP-eligible is 2.3°C. Since a loan at a lower rate than the market rate arguably amounts to a profit transfer and therefore comes close to a bailout when a sector is in trouble, these asset purchases are arguably a bailout that sends financial institutions and markets a strong signal that the risks of continued investment in high-emission assets are limited, as their value will be backstopped when shocks materialize.

With regards to cross-border linkages, it is worth noting that the Fed's SMCCF purchased bonds from multinational oil and gas companies (including most oil supermajors) and high-yield corporate bond ETFs that included foreign companies subject to high credit risk. An example is the Canadian oil company MEG Energy, which had negative earnings in 2019 and 2018, a stock with a -33 percent five-year annualized return, and a B3 rating for its unsecured bonds (Braham, 2020).

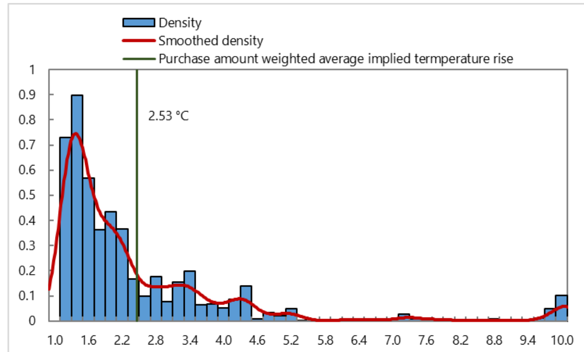
Figure A.4. Implied Temperature Rise of Fed and ECB Asset Purchases During the COVID-19 Crisis

ETF Purchase Amount and Implied Temperature Rise Under Fed SMCCF (Millions of US dollars, left scale; degrees Celsius, right scale)



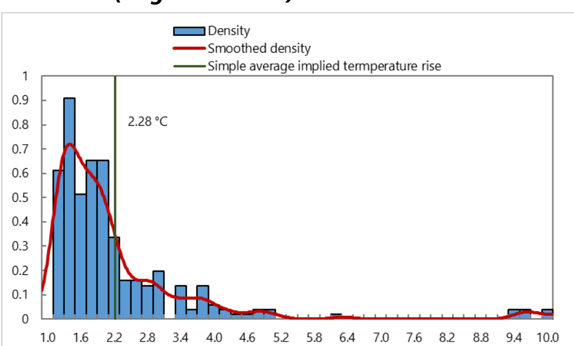
Sources: Federal Reserve; MSCI; and IMF staff calculations.

Density of Purchase Amount Weighted Implied Temperature Rise for Firms Under Fed SMCCF (degrees Celsius)



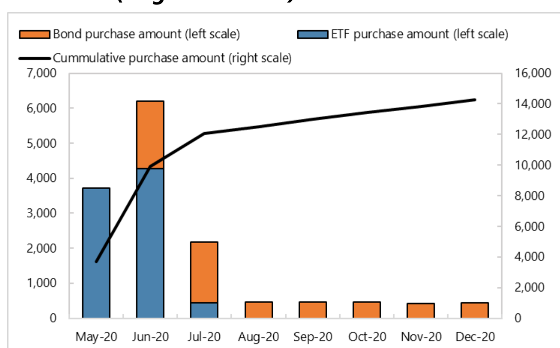
Sources: Federal Reserve; MSCI; and IMF staff calculations.

Density of Implied Temperature Rise for Firms Under ECB CSPP (Degrees Celsius)



Sources: ECB; MSCI; and authors' calculations.

Density of Implied Temperature Rise for Firms Under ECB CSPP (Degrees Celsius)



Sources: ECB; MSCI; and IMF staff calculations.

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