D6.3b – A Race at All Costs? Economic and Environmental Effects of Industrial Policy Nationalism

WP6 – Global Governance and International Cooperation

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Executive Summary

Industrial policy nationalism threatens international collaboration on climate change mitigation. Using regulatory, fiscal, or trade policies to protect and promote the interests of national industries against external competition may increase the cost of transformation and delay the diffusion of key low-carbon technologies. While we need a technology race against climate change, it needs to be a race in a collaborative spirit in which all contestants encourage each other to perform at their best. But a race in the spirit of geopolitical rivalry may cost us the climate.

Contents

Figures

Tables

Introduction

Industrial policy nationalism threatens international collaboration on climate change mitigation. Using regulatory, fiscal, or trade policies to protect and promote the interests of national industries against external competition may increase the cost of transformation and delay the diffusion of key low-carbon technologies. While we need a technology race against climate change, it needs to be a race in a collaborative spirit in which all contestants encourage each other to perform at their best. But a race in the spirit of geopolitical rivalry may thwart climate action and sustainable economic development.

Three major trends have started to shape industrial geopolitics in the last few years. Firstly, companies and governments pay increased attention to supply chain resilience. During the COVID pandemic, the experience of severe backlogs in industrial supply chains has led many companies to reevaluate their previous practices diversifying their supply chains and reshoring key components (Gebhardt et al., 2022). Also many governments are now realising the downsides of dependence on few international suppliers for key components such as microchips and are now pursuing plans to establish domestic industries to overcome these lopsided dependencies (Góes & Bekkers, 2022) in what some have dubbed "techno-nationalism" (Starrs & Germann, 2021; van Manen et al., 2021).

Secondly, the Russian assault on Ukraine and particularly Russia's use of energy trade as a means of war has created a high degree of uncertainty related to energy supply both physical and economical for industries globally. It will have lasting effects on global energy markets and will redraw the map of energy trade flows, in particular related to the EU. It also has alerted industrial and political decision makers about the dangers of lopsided import dependencies elevating energy and resource security as a political and management objective (IEA, 2023). Besides using more domestic resources, one response to this is to engage in "strategic partnerships" with resource rich countries to ensure exclusive or at least preferential access to critical raw material and energy resources (Müller et al., 2023).

Finally, we are now seeing a paradigmatic shift in how climate action is pursued. After inconclusively debating fair and equitable burden sharing of global climate change mitigation for decades, some industrialised countries are finally starting to compete on who can secure the industrial and technology opportunities that arise from the climate transformation (Aiginger & Rodrik, 2020; Cherif & Hasanov, 2019; Hermwille, 2016; Irwin, 2023; Johnstone et al., 2021; Juhász et al., 2023; Meckling, 2021). With the adoption of the Inflation Reduction Act (IRA) in the United States we are now observing a trend towards subsidising domestic green industries which is closely linked to protective trade measures. The European Commission has responded by launching the Green Deal Industrial Plan and proposing its own Net Zero Industry Act (Deloitte, 2023; Grimm et al., 2023; Kleimann et al., 2023; Landais et al., 2023). Other countries had pursued their own industrial policies to realise competitive advantages in green industries: China with its Made in China 2025 Plan (Levine, 2020), India with its Production Linked Incentives scheme (Invest India, 2023; Takyar & Yadav, 2021), and Japan with its Green Transformation (GX) Act (METI, 2023; Ohta & Barrett, 2023).

In addition, export restrictions on critical raw materials have increased fivefold since data collection began in 2019, according to the Organisation for Economic Co-operation and Development (OECD), with 10% of global exports of these materials facing at least one restrictive measure (OECD, 2023). Many countries are now talking about critical mineral clubs and shoring up essential supply chains, with the US actively negotiating critical minerals agreements with key partners.

It seems that these leading industrial powerhouses have started a race for innovation and competitiveness in green technologies. However, there is growing concern that this competition may fuel rivalries and industrial nationalism, lead to protectionism and retaliatory measures and overall impede the transformation progress towards meeting Paris goals and increase transition costs (Georgiewa, 2023; Heydon, 2022; Kaufman et al., 2023; Mehling et al., 2023; Pomerleau, 2022).

The objective of this paper is to better understand the implications of industrial policy nationalism on economic development, employment, structural resilience, import dependence and climate action. To achieve this we proceed through the following analytical steps. First, we define "industrial policy nationalism" and provide an overview of key policies (allegedly) contributing to it. Second, we establish three scenarios of different global collaboration on trade with a focus on green industries. Third, we execute these scenarios in a leading macroeconomic model GEM-E3 with the appropriate level of sectoral and regional granularity that can consistently capture the socioeconomic effects of industrial and trade policies. The model has been enhanced with a bottom-up representation of energy demand and supply sectors and a representation of manufacturing and trade of clean energy technologies (i.e. solar PV, wind turbines, batteries, electric vehicles) and their value chains. And finally, we compare the scenario results in terms of main macroeconomic and sectoral indicators (with a focus on resilience and import dependence) and identify key policy-relevant findings.

Diagnosing Industrial Policy Nationalism

We define industrial policy nationalism as a political strategy of prioritising growth and development of domestic industries and protecting them from or supporting them in the face of external competition. Common features/options of industrial policy nationalism include protectionism and strategic investments. Protectionism here entails implementing tariffs, trade barriers, subsidies, or quotas to shield domestic industries or regulatory support in the form of policies favouring domestic companies and/or restricting foreign investments in strategic sectors. Strategic investments comprise directing government funds or incentives toward specific industries deemed crucial for national development or security.

As stated above, all major industrial countries and the EU have been under the suspicion of industrial policy nationalism. In the last few years, a number of policies have been proposed and some even adopted that feature aspects of industrial policy nationalism. Table 1 below provides an overview of the most prominent policies and a brief assessment of their effects.

Table 1 Selected policies and their significance for industrial policy nationalism.

	Policy	Protectionism	Strategic Investment
US	**Inflation Reduction Act** The IRA promotes economic growth through investments in clean energy, infrastructure, tax cuts, regulation relief, and support for American manufacturing	Buy American close for government procurement, tax credits for hiring new workers, domestic content requirements	Massive infrastructure and green technology investments
EU	**Net Zero Industry Act** is a legislative initiative by the European Commission that aims to accelerate the transition to climate neutrality in the European Union by strengthening the manufacturing capacity of net-zero technologies.	Streamlined regulatory processes (non-discriminatory)	Investments in pilot plants, research and innovation, skill development
EU	**The Carbon Border Adjustment Mechanism (CBAM)** aims to put a price on the carbon emissions embedded in imported goods from non-EU countries. This is designed to level the playing field between EU companies, which are subject to the EU's Emissions Trading System (ETS), and non-EU companies, which are not.	Designed to make imports with high carbon footprint more expensive. Perceived as a protective trade barrier by many third countries.	No
CN	**Made in China 2025 (MIC 2025)** plan is a national policy that aims to make China a global leader in advanced manufacturing industries. It outlines goals for China to achieve self-sufficiency and dominance in key sectors. It includes substantial investments in R&D, incentives for domestic innovation, subsidies for strategic industries, and stringent targets for indigenous production.	Restrictions to foreign investments in specific sectors. Buy Chinese clauses, requirements on data localisation, streamlined regulatory processes, Local content requirements and beneficial treatment for national inputs;	Investments in selected sectors including semiconductors, electric vehicles, biotech, R&D incentives
CN	**Dual Circulation Strategy** aims to boost domestic consumption and technological innovation while reducing reliance on foreign trade (internal circulation) and diversifying trade partners for high-quality exports across various sectors to reduce reliance on specific countries.	Tax breaks or subsidies can incentivize domestic companies in targeted sectors	Ownership limitations in strategic sectors. Direct investments through state-owned enterprises and state-backed investment fund
IN	The **Production Linked Incentive (PLI)** scheme is a performance-based incentive scheme launched by the Indian government in March 2020 to boost domestic manufacturing and reduce dependence on imports. The scheme offers financial incentives to companies that set up new manufacturing units in India and achieve certain sales targets.	streamlined approval processes	provides financial incentives to companies that set up new domestic manufacturing units
JP	The **Green Transformation Act (GX)** is a broad-based industrial policy initiative. It aims to accelerate Japan's transition to a carbon-neutral society. The core components of the strategy include investing in clean energy and energy efficiency, supporting innovation and technology, promoting skills development, reforming regulations, and promoting international cooperation.	streamlining approval processes, local content requirements, promoting collaboration between domestic and foreign businesses in domestic resource extraction	government investment in strategic industries, such as clean energy, energy efficiency, and advanced manufacturing

While none of the policies listed above are a threat to international cooperation on climate change by themselves, we still observe that they are, in part, proposed and adopted in response to developments in the other jurisdictions. As discussed above, the EU's Net Zero Industry Act has been proposed quite explicitly as a response to the USA inflation reduction act (Kleimann et al., 2023; Landais et al., 2023).

Likewise, several countries have reacted to the adoption of the EU's CBAM (Berahab, 2022). India has announced to challenge the EU at the World Trade Organisation (WTO) and has touted its own border adjustment mechanism based on cumulative per capita emissions (Law, 2023). China is actively seeking to shape trade relations (Kynge & Fray, 2024). And despite the lack of an explicit domestic carbon price, bipartisan US lawmakers have also proposed legislation towards building a carbon border tariff (Pomerleau, 2023). If these and similar policy developments accelerate, we might end up in a situation in which international trade of green products and the technologies and resources to produce them becomes ever more restricted inducing an increase in low-carbon technology costs. It might also lead to a situation in which new knowledge and new technologies are shared less, so their development and uptake is constrained.

Alternative visions of green industrial nationalism

To analyse the economic, industrial and environmental impacts of escalating industrial policy nationalism, we develop and compare three alternative scenarios: (1) a strong industrial policy nationalism (sIPN) scenario in which global trade in key green technologies, industrial products and commodities is restricted. In this context, we assume that the five leading economies analysed above - EU, USA, Japan, China, India - unilaterally impose global import duties/tariffs on a set of green industrial products and their supply chains (e.g. clean energy technologies, cars, lithium, steel, copper, aluminium, chemicals) to increase their import price by 50% . In addition, we also simulate a weak industrial policy nationalism (wIPN) scenario, where the same tariff levels are imposed only among the five geopolitical rivals and not with the rest of the world (which is split into 14 regions).

Moreover, we analyse a transatlantic friendshoring scenario. It features the same trade and knowledge spillover restrictions like the wIPN scenario except trade restrictions are lifted between the United States and the EU. Friendshoring describes a strategy in which imports, in particular critical industrial inputs, are sourced from geopolitical allies in order to minimise geopolitical risks for domestic supply chains. The concept of friendshoring has been most prominently proposed by US Treasury Secretary Janet Yellen (Yellen, 2022) but has been picked up more broadly since then (Attinasi et al., 2023; Góes & Bekkers, 2022). A case in point could be the proposed Global Arrangement on Sustainable Steel and Aluminium currently being negotiated between the US and the EU. Under this arrangement, Parties intend to create preferential conditions for trade of green steel and aluminium while also using it as a leverage against competition from "non-market excess capacity", a not very subtle reference to the Chinese steel industry (Tucker & Meyer, 2021; United States of America & European Union, 2021).

Finally, we consider a status quo ante (baseline) scenario which represents the current state of affairs with continuation of current trade policies before the recent uptake of flagship industrial nationalism policies with not free but relatively open trade between major industrial countries and relatively unrestricted knowledge spillover between them. This scenario is used as the baseline against which the alternative policy scenarios are compared in the text and figures below. Table 2 provides an overview of key differences in scenario assumptions.

Table 2 Overview of key scenario assumptions.

	Status quo ante (baseline)	Strong Industrial Policy Nationalism (sIPN)	Weak Industrial Policy Nationalism (wIPN)	Transatlantic Friendshoring (TF)
Mitigation Ambition	NDCs for 2030, long-term net-zero targets (if available)	Same climate policies implemented as in the Status quo ante scenario		
Trade relations between five industrial leaders	No restrictions/ continuation of current trade policies	Impose import duties/tariffs to increase the imported price by 50% between five leading (EU, US, CN, IN, JP regions) in • Clean energy technologies (incl. solar, wind, EV, batteries) • lithium • steel • aluminium • copper • rare earth materials • cars • chemicals		Same as in wIPN scenarios but no restrictions between US and EU.
Trade relations with rest of the world	No restrictions/ continuation of current trade policies	Same duties/tariffs imposed as in trade between leading industrial	No restrictions/ continuation of current trade policies	
Use of tariff revenues	-	Used to subsidise the development of the domestic green technology industries		

Lower economic growth compensates for less effective climate action

Within the GEM-E3 the global economy is represented in an optimal equilibrium state where resources are optimally used. Hence, any imposition of trade barriers and restrictions in green technologies and related products causes economic inefficiencies in the global interconnected economic system[1]. Particularly insightful is the order of magnitude of the effect and its geographical distribution. The trade barriers would lead to a reduction in global GDP of about 0.4%-1% by 2050 depending on (1) the magnitude of these restrictions; the largest impacts are projected in the sIPN scenarios assuming higher trade restrictions among countries globally. It is worth noting that the removal of trade restrictions between the EU and the USA has hardly any impact on global GDP, highlighting the increasing role of developing and emerging economies in the global economic and trade system.

[1] The GEM-E3 model assumes that the economy is in a general equilibrium in each scenario, where capital resources are optimally used in the baseline (Status-quo) scenario. So any change from this scenario caused e.g. by the imposition of additional taxes would have negative economic effects. The analysis focuses on assessing the magnitude and distribution of economic effects across regions, agents and sectors.

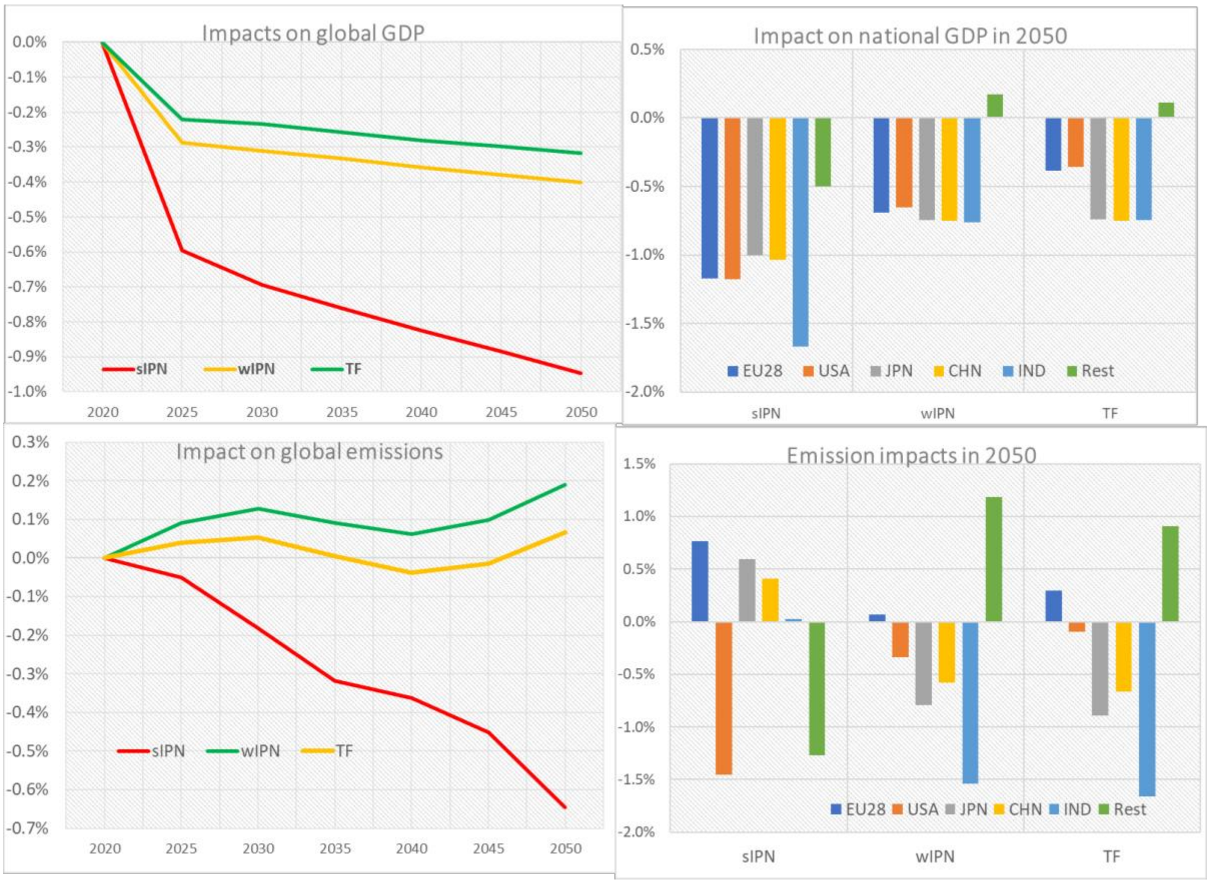

Figure 1: Economic and emission impacts of the trade scenarios compared to the status quo baseline. Upper right shows the impact on global GDP by 2050, and lower right indicates the scenario impacts on global emissions. Upper left show the GDP impacts of scenarios in major economies in 2050 while lower left shows the emission impacts of scenarios in major economies in 2050.

As shown in Figure 1, the imposition of trade barriers would negatively impact the economic activity in all major economies that the study focuses on (EU, USA, China, India, Japan). The sIPN scenario with the strongest trade restrictions has the largest negative impacts across countries with India showing the largest GDP impact. In general, GDP losses in countries/ regions largely depend on the amount of revenues from the trade tariffs as a share of their GDP (India has the highest, Rest of the world has the lowest). In the wIPN and TF scenarios, where trade restrictions are lifted with the rest of the world, GDP impacts to the major 5 economies decline by around 50%, while the rest of world region (which aggregates several other economies modelled in GEM-E3) registers positive impacts. This is due to enhanced competitiveness vis-a-vis the 5 major economies and substitution of imports. The removal of trade restrictions between the EU and USA (TF scenario) further reduces the GDP impacts in these countries to 0.3%, but has hardly any impact on other countries and regions.

The imposition of trade tariffs has limited impacts on global emissions, as these are mostly influenced by the stringency of climate policies and especially by the net-zero targets that constrain the projected outcomes. Two contradictory trends shape the emission projections: on the one hand, reduced GDP due to trade restrictions (as analysed above) lead to reduced emissions as a result of lower economic activity and industrial production; on the other, trade tariffs increase low-carbon technology costs leading to higher emissions. The net effect of these trends is a very limited impact on global emissions, which are found to decrease by 0.6% in the more restrictive sIPN scenario , but increase by 0.1%-0.2%

in the other scenarios. The emission impacts are quite limited also at the national level and are driven by various contradictory effects, including the ambition of climate policies, the GDP impact, the amount of trade tariffs in each country, the sectoral reallocation of production, international competitiveness etc.

The emission projections are also influenced by sectoral production trends. In sIPN, the imposition of duties increases the emissions in the countries implementing the tariff due to increases in domestic production of carbon-intensive sectors but also from reducing the demand of clean energy technologies. The only exception is the US which features decreasing emissions. This effect is mostly driven by the automotive industry. The US is a major exporter of cars, but its export markets are mostly in the rest of the world and much less in other major industrial countries. Consequently, the US automotive industry disproportionately suffers from trade restrictions with the rest of the world. Moreover, there is a reduction in exports in carbon-intensive products in rest of the world countries and as a result there is a (limited) reduction in global emissions.

In the wIPN scenario, the decrease in imports of industrial products is much lower. These are simply substituted by imports from the rest of the world (without trade restrictions) leading to increased production and correspondingly higher emissions there. Moreover, production falls in carbon-intensive industries leading to reduced emissions in the five leading economies, but increases in the rest of the world as there are no trade restrictions there. The removal of trade barriers between the EU and the USA has only marginal impacts on emissions.

Industrial policy nationalism can cause collateral damage

One could assume that geopolitical and geoeconomic competition would only affect the main rivals. However, the sIPN scenario demonstrates that a trade conflict will also have negative effects on the rest of the world. The effect is less pronounced compared to the industrial leaders. This is due to the fact that RoW countries can trade freely among themselves and trade is only restricted in relation to the industrial leaders while the industrial leaders impose tariffs on imports from all countries.

In the wIPN and TF scenarios, the economic outcome of the RoW is actually positive due to their enhanced industrial competitiveness vis-a-vis the five industrial leaders, but that effect is very uneven across rest of the world countries. As stated above, the RoW benefits from the substitution of imports. But only countries with already existing industrial capacities in the affected sectors can benefit. Given the geographic resolution of the GEM-E3 model, South Korea is the only country within the RoW group that significantly benefits from that effect as it has already established strong PV and battery manufacturing capacities.

Does industrial policy nationalism work? Effects on building green industries and import independence

As stated above, industrial policy nationalism is motivated by two main arguments: industrial competitiveness in global markets and resilience of domestic industries and economies. In this section we discuss two sets of indicators that are directly related to those objectives. Industrial competitiveness is reflected by the corresponding share in global manufacturing of key green technologies. And the share of demand covered from domestic production can serve as a proxy for economic resilience (and import dependence).

The imposition of trade tariffs will directly influence the domestic build-up of green industries in major economies (Figure 2). However, the effects differ by country and technology driven by the position of each country in global green technology trade and the competitiveness effects in each scenario and new supply chain risks might be created as we analyse below.

The production of batteries across countries (which are a key ingredient for the massive uptake of electric vehicles) changes significantly; in the most restrictive strong IPN scenario, a large part of the Chinese (and Japanese) manufacturing, which are the main battery exporters currently and in the "status-quo" trade scenarios, is relocated to the EU, USA and India driven by trade restrictions in these countries. However, in scenarios without trade restrictions with the rest of the world (wIPN scenario), battery manufacturing drops in all five major economies to the benefit of the "Rest of world" region, and mostly South Korea, which is already a major player in battery production and has established industrial capacities and strong supply chains. The scenario shows that trade restrictions (if they are not comprehensively applied to all countries) can even cause new unforeseen supply chain dependencies.

The trade restriction impacts are limited in the production of electric vehicles, as in the "status quo" scenario all major economies cover a large share of their demand with domestically produced EVs.

Chinese dominance in PV manufacturing is projected to continue until 2050 in the "status quo" scenarios, but this is somewhat eroded in the scenarios with trade tariffs. However, even the imposition of trade tariffs does not lead to significant build-up of the PV industry in the EU, USA, Japan and India, as the reduced Chinese exports are counterbalanced by exports from other world regions (esp. South-East Asia) due to increased cost efficiency.

The wind industry is currently dominated by European and Chinese manufacturers, which account for the largest share of global production and exports. The imposition of trade tariffs means that these countries will face significant export losses, so their share in global wind turbine manufacturing will decline, mostly to the benefit of the USA which is the only major economy with adequate know-how, labour and financial resources to expand its wind manufacturing (in contrast e.g. to Japan due to limited domestic demand for wind power).

Other markets such as electrolyzers and CCS equipment might also be affected by industrial policy nationalism, but these markets are still in their infancy and too immature to model and project decades into the future.

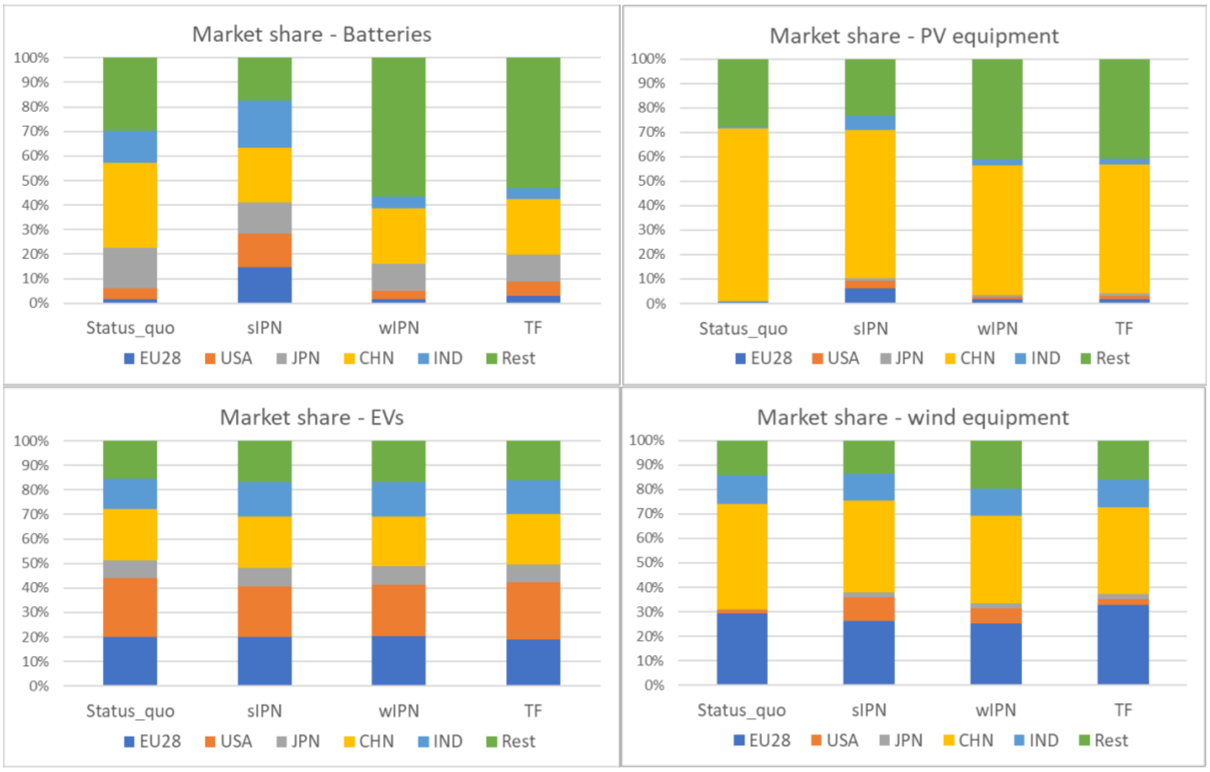

Figure 2: Share of major economies in global manufacturing of clean energy technologies in 2050.

The imposition of trade tariffs will reduce the import dependency of major economies in green technologies and will increase the share of "green" demand covered by domestically produced technologies and equipment (see figure 3). However, when trade tariffs with the rest of the world are removed, the import dependency for clean technology equipment increases again for the EU, USA and India to the benefit of other producers, most importantly South Korea. This highlights the potential limited effectiveness of trade tariffs and restrictions if not imposed comprehensively.

In battery manufacturing, the major battery importers (EU, USA, India) massively increase the share of domestic production especially in the more restrictive strong IPN scenario. In all scenarios, China is self-sufficient in battery manufacturing, while Japan reaches such levels in the sIPN scenario. However, in the weak IPN and friendshoring scenario, the increases of domestic production are only marginal.

similar picture emerges in the solar PV industry. The self-sufficiency of major economies (EU, USA, Japan, India) massively increases when comprehensive trade tariffs are imposed also to other regions (sIPN). This indicates that these countries have a potential to reduce their import dependency by investing more in domestic manufacturing capacities. However, the impacts are much smaller when tariffs are not imposed to countries outside the five major economies and the rate of self-sufficiency worsens to the benefit of exporting countries from the rest of the world region. In all scenarios, China's self-sufficiency is higher than 90%.

In all scenarios, the major wind turbine producers (EU, China, India) are projected to be self-sufficient by 2050 with domestic wind turbine production covering the domestic demand. The imposition of strong IPN trade tariffs would increase the share of demand covered by domestic production in the USA and Japan.

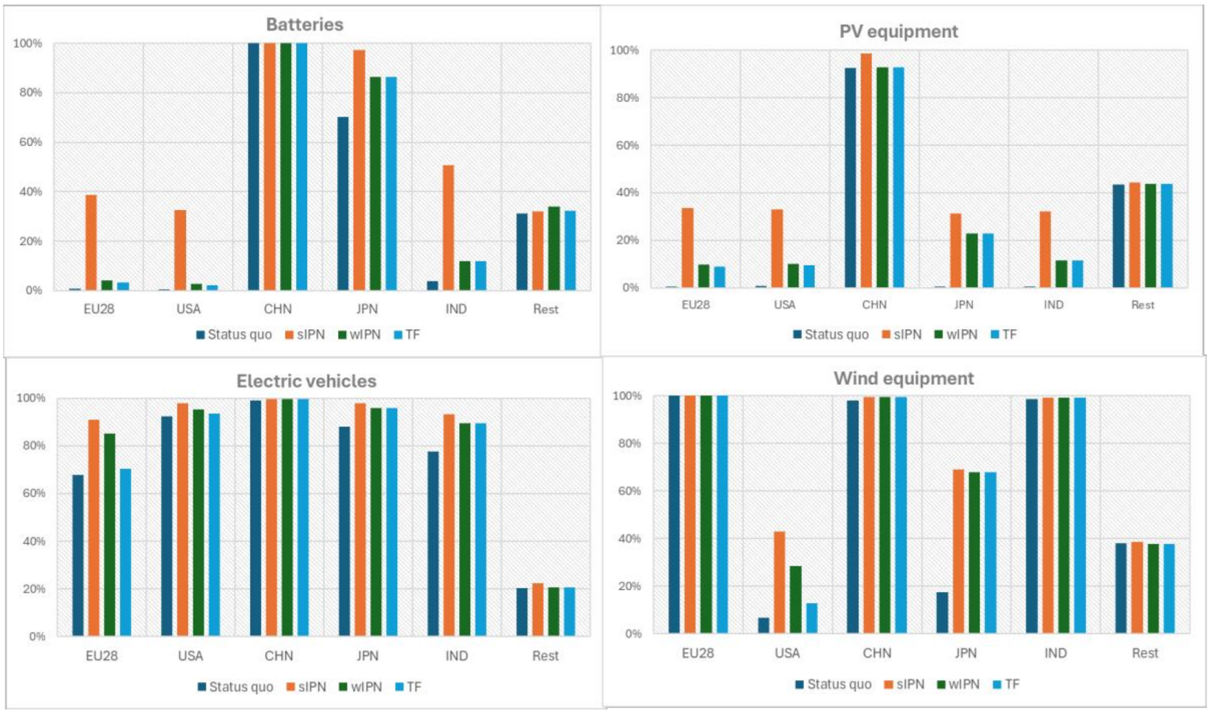

Figure 3: Share of demand for clean energy technologies covered from domestic production by country and scenario over 2020-2050.

The imposition of trade tariffs impacts the competitiveness and trade flows of conventional industries despite not using the revenues from tariffs to subsidise them. However, current market shares and domestic supply are higher than for clean energy technologies. This is particularly true for steel and on a somewhat lower level for other non-ferrous metals, basic chemicals and transport equipment. But the same patterns apply again: we observe significant effects only in the strong IPN scenario. The effect is marginal in the other scenarios (see supplementary analysis 1).

Industrial policy nationalism hurts the economy with limited benefits in terms of reduced green technology import dependence

The environmental effects of industrial policy nationalism are less pronounced than we had anticipated as the imposition of ambitious climate policies to achieve the net-zero targets and pledges of countries is the main emissions driver. Particularly surprising was the result that in some instances industrial policy nationalism can actually be good for the climate, but only because it is bad for the economy as it leads to reduced economic activity and fewer jobs compared to the baseline scenario. This was the case in the strong industrial policy scenario in which we restricted trade not only among the leading industrial rivals but with all countries. In that case, the effects on global economic development are so pronounced that they result in reduced absolute emissions compared to the baseline.

Our second main finding is that industrial policy nationalism does not work under most assumptions. In the weak industrial policy nationalism scenario (and in the transatlantic friendshoring scenario) the industrial rivals fail to achieve a significant build up of domestic green industries in most relevant sectors. Trade restrictions towards the leading industrial rivals will lead to substitution effects and increased imports from other advanced industrial economies. In our analysis it is only South Korea that significantly benefits due to this market-driven effect. In the real world, however, we would plausibly expect a political response to such profiteering in the form of increasing tariffs.

The objectives of leading market shares and a higher degree of domestic supply can only be achieved in the more restrictive strong industrial policy nationalism scenario. And here it does not only affect the core rivals but also the rest of the world. There is a big risk that developing countries will get into the crossfire of geoeconomic competition and suffer collateral damage that will not only make it more difficult to achieve climate commitments but could thwart sustainable development overall.

Finally, it is important to note that even our most restrictive scenario is actually quite optimistic in the sense that industrial policy nationalism is contained to a limited set of sectors relevant for the green industry transformation (which represent a low share of global economic activity). In reality, we might expect that retaliatory measures spiral into a much broader trade conflict affecting all sectors. For instance, the EU responded to imposition of tariffs on steel and aluminium by US President Trump by levying import duties on motorcycles and whiskey (Ewing, 2018). Hence, there is a high risk that industrial policy nationalism may escalate towards a larger trade war with overall limitations on trade which would have much more severe implications for global economic development.

While a more proactive approach towards transformative industrial policy will be necessary to accelerate industrial decarbonization, a prudent industrial policy strategy should seek global collaboration over rivalry. While we need a technology race against climate change, it needs to be a race in a collaborative spirit in which all contestants encourage each other to perform at their best. Our analysis shows that restricting trade to build up domestic industrial competitiveness and resilience is only effective under very stringent conditions which in turn may have negative economic implications not only for the main competitors but globally. Hence a race in the spirit of geopolitical rivalry fuelled by industrial policy nationalism may ultimately hinder the global transformation to low-carbon sustainable economies.

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Supplementary Material

Conventional industries are also impacted by trade restrictions

Here we analyse the effects of trade restrictions on key trade-exposed conventional industries, including ferrous and non-ferrous metals, chemicals and transport equipment.

The main message of the analysis is that the very restricted trade scenario (sIPN) improves national self-sufficiency and import independence of major economies. When trade restrictions with the rest of the world are lifted (wIPN scenario), the effects on conventional industries are limited, while friendshoring scenario does not make much of a difference except maybe for EVs.

In the ferrous metals industry (mostly iron and steel making) all five major economies cover more than 90% of their steel demand with domestically produced steel in the trade-restrictive sIPN scenario. The impacts from trade tariffs are declining in the scenarios assuming lower barriers. These industries are already well-established and are considered critical in major economies as they provide critical materials needed by the economy in general and for the climate transition in particular. This means that even in the status-quo scenario, the share of domestically produced goods to demand is higher than 80% in the EU, China, India and Japan, with the US being the only exception, indicating higher import dependence and vulnerability to imported supply chain risks for ferrous metals.

Similar trends are also observed in the non-ferrous metals, where the imposition of trade tariffs in the sIPN scenario reduces countries' import dependence. However, here most countries (with the notable exception of China) start from a higher level of import dependence than in ferrous metals as illustrated in the figure below. The chemicals sector is also characterised by similar trends as the metals production. The demand for transport equipment is also influenced by the imposition of trade tariffs, especially in the more trade-restrictive scenario sIPN. The impacts are more pronounced in the USA as it starts from a lower level of the share of domestic demand for transport equipment covered by domestic production.

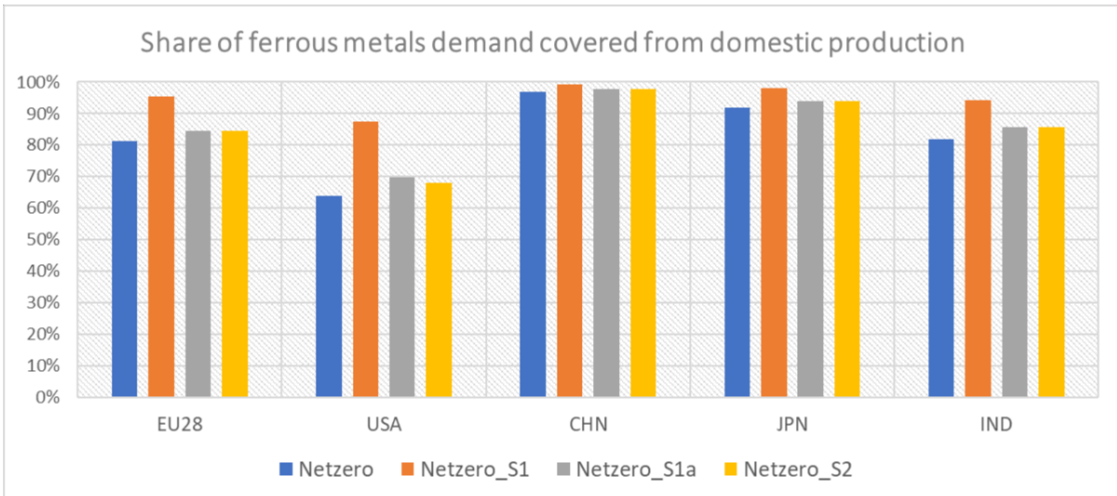

Figure 4: Share of demand for ferrous metals covered from domestic production by country and scenario in 2050.

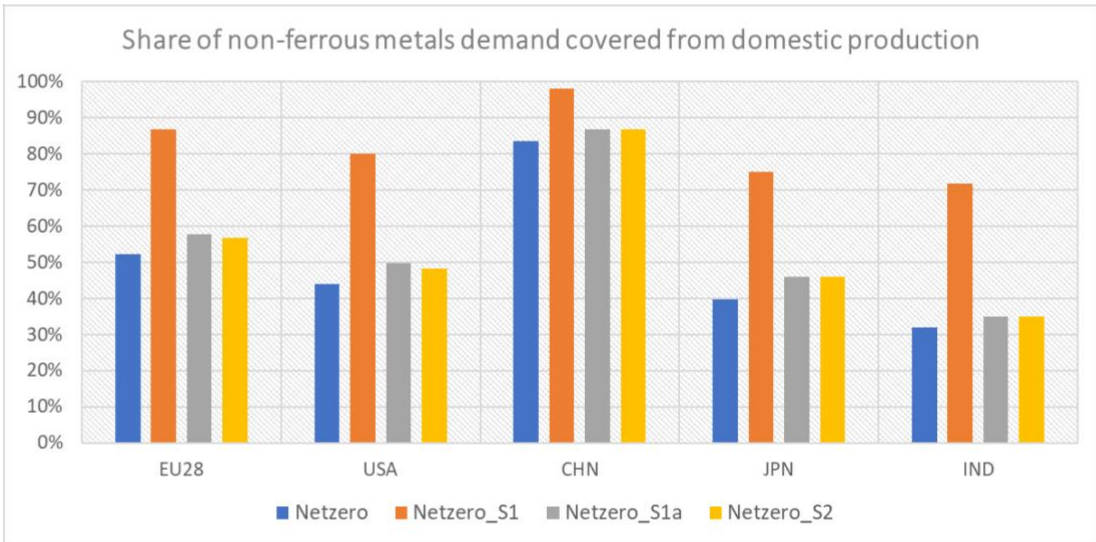

Figure 5: Share of demand for non-ferrous metals covered from domestic production by country and scenario in 2050.

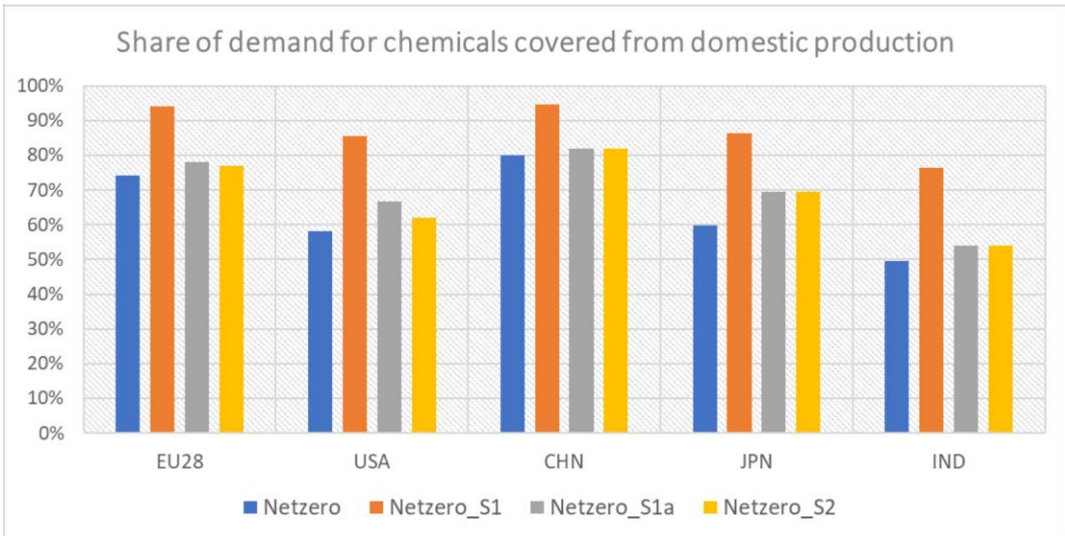

Figure 6: Share of demand for chemicals covered from domestic production by country and scenario in 2050.

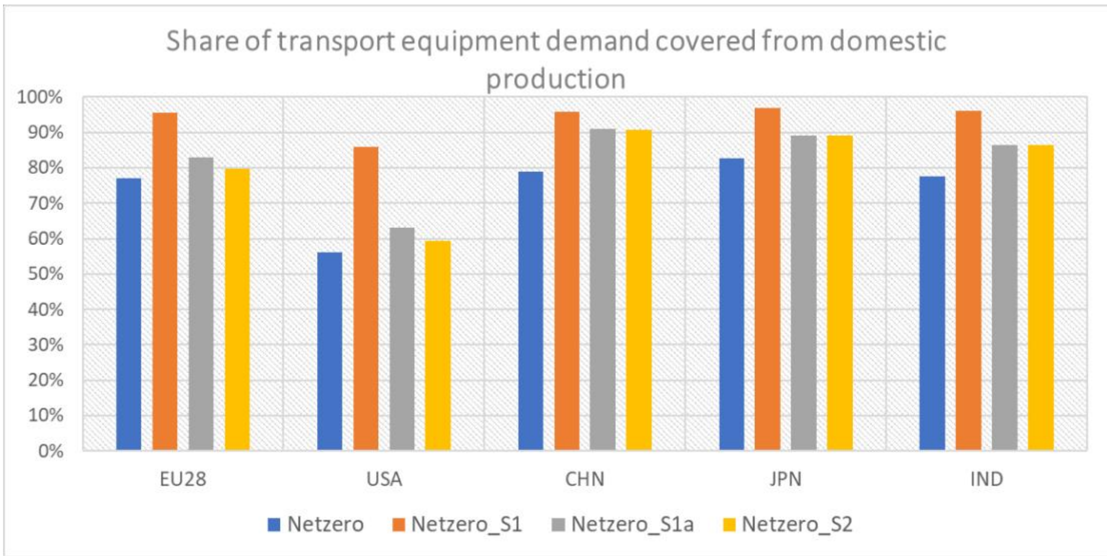

Figure 7: Share of demand for transport equipment covered from domestic production by country and scenario in 2050.

The GEM-E3 model

The GEM-E3-FIT model is a multi-sectoral, recursive dynamic CGE model, which simultaneously represents 46 regions (including all EU countries) and 51 sectors linked through bilateral trade (E3-Modelling, 2017). It is a comprehensive model of the global economy, covering interlinkages between productive sectors, consumption, price formation of commodities, labor and capital, trade, and investment dynamics. GEM-E3-FIT formulates the supply and demand behavior of economic agents with market derived prices to clear markets, allowing for a consistent evaluation of distributional effects of policies. The model is driven by accumulation of capital, equipment and knowledge, features equilibrium unemployment, energy efficiency standards and carbon pricing and can quantify the socio-economic impacts of policies ensuring that in all scenarios the economic system remains in general equilibrium. It provides results for the period 2020 to 2100 in five-year time steps.

Industries operate within a perfect competition market regime and maximize profits. Production functions consider the possibilities of substitution between capital, labor, energy, and materials in each sector and allow for price-driven derivation of intermediate consumption and the services from capital and labor. Households demand, savings and labor supply are derived from utility maximization using a linear expenditure system (LES) formulation. Households receive income from labor supply and from holding shares in companies. Investment by sector is dynamic depending on adaptive anticipation of capital return and sectoral activity growth. All regions and sectors are linked through endogenous bilateral trade flows. Total demand in each country and sector is optimally allocated between domestic and imported goods, under the hypothesis that they are imperfect substitutes (Armington, 1969): at the upper level, firms decide on the optimal mix between domestically produced and imported goods; at the next level, demand for imports is split by country of origin depending on transportation costs, prices and consumer preferences (captured by statistics on trade). GEM-E3 is calibrated using the GTAP dataset that provides a comprehensive and self-consistent accounting of firms' production structures, households' consumption, trade, gross fixed capital formation and sectoral value added (Figure 1). GEM-E3-FIT includes features that go beyond conventional CGE approach, described in detail below.

Conventional CGE models lack a detailed representation of the energy system and related technologies, as they commonly represent the energy sectors using aggregate production functions and they fail to capture crucial sector characteristics reducing the credibility of their simulations. To overcome this, top-down CGE models are often combined with bottom-up models which have a rich representation of energy technologies (Böhringer and Rutherford, 2008; Helgesen, 2013). Two methods are used: (i) a hard link approach where the CGE model is extended to include detailed representation of the energy system and (ii) a soft link approach where the two models are linked through specific variables and an iterative process to ensure models' convergence. GEM-E3-FIT includes a detailed representation of energy system and technologies, thus enhancing the credibility of CGE modeling for climate policy analysis as the substitution patterns in energy supply and demand are based on 'true' technologies rather than restrictive functional forms.

Electricity Production

GEM-E3-FIT adopts a bottom-up approach for electricity sector with power producing technologies treated as separate production sectors. GEM-E3-Power module (Polzin et al., 2021) calculates the optimal investment and operation of electricity system in order to minimize total production costs, including capital costs (CAPEX),1 Operation & Maintenance (O&M) expenditures, carbon costs and costs to purchase fuels, while meeting constraints (e.g., technology potentials, resource availability, policy constraints, system reliability). Thirteen power technologies are included (coal, oil, gas and biomass-fired, nuclear, hydro, PV, wind onshore, wind offshore, geothermal, Carbon Capture and Storage- CCS- with coal, gas, and biomass) and compete based on their Levelized Cost of Electricity to meet electricity requirements in each time segment. The decision to invest in power technologies depends on their relative costs, barriers and potentials, while various policy instruments may influence the electricity system evolution, e.g., ETS prices, phase-out policies, renewable subsidies, etc.

GEM-E3-Power calculates investment in new power plants, which are influenced by sectoral electricity demand, load curves, decommissioning of old plants and policy measures. The modeling includes non-linear cost-supply curves for fossil fuels, renewables, and nuclear plants, which capture exhaustion of renewable energy potential, take-or-pay contracts for fuels, the promotion of domestically produced fuels, social acceptability of technologies, difficulties to develop CO_2 storage areas, policies regarding nuclear site development, etc. (Polzin et al., 2021). The non-linear cost-supply curves are included in the optimization of capacity expansion and system operation of GEM-E3-Power.

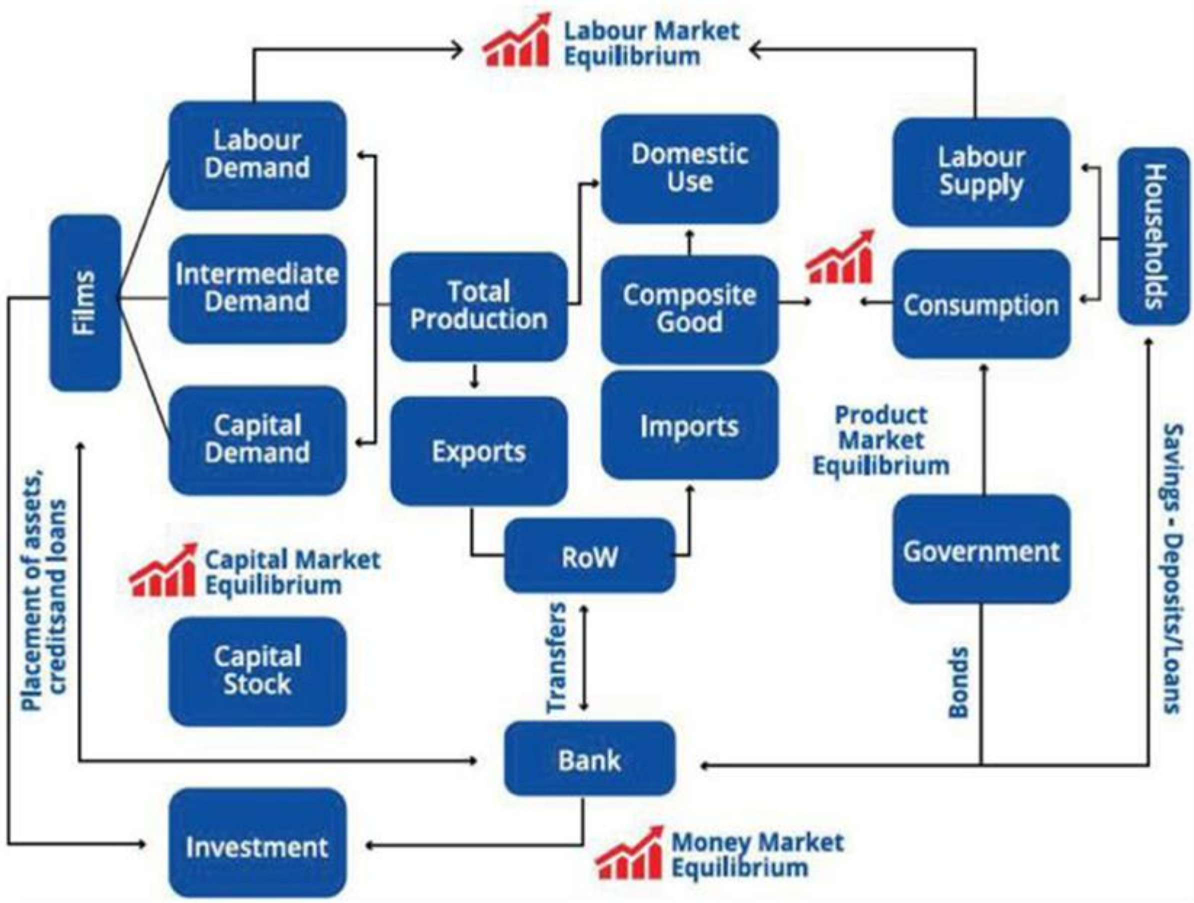

Figure 8: Illustration of the GEM-E3 model.

Transport

GEM-E3-FIT includes a bottom-up representation of passenger and freight transport, simulating the choice of (public and private) transport modes and technologies and the way of using transport equipment. Mobility is split between using private transport means (e.g., cars) and purchasing transport services from transport suppliers (public transport). Private mobility is derived from consumption by purpose of households under the income constraint. The use of private transport involves purchasing of durable goods (vehicles) considering three car types with different capital and fuel consumption features; in particular conventional Internal Combustion Engine (ICE), plug-in hybrid vehicles and battery electric cars (EVs). Each car type uses a different mix of fuels, with ICE cars using diesel, gasoline, gas and biofuels, EVs using electricity, and plug-in hybrids using electricity, oil products and biofuels. The shares of the three car types (r) in new car registrations are calculated based on the Weibull discrete choice representation (Karkatsoulis et al., 2017).

Mobility of private consumers is translated into demand for specific car types, which in turn is related to demand for specific goods via the consumption matrix that links consumption by purpose to demand for specific goods. The technology and fuel mix in transport changes endogenously because of carbon pricing and other policy instruments, while fuel shares in households' consumption matrix can be modified. Public transport is provided by land, air, and maritime transport. Each transport sector produces a homogenous service using inputs from capital, labor, materials and energy, based on endogenous choice of firms toward cost minimization. The demand of other production sectors for transport services derives from cost minimization of their production input mix. Substitutions are possible between transport modes and between transport and non-transport inputs depending on relative prices of goods and services.

Energy Use in Households

Energy demand for households is divided into Heating and cooking demand and Electric Appliances. Useful energy for heating depends on households' income and on the total cost of heating that includes the purchase and the operational costs for energy equipment. The purchase and use of energy services by households derives from their utility maximization (under income constraint). The use of durable goods (cars, heating systems and electric appliances) involves demand for non-durable goods, mainly fuels and electricity. The consumer's decision to purchase durable goods depends on the cost of buying and using the energy equipment (i.e., fuel costs).

At the first level of the heating bundling, households decide between district heating and the use of private heating appliances through a CES function depending on the costs of competing options. At the second level, households decide on the operation of existing appliance stock and the purchase of new appliances. Finally, new appliances are split into options based on the fuel used (coal, oil, gas, biomass, electricity, solar thermal) and technologies (conventional and advanced) characterized by different cost structures in terms of purchase and operation costs. Their competition is modeled as a "Weibull" function (similar to cars), with fuel choice depending on their total costs. The purchase and use of electric appliances follow the same logic as heating and cooking appliances.

Representation of the Decarbonization Process

GEM-E3-FIT captures both energy- and process-related GHG emissions. The emission abatement potential depends on substitution possibilities among fuels and between energy and capital. In the model, the internalization of environmental externalities is achieved either through taxation or system constraints –global, regional, or sectoral-, the shadow cost of which (e.g., carbon price) affects the decisions of economic agents. Emission reductions in GEM-E3-FIT are enabled through:

i. 1) End-of-pipe abatement technologies for non-CO2 emissions are formulated by bottom-up Marginal Abatement Cost Curves (MACCs) that differ among countries, sectors, and pollutants (Harmsen et al., 2019). Marginal costs of abatement are increasing functions of the degree of abatement.
ii. 2) Substitution of fuels toward low-emission energy carriers and technologies: The decision of firms to purchase inputs is influenced by carbon pricing, which increases the cost of fossil fuel inputs and causes a shift in firms' demand away from fossil fuels toward low-emission technologies. Therefore, an imposed cost on emissions (e.g., a carbon price) drives substitution toward less emission intensive inputs, e.g., from coal to gas or renewable energy.
iii. 3) Energy efficiency improvements, modeled through specific investment that enable the substitution of fuel consumption with capital and/or technology equipment (e.g., advanced home appliances, improved thermal insulation, energy management in industries, more

efficient equipment). Thus, climate policies will drive a substitution away from energy to capital.

iv. 4) Decrease of production: The imposition of climate-related constraints causes an additional cost to production, linked to the costs of substitution or installation of abatement equipment. An increasing production cost would drive a reduction in demand, production and emissions for carbon-intensive products, combined with potential substitution toward activities with lower carbon intensity.

The environmental tax is paid by the polluting firm to the government and thus the tax affects the firms' decisions on the use of production factors. In GEM-E3-FIT, the installation of low-emission and energy efficient technologies is considered as an intermediate input and not as investment demand of the firms, as, e.g., the purchase of a more efficient air-condition will not increase the firm's capital stock but will create additional intermediate demand. Firms and households decide on the optimal level of abatement driven by the carbon tax,2 with emissions reduced up to the level that the cost to abate the last ton of emissions equals the carbon price. CO2 emissions can be mitigated through efficiency improvements, uptake of low-emission technologies and fuel substitution away from fossil fuels. In GEM-E3-FIT, a climate policy can be implemented either through the imposition of an exogenous carbon tax, or through an exogenous emission cap, with tax level endogenously estimated to achieve the emission target ensuring the clearing of demand and supply for emission permits.

Representation of Labor Markets

GEM-E3-FIT represents imperfect labor markets, simulated by an empirical labor supply equation that links wages and unemployment through a negative correlation. To adequately capture real-world conditions in labor markets, GEM-E3-FIT represents involuntary unemployment, moving beyond conventional CGE modeling assuming perfect labor markets. GEM-E3-FIT represents labor market imperfections and frictions, so that employees enjoy a premium on top of the wage rate that would correspond to equilibrium between potential labor supply and labor demand. The premium leads to a displacement to the left of the potential labor supply curve, which corresponds to effective labor supply, with equilibrium unemployment determined as the difference between potential and effective labor. In GEM-E3-FIT the efficiency wage approach (Shapiro and Stiglitz, 1984) is selected to represent involuntary unemployment because of its empirical validation and simplicity, assuming a negative correlation of unemployment levels with wages.

Climate policies have differentiated impacts across skills and can cause a mismatch between labor demand and supply for specific skills. Conventional CGE models do not differentiate between skills and assume that labor markets are fully flexible, so that workers can easily migrate to new jobs and industries and are therefore not well-suited to assess the skill impacts of policies. To capture these effects, GEM-E3-FIT has been expanded with a representation of five distinct labor skills combined with the endogenization of households' decision for education that influences the level of its future skills and wages. The five skill levels correspond to GTAP classification: unskilled workers, service and shop workers, technicians, clerks and managers.

GEM-E3-FIT represents labor productivity differentials across countries and labor skills through modeling the links between human capital, knowledge spillovers and absorptive capacity. These affect the growth potential of new high value-added activities requiring increased labor skills and tertiary education. The optimal schooling years are decided by the households depending on the interplay between higher skills (and wages) obtained from tertiary education and education costs, including the cost of schooling and the lost income during schooling years. Households decide on the optimal amount of education based on wage and unemployment rate differentials between different skill levels. The choice on education affects the number and skill distribution of the working age population that in the period t is added to the labor force. For each skill category the demand-supply mismatch results into a skill specific unemployment rate. The model assumes full labor mobility across sectors for each skill type. The supply of each labor skill is determined via an empirically determined wage curve linking wages with unemployment rate (with a wage elasticity of −0.1) consistent with the efficiency wages approach described above.

Representation of Policy Instruments

Various energy and climate policy instruments are represented in GEM-E3-FIT. Policies are analyzed as counterfactual scenarios and are compared against the Business-as-Usual scenario. Policies are evaluated through their impact on growth, employment, income distribution, competitiveness, and welfare. GEM-E3-FIT can assess the impacts of market-oriented instruments, such as carbon taxes and investigates market-driven structural changes, as well as the re-structuring of economic sectors, income and re-location of industrial activities induced by climate policies (Paroussos et al., 2015). The model can support the analysis of social and distributional effects of climate, energy and economic policies, both among countries and among income classes within each country (Fragkos et al., 2021). GEM-E3-FIT can assess the allocation of climate efforts over different countries and sectors with subsequent effects on growth, capital, and labor allocation as well as compensating measures to alleviate negative impacts on vulnerable regions and households.

Climate policies would drive the expansion of renewable energy, energy efficiency and electrification of energy services. GEM-E3-FIT includes several mitigation options, including a variety of renewable technologies, Evs, advanced biofuels, heat pumps, building retrofits, CCS, fuel substitution toward low-emission energy carriers and uptake of efficient equipment. The model endogenously decides on the optimal mix of mitigation options to achieve the climate target, choosing first the options with lower abatement costs. The uptake of specific technologies depends on the availability of other mitigation options, i.e., competition between biofuels and EVs to decarbonize transport. GEM-E3-FIT captures the complex interlinkages among sectors and mitigation options, e.g., the uptake of EVs depends on the provision of green and cheap electricity from the electricity sector.

GEM-E3-FIT can support analysis of structural features of growth related to low-carbon innovation and technology and evaluate the socio-economic implications. It puts particular emphasis on:

- Assessing climate-related market instruments, such as energy or carbon taxes, subsidies to low-carbon technologies, regulations, efficiency standards, etc.
- Exploring the distributional consequences of policies, including social equity and employment for vulnerable regions and low-income classes.
- Assessing policy instruments related to low-carbon innovation, labor market or industry and their interactions with decarbonization.
- Analyzing measures to mitigate negative competitiveness impacts of climate policies on trade-exposed industries, e.g., CBAM, changes in industrial tariffs, etc.

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