Direct and embodied energy and emissions trade in a decarbonised world

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Abstract: In this paper, we investigate global trade patterns in the timeframe 2020-2050, focusing on the development of embodied energy and GHG emissions in trade under three different decarbonisation scenarios: i) a current policies scenario, ii) an NDC-LTS scenario, reaching announced climate pledges, and iii) a 1.5 °C cost-efficient global temperature stabilization scenario. We rely on a comprehensive modelling toolbox building on the POLES-JRC partial equilibrium model, and JRC-GEM-E3 general equilibrium model. Based on multi-regional input output tables (MRIO) computed from this modelling framework, we provide a multidimensional analysis on embodied energy and emission flows, paying particular attention to direct and indirect trade impacts to fossil and non-fossil energy carriers. We assess the changes by region, fuels and sectors, considering the entire value chain of goods and services. Our results highlight how energy embodied in traded goods and services will shift from mainly embodied oil, coal and gas to date, to embodied low carbon electricity. GHG emissions embodied in goods and services are projected to decline, while the gap between production and consumption based accounting metrics of emission´s accounting is projected to decrease. Overall, our results contribute to the growing literature on how trade and globalization might develop in a decarbonizing global economy. Our results illustrate that the trade of goods and products can persist in an expanding and decarbonizing global economy.

1. Introduction

International energy trade plays an important role to balance supply and demand of energy, as resources and technologies are unevenly distributed across the globe. In addition to the direct trade of energy, the global economy significantly relies on the international trade of goods and services, with production using energy as an indispensable input to the production process. Therefore, a country can directly export energy carriers (e.g., barrels of crude oil, tons of coal), or use (domestic or imported) energy resources to produce intermediate and final products, further exporting them to a third country. In this case, the energy used in the production process is exported indirectly, as it is embodied in the traded good or service.

While studies assessing changes in the direct energy trade are frequent, embodied energy trade is a topic less explored in the literature. Input-Output (IO) modelling – eventually combined with other methods (e.g., decomposition analysis, network analysis) – is often used to investigate how economic development and changes in global supply chains *affected* the embodied energy in trade, typically relying on historical data to provide backward looking assessments (e.g., Pan et al., 2022; Gasim, 2015). In a decarbonized world adhering to the Paris Agreement, informing how the trade flows of direct and embodied energy develop over time under different climate ambition scenarios is of uppermost relevance for the global climate policy debate.

In this paper[1], we investigate how global and regional trade patterns change under three different ambition levels – current policies, a pathway that reach the announced climate pledges in the near term (nationally determined contributions, NDC) and in the long-term (long-term strategies and net zero pledges, LTS) and a pathway that reaches the 1.5 °C target. We rely on a comprehensive modelling toolbox to provide a multidimensional analysis, paying particular attention to direct and indirect trade impacts to fossil and non-fossil energy carriers. We assess the changes by region, fuels and sectors of the embodied energy in global trade in a decarbonised world considering the entire value chain of goods and services. We also look at emissions embodied in international trade, allowing for greenhouse gas (GHG) emissions accounting both in the country or region where production or consumption occurs.

2. Methods

The paper builds on the most updated version of the modelling toolbox used in the European Commission's energy and climate policy assessments (Figure 1), covering the impacts on the energy system, transport, agriculture, and the macro-economic effects over multiple sectors, including employment and social welfare.

[1] Part of this work has recently been published as Keramidas et al. (2022). This paper deepens the analysis of direct and embodied energy and emissions in trade, providing in-depth results by regions, fuels and sectors and a comprehensive description of the methodological approach.

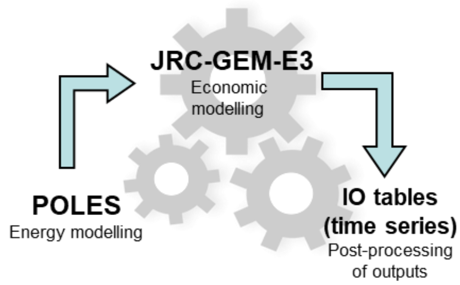

Figure 1. Modelling toolbox. Bottom-up energy system and top-down global economic modelling combined.

The POLES-JRC model is a global partial equilibrium simulation model of the energy sector, covering a wide range of activities from upstream production to final user demand (Després et al., 2018). The model describes how multiple energy resources are put into production, resulting in trade flows from producers to consumers (for oil, gas, coal, bioenergy, hydrogen), and providing full energy and emission balances for 66 countries and regions worldwide. The JRC-GEM-E3 is a multi-regional, multi-sectoral, recursive dynamic Computable General Equilibrium (CGE) model with a consistent macro-economic framework that is extensively used as a tool of policy analysis and impact assessment (Weitzel et al., 2023), being particularly valuable in capturing the effects of the transformation of the energy system and of climate-related policies over the macroeconomic aggregates.

The POLES-JRC and the JRC-GEM-E3 (Capros et al., 2013) models are linked through the PIRAMID tool (Wojtowicz et al., 2019), which reconciles the economic structure with the energy balances from POLES-JRC to integrate and project the Input-Output tables and Social Accounting Matrices (IOTs/SAMs) derived from the Global Trade Analysis Project (GTAP) 10 Power database (Aguiar et al., 2019; Chepeliev 2020) forward in time. The JRC-GEM-E3 model is calibrated to reflect the same socio-economic drivers (GDP, population) as the POLES-JRC model, while fixing the economic values of energy purchases based on energy prices and quantities from POLES-JRC. The PIRAMID tool is based on the multi-regional generalized RAS method (Temursho et al., 2021), which ensures that the JRC-GEM-E3 resembles the energy use and GHG emissions as projected in POLES-JRC, so that the projected input output tables provide a fully consistent baseline scenario. The models includes all Kyoto gases (except land use and land use change in JRC-GEM-E3).

The current policy scenario reflects a world where existing policies as of mid-2022 related to energy supply and demand, as GHG emissions, are enacted. The NDC-LTS scenario considers the targets of NDCs and net zero pledges and other long term commitments (LTS) as of 2022. The 1.5 °C scenario is an economically efficient pathway with a uniform global carbon price, designed to limit global temperature increase with a 50% probability to 1.5°C in 2100. More details on the scenarios can be found in Keramidas et al. (2022).

For the current policy scenario, we use the PIRAMID/CGE combination to project multiregional IO tables forward in time and calculate indicators covering the entire value chain of a good or service (e.g., embodied energy or emissions in trade) for future years. For the NDC-LTS and 1.5 °C we soft-link the POLES-JRC model to JRC-GEM-E3 by imposing transitions projected in POLES-JRC to JRC-GEM-E3 by adjusting parameters that describe the decarbonization of key energy sectors (e.g. electricity, transport, heating). In this process, additional costs, e.g. from higher capital expenses are taken into account (Weitzel et al., 2023). The CGE model then produces input-output tables that describe the interrelations between sectors and regions under more ambitious climate policies. These multi-regional input output tables (MRIO) are then used to calculate embodied energy and emission flows using standard input-output techniques.

3. Results

As for 2015, the direct energy trade across world regions represented close to 4600 Mtoe (Keramidas et al., 2022).

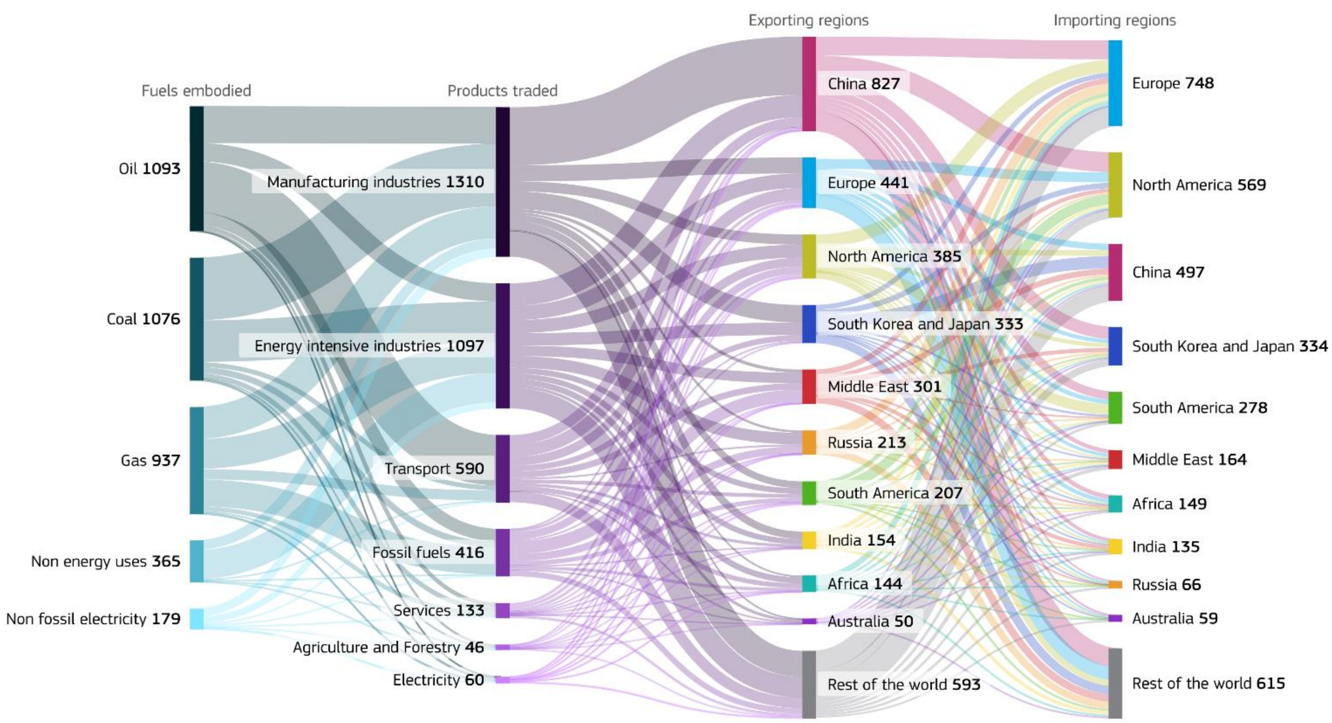

Figure 2 presents the embodied energy trade in 2015, which represented close to 3650 Mtoe, with fossil fuels accounting for 95% of the embodied energy trade. Coal, gas and oil mainly flow through traded products of manufacturing and energy intensive industries. While these figures put embodied and direct energy trade in the same order of magnitude, they account for roughly 35-30% of global primary energy supply in the same year, respectively. Embodied energy is determined by the trade patterns of goods and services across regions, consequently with China ranking as largest exporter of embodied energy, followed by major economies, such as EU and USA. Notably, exporters of fossil fuels are also large exporters of embodied energy. This reflects on the one hand the energy intensive process of fossil fuel production and transportation, on the other also embodied energy in industry exports – economies with cheap fossil energy may have specialized in energy intensive production, and often the energy intensity of any given sector is higher than the world average as incentives for efficient energy use are low.

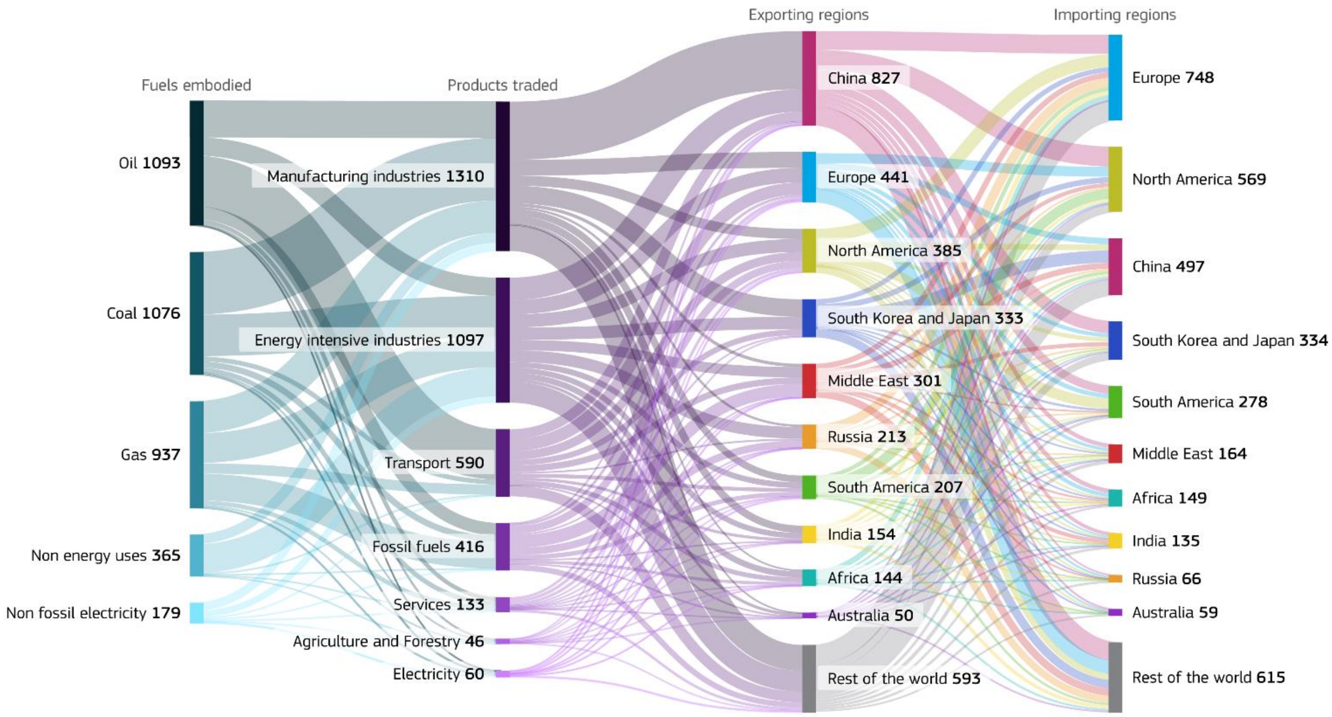

Figure 2. Global embodied energy trade in 2015 (Mtoe).

Under the 1.5 °C scenario, the total embodied energy in goods and services is projected to decrease by about a quarter from 2015 values. Embodied energy from fossil fuels in trade contracts from 3471 Mtoe in 2015 to 833 Mtoe by 2050. At the same time, embodied non-fossil fuel electricity is projected to substantially increase, growing from 179 Mtoe in 2015to 1338 Mtoe by 2050. Figure 3

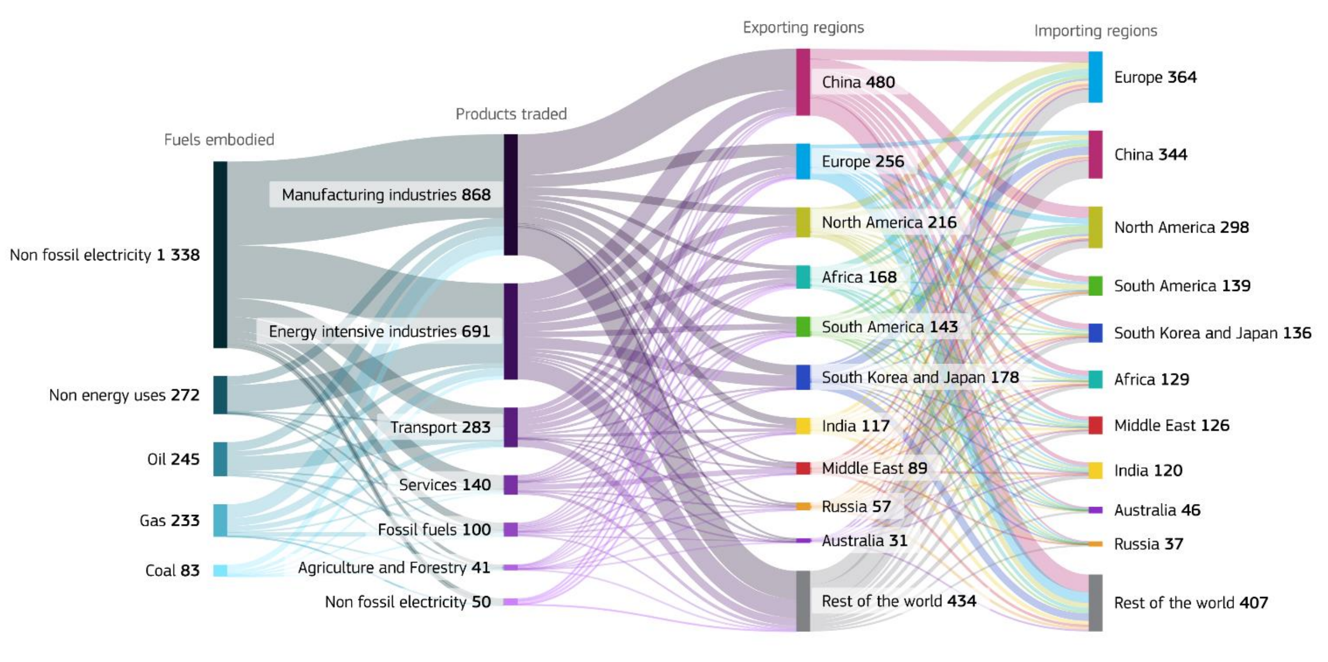

Figure 4 present the development of embodied energy by products in the 1.5°C Scenario in 2030 and 2050, respectively, outlining the strong decrease in fossil fuels and the simultaneous increase in low-carbon electricity embodied in trade.

Embodied coal in trade shows the strongest reduction among all fuels in a 1.5C scenario, reaching 83 Mtoe by 2050, a 90% reduction from 1076 Mtoe by 2015. Embodied oil and gas in trade decrease considerably, albeit remaining at a level of 245 Mtoe and 233 Mtoe, respectively, by 2050. In the 1.5 °C scenario, the embodied energy in traded goods largely consists of embodied zero carbon electricity, reflecting the shift towards renewable electricity in the global power sector and the electrification of end-use sectors, in particular manufacturing industries. We observe that the projected trade of energy embodied in goods and services decreases less than direct energy trade does, reflecting an expansion of the global economy and higher trade volumes in a decarbonizing world.

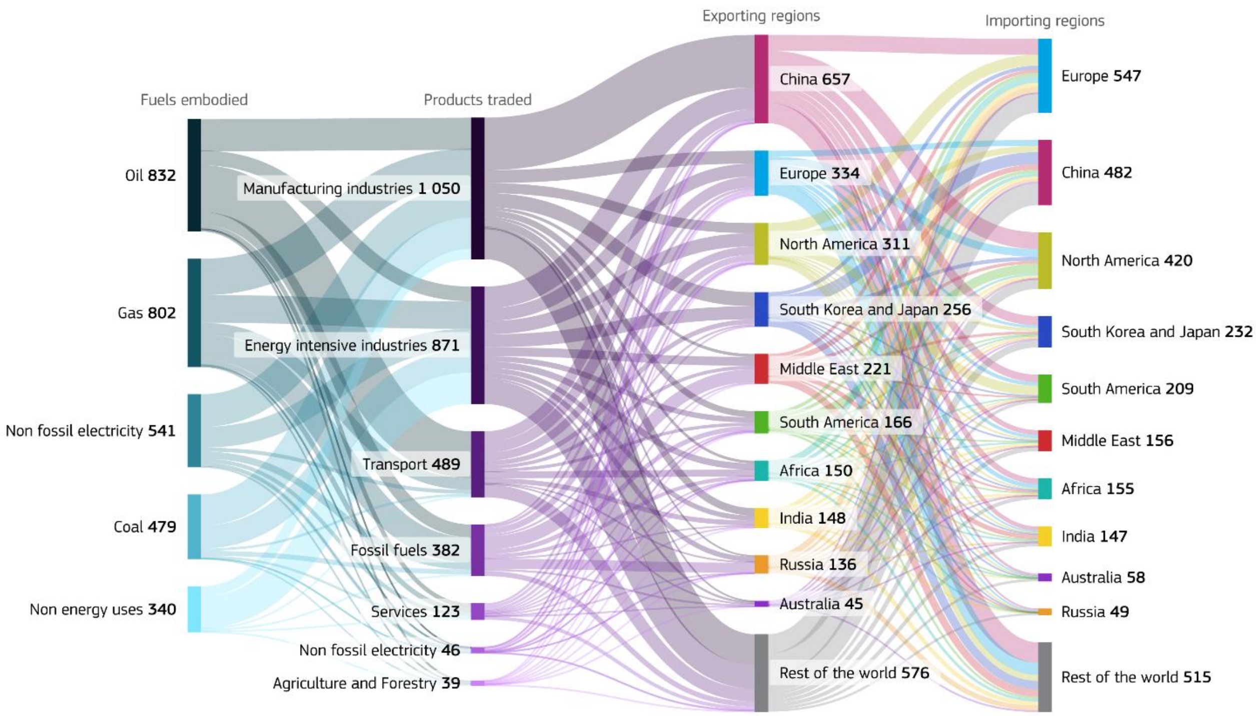

Figure 3. Global embodied energy trade in 2030 under the 1.5 °C scenario (in Mtoe).

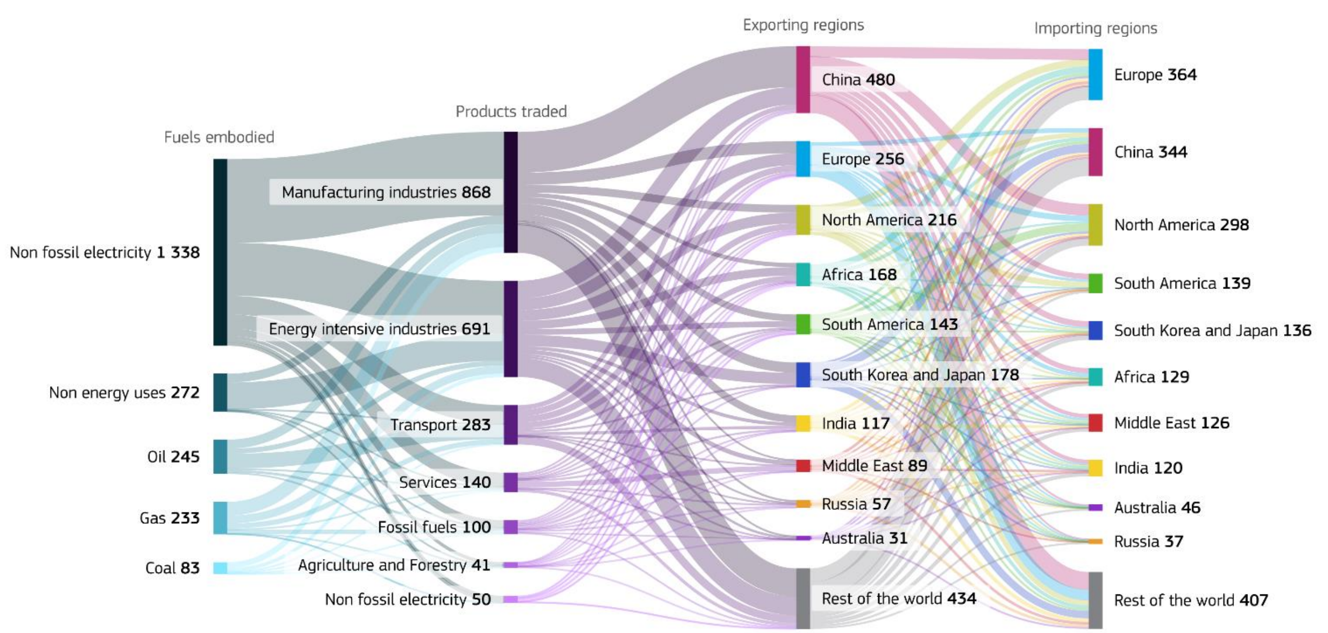

Figure 4. Global embodied energy trade in 2050 under the 1.5 °C scenario (in Mtoe).

When looking at the NDC-LTS, we find a similar pattern of decarbonisation of the embodied energy trade as in the 1.5C scenario. However, in the 1.5 °C scenario mitigation is driven by a least cost approach, hence happening at regions and sectors with the lowest marginal abatement costs, whereas the NDC-LTS scenario translates regionally differentiated policies that reflect announced targets, following countries' submissions to the UNFCCC. Therefore, by 2050, despite the larger share of non-fossil fuel based electricity, we still observe more persistence of embodied oil and gas trade, hence reflecting the fact that not all countries have announced net-zero targets by mid-century.

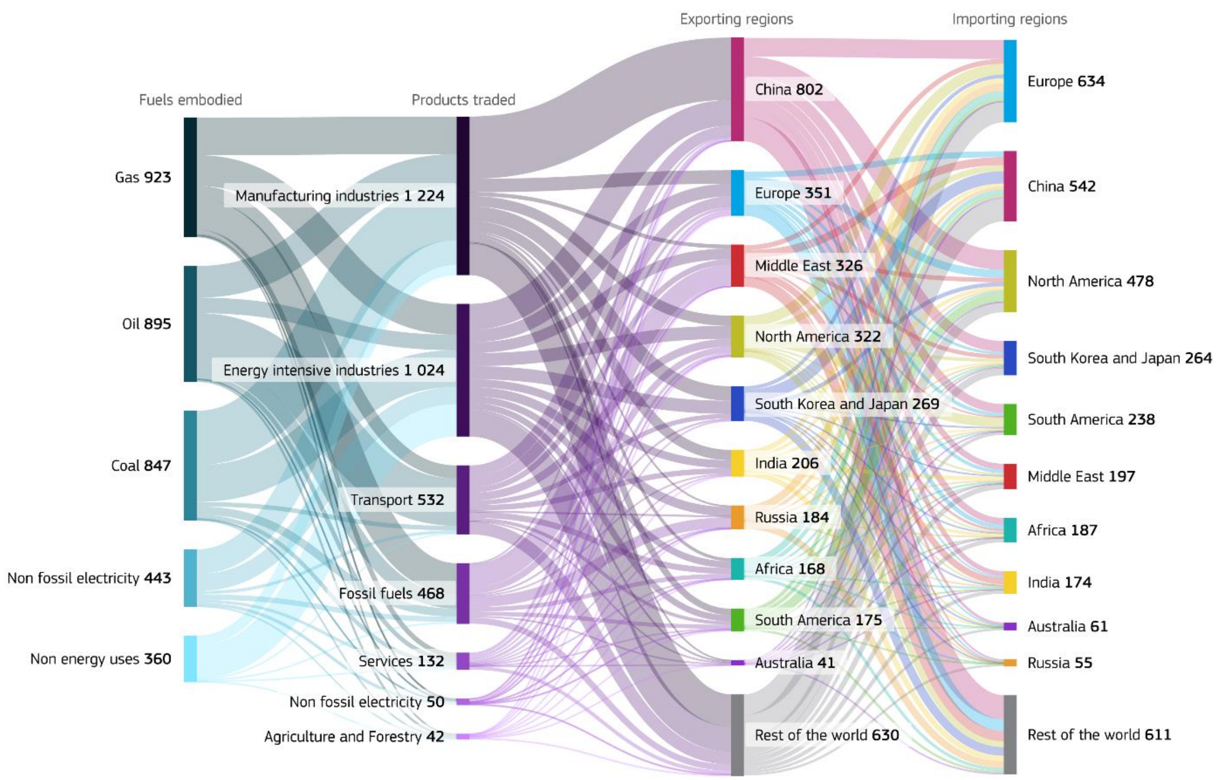

Figure 5. Global embodied energy trade in 2030 under the NDC-LTS scenario (in Mtoe).

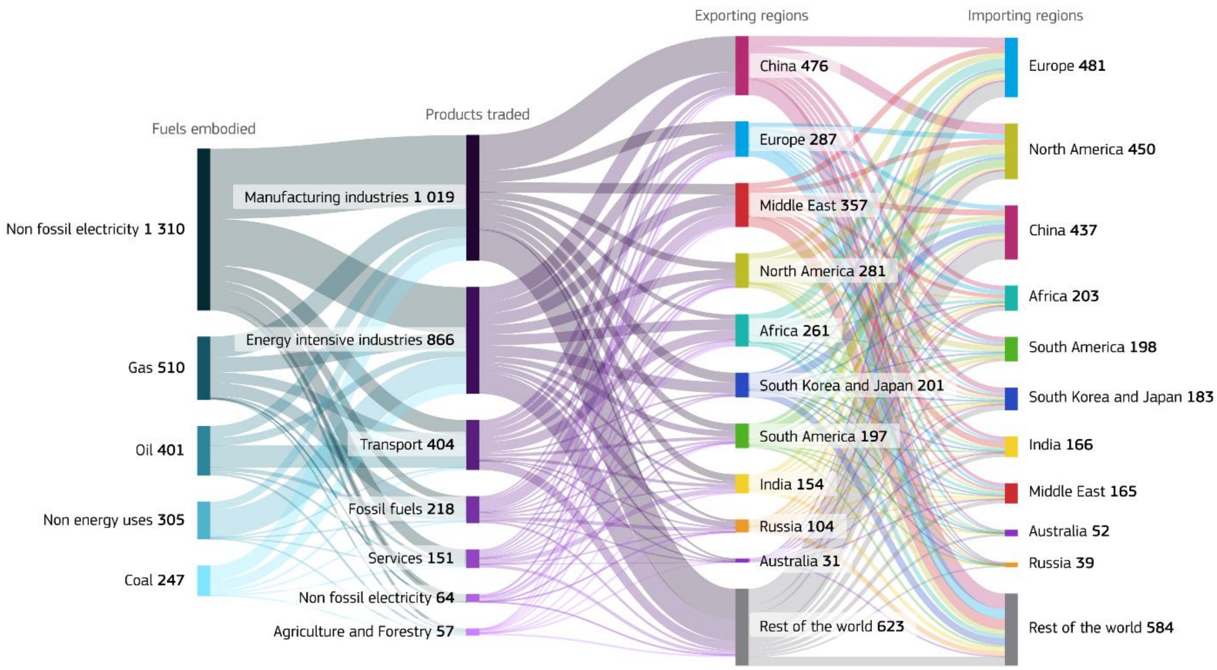

Figure 6. Global embodied energy trade in 2050 under the NDC-LTS scenario (in Mtoe).

The share of embodied non-fossil electricity in traded goods and services is projected to differ strongly across regions and scenarios overtime. Figure 7 illustrates the evolution of net embodied energy traded by fuel, region and scenario for the years 2015, 2030 and 2050. Under the NDC-LTS scenario by 2030 (Fig. 3a), we still observe China, India and oil exporters (Middle East and Russia) as main net exporters of fossil fuels embodied in their traded goods and services, reflecting the low ambition of the NDC targets in these regions. Likewise, by 2050, in the absence of an ambitious long-term target, Middle-East and other regions (other Asian countries, in particular) export more embodied fossil energy. Under the 1.5 °C scenario, while China is projected to become the largest net exporter of non-fossil electricity embodied in goods and services by 2050 (Fig. 3b), the USA becomes the largest net importer, with the EU projected to be a small net importer. Overall, other highly developed regions, such as Japan or South Korea, are expected to remain with comparatively smaller net imports and exports of embodied energy.

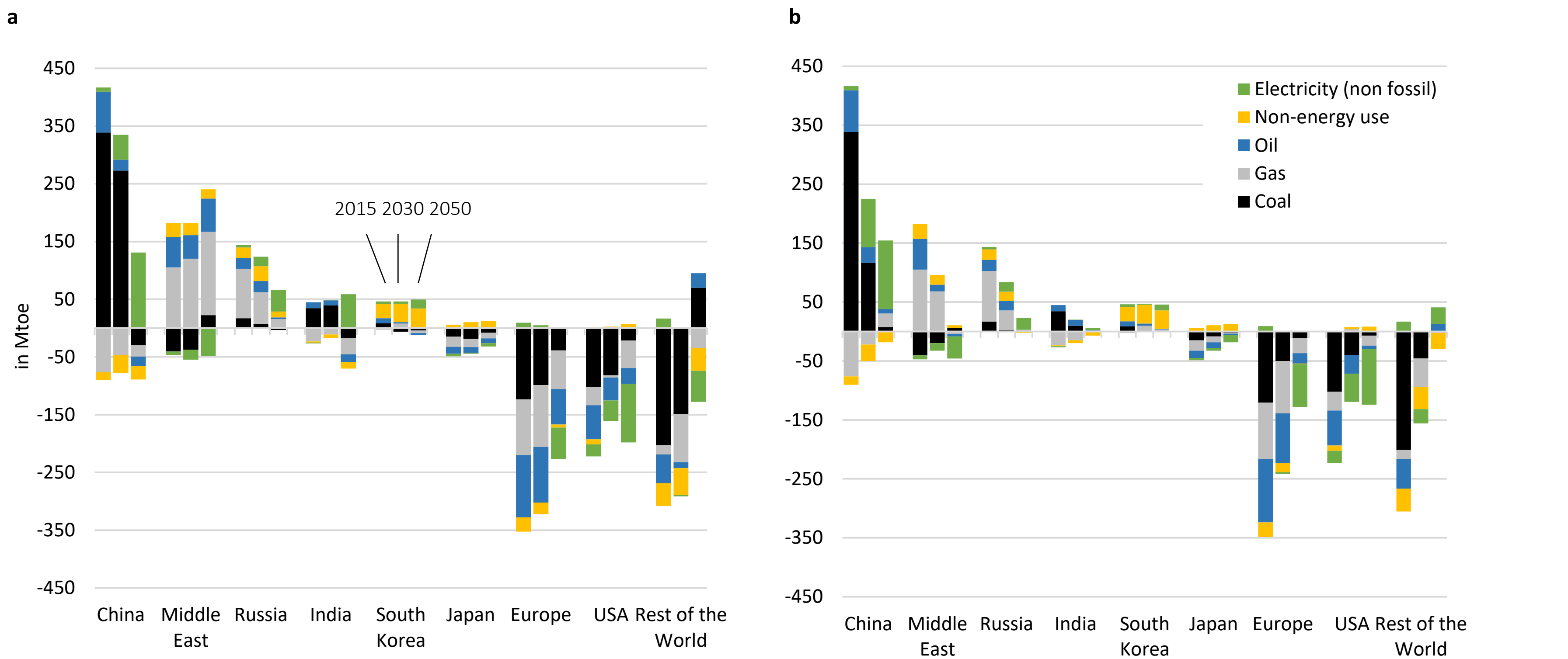

Figure 7. Net exports of embodied energy by fuel in the (a) NDC-LTS scenario and (b) 1.5 °C scenario. Selected countries and regions in 2015, 2030 and 2050. Values in Mtoe.

The development of embodied energy can be further disentangled in its underlying drivers, the development of trade over time, as well as the energy intensity of traded products. Figure 8 shows the average annual growth rate of energy embodied in exports for manufacturing industries energy intensive industries, and fossil fuels, which can be decomposed into the change in exports volumes and the change of the embodied energy intensity of exports. The figure indicates how these drivers are changing for different products in the 1.5°C Scenario.

In an expanding global economy, manufacturing industries and energy intensive industries are projected to experience a growth in exports over the projection horizon. In contrast, fossil fuel, in particular coal, are projected to experience a strong decrease in trade. As the world decarbonises, the energy intensity of products and services traded in a 1.5°C decarbonisation trajectory is projected to decrease across all product categories. The development of embodied energy in trade can be interpreted as the combination of the change in export composition and energy intensity of those exports. The stronger decline in the energy intensity of exports compensates the growing trade in an expanding economy. As a result, all goods and products considered are projected to experience a decline in the trade of embodied energy.

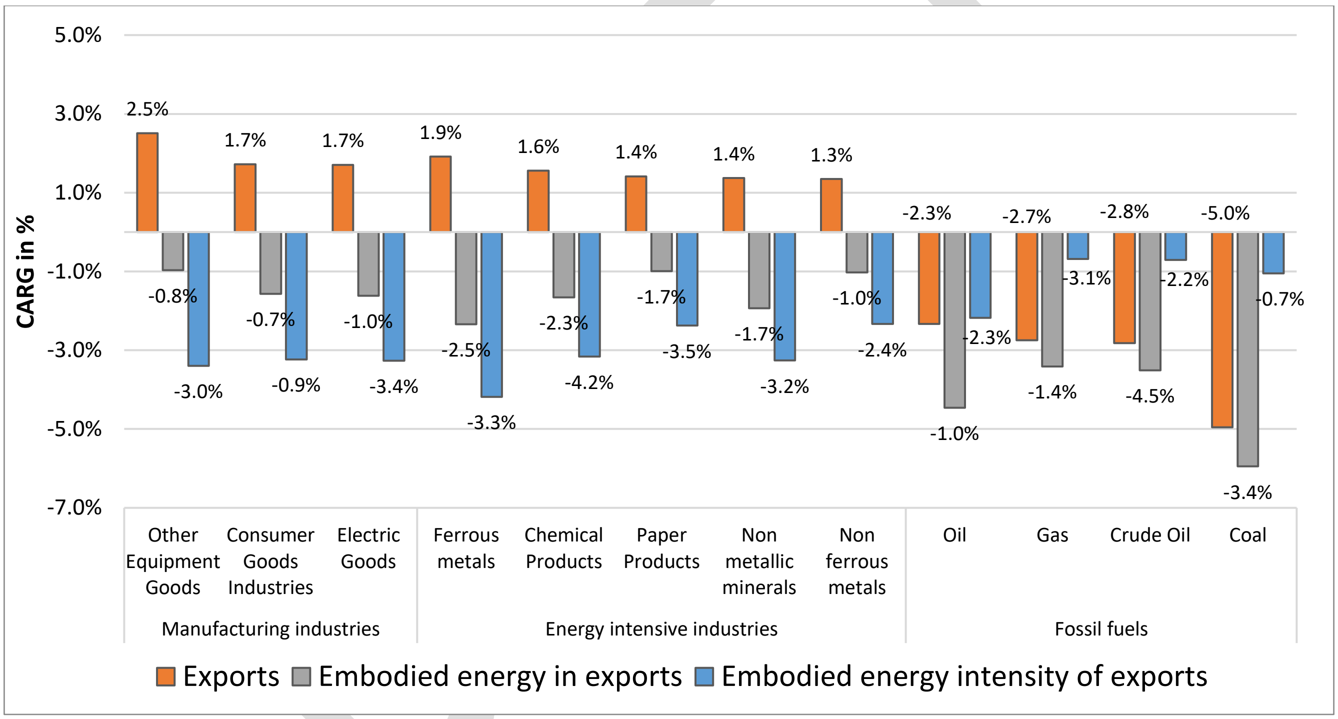

Figure 8: ***Compounded average annual growth rate (CARG) between 2020 and 2050 for energy embodied in exports, embodied energy intensity of exports, and export volumes for different products, 1.5°C Scenario***

We further assess the evolution of GHG emissions in the scenarios based on a production-based accounting (PBA), consumption-based accounting (CBA), and technology-adjusted consumption-based accounting (TCBA). PBA being commonly referred to as "territorial" emissions, while the difference between PBA and CBA reflects the balance of emissions embodied in trade (net embodied emissions). The TCBA accounts for differences in technology of export sectors to adjust the CBA metric (Kander et al., 2015). Figure 9 shows the evolution of GHG emissions according to these three metrics for the largest emitters globally (China, USA, EU and India) over 2015-2050 in the 1.5C scenario. As for 2020, the EU and the USA are net importers of CO_2 emissions, and correspondingly show higher emissions under a CBA than a PBA assignment. China and India show an inverse pattern, being net exporters of emissions.

As decarbonisation advances, the gap between production-based and consumption-based emissions (both in CBA and TCBA) is reduced. This trend is observed both for net importing and net exporting regions (EU and USA, India and China, respectively), reflecting the decarbonisation of producing sectors and the increasing share of non-fossil electricity embodied in goods and services (as show in Figure 7). Overall, a decarbonisation of the global economy towards mid-century requires all countries and regions to reduce emissions at a rapid pace. While both consumption and production-based emissions in the EU and USA have been declining at least since 2015, emissions in China decline prior to 2025 and in India prior to 2030 decade in the 1.5 °C scenario.

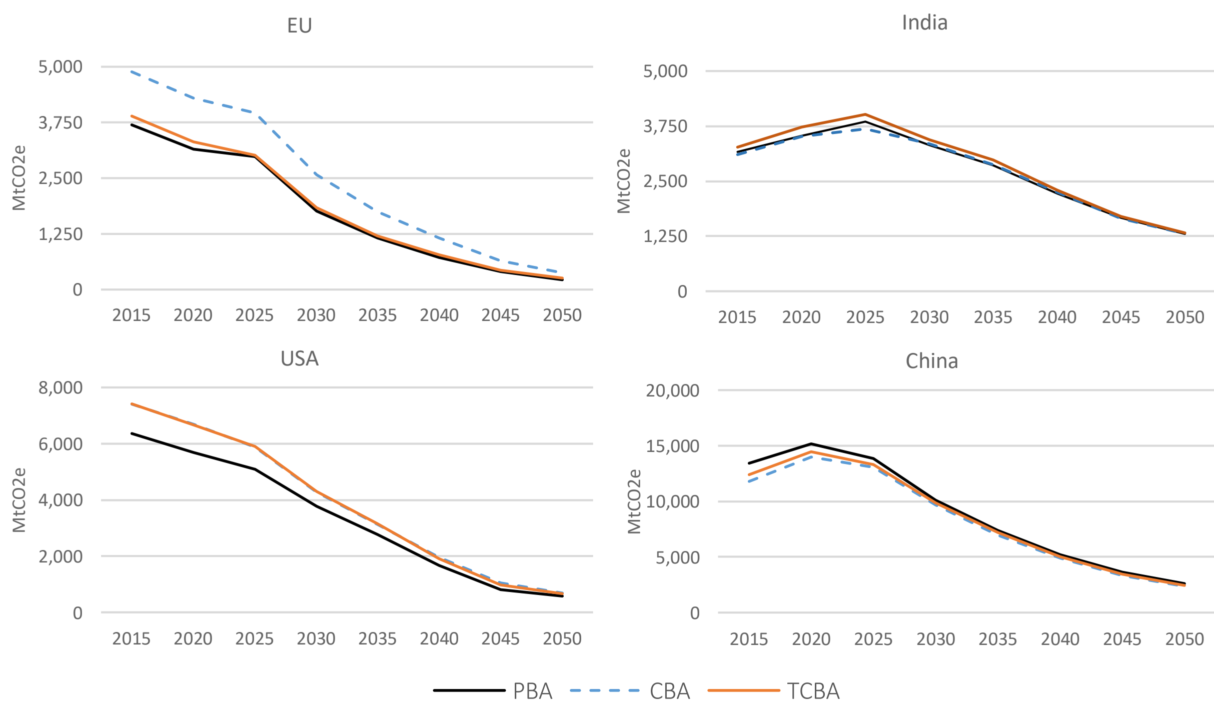

Figure 9. GHG emissions assigned to major emitters by production (PBA), consumption (CBA) and technology-adjusted consumption (TCBA) accounting over 2015-2050 under the 1.5 °C scenario

4. Conclusion

As decarbonisation advances at different speeds, energy and emissions embodied in trade of goods or services, considering their entire value chain, will become a relevant element for the climate policy debate. In this paper, we assess how direct and embodied energy trade might evolve under a decarbonisation pathway, and the evolution of GHG emissions embodied in international trade. While the direct trade of fossil energy carriers is projected to decline in a decarbonizing world, the trade of goods and services will expand in a growing globalized world economy. Energy embodied in traded goods and services will shift from mainly embodied oil, coal and gas to date, to embodied low carbon electricity. At the same time, GHG emissions embodied in goods and services will decline, while the gap between production and consumption based accounting metrics is projected to decrease. Overall, our results contribute to the growing literature on how trade and globalization might develop in a decarbonizing global economy. Our results illustrate that the trade of goods and products can persist in an expanding and decarbonizing global economy.

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