POLITECNICO DI TORINO

Corso di Laurea Magistrale in
Ingegneria Energetica e Nucleare

National energy and carbon footprints
An environmentally extended input-output approach

Relatore:
Prof. Lanzini Andrea

Candidata:
Perrella Angela

Correlatori:
Dott. Minuto Francesco Demetrio
Prof. Ravetti Chiara

a.a. 2020/2021
Luglio 2021

Table of Contents

1. Abstract

In the past decades, high-income countries have started to offshore energy-intensive manufacturing chains, focusing on activities with high value added. Meanwhile, the rapid acceleration of the industrialization process in states like China, India and Brazil allowed these emerging economies to win a large share of the global market by the means of an intensive and unprecedented manufacturing production. International supply chains caused the displacement of entire industrial sectors towards lower-income countries, and thus environmental and social impacts relocated as well. Energy use and emissions associated with each productive step are strictly related to the technology and energy mix of the country where it takes place: the industry sector in low-income nations tends to be less environmentally regulated, and this may result in a rise of global impacts. In this scenario, the energy use of a country estimated within its borders only cannot be considered an exhaustive indicator, as countries may be improving their environmental performance by importing energy-intensive goods from abroad. Although not physically exchanged, energy use, together with carbon emissions, can be considered embodied in global trade. Environmentally extended global multi-regional input-output analysis is the method used to account for international trade-related impacts from a consumption perspective. This technique allows to track energy use and CO_2 emissions of global supply chains and allocate them to final consumers. This approach is known as consumption-based accounting or footprinting. This analysis involved 43 countries and an aggregate representing the rest of the world, over the period 2000-2014. Energy and carbon footprints showed that the traditional production-based perspective underestimates the energy use and carbon emissions that can be attributed to most of the high-income countries while developing economies turned out to be more virtuous. On average, the energy embodied in international trade corresponds to ~1/3 of the energy footprint of a country and even more for carbon emissions. Around 22% of global energy use and carbon emissions are embodied in international trade. The main embodied energy and carbon flows between countries are made explicit, revealing a complex network of trade-related impact displacement.

2. Introduction

Globalization produced an important growth in economic activities and led to complex supply chains extended in several countries. International trade introduced a new level of complexity challenging the classical understanding of the development and environmental impact relationships. While the initial stages of economic growth involve a significant rise in energy consumption, a decline in energy intensity is typical of mature economies. However, high-income countries may be improving their environmental performance by importing energy-intensive goods from abroad, resulting in a lower energy use attribution. Also, relocating production towards nations with laxer climate policies might cause a global rise in carbon emissions and environmental impacts.

To address this issue, the approach proposed by researchers is consumption-based accounting, or "footprinting". It changes the perspective from energy used by the economic activities located in a country (which includes energy spent on the production of exports) to energy related to consumption of goods and services happening within the borders of a country (which includes energy associated with the production of imports but excludes exports). Basically, the difference stands in the allocation principle of embodied energy imports and exports. Environmentally extended global multi-regional input-output analysis is the tool used to account for international trade-related impacts from a consumption point of view.

The introduction section of this thesis work offers an overview of the context in which the analysis develops. It opens with a description of the relationship between energy use and economic growth, followed by a summary of the historical development of globalization and then by the investigation of international trade-related impacts. A literature overview about consumption-based accounting and environmentally extended input-output analysis closes the first chapter.

The second part introduces the fundamental aspects of the input-output framework and its extensions, describing the structure of the input-output tables and the mathematical background. The main characteristics of the chosen dataset and environmental accounts are summarized.

The succeeding section diffusely describes the results obtained for 43 countries and an aggregate representing the rest of the world for the period 2000-2014. The outcome of the analysis consists of the energy and carbon footprints of the represented set of nations, as well as the flows of carbon and energy embodied in international trade linking them. Those findings are detailed and then discussed in a dedicated chapter. Finally, the last section illustrates the concluding remarks and outlines possible developments.

2.1. Energy and economic growth

The relationship between economic growth and energy consumption has received the attention of several ecological economists. As expected, energy use and gross domestic product (GDP) are positively correlated [1], [2]. In pre-industrial societies, scarce energy consumption was accompanied by a stationary behavior or slow growth of their economies [3]. Industrialization was made possible by the unprecedented availability of energy due to the exploitation of fossil fuels and produced extraordinary rates of economic growth. However, a distinguishing feature of high-income economies is a decline in energy intensity (which is energy per unit of GDP) with the respect to previous phases of their development [3]. In other words, while "becoming rich" involves an important rise in energy use, for already affluent countries energy consumption rises slower than GDP. The decrease in energy intensity in high-income countries is often referred to as "decoupling" [1], [4].

Jess [5] analyzes the relationship between energy consumption per capita and GNPpc (gross national product per capita) for 33 countries. He finds economic growth is proportional to energy consumption up to a GNP of around $15,000 per capita, then countries split into two different trajectories. While the world average follows more or less the original behavior, some high-income nations deviate from this linear relationship and, thanks to their increased energy efficiency, show high values of GNPpc at a lower level of energy consumption. Mazur [6] studies the correlation between primary energy consumption per capita and GDPpc for 21 industrialized nations during the period 1980-2006. His study revealed a weak correlation of the two variables, disproving the traditional idea that GDP increase is driven by rising energy consumption: per capita changes of the two quantities can be considered independent over time. As for carbon emissions, Pretty claims that "GDP closely predicts CO_2 emissions by country" [7]. Differences between nations are explained by the author as a span of efficiencies: "carbon inefficient" states like Australia, Canada and the USA emit more CO_2 per unit of GDP than the average, and *vice versa* a group of countries including Norway, Sweden and Switzerland result "carbon efficient". The average trend is a linear relationship between the two variables, where a slope equal to zero would show an absolute decoupling of GDP and carbon emissions. Jackson

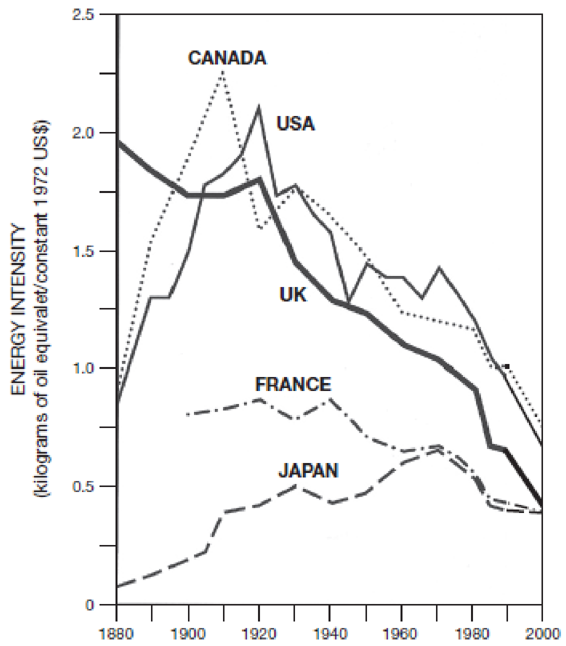


Figure 1: Energy intensity of the GDP declines for maturing economies (Source:[3])

et al. [8] found that in 2018, despite the reoccurrence of growing emissions,19 countries (mostly European and the USA, contributing around 20% of global CO_2 emissions), considerably lowered carbon emissions over the past ten years without a decline in GDP.

The Environmental Kuznets Curve (EKC) is a hypothesis advanced in 1991 by Grossman and Krueger [9] that gave rise to a lot of interest and research, although it was demonstrated by solid evidence only for few environmental indicators [7]. Named after Simon Kuznets, who studied the relationship between inequality and economic development, the idea is that an inverted U-shaped relationship exists between economic growth (per capita income) and environmental impacts. Therefore, as the economic development of the country proceeds, the environmental degradation is expected to rise until it reaches a peak and then finally decreases. While the initial rising of the curve is quite expected, the decreasing trend is usually explained considering factors like efficiency measures, technological change and a cleaner energy mix. Economic development of countries results in an observable shift towards “higher quality” fuels and this is phenomenon is defined as ascending the “energy ladder” [10]. Low-income nations are strongly dependent on biomass to satisfy their energy demand but, as they develop, they start to substitute most of it with fossil fuels or hydroelectric power. When reaching high-income levels, countries reduce their reliance on oil and coal and switch to energy sources like natural gas, renewables and nuclear power, lowering their carbon intensity. However, this last step is less likely to be climbed by nations hosting large fossil fuel reservoirs [10].

Research on EKC gave mixed results and but this hypothesis cannot be considered applying to energy and CO_2 emissions, especially with the beginning of the XXI century [11]. In fact, one of the main criticism against the idea of environmental impacts and resource use decreasing at high levels of economic performances is that the existence of this relationship may be a consequence of international trade and the resulting displacement of environmental impacts in low-income countries [3], [12].

2.2. Impacts of international trade

According to Baldwin, globalization can be described as the sequence of "two great unbundlings" [13]. The first one started during the nineteenth century with the first Industrial Revolution and consists of the separation of producers and consumers. Before then, people's consumption of goods was sustained only by production in close proximity. The invention of steam engines made the costs of transportation fall and thus industries clustered to exploit the economies of scale and the advantages of the agglomeration, accelerating the urbanization process. Industrialization started in Europe and initially spread to few other nations including the United States, Canada, Japan and Australia. International trade prospered among those countries, creating a virtuous cycle of innovations, growth and wealth. During the 19^{th} century, the economies of industrializing nations grew by 20-60% in ten years: the British economy's output in 1900 was around 10 times larger than 100 years before and the GDP of the USA doubled between 1880 and 1900 [3]. On the other hand, this North Atlantic cluster triggered a process of de-industrialization in the rest of the world and Asia and the Middle East, once the core of the global economy, became the periphery. Those areas started to grow later and slowlier than the advanced nations. The result of this first unbundling is the unveiling of a new global economic panorama defined by high and low-income countries, or rather by the divergence between the "global North and South" in terms of per-person incomes and well-being standards. Except for World War I and II, this trend proceeded uninterrupted until the 1980s.

The second unbundling is the split of production itself into several stages or tasks and was made possible by the ICT revolution. Communications costs fell, making it feasible to geographically separate complex manufacturing processes into basic activities and coordinate them remotely: factories changed from making finite products to making parts of them. In addition, the international wages divergence made it convenient to offshore part of these production stages, and thus global value chains were born. Internet was the steam power of the second unbundling, lowering the costs of "transporting" ideas, and allowed spreading those innovations and technical know-how that were once an exclusive prerogative of the higher-income countries. This results in strong industrialization of the lower-income countries and contemporary de-industrialization of the "North of the world". International trade saw the revolution of its previous patterns and grew by 7.5% on average per year during the period 1980-2011 [4].

High-income countries started to offshore energy-intensive manufacturing chains, focusing on activities with high value added [14], [15]. Meanwhile, the rapid acceleration of the industrialization process in states like China, India and Brazil allowed these emerging economies to conquer a significant share of the global market by the means of an intensive and unprecedented manufacturing production. Thus, the role of these once "marginal" powers had become increasingly central on the chessboard of the world economic power [15]. In 2016, exports correspond to up 29% on average of the gross domestic product of a country [16]. International supply chains caused the displacement of entire industrial sectors towards lower-income countries, resulting in a decreased share of environmental effects attributed to advanced nations. Energy use and emissions related to each productive step are also strictly related to technology and energy mix of the country where it takes place: the industry sector in lower-income countries "tends to be more ecologically intensive and less socially regulated" [16] and this may result in a global rise of environmental impacts.

The recent phase of globalization introduced an unprecedented level of complexity and unpredictability [16], [17]. A related and highly debated topic about the effect on the environment of international trade is the so-called "Pollution Haven Hypothesis" (PHH) [18]. It predicts that free international trade will produce the relocation of environmentally intensive productions from high to low-income nations due to the greater stringency of advanced countries' environmental regulations [19]. In other words, polluting industries will move to "pollution havens", meaning countries presenting laxer environmental standards. An associated phenomenon is "carbon leakage". It occurs when a country reduces its greenhouse gases (GHG) emissions by offshoring part of its domestic production towards nations with laxer emission regulations and increases imports from them [20]. The phenomenon of carbon leakage is further clarified by introducing a “strong” and “weak” division. Strong carbon leakage is the emissions displacement induced by the national climate regulations, while the overall net GHG transfer, not necessarily policy-related, is referred to as weak carbon leakage or “demand-driven displacement” [21], [22].

Evidence shows minimal effects of environmental policies on industrial production and trade patterns [21], [22]. Nevertheless, it can be said that international trade expansion affected the geography of environmental impacts and resource use. Consider the impacts associated with the production of a car purchased by a consumer in Italy. Raw materials may be mined in Australia, treated in China and then used by a Japanese car manufacturer whose exports are destined to Italy. Environmental and social impacts linked to a production taking place outside of the Italian borders are relocated as well, away from the site of consumption. But those impacts happening in Australia, China and Japan can be considered “embodied in” the purchase of the Italian consumer. Although not physically exchanged, energy use, together with carbon emissions, water and local jobs may be considered embodied in global trade [16]. According to Peters and Hertwhich, emissions embodied are “all the emissions required to produce the product. This includes all steps in production from raw material extraction through to final assembly and ultimately the final sale of the product” [20]. The definition can be adapted and extended to energy and other environmental impacts.

2.3. From production to consumption-based accounting

In the contemporary globalized scenario, the energy use of a country identified with the consumption happening within its borders cannot be considered an exhaustive indicator: according to Wiedmann and Lenzen [16], about 20-33% of global CO_2 emissions and 29-35% of global energy use are embodied in international trade. To address this issue, the alternative approach proposed by researchers is the Consumption Base Accounting (CBA), or “footprinting” [4], [14], [16], [23], [24]. Consumption-based accounting offers many advantages but requires complex calculations, which introduces uncertainty and the need for some simplifying assumptions [20], [25]. However, it is a powerful tool to extend political decisions outside of the single country in a way that is consistent with its level of consumption, increasing mitigation options.

The standard perspective measuring energy consumption within the territorial boundaries of the state is usually referred to as Production Base Accounting (PBA). It stands for energy spent on domestic production including exports, while it excludes consumption related to imported goods. On the other hand, consumption-based inventories deduct exports but account for imports [4], [23]. Therefore, the CB perspective captures the energy use linked to the consumption of goods and services taking place inside the borders of a nation, reflecting the total and global energy requirements to satisfy the final demand of the country [4], [15], [23]. In a globalized production system, imports may be transferred through various countries before they are allocated to final consumers. The first step to build consumption-based inventories is usually referred to as the National Accounting Matrix with Environmental Accounts (NAMEA). It involves the conversion of technology-based inventories to production-based accounts that are consistent with the System of National Accounts (SNA) [23]. Next, Environmentally Extended Input-Output Analysis (EEIOA) is used to transform production-based accounts into consumption-based inventories.

Environmentally extended global multi-regional input-output (EE GMRIO) analysis has long been recognized as a solid and relevant methodology to account for international trade-related impacts from a consumption standpoint [25]–[29]. This technique allows to track emissions and resource use of global production and supply chains and then attributes them to final consumers. Environmentally extended input-output approaches have been widely applied to evaluate energy [29], [30], land [31] and water use [32], as well as the production of pollutant emissions [33], [34] , carbon dioxide [21], [35], or employment [36] and biodiversity footprints [37].

Input-output analysis is the analytical framework developed by Wassily Leontief in the late 1930s, which earned him the Nobel Prize in Economic Science [27]. During the 1970s, Leontief himself foresaw the application of this tool to investigate the relationship between the economy and the environmental and social sphere [26], [38]; in fact, the basic framework was extended by several researchers and environmental input-output analyses saw a rise with energy applications since the 1970s oil crisis [16]. Afterward, the input-output approach has been adopted for environmental footprinting and life-cycle assessments and became part of the European System of Accounts framework.

Footprint accounting through EE GMRIO has been extensively adopted to track the consumption of resources and the impacts on the environment connected with the consumption of a country [4], [14], [16], [39], [40]. At first, consumption-based approaches were mostly employed for Carbon Footprinting [14] and to estimate emissions embedded in trade, in the attempt to address the problem of carbon leakage and widen the possibilities of climate policies [20], [22], [23]. According to Arto et al. [15], studies estimating the Energy Footprint of countries at a global level are far less common and part of the reason is the scarce availability of adequate energy datasets [15], [40]. In their review, Wiedmann and Lenzen [16] describe the advancement in GMRIO analyses made in recent years and suggest the extension of the use of consumption-based indicators to track progress on the United Nation's Sustainable Development Goals (only material footprints are used as indicators for SDGs 8 and 12). They also state the adoption of CBA confirms that, except for land use, there is no decoupling between environmental impacts and economic growth. Akizu-Gardoki et al. [39] make use of the five main GMRIO databases to assess, for the year 2011, a Hidden Energy Flow indicator of 44 countries, concluding that the energy embodied in goods and services purchased by households is higher than direct consumption in households. They define this result as the "iceberg phenomenon" and remark the importance of including embodied energy flows as targets of the future energy policies towards sustainability.

Lan et al. [30] calculate the energy footprint of 186 nations for the period 1990-2010 and applied structural decomposition analysis to identify the drivers of footprint change in time. According to their results, affluence is the most relevant driver of footprint growth for almost all the countries and the spatial distance between the production and consumption of energy increases with per capita Gross Domestic Product. Kulionis and Wood [4] use structural decomposition analysis to study and compare the energy footprints' trend of the United States of America, United Kingdom, Denmark and France during the period 1970-2009. The main drivers of change result to be a decrease in energy intensity and a counteracting increase in consumption per capita. Energy efficiency improvements have played a main role in reducing footprints in high-income countries, but then became less relevant; on the other hand, efficiency enhancements in their lower-income trade partners are becoming increasingly significant. Moreau and Vuille [1] combine input-output and decomposition analysis to study the case of Switzerland, where embodied energy rose from 45% to 81% of the total energy use of the economic activities between 2001 and 2011. By introducing CBA, they demonstrate that the decoupling between economic growth and total energy use reported by official statistics is just "virtual". Arto et al. [15] compare production-based and consumption-based approaches to estimate the energy requirements to reach high values of human development. They conclude that the first method underestimates the energy needed since it neglects energy embodied in trade. Akizu-Gardoki et al. [14] calculate a Decoupling Index built on Total Primary Energy Footprint for 126 countries over the years 2000-2014 and demonstrate that previous studies based on PBA overestimated decoupling between energy and human development. Their successive research [12] introduces the idea of a Well-being Turning Point, a high-energy threshold after which the correlation between energy consumption and the Human Development Index is negative.

Despite being a powerful tool, the weak points and uncertainties related to EE GMRIO have long been objects of inquiry. Wiedmann et al. [28] offer an overview of its main strengths and weaknesses. An important shortcoming for some analyses is related to how detailed is the sectoral distinction of the model. Results may differ depending on the level of industry aggregation [27], so larger uncertainties are involved when the footprints are calculated from highly aggregated tables. To address the problem of mismatch between the level of detail of the monetary input-output table and satellite accounts, Lenzen [41] demonstrates that disaggregation, even if based on very small information, is a better solution than aggregating environmental accounts. Another limitation is the inadequate availability (in time and spatial extension) of global multi-regional input-output tables and harmonized physical accounts due to the significant effort required to create and update them. Also, there is no standardized procedure as regards the choice or construction of the environmental accounts. Owen et al. [40] calculate energy consumption-based accounts for the United Kingdom, comparing the results obtained by using two different energy extensions and analyzing the uncertainties associated with the construction of the two energy vectors. Wieland et al. [42] widened the aforementioned research, estimating the energy footprint of Austria by applying both Single-Region and Global Multi-Region IOA and making a comparison of the results achieved by adopting different energy extension vectors (supply and use energy datasets).

Input-Output approaches are often combined with other methods as the first step of more complex analyses. In their study, Chen and Li [29] apply a global embodied energy flow network analysis based on EE IOA and discuss their results in the framework of energy security policies. They find that inflows and outflows of embodied energy for five countries represent, respectively, 43.7% and 45.4% of total through-flow and policies targeting them may improve all the network. Chen and Wu [38] apply Systems IOA, which also captures energy use flows caused by intermediate production of industries, and find that the energy use embodied in global trade is up to 90% of the total energy resources and that about one third of global exploited energy is embodied in inter-regional net trades.

3. Materials and methods

3.1. Input-Output Tables

A basic input-output model is built from observed economic data for a definite geographic area (nation, county, continent, etc.) in a specific period (generally a year).

The economic activity in the region is to be split into producing sectors or industries (the words *industry* and *sector* can be considered interchangeably in this context), whose number may vary from a few to hundreds according to the available level of detail. The fundamental data are the flows of products (goods or services) from each industrial sector, considered as a producer, to all sectors, including itself, seen as purchasers. The information concerning all these transactions, or intersectoral flows, is contained in an interindustry transactions table, which can be, in principle, constructed in physical or monetary units. A physical measure of the transactions is a better image of an industry's use of the purchases made from the other sectors, being those flows actually exchanges of physical goods, but robust data availability is scarce, while instead accounts are regularly compiled in monetary terms by the national statistical offices [43], [44].

		Buying Sector					Final Demand	Total Output
		1	⋯	*j*	⋯	*n*		
Selling Sector	*1*	z_{11}	⋯	z_{1j}	⋯	z_{1n}	y_1	x_1
	⋮	⋮		⋮		⋮	⋮	⋮
	i	z_{i1}	⋯	z_{ij}	⋯	z_{in}	y_i	x_i
	⋮	⋮		⋮		⋮	⋮	⋮
	n	z_{n1}	⋯	z_{nj}	⋯	z_{nn}	y_n	x_n
Value Added		va_1	⋯	va_j	⋯	va_n		
Total Input		x_1	⋯	x_j	⋯	x_n		

Table 1: Input-Output Table

Input-output tables collect these and further information about the sale and purchase relationships between the actors in the economy, including both intersectoral relations and final demand. All the sectors are listed on the left side of the table as producers and across the top as purchasers: in this way, each industry is recorded twice. The columns describe each sector's purchases, or *inputs*, coming from all industries (including itself) to produce its output. From the row perspective, the figures represent each sector's *outputs*, which are the sales made by the industry to all sectors, again including itself. *Inter*industry inputs are comprehensive of *intra*industry transactions, meaning sectors purchasing their own output as an input to production. The demand from purchasers external or *exogenous* to the industrial sectors buying finished products (not to be used as further inputs to industrial processes) is referred to as final demand. This generally consists of different additional columns including, for example, demands from households, government, NGOs, changes in inventories and capital formation (it can be considered as inputs into a future production). The last column is the total output of each sector, which is the sum of its intermediate and final demand. The rows labeled value added, account for the other inputs, such as labor, interests, taxes, and depreciation of capital. Finally, in a balanced table, total inputs in each sector equal total outputs.

The main core of the model is the yearly interindustry flows of products, or intermediate demand, in monetary values. The generic transaction from sector i (producer) to sector j (consumer) is denoted by z_{ij}. Consider an economy that can be divided into n industries or sectors. The total output of each sector i (x_i) is the sum of its intermediate and final demand, designated as y_i (Eq. 1).

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \qquad (1)$$

z_{ij} is the interindustry or intermediate sale by sector i to all sectors j including itself (when j=i). Equations like the previous one can be written for the output of each of the n sectors. It is possible to synthesize them by adopting matrix notation (Eq. 2).

$$\mathbf{x} = \mathbf{Zi} + \mathbf{y} \qquad (2)$$

where

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \quad \mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}$$

and **i** is a column vector of dimension *n* whose elements are all equal to one, called "summation" vector: its multiplication by a matrix results in a column vector whose entries are the row sums of the original matrix.

In an input-output table, total inputs in each sector equal total outputs and this balance is expressed in Eq. 3.

$$z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + y_i = z_{1i} + \cdots + z_{ji} + \cdots + z_{ni} + va_i = x_i \tag{3}$$

A fundamental assumption in the input-output analysis is that intermediate sales from sector *i* to *j* in a given period, usually a year, are related to the overall amount of goods, or total output, produced by sector *j* over the same time. The same reasoning does not apply to final purchasers, since the amount of external demand is usually affected by reasons not connected to the amount produced. However, this basic assumption is expressed by Eq. 4.

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{4}$$

The ratio a_{ij} is a technical coefficient, which is assumed to be constant during the considered period. It expresses the relation between a sector's input and its own output, measuring the amount of inter-industry inputs needed to create one unit of output. The limit of the approach is that economies of scale and learning economies are overlooked [27].

The same operation can be performed for all the elements of the interindustry matrix **Z**, obtaining the matrix of the technical coefficients **A**, or matrix of direct intermediate input requirements. The calculation in matrix notation reads as Eq. 5.

$$\mathbf{A} = \mathbf{Z}\,\hat{\mathbf{x}}^{-1} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

The hat over the vector $\mathbf{x}$ denotes a diagonal matrix with elements of the original vector along the main diagonal. From Eqs. 2 and 5:

$$\mathbf{x} = \mathbf{A}\,\mathbf{x} + \mathbf{y} \tag{6}$$

$$\mathbf{y} = \mathbf{x} - \mathbf{A}\,\mathbf{x} \tag{7}$$

$$\mathbf{y} = \mathbf{x}(\mathbf{I} - \mathbf{A}) \tag{8}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{9}$$

$\mathbf{I}$ is the identity matrix and $\mathbf{L}=(\mathbf{I}-\mathbf{A})^{-1}$ is the *Leontief inverse* or the matrix of the total requirements.

The elements in the Leontief inverse show the inputs required, both directly and indirectly, to generate one unit of final demand. It can be calculated as an inverse or through a procedure called "power series approximation", which gives a picture of the calculation needed to account for the total requirements without this powerful tool.

$$\boldsymbol{L} = (\mathbf{I} - \mathbf{A})^{-1} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots) \tag{10}$$

$$\mathbf{x} = \mathbf{L}\,\mathbf{y} = \mathbf{y} + \mathbf{A}\mathbf{y} + \mathbf{A}^2\mathbf{y} + \mathbf{A}^3\mathbf{y} + \cdots \tag{11}$$

The demands of direct inputs create the necessity for further indirect inputs from the industrial sectors, as shown in the table. This process ideally keeps moving backward for an infinite number of stages to include the complete supply chain. Each term of the power series represents a stage of the production, but the majority of the effects linked to a certain final consumption can be estimated by using the first few terms.

Leontief inverse is an alternative to this approximation via reiteration allowing to easily investigate the indirect requirements related to a variation in final demand. Its elements capture the overall chain of direct and indirect effects.

3.2. Multi-Regional Input-Output Analysis

Multi-regional input-output (MRIO) models require a simple extension of the analysis previously described, in an attempt to capture the technological differences between regions within a country or even between nations [25], [27].

Consider k regions or countries, denoted by r and s, and n industries per region, denoted by i and j. The transaction matrix **Z** now consists of k^2 sub-matrixes. The sub-matrixes on the diagonal describe the transactions within a region, while the others capture international supply chains.

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{11} & \cdots & \mathbf{Z}^{1s} & \cdots & \mathbf{Z}^{1k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{Z}^{r1} & \cdots & \mathbf{Z}^{rs} & \cdots & \mathbf{Z}^{rk} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{Z}^{k1} & \cdots & \mathbf{Z}^{ks} & \cdots & \mathbf{Z}^{kk} \end{bmatrix}$$

The generic $\mathbf{Z^{rs}}$ is an nxn matrix. The element $z_{ij}{}^{rs}$ represents a sale from the industry i of the region r to the sector j of the region s.

$$\mathbf{Z}^{rs} = \begin{bmatrix} z_{11}^{rs} & \cdots & z_{11}^{rs} & \cdots & z_{11}^{rs} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ z_{i1}^{rs} & \cdots & z_{ij}^{rs} & \cdots & z_{in}^{rs} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ z_{n1}^{rs} & \cdots & z_{nj}^{rs} & \cdots & z_{nn}^{rs} \end{bmatrix}$$

The matrix of technical coefficient **A** is calculated by Eq. 5 and shows the same structure of the interindustry transaction matrix **Z**.

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1s} & \cdots & \mathbf{A}^{1k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{A}^{r1} & \cdots & \mathbf{A}^{rs} & \cdots & \mathbf{A}^{rk} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{A}^{k1} & \cdots & \mathbf{A}^{ks} & \cdots & \mathbf{A}^{kk} \end{bmatrix}$$

The same reasoning applies to the Leontief inverse matrix.

$$\mathbf{L} = \begin{bmatrix} \mathbf{L}^{11} & \cdots & \mathbf{L}^{1s} & \cdots & \mathbf{L}^{1k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{L}^{r1} & \cdots & \mathbf{L}^{rs} & \cdots & \mathbf{L}^{rk} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{L}^{k1} & \cdots & \mathbf{L}^{ks} & \cdots & \mathbf{L}^{kk} \end{bmatrix}$$

The generic sub-matrix $\mathbf{L^{rs}}$ is an *nxn* matrix. The element l_{ij}^{rs} represents the requirements by industry *i* in country *r* to produce one unit of final demand for sector *j* from country *s*.

$$\mathbf{L}^{rs} = \begin{bmatrix} \mathrm{l}_{11}^{rs} & \cdots & \mathrm{l}_{11}^{rs} & \cdots & \mathrm{l}_{11}^{rs} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathrm{l}_{i1}^{rs} & \cdots & \mathrm{l}_{ij}^{rs} & \cdots & \mathrm{l}_{in}^{rs} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathrm{l}_{n1}^{rs} & \cdots & \mathrm{l}_{nj}^{rs} & \cdots & \mathrm{l}_{nn}^{rs} \end{bmatrix}$$

Each region's final demand is fulfilled by local production and imports. The final demand vector becomes a matrix having as many columns as regions. Each block is a vector of *n* elements as the number of sectors considered.

$$\mathbf{Y} = \begin{bmatrix} \mathbf{y}^{11} & \cdots & \mathbf{y}^{1s} & \cdots & \mathbf{y}^{1k} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{y}^{r1} & \cdots & \mathbf{y}^{rs} & \cdots & \mathbf{y}^{rk} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{y}^{k1} & \cdots & \mathbf{y}^{ks} & \cdots & \mathbf{y}^{kk} \end{bmatrix} \quad \mathbf{y}^{rs} = \begin{bmatrix} \mathrm{y}_1^{rs} \\ \vdots \\ \mathrm{y}_i^{rs} \\ \vdots \\ \mathrm{y}_n^{rs} \end{bmatrix}$$

The vector of total output is made of *k* blocks as well, each one consisting of *n* elements.

$$\mathbf{x} = \begin{bmatrix} \mathbf{x^1} \\ \vdots \\ \mathbf{x^r} \\ \vdots \\ \mathbf{x^k} \end{bmatrix}$$

Eqs. 9 and 11 still apply in the case of multi-regional models.

3.3. Environmentally Extended Input-Output Analysis

Environmentally extended input-output (EEIO) analysis is an extension of the basic input-output framework. Its aim is to identify environmental impacts embodied in goods and services locally or globally traded and allocate them to final consumers.

Physical quantities are integrated into the previously described model through environmental extensions or satellite accounts, consisting of environmental variables collected in a way that is consistent with the input-output table regional and sectoral division. In its *Environmental Repercussions and the Economic Structure: An Input-Output Approach*, Leontief said that "undesirable outputs can be described in terms of structural coefficients similar to those used to trace structural interdependence between all the regular branches of production and consumption" [26], meaning that those environmental streams can be considered required input of the economic activities [42] and hence integrated into the analytical framework.

	Purchases from intermediate demand		
Sales to intermediate demand	Transaction Matrix (Z)	Sales to Final Demand (Y)	Total Output (X_{out})
	Value Added (VA)		
	Total Input (X_{in})		
	Environmental Extensions (F)		

Table 2: An overview of the extended input-output table in matrix notation

Environmentally extended global multi-regional input-output analysis (EE GMRIOA) is the synthesis of the models described above that allows to evaluate streams of impacts embodied in global trade and to assess the environmental footprint of the countries.

The components of the table can be written in matrix notation:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{11} & \cdots & \mathbf{Z}^{1s} & \cdots & \mathbf{Z}^{1k} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{Z}^{r1} & \cdots & \mathbf{Z}^{rs} & \cdots & \mathbf{Z}^{rk} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{Z}^{k1} & \cdots & \mathbf{Z}^{ks} & \cdots & \mathbf{Z}^{kk} \end{bmatrix} \quad \mathbf{Y} = \begin{bmatrix} \mathbf{y}^{11} & \cdots & \mathbf{y}^{1s} & \cdots & \mathbf{y}^{1k} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{y}^{r1} & \cdots & \mathbf{y}^{rs} & \cdots & \mathbf{y}^{rk} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{y}^{k1} & \cdots & \mathbf{y}^{ks} & \cdots & \mathbf{y}^{kk} \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}^{1} \\ \vdots \\ \mathbf{x}^{r} \\ \vdots \\ \mathbf{x}^{k} \end{bmatrix} \quad \mathbf{f} = \begin{bmatrix} \mathbf{f}^{1} \\ \vdots \\ \mathbf{f}^{r} \\ \vdots \\ \mathbf{f}^{k} \end{bmatrix}$$

where

- $\mathbf{Z^{rs}}$ is the sub-matrix of the intermediate sales from country *r* to country *s*, with purchasing industries in columns and selling industries in rows;
- $\mathbf{y^{rs}}$ is the column vector of final demand of country *s* for products from country *r*;
- $\mathbf{x^{r}}$ is the vector of total output produced by country *r*;
- $\mathbf{f^{r}}$ is the vector of environmental impacts by industry in country *r*.

Eq. 12 defines the relationship between **Z**, **Y** and **x**.

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yj} \tag{12}$$

where **i** and **j** are summation vectors. It can be written as a standard input-output equation as follows.

$$\mathbf{x} = \mathbf{Ax} + \mathbf{Yj} \tag{13}$$

The solution is given by Eq. 14.

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Yj} = \mathbf{LYj} \tag{14}$$

The matrix L is the Leontief inverse. Global impact intensity is given by Eq. 15.

$$\mathbf{q} = \hat{\mathbf{x}}^{-1}\mathbf{f} \tag{15}$$

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}^1 \\ \vdots \\ \mathbf{q}^s \\ \vdots \\ \mathbf{q}^k \end{bmatrix} \text{ and } \mathbf{q}^s = \begin{bmatrix} q_1^s \\ \vdots \\ q_j^s \\ \vdots \\ q_n^s \end{bmatrix}$$

$\mathbf{q}$ is the vector of impact intensity, whose elements are the direct impact coefficients representing the amount of impact associated with a unit of industry output.

Finally, the environmental impacts related to the production by industry to fulfill the final demand are calculated from Eqs. 14 and 15, which become the *environmentally extended Leontief inverse equation*.

$$\mathbf{e} = \hat{\mathbf{q}}\mathbf{x} = \hat{\mathbf{q}}\mathbf{LY} \tag{16}$$

The calculation can be made more explicit considering the evaluation of the energy use for the example of two countries, or better one country and a region consisting in the rest of the world.

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix}$$
$$= \begin{bmatrix} \hat{q}^1L^{11}y^{11} + \hat{q}^1L^{12}y^{21} & \hat{q}^1L^{11}y^{12} + \hat{q}^1L^{12}y^{22} \\ \hat{q}^2L^{21}y^{11} + \hat{q}^2L^{22}y^{21} & \hat{q}^2L^{21}y^{12} + \hat{q}^2L^{22}y^{22} \end{bmatrix} \tag{17}$$

e^{11} and e^{22} express local energy consumption, e^{12} gives the energy used to produce exports from country 1 to country 2 and e^{21} represents the energy required to produce imports to country 1 from country 2. The consumption-based (CB) energy use in country 1 is given by Eq. 18.

$$e^{CB} = e^{11} + e^{21} \tag{18}$$

The production-based (PB) energy use in country 1 is given by Eq. 19.

$$e^{PB} = e^{11} + e^{12} \tag{19}$$

Finally, the total energy footprint can be obtained by Eq. 20.

$$\mathbf{TEF} = \mathbf{qLY} + \mathbf{h} \tag{20}$$

In this case, $\mathbf{q}$ is not diagonal, and $\mathbf{h}$ is the direct energy use by the household vector.

3.4. Environmental Accounts

The input-output analysis relies on statistical data compiled and periodically updated by statistical agencies according to international standards [16]. Nowadays, the most employed GMRIO databases in environmental analyses are basically five [40]: WIOD (World Input-Output Database) [45], Eora [46], EXIOBASE [47], OECD (Organisation for Economic Co-operation and Development), GTAP (Global Trade Analysis Project) [48]. Differences among WIOD, EXIOBASE, GTAP and Eora databases are lower than 10% in the majority of the large economies [14] and divergences between the results of the analysis carried out using one or another are mainly attributed to the adopted environmental accounts [16], [49].

The database chosen for this analysis is the World Input-Output Database (WIOD) [50]. The latest release of the WIOD in 2016 includes a series of monetary multi-regional input-output tables (in $ million) covering 56 sectors for 28 European Union (EU) and 15 extra-EU countries, plus an aggregate for the rest of the world (with a total of 44 regions, see Appendix A). The tables are available for the period 2000-2014.

In addition, the WIOD provides environmental satellite accounts already consistent with its sectoral classification, published by the Joint Research Centre of the European Commission for 2000-2016 [51]. The database offers CO_2 emission data (in 1000 tonnes) and two types of energy accounts (in TJ): gross energy use (GEU) and emissions relevant energy use (EREU). The gross energy use is estimated as the sum of exports, intermediate consumption and final uses and is defined in a way that is consistent with the framework of national accounting systems [15]. The EREU is defined as "the use of energy that causes emissions directly" [51]: starting from the GEU, it avoids any double-counting by excluding non-energetic use of energy carriers and fuel input for transformation into different fuels.

The main source of data for the energy accounts is the extended energy balances by the International Energy Agency (IEA), which are then adjusted to be consistent with the System of National Accounts (SNA) on which WIOD is based [51]. The SNA follows the residence

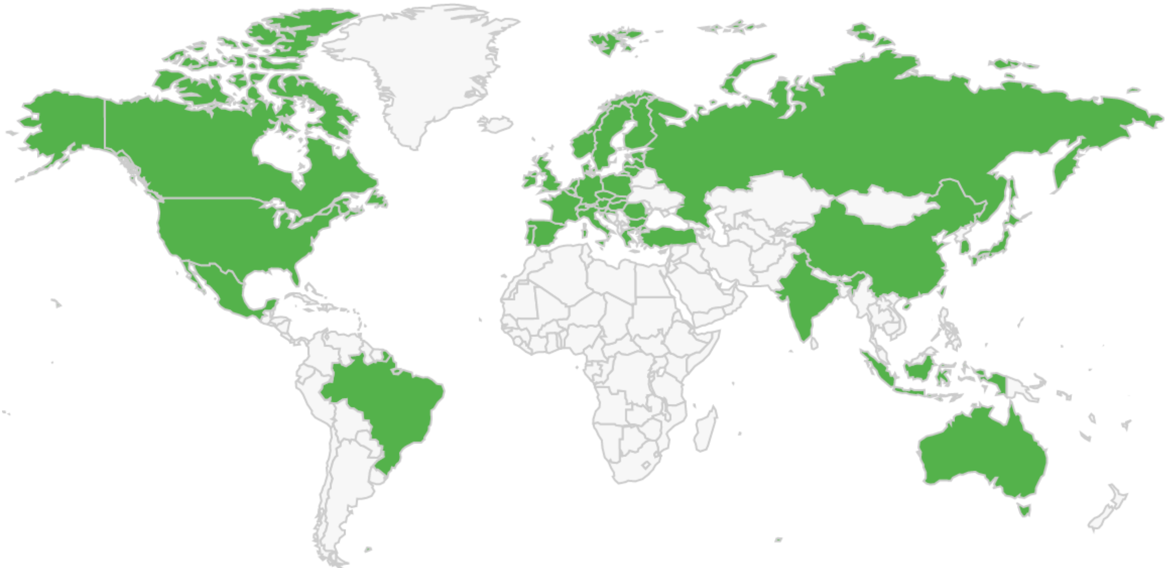


Figure 2: Countries included in WIOD are highlighted in green

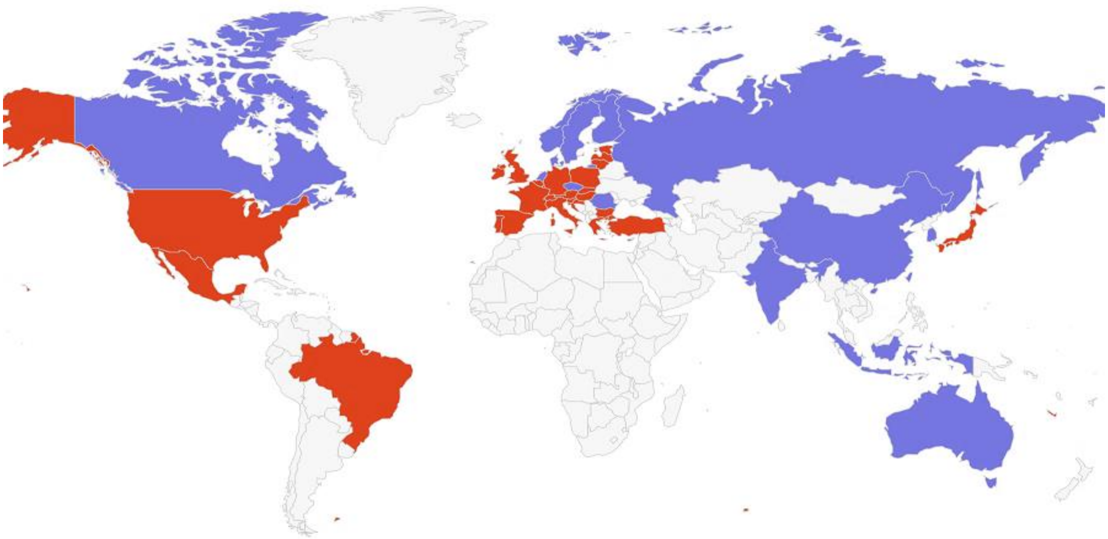
principle, while energy balances are compiled according to the territorial principle. By the national accounting system, all energy use of a resident, whether physically inside or outside of the territory, is attributed to the country of residence. The territorial principle allocates the energy use to the country where it actually takes place, without distinguishing between residents or non-residents [52]. The main source for CO_2 emission accounts by sector is Eurostat; for the countries whose data are not available, carbon emissions are calculated using the EREU and the emission factor from the IPCC Guidelines and adding non-energy-related emissions [51].
In this study emission relevant energy use (EREU) and CO_2 emissions are analyzed.

4. Results

4.1. Energy embodied in trade and energy footprints

Consumption-based accounts (CBA) have been calculated and compared with the original production-based accounts (PBA) for 43 countries and the "rest of the world" aggregate (RoW). As previously defined, PBAs are constructed as the sum of energy domestic consumption plus

2000



2014

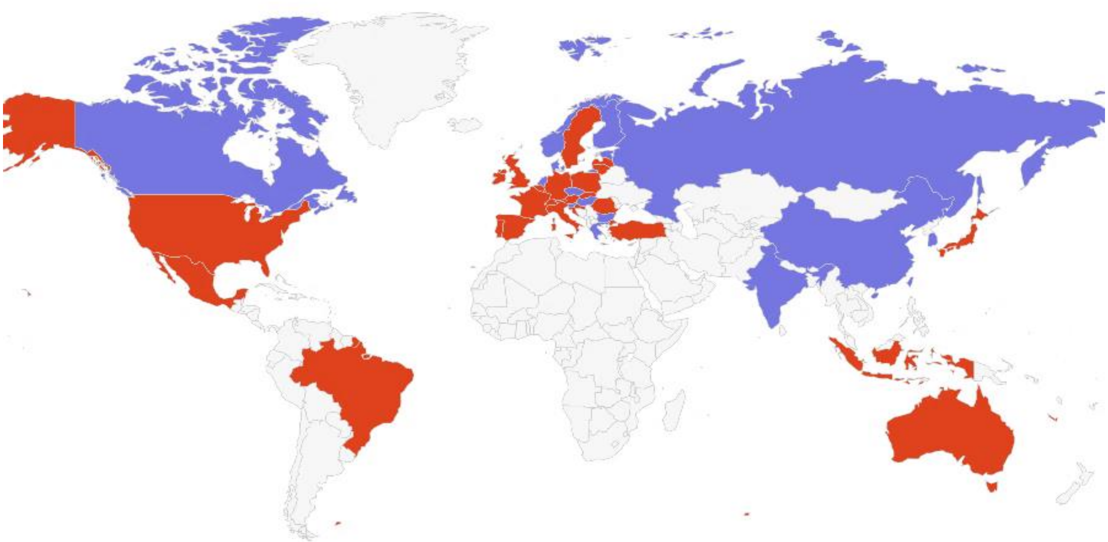


Figure 3: Comparison between 2000 and 2014: embodied energy net importing countries are highlighted in orange, while exporters are in violet.

exports, while CBAs subtract exports and add imports. The comparison between the two inventories allows identifying each country as an embodied energy net importer (EENI), or exporter (EENE).

In 2000 most European countries, as well as the United States, Japan, Mexico and Brazil, are embodied energy net importers while most Asian countries, Canada and Australia are embodied energy net exporters. In 2014 the situation is almost the same, with just few nations switching sides: Australia, Indonesia, Bulgaria, Sweden, Estonia and Hungary become importers, while Greece, Romania and Slovenia change to exporters.

By adding the direct energy consumption by households, the total energy footprint (TEF) of the selected countries is determined and compared in figure 4 with the original accounting framework (total energy use, TEU). As a consequence of the previous definitions, the TEF is higher than TEU for EENIs and, *vice versa*, is lower for EENEs. In 2000 the United States shows the highest energy use by far, whatever the accounting framework is, even larger than

Figure 4: 2000 and 2014 comparison of countries' Total Energy Footprint (TEF) and Total Energy Use (TEU)

the RoW (that ideally includes more than 160 countries and a population that is more than 7 times larger). In 2014 the record moves to China, although the distance with the USA reduces

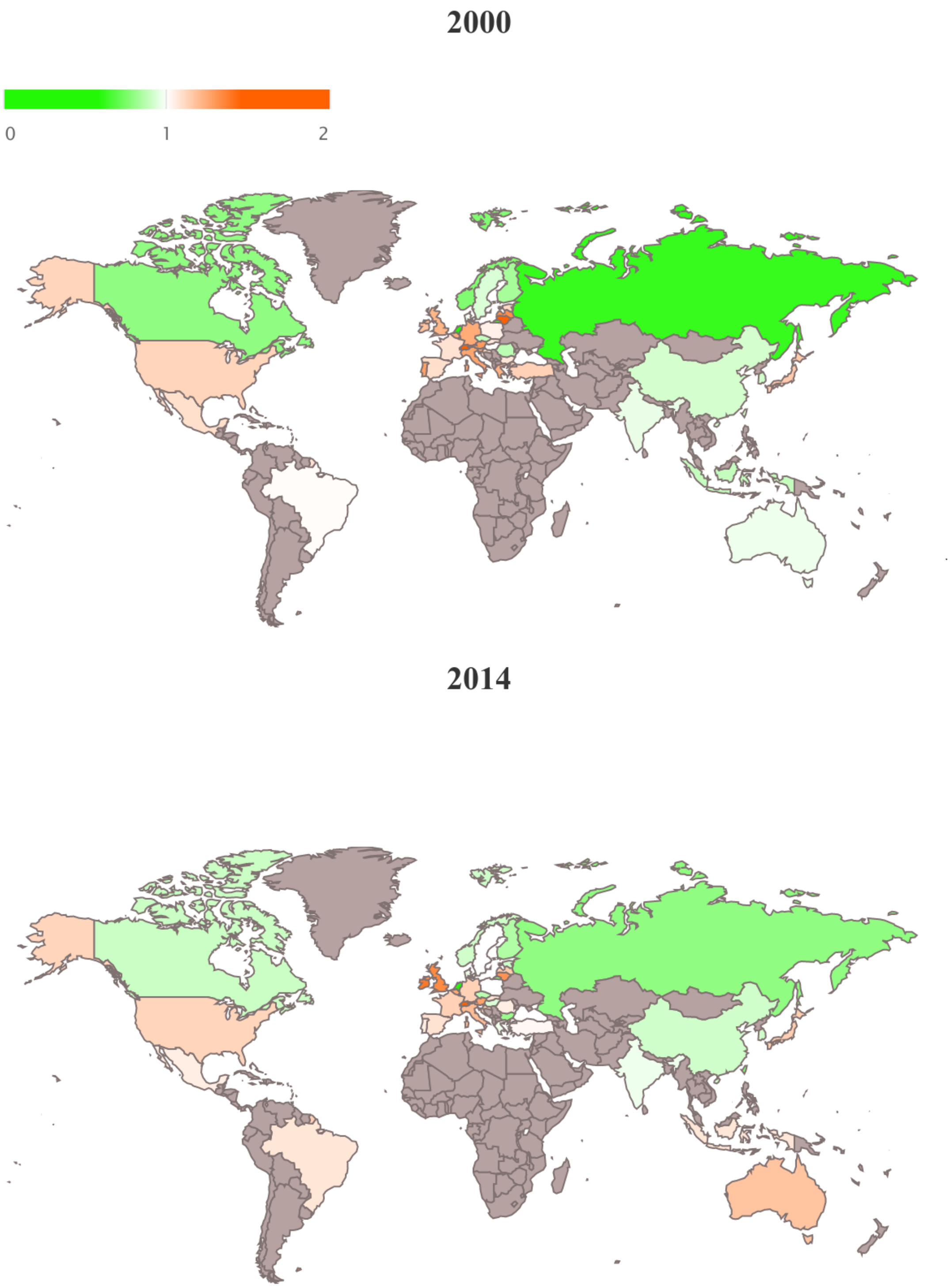


Figure 5: Total Energy Footprint (TEF) and Total Energy Use (TEU) ratio

significantly. Both in 2000 and 2014 the USA is the largest net importer (the net embodied energy import/export difference is equal to 12.53 EJ in 2000, 13.01 EJ in 2014); the largest net exporter is Russia in 2000 (-12.71 EJ) and China in 2014 (-12.10 EJ)

In 2000, TEF is 20% higher than TEU on average among EENI countries, and the maximum is reached by Switzerland, whose energy footprint is 1,72 times its total energy use. In 2014, the difference is reduced to 17%, but the record is still Swiss (60% higher). EENE countries, instead, show a TEF 15% lower than TEU on average in 2000, and then 12% in 2014.

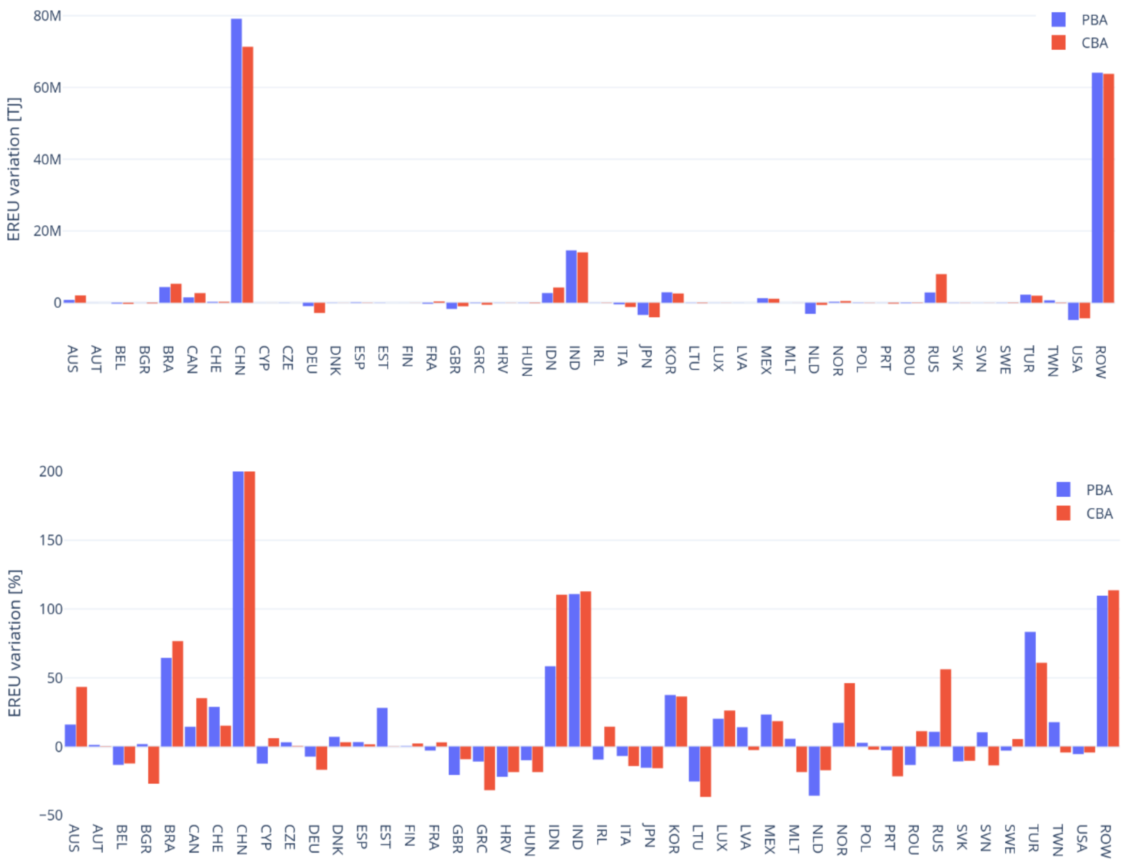


Figure 6: Absolute and percentage variation of energy used by economic activities in 2014 with the respect to 2000. Comparison between the two accounting principles

In figure 6 the variation of energy used by economic activities between 2000 and 2014 is analyzed. China confirms the highest increase, with a more than 200% escalation in trade-related energy use both from the production and the consumption perspective. India and Indonesia immediately follow; India more than doubles energy spent by industries and the energy use CB inventory of Indonesia increases by 110% as well. On the contrary, the USA,

Figure 7: 2000 and 2014 percentage contribution to the energy footprint of a country of households' energy use, local industries' consumption and energy embodied in international trade

Japan and most European countries show a general reduction or at least a slight increase in the energy use of the economic activities. The highest decrease of CB accounts (about 30%) happens in Greece and Lithuania.

The overall energy footprint is made of different contributions (figure 7). The measurement of the energy use related to households and domestic industrial activity is shared with the production-based perspective, so the real distinction is made by the share of energy use linked to international trade, whose weight, actually, is dependent on the exporting countries. The energy embodied in international trade corresponds to 32% of the energy footprint on average in 2000, but the difference between countries is not negligible. In the case of Switzerland, Belgium, and Luxembourg, for example, this fraction reaches, respectively, 61%, 57% and 56% in 2000, confirming the previous observation about the disproportion between Swiss energy footprint and production-based inventories. On the other hand, the percentage is much lower for countries as the US (17%) or Japan (31%), also an EENI, and even smaller for EENEs like Russia and China (respectively, 3% and 8%). Although being the largest energy net importer, the main part of the energy footprint of the United States is related to domestic energy use (68% for local economic activities plus 15% to households' consumption). The reason can be easily found in the huge disproportion between the US and everyone else's energy use in absolute terms. Finally, Indian and Indonesian energy footprints see the largest households' contribution, being higher than 1/3 of the TEF.

Figure 8: Absolute and percentage variation of each part of the energy footprint in 2014 with the respect to 2000

According to figure 8, in 2014 there is a general increase in energy embodied imports share, which reaches 36% of the total energy footprint on average. China and Russia saw an increment

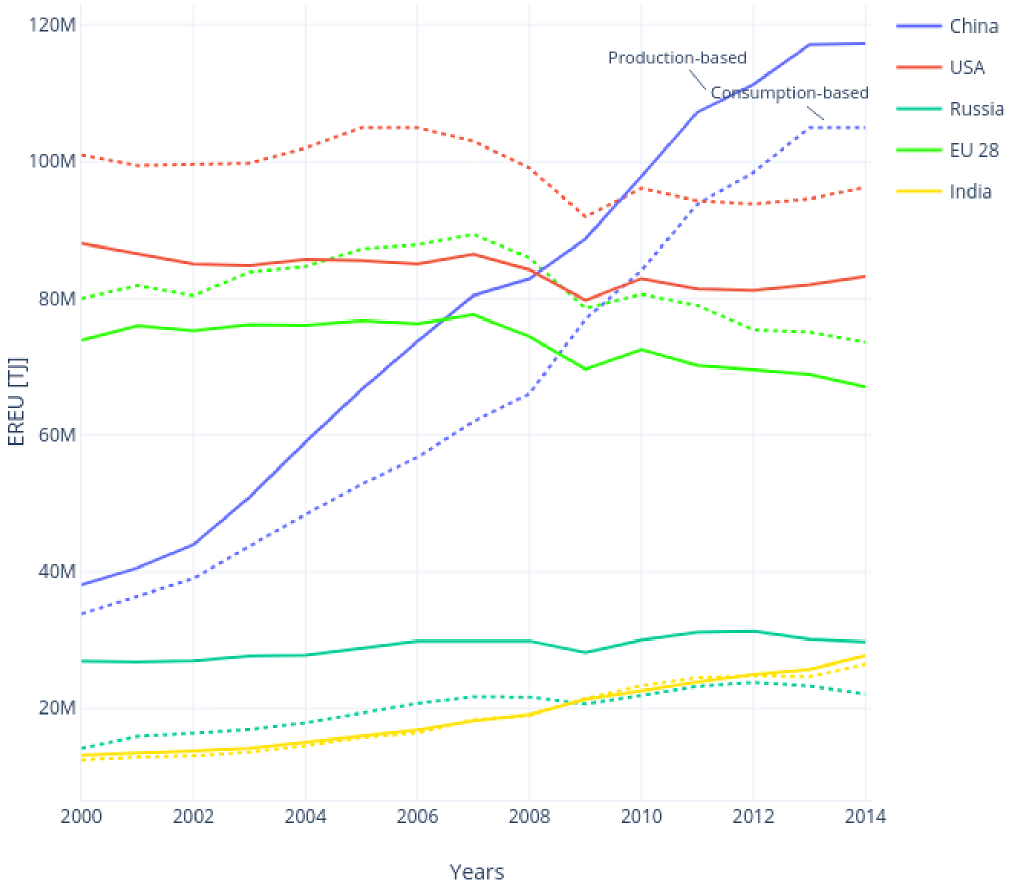


Figure 9: Energy use trends over time of China, the United States of America, India, Russia, and an aggregate comprising the 28 European countries (EU 28). The chart shows both production and consumption-based energy use of economic activities, respectively in solid and dashed lines.

higher than 300% of embodied energy imports, although those remain a minor contribution to countries' overall energy footprint (13% and 21% respectively). China also shows a 200% increase in local economic activities energy use, confirming a massive growth from all perspectives. India and Indonesia double energy use related to local trade and triple the one linked to international trade imports. Luxembourg's increase in households' consumption is around 118% and in 2014 direct households' energy use represents over 40% of TEF. Luxembourg's embodied energy imports are 49% of its total energy footprint, but Switzerland still holds the record (61%), followed by Belgium (60%). It is interesting to notice that, for the USA, Japan and most European countries, the increase of the international trade contribution is accompanied by a decrease in energy use of local economic activities, suggesting a more efficient consumption of domestic industries or the outsourcing of energy-intensive sectors. Figure 9 shows a focus on few selected countries: China, the United States, Russia, India and

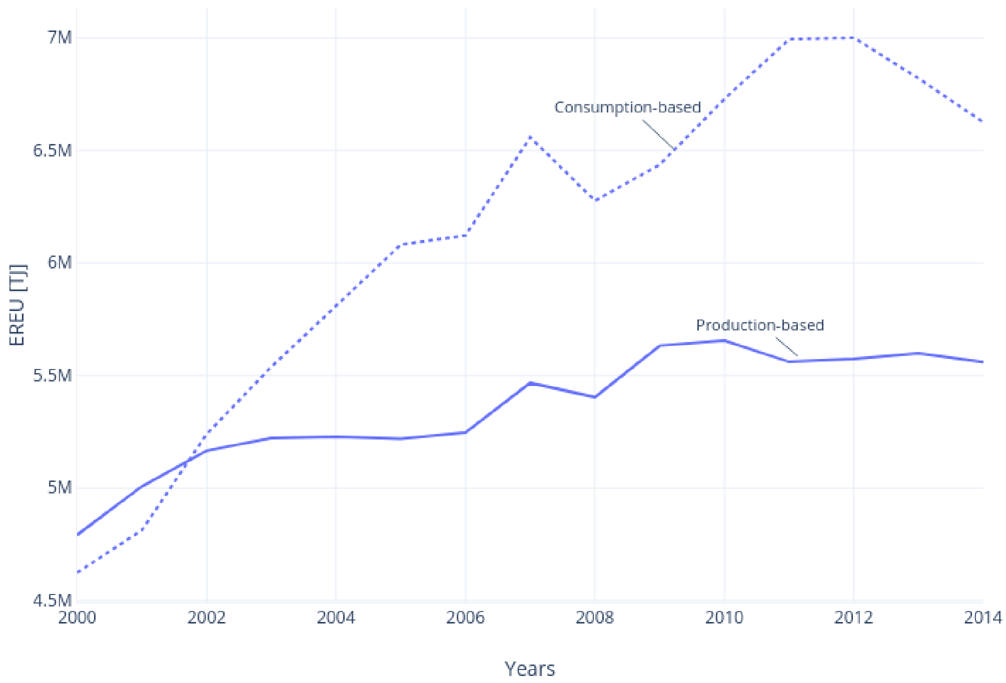


Figure 10: Australian energy use trend over time. The chart shows both production and consumption-based energy use of economic activities, respectively in solid and dashed lines.

an aggregate comprising the 28 European countries (EU 28). Energy used during the period 2000-2014 by the economic activities is evaluated from both production and consumption perspectives. EU 28 and USA show a slightly decreasing trend, while China confirms a steep increase, surpassing both Europe and the USA around 2006-2008. On the other hand, by comparing CB accounted energy, the Chinese overtaking is delayed by three years and in 2014 the difference between China and the USA is reduced by half. Russia presents a steadier behavior, with a progressive reduction of the difference between the two accounts (as PBA grows by 11%, while CBA rises by 56%). India shows a steady increase during the analyzed period, in both PB and CB accounts, doubling its energy use. According to the consumption perspective, in 2014 Indian energy use is larger than the Russian one. It is interesting to notice that EU 28, Russia, and the USA report a dip in their trend corresponding with 2009, in correspondence with the economic crisis.

Figure 10 is a focus on Australia, whose trend diverges from the other high-income countries. In 2000 Australia is an EENE, then in 2002 the growing consumption-based account surpasses production-based accounts, which remains quite steady during the period. According to the

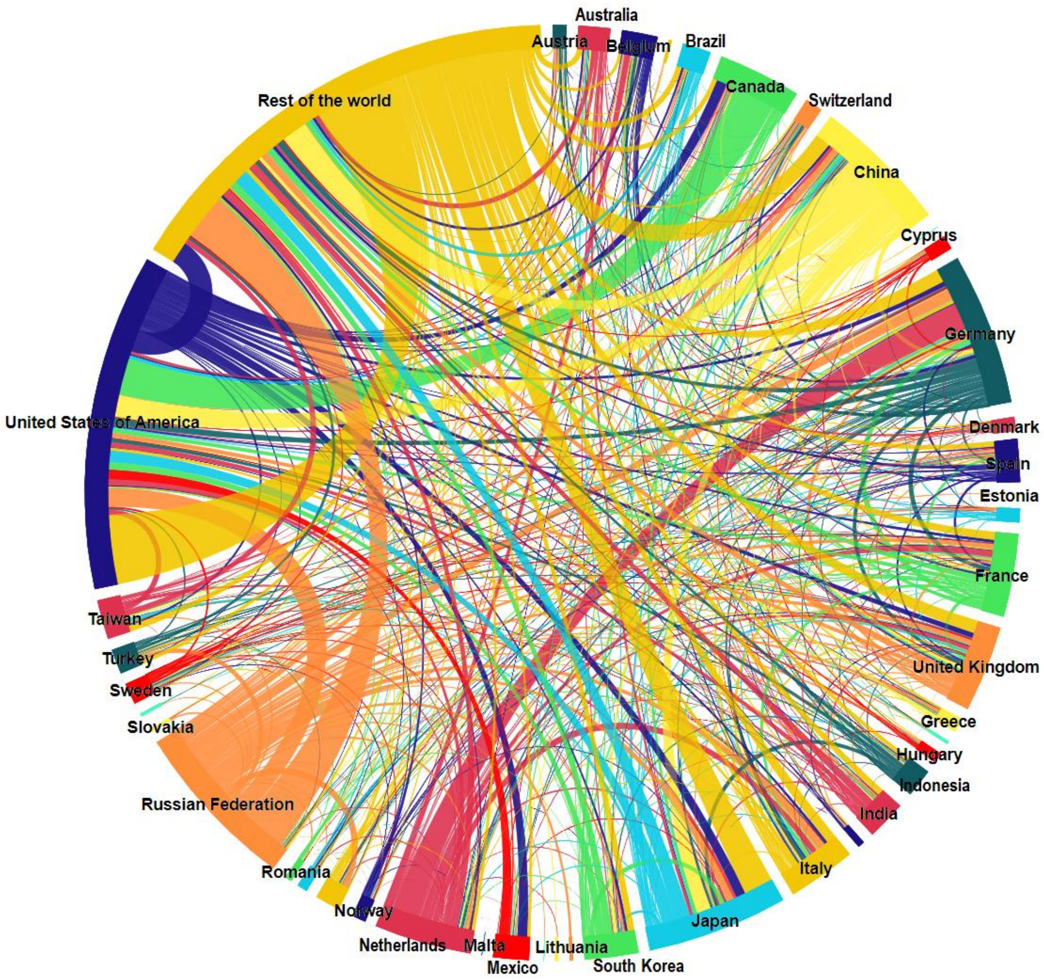


Figure 11: 2000 Main embodied energy connections between the 43 countries + Rest of the world. The embodied energy flow between every two nation is represented by a chord. The thickness of the chord is weighted on the volume of embodied energy traded. The color of the chord corresponds to the one of the country where the flow starts.

IEA, Australia is reducing its energy demand mainly due to many energy-intensive industries closing [53]. This may have driven an increase in energy-intensive imports.

Figures 11 and 12 show the main energy embodied connections among the 43 countries and the rest of the world. In 2000 (figure 11), the most significant embodied energy imports to the United States come from Canada (3.16 EJ, 16% of the total imports), the EU (3.07 EJ, 15%), China (1.87 EJ, 9%), Russia (1.6 EJ, 8%), and the rest of the world (6 EJ, 30%). Germany imports embodied energy mostly from the rest of the EU (4.57 EJ, 55%), where the Netherlands alone accounts for a whole 27%, Russia (0.98 EJ, 12%) and RoW (1.12 EJ, 14%). 24% of China's EE exports go to the USA, while 19% is directed to Japan and South Korea (1.47 EJ in total), 18% to Europe (1.4 EJ) and 28% to RoW (2.23 EJ). As for Russia, 39% of embodied

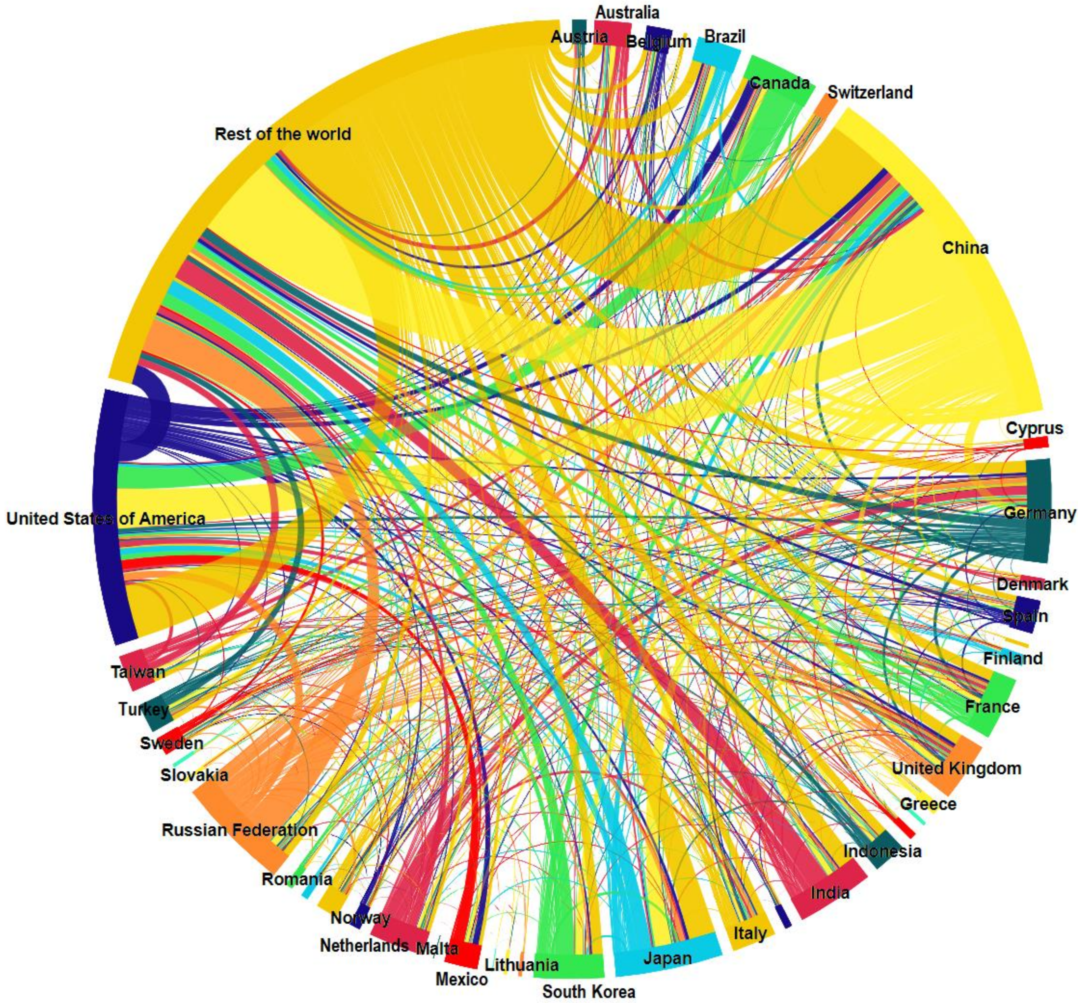


Figure 12: 2014 Main embodied energy connections between the 43 countries + Rest of the world.

energy exports are destined to the EU (5.15 EJ), above all to Germany and Italy, 12% to the USA and 29% to the rest of the world (3.83 EJ).

The 2014 scenario (figure 12) sees the affirmation of Chinese economic strength. Chinese embodied energy exports are destined, respectively, for 17% to the United States (4.67 EJ), 16% to Europe (4.26 EJ), 10% to Japan and the Republic of Korea, and 37% is directed to the markets of the rest of the world (9.99 EJ). As regards the USA, the most significant part of EE imports comes from China (22%), Canada (12%, 2.6 EJ), EU (11%, 2.21 EJ), Russia (4%), and another 30% from RoW (6.37 EJ). European countries contribute 41% to German embodied energy imports (2.84 EJ), and among them, 14% comes from the Netherlands, which is also German first economic partner. The same percentage originates from China, while Russia accounts for 8% and RoW for 20%. So, China is confirmed as a major importer for all the main economic powers but also those countries collected under the label “rest of the world”, which also gains more weight in the 2014 scenario. As for Russian EE exports, they are directed for

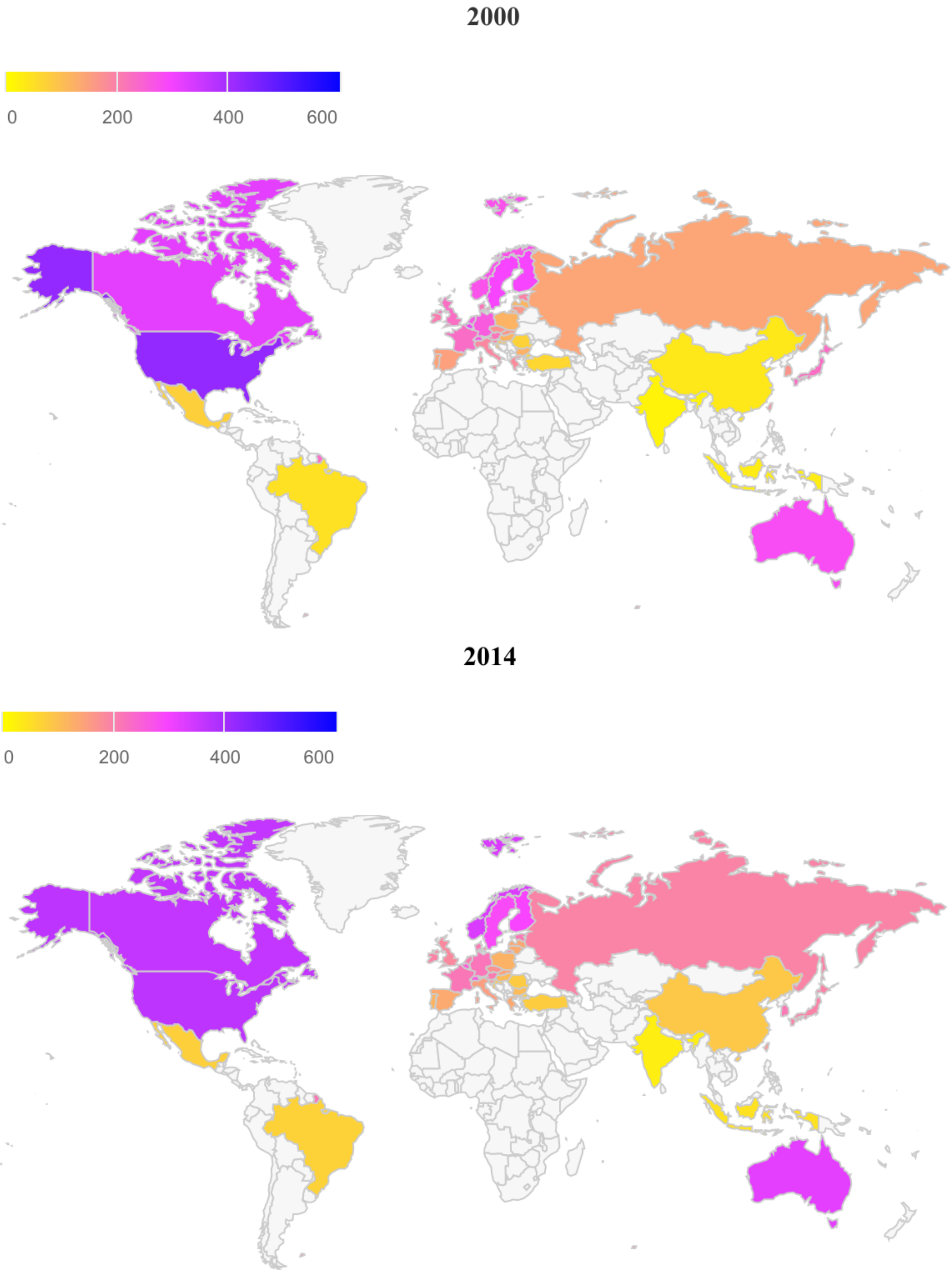


Figure 13: Distribution of energy footprint per capita in 2000 and 2014, in GJ/cap.

Figure 14: 2000 and 2014 comparison of countries' per capita Total Energy Footprint (TEF) and Total Energy Use (TEU)

27% to the EU, 9% to China and 8% to the USA, while 38% flows to the rest of the world. Figure 13 shows in space the energy footprint per capita in 2000 and 2014, while figure 14 presents a comparison between total energy footprint and total energy use per capita. Once normalized over the population, in 2000, the highest values of TEFs are recorded in the USA, Canada, Japan, Australia, and Northern Europe (Luxembourg above all). Russia and Southern Europe are at medium levels, while Mexico, Brazil and Asian countries show the lowest values. In 2014 the situation in Europe is almost the same, except for a further increase of the per capita energy footprint of Luxembourg (+52%). The United States and Japan show a slight decrease, Canada, Japan, Australia, and Northern Europe (Luxembourg above all). Russia and Southern Europe are at medium levels, while Mexico, Brazil and Asian countries show the lowest values. while all the other sampled countries present a noticeable rise. As regards China, the per capita energy footprint grows by 160%, Brazil increases by 75%, India and Indonesia by more than

80%. Asian countries and the RoW are generally the ones experiencing the largest growth during the investigated period.

4.2. Carbon embodied in trade and carbon footprints

In this paragraph, the same analysis is repeated for CO_2 emissions. In 2000, the situation described by figure 15 is quite similar to figure 4, with few exceptions: countries like Sweden and the Netherlands which, despite being embodied energy net exporters, result as embodied carbon net importers (ECNI), while the opposite stands for Luxembourg and Slovakia. This resemblance suggests there is no relevant difference among countries regarding the composition of their energy mix, being fossil fuels predominant almost everywhere. Again, the United Stated holds the record and results in the largest embodied carbon net importer (the net embodied

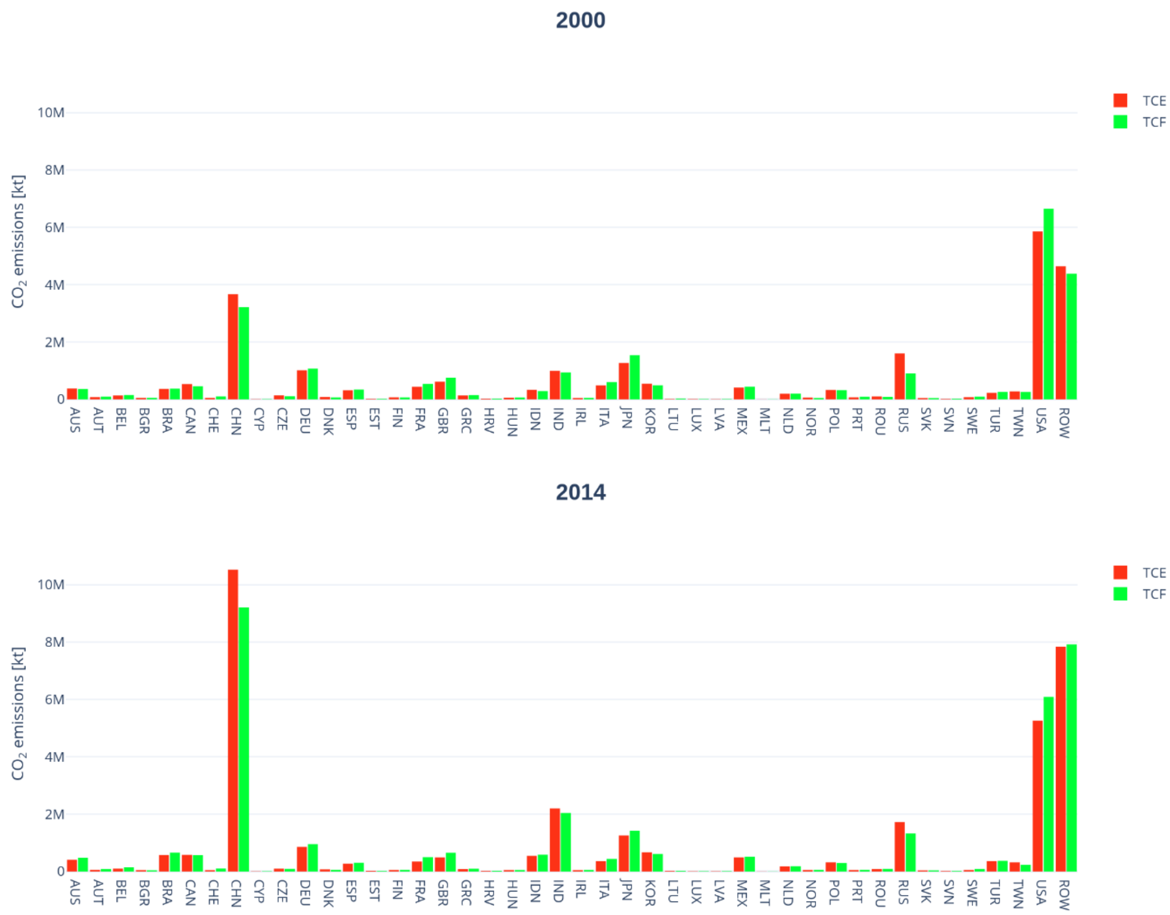
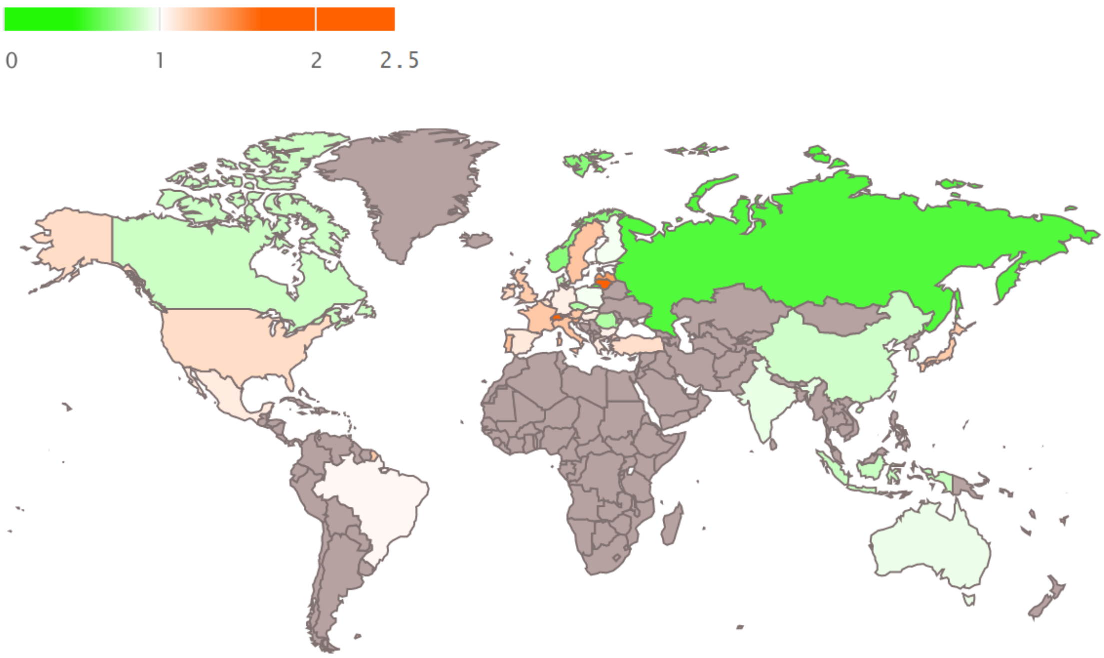


Figure 15: 2000 and 2014 comparison of countries' Total Carbon Footprint (TCF) and Total Carbon Emissions (TCE)

2000



2014

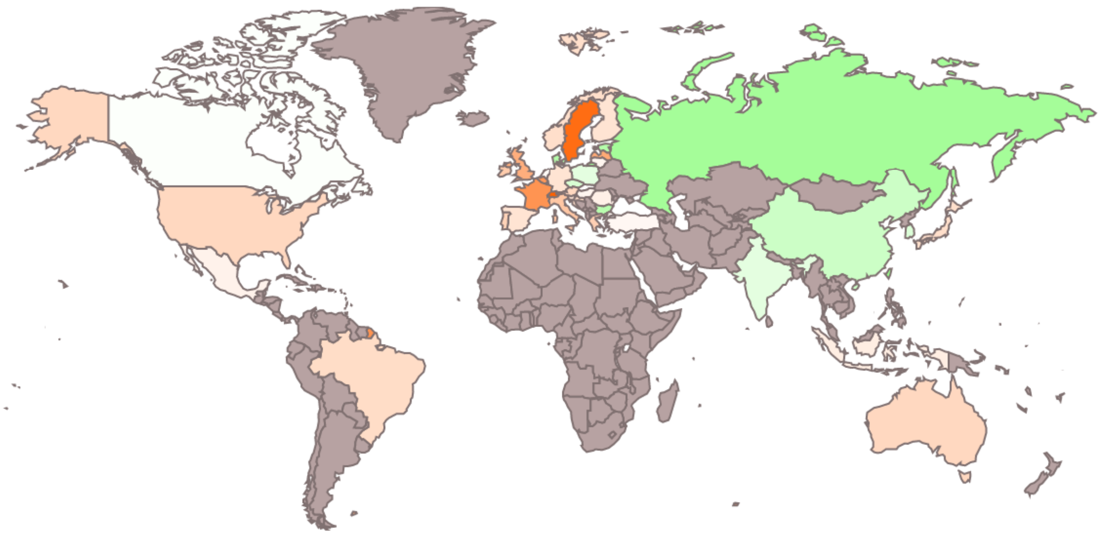


Figure 16: Total Carbon Footprint (TCF) and Total Carbon Emissions (TCE) ratio

carbon import/export difference is equal to 802 Mt), with a footprint that is 14% higher than the production-based accounted emissions. On average, the Total Carbon Footprint (TCF) is

22% larger than the Total Carbon Emission (TCE) for ECNIs, while embodied carbon net exporter (ECNE) countries report a TFC 13% lower than TCE. Russia is the largest ECNE (-698 Mt), and its carbon footprint is 44% smaller than TCE. Switzerland confirms the same trend highlighted for energy: its carbon footprint is more than two times its TCE. In 2014 the USA is still the largest net importer (+833 Mt), while China becomes the main embodied carbon net exporter (-1316 Mt). In this scenario, the great majority of the countries are ECNIs, and just 12 of them are ECNEs (among them China, India, Russia and Canada). Also, the gap between China and other countries is visibly wider than the one shown by the energy analysis. Total Carbon Footprint is still 22% higher than TCE on average among ECNIs, and the maximum is scored by Switzerland (+131%). As for ECNE countries, the difference is also steady (-13%).

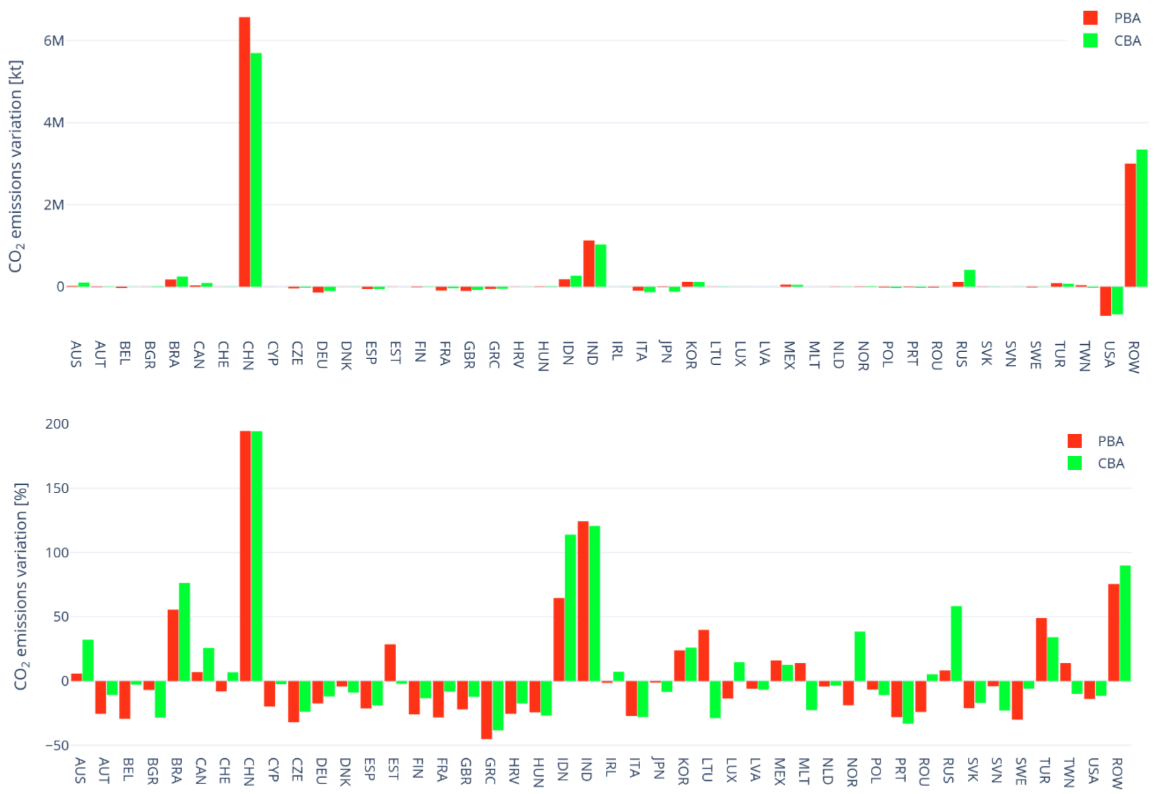


Figure 17: Absolute and percentage variation of carbon emissions related to economic activities in 2014 with the respect to 2000. Comparison between the two accounting principles

Figure 17 shows the variation of CO_2 emissions related to economic activities between 2000 and 2014. China experiences the largest growth in trade-related emissions, +94% whether from the production or the consumption perspective. India, Indonesia, and Brazil show a great increase as well, while most European countries present a general emission decrease (more important than the reduction of energy use). The larger cut of CB accounts (more than 30%) is registered in Greece and Portugal.

The different contributions to the total carbon footprint are shown in figure 18. In 2000, the CO_2 emissions embodied in international trade corresponds to 35% of the total carbon footprint on average and reaches 42% in 2014. In 2000, for Switzerland, Norway, and Luxembourg, this fraction of the carbon footprint corresponds to 65%, 60% and 50% respectively, and in 2014 becomes 70%, 61% and 75%. Despite being the largest embodied carbon net importer, in 2000 only 19% of the US carbon footprint is related to emissions embodied in international trade, while CO_2 emissions of local economic activities account for 69% of the total. The percentage of embodied carbon imports is even lower for ECNE countries like Russia and China

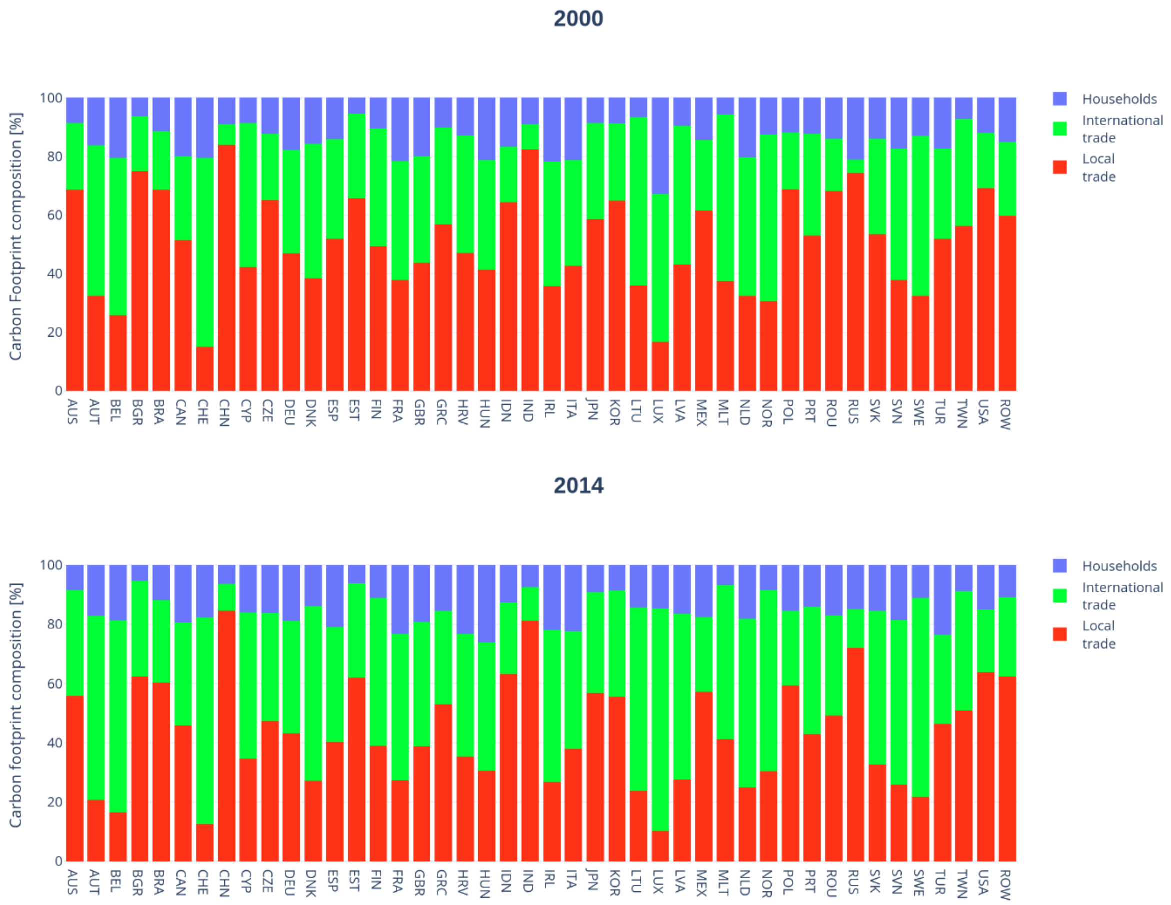


Figure 18: 2000 and 2014 percentage contribution to the carbon footprint of a country of households' and local industries' CO_2 emissions and carbon embodied in international trade

(respectively, 5% and 7%). As a general observation, the fraction of households' contribution is generally smaller than the case of the energy footprint.

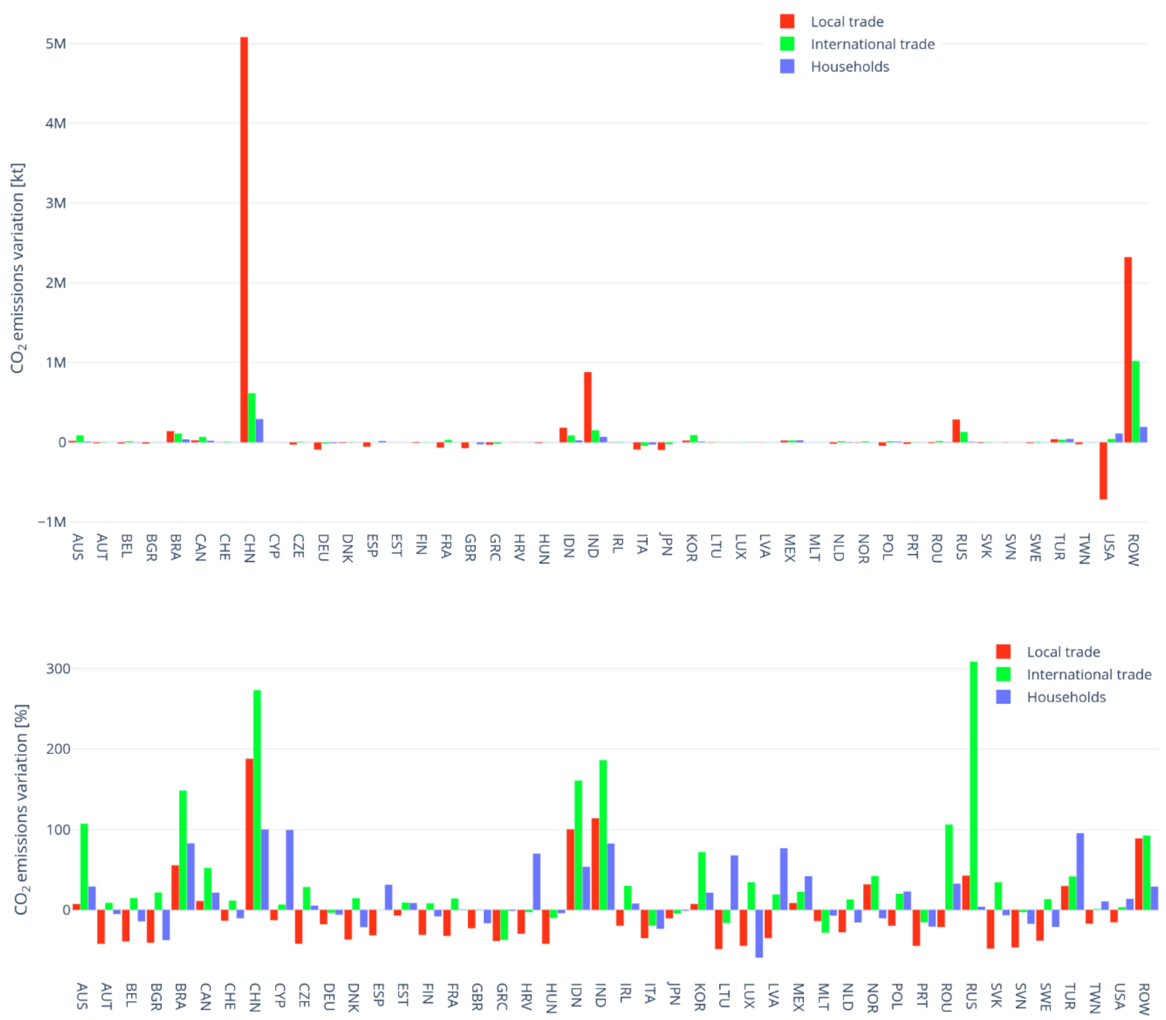


Figure 19: Absolute and percentage variation of each part of the carbon footprint in 2014 with the respect to 2000

Figures 18 and 19 show an overall rise in embodied carbon imports in 2014. Russia saw an increase higher than 300% of embodied carbon imports (130 Mt), followed by China (273%, 616 Mt). However, those contributions remain a small (although higher than 2000) fraction of the total footprint (13% and 9% respectively). Again, the USA, Japan and most European countries see the increase of the international trade-related embodied carbon contribution together with a substantial decrease of the CO_2 emissions linked to local economic activities, exposing the limits of local decarbonization strategies. Despite showing a strong increase in households' energy use, Luxembourg presents the largest reduction of households' carbon

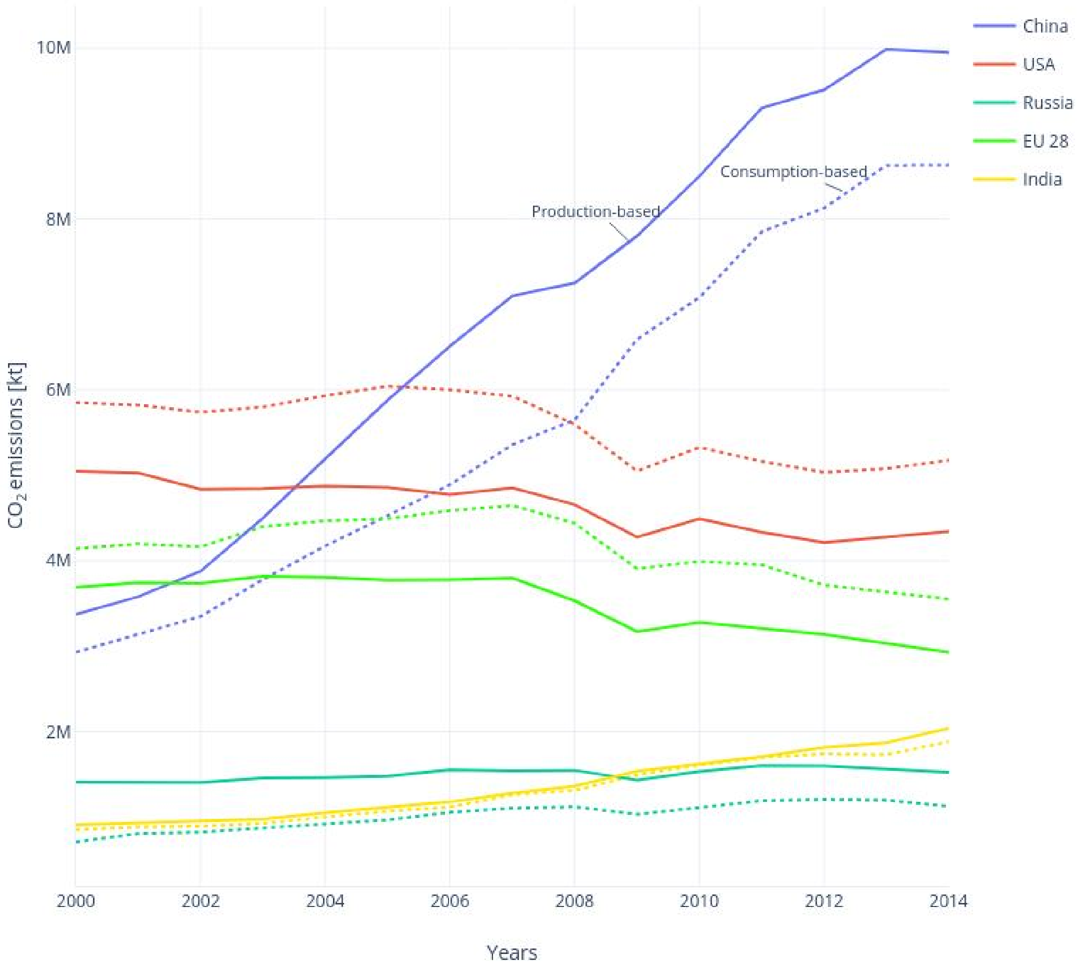


Figure 20: CO_2 emission trends over time of China, the United States of America, India, Russia and an aggregate comprising the 28 European countries (EU 28). The chart shows both production and consumption-based carbon emissions of economic activities, respectively in solid and dashed lines.

emissions (-60%). In 2014 this share represents just 15% of the carbon footprint, while in 2000 it is around 1/3 of the TCF. India and Indonesia double carbon emissions related to local trade and almost triple those linked to international trade imports.

Figure 20 focuses on the trend over time of China, the United States, EU 28, Russia and India. CO_2 emissions related to economic activities are evaluated from both production and consumption perspectives during the period 2000-2014. The area between the solid and dashed lines is the net embodied carbon import/export. The country is a net exporter of embodied carbon emissions if the solid line is above the dashed line, otherwise, the nation is a net importer. The overall evolution is similar to the one shown in figure 9. Chinese overtaking is brought forward by few years: EU 28 is surpassed around 2001-2002, while the USA around

Figure 21: Australian CO_2 emission trend over time. The chart shows both production and consumption-based carbon emissions of economic activities, respectively in solid and dashed lines.

2003-2004. By comparing CB accounts, China does not cross and overcome the USA until 2008, when the United States starts a more decisive reduction trend (12% decrease from 2000). From the production perspective, India surpasses Russia around 2008-2009, when there is a contraction in emissions (just like in the energy use); from the consumption point of view, Russian carbon emissions are always lower than the Indian ones. Over the analyzed period, India shows an increase in CO_2 emissions higher than 120%, whether the accounting framework.

In figure 21 a focus on Australia is presented. Australian energy system, which is highly reliant on fossil fuels, is transforming, increasing the share of natural gas and renewables energies [53]. The trend is similar to the one of the energy use, but it shows a stronger decline after the period 2010-2012.

Figures 22 and 23 illustrate the main embodied carbon connections among the 43 countries plus the rest of the world. Figure 22 shows the 2000 scenario. The largest embodied carbon imports of the United States arrive from the EU (166 Mt, 13% of the total imports), China (163 Mt,

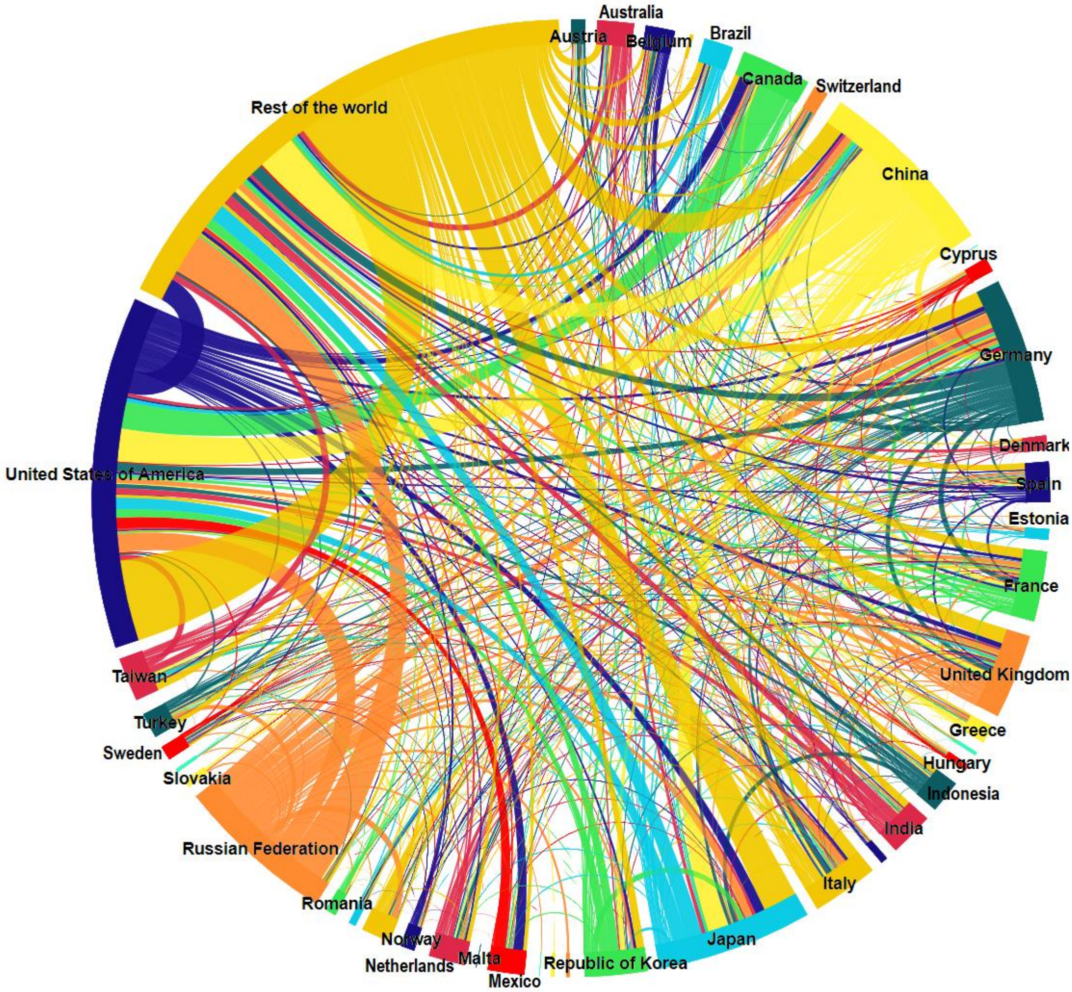


Figure 22: 2000 Main embodied carbon connections between the 43 countries + Rest of the world. The embodied CO_2 flow between every two nation is represented by a chord. The thickness of the chord is weighted on the volume of embodied carbon traded. The color of the chord corresponds to the one of the country where the flow starts.

13%), Canada (135 Mt, 11%), Russia (92 Mt, 7%), and the rest of the world (407 Mt, 33%). As for Chinese embodied carbon exports, 24% of them go to the USA, 15% to Japan (102 Mt), 18% to Europe (120 Mt), and 28% to RoW (188 Mt). Germany imports embodied carbon mostly from the rest of the EU (145 Mt, 39%), Russia (53 Mt, 14%), China (30 Mt, 8%) and the rest of the world (76 Mt, 20%). Although being one of the main German embodied energy importers, the role of the Netherlands in embodied CO_2 imports is very limited (5%). 38% of Russian embodied carbon exports are directed to EU 28 (278 Mt), 13% to the USA and 28% to the rest of the world (200 Mt).

In 2014 (figure 23), a significant part of the USA embodied carbon imports comes from China (375 Mt, 29%), Canada (114 Mt, 9%), EU (105 Mt, 8%), Russia (48 Mt, 4%), India (50 Mt,

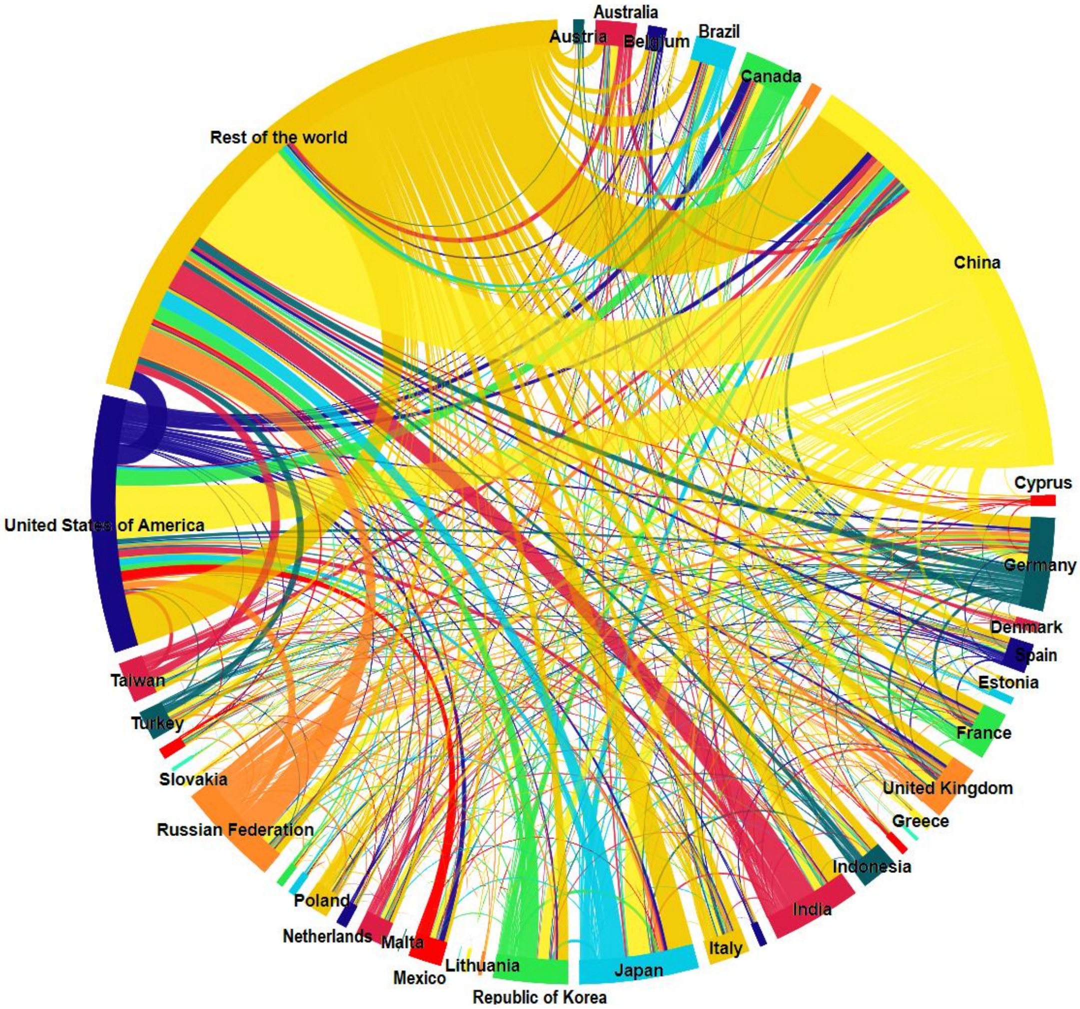


Figure 23: 2014 Main embodied carbon connections between the 43 countries + Rest of the world.

4%) and another 28% from the rest of the world (363 Mt). German embodied carbon imports from China account for 22% of the total (79 Mt), while EU countries contribute 30% (108 Mt), Russia the 9% (31 Mt) and RoW the 22%. Chinese embodied CO_2 emission exports are directed, respectively, for 17% to the United States, 16% to Europe (342 Mt), 11% to Japan and the Republic of Korea, and 38% is directed to the markets of the rest of the world (810 Mt). As for Indian embodied carbon exports, they are directed for 15% to the EU (58 Mt), 7% to China (29 Mt), and 13% to the USA (50 Mt), while 48% flows to the rest of the world (186 Mt). 27% of Russian exports are destined to Europe (145 Mt), 9% to China and the United States (50Mt), and 38% to the rest of the world (206 Mt).

Figure 25 shows a comparison between total carbon footprint and total carbon emissions per capita in 2000 and 2014, while figure 24 represents the carbon footprint per capita in space. In 2000, the highest values of TCFs are recorded in the USA, Luxembourg, Australia and Canada.

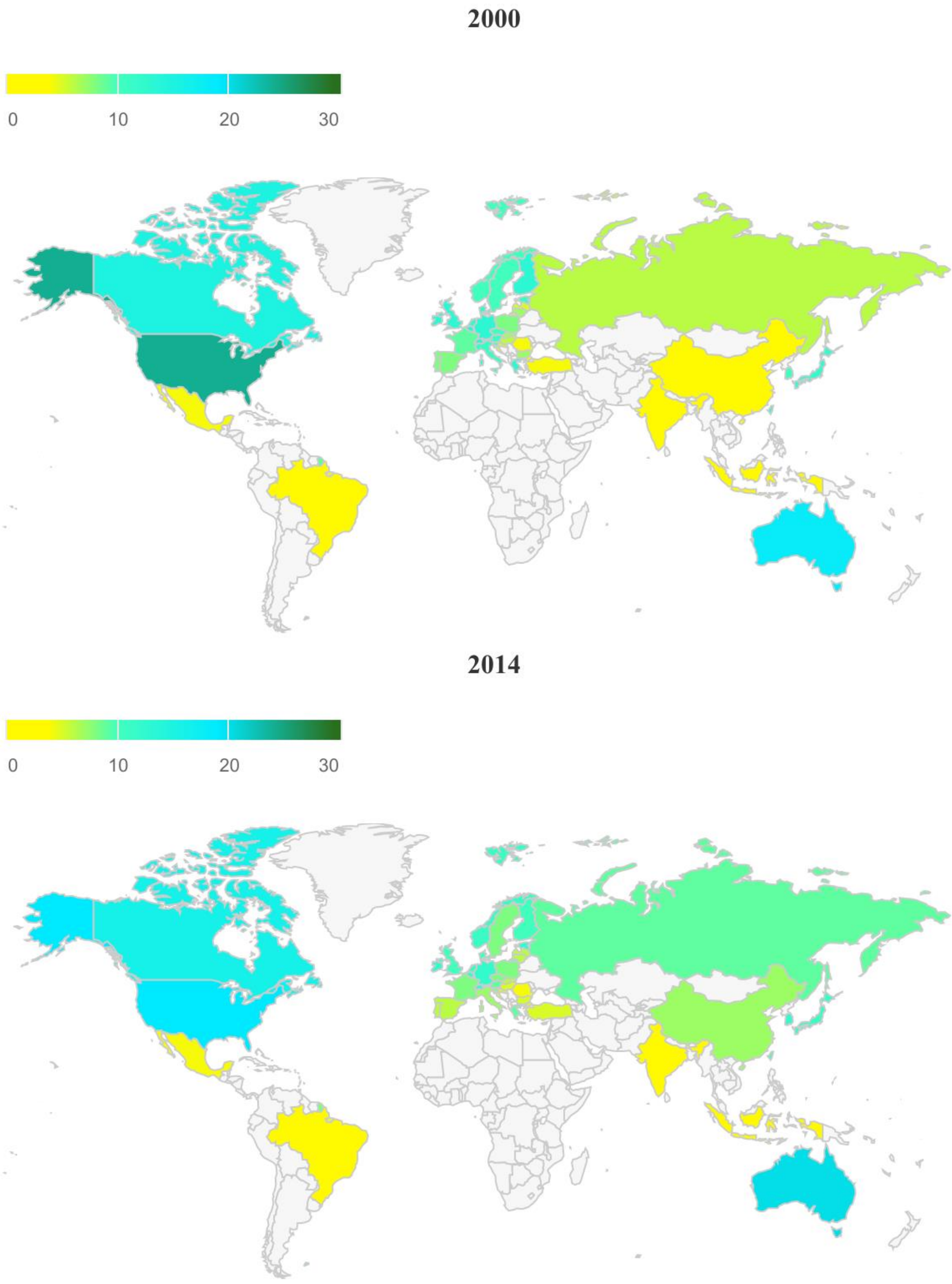


Figure 24: Distribution of carbon footprint per capita in 2000 and 2014, in t/cap.

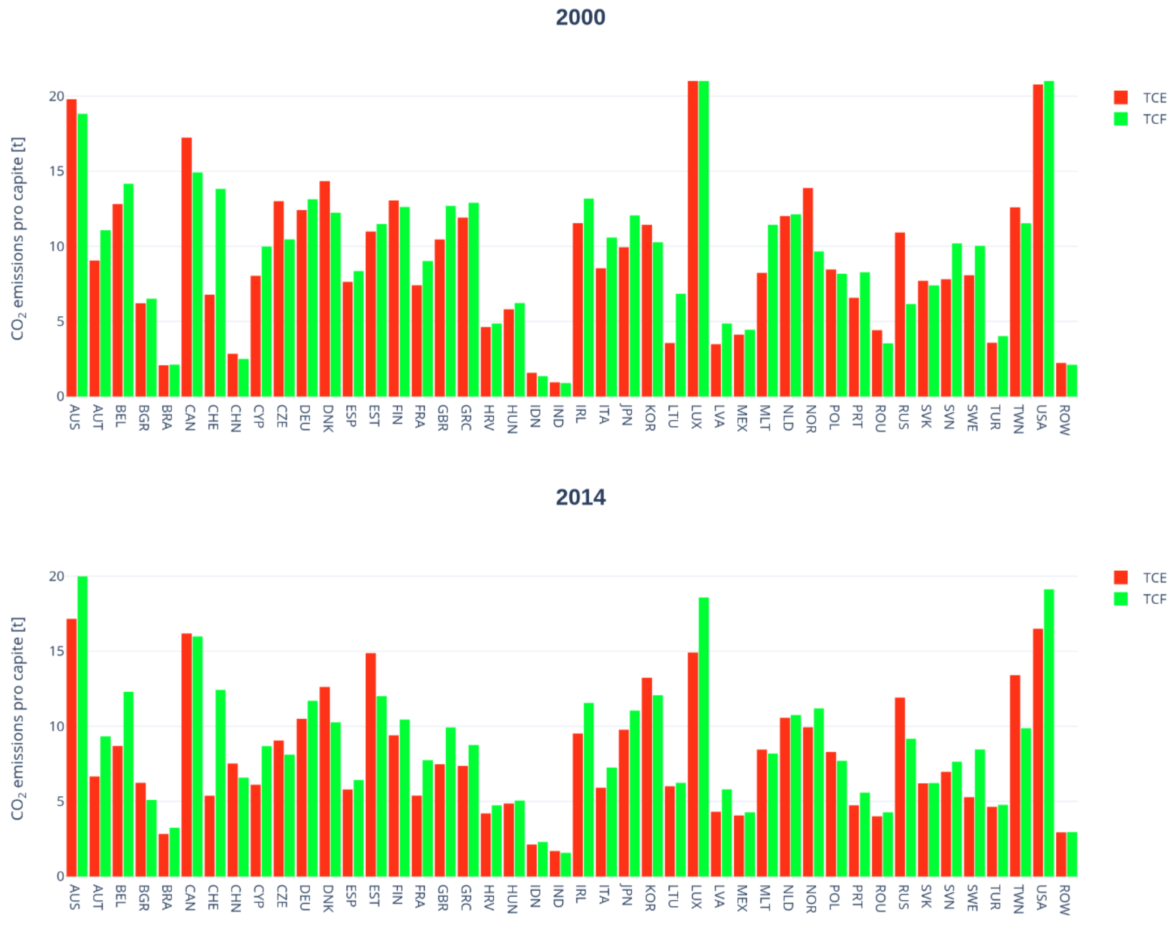


Figure 25: 2000 and 2014 comparison of countries' per capita Total Carbon Footprint (TCF) and Total Carbon Emissions (TCE)

Most of the European countries show intermediate footprint values, while India, Brazil, China and Indonesia are at the lowest levels. In 2014 European countries show a slight decrease in TCF per capita levels, together with the United States. The highest value of carbon footprint per capita is recorded in Australia, followed by the USA. China presents a visible increase, reaching the same level as European countries.

5. Discussion

Energy and carbon footprints showed how the traditional production-based perspective underestimates the energy use and carbon emissions that can be attributed to most of the high-income nations. Nevertheless, there are few exceptions, among them the Netherlands.

In both 2000 and 2014, the total energy footprint of the Netherlands is lower than its total energy use. The Netherlands is a wealthy trading country and an important exporter. According to the International Energy Agency report, the Dutch economy is focused on energy-intensive industries, including chemical and petrochemical and production of iron and steel [54]. In 2014 both production and consumption-based energy use inventories reduce due to a large cut of energy consumption related to domestic economic activities, but embodied energy imports see a small increase. This closes the gap between the two accounts. The Netherlands extensively contributes to German embodied energy imports, but its weight in embodied CO_2 imports is limited. This suggests that the Dutch energy mix, although being based on oil and natural gas, is relatively less carbon-intensive than the other exporting countries' one.

Another interesting consideration arises from the comparison of energy and carbon footprint results. In 2000, the resemblance between energy and CO_2 scenarios suggests there is no relevant difference among countries regarding the composition of their energy mix, being fossil fuels predominant almost everywhere. In 2014 USA, Japan and most European countries show an important cut of carbon emissions related to domestic economic activities, while the trend for energy is not that uniform among nations. This proves a general shift towards "cleaner" energy sources, cutting emissions more than energy use. However, in most cases, it is accompanied by an increase in the international trade contribution, suggesting the outsourcing of carbon-intensive sectors or, at least, a change in the final demand of goods and products.

According to the production-based accounting principle, in 2000 EU and the US together account for 44% of the global energy use and 39% of CO_2 emissions related to economic activities, and then decrease to 28% and 23%, respectively, in 2014. From the consumption-based perspective, their share increases to 49% and 45% in 2000 ad 32% and 27% in 2014. Since those countries account for a small fraction of the world's population, it is useful to introduce another layer by evaluating impacts per capita. Despite their outstanding growth, China and India's per capita energy use is much lower than Europe and the US level. However, in 2014, due to a balance between high-income countries' tendency to decarbonization and

China’s emissions growth, the Chinese per capita emissions almost reaches European average levels.
Around 26% of global energy use and carbon emissions related to economic activities are embodied in international trade. This result is consistent with the assessment of Zhang et al. about global carbon emissions in 2009 [18]. Global CO_2 emissions embodied in international trade increase from 5.85 billion tons in 2000 to 8.16 billion tons in 2008 and finally to 8.35 billion tons in 2014, revealing a decline in the recent growth rate. The initial increasing trend is confirmed by literature. Peters et al. [21] estimated that carbon emissions embodied in international trade rise from 4.3 to 7.8 billion tons during the period 1990-2008. Their calculation is based on the GTAP database. Including CO_2 emitted by households, the percentage of carbon embodied in international trade drops to 23%. As for energy use, this share corresponds to ~21%. Global energy use embodied in international trade is 97.8 EJ in 2000 and reaches 138.93 EJ in 2014 (+29.5%).
On average, the energy embodied in imports corresponds to 32% of the energy footprint of a country in 2000 and 36% in 2014. As for the carbon footprint, this percentage is even higher: 35% in 2000 and 42% in 2014. However, a comparison between countries shows significant distinctions in the composition of their energy and carbon footprints. For example, the industry sector in the USA and China is such that domestic consumption makes up for most of the national energy and carbon footprint. The United States is the largest embodied energy and carbon net importer, but imports correspond to just 18% of its energy footprint and 21% of its carbon footprint in 2014. The ratio between the TEF and TEU is ~1.1 and slightly higher for CO_2 emissions. On the other hand, for countries like Switzerland this ratio reaches values higher than to 2. Switzerland is reported in the literature as an example of false or “virtual” decoupling due to its great dependence on imports (physically and also in terms of embodied energy) [1], [39].
An interesting point of this study is it captures the Chinese extraordinary development. Whatever the accounting perspective or the object of the analysis, the escalation of Chinese figures is unbeaten. China entered the World Trade Organization in 2001 and then the dimension of its international trade rapidly increased [18]. It becomes the largest net exporter of both energy and carbon embodied in 2014, and imports account for 9% of its carbon footprint and 12% of its carbon footprint. Lan et al. [30] report that imports account for less than 10% of the Chinese energy footprint during the period 1990-2010. China is a major importer for all the

main economic powers but also those countries collected under the label "rest of the world". It is noteworthy that together with the expected energy and carbon embodied emissions exports rise, China also records an important growth in imports, especially from the rest of the world. This may suggest also China relocates energy and carbon-intensive steps of the production chain, as in fact, this country develops in an already highly interconnected economic framework. Another possible reason is that the demand for goods from abroad increased to sustain domestic production. During the period 1990-2010 Chinese industry saw an increase in mechanization and complexity and even if some reduction of energy consumption and emission policy begins to be implemented, this was not able to counter-balance the energy required by the growth [30].

The trend in time of EU and the USA shows they are reducing energy use and CO_2 emission during the period 2000-2014. Production and consumption accounts of these large economies seem to follow a similar trend, revealing how the two dimensions are highly interconnected. What changes with the adoption of one accounting perspective rather than the other is the absolute value of their energy use or carbon emissions. The difference between the production and consumption-based accounts represents the net embodied export/ import and it has been reducing since 2008 for Europe, the United States and China. This may be due to several reasons: for example, a change in the volume of these countries' imports/exports or a reduction of carbon and energy intensity of the goods they imported (based on technology improvements of the exporting nations or a shift in final demand).

6. Conclusions

This study used Environmentally Extended Global Multi-Regional Input-Output Analysis to evaluate international trade-related impacts from a consumption perspective. The analysis involved 44 countries (28 EU, 15 extra-EU and the "rest of the world") and two environmental indicators: emission relevant energy use and CO_2 emissions. The resulting consumption-based accounts were compared with the production-based inventories, revealing how the traditional perspective cannot be considered an exhaustive indicator in a globalized world. International trade has a relevant role in contemporary society and changed the global geography of environmental impacts. During the period 2000-2014, around 26% of global energy use and carbon emissions related to economic activities were embodied in international trade.
The footprint of a country accounts for energy used and CO_2 emitted locally and abroad to satisfy the national demand of goods and services, tracking down all the stages of the supply chain. Energy and carbon footprints showed that, in general, the traditional production-based measurements underestimated the energy use and carbon emissions assigned to high-income countries and, *vice versa*, developing economies turned out to be more virtuous. During the period 2014-2000 most European countries, the USA and Japan present a reduction of carbon emissions related to domestic economic activities, while the trend for energy is not that uniform among nations. However, it is generally accompanied by an increase in the international trade share, suggesting the outsourcing of relatively carbon-intensive sectors or, at least, a change in the final demand of goods and products.
A comparison between energy and carbon footprints composition shows significant differences among countries. For example, the industry sector in the USA and China is such that domestic consumption constitute most of the national energy and carbon footprint. The United States is the largest embodied energy and carbon net importer, but imports correspond to just 18% of its energy footprint and 21% of its carbon footprint in 2014. China is the largest embodied energy and carbon net exporter in 2014, and imports account for an even smaller percentage of the footprints. However, China records an important growth in embodied impacts imports, especially from the rest of the world, during the investigated period. On the other hand, for countries like Switzerland, the ratio between consumption and production-based accounts reaches values higher than 2, revealing how dependent they are on embodied energy and carbon imports.

The original question was: are high-income countries reducing their impacts *because* they are relocating abroad ecologically intensive steps of the production chains? The answer is not easy. Affluent economies resulted in most cases net importers of environmental loads, confirming that the impacts to sustain their consumption and lifestyle are often displaced outside of their borders. However, taking European Union as an example, both production and consumption-based accounts are declining in time during the period 2000-2014, even if the absolute value of the two indicators is different. Moreover, the forces driving these changes in time should be furtherly investigated. From a production-based perspective, energy efficiency improvements are effective measures for a country to save energy. The reduction of the energy footprint instead includes actions on the entire supply chain and a shift towards a more “sustainable” consumption. Additional developments of this study may include extending the analyzed period and investigating the relationship between consumption-based accounts (or an indicator of environmental impacts constructed on these results) and GDP or other well-being or human development indexes. Also, a larger sample of countries would be needed to take into account low-income nations' perspective.

Another interesting question arises from these conclusions: does international trade generate a global increase of environmental loads? The answer is not straightforward due to the complex network of goods and impact transfers. International flows should be analyzed in terms of balance between created and avoided ecological burdens.

The acknowledgment that globalization reshaped the way goods are produced and consequently how energy is used has several policy implications. Consumption-based accounting requires complex calculations, but it is a powerful tool to extend political decisions outside of the single country and adopt targets that are consistent with its level of consumption. The Paris agreement required participating countries to prepare and attain Nationally Determined Contributions (NDCs), consisting of long-term mitigation commitments about GHG reduction. Most countries submitted absolute reduction targets, but others like China and India communicated targets per unit of GDP, leaving space to further emission increase in absolute terms [55]. Governments should guarantee that national reduction attempts are not counterbalanced by the displacement of emissions towards countries with only relative commitments, trying to balance economic development and environmental protection. Countries could periodically calculate energy and carbon footprint together with traditional accounts, considering also impacts embodied in imports part of their environmental loads [28]. In the end, both perspectives should be addressed to find a global model that is sustainable for the environment and also fair.

Appendix A

A.1. WIOD country coverage list

No	Abbreviation	Country
1	AUS	Australia
2	AUT	Austria
3	BEL	Belgium
4	BGR	Bulgaria
5	BRA	Brazil
6	CAN	Canada
7	CHE	Switzerland
8	CHN	China
9	CYP	Cyprus
10	CZE	Czechia
11	DEU	Germany
12	DNK	Denmark
13	ESP	Spain
14	EST	Estonia
15	FIN	Finland
16	FRA	France
17	GBR	United Kingdom
18	GRC	Greece
19	HRV	Croatia
20	HUN	Hungary
21	IDN	Indonesia
22	IND	India
23	IRL	Ireland
24	ITA	Italy
25	JPN	Japan
26	KOR	Republic of Korea

27	LTU	Lithuania
28	LUX	Luxembourg
29	LVA	Latvia
30	MEX	Mexico
31	MLT	Malta
32	NLD	Netherlands
33	NOR	Norway
34	POL	Poland
35	PRT	Portugal
36	ROU	Romania
37	RUS	Russian Federation
38	SVK	Slovakia
39	SVN	Slovenia
40	SWE	Sweden
41	TUR	Turkey
42	TWN	Taiwan
43	USA	United States of America
44	ROW	Rest of the World

A.2. WIOD sector coverage list

No	Sector
1	Crop and animal production, hunting and related service activities
2	Forestry and logging
3	Fishing and aquaculture
4	Mining and quarrying
5	Manufacture of food products, beverages and tobacco products
6	Manufacture of textiles, wearing apparel and leather products
7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials

8	Manufacture of paper and paper products
9	Printing and reproduction of recorded media
10	Manufacture of coke and refined petroleum products
11	Manufacture of chemicals and chemical products
12	Manufacture of basic pharmaceutical products and pharmaceutical preparations
13	Manufacture of rubber and plastic products
14	Manufacture of other non-metallic mineral products
15	Manufacture of basic metals
16	Manufacture of fabricated metal products, except machinery and equipment
17	Manufacture of computer, electronic and optical products
18	Manufacture of electrical equipment
19	Manufacture of machinery and equipment n.e.c.
20	Manufacture of motor vehicles, trailers and semi-trailers
21	Manufacture of other transport equipment
22	Manufacture of furniture; other manufacturing
23	Repair and installation of machinery and equipment
24	Electricity, gas, steam and air conditioning supply
25	Water collection, treatment and supply
26	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
27	Construction
28	Wholesale and retail trade and repair of motor vehicles and motorcycles
29	Wholesale trade, except of motor vehicles and motorcycles
30	Retail trade, except of motor vehicles and motorcycles
31	Land transport and transport via pipelines
32	Water transport
33	Air transport
34	Warehousing and support activities for transportation
35	Postal and courier activities
36	Accommodation and food service activities
37	Publishing activities

38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
39	Telecommunications
40	Computer programming, consultancy and related activities; information service activities
41	Financial service activities, except insurance and pension funding
42	Insurance, reinsurance and pension funding, except compulsory social security
43	Activities auxiliary to financial services and insurance activities
44	Real estate activities
45	Legal and accounting activities; activities of head offices; management consultancy activities
46	Architectural and engineering activities; technical testing and analysis
47	Scientific research and development
48	Advertising and market research
49	Other professional, scientific and technical activities; veterinary activities
50	Administrative and support service activities
51	Public administration and defence; compulsory social security
52	Education
53	Human health and social work activities
54	Other service activities
55	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
56	Activities of extraterritorial organizations and bodies

Appendix B

B.1. Energy Footprints

TEF: Total Energy Footprint

TEU: Total Energy Use

Delta: Difference between TEF and TEU

TEFpc: Total Energy Footprint pro capite

TEUpc: Total Energy Use pro capite

If Delta is positive, the country listed is an embodied energy net importer and is highlighted in green. *Vice versa*, it is highlighted in yellow.

2000

Country	TEF [TJ]	TEU [TJ]	Delta [TJ]	Population	TEFpc [GJ]	TEUpc [GJ]
USA	118499975.3	105968519.4	12531455.84	281710914	420.64	376.16
DEU	20971147.12	16951657.66	4019489.46	81400883	257.63	208.25
JPN	29031574.8	25296453.72	3735121.08	127524168	227.66	198.37
GBR	13298941.05	10979673.47	2319267.58	58923305	225.70	186.34
ITA	10671746.72	8441109.272	2230637.45	56692178	188.24	148.89
FRA	13591879.07	12611090.67	980788.40	59015092	230.31	213.69
CHE	1909408.489	1108493.073	800915.42	7143764	267.28	155.17
MEX	7365614.455	6765079.307	600535.15	98899845	74.48	68.40
BEL	3167571.023	2567687.995	599883.03	10282046	308.07	249.73
ESP	6082380.805	5571912.946	510467.86	40824745	148.99	136.48
TUR	4012053.205	3555011.021	457042.18	63240196	63.44	56.21
AUT	1754248.946	1364158.427	390090.52	8069276	217.40	169.06
GRC	2028238.474	1668572.506	359665.97	11082103	183.02	150.56
PRT	1480501.249	1167573.4	312927.85	10297117	143.78	113.39
LTU	566803.0063	369523.5535	197279.45	3501842	161.86	105.52
POL	4579604.272	4392173.816	187430.46	38556699	118.78	113.91
IRL	778456.901	667264.5128	111192.39	3783095	205.77	176.38
BRA	8191790.173	8116229	75561.17	174790339	46.87	46.43
SVN	390743.4084	323602.9508	67140.46	1987710	196.58	162.80
LVA	276205.0986	209227.9509	66977.15	2384150	115.85	87.76
BGR	981721.5429	917957.7224	63763.82	7997951	122.75	114.77
SVK	868056.734	818574.194	49482.54	5399207	160.77	151.61
HRV	429005.1892	389873.9907	39131.20	4428075	96.88	88.05
CYP	139529.8463	103691.9808	35837.87	943288	147.92	109.93
EST	272987.2455	246252.6178	26734.63	1399111	195.11	176.01
LUX	201039.9821	177192.3764	23847.61	436106	460.99	406.31

MLT	77584.78722	55934.49107	21650.30	393649	197.09	142.09
HUN	1220241.189	1213325.063	6916.13	10220509	119.39	118.71
DNK	1154216.4	1182812.945	-28596.55	5341192	216.10	221.45
AUS	5361320.897	5528943.643	-167622.75	18991434	282.30	291.13
SWE	2630078.86	2818254.657	-188175.80	8881642	296.13	317.31
CZE	1785109.281	2007398.737	-222289.46	10289374	173.49	195.09
ROU	1555016.972	1795978.417	-240961.45	22137423	70.24	81.13
TWN	3960952.713	4263215.016	-302262.30	21966528	180.32	194.08
FIN	1533917.444	1843647.976	-309730.53	5187953	295.67	355.37
NOR	1222810.908	1613249.339	-390438.43	4499375	271.77	358.55
IND	18593482.82	19306904.1	-713421.28	1056575548	17.60	18.27
KOR	7841084.44	8592081.486	-750997.05	47379237	165.50	181.35
IDN	6282385.211	7074694.891	-792309.68	211513822	29.70	33.45
ROW	78986932.45	81188516.05	-2201583.60	2 075 932 691	38.05	39.11
CAN	9757840.056	12343797.85	-2585957.80	30588379	319.00	403.55
CHN	46330758.21	50602059.87	-4271301.66	1290550767	35.90	39.21
NLD	4259469.328	9344395.424	-5084926.10	15926188	267.45	586.73
RUS	20635381.9	33343248.43	-12707866.54	146404890	140.95	227.75

2014

Country	TEF [TJ]	TEU [TJ]	Delta [TJ]	Population	TEFpc [GJ]	TEUpc [GJ]
USA	117398545.87	104384131.57	13014414.30	318673422	368.40	327.56
GBR	12128967.74	9057496.19	3071471.55	65423048	185.39	138.45
JPN	24927097.01	21864565.18	3062531.83	128168630	194.49	170.59
DEU	17719742.74	15632843.84	2086898.90	81450370	217.55	191.93
FRA	13698932.92	12086325.88	1612607.04	64193550	213.40	188.28
ITA	9162876.98	7715466.59	1447410.39	60409622	151.68	127.72
AUS	7523038.71	6457039.97	1065998.74	23596426	318.82	273.64
BRA	14360502.23	13397300.36	963201.87	202763744	70.82	66.07
CHE	2161500.11	1344179.58	817320.54	8206003	263.40	163.80
IDN	11384064.36	10653793.23	730271.13	255128076	44.62	41.76
BEL	2804824.36	2258635.51	546188.85	11221225	249.96	201.28
MEX	8904944.64	8455205.37	449739.26	120355137	73.99	70.25
ESP	6223987.26	5782283.90	441703.37	46777927	133.05	123.61
AUT	1776002.35	1401809.91	374192.43	8615205	206.15	162.71
IRL	894957.91	644117.61	250840.30	4626852	193.43	139.21
TUR	6046013.54	5920533.81	125479.73	77229262	78.29	76.66
LTU	391374.12	299500.40	91873.72	2971498	131.71	100.79
ROU	1671404.48	1598984.04	72420.44	20035928	83.42	79.81
PRT	1230216.89	1164832.07	65384.82	10418224	118.08	111.81
CYP	158315.65	103960.51	54355.14	1152297	137.39	90.22
SVK	780674.91	732555.53	48119.38	5428798	143.80	134.94
LVA	274436.22	232657.41	41778.81	2021220	135.78	115.11

HRV	371820.43	330266.48	41553.95	4255518	87.37	77.61
LUX	305520.90	268141.62	37379.27	554512	550.97	483.56
POL	4622876.14	4614486.62	8389.52	38091095	121.36	121.14
MLT	65325.24	59882.10	5443.14	430190	151.85	139.20
SWE	2754296.95	2748938.73	5358.22	9692137	284.18	283.63
SVN	351551.05	352655.77	-1104.72	2067488	170.04	170.57
EST	277146.22	305944.89	-28798.67	1316273	210.55	232.43
GRC	1443401.35	1484497.20	-41095.85	10701460	134.88	138.72
DNK	1175567.84	1241910.24	-66342.40	5664199	207.54	219.26
HUN	1056439.41	1131892.45	-75453.05	9804991	107.75	115.44
NOR	1705149.86	1873422.05	-168272.19	5142269	331.59	364.32
BGR	766101.35	949630.05	-183528.70	7245648	105.73	131.06
CZE	1823613.43	2090577.71	-266964.28	10591104	172.18	197.39
FIN	1603074.56	1889020.82	-285946.26	5461410	293.53	345.89
KOR	10662340.72	11762766.46	-1100425.74	50607904	210.69	232.43
TWN	3878206.13	5020722.27	-1142516.15	23491976	165.09	213.72
IND	35112500.40	36379701.62	-1267201.22	1295600768	27.10	28.08
CAN	12883240.75	14257848.15	-1374607.40	35664338	361.24	399.78
ROW	153921520.65	156409274.83	-2487754.18	2673971902	57.56	58.49
NLD	3506673.35	6109181.02	-2602507.67	16892517	207.59	361.65
RUS	28068697.09	35686857.39	-7618160.30	144664837	194.03	246.69
CHN	121079198.60	133175694.82	-12096496.22	1399453966	86.52	95.16

B.2. Carbon footprints

TCF: Total Carbon Footprint

TCE: Total Carbon Emissions

Delta: Difference between TCF and TCE

TCFpc: Total Carbon Footprint pro capite

TCEpc: Total Carbon Emissions pro capite

2000

Country	TCF [kt]	TCE [kt]	Delta [kt]	Population	TCFpc [t]	TCE[t]
USA	6655702.91	5853864.13	801838.78	281710914	23.63	20.78
JPN	1537106.83	1267232.32	269874.51	127524168	12.05	9.94
GBR	747797.02	616151.43	131645.59	58923305	12.69	10.46
ITA	600287.07	483616.24	116670.83	56692178	10.59	8.53
FRA	532273.30	437276.20	94997.10	59015092	9.02	7.41

DEU	1068982.24	1010032.54	58949.70	81400883	13.13	12.41
CHE	98690.58	48474.83	50215.74	7143764	13.81	6.79
MEX	439922.37	407039.89	32882.48	98899845	4.45	4.12
ESP	340868.80	311656.22	29212.57	40824745	8.35	7.63
TUR	254457.25	226029.84	28427.41	63240196	4.02	3.57
PRT	85096.51	67669.30	17427.21	10297117	8.26	6.57
SWE	89030.53	71716.77	17313.76	8881642	10.02	8.07
AUT	89237.76	73010.63	16227.13	8069276	11.06	9.05
BEL	145644.83	131728.07	13916.76	10282046	14.16	12.81
LTU	23904.39	12437.79	11466.60	3501842	6.83	3.55
GRC	142968.11	131928.68	11039.43	11082103	12.90	11.90
BRA	370298.92	360456.17	9842.75	174790339	2.12	2.06
IRL	49818.35	43696.19	6122.16	3783095	13.17	11.55
SVN	20251.59	15508.39	4743.20	1987710	10.19	7.80
HUN	63484.89	59355.51	4129.38	10220509	6.21	5.81
LVA	11572.28	8298.49	3273.79	2384150	4.85	3.48
BGR	52073.93	49593.50	2480.43	7997951	6.51	6.20
NLD	193122.82	191272.48	1850.34	15926188	12.13	12.01
CYP	9417.95	7579.40	1838.55	943288	9.98	8.04
MLT	4501.99	3236.62	1265.37	393649	11.44	8.22
HRV	21490.78	20439.64	1051.14	4428075	4.85	4.62
EST	16053.97	15354.58	699.39	1399111	11.47	10.97
LUX	11406.79	11580.89	-174.10	436106	26.16	26.56
SVK	39942.68	41533.15	-1590.47	5399207	7.40	7.69
FIN	65459.66	67688.96	-2229.30	5187953	12.62	13.05
POL	315104.30	326080.13	-10975.84	38556699	8.17	8.46
DNK	65271.28	76548.35	-11277.08	5341192	12.22	14.33
AUS	357481.15	376013.32	-18532.17	18991434	18.82	19.80
NOR	43468.23	62488.51	-19020.28	4499375	9.66	13.89
ROU	78294.15	97555.23	-19261.08	22137423	3.54	4.41
TWN	253581.83	276779.81	-23197.98	21966528	11.54	12.60
CZE	107639.43	133814.55	-26175.12	10289374	10.46	13.01
IDN	285727.58	333219.14	-47491.57	211513822	1.35	1.58
KOR	486987.41	541726.04	-54738.63	47379237	10.28	11.43
IND	938216.05	994487.72	-56271.67	1056575548	0.89	0.94
CAN	456567.88	527300.08	-70732.20	30588379	14.93	17.24
ROW	4385973.30	4638796.46	-252823.16	2075932691	2.11	2.23
CHN	3222940.57	3667640.83	-444700.27	1290550767	2.50	2.84
RUS	901689.60	1599284.30	-697594.70	146404890	6.16	10.92

2014

Country	TCF [kt]	TCE [kt]	Delta [kt]	Population	TCFpc [t]	TCE[t]
USA	6090717.72	5257452.26	833265.46	318673422	19.11	16.50

JPN	1415777.35	1251980.26	163797.09	128168630	11.05	9.77
GBR	649028.02	488331.99	160696.03	65423048	9.92	7.46
FRA	497233.71	345586.80	151646.91	64193550	7.75	5.38
DEU	951904.83	855312.28	96592.55	81450370	11.69	10.50
ROW	7922496.13	7835123.08	87373.05	2673971902	2.96	2.93
BRA	655224.53	572372.75	82851.78	202763744	3.23	2.82
ITA	437797.69	356596.75	81200.94	60409622	7.25	5.90
AUS	471591.49	404864.84	66726.65	23596426	19.99	17.16
CHE	101932.75	44067.03	57865.72	8206003	12.42	5.37
BEL	138059.20	97560.21	40498.99	11221225	12.30	8.69
IDN	582488.49	542875.53	39612.95	255128076	2.28	2.13
SWE	81925.93	51175.94	30749.98	9692137	8.45	5.28
ESP	299998.88	270385.53	29613.35	46777927	6.41	5.78
MEX	513475.39	488677.53	24797.86	120355137	4.27	4.06
AUT	80354.67	57324.87	23029.80	8615205	9.33	6.65
GRC	93618.17	78655.82	14962.35	10701460	8.75	7.35
TUR	368384.44	357559.97	10824.48	77229262	4.77	4.63
IRL	53473.53	44079.03	9394.50	4626852	11.56	9.53
PRT	58149.23	49364.00	8785.23	10418224	5.58	4.74
NOR	57528.44	51116.22	6412.22	5142269	11.19	9.94
FIN	57031.29	51307.35	5723.94	5461410	10.44	9.39
ROU	85408.66	80216.34	5192.32	20035928	4.26	4.00
LVA	11701.41	8695.80	3005.60	2021220	5.79	4.30
CYP	10005.83	7029.16	2976.68	1152297	8.68	6.10
NLD	181436.78	178544.83	2891.95	16892517	10.74	10.57
HRV	20152.16	17850.67	2301.49	4255518	4.74	4.19
LUX	10298.00	8270.31	2027.69	554512	18.57	14.91
HUN	49458.02	47587.41	1870.61	9804991	5.04	4.85
SVN	15799.85	14409.52	1390.33	2067488	7.64	6.97
LTU	18536.37	17832.49	703.88	2971498	6.24	6.00
SVK	33747.82	33564.67	183.15	5428798	6.22	6.18
MLT	3521.25	3634.28	-113.03	430190	8.19	8.45
EST	15797.09	19565.94	-3768.85	1316273	12.00	14.86
CAN	569933.83	576979.86	-7046.02	35664338	15.98	16.18
BGR	36949.64	45142.47	-8192.83	7245648	5.10	6.23
CZE	85800.65	95800.13	-9999.48	10591104	8.10	9.05
DNK	58125.21	71497.68	-13372.47	5664199	10.26	12.62
POL	293145.80	315600.41	-22454.61	38091095	7.70	8.29
KOR	611193.88	670005.04	-58811.15	50607904	12.08	13.24
TWN	231955.98	314702.05	-82746.07	23491976	9.87	13.40
IND	2038225.46	2195307.32	-157081.86	1295600768	1.57	1.69
RUS	1324808.28	1723086.13	-398277.84	144664837	9.16	11.91
CHN	9212069.52	10528552.99	-1316483.47	1399453966	6.58	7.52

Appendix C

C.1. Glossary

e_{11} Goods produced in country 1 purchased in country 1	**e_{12}** Goods produced in country 1 purchased in country 2 (exports from country 1 to 2)
e_{21} Goods produced in country 2 purchased in country 1 (imports of country 1 from 2)	**e_{22}** Goods produced in country 2 purchased in country 2

Embodied energy: energy used to produce goods including all stages from material extraction to the final sale

Production-based account (PBA): traditional accounting principle of energy related to economic and industrial activities. It corresponds to domestic energy use including energy consumption to produce exports. For country 1 it is equal to $e_{11}+e_{12}$

Consumption-based account (CBA): starting from PBA, it excludes exports but includes energy associated with the production of imports. For country 1 it is equal to $e_{11}+e_{21}$

Total Energy Use (TEU): production-based accounts of energy related to economic activities + households consumption

Total Energy Footprint (TEF): consumption-based accounts of energy related to economic activities + households consumption

Embodied energy net exporter (EENE): PBA-CBA= $e_{12}- e_{21}>0$

Embodied energy net importer (EENI): PBA-CBA= $e_{12}- e_{21}<0$

Bibliography

[1] V. Moreau and F. Vuille, "Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade," *Applied Energy*, vol. 215, Apr. 2018, doi: 10.1016/j.apenergy.2018.01.044.

[2] C. Pasten and J. C. Santamarina, "Energy and quality of life," *Energy Policy*, vol. 49, pp. 468–476, Oct. 2012, doi: 10.1016/j.enpol.2012.06.051.

[3] V. Smil, *Energy and Civilization: A History*. The MIT Press, 2017. doi: 10.7551/mitpress/10752.001.0001.

[4] V. Kulionis and R. Wood, "Explaining decoupling in high income countries: A structural decomposition analysis of the change in energy footprint from 1970 to 2009," *Energy*, vol. 194, p. 116909, Mar. 2020, doi: 10.1016/j.energy.2020.116909.

[5] A. Jess, "What might be the energy demand and energy mix to reconcile the world's pursuit of welfare and happiness with the necessity to preserve the integrity of the biosphere?," *Energy Policy*, vol. 38, no. 8, pp. 4663–4678, Aug. 2010, doi: 10.1016/j.enpol.2010.04.026.

[6] A. Mazur, "Does increasing energy or electricity consumption improve quality of life in industrial nations?," *Energy Policy*, vol. 39, no. 5, pp. 2568–2572, May 2011, doi: 10.1016/j.enpol.2011.02.024.

[7] J. Pretty, "The Consumption of a Finite Planet: Well-Being, Convergence, Divergence and the Nascent Green Economy," *Environmental and Resource Economics*, vol. 55, no. 4, Aug. 2013, doi: 10.1007/s10640-013-9680-9.

[8] R. B. Jackson *et al.*, "Global energy growth is outpacing decarbonization," *Environmental Research Letters*, vol. 13, no. 12, Dec. 2018, doi: 10.1088/1748-9326/aaf303.

[9] G. Grossman and A. Krueger, "Environmental Impacts of a North American Free Trade Agreement," Cambridge, MA, Nov. 1991. doi: 10.3386/w3914.

[10] P. J. Burke, "The national-level energy ladder and its carbon implications," *Environment and Development Economics*, vol. 18, no. 4, Aug. 2013, doi: 10.1017/S1355770X13000090.

[11] T. Luzzati, M. Orsini, and G. Gucciardi, "A multiscale reassessment of the Environmental Kuznets Curve for energy and CO2 emissions," *Energy Policy*, vol. 122, pp. 612–621, Nov. 2018, doi: 10.1016/j.enpol.2018.07.019.

[12] O. Akizu-Gardoki, C. Kunze, A. Coxeter, G. Bueno, T. Wiedmann, and J. M. Lopez-Guede, "Discovery of a possible Well-being Turning Point within energy footprint accounts which may support the degrowth theory," *Energy for Sustainable Development*, vol. 59, Dec. 2020, doi: 10.1016/j.esd.2020.09.001.

[13] R. Baldwin, "Globalisation: the great unbundling(s)," *Economic Council of Finland*. Economic Council of Finland, 2006.

[14] O. Akizu-Gardoki *et al.*, "Decoupling between human development and energy consumption within footprint accounts," *Journal of Cleaner Production*, vol. 202. Elsevier Ltd, pp. 1145–1157, Nov. 20, 2018. doi: 10.1016/j.jclepro.2018.08.235.

[15] I. Arto, I. Capellán-Pérez, R. Lago, G. Bueno, and R. Bermejo, "The energy requirements of a developed world," *Energy for Sustainable Development*, vol. 33, pp. 1–13, Aug. 2016, doi: 10.1016/j.esd.2016.04.001.

[16] T. Wiedmann and M. Lenzen, "Environmental and social footprints of international trade," *Nature Geoscience*, 2018, doi: 10.1038/s41561-018-0113-9.

[17] R. Baldwin and J. Lopez-Gonzalez, "Supply-chain Trade: A Portrait of Global Patterns and Several Testable Hypotheses," *The World Economy*, vol. 38, no. 11, Nov. 2015, doi: 10.1111/twec.12189.

[18] Z. Zhang, K. Zhu, and G. J. D. Hewings, "A multi-regional input–output analysis of the pollution haven hypothesis from the perspective of global production fragmentation," *Energy Economics*, vol. 64, pp. 13–23, May 2017, doi: 10.1016/j.eneco.2017.03.007.

[19] M. S. Taylor, "Unbundling the pollution haven hypothesis," *Advances in Economic Analysis & Policy*, vol. 4, no. 2, 2005.

[20] G. P. Peters and E. G. Hertwich, "Post-Kyoto greenhouse gas inventories: production versus consumption," *Climatic Change*, vol. 86, pp. 51–66, 2008, doi: 10.1007/s10584-007-9280-1.

[21] G. P. Peters, J. C. Minx, C. L. Weber, and O. Edenhofer, "Growth in emission transfers via international trade from 1990 to 2008," *Proceedings of the National Academy of Sciences*, vol. 108, no. 21, May 2011, doi: 10.1073/pnas.1006388108.

[22] G. P. Peters and E. G. Hertwich, "Policy Analysis CO 2 Embodied in International Trade with Implications for Global Climate Policy," *Environmental Science & Technology*, vol. 42, no. 5, pp. 1401–1407, 2008, doi: 10.1021/es072023k.

[23] G. P. Peters, "From production-based to consumption-based national emission inventories," *Ecological Economics*, vol. 65, no. 1, pp. 13–23, Mar. 2008, doi: 10.1016/j.ecolecon.2007.10.014.

[24] Z.-M. Chen *et al.*, "Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries," *Nature Communications*, vol. 9, no. 1, Dec. 2018, doi: 10.1038/s41467-018-05905-y.

[25] T. Wiedmann, "A review of recent multi-region input-output models used for consumption-based emission and resource accounting," *Ecological Economics*, vol. 69, no. 2. Elsevier, pp. 211–222, Dec. 15, 2009. doi: 10.1016/j.ecolecon.2009.08.026.

[26] W. Leontief, “Environmental Repercussions and the Economic Structure: An Input-Output Approach,” *The Review of Economics and Statistics*, vol. 52, no. 3, Aug. 1970, doi: 10.2307/1926294.

[27] R. E. Miller and P. D. Blair, *Input-Output Analysis: Foundations and Extensions*, 2nd ed. Cambridge, UK: Cambridge University Press, New York, 2009.

[28] T. Wiedmann, H. C. Wilting, M. Lenzen, S. Lutter, and V. Palm, “Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis,” *Ecological Economics*, vol. 70, no. 11, pp. 1937–1945, Sep. 2011, doi: 10.1016/j.ecolecon.2011.06.014.

[29] B. Chen *et al.*, “Global energy flows embodied in international trade: A combination of environmentally extended input–output analysis and complex network analysis,” *Applied Energy*, vol. 210, pp. 98–107, Jan. 2018, doi: 10.1016/j.apenergy.2017.10.113.

[30] J. Lan, A. Malik, M. Lenzen, D. McBain, and K. Kanemoto, “A structural decomposition analysis of global energy footprints,” *Applied Energy*, vol. 163, Feb. 2016, doi: 10.1016/j.apenergy.2015.10.178.

[31] G. Q. Chen and M. Y. Han, “Global supply chain of arable land use: Production-based and consumption-based trade imbalance,” *Land Use Policy*, vol. 49, pp. 118–130, Dec. 2015, doi: 10.1016/j.landusepol.2015.07.023.

[32] I. Arto, V. Andreoni, and J. M. Rueda-Cantuche, “Global use of water resources: A multiregional analysis of water use, water footprint and water trade balance,” *Water Resources and Economics*, vol. 15, Jul. 2016, doi: 10.1016/j.wre.2016.04.002.

[33] J. Meng *et al.*, “Globalization and pollution: tele-connecting local primary $PM_{2.5}$ emissions to global consumption,” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 472, no. 2195, Nov. 2016, doi: 10.1098/rspa.2016.0380.

[34] K. Kanemoto, D. Moran, M. Lenzen, and A. Geschke, “International trade undermines national emission reduction targets: New evidence from air pollution,” *Global Environmental Change*, vol. 24, no. 1, pp. 52–59, Jan. 2014, doi: 10.1016/j.gloenvcha.2013.09.008.

[35] A. Gazheli, J. van den Bergh, and M. Antal, “How realistic is green growth? Sectoral-level carbon intensity versus productivity,” *Journal of Cleaner Production*, vol. 129, Aug. 2016, doi: 10.1016/j.jclepro.2016.04.032.

[36] A. Alsamawi, J. Murray, and M. Lenzen, “The Employment Footprints of Nations,” *Journal of Industrial Ecology*, vol. 18, no. 1, Feb. 2014, doi: 10.1111/jiec.12104.

[37] A. Chaudhary and T. M. Brooks, “National Consumption and Global Trade Impacts on Biodiversity,” *World Development*, vol. 121, pp. 178–187, Sep. 2019, doi: 10.1016/j.worlddev.2017.10.012.

[38] G. Q. Chen and X. F. Wu, “Energy overview for globalized world economy: Source, supply chain and sink,” *Renewable and Sustainable Energy Reviews*, vol. 69. Elsevier Ltd, pp. 735–749, Mar. 01, 2017. doi: 10.1016/j.rser.2016.11.151.

[39] O. Akizu-Gardoki *et al.*, “Hidden Energy Flow indicator to reflect the outsourced energy requirements of countries,” *Journal of Cleaner Production*, vol. 278, p. 123827, Jan. 2021, doi: 10.1016/j.jclepro.2020.123827.

[40] A. Owen, P. Brockway, L. Brand-Correa, L. Bunse, M. Sakai, and J. Barrett, “Energy consumption-based accounts: A comparison of results using different energy extension vectors,” *Applied Energy*, vol. 190, Mar. 2017, doi: 10.1016/j.apenergy.2016.12.089.

[41] M. Lenzen, “AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT,” *Economic Systems Research*, vol. 23, no. 1, Mar. 2011, doi: 10.1080/09535314.2010.548793.

[42] H. Wieland *et al.*, “Supply versus use designs of environmental extensions in input–output analysis: Conceptual and empirical implications for the case of energy,” *Journal of Industrial Ecology*, vol. 24, no. 3, Jun. 2020, doi: 10.1111/jiec.12975.

[43] H. Weisz and F. Duchin, “Physical and monetary input-output analysis: What makes the difference?,” *Ecological Economics*, vol. 57, no. 3, pp. 534–541, May 2006, doi: 10.1016/j.ecolecon.2005.05.011.

[44] A. Schaffartzik, D. Wiedenhofer, and N. Eisenmenger, “Raw Material Equivalents: The Challenges of Accounting for Sustainability in a Globalized World,” vol. 7, pp. 5345–5370, 2015, doi: 10.3390/su7055345.

[45] E. Dietzenbacher, B. Los, R. Stehrer, M. Timmer, and G. de Vries, “THE CONSTRUCTION OF WORLD INPUT–OUTPUT TABLES IN THE WIOD PROJECT,” *Economic Systems Research*, vol. 25, no. 1, Mar. 2013, doi: 10.1080/09535314.2012.761180.

[46] M. Lenzen, D. Moran, K. Kanemoto, and A. Geschke, “BUILDING EORA: A GLOBAL MULTI-REGION INPUT–OUTPUT DATABASE AT HIGH COUNTRY AND SECTOR RESOLUTION,” *Economic Systems Research*, vol. 25, no. 1, Mar. 2013, doi: 10.1080/09535314.2013.769938.

[47] R. Wood, T. R. Hawkins, E. G. Hertwich, and A. Tukker, “HARMONISING NATIONAL INPUT—OUTPUT TABLES FOR CONSUMPTION-BASED ACCOUNTING — EXPERIENCES FROM EXIOPOL,” *Economic Systems Research*, vol. 26, no. 4, Oct. 2014, doi: 10.1080/09535314.2014.960913.

[48] G. P. Peters, R. Andrew, and J. Lennox, “CONSTRUCTING AN ENVIRONMENTALLY-EXTENDED MULTI-REGIONAL INPUT–OUTPUT TABLE USING THE GTAP DATABASE,” *Economic Systems Research*, vol. 23, no. 2, Jun. 2011, doi: 10.1080/09535314.2011.563234.

[49] D. Moran and R. Wood, “CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU’S CONSUMPTION-BASED CARBON ACCOUNTS,”

Economic Systems Research, vol. 26, no. 3, Jul. 2014, doi: 10.1080/09535314.2014.935298.

[50] M. P. Timmer, E. Dietzenbacher, B. Los, R. Stehrer, and G. J. de Vries, "An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production," *Review of International Economics*, vol. 23, no. 3, Aug. 2015, doi: 10.1111/roie.12178.

[51] T. D. Corsatea *et al.*, "World Input-Output Database Environmental Accounts. Update 2000-2016," Luxembourg, 2019.

[52] A. Genty, I. Arto, and F. Neuwahl, "Final database of environmental satellite accounts: technical report on their complilation," Apr. 2012. Accessed: May 17, 2021. [Online]. Available: http://www.wiod.org/publications/source_docs/Environmental_Sources.pdf

[53] IEA, "Energy Policies of IEA Countries: Australia 2018 Review," Paris, 2018. Accessed: Jun. 28, 2021. [Online]. Available: https://www.iea.org/reports/energy-policies-of-iea-countries-australia-2018-review

[54] IEA, "The Netherlands 2020," Paris, 2020. Accessed: Jun. 26, 2021. [Online]. Available: https://www.iea.org/reports/the-netherlands-2020

[55] United Nations, "Aggregate effect of the intended nationally determined contributions: an update ," 2016. Accessed: Jun. 28, 2021. [Online]. Available: https://unfccc.int/resource/docs/2016/cop22/eng/02.pdf