Journal of Cleaner Production 278 (2021) 123827

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Hidden Energy Flow indicator to reflect the outsourced energy requirements of countries

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ARTICLE INFO

Article history:
Received 30 April 2020
Received in revised form
29 July 2020
Accepted 14 August 2020
Available online 22 August 2020

Handling editor. Yutao Wang

Keywords:
Hidden energy flow indicator
Energy footprint
Energy transition
Consumption-based accounts
Sustainability
Energy justice

ABSTRACT

Globalisation and the outsourcing of industrial manufacturing from developed to less developed countries has an increasing effect on the national energy balances of most developed economies. The current standard metric Total Primary Energy Supply of a country does not take into account the energy embodied in goods and services imported from other countries, leading to the perverse outcome of a country appearing to be more sustainable the more it outsources its energy-intensive industries. Academia has addressed this problem by suggesting the use of the Total Primary Energy Footprint as an additional metric, but there has not been a clear proposal put forward by academia to governments or international institutions about how to officially adopt Consumption-Based Accounting in the field of energy. This article states that acknowledging the existence of embodied energy flows is indispensable when formulating new national and international energy policies for the transition towards energy systems that are socially and environmentally more sustainable. In this study, the Hidden Energy Flow indicator of 44 countries has been quantified using, for the first time, five different Global Multi-Regional Input-Output databases for the latest available year, 2011. The proposed indicator provides a percentage to be added to or subtracted from the Total Primary Energy Used value of a country, provided by the International Energy Agency, to get its real consumption-based energy requirement. This study demonstrates that, from 44 countries analysed, the ten most developed countries demand on average 18.5% more energy than measured by the International Energy Agency; the medium developed 24 countries demand 12.4% more, and the ten least developed countries demand 1.6% less. This means that most developed and medium developed countries displace their indirect energy consumption towards less developed countries in a hidden way. Furthermore, this research supports evidence that direct energy consumption in households is less relevant than the energy embodied in goods and services purchased by households, reaching 59.1% in the case of Switzerland, used as a reference among developed countries. The proposed Hidden Energy Flow indicator supports scientists, policymakers and citizens in the effort to focus the energy transition actions towards conducting the necessary energy consumption and production changes in the most effective way, improving energy justice and energy democracy.

1. Introduction

In the current globalised era, high-income countries tend to outsource their heavy industry production or even service management from lower-income countries, mainly to be competitive and make more profit in internationalised markets. The value of

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https://doi.org/10.1016/j.jclepro.2020.123827
0959-6526/

world merchandise exports grew more than 260-fold from 1948 (US$59 billion) to 2016 (US$15,464 billion) and, on average, exports made up 29% of a country's gross domestic product in 2016 (Wiedmann and Lenzen, 2018). Thus, taking into account the complexity of international production flows, traditional production-based energy measurement systems (Production Based Accounts, PBA) are no longer able to provide a whole panorama of the energy consumed by the inhabitants of a country as a result of their lifestyle. Therefore, the whole international energy consumption panorama is now being reinterpreted with Consumption Based Accounts (CBA). For some countries that have apparently been decreasing their energy consumption in recent years (such as the United Kingdom or Switzerland), it has been detected that this is partial interpretation due the outsourcing of their energy consumption (Hardt et al., 2018) (Moreau and Vuille, 2018) (Akizu-Gardoki et al., 2018). According to Hardt et al. (2018), most of the energy reductions from structural changes in the UK are the result of offshoring production. In fact, in the case of Switzerland, a "virtual decoupling" has been detected, meaning that, while a national reduction in energy consumption is claimed, in reality, an increase in consumption is occurring when taking into account the energy consumed outside national boundaries (Moreau and Vuille, 2018). The same problematic virtual decoupling phenomenon has been detected in later analyses in 10 countries for years 2000–2014: Australia, Canada, Czech Republic, Luxemburg, Norway, Netherlands, Romania, Tajikistan, Slovakia and Switzerland (Akizu-Gardoki et al., 2018). Similarly, countries that have apparently had a high energy consumption increase in the last 20 years (such as China, India, Korea, Russia, or Bulgaria) have been reported to use only part of that energy to satisfy their own needs and part to provide goods and services to other countries (Moreau and Vuille, 2018), (Arto et al., 2016).

This energy displacement between developed and developing countries generates a confusion when examining the energy requirements for the achieved living standards, since most developed countries seem to show that they need less energy than the quantity really needed in order achieve higher development standards. This could generate confusions even when choosing the "most sustainable countries of reference" and their respective energy policies to be followed, or to find out how much energy per capita is required to achieve high standards of development.

The problem has been previously addressed in significant studies, and Total Primary Energy Footprint (TPEF) data has been calculated for several countries for certain year periods, offering an alternative to the PBA Total Primary Energy Supply (TPES) estimations. In the estimation of country footprints, variations and errors in results have been detected due to different sectorial aggregations (Zhang et al., 2018), suggesting a non-aggregated use of data. However, the standardisation of energy footprint data is lacking and there are discrepancies in results; thus, it is difficult to replace the use of TPES data with TPEF data in an extensive and normalised way. This has been thoroughly dealt with in CO_2 Consumption Based Accounts (CBA) (Moran and Wood, 2014), (Owen, 2017), where Eora, GTAP and WIOD Databases are compared. GTAP and WIOD databases have also been compared in Carbon Footprints, concluding similarities higher than 75–80% (Arto et al., 2014). Furthermore, although the CBA in policy applications have been considered necessary to minimise their uncertainty and ensure their robustness (Rodrigues et al., 2018), there is an absence of comparative information in the energy sector at global level.

Given this context, the main goal of this research is to generate a unified indicator of Hidden Energy Flows using the latest reliable data currently available (2011). This study does not aim to emit an ethical judgement of exporting or importing embodied energy, but rather to attain the ability to measure net embodied energy in a standardised way, within a single indicator. The percentage difference (±%) between TPES (offered by the International Energy Agency, IEA) and TPEF calculated by Global Multi-Regional Input-Output methodology (GMRIO) has been defined as Hidden Energy Flows (HEF). The concept of HEF has its origins in the term Hidden Debt (between developed and non-developed countries) in the frame of International Cooperation and coined by Akizu et al. (2017) (Akizu et al., 2018). HEF allows us to understand the extent to which a country's energy consumption according to the CBA deviates from traditional measurements of energy consumption based on PBA. If countries are sincere and can recognise their energy consumption, it may enhance global energy literacy and promote the transition towards socio-environmentally lower-impact energy systems.

Thus, the specific aims of this article are twofold. The first is to define a standardised HEF indicator, in order to offer the amount of energy requirement that all of the 43 counties analysed and RoW (rest of the world) have imported or exported embodied in products or services. This first novel contribution is a tool to better understand global Energy Justice (Sovacool and Dworkin, 2015), since it shows in precise numbers how developed countries are using the energetic resources of non-developed ones in general, and how some of the developed countries are more dependent than others. This first goal also provides a country more tools to disaggregate the Total Primary Energy Consumption into different consumption categories, such as: energy consumed directly at homes, energy consumed embodied in products and services, as well as transformation and losses; giving more knowledge to the inhabitants of a country to decide where to start reducing energy consumption and contributing to the Democratization of Energy (Burke and Stephens, 2017). The HEF indicator will help academics, policymakers and even citizens to understand how much energy is needed when consumption-based accounts are taken into account and standards of living can be reflected.

Secondly, this article allows us to understand why five MRIO databases (Eora, WIOD, EXIOBASE, OECD and GTAP) provide diverging results when calculating the average HEF for the year 2011. This shows the need for further standardisation of GMRIO databases, since IO analysis is a relatively new field in the environmental economic sector. In the incoming years, further standardisation could provide direct and significant benefits in environmentally friendly policymaking.

2. Literature review

The following literature review contextualises this research within 34 relevant (cited) international articles using "footprint" and "energy footprint" keywords, mainly using the ScienceDirect research engine, which encompasses the Journal of Cleaner Production (classification of analysed papers in Supplementary Material Table A.1). One of the first national Energy Ecological Footprint (EEF) analyses was developed for China (Chen and Lin, 2008), integrating the CO_2 emissions from burning fossil fuels within the corresponding bioproduction area. For the UK, the development of the first empirical comparison of energy footprints embodied in trade (Wiedmann, 2009) clearly detected that the use of National Footprint Accounts (NFA) was very restrictive, and Input-Output based models, such as UK-MRIO were more comprehensive, robust, and offered results of higher relevance. The first global energy footprint was calculated with the GTAP database (Chen and Chen, 2011) (Chen and Chen, 2013), but inaccuracies due to differences in the Input-Output (IO) structure were perceived (Arto et al., 2016). The accuracy of the results for 39 countries in the period 1998 to 2008 was improved with the use of the WIOD database (Arto et al., 2016). Accuracy analyses have also been performed with the structural decomposition analysis of global energy footprints (Lan et al., 2016), using the Eora dataset for 189 countries. Recent research has been carried out trying to detect not only the final consumption activities in the economic system but also the intermediate production of industries separately (Wu and Chen, 2017).

Owen et al. (2017) have made a footprint analysis for the UK, detecting the difficulties when aggregating the TPES data for each of the five currently most used databases for the calculation of the TPEF. Min and Rao (2017) have detected that uncertainty could be higher in over 20% of household Energy Footprints at most income levels in the case studies of Brazil and India. Kucukvar et al. (2017) have made one of the first footprint forecasts, just for the electric part of the energy sector for the UK and Turkey, creating scenarios until 2050. Rocco et al. (2018) compared CBA energy consumption to the Global Multi-Regional Input-Output (GMRIO) PBA in South Africa and Botswana, discovering not only the relevance of empowering efficient local industries to decrease inland energy consumption, but also the embodied exported energy in goods and services. The use of CBA has been considered vital in Switzerland, where a “virtual decoupling” reality has been detected (Moreau and Vuille, 2018), and the Decoupling Index has been analysed with the Eora database for 126 countries (Akizu-Gardoki et al., 2018), detecting some virtually decoupled countries and others that have really managed to achieve decoupling (reducing energy consumption while increasing their HDI). In this context, it has been argued that footprint accounts should be considered when evaluating the relationship between resource consumption and welfare (Wiedmann and Lenzen, 2018). One prominent example of where consumption-based accounting has been applied in a policy context is the inclusion of the material footprint as an indicator for two Sustainable Development Goals (SDGs 8 and 12) (Allen et al., 2016) (Wiedmann and Lenzen, 2018). However, CBA has not been internationally recognised in national energy consumption measurements thus far.

Furthermore, although global energy reduction has been deemed necessary to maintain the sustainable use of resources (McGlade and Ekins, 2015), Kaltenegger et al. (2017) detected that global energy consumption increased by 29.4% from 1995 to 2009, and may increase by 52.9% from 1995 to 2030. Wu and Chen (2017) found that overall, the energy use embodied in international trade has reached 90% of global energy use, in which energy induced by final product trade is around 20%, while the rest is induced by intermediate trade consumption. Furthermore, Wood et al. (2018) found that the energy consumption displaced through trade rose from 20 to 29% during the 1995 to 2011 period. Chen et al. (2018) have found that embodied energy inflows and outflows for five world economies (USA, CHN, JPN, RUS and IND) constitute more than 43.7% and 45.4% of total through-flow, concluding that footprint accounting polarises countries according to their incomes.

Concern about direct and indirect energy use in households arose in the 1970s (Bullard and Herendeen, 1975) (Hannon, 1981), where a 357 sector based Input-Output calculation was computed to calculate the energy embodied in the goods and services of the US economy. The relevant indirect energy consumption in national contexts was also identified in several other studies; in Norway it was detected that, in 1973, approximately 23% of the energy was indirectly consumed among rich families, and 13% by poor ones; and in New Zealand, when comparing the growth of income to the increase in energy consumption (Herendeen, 1978) (Peet et al., 1985). van Engelenburg et al. (1994) proposed a method to calculate national energy footprints in ten steps. In the Netherlands, Vringer and Blok (1995) calculated that indirect energy requirements were 54% of the total, and a further disaggregation by sector was made in order to provide insights into understanding where to reduce energy consumption. In Australia, Lenzen (1998) defined that 70% of the energy was consumed, on average, in an indirect way by households during 1993–94. In 1999 it was found that in the Netherlands, during the period from 1950 to 1995, the share of indirect energy consumption embodied in goods in the total energy requirements fluctuated between 50% and 60% (Biesiot and Noorman, 1999), using a combined Life Cycle Assessment (LCA) and Input-Output Analysis. Similarly, in the Netherlands it was found that, in 1990, 59% of energy consumption was indirect (Wilting et al., 1999). It was also stated that direct consumption (41%) had a reduction potential of 55%, and total consumption (direct plus indirect) had reduction potential of 59% (Wilting et al., 1999).

In this respect, cities were identified as places where indirect energy or energy embodied in the consumption of goods and services by their residents is as important as direct energy use (Lenzen et al., 2004a), (Harris et al., 2020). Lenzen et al. also expressed the need to calculate global impacts through Input-Output analysis and their origins in order to truly be able to act and “think global”.

In Brazil, 11 cities were analysed, calculating the rate of direct and indirect energy consumption embodied in goods and services in 1995–96, using Input-Output methodology (Cohen et al., 2005). According to that study, an average of 48.22 MWh/cap were consumed, of which 61% was indirect. A similar study shows that, in India, indirect energy consumption was also higher than direct consumption (Pachauri, 2004), being up to ten times higher in some households (Pachauri and Spreng, 2002). A later study analysed how energy intensity and national expenditure were related in a number of countries, arguing that, within footprint accounts, energy expenditure in households does not apparently lead to sustainable energy management, in contrast with Kuznets theory (Lenzen et al., 2006).

Thus, measuring the embodied energy requirement and the corresponding emissions is deemed necessary in order to accomplish an energy transition in affluent and urbanised societies, where direct energy is less important than embodied energy (Lenzen et al., 2008), (Wiedenhofer et al., 2011), (Vetőné Mózner, 2013), (Caro et al., 2017). A later study confirms that indirect energy is higher in urban areas than in rural areas, such as in the eastern Australian area, where indirect energy is 74% in the former and 67% in the latter (Wiedenhofer et al., 2013).

3. Methodology and data

3.1. Methodology

Environmentally Extended Global Multi-Regional Input-Output analysis (EE-GMRIO) has been widely used to calculate the environmental footprints of nations (Wiedmann and Lenzen, 2018) (Owen et al., 2017), (Oita et al., 2016), (Lenzen et al., 2004b), (Wiedmann et al., 2007), (Kulionis and Wood, 2020), (Chen et al., 2020). In our case, we use this method to assess the energy footprint of countries (TPEF) by combing GMRIO data and the original data from the IEA on the energy consumption of countries (defined as TPES). The relation between the two has been defined as the Hidden Energy Flows (HEF) of a country and is given as a percentage to add to or subtract from the TPES in order to obtain the consumption-based reality of a country (Eq. (1)). Since the obtained results have some variations across all of the 5 databases, an average value has been obtained in order to define the HEF of a country (Eq. (2)), and the typical deviation has also been reflected so as to understand the accuracy of a certain country's HEF.

$$HEF\,(\%) = (TPEF\text{-}TPES)/TPES \cdot 100 \tag{1}$$

$$\overline{HEF} = (HEF_{WIOD} + H_{Eora} + H_{EXIOBASE} + H_{GTAP} + H_{OECD})1\ /\ 5 \qquad (2)$$

Fig. 1 summarises the GMRIO framework, where $\mathbf{Z}^{\mathbf{RS}}$ denotes a sub-matrix of intermediate deliveries from country R to country S, with destination industries in columns and delivering industries in rows; $\mathbf{y}^{\mathbf{RS}}$ denotes the final demand of country S for goods and services produced by country R; $\mathbf{x}^{\mathbf{R}}$ is the vector of gross output by industry in country R; $\mathbf{va}^{\mathbf{R}}$ represents the vector of value added by industry in country R; $\mathbf{q}^{\mathbf{R}}$ denotes the vector of energy use by industry in country R; and $\mathbf{h}^{\mathbf{R}}$ is the vector of direct energy consumption by households in country R.

The relation between $\mathbf{x}$, $\mathbf{Z}$ and $\mathbf{Y}$ is defined by the accounting equation:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yj} \qquad (3)$$

where $\mathbf{i}$ and $\mathbf{j}$ are column summation vectors of appropriate dimension (vectors of ones).

For any country R, the production-based energy consumption (which is equal to the TPES) can be expressed as the sum of the energy consumption of all the industries in country R plus the direct energy consumption by households:

$$TPES^R = \mathbf{q}^{\mathbf{R}}\mathbf{i} + h^R \qquad (4)$$

From Eq. (3), the input coefficients are obtained as:

$$\mathbf{A}^{\mathbf{RS}} = \mathbf{Z}^{\mathbf{RS}}\left(\widehat{\mathbf{x}}^{\mathbf{R}}\right)^{-1} \qquad (5)$$

where $(\widehat{\mathbf{x}}^{\mathbf{R}})^{-1}$ denotes the inverse of a diagonal matrix of total outputs in country R.

Likewise, the energy coefficients ($\mathbf{c}^{\mathbf{R}}$) for country R are defined as:

$$\mathbf{c}^{\mathbf{R}} = \left(\widehat{\mathbf{x}}^{\mathbf{R}}\right)^{-1}\mathbf{q}^{\mathbf{R}} \qquad (6)$$

Eq. (3) can now be written as a standard input-output model as:

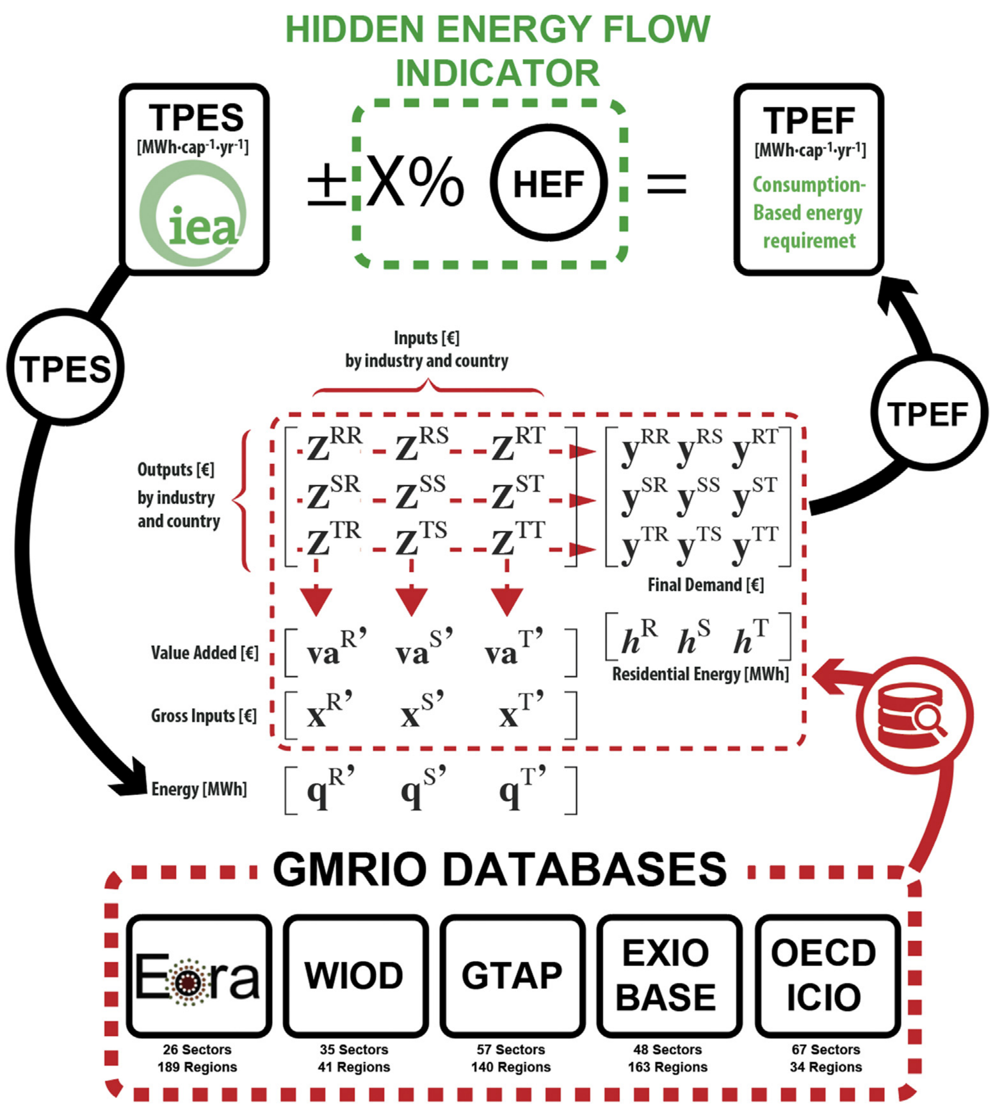

Fig. 1. The creation of a standardised HEF indicator is the aim of this research, in order to obtain TPEF directly from IEA data. Countries and their inhabitants would be able to know the average amount of energy embedded in imported/exported products and services. This figure represents HEF calculations for three regions R, S and T, and it has adapted in our algorithm to the number of regions and industrial sectors used in each of the five databases.

$$\mathbf{x} = \mathbf{Ax} + \mathbf{Yj} \tag{7}$$

The solution to the this model is given by:

$$\mathbf{x} = \mathbf{LYj} \tag{8}$$

where $\mathbf{L} \equiv (\mathbf{I} - \mathbf{A})^{-1}$ denotes the so-called Leontief inverse. From Eqs. (6) and (8), the energy consumption by industry can be calculated as:

$$\mathbf{q} = \hat{\mathbf{c}}\mathbf{LYj} \tag{9}$$

Finally, operating in Eq. (9) and adding the energy directly used by households, we can derive the expression for the TPEF of country R as:

$$TPEF^R = \mathbf{c}^{'}\mathbf{Ly^R} + h^R \tag{10}$$

where $\mathbf{y^R}$ is a column vector that represents the domestic final demand of country R for final goods produced domestically ($\mathbf{y^{RR}}$) and imported ($\mathbf{y^{SR}}$, $\mathbf{y^{TR}}$).

3.2. Data and standardisation

Energy data have been drawn from the IEA database (International Energy Agency, 2019) and economic data have been extracted from five databases: Eora 26 (Lenzen et al., 2012a), with 189 countries and 26 industrial sectors; WIOD (Timmer et al., 2015), with 43 countries and 57 industrial sectors; EXIOBASE (Tukker et al., 2009), (Tukker et al., 2013), (Stadler et al., 2018) with 44 regions and 163 sectors; GTAP, with 140 regions and 57 sectors (Huff, McDougall and WALMSLEY, 2000) (Narayanan et al., 2015); and OECD, with 64 regions and 34 sectors (OECD, 2015). The year 2011 has been used to calculate the HEF indicator since EXIOBASE database has the latest release of that year.

All the GMRIO databases have been standardised using a concordance matrix that map the sectors and regions of different GMRIO models into our defined sector and regional classification within 17 sectors (Supplementary Material Tables B.1 to B.5) (Eq. (11)). Also, the regions have been standardised, converting them into 43 regions plus the rest of the world (RoW) grouped into a 44th one. Similar aggrupation methods among MRIO databases have been used with sectors 18 and 19 (Owen et al., 2014).

$$GMRIO_{(17\ x\ 17\ DIMENSION)} = Concordance\ Matrix \cdot GMRIO_{(i,j\ DIMENSION)} \tag{11}$$

Later on, IEA energy consumption data (TPES), also known as satellite data, has been converted from the original TPES values to the 17 industrial sectors of our IO matrix. During the standardisation process, firstly a direct concordance was used to extract TPES from IEA (Supplementary Material Tables C.1). Nevertheless, authors have realised that making these assumptions transportation sector was not properly disaggregated to take into account residential use of fuel, and also non-resident inhabitants' consumption in other countries was not faced. To solve this problem, satellite data from EXIOBASE database (denominated as Net Energy Use, NEU) has been used (Eq. (12)) developed by Usubiaga-Liaño et al. (2020). Thus, identical satellite data has been used in the different algorithms of five databases in order to calculate the TPEF and respective HEF.

$$Q_{NEU\_17\_SECTOR} = Concordance\ Matrix \cdot Q_{NEU\_163\_SECTOR} \tag{12}$$

4. Results

The main result of this research has been obtaining the HEF from the five most relevant databases (Fig. 2), which provides the possibility to standardise the HEF for year 2011 (Fig. 3). This allows to obtain for all the countries their energy footprint value from the TPES, integrating a new global consumption reality based on CBA.

Fig. 2 shows the HEF values for the 43 countries analysed and for RoW. These values have also been compared to the achieved HDI values of each country. Countries have been organised along the X axis from the highest HDI value to the lowest. We can see that, in general, the most developed countries have a higher HEF than less developed ones. The results show that the ten most developed countries demand on average a Hidden Energy Flow of +18.5% (on average 8.98 MWh$\cdot$cap^{-1}), while for the medium developed 24 countries the average HEF is +12.4% (on average 5.19 MWh$\cdot$cap^{-1}), and the ten least developed countries have an average HEF of −1.6% (on average −1.34 MWh$\cdot$cap^{-1}). This means that the ten least developed countries are feeding the embodied energy requirements of the most and even medium developed ones. It must be said that, although a general trend has been observed, countries such as NDL, DEU, USA and CAN have a lower HEF than other countries with similar HDI values.

Variations in the results point to the need for the homogenisation of the GMRIO databases. In this research, a deviation of over 30% has been detected in two countries (MLT 40% and LUX 35%), between 10% and 21% in twelve countries (BEL, CYP, GRC, SVK, IRL and DNK), and the remaining 36 countries have a standard deviation of less than 10%. As a result, the footprint accounts in the energy field could be accurate enough to start including them in national and international policies. Nevertheless, divergences in the economic data of GMRIO databases are still significant. These variations coincide with those previously detected by Moran and Wood (2014), whose sensitivity analysis within a harmonised carbon footprint satellite account obtained a positive view, reporting differences of less than 10% in most major economies among Eora, WIOD, EXIOBASE and GTAP databases. Taking all of this into account, our research confirms that reducing uncertainty in MRIO analyses is relevant work for the future standardisation of results (Rodrigues et al., 2018).

The sectorial difference between TPEF and TPES in each sector has also been calculated (Fig. 4). This allows us to understand firstly that in all data bases, sectors that have higher footprint than the supply are the Commercial and public services, Construction, Electricity and Petrochemical sectors. Secondly, Fig. 4 shows that the major variations among databases occur in the sector defined as Commercial and public services where higher uncertainty is cumulated (with a total deviation of 11,000 TWh), followed by the Commercial and Public Service sector (2417 TWh). To a lesser extent, the Petrochemical sector also display significant differences (1608 TWh), as does the Electricity and Construction sectors (1251 and 1217 TWh). These are the sectors that most need to be standardised across the five different databases analysed.

4.1. Including HEF results in a COUNTRY'S reality

In order to show how the HEF indicator can modify our perception of the national energy consumption reality, the country with the highest HEF rate has been analysed. Switzerland, with a +68% HEF is the country with the highest energy consumption embodied in imported products and services. This converts its national average energy consumption from the 25.36 MWh/cap declared by the IEA into 44.67 MWh/cap in year 2011. This means that, to maintain the average consumption quality and life standards in Switzerland, almost double the nationally measured

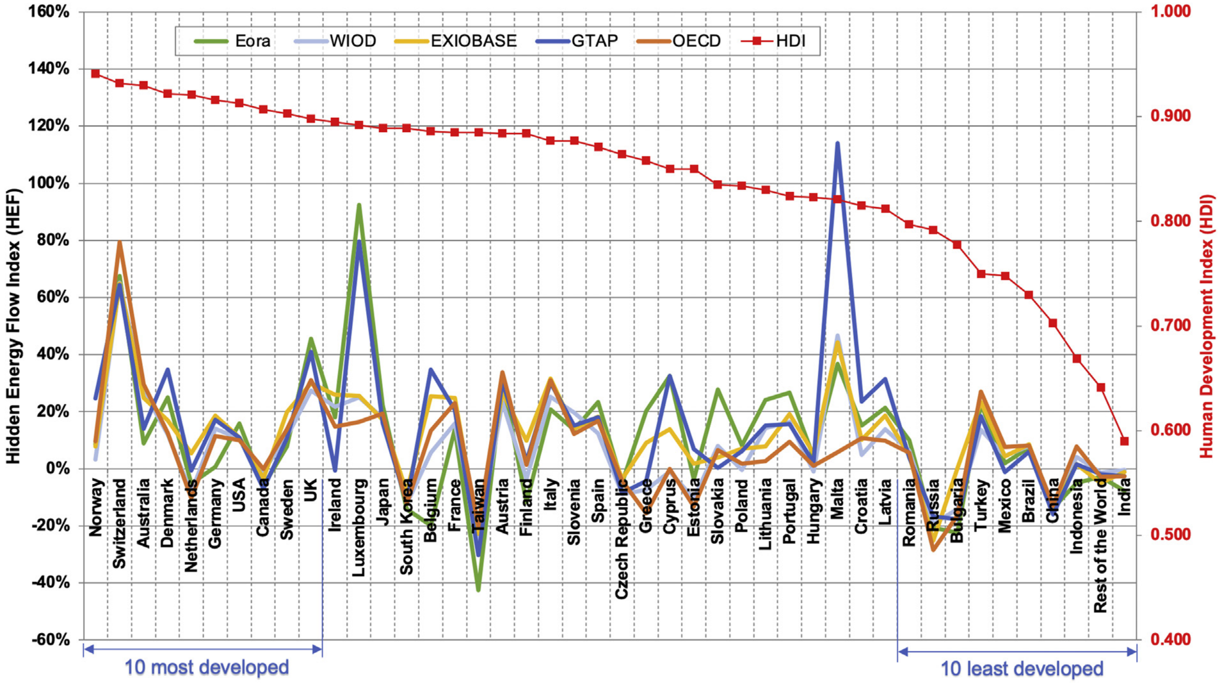

Fig. 2. HEF comparison between the analysed five GMRIO databases.

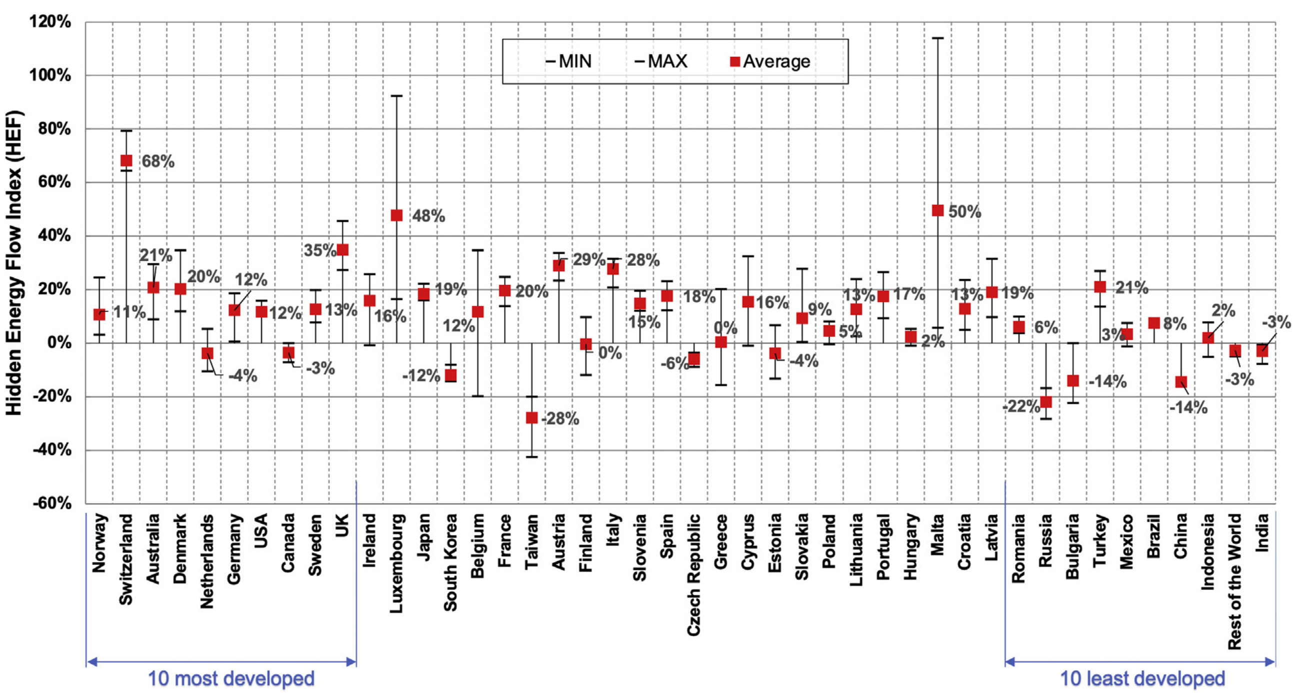

Fig. 3. Average HEF for year 2011 from the five databases considered and their deviation. This HEF percentage can convert the TPES values into TPEF values.

energy is required. Furthermore, this does not take into account the energy consumed in other countries in tourism travels (Lenzen et al., 2018).

To further illustrate these proportions, Fig. 5 shows the national energy use reality according to the CBA. Now it can be observed that the energy consumed at homes in terms of electricity only accounts for 3.6% of the national energy consumption, and the residential thermal consumption represents 8.9% of the TPEF. A further 14.0% of total consumption derives from the transportation sector. However, when citizens try to reduce energy consumption, the maximum effort is placed on the energy consumed at homes, especially in electric form. Nevertheless, 59.1% of the energy consumption corresponding to a person is hidden in consumed goods and services, thus related to material lifestyle and to the material consumption model of the Swiss population. Lastly, 14.4% of the consumption is due to the transformation and losses of the current

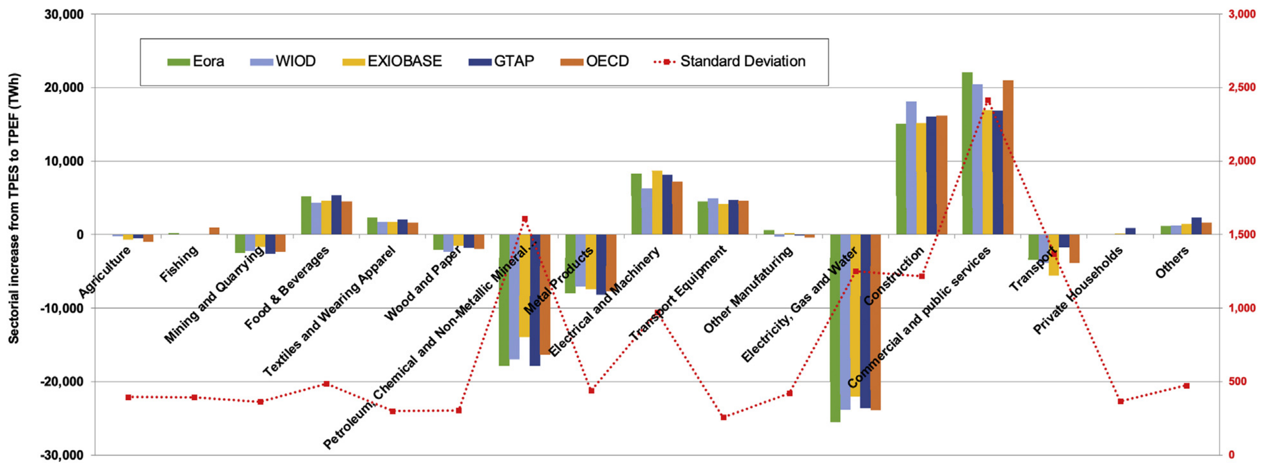

Fig. 4. Comparison of TPEF minus TPES by sector across GMRIO databases. The secondary axis provides the standard deviation of each sectorial difference.

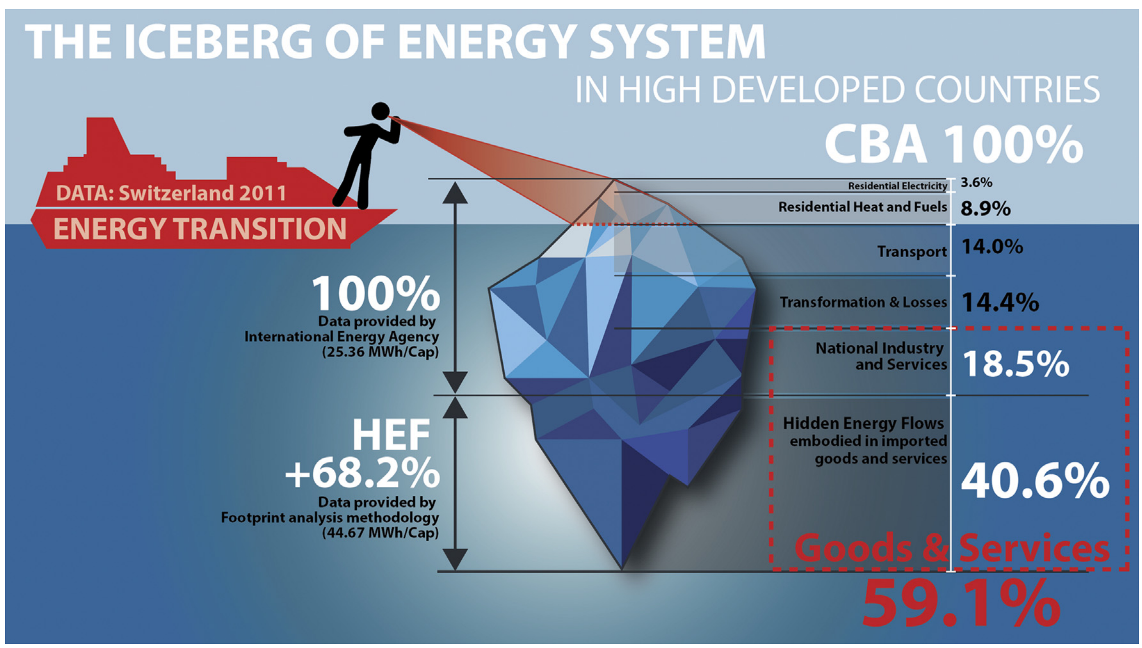

Fig. 5. The "iceberg effect" in the current energy transition, using energy consumption data from Switzerland in 2011 and integrating the Hidden Energy Flows (HEF). It can be seen that only 11.1% of energy is consumed in homes, (and just 3.2% in the form of electricity) whereas 63.7% is consumed in the form of products and services.

fossil fuel based and centralised energy system.

In this paper we would like to define this phenomenon as the "iceberg phenomenon", and we might view the national energy transition strategy as a "cruise ship". In order to avoid our cruise possibly colliding with the iceberg, we have to fully visualise the challenge that we face of reducing energy consumption. As inhabitants of a country, we normally try to change what we understand as energy: the energy at home, especially electricity. Meanwhile, however, we are not able to see the energy hidden behind the current material consumption model, 40.6% of which is actually consumed outside the national boundaries.

Attempts to reduce electricity consumption in households are easily perceived by citizens, since these directly impact their electricity bill; therefore, society is driven to act on these. Nevertheless, switching to low-energy consumption appliances, such us energy-efficient bulbs, refrigerators, washing machines, televisions, etc. could actually increase the global Total Primary Energy Footprint (TPEF), since producing these goods corresponds to 59.1% of the "iceberg", despite the aim to reduce the 3.6%.

Following the ETH researchers' advice to emit a maximum of 1 tCO_2-eq emissions per person and year, the Swiss government have established a target to reduce the national average energy consumption to 17.5 MWh per capita per annum (equivalent to 2000 W, during 365 days a year and 24 h per day, called the "2000 Watt society") as a sustainable amount (Stulz et al., 2011). Nonetheless, this goal has not been achieved. In fact, the energy consumed in the country has been increasing in a hidden way. The HEF indicator helps to track energy consumption in a global context, and it could be especially helpful in a city context, as cities consume high amounts of energy embedded in goods and services (Villamor et al., 2020).

5. Discussion

These results bring us to conclude that, in order to transition towards a sustainable energy model, there is a profound need to change our current material lifestyle, due to its significant energy and socio-environmental costs. This affirmation has been made in the past (Baynes et al., 2011) (Wiedenhofer et al., 2011) (Wiedenhofer et al., 2013) (Zhang et al., 2016) (Lenzen, 2016), but we consider that HEF indicators provide solidity. An international HEF indicator comparing 44 countries by the same standards, goes beyond previous country-based analyses where individual countries or couples of countries were analysed (Owen et al., 2017) (Min and Rao, 2017) (Kucukvar et al., 2017) (Rocco et al., 2018) (Moreau and Vuille, 2018) (Wilting et al., 1999). We also consider that the results of our broad international study could be further analysed in city-based models within a nation and we support city-based studies to better define different national realities, such as was already attempted in the research developed by Cohen et al. (2005).

These results also support the theory that social aspect of the energy transition will gain importance over technological efficiency (Morris and Jungjohann, 2017). There is a huge energy reduction capacity in changing the current material consumption system, especially in developed countries. In fact, trying to change the current energy system by increasing the purchase of efficient high-tech appliances (a reflection of our current consumerist society) may produce a confusing placebo effect among citizens, and even contribute to perpetuating our old unfair energy system. In this context, claims like that regarding degrowth (Weiss and Cattaneo, 2017) could be relevant when approaching a low energy consumption system, where the iceberg phenomenon will be taken into account.

It is clear that the current energy model needs to be transformed. It is environmentally unsustainable (Inman, 2008) (Gies, 2017), socially unfair (Sovacool et al., 2016) (Eisenstein, 2017), and further economic losses and crises have been forecast (Hsiang et al., 2017) (Fouquet, 2017) (Inman, 2013). Politicians, scientists and citizens are aware of this, which begs the question: how can we implement the transition towards a sustainable energy model? Citizens in the Global North, in general, and particularly citizens living in large cities (Lenzen et al., 2008), are historically responsible for this situation, and are now at the centre of providing responses to be able to create a socio-environmentally stable panorama.

In order to bring about a deep energy transition, the recognition of the “real” global consumption-based energy demand of countries is essential. Current statements defining energetically sustainable countries as an example to be followed could be contradictory because of the lack of integrating HEF, such as: “The Danish economy since the 1980s has grown by around 80% while maintaining constant energy consumption and, at the same time, decreasing CO_2 emission by 34%.” (Wang et al., 2017); “An active Danish energy policy that focuses on energy efficiency, energy diversification and the development of renewable energy has resulted in a resilient energy system in Denmark [...]” (Hertel et al., 2015); “The German *Energiewende* constitutes a major challenge for the energy supply system.” (Uhlig et al., 2014); or “The energy sector is at the core of any modern economy, and Germany serves as an international showcase for the transition of a large industrialised economy to a low-carbon energy system.” (Rommel et al., 2018). These statements could be misleading when visualising only the consumption-based total energy requirement of countries. Overlooking the energy embodied in imported goods and services could generate erroneous “reference countries” to be followed in coming years (Akizu-Gardoki et al., 2018) for the creation of a sustainable energy system. Some previous examples, such as the case of Denmark, have already been criticised in footprint-based accounts (Munksgaard et al., 2000) (Wier et al., 2001) (Wier et al., 2003).

In the process of finding sustainable energy system reference countries, or being able to understand the full reality of our own country outside the illusion of the iceberg phenomenon, Fig. 3 (as well as Supplementary Material Table D.1) offers the HEF percentage to convert the TPES value into the TPEF and also into absolute value per country in MWh·cap^{-1}, thus a consumption-based energy requirement comparison can be made. Attempts to introduce CBA-based policies instead of the traditional CBA have already been considered in previous works, especially in the Climate Change Mitigation and Adaptation field (Filho and Leal-Arcas, 2018) (Karakaya et al., 2019), and these works also support the idea that CBA indicators (such as HEF) could be introduced into national policies to better shape environmental and social policies.

Being conscious of the Hidden Energy Flows among countries not only provides a new energy reality for a given country, as shown in Fig. 5, but also helps to understand how developed countries are using the energetic resources of non-developed countries. Thus, the acknowledgment of HEF can also trigger international solidarity towards fairer and more proportionate payment for the energy that developed countries consume in non-developed ones. Furthermore, international cooperation to improve the energy efficiency of developing countries could become a common interest. Measuring the energy consumed in other countries will be the first step towards the recognition of a country’s responsibility in socio-environmental impacts, and towards a shared responsibility between Global North and Global South countries to reduce said impacts. The new energy model not only needs to be environmentally sustainable, but also socially fair and equitable, based on the democratic management of resources.

6. Conclusions

Consumption-Based Accounts (CBA) have been suggested to be a complementary indicator to address the current environmental and climate change mitigation policies (Afionis et al., 2017), (Kander et al., 2015), (Steininger et al., 2016). United Nations has considered it a strategic tool to link global economies to their respective environmental impacts (United Nations, 2018). Following in this line of research, our Hidden Energy Flow indicator (HEF) provides a clear example of where the relevance of CBA can directly help to generate changes in future policymaking and practices in cleaner national and international production systems.

This research shows how developed countries depend on the energy consumed in non-developed countries (consuming on average 18.5% more energy than that declared). The integration of Hidden Energy Flows in the national accounts gives a country the possibility to understand the same energy consumption reality from a different perspective, where the energy embodied in products and services gains relevance, and energy consumed at homes loses magnitude (energy embodied in products and services can reach up to 59.1% of the energy consumed country wide).

This research shows for the first time how the TPES data provided by the International Energy Agency can be adjusted to the Consumption-Based Accounts with the use of HEF, overcoming the current individual countries’ footprint analysis or non-uniformised studies. The limitations of this study lie in the degree of accuracy of the indicator, which depends on the lack of uniformisation of the currently most relevant five global GMRIO databases (even though most of the countries analysed, 36 out of 44, 82%, have a standard deviation of under 10%). It has also been detected that these differences are mainly generated in four sectors: “Commercial and Public Services”, “Petroleum, Chemical and Non-Metalic Mineral”, “Electric, Gas and Water”, and “Transport”.

Shifting the focus from changes in residential electricity consumption to the whole energy consumption panorama could boost the necessary energy transition towards a low socio-environmental impact and sustainable energy model, acting directly upon the current consumerist consumption model. Having the HEF data available, countries could adapt their international energy policies in order firstly to reduce their energy dependency, and secondly to start promoting a responsibility campaign for the socio-environmental impacts underlying the indirect energy consumption. This can lead to modifying not only the consumption attitudes of citizens but also the industrial production system on an international scale, going one step forward from the current literature, firstly going beyond national IO analysis and secondly going beyond the individual GMRIO analysis.

The potential international collaboration between countries has been discussed in great depth in the climate policy arena, but it is difficult to implement specific changes in the international field. In this respect, the HEF indicator could be a small but firm and tangible contribution to the field. HEF offers a real panorama of the complex energy dependencies and corresponding responsibilities, where countries could have the freedom to act according to their available resources and ethical values. This will boost the achievement of "Goal 12", enhancing sustainable consumption patterns among countries (UN, 2015); "Goal 7" of SDG, promoting insights to reach a sustainable energy system for all individuals; and "Goal 10" of the SDG, nurturing the reduction of global inequality.

As future research lines for this study, and to further contribute to understanding a consumption-based energy reality, city-based national studies could be performed in order to provide individual citizens with more specific data. Currently, GMRIO methodology displays difficulties for city-level application, but current research efforts are focused to overcome this challenge. Furthermore, we consider it interesting to take steps towards increasing the number of countries where a HEF indicator could be obtained, as well as updating the analysis year, since some databases are still only able to provide accurate data for 2011.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Ortzi Akizu-Gardoki, Takako Wakiyama, Thomas Wiedmann, Gorka Bueno, Iñaki Arto, Manfred Lenzen, Jose Manuel Lopez-Guede.

Acknowledgements

The research has been a collaboration between the University of the Basque Country (UPV/EHU) and the UNSW Sydney, Australia, with the Sustainability Assessment Program (SAP). The research was funded by the team "EKOPOL: TRANSITION PATHWAYS" recognised by the Basque Government (IT-1365-19) and the University of the Basque Country (GIC-18/22). The Australian Industrial Ecology Virtual Laboratory electronic research infrastructure was used for computation, supported by the Australian National eResearch Collaboration Tools and Resources project (NeCTAR, grant VL201) and by the Australian Research Council (grants DP0985522, DP130101293 and LE160100066).

Thanks also for the support of the Spanish Ministry of Science, Innovation, and Universities, through the project MALCON, RTI 2018-099858-A-I00, the Spanish State Research Agency through María de Maeztu Excellence Unit accreditation 2018–2022 (Ref. MDM-2017-0714), the Basque Government BERC Programme, the Czech Science Foundation under the project VEENEX GA ČR 16-17978 S, and the EU H2020 project LOCMOTION GA no 821105.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123827.

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