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The energy requirements of a developed world

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ABSTRACT

Through history, special attention has been paid to the study of the relationship between the energy use of a country and its level of development. While the interest of this research area is unquestionable, the energy indicators commonly used (e.g. total primary energy) are problematic. In the current context of globalization, the energy used by a country is not anymore a suitable indicator for measuring the total energy requirements associated with its level of development; the significant variable is the energy consumed worldwide to produce the goods and services demanded by that country, i.e. its energy footprint. In this study, we compare the human development index of 40 countries with their total primary energy demand and total primary energy footprint for the period 1995–2008. The results show that the total primary energy demand underestimates the energy required to maintain a high level of development, since a significant part of the energy used by emerging countries is being increasingly devoted to sustain the welfare of developed countries by means of international trade. We also find that the minimum total primary energy footprint per capita to achieve a high level of development is 33% higher than current world's per capita energy use.

Introduction

An adequate energy supply has been identified as a key prerequisite for economic, cultural and social development in complex societies (White, 1943; Cottrell, 1955; Tainter, 1990). The United Nations General Assembly adopted in 1986 its "Declaration on the Right to Development" (UN, 1986), which established the right to development 'as an universal and inalienable right and an integral part of fundamental human rights', setting out a catalog of objectives for 'equality of opportunity for all in their access to basic resources, education, health services, food, housing, employment and the fair distribution of income'. Ultimately, energy, in its different forms, is essential to provide all these goods and services linked to the achievement of human development targets, playing a key role for overcoming poverty (Najam and Cleveland, 2003; Karekezi et al., 2012).

A number of authors have investigated the relation between the degree of development of a country and its energy use (Cottrell, 1955; Mazur and Rosa, 1974; Olsen, 1992; Suárez, 1995; Rosa, 1997; Alam et al., 1998; Pasternak, 2000; WBGU, 2003; Smil, 2005; Dias et al., 2006; Martínez and Ebenhack, 2008; Steinberger and Roberts, 2010; Lambert et al., 2014). Most studies have found strong correlations between energy use and living standards at lower energy use levels ("developing countries"), and decoupling at higher levels ("developed countries"). This can be seen when comparing the relation between the per capita total primary energy demand (TPED)[1] and the human development index (HDI).[2]

Fig. 1 shows the relation between the per capita TPED and the HDI of a selected group of countries for the period 1995–2008. While in highly developed countries variations in the use of energy barely affect the

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[1] The TPED includes the consumption of the energy sector, the losses during transformation (for example, from coal or gas into electricity) and distribution of energy, and the final consumption by end users. This indicator is also referred to as the gross inland energy consumption and represents the quantity of all energy necessary to satisfy inland consumption. The TPED is equivalent to the total primary energy supply (TPES), which is calculated as the production plus imports, minus exports, minus international marine bunkers plus/minus stock changes.

[2] The HDI is an indicator developed by the United Nations Environment Program of the average achievement of each country in three basic areas of human development: life expectancy at birth, adult literacy and school enrolment, and standard of living as measured by the Gross National Product per capita. The HDI uses a scale from zero to one where zero would indicate the lowest level of human development and one the highest level of human development (see (Klugman et al., 2011) for further information on the HDI). In this paper we refer to "highly developed countries" to those with a HDI > 0.8, where the advanced industrialized countries currently stand (i.e. European Union, Japan, USA, etc.), and represents the level of material well-being that most countries want to achieve or, in other words, the level of development that most countries aspire to converge with.

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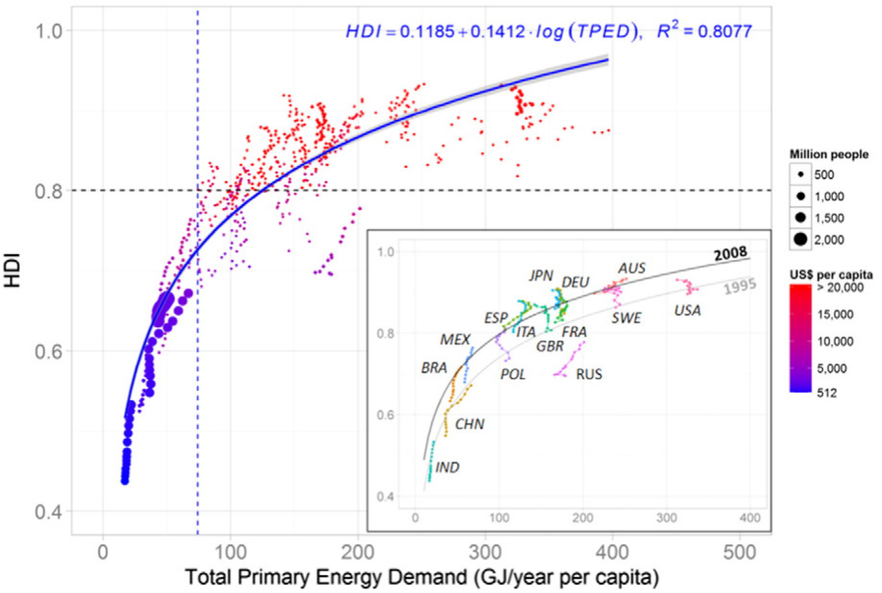

Fig. 1. Human development index, total primary energy demand per capita, population and GDP per capita of selected countries, 1995–2008.
Notes:

1) HDI: human development index; TPED: total primary energy demand.
2) AUS: Australia; BRA: Brazil; CHN: China; DEU: Germany; ESP: Spain; FRA: France; GBR: United Kingdom; IND: India; ITA: Italy; JPN: Japan; MEX: Mexico; POL: Poland; RUS: Russia; SWE: Sweden; USA: United States of America.
3) The points in the main figure represent the pairs of TPED-HDI for the 40 countries detailed in Fig. 4 and for the period 1995–2008; the regression corresponds to the corresponding 560 observations (i.e. 40 countries times 15 years).
4) The points in the detailed figure represent the pairs of TPED-HDI of a selected group of 15 countries for the period 1995–2008; the two regressions correspond to the observations of the 40 countries for the years 1995 and 2008 respectively.
5) The vertical blue dotted line represents the threshold of the minimum energy to achieve a HDI > 0.8 for the set of countries and years analyzed (i.e. Malta 2000, with TPED of 74 GJ/cap and HDI of 0.801). Countries above the horizontal line are classified as developed countries (i.e. HDI > 0.8), otherwise they are considered as developing countries.
6) GDP per capita in US$, constant prices of 2008. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

level of development, in low and medium developing countries as well as in emerging economies (e.g. BRIIC countries: Brazil, Russia, India, Indonesia, China), changes in the use of energy translate into changes in the degree of development. Similarly, HDI increases with the GDP until a certain level, but further, HDI becomes insensitive to GDP variation. This threshold is identified through a simple screening method in Fig. 1 at around 20,000 US$.[3] This phenomenon is referred in the literature as a "plateau" by (Pasternak, 2000) or "saturation" by (Martínez and Ebenhack, 2008). The observation of paths at the country level reveals that for some high-developed economies (e.g. Germany, Japan, Sweden, the United Kingdom or the United States of America (USA)) there is not a strong positive relation between changes in the HDI and in the TPED, furthermore, in some cases the relation is negative. Moreover, the ability of countries to reach higher development levels with the same amount of TPED has slightly improved between 1995 and 2008 (see detail in Fig. 1). This is the consequence of a combination of factors: the effect of climate and energy efficiency policies, the impact of high energy prices (especially from 2004 onwards), technological progress, changes in the economic structure, and other factors affecting human development such as health improvement. To some extent, this is also reflected in the fact that similar levels of development can be achieved with very different amounts of energy use: for example, in 2008, both USA and Germany had a HDI over 0.9, but the TPED of the USA was 63% higher.

To date, most of the attention has focused on the assessment of the relationship between low levels of development and energy use (WBGU, 2003; Guruswamy, 2011; Kaygusuz, 2011; Bhattacharyya, 2012; Karekezi et al., 2012; Sovacool, 2012). However, although poverty is still a serious and persistent problem, in recent decades many countries have been experiencing relevant progress in terms of development. Between 1990 and 2014 the share of people leaving in less developed countries (with HDI < 0.55) has decreased from 60% to 12%, while the share of people living in developed countries (with HDI > 0.8) has increased from 11% in 1990 to 18% in 2014 (UNDP, 2015). Furthermore, by 2014 more than 50% of world's population was living in countries with a HDI >0.7 (compared to 24% in 1990) (UNDP, 2015). These trends are expected to continue in the future, translating into higher energy requirements to sustain the enhanced living standards.

In this context, a key research question is the identification of the minimum rate of energy use to achieve a certain level of development. This is an important issue in order to support the design and implementation of energy policies linked to the deployment of the infrastructure and technologies required to promote human development. Regarding this research question, it is important to highlight that the minimum per capita energy use in order to reach high development is a normative issue and cannot be globally set due to territorial, climatic, historical and/or cultural differences (WBGU, 2003). For example, the need for heating and the amount of energy used for this purpose depend on local climatic and building conditions which vary between countries. Similarly, although there is a minimum requirement for mobility because schools, medical facilities and markets must be accessible for everyone under acceptable conditions, it also varies substantially (WBGU, 2003). Moreover, basic needs vary not only with climate, region, time, age or sex, but also with personal outlook and expectations (Spreng, 2005). Despite this constraint, several studies have approximated these thresholds or minimum energy use levels following different methodologies.

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[3] Note that this is a just a rough approximation for illustrative purposes. This analysis should be done based on regression of HDI vs GDP at several points in time, since the relation is known to by dynamic (Steinberger et al. 2012; Jorgenson et al., 2014).

Table 1
Threshold energy requirements annual per capita total primary energy demand and human development index as estimated by different authors.

Study	Threshold	Well-being criteria
Contemporary situation		
(Goldemberg, 2001)	TPED: 42 GJ	"acceptable standard of living"
(Martínez and Ebenhack, 2008)	16.7 GJ < TPED < 33.5 GJ TPED: 121.4 GJ	"extremely low" < HDI < 0.7 HDI > 0.9
(Pasternak, 2000)	EC: 4000 kWh (14.4 GJ)	HDI > 0.9
(Rao et al., 2014)	TPED: 30 GJ	90% of population living in "decent conditions"
(Steckel et al., 2013)	FEC: 100 GJ	"very likely" HDI > 0.8
(Steinberger and Roberts, 2010)	TPED dynamic function: 60 GJ (2005)	HDI > 0.8
(WBGU, 2003)	Average TPED *: 35.4 GJ	0.7 < HDI < 0.8
Potential future after generalized efficiency improvements and/or fuel shifts		
(Goldemberg et al., 1985)	FEC: 1 kW (31.5 GJ)	Achieving material standard of living of Europe in the 1970s
(Steinberger and Roberts, 2010)	TPED dynamic function: 45 GJ (2030)	HDI > 0.8
(WBGU, 2003)	Average TPED: 25.5 GJ (2020)	0.7 < HDI < 0.8

Notes

1) TPED: annual per capita total primary energy demand.
2) EC: annual per capita electricity consumption.
3) FEC: annual per capita final energy consumption.
4) * accounting for traditional energy consumption.

Indirect, aggregated top-down methods are the most commonly used in order to obtain some rough estimates.[4] Table 1 shows the main findings of some of the most representative studies in the literature. These studies follow two approaches: *i*) the "contemporary situation" approach: analyses the situation in a specific year (Pasternak, 2000; Goldemberg, 2001; Martínez and Ebenhack, 2008; Steinberger and Roberts, 2010; Rao et al., 2014), and *ii*) the "potential future" approach: estimates how generalized efficiency improvements and fuel shifts policies could reduce the threshold (Goldemberg et al., 1985; WBGU, 2003; Steinberger and Roberts, 2010).

For example, Martínez and Ebenhack (2008) isolated the consumption patterns of certain nations from the rest of the world in order to capture the primary trend. Through a simple screening method, they found that "no country has extremely low HDI with TPED above 400 kgoe (16.7 GJ) and no country has an HDI above 0.7 with a TPED below 800 kgoe (33.5 GJ)". They also concluded that, using the top five performers from the primary trend, energy-poor nations would require at least an additional 2500 kgoe (i.e. 120 GJ) to potentially achieve HDI values near 0.9. Steinberger and Roberts (2010) adopted a different approach, fitting historic data with a threshold function as a function of time, setting a set of constraints required to fulfill the definition of "high human development" by the UNDP: life expectancy of 70 years at birth, a GDP of 10,000 USD, a literacy rate of 80%, and an HDI of 0.8. They found a decoupling trend on the per capita energy requirements, falling from roughly 100 GJ in 1975 to 60 GJ in 2005. By extrapolating the threshold functions to 2030, they found a potential threshold of 45 GJ per capita. WBGU (2003) approximated a "guard rail" following a different approach, selecting a representative set of countries with a relatively high HDI (0.7–0.8) and low HPI (Human Poverty Index) (11–29). The arithmetic mean of these ten countries' annual per capita GDP was calculated (US$2900 per person and year), which the WBGU considered to be the lower limit for a life in human dignity. Therefore, a macroeconomic minimum energy requirement per person and year is derived from the primary energy consumption of the ten countries selected: 4500–10,500 kWh (16.2–37.8 GJ per person and year, with a mean of 7500 kWh (27 GJ) per person and year. Goldemberg et al. (1985) estimated that basic needs "and much more" could be attained for one kilowatt per capita, equivalent to the material standard of living of Western Europe in the mid 1970s.

Other authors have worked with electricity as proxy for energy consumption. For example, Pasternak (2000) found for the years 1980 and 1997 that no country with annual electricity consumption below 4000 kWh (14.4 GJ) per person has an HDI of 0.9 or greater. Above 5000 kWh per capita, no country has an HDI below 0.9. Furthermore, as electricity consumption increases above 4000 kWh (17.1 GJ), no significant increase in HDI is observed.

All the aforementioned studies analyzing the links between energy and development assess the relation between a certain level of human development and a per capita energy use indicator. Despite its shortcomings (e.g. Sagar and Najam, 1998; Ranis et al., 2006; Fleurbaey and Blanchet, 2013), the HDI is yet the most accepted indicator to assess the development of a country. In the case of the energy use per capita, most studies apply three different indicators reported in the energy balances of the International Energy Agency (IEA). While some authors apply the TPED, other studies focus on the final energy consumption by end users, which only computes the total energy consumed by end users in a country, such as households, industry and agriculture (i.e. excluding the energy used by the energy sector as well as the transformation and distribution losses). Finally, other authors use the per capita electricity consumption of a country.

Although the scope of these energy indicators clearly differs, all of them are focused on measuring the energy used *within* the borders of the country under scrutiny. However, in the current context of globalization, the energy used by a country is not anymore a suitable indicator for measuring the total energy requirements associated with its level of development. Over the last few decades, developed countries have specialized in economic activities with high value added, while reducing their share of energy intensive sectors and manufacturing industries. At the same time, some emerging economies like China, India or Brazil have experienced a process of rapid industrialization, increasing their share in the global economy, and are exporting enormous volumes of manufactured products to developed countries (Weber, 2009; Baiocchi and Minx, 2010). This shift of economic activities among countries has also had consequences in terms of energy use.

For example, let be the case of a country A that consumes 10,000 tons of clothes/year to maintain a certain level of development, and these clothes are produced by a company located in A with an associated energy use of 1 exajoule (EJ). Now, suppose that country A's textile manufacturer shifts its activity to a second country B, but continues selling all its production in country A. In such a case, country A would

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[4] Bottom-up methods rest on a number of assumptions regarding the type of energy consuming equipment (stove, light bulbs, etc.), their sizes, efficiencies and intensity of consumption (e.g. Goldemberg et al., 1985).

still consume 10,000 tons of clothes/year and, ceteris paribus, its development level derived from the consumption of those clothes would remain constant. However, country A's energy use would have dropped by 1 EJ, which would correspond with the increase in country B′s energy use. In other words, thanks to international trade, country A could maintain its development level while reducing its energy use, since part of the energy requirements to satisfy its consumption has been shifted to country B and, therefore, it is computed as country B's energy use. Thus, the energy use indicator would provide biased information on the energy requirements to support a certain level of development, by not considering the energy embodied in international trade.

In an increasing globalized world, it can be argued that in order to give a more accurate picture of the relation between energy and development, the *global* energy requirements to support a specific level of development should be taken into account, regardless of the country in which those energy resources were actually consumed. This indicator is commonly referred to as the *energy footprint* (EF) or *total primary energy footprint* (TPEF, when applied to primary energy), and it reflects the energy consumed worldwide to satisfy the domestic final demand (private and public consumption, and investment) of a country, including both the direct energy consumption of households (e.g. the fuel consumed when driving a car) and the global energy requirements to produce the goods and services demanded by final users (e.g. all the energy used worldwide for the production of a car). The energy footprint approach has already been applied to individual countries (Machado et al., 2001; Liu et al., 2010; Cui et al., 2015), at global level but for a static year (Chen and Chen, 2011, 2013) but rarely at both global and dynamic scale (Cortés-Borda et al., 2015). In fact, the studies estimating the TPEF of nations are scarce and, to date, no one has focused on development issues. This framework is also related to some hot research topics such as environmental footprints (Arto et al., 2012; Hoekstra and Mekonnen, 2012; Hoekstra and Wiedmann, 2014; Steen-Olsen et al., 2012; Wiedmann et al., 2013; Yu et al., 2013), the environmental consequences of international trade (Peters and Hertwich, 2008; Arto et al., 2014a), and the share of responsibility for environmental degradation between consumers and producers (Lenzen et al., 2007).

Steinberger et al. (2012) applied a similar methodology to assess the links between human development and consumption-based CO_2 emissions. In fact, in the current context of a fossil fuel-based socioeconomic system (more than 80% of the global TPED is currently covered by oil, gas and coal) CO_2 emissions are closely linked to human development. However, the factor that ultimately supports human needs is energy rather than emissions (White, 1943; Cottrell, 1955; Tainter, 1990). Energy is actually the fundamental factor for producing the goods and services linked to human welfare and development, while emissions are just a waste that could eventually be eliminated through substitution (e.g. renewable energy, nuclear) or technological improvements (e.g. carbon capture and storage). In fact, there is a significant spread in the emission intensity per unit of energy use due to the differences in the energy mix between countries. For example, countries with a high share of renewable and/or nuclear (e.g. Brazil, Sweden or France) depict emission intensities about two times smaller than those with a high share of coal (e.g. Poland, China or Australia). This feature is reflected in both the territorial and consumption-based perspective, since most of the consumption is usually satisfied by domestic products.[5] Costa Rica, a country classified as a paradigmatic successful case of decoupling between development and emissions (Steinberger et al., 2012), reported in the year 2005 a participation of renewable in the total primary energy mix of around 80%. Thus, the assessment of human development paths considering emissions might be biased by the differences in the energy mix. In this sense, recent research has demonstrated that future climate scenarios underestimate the importance of energy consumption to reach high development levels (Steckel et al., 2013). In light of an increasing trend toward low carbon energy sources in many countries, the emissions approach to assess human development could be problematic.

In addition, as pointed before, the energy indicators commonly used in the literature come from the energy balances produced by the IEA. These balances follow the territorial principle, which means that all the energy sold in a country is computed as that country's use regardless of who is purchasing and actually consuming that energy. Following this principle, the energy used by the residents of country A (e.g. tourists) in a second country B would be accounted as part of the energy use of B, although country A would take advantage of the services derived from the use of that energy. This could be also a source of bias in the assessment of the links between energy and development. In contrast, the TPEF approach would allocate the energy used by non-residents to the country where these consumers originate from.

In this context, the main objective of this paper is to revisit the questions of the relation between energy and development, and the minimum quantity of energy required to reach a certain level of development, but using the TPEF as a measure of the energy requirements. We will also compare these results with those derived from the traditional approach which analyzes the relation between development and TPED, and discuss which indicator is more appropriate to assess the links between energy and development.

The remaining of the paper is structured as follows: Section 2 reports the methodology used for the calculation of the energy footprint of a set of 40 countries for the period 1995–2008, Section 3 presents the main results, Section 4 discusses the results, Section 5 concludes.

Methodology

Multi-regional input–output (MRIO) analysis is commonly accepted as the method for the calculation of environmental footprints of nations (Arto et al., 2012; Hoekstra and Mekonnen, 2012; Steen-Olsen et al., 2012; Wiedmann et al., 2013; Yu et al., 2013; Arto and Dietzenbacher, 2014; Hoekstra and Wiedmann, 2014; Jiang and Liu, 2015). Some studies have calculated the energy footprint of single countries: Machado et al. (2001) for Brazil for the year 1995, Liu et al. (2010) and Cui et al. (2015) for China between 1992 and 2005 and Tang et al. (2013) for UK for the period 1980–2010. Chen and Chen (2011, 2013) assessed the energy embodied in global trade flows using the GTAP database for the years 2004 and 2007 respectively. However, as pointed by these and other authors Hertwich and Peters (2009) and Arto et al. (2014b), the GTAP database shows some shortcomings when applied to footprint analysis, especially when investigating time series and because of the differences in the IO structures with respect to the official data.

To some extent, the lack of studies in this area could be related to the absence of global MRIO databases extended with energy accounts able to compute the energy embodied in the worldwide flows of goods and services. In our case, we will use the recently published World Input–Output Database (WIOD) (Timmer, 2012; Dietzenbacher et al., 2013). This database comprises a time series of harmonized supply, use, and symmetric IO tables. It also includes data on international trade and satellite accounts related to environmental and socioeconomic indicators. The WIOD covers the period 1995 to 2008 (with preliminary figures for 2009), with information for 35 industries, 59 products and 40 countries (the 27 member states of the European Union (EU-27), and 13 non-EU countries: Australia, Brazil, Canada, China, India, Indonesia, Japan, South Korea, Mexico, Russia, Turkey, and the USA), and the Rest of the World (RoW) as an aggregated region. These 40 countries represent 65% of world's population and 90% of the GDP. The time coverage of WIOD makes this database specially

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[5] For example, from the territorial perspective, Brazil, Sweden and France showed a range of 27–39 tCO_2/GJ in the period 1995–2008 vs. a range of 67–86 tCO_2/GJ for Poland, China and Australia. From the consumption-based perspective, due to the international exchanges, those differences are slightly reduced and the emissions intensities range between 37 and 44 tCO_2/GJ vs. 64–84 tCO_2/GJ.

appropriated for the purpose of our analysis (Arto et al., 2014b), providing a total of 560 observations (14 years times 40 countries).

The WIOD reports information on the gross energy use (GEU) by country and sector (Genty et al., 2012). The GEU refers to the sum of the intermediate energy used in energy transformation processes, plus final energy use, plus exports. This concept is very useful for modeling purposes, since it is fully consistent with the structure of the "Use table" in the national accounts framework and the production functions used in models. However, it is important to highlight that the information from the energy accounts of WIOD cannot be directly used for footprint analysis, since it accounts twice certain energy flows. For example, the GEU accounts include all the energy inputs in the electricity sector (e.g. the coal burned for producing electricity) but also the electricity used in the different sectors of the economy. Thus, in order to avoid any double counting, we proceeded to transform the GEU into net energy use (NEU)[6] using the WIOD energy accounts and the energy balances from the International Energy Agency (see Genty et al., 2012 for a detailed discussion on the differences between gross and net energy use). Within this accounting framework, the energy consumed by each sector represents the volume of energy it dissipates. For example, in the electricity sector we compute as energy use the difference between the primary energy used in the transformation process (coal, gas, nuclear, etc.) and the electricity produced, plus the distribution losses; while the energy actually consumed by final users will be computed as energy use of the corresponding sector (e.g. mining, car manufacturing industry, households, etc.). Moreover, the NEU (and the GEU) follows the residence principle instead of the territorial principle of the energy balances. In this sense, the energy accounts of WIOD are fully consistent with the national accounts and allocate the use of energy according to the residence of the consumer. Finally, it is important to stress that, while at the country level there will be differences between the NEU and the TPED due to the different accounting principles (residential versus territorial), at the world level the NEU and the TPED are equal.

The MRIO model used for the calculation of the energy footprints is described below for the case of three regions with n sectors, but it can be applied to any number of regions and sectors. In this study, the model is applied to 41 regions (40 countries plus the rest of the world as an aggregate region), 35 industries and 5 final demand categories.

The starting point of the model is the MRIO table at basic prices. This table describes the flows of goods and services from all sectors to all intermediate and final users, explicitly distinguishing the countries of origin and destination for each flow.

We can differentiate three main components in the MRIO table:

$$\mathbf{Z}=\begin{bmatrix}\mathbf{Z}^{11} & \mathbf{Z}^{12} & \mathbf{Z}^{13}\\ \mathbf{Z}^{21} & \mathbf{Z}^{22} & \mathbf{Z}^{23}\\ \mathbf{Z}^{31} & \mathbf{Z}^{32} & \mathbf{Z}^{33}\end{bmatrix}, \mathbf{f}=\begin{bmatrix}\mathbf{f}^{1}\\ \mathbf{f}^{2}\\ \mathbf{f}^{3}\end{bmatrix}=\begin{bmatrix}\mathbf{f}^{11}+\mathbf{f}^{12}+\mathbf{f}^{13}\\ \mathbf{f}^{21}+\mathbf{f}^{22}+\mathbf{f}^{23}\\ \mathbf{f}^{31}+\mathbf{f}^{32}+\mathbf{f}^{33}\end{bmatrix}, \mathbf{x}=\begin{bmatrix}\mathbf{x}^{1}\\ \mathbf{x}^{2}\\ \mathbf{x}^{3}\end{bmatrix},$$

where $\mathbf{Z}^{rs}$ is the intermediate matrix with sectorial deliveries from country r to country s; $\mathbf{f}^{rs}$ is the column vector of country s final demand (including household consumption, government consumption, and investment) for goods produced by country r; and $\mathbf{x}^{r}$ is the column vector of gross output for country r.

The relation between $\mathbf{x}$, $\mathbf{Z}$ and $\mathbf{f}$ is defined by the accounting equation $\mathbf{x}=\mathbf{Zi}+\mathbf{f}$, where $\mathbf{i}$ is the column summation vector consisting of ones.

Further, the global MRIO table is extended with: a vector $\mathbf{s}^{r}$ with element s_i^r indicating the NEU by sector i in country r; the scalar h^r which gives the direct NEU of households in country r. We define

$$\mathbf{s}=\begin{bmatrix}\mathbf{s}^{1}\\ \mathbf{s}^{2}\\ \mathbf{s}^{3}\end{bmatrix}\mathbf{h}=\begin{bmatrix}h^{1}\\ h^{2}\\ h^{3}\end{bmatrix}.$$

Accordingly, the NEU of country r can be expressed as

$$e^r=(\mathbf{s^r})'\mathbf{i}+h^r.$$

The input coefficient matrix for the whole system is defined as $\mathbf{A}=\mathbf{Z}(\hat{\mathbf{x}})^{-1}$, where $(\hat{\mathbf{x}})$ is a diagonal matrix with the values of vector $\mathbf{x}$ long its diagonal and zero elsewhere. Thus, the accounting equation can now be written as the standard input–output model: $\mathbf{x}=\mathbf{Ax}+\mathbf{f}$. For an arbitrary final demand vector $\mathbf{f}$, the solution to the model is given by $\mathbf{x}=\mathbf{Lf}$, where $\mathbf{L}\equiv(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the Leontief inverse.

The energy coefficients vector, $\mathbf{c}=(\hat{\mathbf{x}})^{-1}\mathbf{s}$, gives the amount of energy per unit of output. Hence, the amount of energy required for the production of the goods and services in order to satisfy total final demand $\mathbf{f}$ is given by

$$\mathbf{s}=\hat{\mathbf{c}}\mathbf{x}=\hat{\mathbf{c}}\mathbf{Lf}. \tag{1}$$

We can write [1] in its partitioned form as

$$\begin{bmatrix}\mathbf{s}^{1}\\ \mathbf{s}^{2}\\ \mathbf{s}^{3}\end{bmatrix}=\begin{bmatrix}\hat{\mathbf{c}}^{1} & 0 & 0\\ 0 & \hat{\mathbf{c}}^{2} & 0\\ 0 & 0 & \hat{\mathbf{c}}^{3}\end{bmatrix}\begin{bmatrix}\mathbf{L}^{11} & \mathbf{L}^{12} & \mathbf{L}^{13}\\ \mathbf{L}^{21} & \mathbf{L}^{22} & \mathbf{L}^{23}\\ \mathbf{L}^{31} & \mathbf{L}^{32} & \mathbf{L}^{33}\end{bmatrix}\begin{bmatrix}\mathbf{f}^{11}+\mathbf{f}^{12}+\mathbf{f}^{13}\\ \mathbf{f}^{21}+\mathbf{f}^{22}+\mathbf{f}^{23}\\ \mathbf{f}^{31}+\mathbf{f}^{32}+\mathbf{f}^{33}\end{bmatrix}. \tag{2}$$

From [2] we can calculate the primary energy embodied the domestic final demand of region 1 or total primary energy footprint as

$$pef^1=\mathbf{cLg}^1+h^1 \tag{3}$$

where $\mathbf{g}^1$ is a column vector that represents the domestic final demand of country 1:

$$\mathbf{g}^1=\begin{bmatrix}\mathbf{f}^{11}\\ \mathbf{f}^{21}\\ \mathbf{f}^{31}\end{bmatrix}.$$

Eq. (3) has been applied to compute the TPEF of the 41 regions covered in the WIOD, which has been used to assess the relations between energy (TPEF) and development (HDI). Furthermore, these results have been compared from those resulting from the comparison of the TPED and the HDI. Data for the HDI have been obtained from the United Nations while the data of the TPED are from the International Energy Agency (see Supplementary data).

Results

Figs. 1 and 2 show, for the period 1995–2008, the relation between the HDI and the per capita total primary energy demand (TPED) and footprint (TPEF) respectively, while Fig. 3 shows data for both indicators for the year 2008. These figures are especially relevant to understand the relation between human development and energy use.

The semi-logarithmic least square fit is the most commonly employed function in the literature to analyze the relation between energy and HDI, although it shows some shortcomings, especially in relation to the residuals (Steinberger and Roberts, 2010). The expression for the logarithmic fit is $HDI=a+b\ln(x)$, where x represent the TPED or the TPEF. This regression clearly reveals that in both cases the HDI increases with the per capita energy use (TPED in Fig. 1 or TPEF in Fig. 2) at lower levels of development reaching a saturation or "plateau" at higher levels. However, considering the energy use linked to

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[6] Note that "Net Energy Use" in this context is not related with the net energy after computing the energy return on energy invested (EROEI) (Cleveland 2005).

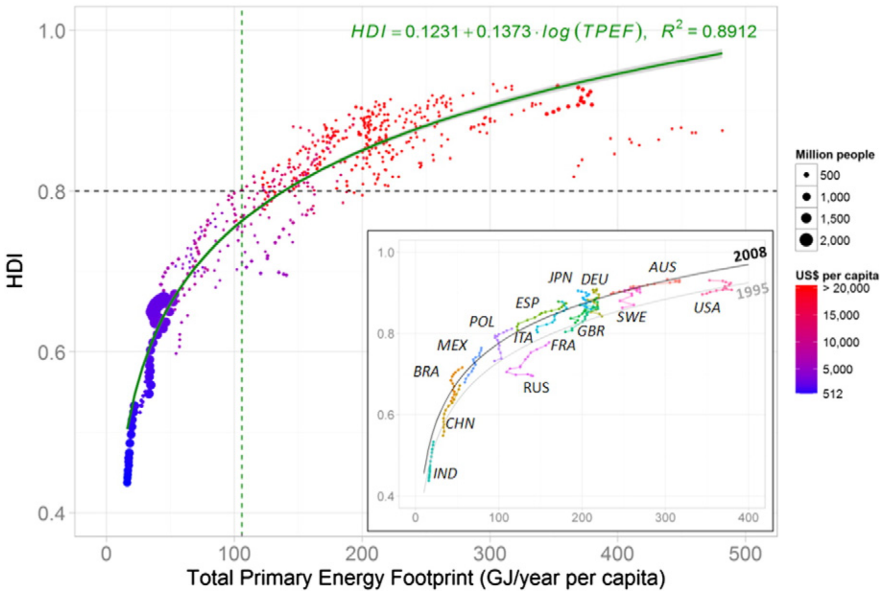

Fig. 2. Human development index, total primary energy footprint per capita, population and GDP per capita of selected countries, 1995–2008.
Notes:

1) HDI: human development index; TPEF: total primary energy footprint.
2) AUS: Australia; BRA: Brazil; CHN: China; DEU: Germany; ESP: Spain; FRA: France; GBR: United Kingdom; IND: India; ITA: Italy; JPN: Japan; MEX: Mexico; POL: Poland; RUS: Russia; SWE: Sweden; USA: United States of America
3) The points in the main figure represent the pairs of TPEF-HDI for the 40 countries detailed in Fig. 4 and for the period 1995–2008; the regression corresponds to the corresponding 560 observations (i.e. 40 countries times 15 years).
4) The points in the detailed figure represent the pairs of TPEF-HDI of a selected group of 15 countries for the period 1995–2008; the two regressions correspond to the observations of the 40 countries for the years 1995 and 2008 respectively.
5) The vertical green dotted line represents the threshold of the minimum energy to achieve a HDI > 0.8 for the set of countries and years analyzed (i.e. Poland 2006, with TPEF of 106 GJ/cap and HDI of 0.802). Countries above the horizontal line are classified as developed countries (i.e. HDI > 0.8), otherwise they are considered as developing countries.
6) GDP per capita in US$, constant prices of 2008. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

internationally traded goods and services (i.e. using the TPEF), the goodness of fit improves from ${R_{TPED}}^2 = 0.81$ to ${R_{TPEF}}^2 = 0.89$. In addition, the coefficient of the explanatory variable is higher for the regression of the TPED than for the TPEF. This means that, for a certain level of development, the energy needs are lower when they are accounted in terms of TPED than when accounted in terms of TPEF. Further analysis reveals that this result is mainly driven by the income component of the HDI. Both results are consistent with previous research on the relation between human development and CO_2 emissions (Steinberger et al., 2012).[7]

We have calculated the correlation coefficients $r_{HDI,TPED}$ and $r_{HDI,TPEF}$ using the data of the whole sample (i.e. 560 observations corresponding to 40 countries and 14 years). We have further split the sample into two groups: those with a HDI > 0.8 (352 observations) and those with a HDI < 0.8 (208 observations). These two samples have been used to calculate the corresponding correlation coefficients in terms of TPED and TPEF. Focusing on the relation between HDI and TPEF (Fig. 2), we find a positive relationship between both variables with a correlation coefficient $r_{HDI,TPEF} = 0.81$. This relation is especially strong at the lower levels of development; for instance below a HDI of 0.8, the correlation coefficient between HDI and TPEF is $r_{HDI<0.80,TPEF} = 0.82$, while for a HDI over 0.8 the correlation between the two variables decreases to $r_{HDI>0.80,TPEF} = 0.58$, revealing a saturation point. In terms of TPED, the interpretation of the results is similar but the correlation coefficients are lower: $r_{HDI,TPED} = 0.74$, $r_{HDI<0.80,TPED} = 0.70$ and $r_{HDI>0.80,TPED} = 0.57$.

Anyhow, the relation between the HDI and TPEF or TPED is not unique and we can find many different pairs of development and energy requirements. Thus, in order to facilitate the interpretation of these results we have split the countries according to their HDI. We consider as "developed" those countries whose HDI is over the threshold of 0.8 (countries over the dotted line in Figs. 1, 2 and 3, and countries highlighted in green in Fig. 4), while countries with a HDI below 0.8 will be labeled as "developing" countries (countries under the dotted line in Figs. 1, 2 and 3, and countries highlighted in red in Fig. 4).

According to this taxonomy, in the year 2008, 31 out of 40 countries analyzed belong to the "developed" group of countries (18 in 1995, see 2nd and 3rd columns in Fig. 4). These countries represented in that year 15% of global population, 42% of global TPED, and 49% of global TPEF. The average HDI of these countries is 0.875 (with a standard deviation $\sigma = 0.037$), but with different energy requirements depending on the indicator: the average TPEF of these countries is 215 GJ/cap ($\sigma = 74$) while the average TPED is 176 GJ/cap ($\sigma = 72$). In other words, the energy requirements to achieve a certain level of development are higher when measured in terms of footprint than when measured in terms of energy use. This can also be confirmed at the country level: in 2008, in 27 out of these 31 developed countries the share of TPED over TPEF is below 100% (see Fig. 4 and Table B1 of Appendix B). Likewise, as it is shown in Supplementary Material, the paths of the evolution of the energy requirements and HDI of these countries are significantly altered and shifted to the right when using the TPEF: higher levels of energy for the same level of development (this is the case of Denmark and the USA in the detailed chart of Fig. 3). The opposite can be observed for emerging developing countries (e.g. China and Russia in the detailed chart of Fig. 3).

In 2008, the top ten countries in terms of HDI are Australia (HDI = 0.934; TPEF = 302 GJ/cap; TPED = 252 GJ/cap), the USA (0.931; 353; 313), Ireland (0.919; 255; 142), the Netherlands (0.914; 222; 203), Sweden (0.910; 263; 226), Canada (0.909; 333; 335), Germany

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[7] These authors report a $R^2 = 0.77$ for the regression of territorial emissions and $R^2 = 0.87$ for the footprint approach.

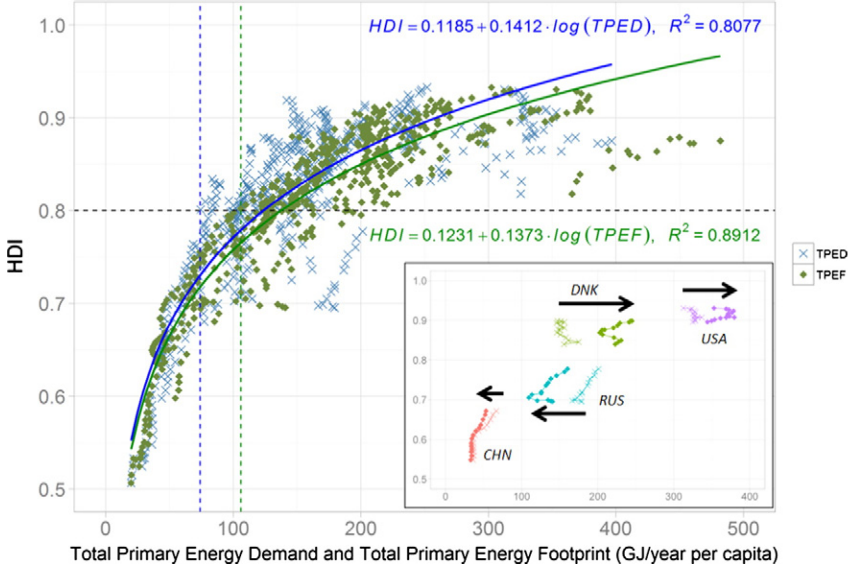

Fig. 3. Human development index, total primary energy demand per capita and total primary energy footprint per capita of selected countries, 1995–2008.
Notes:

1) HDI: human development index; TPED: total primary energy demand; TPEF: total primary energy footprint.
2) The points in the main figure represent the pairs of TPED-HDI and TPEF-HDI for the 40 countries detailed in Fig. 4 and for the period 1995–2008; each regression corresponds to the corresponding 560 observations (i.e. 40 countries times 15 years).
3) The points in the detailed figure represent the pairs of TPED-HDI and TPEF-HDI of a selected group of 4 countries for the period 1995–2008.
4) The vertical dotted lines represent the threshold of the minimum energy to achieve a HDI > 0.8 for the set of countries and years analyzed. In the case of TPED, this minimum energy is represented by blue line (i.e. Malta 2000, with TPED of 74 GJ/cap and HDI of 0.801), and in the case of the TPEF, by the green one (i.e. Poland 2006, with TPEF of 106 GJ/cap and HDI of 0.802). Countries above the horizontal line are classified as developed countries (i.e. HDI > 0.8), otherwise they are considered as developing countries.
5) Data for all countries for the year 2008 is shown in Table B1 of Appendix B. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database. Data for all countries for the year 2008 is shown in Table B1 of Appendix B.

(0.909; 217; 170), Japan (0.905; 195; 164), Denmark (0.898; 245; 147), and South Korea (0.895; 190; 199). These countries show high levels of development, and, with the exception of Canada and South Korea, the energy use required to sustain them is higher when measured in terms of TPEF (above 190 GJ/cap in all developed countries) than when measured in terms of TPED (the lower bound is 140 GJ/cap) (i.e. TPED/TPEF < 100%). In the case of Canada this is closely linked to the exports of high-energy intensive raw materials (mainly fossil fuels) and in the case of South Korea to the exports of manufactures. Within this group of countries, the highest differences between TPED and TPEF are in Ireland (TPED/TPEF = 56%), Denmark (60%), Germany (78%), and Australia (83%). We also found high differences in terms of TPED to TPEF ratio in the United Kingdom (72%), France (80%), and Japan (84%). Moreover, these differences are increasing since 1995 (see heat map in Fig. 4 and Table B1 of Appendix B).

Another interesting result from this list of developed countries is the identification of the countries that attained a HDI over 0.8 with the lowest energy requirements (i.e. the minimum quantity of energy to achieve a high level of development). This threshold varies depending on the indicator used to approximate the energy needs of human development. In terms of TPEF, in the year 2008 Poland is the benchmark with a TPEF of 116 GJ/cap and a HDI of 0.811. Poland is also the developed country with the lowest TPEF of the whole period 1995–2008 (106 GJ/cap in 2006 and HDI of 0.802). From the TPED perspective, in 2008, Latvia represents the energy-development threshold with a TPED of 83 GJ/cap and a HDI of 0.812, while for the whole period 1995–2008, Malta in 2000 shows the lowest TPED for a high level of development (TPED = 74 GJ/cap; HDI = 0.801).[8] On the basis of the regressions, the threshold for HDI > 0.8 corresponds to a TPEF of 140 GJ/cap, which is 13% higher than the threshold in terms of TPED (124 GJ/cap).

On the opposite side, in 2008, the ten developing countries analyzed represent 85% of global population, 58% of the TPED and 51% of the TPEF, with an average HDI of 0.699 ($\sigma = 0.083$). The average per capita TPEF of these countries is 70 GJ/cap ($\sigma = 39$) and the average TPED is 74 GJ/cap ($\sigma = 54$). These countries are Romania (HDI: 0.784; TPEF: 87 GJ/cap; TPED: 77 GJ/cap), Russia (0.778; 160; 201), Bulgaria (0.773; 90; 108), Mexico (0.764; 79; 69), Brazil (0.716; 56; 54), Turkey (0.704; 77; 58), China (0.672; 53; 67), Indonesia (0.601; 34; 34) and India (0.533; 22; 22). In all these countries, except Russia, both the TPEF and the TPED are below 110 GJ/cap. The aggregate region of the RoW has a HDI of 0.665 and a TPEF and TPED of 50 GJ/cap and covers 36% of world's population (see Appendix B).

In the case of emerging developing economies (i.e. BRIIC), we can observe in all cases except Brazil that the TPEF is higher than the TPED. China and Russia stand out in this list, both displaying a TPEF 20% lower than the TPED.

Discussion

The relation between energy and human development shows a clear positive correlation with a saturation point, regardless of the energy indicator used for the analysis (either the TPED or the TPEF). However, the energy requirements associated with a high level of development (i.e. HDI > 0.8) are greater when measured in terms of TPEF than in terms of TPED. The reason for this is closely related to different economic processes linked to globalization (e.g. specialization, offshoring or production relocation) that have resulted in a shift of economic activities between countries and in a dramatic growth in international trade. All these transformations have also had consequences in terms of energy use, and the amount of energy embodied in the net exports

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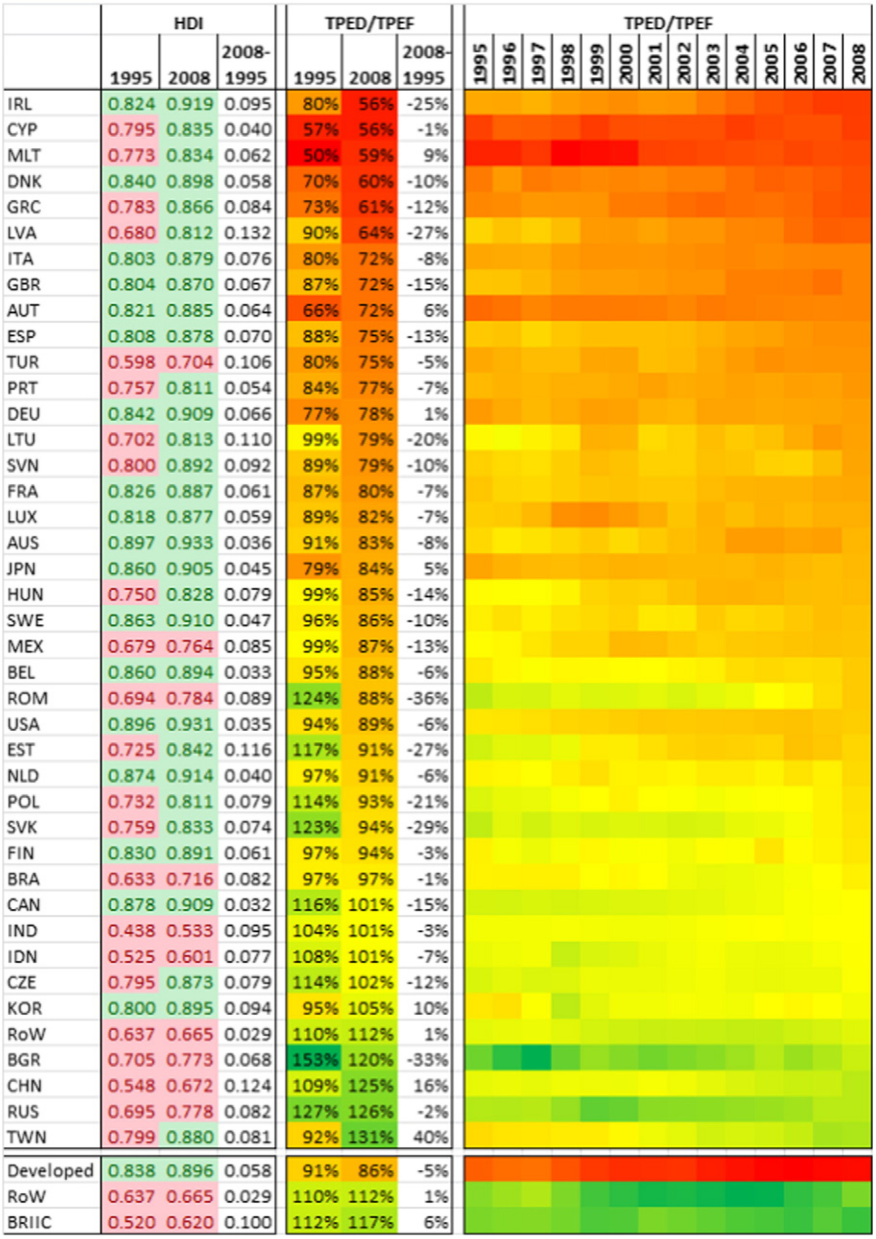
[8] Since the results for Malta might be biased due to the small-scale of the country, Latvia in 2008 could represent an alternative threshold with a TPED of 83 GJ/cap and a HDI of 0.81.



	HDI			TPED/TPEF		
	1995	2008	2008-1995	1995	2008	2008-1995
IRL	0.824	0.919	0.095	80%	56%	-25%
CYP	0.795	0.835	0.040	57%	56%	-1%
MLT	0.773	0.834	0.062	50%	59%	9%
DNK	0.840	0.898	0.058	70%	60%	-10%
GRC	0.783	0.866	0.084	73%	61%	-12%
LVA	0.680	0.812	0.132	90%	64%	-27%
ITA	0.803	0.879	0.076	80%	72%	-8%
GBR	0.804	0.870	0.067	87%	72%	-15%
AUT	0.821	0.885	0.064	66%	72%	6%
ESP	0.808	0.878	0.070	88%	75%	-13%
TUR	0.598	0.704	0.106	80%	75%	-5%
PRT	0.757	0.811	0.054	84%	77%	-7%
DEU	0.842	0.909	0.066	77%	78%	1%
LTU	0.702	0.813	0.110	99%	79%	-20%
SVN	0.800	0.892	0.092	89%	79%	-10%
FRA	0.826	0.887	0.061	87%	80%	-7%
LUX	0.818	0.877	0.059	89%	82%	-7%
AUS	0.897	0.933	0.036	91%	83%	-8%
JPN	0.860	0.905	0.045	79%	84%	5%
HUN	0.750	0.828	0.079	99%	85%	-14%
SWE	0.863	0.910	0.047	96%	86%	-10%
MEX	0.679	0.764	0.085	99%	87%	-13%
BEL	0.860	0.894	0.033	95%	88%	-6%
ROM	0.694	0.784	0.089	124%	88%	-36%
USA	0.896	0.931	0.035	94%	89%	-6%
EST	0.725	0.842	0.116	117%	91%	-27%
NLD	0.874	0.914	0.040	97%	91%	-6%
POL	0.732	0.811	0.079	114%	93%	-21%
SVK	0.759	0.833	0.074	123%	94%	-29%
FIN	0.830	0.891	0.061	97%	94%	-3%
BRA	0.633	0.716	0.082	97%	97%	-1%
CAN	0.878	0.909	0.032	116%	101%	-15%
IND	0.438	0.533	0.095	104%	101%	-3%
IDN	0.525	0.601	0.077	108%	101%	-7%
CZE	0.795	0.873	0.079	114%	102%	-12%
KOR	0.800	0.895	0.094	95%	105%	10%
RoW	0.637	0.665	0.029	110%	112%	1%
BGR	0.705	0.773	0.068	153%	120%	-33%
CHN	0.548	0.672	0.124	109%	125%	16%
RUS	0.695	0.778	0.082	127%	126%	-2%
TWN	0.799	0.880	0.081	92%	131%	40%
Developed	0.838	0.896	0.058	91%	86%	-5%
RoW	0.637	0.665	0.029	110%	112%	1%
BRIIC	0.520	0.620	0.100	112%	117%	6%

Fig. 4. Human development index and ratio between total primary energy demand and total primary energy footprint of selected countries, 1995–2008.
Notes:

1) HDI: human development index; TPEF: total primary energy footprint per capita; TPED: total primary energy demand per capita.
2) Data shorted from lowest to highest TPED/TPEF ratio in 2008.
3) In second and third columns, figures with HDI > 0.8 (developed countries) are highlighted in green while those with HDI < 0.8 (developing countries) are highlighted in red.
The heat color scale in the columns showing the ratio TPED/TPEF represents the deviation with respect 100%; i.e. yellowish colors represent a TPED/TPEF ratio close to 100% (or TPED similar to TPEF), reddish colors represent a TPED/TPEF ratio below 100% (or TPED lower than TPEF) and greenish cells represent al TPED/TPEF ratio over 100% (TPED greater than TPEF).
4) Developed: AUS: Australia; AUT: Austria; BEL: Belgium; BGR: Bulgaria; CAN: Canada; CYP: Cyprus; CZE: Czech Republic; DEU: Germany; DNK: Denmark; ESP: Spain; EST: Estonia; FIN: Finland; FRA: France; GBR: United Kingdom; GRC: Greece; HUN: Hungary; IRL: Ireland; ITA: Italy; JPN: Japan; KOR: South Korea; LVA: Latvia; LTU: Lithuania; LUX: Luxembourg; MLT: Malta; NLD: Netherlands; POL: Poland; PRT: Portugal; ROM: Romania; SVK: Slovakia; SVN: Slovenia; SWE: Sweden; TUR: Turkey; TWN: Taiwan; USA: United States of America. BRIIC: BRA: Brazil; RUS: Russia; IDN: Indonesia; IND: India; CHN: China. RoW: Rest of the World including MEX: Mexico. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

from emerging developing economies to developed countries has increased from 13.5 EJ in 1995 (equivalent to 6.6% of the TPED in developed countries) to 29 EJ in 2008 (13.8% of the TPED in developed countries). In other words, in 2008 the TPED of developed countries covered just 86% of the total energy required to satisfy their high living standards (91% in 1995). This can be clearly seen in Fig. 4, where most developed countries are reducing their TPED to TPEF ratio (i.e. moving toward more red colors). This gap between TPED and TPEF is offset by energy consumed in emerging developing countries that is embodied in the exports to developed countries. For instance, in 1995 the TPED in BRIIC countries was 12% greater than the TPEF, while in 2008 it was 17% higher. Thus, developed countries have reduced their share of domestic energy use to satisfy their demands and at the same time they have increased their welfare; and this has been done at the expense of a higher energy use in emerging economies and by means of international trade (see Fig. 4). Ultimately, trade enables countries to maintain/increase their development level by benefiting from consuming goods and services produced abroad and without the need of consuming energy to produce them.

These results are consistent with previous studies analyzing the relation between human development and carbon emissions (Steinberger et al., 2012). However, since countries depict different emission intensities per energy use, the analysis based on emissions would be reflecting not only the resources basis of development but also the differences in the energy mix. Moreover, while in future human development could be fully decoupled from emissions through cleaner technologies, this is unfeasible in energy terms: energy is the key factor that drives any economic process and is intrinsic to human development in complex societies (White, 1943; Cottrell, 1955; Tainter, 1990). In addition, some pathways of de-carbonized development might be constrained by resources availability and, therefore, could be unachievable.

What are the policy implications of our findings? First, focusing on the issue of the minimum energy requirements to achieve a high level of development, we find that in the period 1995–2008 none of the developed countries analyzed show a HDI over 0.8 with a TPEF below 100 GJ/cap, being the lowest figure 106 GJ/cap (Poland in 2006). This threshold is 20% higher than the one resulting from considering the TPED (74 GJ/cap of Malta in 2000). Therefore, studies that focus on the energy use as a proxy of the energy basis of development would be underestimating the energy requirements of high development standards. Furthermore, this conclusion critically affects the issue of the total energy that would be required annually to achieve a high level of development worldwide.

Indeed, another relevant policy implication of our analysis links to the target of improving living standards of developing countries: here the key question is how much energy would be necessary to achieve a high level of development worldwide. For instance, considering the country that displays the minimum TPED with a HDI value over 0.8 for the period studied (74 GJ/cap Malta in 2000), and extrapolating its value to global population in the year 2012 (7 billion) would result on a global TPED of 518 EJ, which is 8% below the global TPED in the year 2012 (560 EJ). Therefore, from this perspective, the issue of the minimum energy requirements to reach a universal level of development could be interpreted as a mere question of inequality in the distribution of energy resources. However, if the minimum TPEF (106 GJ/cap of Poland in 2006) is used instead of the minimum TPED as a benchmark to compute the energy requirements for a developed world, it would result on a figure exceeding by 33% the energy use of 2012. Or, in other words, maintaining a high "developed world" standard, would require not only a redistribution of the shares of the energy footprint across countries, but also a significant increase in the global annual energy requirements. Furthermore, assuming that typical population projections for the next decades point to 9 billion people by 2050 (UN, 2011), the energy requirements for a developed world in 2050 would exceed 2012's world energy use by 70% (i.e. 950 EJ). Hence, when introducing the concept of TPEF, the problem of global development might hit the "wall" of energy resource constraints on a finite planet (Chow, 2003; Kerschner et al., 2013). An increasing scientific evidence is showing that the world is facing the end of the era of cheap and abundant energy (Heinberg and Fridley, 2010; Murphy and Hall, 2011; Dittmar, 2013). These limits are related to fossil fuel depletion (Kerr, 2011; Hughes, 2013; Mohr et al., 2015), uranium scarcity (EWG, 2006; Dittmar, 2013), and to the sustainable potential of renewable energies (Moriarty and Honnery, 2009; Trainer, 2010; de Castro et al., 2014). In consequence, research assessing the physical basis of human development should pay special attention to the issue of the availability of energy resources.

It is important to highlight that this benchmark represents the current status quo of the relation between energy and development in each specific country. Therefore, the conclusions derived from the extrapolation to other countries or to the future should be interpreted with caution. On the one hand, the energy requirements depend on many different parameters and some of them are country specific. Moreover, our analysis is constrained by the limited geographical coverage of the WIOD. This is clearly a shortcoming for the case of developing economies, since only nine developing countries are represented in that database (mostly emerging economies). However, this does not invalidate the arguments derived from the analysis, especially those related to the high-development thresholds. The set of 40 countries analyzed represent 65% of world's population and 90% of the GDP, and the 31 developed economies represent 94% of the population living in countries with a HDI over 0.8.[9]

Regarding the indicators used to measure the energy requirements, one should have in mind that while the TPED can be measured directly (at least in principle, if the data are available), the TPEF indicator requires input–output analysis, so the analysis requires more resources (access to up-to-date databases, input–output knowledge, computational skills, etc.) and the results are less transparent.

On the other hand, the concept of primary energy may not accurately represent the actual energy needs of a country, and the analysis could be extended in the future to other indicators such as the final energy (excluding the losses in the energy system) or the net energy (the energy available after investments to obtain that energy) (Lambert et al., 2014). Fuel switching, especially in the power generation sector, and a transition to more efficient technologies (e.g. a society with a very high share of electricity from renewable sources in its final consumption) might have a significant effect in terms of the TPED and TPEF of a country, with virtually no change in its final energy use or footprint, as different fuels and technologies convert primary energy into useful energy at different efficiency rates.

Furthermore, efficient energy use can also reduce the energy footprint of human development. In recent decades energy efficiency has substantially increased (IEA, 2008) contributing to reduced energy requirements to sustain a specific level of development (Steinberger and Roberts, 2010). For example, in Fig. 2 we can observe that the curve relating HDI to TPEF has shifted upwards with time. Thus, in the future, it could be expected that part of the increase of the energy demand to support higher levels of development would be off-set by efficiency gains. Furthermore, the generalization of different available options for increasing energy efficiency can significantly contribute to reduce the energy needs of high living standards (UNIDO, 2010; Banerjee et al., 2012; Kahn Ribeiro et al., 2012; Ürge-Vorsatz et al., 2012; Molenbroek et al., 2015).

Finally, the current formulation of the HDI might not be the best to identify highly developed countries due to normalization, weighting and aggregation issues (Böhringer and Jochem, 2007). For instance, some countries with high life expectancies and schooling levels are not listed among the top developed countries, just because they have moderate or low incomes. Taking into account the implications of income generation in terms of energy (see Appendix A) or emissions (Steinberger et al., 2012), one could argue that those countries that are able to cover their health and education needs with lower income (i.e. generating lower environmental pressures) are the ones closer to the concept of "sustainable" human developed. In this sense, Rao et al. (2014) find a set of countries showing decent living standards, low

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[9] Note that we are just focusing on the differences between nations, ignoring the inequalities within countries.

per capita income (below 10,000 US$/cap) and with levels of energy use lower than the world average (although in this case the energy use is not corrected by trade).

Conclusions

The use of the TPED as indicator to assess the links between energy and development results in an underestimation of the energy requirements to obtain high levels of development, since it does not take into account the energy embodied in international trade. Similarly, the TPED would overestimate the energy required at lower levels of development. This question is especially relevant for development policies, which usually put the accent on the relation between the energy used by countries and their development, ignoring that, in a globalized world, the welfare of a country also relies on the energy embodied in the goods and services produced abroad. Thus, the use of the footprint approach would be a better option for this type of studies, as it has been already recognized when assessing the links between development and carbon emissions (Moran et al., 2008; Steinberger et al., 2012) or the ecological footprint (Moran et al., 2008). This claim would be also valid for other research topics like the (in)equality in the use of energy resources worldwide or the responsibility/drivers for the growth in global energy use.

The results in terms of energy footprint show that the generalization of the living standards from the so-called highly developed countries to the rest of the world would require a substantial increase in the global energy use rates. In consequence, research assessing the physical basis of human development should pay special attention to the issue of the availability of energy resources, considering that energy may be actually a positional good.

Furthermore, the use of the TPEF instead of the TPED might also be useful in other research fields. For instance, when analyzing the relationship between GDP and energy, it is remarkable that the positive correlation between both variables improves significantly when using the footprint approach (see Appendix A). Thus, research focusing on topics such as the Environmental Kuznets Curve hypothesis (Suri and Chapman, 1998; Luzzati and Orsini, 2009) or the GDP growth-energy causality (Cleveland, 2005; Ayres et al., 2013; Giraud and Kahraman, 2014), that typically consider the energy use, might benefit from the use of the TPEF concept. Climate mitigation research might also benefit from incorporating this concept to the design of welfare scenarios (Steckel et al., 2013).

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Appendix A

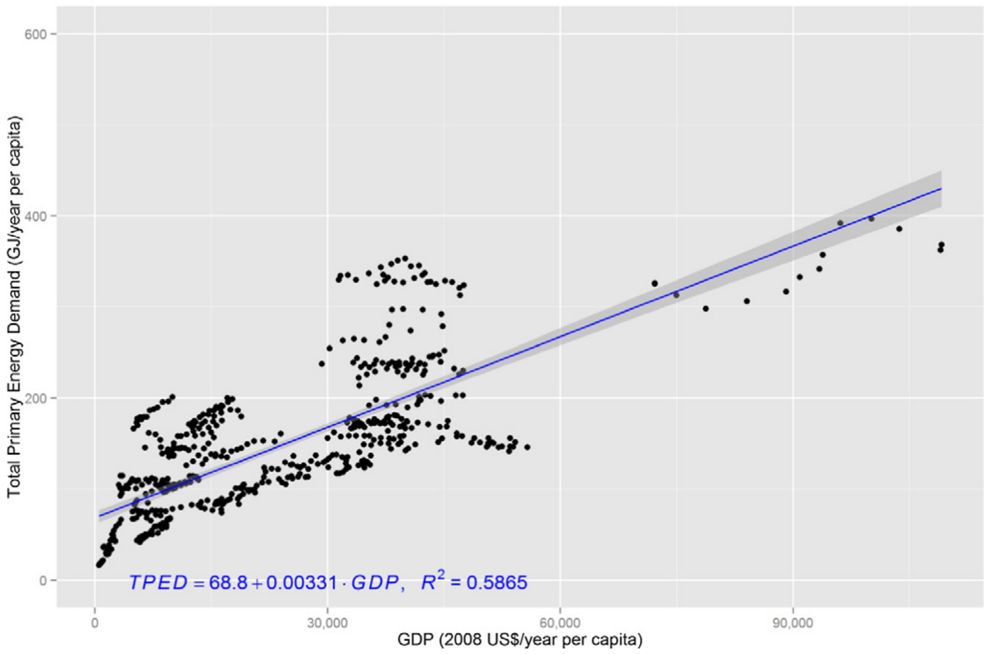

Fig. A1. Total primary energy demand per capita and GDP per capita, 1995–2008.
Notes
1) GDP: Gross Domestic Product; TPED: total primary energy demand per capita.
2) GDP per capita in US$, constant prices of 2008. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

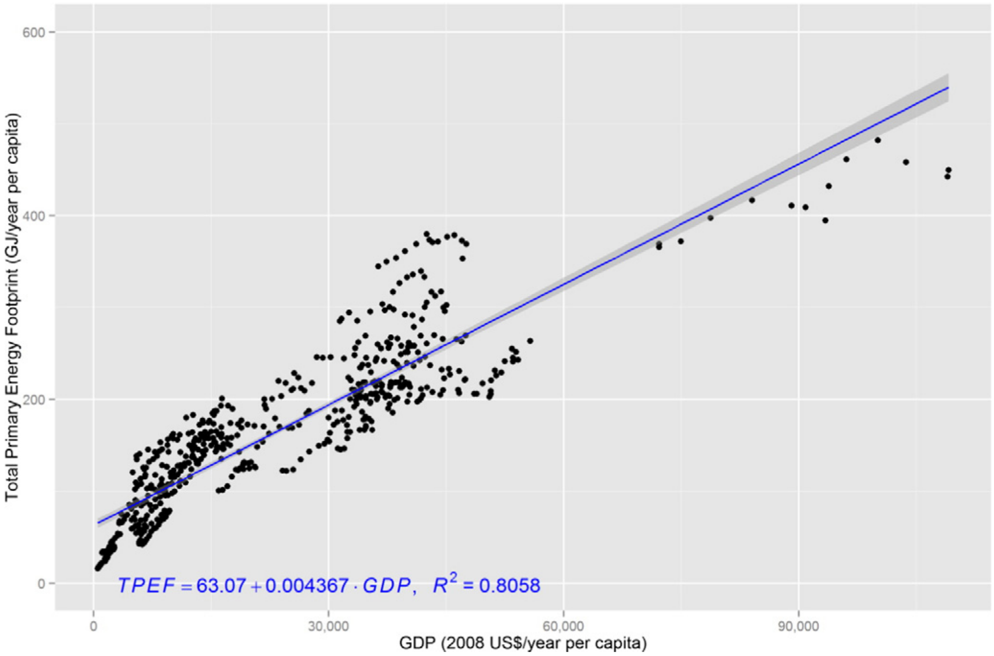

Fig. A2. Total primary energy footprint per capita and GDP per capita, 1995–2008.
Notes:

1) GDP: Gross Domestic Product; TPEF: total primary energy footprint per capita.
2) GDP per capita in US$, constant prices of 2008. Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

Appendix B

Table B1
Human development index, total primary energy footprint and total primary energy demand 2008.

	Developed			
	HDI	TPEF GJ/cap	TPED GJ/cap	TPED/TPEF
AUS	0.933	302	252	83%
USA	0.931	353	313	89%
IRL	0.919	255	142	56%
NLD	0.914	222	203	91%
SWE	0.91	263	226	86%
CAN	0.909	333	335	101%
DEU	0.909	217	170	78%
JPN	0.905	195	164	84%
DNK	0.898	245	147	60%
KOR	0.895	190	199	105%
BEL	0.894	261	230	88%
SVN	0.892	203	161	79%
FIN	0.891	296	279	94%
FRA	0.887	218	175	80%
AUT	0.885	233	169	72%
TWN	0.88	146	191	131%
ITA	0.879	171	124	72%
ESP	0.878	172	128	75%
LUX	0.877	442	362	82%
CZE	0.873	177	180	102%
GBR	0.87	197	142	72%
GRC	0.866	188	114	61%
EST	0.842	188	170	91%
CYP	0.835	246	137	56%
MLT	0.834	143	84	59%
SVK	0.833	151	142	94%
HUN	0.828	130	110	85%
LTU	0.813	145	114	79%
LVA	0.812	130	83	64%
POL	0.811	116	108	93%
PRT	0.811	126	96	77%
	Developing			
	HDI	TPEF GJ/cap	TPED GJ/cap	TPED/TPEF
ROM	0.784	87	77	88%
RUS	0.778	160	201	126%
BGR	0.773	90	108	120%
MEX	0.764	79	69	87%
BRA	0.716	56	54	97%
TUR	0.704	77	58	75%
WORLD	**0.683**	**77**	**77**	**100%**
CHN	0.672	53	67	126%
RoW	0.665	45	50	112%
IDN	0.601	34	34	101%
IND	0.533	22	22	101%

Appendix C. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2016.04.001.

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Notes to Table B1:

1) HDI: human development index; TPED: total primary energy demand; TPEF: total primary energy footprint.
2) Data shorted from highest to lowest HDI.
3) AUS: Australia; AUT: Austria; BEL: Belgium; BRA: Brazil; BGR: Bulgaria; CAN: Canada; CHN: China; CYP: Cyprus; CZE: Czech Republic; DEU: Germany; DNK: Denmark; ESP: Spain; EST: Estonia; FIN: Finland; FRA: France; GBR: United Kingdom; GRC: Greece; HUN: Hungary; IDN: Indonesia; IND: India; IRL: Ireland; ITA: Italy; JPN: Japan; KOR: South Korea; LVA: Latvia; LTU: Lithuania; LUX: Luxembourg; MEX: Mexico; MLT: Malta; NLD: Netherlands; POL: Poland; PRT: Portugal; ROM: Romania; RoW: Rest of the World; RUS: Russia; SVK: Slovakia; SVN: Slovenia; SWE: Sweden; TUR: Turkey; TWN: Taiwan; USA: United States of America.

Source: own elaboration from data of the International Energy Agency, United Nations and World Input–Output Database.

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