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Global Multi-Regional Input-Output methodology reveals lower energy footprint in an alternative community project

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ABSTRACT

Identifying the energy needs of citizens and taking into account different lifestyles and patterns of consumption is a first step for a global transformation towards renewable, fair and democratic energy systems. Currently, Total Primary Energy Supply (TPES) is the most widely used metric of energy consumption, which only includes the energy consumed within a country. This research addresses an alternative indicator, Total Primary Energy Footprint (TPEF), which also includes the energy embedded in imported goods and services. The research is innovative in its pioneering combination of a Global Multi-Regional Input-Output (GMRIO) methodology with household budget surveys (HBS) and consumption to production sectorial bridge matrices to calculate TPEF at a small community level. Errekaleor, the largest off-grid alternative intentional community located in Basque Country, Spain, was taken as a case study.

The results show, firstly, that alternative communal living can reduce energy consumption. In terms of the specific case study, even if direct residential energy consumption (4.46 MWh$\cdot$cap$^{-1}\cdot$yr^{-1}) was shown to be 32 % and 15 % higher in Errekaleor as compared with Basque and Spanish averages, a TPEF of 31.10 MWh$\cdot$cap$^{-1}\cdot$yr^{-1} per capita was determined for the community, 24 % and 14 % below the regional and national averages. Secondly, the relevance of indirect energy embedded in acquired goods and services in determining consumption-based energy use was shown. This accounts for 80.7 % of total consumption in Spain, 74.9 % in the Basque Country, and 66.3 % in Errekaleor. Within Errekaleor, individual arrangements impacted significantly, as people living in families have 33.5 % smaller energy footprints (28.45 MWh$\cdot$cap$^{-1}\cdot$yr^{-1}) than individuals living alone (42.79 MWh$\cdot$cap$^{-1}\cdot$yr^{-1}), who have a TPEF above the Basque average. Thus, the combination of GMRIO and HBS in the analyzed bottom-up case study made an important contribution in terms of clarifying the existing debate about the relative energy efficiency of alternative communities.

1. Introduction

Peak oil and fossil fuel depletion have been identified as drivers of the current energy crisis (Bardi, 2009; Wachtmeister et al., 2018; Capellán-Pérez et al., 2014). Difficulties in accessing fossil fuels are increasing the gap between social classes and deepening ongoing structural inequalities (Papathanasopoulou and Jackson, 2009). Furthermore, in order to satisfy the energy demands of the Global North, big energy infrastructure and generation projects are multiplying in the Global South (EJOLT, 2016), where colonial relations have already led to new forms of accumulation, such as accumulation by dispossession (Harvey, 2005). These energy projects are directly generating eco-social conflicts, the consequences of which are being suffered by people from rural areas, especially indigenous people (EJOLT, 2016). Women are also disproportionately affected, due to the larger burden of care work placed on them and the gendered violence they suffer in addition to the violence specifically related to eco-social conflicts (Front Line Defenders, 2020; Garcia-Torres, 2018; Silva Santistevan, 2018). The minority favoured by the existing socio-economic system is the primary driver of the global environmental degradation that has

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occurred over the last half century (Wiedmann et al., 2020). Moreover, a number of adaptation policies responding to the rapidly changing climate (Intergovernmental Panel on Climate Change (IPCC), 2021) are exacerbating inequalities, further marginalizing the poor and powerless (Dunlap and Brulle, 2015).

Thus, there is a clear need to transition towards a sustainable, fair and democratic energy model. However, a simple substitution of fossil energy for renewable sources is a challenge due to physical constraints on the implementation of renewable energy systems (RES), such as land occupation (Capellán-Pérez et al., 2017) and the need for very specific raw materials (Valero et al., 2018). Furthermore, there is debate within the scientific community as to whether the Energy Return Over Investment (EROI) of RES is a further constraint on their implementation (de Castro and Capellán-Pérez, 2020; Hall et al., 2014) or whether it is competitive with the EROI of fossil fuels (Kittner et al., 2016; Raugei et al., 2012). In either case, it is widely acknowledged that energy transition will also demand a drastic reduction of global primary energy consumption from the current 21.8 $\text{MWh} \cdot \text{cap}^{-1} \cdot \text{yr}^{-1}$ (International Energy Agency (IEA), 2018) to an estimated 10.8 $\text{MWh} \cdot \text{cap}^{-1} \cdot \text{yr}^{-1}$ (O'Neill et al., 2018; Akizu-Gardoki et al., 2018). As part of achieving this reduction in energy consumption, contributions that can be made by individuals and households have been identified (Akenji, 2014). Communities and grassroots movements have in fact been identified as key agents in bottom-up energy transitions (Akizu et al., 2018; van der Schoor et al., 2016), as individuals organized in groups can better act as agents for social change (Grabs et al., 2016).

One tool needed to achieve reductions is an appropriate set of indicators, or means for measuring and comparing energy consumption. The most widely used indicator for evaluating global energy consumption and the energy consumption of a country is Total Primary Energy Supply (TPES). This measure is a Production-Based Account (PBA) that assesses the amount of energy directly used in all the industrial production sectors of a country. The main problem with PBA measurements is that they attribute the energy embedded in a good to the country where the good is produced, not where it is consumed. Total Primary Energy Footprint (TPEF), in contrast with TPES, also reveals hidden energy flows (HEF), that is, the energy that is allocated to a producer country even though is consumed elsewhere (Arto et al., 2016; Akizu-Gardoki et al., 2018; Akizu-Gardoki et al., 2021). By taking into account energy transfer in goods traded internationally, as well as nationally consumed products and services, direct residential and transport energy consumption, TPEF, a Consumption-Based Account (CBA), reflects the real primary energy needs of the inhabitants of a country in order to maintain their life style. Hence, it is an essential indicator for doing a real diagnosis of energy consumption at country level, and is thus key in designing energy transition policies.

This paper makes use of Global Multi-Regional Input-Output (GMRIO) methodology in order to calculate TPEF at a community level, by using household budget surveys (HBS) and consumption to production sectorial bridge matrices. In this way, it was possible to analyze **how the characteristics of an alternative intentional community affect its TPEF, comparing it with national and regional values and understanding internal differences.** Errekaleor, the largest electrically self-sufficient intentional community in the Basque Country, was used as a case study.

This article is structured as follows: In the Literature review section, state-of-the-art GMRIO methodology for calculating TPEF is described and existing research on sustainable communities and their energy features is presented. The Methods section details the calculation of the neighborhood-level TPEF using GMRIO; at the end of the section, the case study selected, Errekaleor, and the characteristics of the sample of residents included in the study are presented. Along with some reflections on the application of the methodology, the main results of the research are presented in the Results and discussion section, describing the direct and indirect energy footprint of Errekaleor and providing comparisons with Spanish and Basque averages and other alternative intentional communities. Finally, the principal findings of the paper are reiterated in the Conclusions.

2. Literature review

In their pioneering work, Arto et al. (2016) calculated the TPEF of 40 countries using a GMRIO methodology at dynamic and multi-country scale on the basis of the WIOD database, avoiding the traditional double accounting problems found in similar analysis (Usubiaga-Liaño et al., 2021). They subsequently called into question findings by Steinberger and Roberts (2010) that indicated a decoupling of the Human Development Index (HDI) and primary energy consumption. It was shown that TPES, used by Steinberger and Roberts, in fact underestimates the total primary energy a country consumes to maintain a high HDI. Akizu-Gardoki et al. (2018) calculated the TPEF of 126 countries by using Eora input-output database and energy data provided by the International Energy Agency (IEA) in order to obtain a Decoupling Index (which measures the decoupling between the HDI and the energy consumption) for each country, showing a reduction in decoupling when TPEF is used instead of TPES. The GMRIO methodology was standardized by Akizu-Gardoki et al. (2021), who calculated the TPEF of 44 countries by using five different input-output databases.

The introduction of GMRIO metrics gave solid support to the old evidence which showed that high energy consumption in developed countries does not really improve quality of life (Martínez and Ebenhack, 2008). Going further, Akizu-Gardoki et al. (2020) found a turning-point on the TPEF (98.67 $\text{MWh} \cdot \text{cap}^{-1} \cdot \text{yr}^{-1}$ in 2015) above which increasing the national energy consumption on a footprint basis can even lead to reduced life-quality, supporting the degrowth theory. Milward-Hopkins et al., who built a bottom-up energy model in order to estimate the minimal energy required for decent living, have also claimed that global primary energy consumption can be reduced to levels of the 1960s without negative consequences (Millward-Hopkins et al., 2020). Income and life-style have been proven to be one of the most relevant factors influencing individuals' energy footprints, as the energy intensity of goods and services often increases with their prices. This also contributes to a large inequality in energy footprints (Oswald et al., 2020). While a majority of existing literature addresses the Global North, Baltruszewicz et al. recently calculated the final energy footprint of different households in Zambia, classified according to their economic capability (Baltruszewicz et al., 2021). An average total final energy footprint of 22.61 MWh per household was estimated for 2015, indicating that Zambians consume in average only the 12 % of the energy used by the average United States citizen, and about 20 % of the energy required by the average German citizen. This shows that a minimum energy threshold in order to achieve currently understood decent life standards could be in conflict of planetary boundaries.

Such is the importance of grassroots movements on the path towards a fair and democratic energy model that some authors attribute the progress of energy transitions in different countries to the presence of this kind of initiatives (Kooij et al., 2018). These communities have been defined as spaces where previously considered utopic sustainable living scenarios can be materialized (Hong and Vicdan, 2016). The low emission targets achieved in ecovillages are an example (Akizu et al., 2018). As Daly (2017) shows, intentional communities have an average carbon footprint (CF) 35 % lower than the mainstream. He reviewed 17 ecovillages and co-housing communities, in which CF was 22 % to 73 % lower than their local or national averages; only three of them presented a higher CF. However, a straightforward comparison between studies is difficult as in each work different methodologies, and even carbon metrics, have been used to calculate the CF. None of them used GMRIO methodology. Later on, Vita et al. (2020) calculated the CF of 141 members of 12 different grassroots initiatives (but not intentional communities) in Italy, Germany, Romania and Spain, by using Life Cycle Assessment (LCA) methodology, resulting in a 16 % lower total CF than their mainstream regional socio-demographic counterparts.

Despite the mentioned studies on CF, there is a lack of scientific literature quantifying energy consumption in ecovillages or other kinds of alternative communities. Cattaneo and Gavaldà studied the *rurban* (simultaneously rural and urban) communities of Kan Pascual and Can Masdeu, located in the hills of Collserola (Barcelona) (Cattaneo and Gavaldà, 2010). However, only the final energy consumption of the "productive" activities in the communities was taken into account (household and social center), excluding the energy consumption of inhabitants. Sherry looked into the ecological impacts of the inhabitants and activities of three US ecovillages (Earthaven, Ecovillage at Ithaca and Sirius) using LCA methodology, focusing on residential and transport energy consumption, as well as energy consumption related to food production and waste disposal (Sherry, 2019). Finally, Akizu et al. calculated the TPES of three German communities: the ecovillage Sieben Linden, the rural village Feldheim and the urban neighborhood Solar Settlement (Akizu et al., 2018). The main results of the studies mentioned above are shown in Table 1.

As it can be seen, reductions ranging 46 % to 79 % are obtained in the communities with respect to national averages for residential and transport energy consumption. Although the proportional reductions are similar for all communities, absolute energy consumption differs greatly. In Earthaven, at Ecovillage at Ithaca and Sirius, residential energy consumed by inhabitant per year ranges from 7.91 MWh to 12.27 MWh, whereas in Sieben Linden, Feldheim and Solar Settlement it ranges from 0.35 to 0.71 MWh, 95 % less on average, showing the uncertainty of values. It is also interesting to note that in two of the three studies, attention is centered on residential and transport energy. Only one study broadens its analysis to include the calculation of the TPES and with very generic measures and assumptions. However, none of the research takes into account the TPEF, since, as far as it was possible to determine, the TPEF of a sustainable community had not yet been calculated prior to this paper.

3. Methods

Global Multi Regional Input-Output (GMRIO) was the core analytic tool used in this study. The application of this methodology for the calculation of the Spanish TPEF used in this research, shown in Fig. 1, was developed and tested by our team as part of earlier research (Akizu-Gardoki et al., 2018; Akizu-Gardoki et al., 2021). Input-output (IO) data for the model was obtained from the Eora 26 database (Lenzen et al., 2012). This data includes economic information on 26 industrial sectors from 189 countries for the year 2015, and provides the most recent data available from IO databases. In addition to the 189 countries, it provides economic information about the rest of the world (RoW) aggregated into a single sector. This data allowed the authors to create matrix **T** "intermediate deliveries" between countries, matrix **Y** "final demand of goods and services", vector **x** "sectorial gross inputs" and vector **v** "sectorial added value" for the GMRIO framework (Akizu-Gardoki et al., 2018; Akizu-Gardoki et al., 2021). The row vector **q**, TPES per industrial sector by country, was created by relating the data provided by the IEA for each sector and country (International Energy Agency (IEA), 2015) to the Eora 26 database. The TPES was constructed by using the instructions provided by the IEA (International Energy Agency (IEA) et al., 2004), as done by the authors of this paper in earlier research (Akizu-Gardoki et al., 2018; Akizu-Gardoki et al., 2021). In order to avoid double accounting (Usubiaga-Liaño et al., 2021), the following were added to obtain the TPES: *i*) total final consumption per sector, *ii*) transformation process flows, *iii*) distribution losses, *iv*) own use flows in energy production and *v*) statistical differences. After creating the vector **q**, the global TPES was compared with the sum of all the components of the vector, in order to prove its construction was accurate. The correspondence between IEA and Eora 26 sectors is shown in Table S.2 (see Supplementary material). TPES data for only 134 countries, in addition to the global TPES, was available, thus reducing the original number of countries included from 189 to 134. In order not to leave out the energy embedded in the imports from the remaining countries, the code developed in this work calculates the TPES of the RoW by subtracting the TPES of the mentioned 134 countries to the global TPES. Hence, the TPES of the countries which are not specifically included in the IEA Energy Balances was allocated to the RoW component of the **q** vector. Direct residential and transport energy consumption were removed from the **q** vector prior to the TPEF calculation, in order to avoid their distribution within the indirect accounts into the Eora 26 sectors. However, due to the addition of transformation process flows, distribution losses and own use flows in energy production when calculating the TPES, the primary energy requirements behind final direct energy consumption were included in the **q** vector. Direct residential energy consumption was obtained directly from the IEA, while production and distribution losses were attributed to the electricity industry (Eora sector *Electricity, Gas and Water*). Residential transport energy was dis-aggregated by multiplying the percentage of

Table 1
Energy consumption at different sustainable communities. Data obtained from Cattaneo and Gavaldà (2010), Sherry (2019) and Akizu et al. (2018).

Community	Residential energy		Transport energy		Total Primary Energy Supply	
	$MWh\cdot cap^{-1}\cdot yr^{-1}$	% reduction with respect to national	$MWh\cdot cap^{-1}\cdot yr^{-1}$	% reduction with respect to national	$MWh\cdot cap^{-1}\cdot yr^{-1}$	% reduction with respect to national
Kan Pascual (Cattaneo and Gavaldà, 2010)	4.32[a]	–	0.31[a]	–	–	–
Can Masdeu (Cattaneo and Gavaldà, 2010)	1.41[a]	–	0.31[a]	–	–	–
Earthaven (Sherry, 2019)	8.67	62 %	10.73	63 %	–	–
Ecovillage at Ithaca (Sherry, 2019)	7.91	65 %	11.94	58 %	–	–
Sirius (Sherry, 2019)	12.27	46 %	14.50	49 %	–	–
Sieben Linden (Akizu et al., 2018)	0.35	79 %	4.80[b]	57 %	10.65	77 %
Feldheim (Akizu et al., 2018)	0.71	58 %	–	–	26.77	42 %
Solar Settlement (Akizu et al., 2018)	0.58	66 %	–	–	39.93	13 %

[a] The per capita values shown in this table for Kan Pascual and Can Masdeu were derived from the original study by the authors of the present article, with the original article providing values for physical sites and not inhabitants. While endosomatic energy is included in the study by Cattaneo et al., it is excluded from this table.
[b] Transportation of goods is also included.

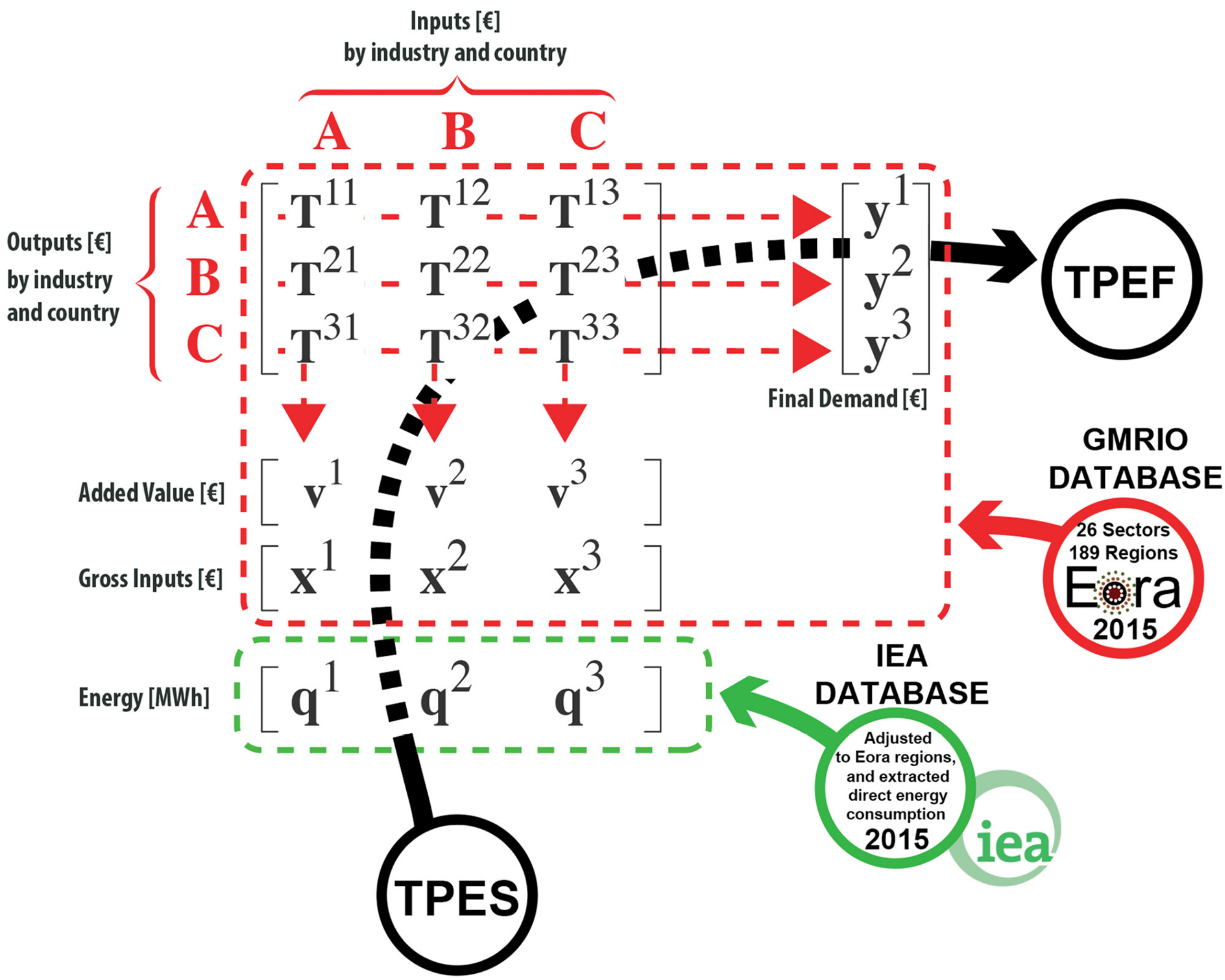

Fig. 1. Global Multi-Regional Input-Output (GMRIO) methodology and necessary matrix in order to generate national Total Primary Energy Footprint (TPEF) data from Total Primary Energy Supply (TPES) national data.

private cars (out of the total vehicle fleet of each country) with the total transport energy of a country, using data published by Fountas et al. (2020). Finally, direct residential and transport energy were reintroduced into the TPEF after the calculation of the footprint in each Eora 26 sector.

In addition to the Spanish TPEF, the indirect energy consumption of 134 countries (embedded in products and services) for the year 2015 was obtained and is presented in Table S.3 (see Supplementary material). This data, which includes sectorial embedded energy consumed by country, TPES and TPEF, is relevant to both the scientific community and policy makers since it allows Hidden Energy Flows (HEF) to be better understood. Furthermore, Table S.4 shows TPES, TPEF and HEF of 134 countries from year 2000 to 2015.

Once the Spanish national energy footprint was obtained, the second part of the methodology consisted of extrapolating this to a regional level (Basque Country) and the community level of Errekaleor. The conversion of the national TPEF to a regional or consumer level using a GMRIO methodology is often performed through Household Budget Surveys (HBS) (Christis et al., 2019). In this paper, per capita expenditures of Spain, the Basque Country and Errekaleor for a whole year were compared in order to proportionally obtain the TPEF in each of the Eora 26 sectors. This comparison, however, was not straightforward, due to incompatibilities between HBS and IO tables, based on National Accounts (NA) (Mongelli et al., 2010; Cazcarro et al., 2020). Hence, the use of HBS in GMRIO calculations can lead to uncertainties (Min and Rao, 2018), which need to be addressed. In this paper HBS data were adapted as suggested by Cazcarro et al. (2020) with the purpose of addressing those uncertainties. The steps taken in order to adapt HBS data for the calculation of the TPEF of the Basque Country and Errekaleor (Sections 3.3–3.4) are explained over the course of this section. The HBS from all three regions (Spain, Basque Country and Errekaleor) were adapted.

3.1. Collection of household budget surveys

Spanish and Basque HBS were obtained from the Spanish National Institute of Statistics (INE) (Instituto Nacional de Estadística (INE), 2015). Data from 2015 were used in order to be consistent with the year of the Eora database. HBS were computed in 40 different consumption-based categories (INE categories), which are related to the three-digit Classification of Individual Consumption According to Purpose (COICOP) categories (United Nations Statistics Division, 2018) as shown in Table S.5 (see Supplementary material).

Data from Errekaleor were obtained through a survey following INE methodology (Instituto Nacional de Estadística (INE), 2016). As the photovoltaic (PV) system was installed in mid-2018, the survey was conducted in 2019. It was assumed that international, national and regional consumption habits remained mostly unchanged over the 2015–2019 period, so adjustments to correct the discrepancy in the age of data were not made.

Residents were divided into three categories, based on household types within the neighborhood: community, family and individual. These categories are explained below.

- **Community**: 4 to 10 people sharing a whole building (6 apartments) as well as the household economy.
- **Family**: 2 to 3 people sharing a single apartment as well as the household economy.
- **Individual**: a single person living in her/his own apartment.

Taking into account that in each category household economies include very different numbers of people, we hypothesized that the expenditures per capita would differ noticeably across each category. In consequence, the energy footprint of each category would also differ, resulting in a lower TPEF per capita for people living in a community or family and a higher TPEF per capita for individuals living alone. Therefore, proportional stratified sampling was used in order to reduce the error with respect to a random sampling (Argibay, 2009). 34.5 % of residents (40 out of 116) were surveyed, a proportion of the population far higher than that used by the INE to obtain national and regional HBS (Instituto Nacional de Estadística (INE), 2016). The number of total neighbors in each category, as well as the number included in the sample, is shown in Table 2. The sample is addressed in more detail in Section 3.8.2.

Mean expenditure per capita was calculated by performing a weighted average. Neighborhood expenditures (those used for the common projects mentioned above) were divided by the total number of residents and added to the mean expenditures per capita. Table S.6 (see Supplementary material) compares yearly expenditures, without any adaptation or elevation of the data, for an average person living in Spain, the Basque Country and Errekaleor. As shown in the table, both *Real* and *Imputed rentals* (categories 04.1 and 04.2) in Errekaleor were considered free of economic and energy costs, as Errekaleor inhabitants have been reusing buildings that were due to be demolished years ago. Hence, life cycle impacts of the construction of dwellings were assigned to the previous users, as is done in the cut-off system model approach (Ecoinvent, n.d.). Regarding the *Water services and miscellaneous services related to the dwelling* (category 04.4), the same average expenditures as in the Basque Country were assumed.

In addition to the expenditures of an average Errekaleor inhabitant, the mean expenditures of a person living in a community, in a family or living alone were obtained and analyzed.

3.2. Supplementary questionnaire

The same sample group that filled out Household Budget Surveys on which input-output calculations were based (see Table 2) also answered to a supplementary questionnaire including the following three questions, which aimed to discover residents' estimates of the size of their energy footprints and the importance they placed on this issue.

- What was your motivation to live in Errekaleor?
- Do you think Errekaleor plays a role in energy transition?
- Do you try to consume responsibly? How?

Table 2
Number of residents in Errekaleor in each household category, number of people included in the sample in each household category, and number of household units in each sample.

Category	Total neighbors (N)	Neighbors in sample (n)	Household units in sample
Community	45	16	3 communities
Family	47	16	7 families
Individual	24	8	8 individuals
Total	116	40	

3.3. Elevation of household budget surveys into national accounts principles

Several elevations were carried out in this step. The first was to elevate the Spanish and Basque HBS data according to population data, as the total population assumed by the HBS is smaller than the actual population.

Once this was done, the Spanish Household Financial Consumption Expenditures (HFCE) from National Accounts (NA) were obtained from Eurostat (Eurostat, 2015). By comparing the population-elevated Spanish HBS to the HFCE, a correction factor was obtained for each category (see Table S.6 from Supplementary material), similar to the ones obtained by Cazcarro et al. for 2011 (Cazcarro et al., 2020). Subsequently, population-elevated Basque HBS and Errekaleor HBS were elevated according to the previously obtained correction factors, assuming that consumption habits and the origin of goods were similar and that, therefore, the factors were not significantly different for Spain (i.e. Spanish factors are valid for both the Basque Country and Errekaleor). Finally, the category *Financial Services n.e.c.* (category 12.5), which was missing in the Spanish and Basque HBS, was directly obtained from NA.

3.4. Direct transport and residential expenditures

After elevating the HBS, direct transport expenditures (category 07.2.2 *Fuels and Lubricants*) were removed, so as not to include them in IO calculations. Direct transport energy consumption in the Basque Country and in Errekaleor were proportionally calculated from the Spanish data by using the proportions of the Spanish, Basque and Errekaleor expenditures in category 07.2.2.

Although the category 04.5 *Electricity, gas and other fuels* is directly related to direct residential energy, it allows for transformation and transport losses. Hence, expenditure in this category was not removed from the HBS. In the case of Errekaleor, the expenditure on the whole PV system was divided by its life time (assumed to be 20 years) and included in category 04.5. However, expenditure on biomass (mainly wood coming from nearby villages) was removed as it does not generate losses in electricity or gas supply systems.

After performing IO calculations, direct transport and residential energy consumption was added to the sum of the indirect energy embedded in products and services, in order to obtain the TPEF of the Basque Country and Errekaleor.

3.5. Conversion of consumption-based categories into production-based categories by the use of sectorial bridge matrices

While elevated HBS data are computed by using consumption-based categories (COICOP or INE), IO tables are related to production-based categories. In the work already cited in this article, Cazcarro et al. (2020) provide a bridge matrix for converting data from COICOP into Classification of Products by Activity (CPA) categories (Eurostat, 2008), which was computed by using data from 2011. Cai and Vandyck (2020), provide another COICOP to CPA bridge matrix based on 2015 data. It was assumed that bridging is the same throughout Spain, and both matrices were used and compared in this work. Some of the COICOP sectors were aggregated in these matrices (see Table S.5), in order to implement an INE to CPA bridging. The matrix calculation to convert the HBS data (given in consumption-based INE categories) into production-based CPA categories is the following:

$$\mathbf{i} \cdot \mathbf{B} = \mathbf{c},$$

where $\mathbf{i}$ are the HBS in the form of a row vector of 40 components, each one indicating the yearly expenditure per inhabitant in the corresponding INE category (Table S.5); $\mathbf{B}$ is the 40×64 INE to CPA bridge matrix proposed by either Cazcarro et al. (2020) or Cai and Vandyck (2020); and $\mathbf{c}$ is a row vector of 64 components indicating the yearly expenditure per inhabitant in the corresponding CPA category (see

Table S.7). The matrix form of the previous equation can be expressed as follows:

$$(i_1\ \ i_2\ \ldots\ i_{40}) \cdot \begin{pmatrix} B_{1-1} & B_{1-2} & \ldots & B_{1-64} \\ B_{2-1} & B_{2-2} & \ldots & B_{2-64} \\ \ldots & \ldots & \ldots & \ldots \\ B_{40-1} & B_{40-2} & \ldots & B_{40-64} \end{pmatrix} = (c_1\ \ c_2\ \ \ldots\ \ c_{64})$$

3.6. Adjustment from purchaser's prices to basic prices

In order to be consistent with IO tables, the converted data were adjusted from purchasers to basic prices by using the tool developed by Cazcarro et al. (2020). The tool was also assumed to be valid throughout Spain in this case.

3.7. Modification to an industry-by-industry classification

Finally, it was necessary to adapt the data into the IO industry classification. This was done by aggregating the 64 CPA categories into Eora 26 industrial sectors. The correspondence shown in Table S.7 (see Supplementary material) was used to this end in the form of a bridge matrix, which was applied as indicated below:

$$\mathbf{c} \cdot \mathbf{D} = \mathbf{y},$$

where **c** is the row vector explained in Section 3.5 after adjustment to basic prices (Section 3.6); **D** is the 64 × 26 CPA to Eora 26 bridge matrix, which was based on Table S.7; and **y** is a row vector of 26 components, which represent the total final demand for goods and services per inhabitant for all the Eora 26 categories by region (Spain, Basque Country or Errekaleor). The proportional regional TPEF in each of the Eora 26 sectors was obtained by comparing the **y** vectors of Basque Country and Errekaleor with the Spanish **y** vector. The matrix form of the previous equation is further developed below:

$$(c_1\ \ c_2\ \ \ldots\ \ c_{64}) \cdot \begin{pmatrix} D_{1-1} & D_{1-2} & \ldots & D_{1-26} \\ D_{2-1} & D_{2-2} & \ldots & D_{2-26} \\ \ldots & \ldots & \ldots & \ldots \\ D_{64-1} & D_{64-2} & \ldots & D_{64-26} \end{pmatrix} = (y_1\ \ y_2\ \ \ldots\ \ y_{26})$$

3.8. Case study

3.8.1. Description of Errekaleor

Errekaleor is a neighborhood located in the outer suburbs of the city of Vitoria-Gasteiz, Basque Country. It was constructed in the early 1960s in order to house workers and their families migrating to the city from surrounding villages and other parts of Spain, attracted by the work available in the growing industrial sector. In 2002 the City Council initiated a process of relocating the residents living in the neighborhood, with the stated aim of demolishing the 16 apartment blocks and other buildings on the site for the subsequent creation of higher quality housing (Basque Radio-Television, 2013). The foundation of the currently existing alternative intentional community began in 2013, before the process of relocation was complete, in collaboration with residents resisting this process. The first building was squatted by a group of students, giving birth to the project *Errekaleor Bizirik!* (*Errekaleor Alive!* in Basque language) (Errekaleor Bizirik!, 2013). While the last of the suburb's historic residents left in 2017, around 120 people with diverse socioeconomic profiles are currently occupying more than 50 apartments. The *Errekaleor Bizirik!* project aims to influence society by building a practical alternative to the current economic system. It is both a political and lifestyle project, based on commitments to anti-capitalism, assemblyism, feminism, the Basque language and self-sufficiency. Different working groups focused on these areas coordinate political organization and everyday activities. These groups include the infrastructure maintenance and repair group, the communication group, the feminism group, the energy sovereignty group and the culture group. In addition, several open community projects have been created in the neighborhood, including vegetable gardens, a printing press, a bike repair workshop and a popular gym, among others (Abezia and Arregi, 2015).

In 2017 mains electricity to the entire suburb was cut off as part of a local government anti-squatting campaign. In response, a self-sustainability plan was launched with the assistance of thousands of nonresident supporters. The central component of this plan was the installation of an off-grid PV system, which was designed by professionals from the sector who shared their expertise and knowledge with Errekaleor inhabitants. It was financed by a crowdfunding campaign and installed by residents and volunteers. Since 2018 the neighborhood has been self-sufficient in terms of electrical energy, thanks to the 65 kWp solar installation connected to a 300 V and 750 Ah in C10 battery set and a 50 kW inverter. The success of this installation has meant that Errekaleor has become a point of reference in communal energy transition processes and currently is the biggest electrically self-sufficient community of the Basque Country without a connection to the national electric grid (Basque Radio-Television, 2018; El Salto TV, 2018; Basurko et al., 2021).

3.8.2. Characteristics of the sample

The socioeconomic characteristics of the chosen sample (gender, nationality, age, working hours and income) were representative of Errekaleor as a whole. As shown in Table S.1 (see Supplementary material), while men and women were represented almost equally – 21 men and 19 women in the sample, with non-binary people included in the category 'women' (Butler, 1990), as common practice by Errekaleor inhabitants. The distribution of gender by household type is very uneven. Whereas most women live within a community or family, men constitute a majority of individual households. A majority of residents in the suburb and the sample groups are Basque (30 out of 40 in the sample) and young (19 were born between 1990 and 1994, both included). The majority had part-time jobs (17) and an income of less than €5000 per year (14 people in the sample). In addition, university students and recent graduates constitute 40 % of the sample.

4. Results and discussion

4.1. Answers to the supplementary questionnaire

The most common answers to the question: *What was your motivation to live in Errekaleor?* included ideas around support for the political project and alternative lifestyle it represented, ideological coherence and a willingness to live in a community. Some people also mentioned affective ties, their need for housing in Vitoria-Gasteiz, and economic need. Finally, anti-capitalist ideals or values, including solidarity, self-management, feminism and the struggle against private property were also mentioned. Only four respondents (10 % of the sample) mentioned environmentalism or degrowth.

To the question: *Do you think Errekaleor plays a role in energy transition?* all the answers stated that it did play a role. A majority (74 %) focused on direct residential energy and especially on the self-managed PV system. Comments included "the electricity cut-off opened up a new path to us", "the PV system is a first step", "it gives us independence with respect to the electricity market", and "we have become a point of reference by showing that another lifestyle is possible". 18 % of that majority also indicated awareness of other sources of residential energy. Only 26 % of the survey responses mentioned indirect energy embedded in goods and services. Those people referred to self-management, community, anti-capitalism, anti-consumerist culture and reusing resources as ways to reduce energy consumption. However, most also mentioned the high dependence on fossil fuels, the need for more efficient heating systems, the need for a neighborhood-wide energy plan and a general lack of awareness. It was also mentioned that the PV system was installed in response to an immediate need, not because it was part of a coherent pro-environmental strategy.

Finally, in response to the question: Do *you try to consume responsibly?* 21 % of the answers were related to direct energy consumption (“I use low power devices”, “I try to use certain devices only when we have plenty of electricity”, “I try not to light the fire too much”, “I use a bicycle instead of a car”) but more answers (74 %) were related to indirect consumption habits. People claimed to recycle, reuse and repair; they also talked about self-sufficiency and “free” or second-hand shops; some respondents reported trying not to consume unnecessarily and avoiding big supermarket chains; instead, they reported trying to shop locally and buying organic, fair trade and mainly plant-based products. However, some people (5 %) admitted that this was not a priority and that they often bought products that they did not need from multinationals.

4.2. Direct residential energy consumption

Although direct residential energy is only a small part of the overall energy footprint for Spain, Basque Country or Errekaleor (ranging from 7.5 % to 14.4 %, as shown in Section 4.3), every-day habits are shown in the values. Fig. 2 shows the total amount of direct residential energy ($MWh \cdot cap^{-1} \cdot yr^{-1}$) consumed in Spain, Errekaleor and the Basque Country, as well as the proportion of each type of fuel source. Spanish data were obtained from the IEA (International Energy Agency (IEA), 2015) and the proportion of renewable and non-renewable electricity was obtained from the National Electricity Mix (Red Eléctrica Española (REE), 2015). Basque data were obtained from the Basque Energy Agency (Ente Vasco de Energía (EVE), 2015), applying the Spanish proportion for renewable and non-renewable electricity to imported electricity. Finally, the electricity consumption of Errekaleor was obtained from the neighborhood electric meter, the amount of diesel used for the support generator set was provided by the Energy group and the quantity of wood and butane consumed in each house were obtained from the surveys. Several conversion tools were used in order to convert the consumed diesel liters, wood tones and butane bottles into MWh (Universities and Colleges Climate Commitment for Scotland (UCCCfS), 2015; Food and Agriculture Organization (FAO), 2017).

Residential energy sources are very different in the three regions. In Spain non-renewable and renewable electricity is the most consumed (40.6 %), followed by natural gas (20.3 %), biofuels and renewable thermal (18.5 %), oil products (13.0 %) and Liquefied Petroleum Gases (LPG, 7.0 %). In the Basque Country, the use of natural gas (43.0 %) surpasses the use of electricity (40.6 %), probably due to the promotion of natural gas by the Basque Government over past decades (Gobierno Vasco, 2020). Electricity is followed by oil products (9.6 %), while biofuels and renewable thermal account for only a small proportion (6.9 %). In Errekaleor the distribution changes dramatically. The primary fuel source is wood for heating spaces with stoves (82.1 %), followed by a much smaller proportion of butane gas (12.8 %), which is mainly used for cooking and heating water. Finally, even though the PV system is one of the main symbols of Errekaleor and has a crucial importance for residents, electricity obtained from the PV system (4.1 %) and from the support generator set (diesel 1.1 %) represents a very small portion of the overall residential energy mix. If the whole TPEF is taken into account, the PV system only represents 0.6 % over the total.

Far from reflecting the reductions documented in studies of other sustainable communities (see Table 1), total direct residential

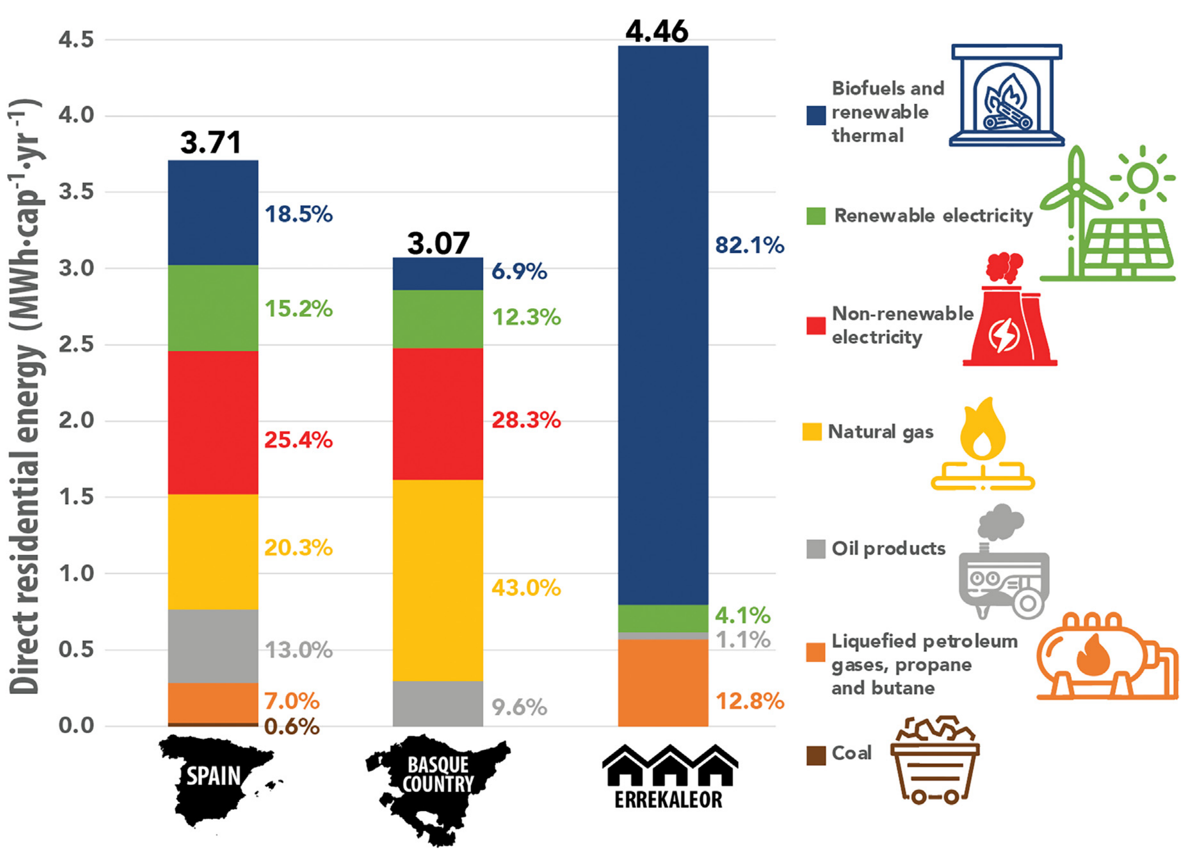

Fig. 2. Direct residential energy use (in $MWh \cdot cap^{-1} \cdot yr^{-1}$) separated by source, for Spain, the Basque Country and Errekaleor. Direct transport energy consumption is not included in this figure.

energy consumption was found to be 20.7 % higher in Errekaleor (4.46 $MWh \cdot cap^{-1} \cdot yr^{-1}$) than Spain (3.71 $MWh \cdot cap^{-1} \cdot yr^{-1}$) and 45.1 % higher than in the Basque Country (3.07 $MWh \cdot cap^{-1} \cdot yr^{-1}$). There is a clear discrepancy with the ecovillages analyzed in Table 1, which have an average reduction of 62 % as compared with the national direct residential energy consumption. This is probably due to inefficient heating systems (wood stoves) in Errekaleor and the fact that the houses are old and not well insulated. However, in terms of primary energy, consumption is similar across all three regions, since 33 % generation and transformation losses should be added in the case of Spain and the Basque Country (International Energy Agency (IEA), 2015), due to their fossil-fuel-based and centralized energy model. In addition, 86.2 % of the residential energy consumed in Errekaleor is renewable (biomass and PV), whereas the Basque Country and Spain exhibit a notable dependence on fossil fuels, especially natural gas, non-renewable electricity and oil products. Biomass consumption (in the form of wood) represented 82.1 % of the total residential energy consumption in Errekaleor. Interestingly, this phenomenon was also true of other communities studied, including Can Masdeu, Sieben Linden and Kan Pascual, where wood consumption represented 61 %, 82 % (in this case together with solar thermal) and 90 % of the total residential consumption, respectively (Cattaneo and Gavaldà, 2010; Akizu et al., 2018). Even so, Errekaleor inhabitants consumed, on average, almost a wood tonne (3.66 MWh) per person per year. Considering that Basque forests have over 6.2 · 10^6 m^3 stocks of potentially-exploitable wood products (Ente Vasco de Energía (EVE), n.d.) and that 5 % of this stock could be directed to energy use annually within sustainability limits, around 0.9 tonnes of timber per year would correspond to every Basque inhabitant. Hence, the Errekaleor consumption is 10 % beyond the sustainable limit. This limit also depends on geographical location. Akizu et al. (2018) identified a lower sustainable limit of 1.65 $MWh \cdot cap^{-1} \cdot yr^{-1}$ for wood consumption in Germany, which indicates that the Errekaleor energy model cannot be universalized.

4.3. Total primary energy footprint

Energy footprints for Spain, the Basque Country and Errekaleor were calculated in three different ways: *i)* with data elevation (Section 3.3) using Cai and Vandyck's bridge matrix (Cai and Vandyck, 2020) for INE to CPA conversion (Section 3.5); *ii)* with data elevation using Cazcarro et al.'s bridge matrix (Cazcarro et al., 2020) for INE to CPA conversion; and *iii)* without data elevation using Cai and Vandyck's bridge matrix for INE to CPA conversion. Table S.8 (see Supplementary material) shows the energy footprints obtained for the Eora 26 sectors for *i)*, and Table S.9 shows the results for *ii)* and *iii)*.

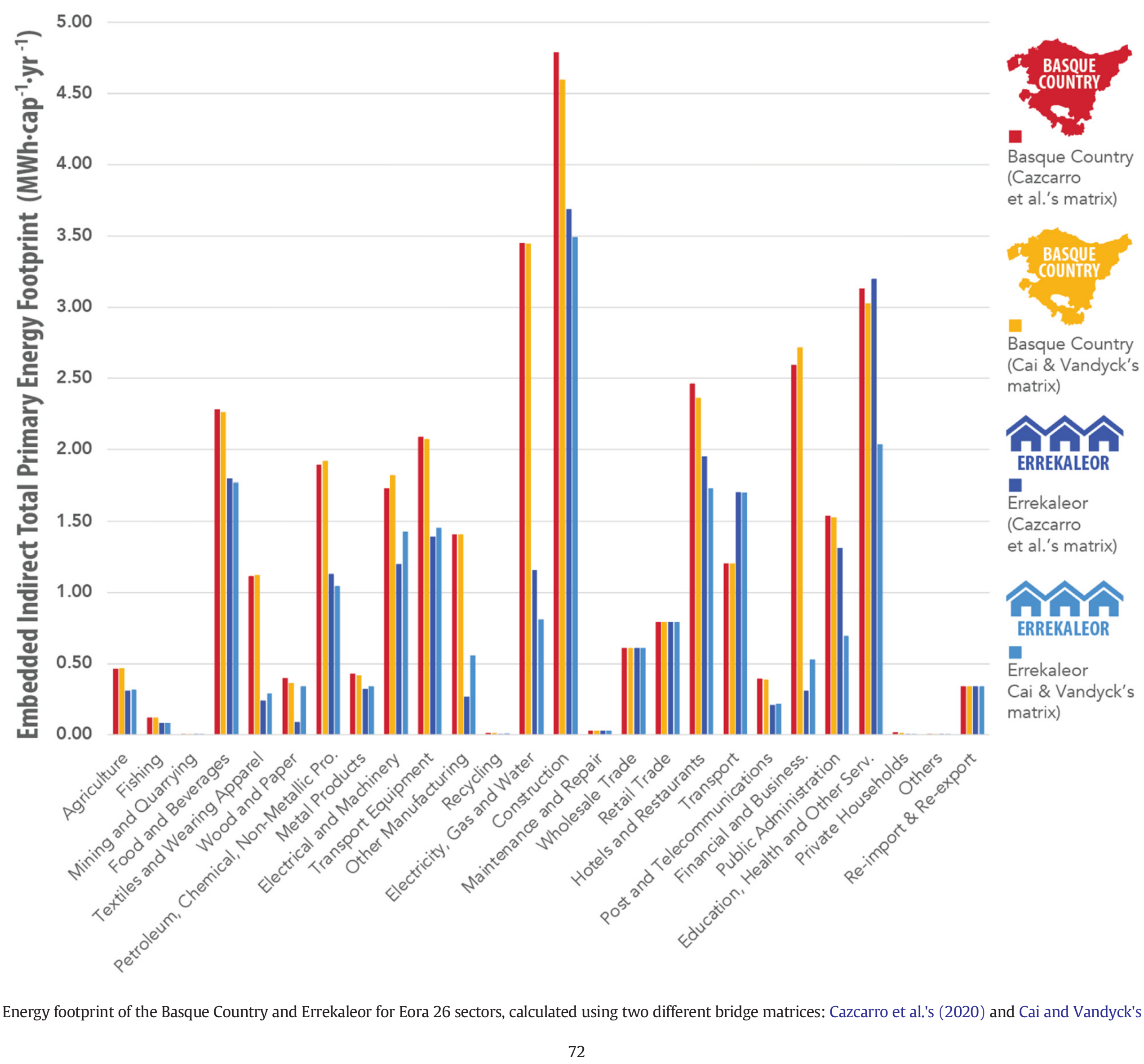

Fig. 3. Energy footprint of the Basque Country and Errekaleor for Eora 26 sectors, calculated using two different bridge matrices: Cazcarro et al.'s (2020) and Cai and Vandyck's (2020).

In the case of the Basque Country, when these tables are compared it can be seen that data elevation makes a small difference in some sectors, due to the elevation factors and the adjustment of the data to basic prices. This results in a TPEF of 40.38 $MWh\cdot cap^{-1}\cdot yr^{-1}$ for non-elevated data and 40.94 $MWh\cdot cap^{-1}\cdot yr^{-1}$ for elevated data (using, in both cases, Cai and Vandyck's bridge matrix). However, the use of a different bridge matrix produces a larger difference than data elevation. Hence, the Basque TPEF calculated with Cazcarro et al.'s bridge matrix (with data elevation) is 41.19 $MWh\cdot cap^{-1}\cdot yr^{-1}$. These differences are even higher in the case of Errekaleor, where the uncertainty is greater due to the small population. The TPEFs calculated were 30.32 $MWh\cdot cap^{-1}\cdot yr^{-1}$ (Cai and Vandyck's bridge matrix; not-elevated) 31.20 $MWh\cdot cap^{-1}\cdot yr^{-1}$ (Cai and Vandyck's bridge matrix; elevated) and 32.62 $MWh\cdot cap^{-1}\cdot yr^{-1}$ (Cazcarro et al.'s bridge matrix; elevated). The results obtained by using Cai and Vandyck's and Cazcarro et al.'s bridge matrices (both elevated) are compared graphically in Fig. 3, where the energy footprints for all Eora 26 sectors are represented. In addition, the average Basque sectorial TPEF was found to be 0.94 % higher when using Cai and Vandyck's bridge matrix, as compared to Cazcarro et al.'s matrix (with data elevation). In the case of Errekaleor, a 2.23 % lower average sectorial TPEF was calculated with Cai and Vandyck's matrix. Differences are, thus, relatively small, with low standard deviations of 6 % and 35 % for Basque Country and Errekaleor, respectively. This provides more confidence in the overall results.

The energy footprints for Errekaleor calculated using different matrices differ significantly in sectors E22 (*Public Administration*) and E23 (*Education, Health and other services*). Using Cazcarro et al.'s matrix, INE categories 12.3 (*Social protection*) and 12.6 (*Other Services*) are transferred almost entirely to the sectors E22 and E23 mentioned above. Moreover, these categories have high correction factors (see Table S.5), which further increases their footprint. By contrast, using Cai and Vandyck's matrix, categories 12.3 and 12.6 are spread over different Eora sectors. We consider this matrix more reliable because the consumption of residents in Errekaleor in these two categories is broader than the single area of public administration and services. For example, in the case of Errekaleor inhabitants, category 12.3 includes private psychological services and category 12.6 includes subscriptions to different associations and workers unions. In spite of the variations in results across different matrices, standard deviations are small and the values of the footprints calculated are in all cases within the same order of magnitude, and as such considerable confidence can be placed in the results. Hence, we evaluate the methodology presented in this paper as being reliable for the calculation of the TPEF of a small community. Nevertheless, it is relevant to note one limitation, that the input-output methodology, combined with consumption to production sectorial bridge matrices, homogenizes energy footprint values in each consumption sector. To identify one specific issue, the use of organic or local products might potentially be reducing the real TPEF of Errekaleor inhabitants, but it is not currently possible to include this in the modelling.

Due to its greater reliability and its use of 2015 economic data, the results discussed from this point on were all obtained using Cai and Vandyck's bridge matrix. In addition to the TPEF of the Basque Country and Errekaleor, the TPEF for all Spanish Autonomous Communities was obtained as shown in Table S.10 (see Supplementary material).

Fig. 4 shows the TPEF of Spain, the Basque Country and Errekaleor, separated into direct residential energy, direct transport energy and energy indirectly consumed through national and imported goods and services. The highest TPEF corresponds to the Basque Country (40.94 $MWh\cdot cap^{-1}\cdot yr^{-1}$), followed by the Spanish one (36.21 $MWh\cdot cap^{-1}\cdot yr^{-1}$) and finally by Errekaleor's (31.09 $MWh\cdot cap^{-1}\cdot yr^{-1}$), which has a 24 % lower energy footprint than the Basque Country and a 14 % lower energy footprint than Spain. This falls in the range of 35 % and 16 % lower carbon footprints in intentional communities and grassroots movements reported by Daly (2017) and Vita et al. (2020). It is interesting to note that although the expenditures of an average Errekaleor inhabitant are 53.6 % smaller than those of an average Basque inhabitant (see Table S.5), the TPEF of an Errekaleor inhabitant is only 24 % below the Basque average. This is, on the one hand, due to the different energy intensities of different industrial sectors and the fact that

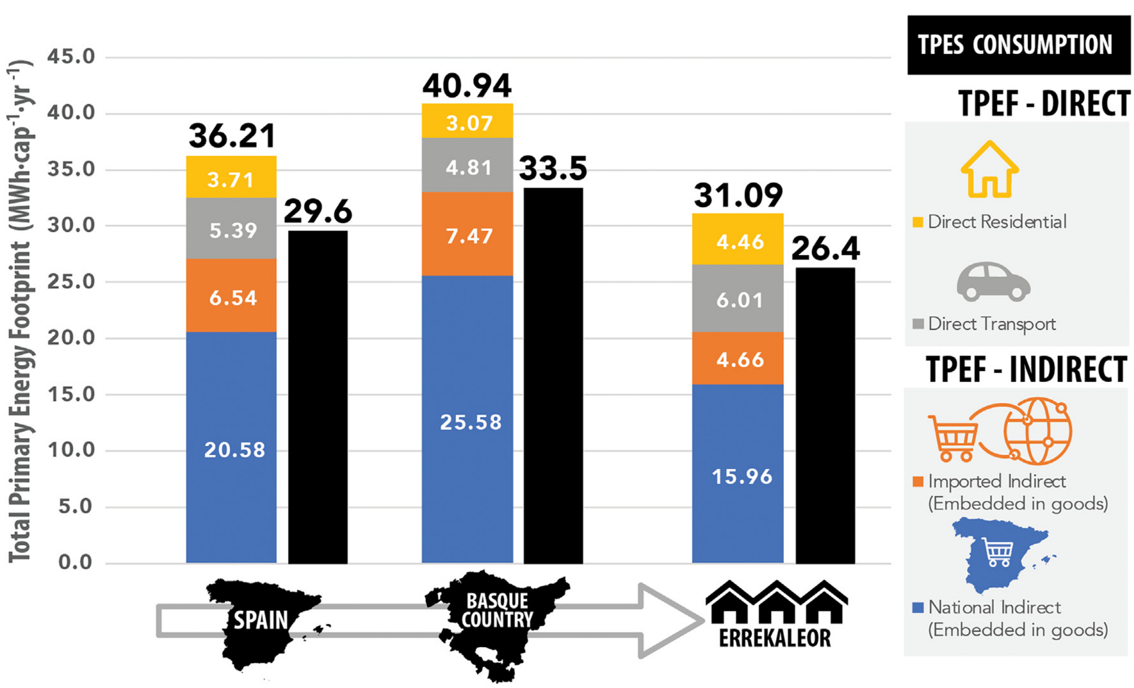

Fig. 4. Energy footprints for Spain, the Basque Country and Errekaleor. The contribution of direct residential and transport energy to the total, as well as that of the energy indirectly consumed in imported and national goods and services is shown.

Errekaleor inhabitants expend more money in the most energetically intensive categories. By contrast, a large amount of money is saved in housing rental, which, as stated above, falls within a sector that produces a negligible energy footprint. On the other hand, high elevation factors of some sectors (see Table S.5) reflect the fact that in these sectors the real cost is higher than the expenditure reported by Errekaleor inhabitants.

From a national through to a community level, our model indicates that direct (residential and transport) energy accounts for only a minority of the total energy footprint, on average 26 % of the TPEF across the three cases analyzed. Particularly, in Errekaleor it was observed to be 32 % and 15 % above the Basque and Spanish averages respectively. The fact that residential energy constitutes the smallest proportion of the TPEF in all three cases (ranging from 7.5 % to 14.4 %) is also relevant. Errekaleor exhibited the highest consumption of residential energy both in absolute and relative terms, i.e., the highest amount of direct residential energy is consumed there (see Fig. 4) and in addition, because indirect consumption is smaller, the percentage of the TPEF that it represents is very high. Taking into account that the energy provided by the PV system covers 4.1 % of direct residential energy consumption, it makes up only 0.6 % of the TPEF. Direct energy consumption for transport is also highest in Errekaleor, which can be linked to the relatively greater use of energy-intensive forms of transport by the predominantly younger inhabitants. It amounts to 6.01 $MWh \cdot cap^{-1} \cdot yr^{-1}$, or 19.3 % of the TPEF. Spanish direct transport energy consumption is 5.39 $MWh \cdot cap^{-1} \cdot yr^{-1}$ (14.9 % of the TPEF) and in the Basque Country it is 4.81 $MWh \cdot cap^{-1} \cdot yr^{-1}$ (11.8 % of the TPEF).

As for indirect energy consumption, the data reveals the opposite trend: it is highest in the Basque Country (33.05 $MWh \cdot cap^{-1} \cdot yr^{-1}$), followed by Spain (27.12 $MWh \cdot cap^{-1} \cdot yr^{-1}$) and Errekaleor (20.62 $MWh \cdot cap^{-1} \cdot yr^{-1}$), where it is 38 % smaller than in the Basque country and 24 % smaller than in Spain. Although Errekaleor was found to have the highest direct energy consumption and the Basque Country the smallest one, taking indirect consumption into account inverts the overall TPEF. This shows the relevance of indirect consumption. As it is shown in Fig. 4, the indirect energy footprint was separated into national (energy embedded in national goods or services) and imported (energy embedded in imported goods and services) categories. The imported indirect energy footprint is closely related to Hidden Energy Flow (HEF) (Akizu-Gardoki et al., 2021), but it is conceptually different. Whereas HEF indicates the percentage added to the TPES in order to obtain the TPEF, the imported energy footprint indicates the percentage of the TPEF that corresponds to the energy embedded in imported goods and services. The Spanish imported indirect energy footprint was obtained by computing the difference between the TPEF, calculated in this work, and the TPES, provided by the IEA. For the Basque Country, the difference between the TPEF and the TPES, provided by the Basque Energy Agency, was computed. In the case of Errekaleor, the same proportion of national and imported indirect energy footprint as for the Basque Country was used in order to compute the percentages shown in Fig. 4.

Given that imported goods and services make up 15 % of the TPEF of Errekaleor, the average TPES of the neighborhood is 26.4 $MWh \cdot cap^{-1} \cdot yr^{-1}$, 21.2 % smaller than the Basque TPES of 33.5 $MWh \cdot cap^{-1} \cdot yr^{-1}$ and 11.0 % smaller than the Spanish one of 29.6 $MWh \cdot cap^{-1} \cdot yr^{-1}$. The TPES of Errekaleor is more than twice that of the German ecovillage Sieben Linden (see Table 1), which at 10.7 $MWh \cdot cap^{-1} \cdot yr^{-1}$ is 77 % below the figure for Germany as a whole (Akizu et al., 2018). It is, however, very similar to the TPES of the rural village Feldheim (26.8 $MWh \cdot cap^{-1} \cdot yr^{-1}$), 42 % smaller than the German TPES and almost a half that of the urban neighborhood Solar Settlement (39.9 $MWh \cdot cap^{-1} \cdot yr^{-1}$, 13 % smaller than the German TPES). It is interesting to note that Errekaleor has both rural and urban characteristics – it could be defined as a *rurban* community (Cattaneo and Gavaldà, 2010) – and its energy consumption also falls between values typical for rural and urban communities.

Fig. 5 shows the TPEF of Spain, the Basque Country and Errekaleor for 13 indirect sectors (obtained by aggregating the Eora 26 sectors as indicated in Table S.11 in the Supplementary material) plus direct transport and residential energy consumption. The energy footprint of Errekaleor is the smallest of the three in every sector, except for direct residential energy, direct transport energy and transport services. This can be attributed to the low average age of the population of the neighborhood,

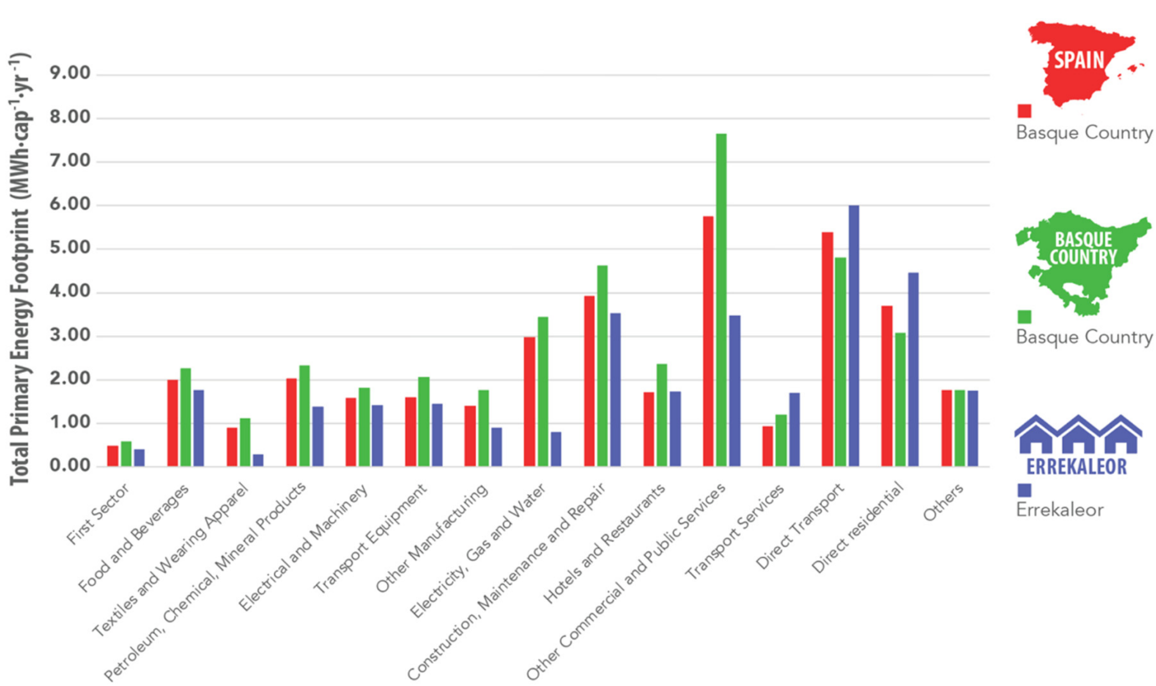

Fig. 5. Energy footprints for Spain, the Basque Country and Errekaleor across 15 different sectors: 13 indirect sectors, direct residential and direct transport.

which implies higher mobility than the Basque or Spanish average. The sector *Construction, maintenance and repair* also deserves mention. While smaller in Errekaleor than in other contexts, it makes up a relatively large proportion of the footprint. This is due to the fact that the houses are 62-year-old (a lifespan of 50 years is normally used for Life Cycle Assessment calculations), and in most cases, deteriorated. Therefore, even though the energy cost of the construction of dwellings is allocated to past users, the current users yearly expend, on average, €102.64 in the INE consumption category *Maintenance and repair for dwellings*. Finally, there are some sectors in which the energy footprint is notably smaller for Errekaleor, such as *Electricity, Gas and Water* and *Other Commercial and Public Services*. The big difference in the last area (*Other Commercial and Public Services*) is probably due to the fact that many sectors (E20 to E23) are aggregated here. With respect to *Electricity, Gas and Water*, taking into account that the expenditure on water services was assumed to be the same for the Basque and Errekaleor, the difference in this category comes from a difference in the energy sector (electricity and gas), which mainly accounts for transformation and transport losses. These losses are negligible in Errekaleor due to its decentralized consumption. Only expenditures on butane and the fabrication of the PV system contribute in this sector. As mentioned above, taking losses into account, the total primary energy involved in residential consumption is very similar across all three cases.

Finally, the initial hypothesis that TPEF varies according to household type was proven. Fig. 6 shows the average Errekaleor TPEF, as well as the TPEF of each category. This is shown for the 13 indirect sectors plus direct transport and residential energy sectors. In addition, total direct and indirect consumption in each category is shown. The hypothesis was proven to be true, as the TPEF of an individual living alone (42.79 MWh·cap^{-1}·yr^{-1}) is much higher than that of a person living in a community (28.84 MWh·cap^{-1}·yr^{-1}) or a family (28.45 MWh·cap^{-1}·yr^{-1}). It is even higher than the TPEF of an average inhabitant in the Basque Country (40.94 MWh·cap^{-1}·yr^{-1}). However, direct residential energy (which is about 3 MWh·cap^{-1}·yr^{-1} higher in the case of individuals) and energy consumed on construction, maintenance and repair (about 2 MWh·cap^{-1}·yr^{-1} higher) are, according to the estimate of the authors, the only ones which should be intrinsically higher, as they are similar for all apartments, independent of the number of people living there. In other sectors, the relatively larger size of the energy footprint can be attributed to individual lifestyle decisions. In general, young people do not have responsibility for dependents, and insertion in the labor market increases their purchasing power. This is evident in the sector *Other Commercial and Public Services*, and more significantly in the transport sector. The fact that the consumption on transport services is slightly smaller in the case of individuals, whereas direct transport energy consumption is larger, indicates that most of the individuals living alone have private cars, the purchase and maintenance of which increases the footprint of *Transport Equipment* to 4.42 MWh·cap^{-1}·yr^{-1}. That is not as often the case for people living in a community or family, who have an average footprint of 1.30 MWh·cap^{-1}·yr^{-1} and 0.46 MWh·cap^{-1}·yr^{-1} respectively in the same sector.

5. Conclusions

This research made pioneering use of the methodology proposed by Cazcarro et al. to calculate the TPEF of an intentional community (Errekaleor) and a region of Spain (the Basque Country) from HBS by using consumption to production sectorial bridge matrices. The use of two distinct bridge matrices (Cai and Vandyck's or Cazcarro et al.'s) produced small differences: an average sectorial TPEF 2.23 % smaller for Errekaleor and 0.94 % higher for the Basque Country. Given the size of these differences, the methodology has shown itself to be reliable for the calculation of energy footprints at a neighborhood level, as well for other regions or communities within the Basque Country, Spain, and beyond.

The research also shows that TPEF provides a more accurate measure of energy consumption patterns in the current globalized era, as well as demonstrating that alternative communal living does have a smaller energy footprint. Direct energy consumption, which on average

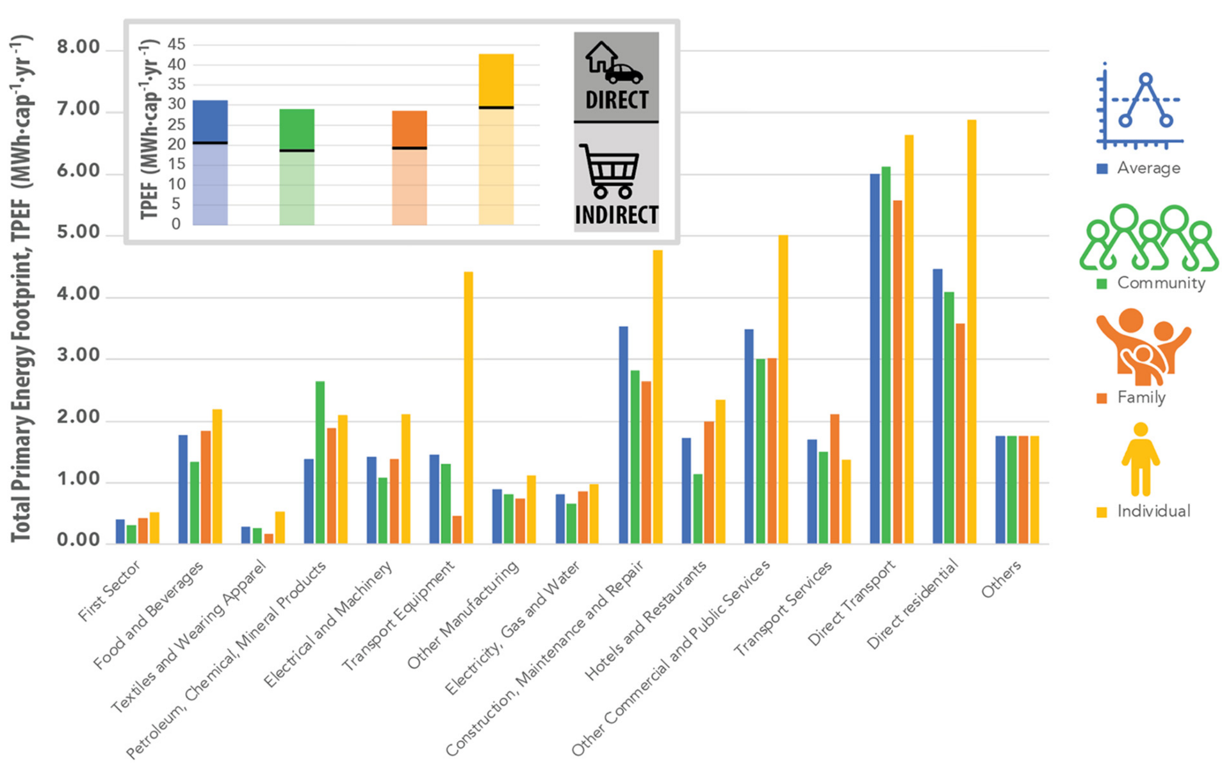

Fig. 6. Comparison of the energy footprints per capita of different household types in Errekaleor.

accounted for only 26 % of the TPEF across the three cases analyzed, in Errekaleor was observed to be 32 % and 15 % above the Basque and Spanish averages respectively. With respect to direct residential energy, the major single source was the massive use of wood for heating, since the electricity provided by the PV system, an icon of the project as a whole, provides only 4.1 % of the direct residential energy and accounts for only 0.6 % of the TPEF. For direct transport energy, consumption of 6.01 $\text{MWh}\cdot\text{cap}^{-1}\cdot\text{yr}^{-1}$ was observed in Errekaleor, 24.9 % and 11.5 % greater than regional and national averages.

Despite this, the overall energy consumption of the community was relatively low, with a per-capita TPEF 24 % and 14 % below the average for the Basque Country and Spain. This apparent contradiction can be explained by the massive importance of energy embedded in products and services, which can be identified through the TPEF. Due to the community and do-it-yourself focused lifestyles prevalent in Errekaleor, average indirect energy consumption per capita was observed to be 38 % and 24 % below the Basque and Spanish average. While positive, the neighborhood TPEF of 31.09 $\text{MWh}\cdot\text{cap}^{-1}\cdot\text{yr}^{-1}$ is still 288 % above the estimated global sustainability limit of 10.8 $\text{MWh}\cdot\text{cap}^{-1}\cdot\text{yr}^{-1}$. Hence generalizing the alternative community lifestyle of Errekaleor inhabitants would not achieve sufficient global reduction of either direct or indirect energy consumption. It must also be noted that while the average TPEF of an Errekaleor inhabitant is below the Basque average, individual lifestyles play a decisive role in energy consumption. While families have a lower TPEF (28.45 $\text{MWh}\cdot\text{cap}^{1}\cdot\text{yr}^{-1}$), individuals living alone generally have a TPEF (42.79 $\text{MWh}\cdot\text{cap}^{-1}\cdot\text{yr}^{-1}$) above the Basque Country average. In terms of individual choices, relatively high levels of consumption can be traced to, on the one hand, the use of wood for heating. In spite of wood being a renewable resource, its use is 10 % above the capacity of Basque forests. On the other hand, the relatively high consumption of Errekaleor residents in the most energy intensive sectors is also important to take into account. Even in the cases identified above, structural factors which condition individual lifestyle choices, including the condition of the available housing and the accessibility of quality public transportation, influence energy consumption.

Beyond its value in academic terms, this paper has become a valuable tool for the neighborhood itself, as it identifies specific opportunities to reduce the TPEF. As mentioned above, the indirect energy footprint makes up a majority (66.3 %) of the TPEF, indicating that greater efforts should be focused in this area. Increasing self-sufficiency at different levels (food production, house maintenance and leisure, among others), expanding local production and promoting community lifestyles would all contribute in this area. With respect to direct transport energy (19.3 % of the TPEF) and indirect energy related to transport equipment, sharing the use and the ownership of cars would also notably reduce the energy footprint of Errekaleor inhabitants. Finally, excessive direct residential energy consumption (14.4 % of the TPEF) could be reduced, for example, by insulating the apartments and installing more efficient heating systems. These findings have been adopted as one tool for the development of an integral energy plan, which aims to identify and implement community-wide solutions and alternatives to the current energy model, collectively reducing the TPEF of every Errekaleor inhabitant.

In terms of further research, on the one hand, the uncertainty produced by the use of different bridge matrices (with an average standard deviation of 20.5 % for the sectorial TPEFs calculated by using Cazcarro et al.'s or Cai and Vandyck's matrices) could and should be reduced by increasing their accuracy. On the other hand, the assumption of standard energy densities (with respect to each economic sector) throughout Spain should be revised using local IO tables as well as locally adapted correction factors and bridge matrices. Additionally, in order to overcome the limitation that GMRIO methodology homogenizes energy footprint values in each consumption sector, a LCA methodology could be used in order to model potential reductions in TPEF due to the particular choices of Errekaleor inhabitants, such as the use of organic or local products. Moreover, while the impact of different household types in Errekaleor has been mentioned, the results suggest that TPEF also varies according to other factors, including gender, age and, especially, income. A more detailed analysis of the TPEF for Errekaleor and the Basque Country addressing these variables could produce a richer comparison. In this direction, the use of microdata would allow the comparison of more specific profiles. Finally, repeating this study in Errekaleor in the future would also represent an opportunity to verify a process of energy transition, and develop a process of verification that could be applied in other cases. This would enable an assessment of a number of factors affecting TPEF, including the effects of the implementation of a medium-term energy plan in the suburb, and the anticipated stabilization of the community including an increase in average age and a diversified population.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.09.003.

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