SERIEs (2021) 12:151–229
https://doi.org/10.1007/s13209-020-00227-z

ORIGINAL ARTICLE

Are we moving toward an energy-efficient low-carbon economy? An input–output LMDI decomposition of CO_2 emissions for Spain and the EU28

Darío Serrano-Puente[1]

Received: 3 June 2020 / Accepted: 24 December 2020 / Published online: 10 February 2021
© The Author(s) 2021

Abstract

Spain is on a path toward the decarbonization of the economy. This is mainly due to structural changes in the economy, where less energy-intensive sectors are gaining more relevance, and due to a higher use of less carbon-intensive primary energy products. This decarbonization trend is in fact more accentuated than that observed in the EU28, but there is still much to be done in order to reverse the huge increases in emissions that occurred in Spain prior to the 2007 crisis. The technical energy efficiency is improving in the Spanish economy at a higher rate than in the EU28, although all these gains are offset by the losses that the country suffers due to the inefficient use of the energy equipment. There is an installed energy infrastructure (in the energy-consumer side) in the Spanish economy that is not working at its maximum rated capacity, but which has very high fixed energy costs that reduce the observed energy efficiency and puts at risk the achievement of the emissions and energy consumption targets set by the European institutions. We arrive to these findings by developing a hybrid decomposition approach called *input–output logarithmic mean Divisia index* (IO-LMDI) decomposition method. With this methodological approach, we can provide an allocation diagram scheme for assigning the responsibility of primary energy requirements and carbon-dioxide emissions to the end-use sectors, including both economic and non-productive sectors. In addition, we analyze more potential influencing factors than those typically examined, we proceed in a way that reconciles energy intensity and energy efficiency metrics, and we are able to distinguish between tech-

This article was published as the working paper n. 2104 of the Bank of Spain - Working Paper Series in January 2021. The views expressed in this paper are those of the author and do not necessarily coincide with the views of the Bank of Spain or the Eurosystem. Data sources are free for scholars and they are listed in the document. Stata replication files are available upon request.

✉ Darío Serrano-Puente
darioserrapuente@gmail.com
https://sites.google.com/view/darioserranopuente/

[1] Banco de España, Madrid, Spain

nical and observed end-use energy efficiency taking into account potential rebound effects and other factors.

Keywords CO_2 emissions · Energy efficiency · Decomposition analysis · Input–output · LMDI

JEL Classification C67 · O13 · Q4 · Q5

1 Motivation

There is huge evidence and consensus that global emissions of greenhouse gases are causing global air temperatures to increase, resulting in climate change.[1] At a global level, the potential consequences include rising sea levels, increased frequency and intensity of floods and droughts, changes in biota and food productivity, and upstream trends in diseases.[2] Thus, climate change has posed a severe threat to the sustainable development of the human society, the economy, and the environment.

At the particular level of the European Union (EU28, hereafter), conforming to the European Environment Agency (2015), more than 80% of the total greenhouse gas emissions are encountered to be a consequence of energy production and energy consumption by the end-use sectors (agriculture, industry, commercial and public services, households, and transport).[3] These energy-related greenhouse gas emissions are mainly compounded by carbon dioxide (CO_2) emissions, an essential environmental pollutant that has greatly contributed to global climate change, as shown by Ozturk and Acaravci (2010).[4] Despite not being the world's largest emitter of energy-related CO_2, the EU28 contributes to the mentioned global emissions by 10%, which indicates that it has a non-insignificant role in the global warming trends.[5]

Hence, while efforts to mitigate the adverse effects of climate change are partly focused on limiting the emissions of all greenhouse gases, particular attention is being also paid to energy production and consumption due to its crucial importance for the evolution of the energy-related CO_2 emissions. There is a clear interrelationship between energy consumption, the share of low-carbon energy sources in such consumption, energy efficiency, and greenhouse gas emissions. Therefore, the energy and climate targets set by supranational bodies and national authorities approach all these elements. For instance, at an United Nations conference in August 2007, it was agreed

1 Greenhouse gas emissions are those covered by the Kyoto Protocol and include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and three fluorinated gases, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6).

2 See the report published by the Intergovenmental Panel on Climate Change (2007) for a more detailed description of the causes of climate change and its adverse effects.

3 Emissions coming from energy consumption by international maritime bunkers and international aviation are usually not included in national total emissions.

4 In 2017, according to the *Air Emission Accounts* published by Eurostat (2020a), more than 95% of the European energy-related greenhouse gas emissions were anthropogenic emissions of CO_2.

5 According to Our World in Data (2020), China alone is responsible for 29% of the total energy-related CO_2 emissions, United States for 15%, and Asia and Pacific Ocean for 14%.

that an emission reduction in the range of 25–40% with respect to 1990 levels is necessary to avoid the most catastrophic forecasts. More recently, *"doubling the global rate of improvement in energy efficiency"* or *"increasing substantially the share of renewable energy in the global energy-mix"* were set as key objectives by the United Nations (2015) in their *"2030 Agenda for Sustainable Development"*.

Turning again to the European sphere, together with the well-known targets established by the European Comission (2012-10-25, later modified in 2013) in its *Europe 2020 Strategy* or *Horizon 2020* (H2020, hereafter), the European Union authorities have defined an even more ambitious climate scenario that is amongst their main priorities. For 2030, (1) greenhouse gas emissions must be reduced by 40% with respect to 1990 levels (20% for H2020), (2) primary energy use must experience a 32.5% reduction to be achieved by improving energy efficiency (20% for H2020), and (3) a share of 32% in the final energy-mix in favor of renewable energies must be reached (20% for H2020). Furthermore, the European Comission (2019-10-31) declared in a report to the European Parliament and the Council that the objective is to achieve climate neutrality by 2050, i.e., net-zero greenhouse gas emissions in 2050. This translates into a plan to decarbonize the European economy by 80–95% with respect to the emission levels of 1990, accompanying this with a strong reduction of energy consumption, which points out again the relevance of making progress toward energy efficiency.

Within those forming the EU28, Spain is another country that, due to its geographical location and socioeconomic characteristics, is also vulnerable to climate change, as shown by the Ministerio de Medio Ambiente (2005). Conjointly with the rest of the EU28 member states, Spain faces strong commitments derived from the ambitious European climate targets for 2020 and 2030. Each member state can set its own targets as long as they match those defined at European level. In this sense, according to the Ministerio de Turismo, Energía y Agenda Digital (2017) and the Ministerio de para la Transición Ecológica (2017), the targets fixed by the Spanish authorities would entail (1) achieving a 42% share of renewable energies in the final energy use for 2030 (20% for 2020),[6] (2) improving the country's energy efficiency by 39.5% for 2030 (20% for 2020), and (3) reducing greenhouse gas emissions by 23% with respect to 1990 levels for 2030 (10% with respect to 2005 levels for 2020).[7]

Aiming to comply with the targets set by the European Union as well as by the national authorities, both Spain and the EU28 as a whole adopted different policies and measures. An overview of these policy trends is recovered from the *ODYSSEE* database published by ODYSSEE-MURE (2020b). Some of these measures are (1) the promotion of renewable energy (including electricity from renewable sources), (2) the creation of the EU emissions trading scheme (a market for carbon dioxide allowances to ensure that emissions reductions can be made where it is most economically efficient), (3) the development of combined heat and power, (4) the improvement in the energy efficiency performance of buildings, (5) the stimulus to use alternative fuels in

6 For the case of electricity generation, the percentage of renewable energies in 2030 must be 74%.

7 The Spanish emission target translates into a reduction of 38% with respect to the 2017 levels for 2030.

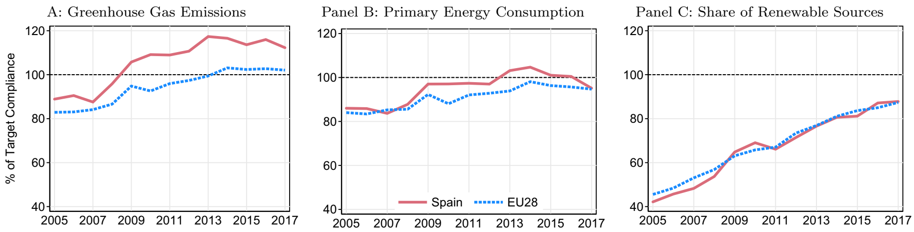

Fig. 1 Compliance with H2020 Targets. *Note:* Levels above 100 indicate target compliance

transport (in particular biofuels), (6) the reduction of the average CO_2 emissions of new passenger cars, and (7) the taxation of certain energy products and electricity.[8]

Following the implementation of these measures, mainly after the 2007 crisis, it can be noted that both the EU28 and Spain were progressively moving toward meeting the H2020 targets in recent years. This is shown in Fig. 1. Further, in Fig. 2 we observe that Spain has done a great effort in reducing emission levels since 2005. However, this positive evolution cannot compensate the huge increase of emissions occurred from 1995 to 2005, which still leaves Spain in 2017 with higher emission levels than those observed in 1995. On the contrary, the EU28 has experienced a long-term downward trend, but at a lower decreasing growth rate than the last years of the Spanish trend. Considering the year 2017, the last year of analysis in this study, we recognize how greenhouse gas emissions (in Panel A of Fig. 1) are the only magnitude that meets its European target H2020 both in Spain and in the EU28. The other two H2020 targets (the share of renewables in the final energy-mix and the use of primary energy) are not met, either in Spain or in the EU28 (in Panels B and C of Fig. 1, respectively). We can only notice how the reduction target for primary energy use was fulfilled in Spain during the years 2013 to 2015, but in the last two years the magnitude is again not complying with the H2020 target.

Consequently, although the reduction of greenhouse gas emissions is on a positive trend that leads Spain (in 2017) to accomplish the European target H2020 for such magnitude, both the EU28 and Spain have to continue making efforts to fulfill the rest of the 2020 targets. Furthermore, Spain should be careful with the last developments of CO_2 emissions, which experienced a slight increasing trend that could lead to a deviation form the target compliance. In addition, both regions must continue working vigorously in a direction that permits them to later satisfy the 2030 targets, which are even more ambitious than those for 2020, as we have seen above. Besides, according to some analyses published by the World Bank and ClimateWorks Foundation (2014), this line of work to control the emissions can offer opportunities for the economic performance of the country, generate new jobs, benefit agriculture, and boost the development of better technologies for the supply of energy.

Obviously, one of the major areas to be addressed in order to effectively control emissions is the efficient use of energy. Improving energy efficiency seems very handy to offer a win-win situation, as it decreases energy costs, energy use, and at the same

[8] See the report published by the Directorate-General for Climate Action (European Commission) et al. (2016) for a detailed description of the main legislation developments on energy and climate issues.

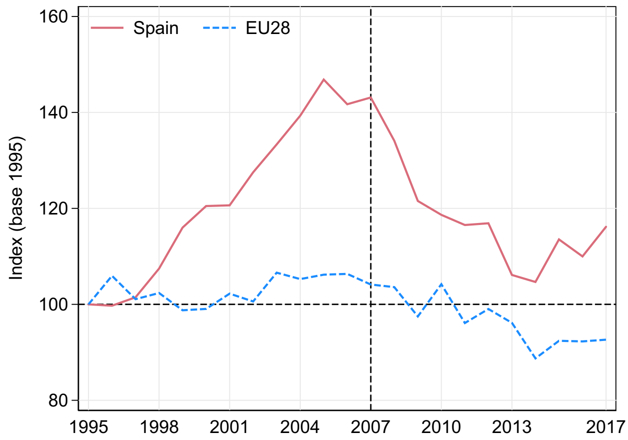

Fig. 2 Energy-related CO_2 emissions. *Note:* This figure is depicted using the estimation approach presented in this document. The energy-related CO_2 emissions shown are those associated to final energy consumption. This final energy consumption has been climate-adjusted in order to abstract from potential weather effects, which results in a magnitude that is comparable across regions

time, negative impacts related to such energy use, like CO_2 emissions. Further, using less energy for a certain task gives better possibilities to use energy sources with a predictable price development, which in practice means domestic energy sources, especially in countries that heavily depend on energy imports, like Spain. These arguments clearly highlight the need to implement measures in this regard. However, not all the increase in energy efficiency is translated into energy savings.

Some energy equipment could experience an efficiency increase, but if this equipment is not utilized at its maximum rated capacity, sometimes the efficiency improvement is not translated into energy savings. Moreover, technological or efficiency improvements generate cost savings, but these savings could be devoted to new energy consumption and investment, which also requires more energy services, which could consequently increase energy-related emissions. Both pathways generate more activity and may reduce, and even eliminate, the environmentally positive effects of the improvements. This is the so-called rebound effect. Indeed, this effect may be large enough to exceed the maximum expected energy savings from technological or efficiency improvements. Hence, for a better understanding of the impacts of efficiency improvements on our process of energy-use reduction, rebound effects must be incorporated to our analyses. Therefore, care about these rebound effects needs to be taken by policy-makers when calculating the energy saving potential of different measures oriented to improve energy efficiency. Freire-González and Puig-Ventosa (2015) argue that for energy-efficiency-improving policies to be effective, they must be accompanied by other measures such as an effective communication and awareness of the citizens, regulatory instruments and/or an appropriate taxation. An effective combination of traditional efficiency measures with new policies oriented to tackle the rebound effect would maximize the effectiveness of the policy objective of reducing energy consumption. For Vivanco et al. (2016), it is crucial to establish economic instruments for the energy efficiency measures to be completely effective and deal with rebound effect problems. These authors suggest that economy-wide cap-and-trade systems as well as energy and carbon taxes, when designed appropriately, emerge as the most effective policies in setting a ceiling for emissions and addressing energy use across the economy. In addition, these rebound effects vary across end-use sectors. In this sense, Medina et al. (2016) intends to identify the Spanish economic sectors where investment from energy-efficiency-improving measures should be allocated in order to reach the targeted energy efficiency levels in the overall economic system.

Besides, only if these energy-efficiency-improving measures are always pursued alongside the decarbonization of the energy system, the carbon-reducing potential of such measures can be guaranteed, as suggested by Malpede and Verdolini (2016). However, these efforts to develop an adequate energy efficiency policy and to promote the use of a lower-carbon energy-mix should not damage the domestic competitiveness of the economy. The relationship between economic growth, energy consumption and CO_2 emissions is an essential issue that we face in the 21st century, and it is of far-reaching concern to scholars worldwide. To investigate this matter, several methodologies have been traditionally applied. Zhang et al. (2018) list some of the main ones: the Kuznets curve theory, the Granger causality analysis and co-integration tests, the vector auto-regressive models used to analyze the long-term dynamics, and the decoupling models. The latter approach is followed by Fernández-González et al. (2014), who show that there is a usually a coupling process between energy consumption and economic growth in advanced economies. Therefore, in these economies is more difficult to reduce energy consumption and alternative efforts should be made in order to achieve the decarbonization of the economy, as suggested by Román-Collado and Colinet (2018).

Nevertheless, we must bear in mind that the above-mentioned measures to promote efficiency do not explain or influence by themselves alone the evolution of the energy-related CO_2 emissions. There may be many potential factors underlying the progression observed both in Spain and in the EU28 and their convergence to the established targets, irrespective of the impact of the energy efficiency policies and measures, as suggested by Economidou and Román-Collado (2019). Some of these factors could be the economic activity level, the efficiency of the conversion sector, the demography, lifestyle changes, the weather, etc. For example, the 2007 crisis could have a profound impact on the industrial sectors and services which in turn could affect energy consumption and consequently energy-related CO_2 emissions. Another example includes weather fluctuations, which could affect the heating and air cooling demand provoking that, in a particular warm year, energy consumption may simply drop due to lower heating demand in the residential and services sectors.

Therefore, in order to support the most appropriate energy policy decisions, an integrated analytical method to understand the driving forces behind the observed developments of energy-related CO_2 emissions, energy consumption and energy efficiency (the three main energy and climate targets previously presented) is irremediably needed. It is precisely here where our work enhances the available related literature, since we develop a methodological framework to investigate the contributions of various influencing factors to the evolution of the energy-related CO_2 emissions between 1995 and 2017 both in Spain and in the EU28. With our proposed method, in addition to many macro and efficiency influencing factors discussed before, we are able to capture the role that the primary energy consumption and the share of renewable sources in the energy-mix play in the developments of the energy-related CO_2 emissions. This implies that all magnitudes for which the main energy and climate targets are defined and their interrelationships can be monitored within one comprehensive methodological framework. Our period of analysis, 1995–2017, is determined by the availability of data. We should mention that for the findings about the changes that occurred between 1995 and 2017 to be representative of what certainly happened, we must identify two clearly distinct sub-periods, as shown in Fig. 2. These sub-periods are delimited by the year 2007, since it marks the end of a economic expansion period and the beginning of a deep recession followed by a posterior recovery. In this way, we first analyze the 1995-2007 sub-period, and subsequently the 2007–2017 sub-period, both for the EU28 and for Spain. The results that we present give interesting information related to the drivers and inhibitors of the energy-related CO_2 emissions in both the Spanish economy and the European economy as a whole. These results are useful not only for researchers, but also for private utility companies and policy-makers, as they can contribute to construct and implement the optimal saving and efficiency measures to achieve the mentioned climate and energy targets. In fact, this paper speaks directly to Spanish and European authorities in the field of energy and climate.

The remainder of the document is organized as follows. Section 2 sheds light on the relevance of our analysis by reviewing the existing literature. Section 3 presents the methodology and the databases utilized in our work. Section 4 reports the results. And finally, Sect. 5 concludes.

2 Conceptual and empirical framework

In this Section, we revise the existing literature and remark the contributions of our work. We first introduce the rationale behind our hybrid approach in Sect. 2.1. Second, we propose an allocation diagram scheme for assigning the responsibility of primary energy requirements and CO_2 emissions to end-use sectors in Sect. 2.2. Third, we present the selected influencing factors to be analyzed in Sect. 2.3. Fourth, we discuss about the differences between energy intensity and energy efficiency metrics in Sect. 2.4. Fifth, we propose and describe a method to distinguish between technical and apparent end-use energy efficiency in Sect. 2.5. Finally, we overview the main contributions of this work in Sect. 2.6.

2.1 Hybrid approach mixing SDA and IDA

There are several methodologies to assess the developments of certain energy or environmental magnitudes like emissions. Among others, in a very enriching survey work by Wang et al. (2017), we find methods based on econometric models, system dynamics approaches, computable general equilibrium (CGE) models, and decomposition analyses. Our work focuses on the latter, and more precisely, on two different methods: the structural decomposition analysis (SDA, hereafter) and the index decomposition analysis (IDA, hereafter). In recent times, many researchers are using SDA and IDA techniques as tools for analyzing energy or environmental trends.

Both decomposition techniques have been compared in many survey papers, e.g., Su and Ang (2012), Hoekstra and van den Bergh (2003), and Wang et al. (2017). The comparison encounters that the IDA approach is more flexible in its formulation and has a relatively lower data requirement than the SDA approach. However, the IDA method only provides information about the direct effects, ignoring the indirect and final demand effects, as shown by Zeng et al. (2014). On the other hand, the SDA, a framework based on the development of input–output models/tables, provides a wider range of information regarding technical concerns, including final demand effects, and more detailed explanation of the structural factors, such as the Leontief effect (or technical effect), as argued by Cansino et al. (2016) and Xie (2014). Further, the SDA method can shape socioeconomic drivers from both production (or supply) and final demand (or end-use) perspectives. When it particularly comes to the IDA method, we find several decomposition techniques that are documented extensively in a survey paper by Ang and Zhang (2004). Among others, we find the Laspeyres decomposition method and the Divisia index decomposition method. The latter contains the logarithmic-mean Divisia index (LMDI, hereafter) and the arithmetic mean Divisia index (AMDI), both in the additive and multiplicative formulations (leading to redundant results). As suggested by Ang (2015), the logarithmic-mean Divisia index in its additive formulation is the most recommended IDA approach due to its theoretical foundation, robustness, adaptability, ease of use, and result interpretation. It provides a perfect decomposition (i.e., the results do not contain any residual term), permits the investigation of more than two factors, provides a simple and direct association between the additive and the multiplicative decomposition form, and is consistent-in-aggregation (i.e., the estimates of an effect at the subgroup level can be aggregated to give the corresponding effect at the group level).

Through these techniques, many research works attempt to identify quantitatively the contributions of many influencing factors to the evolution of some energy or environmental aspects. For example, an increasing proportion of the thermal power in the end-use sectors will increase the energy-related CO_2 emissions, while increasing end-use energy efficiency will reduce them. These driving forces can be analyzed within this type of methodologies, which have been widely used in the literature. Focusing on the performance assessment, we can classify these research works into three different types. The first type deals with assessments over time in a specific country, i.e., single-country temporal analysis. This category accounts for most of the developed studies in the literature. The second type gathers studies that analyze the performance of more than one country. A temporal analysis like the one in the first type is here applied independently for several countries or regions in a way that the results can be compared between countries, i.e., multi-country temporal analysis. The third type of studies focuses on comparative analyses between countries using the data of a specific year, i.e., single-year spatial or cross-country analysis.

The first type of studies comprises the conventional IDA and SDA studies applied to one single country or region, where no further elaboration is required. When it particularly comes to applying SDA techniques for the Spanish case, we find different works. For instance, Butnar and Llop (2007) investigate the composition of greenhouse gas emissions in Spain in an input–output fashion, Cazcarro et al. (2013) use the same methodology to study the evolution of water consumption in Spain, Alcántara and Roca (1995) propose a similar framework to examine the energy-related CO_2 emissions and their relationship with energy consumption, and, finally, Cansino et al. (2016) use a SDA approach to undercover the main drivers of changes in CO_2 emissions in the Spanish economy. On the other hand, we can also find thousands of studies following different IDA approaches for a number of geographies in a single-country temporal fashion. More precisely, for the Spanish case, we encounter Cansino et al. (2012), who analyze the greenhouse gas emissions in the Spanish economy, and Cansino et al. (2015), who investigates the driving forces of Spain's CO_2 emissions. Finally, in a recent work that makes use of both SDA and IDA methods separately, Román-Collado and Colinet (2018) determine whether energy efficiency is a driver or an inhibitor of the energy consumption changes in Spain.

The second category of studies is a direct extension of the first one. A requirement of these works is that the same decomposition method and a consistent data format are used for every region analyzed so that the results obtained can be meaningful compared. There are several papers applied to very different geographies that use SDA and IDA methods to investigate such concerns in a multi-country temporal fashion. When it comes to the SDA approach, there are studies that establish a relationship between energy consumption in Spain and that of other countries of the European Union, like Alcántara and Duarte (2004). On the other hand, we can encounter many research works following different IDA approaches in a multi-country temporal way. Goh and Ang (2019) elaborates a survey gathering the main studies that implement the LMDI method in recent years worldwide. But more precisely, for the European and the Spanish case we find numerous papers applying the LMDI methodology. Examples of it are Economidou and Román-Collado (2019), who assess the progress toward energy and climate targets in the European Union, and Mendidulce et al. (2010), who compare of the evolution of energy intensity in Spain and in Europe. Our work will contribute to this second type of decomposition studies, since it assesses through SDA and IDA techniques the evolution of energy-related CO_2 emissions in Spain and in the EU28 applying to each region the same temporal analysis separately. These studies, where our work is also framed, show the growing popularity of researches where the main focus is to compare the development or performance of a group of countries over time. However, one should note that the resulting comparisons are not direct because mathematically there are no direct linkages between the results of the countries compared.

The third type of studies, single-year spatial, is very different from the first two ones explained above. Using the data of a specific year, the spatial analysis conducted is static and the results obtained are valid for the year of analysis. Ang et al. (2015) review the literature of the spatial decomposition analysis, investigate the methodological issues, and propose a spatial decomposition analysis framework for multi-region comparisons. Some examples applying this type of spatial analysis for the European and Spanish spheres are Sun (2000), who analyzes the CO_2 emission intensity for 15 European countries in 1995, and Bartoletto and del Mar Rubio-Varas (2008), who perform a spatial analysis of the CO_2 emissions for Spain and Italy in years 1861 and 2000, respectively. However, with this third type of studies, changes in regional disparities over time cannot be traced analytically since the spatial analyses conducted are different for different years. To address this issue, Ang et al. (2016) develop an IDA procedure that integrates the key features of type 2 and type 3 studies, where both spatial differences between regions and temporal developments in individual regions are captured simultaneously, i.e., spatial–temporal index decomposition analysis (ST-IDA). This methodology essentially establishes formal linkages of the static spatial comparison results of a group of regions for each year over a specific time period. The consolidated results of this new empirical framework reveal each and every region's performance over time as well as how it is compared to those of other regions at any point in time on an equal footing. However, this methodology has the disadvantage that the interpretation of its results is not as straightforward as in the second type of studies presented in this Subsection, which may lead to less clearly understandable conclusions.

When listing typical influencing factors analyzed through decomposition methods, population, income, economic structure, energy intensity and energy-mix are factors commonly encountered to be analyzed through IDA techniques. On the other hand, the SDA approach examines contributions of some technical influencing factors such as the efficiency of the energy conversion sector. Nevertheless, according to the deep literature review of decomposition methods applied to environmental concerns carried out by Ma et al. (2018), it is still difficult to find evaluations of all the previous factors within a single and comprehensive methodology that combines both SDA and IDA approaches. One of these examples is the mentioned work by Ma et al. (2018), who analyzes energy-related CO_2 emissions in China using a hybrid approach that mixes an input–output model and some LMDI decompositions.[9] But, to the best of our knowledge, there is no work developing such a hybrid approach for Spain and the EU28. This is where our paper adds value and contributes to the literature, since we propose a method that takes into account jointly the effects that (1) technical aspects of the physical energy system (analyzed through energy input–output models) and (2) macro-level influencing factors traditionally employed (studied through IDA decomposition methods) have in the evolution of energy-related CO_2 emissions in Spain and in the EU28. Thus, we refer to this hybrid integrated approach, which benefits from the advantages of both SDA and IDA techniques, as *input–output logarithmic mean Divisia index* (IO-LMDI, hereafter) decomposition method.

2.2 Responsibility of energy-related CO_2 emissions

Key in this type of research work is to have a deep understanding of how the energy system works in order to distribute the responsibility of the primary energy requirements and the energy-related CO_2 emissions. As an example of the energy flow in Spain and in the EU28, a graphical overview of the process is depicted in Figs. 13 and 14 of Appendix. In a national energy system, primary energy (mainly derived from domestic production and imports) is first processed, transported, and converted

[9] Patiño et al. (2019) undertake a similar exercise for Colombia, but they do not completely use both input–output and LMDI analyses in a single theoretical framework. They just simply use the input–output models to estimate the primary energy consumption.

into numerous types of secondary energy. This conversion process generates many emissions, principally heat and electricity generation based on fossil fuels. The secondary energy is then distributed to the end-use sectors, which are also emission generators (e.g., fuel burning). This shows that both energy conversion and energy use by the end-use sectors greatly influence the emissions from the energy system, thus an analytical method like that here proposed by us is needed to study both sides of the energy system in a unified way. However, this kind of analyses requires a criteria definition to determine who have the responsibility of the CO_2 emissions derived from the energy transformation process (e.g., electricity generation). After a search of the literature, we encounter two ways to allocate the responsibility of the primary energy requirements, and consequently the CO_2 emissions: (1) considered as direct energy consumption/emissions of the conversion process or (2) considered as indirect consumption/emissions of the end-use sectors.

The first allocation criteria directly follows from the energy balances or the emission inventories, where the reported amount of energy consumption/emissions of each sector is just the direct quantity. This means that, for example, emissions from the transformation of primary fuels in thermal stations to deliver heat and electricity to the residential sector are reported under energy industries, whereas emissions from the burning of coal in a stove by a household would be reported as part of emissions from the residential sector. Nonetheless, we opt for the second allocation way since it seems to be the most appropriate to us, in as much as, for instance, the CO_2 emitted from a coal fired power station is not assigned to the electricity sector, but rather distributed among those who use the electricity generated by such power plant. In this type of demand-side-oriented setup, the energy sector would be included directly (as end-use sector) and indirectly. On the one hand, the energy used by the conversion sector as input to produce final energy products would be considered as primary energy requirement whose responsibility would lie with the end-use sectors. On the other hand, the final energy consumed by the energy sector in the form of own-produced energy or energy purchased by the producers to operate their installations would not be distributed to the end-use sectors. This type of strategy permits a better understanding of the underpinning trends from an energy demand perspective by linking final energy consumption and CO_2 emissions. This could be useful from a policy viewpoint, as for example, policies to improve the insulation of residential buildings could reduce both direct and indirect emissions.

Aiming to perform this class of approach, we build an energy input–output table using the observed energy flows of the system that will serve us to allocate the responsibility of primary energy requirements and energy-related CO_2 emissions to the end-use economic sectors (including the energy branch as final-energy user), the different existing transport modes and the various energy end-uses of households and services. This strategy is based on the allocation diagrams for CO_2 emissions developed by the European Environment Agency (2015), Alcántara and Roca (1995) and Ma et al. (2018), and allows us to fully identify the responsibility of CO_2 emissions of various sectors in each stage of the energy system, which means that our analysis would depict a complete figure of the energy system as it incorporates all sectors of the economy.[10] In practice, in order to implement the mentioned strategy, we first propose two parameters: (2) the derived primary energy quantity conversion factor (K_{PEQ}) and (2) the primary carbon dioxide emission factor (K_C) of each secondary energy.[11] Both are key technical influencing factors obtained from an structural energy input–output model. Second, we build a method using K_{PEQ} and K_C to calculate the equilibrium data of energy and CO_2 emissions for the whole physical process of energy use, i.e., we can trace the primary energy and the derived CO_2 emissions along the different energy flows from production (or imports) to final use. Finally, we use this equilibrium data to allocate the responsibility of primary energy requirements and CO_2 emissions among the end-use sectors.

2.3 Influencing factors entering the decomposition

In addition, making use of the mapping previously presented, we develop an improved LMDI decomposition method to depict the contributions of many influencing factors to the evolution of the energy-related CO_2 emissions at the Spanish and the European level from 1995 to 2017. When selecting the influential factors to be analyzed, a common starting point is the *Kaya* identity. Kaya (1990), in his very influential work, applied the idea of an *IPAT* identity to identify the major drivers of environmental impact (I) and CO_2 emissions: the amount of population (P), the affluence of that population (A), and the level of technology (T). Waggoner and Ausubel (2002) added a new term, consumption (C), to the identity and called the result *ImPACT* identity. Based on such body of literature, we propose to extend our defined expression for energy-related CO_2 emissions to include the impact of not only the aforementioned traditional factors, but also many novel ones regarding technical and some other extra aspects. That is, we develop an augmented version of the *Kaya* identity. More precisely, the following factors are included in our proposed decomposition: (1) population; (2) income per capita level (in purchasing power parity form in order to make it comparable across regions); (3) economic structure and (4) its intra-sectoral composition; (5) some social and (6) living-standards factors; (7-8) final energy intensity; (9) different types of end-uses of energy; (10) weather; (11) energy-mix (to study the influence of the share of renewable energy sources, principally); (12) efficiency of the conversion sector; and (13) type of primary energy sources (high- or low-carbon) used to make final energy consumption available.

2.4 End-use energy intensity versus end-use energy efficiency

Out of all the aforementioned factors, which will be explained in detail in the rest of the document, the element related to energy intensity (the well-known energy consumption

[10] It should be noted that, despite its potential relative importance, our approach abstracts from the effect of cross-border trading of energy flows on the energy-related CO_2 emissions.

[11] The derived primary energy quantity conversion factor (K_{PEQ}) refers to what Sessler (1987) calls energy requirement for energy (ERE), which for any energy used by the sectors considered would necessarily have a value greater than the unit.

to monetary output quotient) deserves a special consideration. This ratio has been traditionally understood as a key driver of emission trends, as it was assumed to be a good indicator of changes in energy efficiency of the end-use sectors (when final energy consumption was used as a measure) and changes in energy efficiency of the transformation sector (when primary energy consumption was used as a measure). In our particular case, as explained previously, the methodology that we use enables us to clearly identify the aspects related to the efficiency of the energy transformation system through the primary energy quantity conversion factor (K_{PEQ}). It means that, in our setup, the energy efficiency of the conversion sector is measured by means of the SDA method through changes in the Leontief inverse matrix. Therefore, once the energy efficiency of the transformation sector is addressed, one might think that by including energy intensity (the ratio of final consumption to monetary output) as a factor of the LMDI decomposition, we capture changes in the end-use energy efficiency. However, we do not agree that this is the appropriate approach as, in our view, energy intensity is not a valid proxy for end-use energy efficiency.

A few grounds for rejecting energy intensity as an efficiency metric are detailed in what follows. Energy intensity, although it is undoubtedly affected to a greater or lesser extent by efficiency in energy use, may be influenced by other factors such as the production structure, the degree of vertical integration or the capital-labor ratio, the scale of operations, etc. For instance, a decrease in energy intensity is not a synonym for energy savings, technical progress, reduction of energy waste or lower energy consumption in absolute terms, but it may also occur if energy consumption grows at a lower rate than the monetary output of what is produced with said energy. Moreover, apart from the quantitative characteristics of economic sectors, energy efficiency is also influenced by the requirements of the private residential and transport sectors. But to calculate energy intensity we need to know the monetary value of the output of the energy-consuming sector, and this value cannot be measured for non-productive sectors such as households and transport. Thus, energy intensity would not be an appropriate measure of the end-use energy efficiency.

For all these reasons, an alternative factor seems to be necessary to provide a good measurement of the end-use energy efficiency, since it is a determinant influence on CO_2 emissions and occupies a prominent place on the environmental policy agenda. However, since our formulation of the LMDI identity is conducive to the presence of energy intensity as a contributing factor, the best method to solve the above-mentioned issue is to separate observed physical energy intensity from structural changes affecting the energy intensity. In this sense, following the method proposed by Torrie et al. (2018), what we do is to subject the energy intensity factor to further extension or factorization that allows us to identify to what extent the observed physical energy efficiency influences changes in energy intensity, and therefore in CO_2 emissions. This is done by decomposing the energy intensity ratio between (1) consumption per physical unit of output (e.g., energy used per produced car) and (2) the ratio of physical output to the monetary output (e.g., produced cars per monetary value added of those cars). To this end, physical activity drivers have to be defined, which will vary significantly between sectors. This irremediably implies an additional data requirement and relies on a one-to-one correspondence between energy consumption data and physical activity data. An additional strength of this strategy is the possibility to study in a consolidated manner the energy efficiency of both productive and private sectors, as we can also define energy efficiency factors for the transportation sector (e.g., energy use per passenger-kilometer) and the households (e.g., energy consumption per m^2 of dwelling). As a result, another contribution to the literature is made, as we are able to reconcile the energy efficiency and energy intensity metrics within a refined decomposition approach that is applied for the Spanish economy and the EU28 economy as whole.

2.5 Apparent versus technical end-use energy efficiency

One must note that the observed physical end-use energy efficiency presented in the previous Subsection need not be an accurate measure of the actual technological progress. That is, we must differentiate between (i) observed or apparent physical end-use energy efficiency and (ii) technical end-use energy efficiency. In our analysis, we assume that a technological advance cannot be reversed. In other words, technical energy efficiency cannot decrease. Normally, we associate a fall in energy consumption per physical unit, i.e., an increase in apparent energy efficiency, with an increase in energy efficiency of the end-use sectors.

However, in certain cases, the observed or apparent energy efficiency of the end-use sectors (the energy consumption per unit produced or per physical unit installed) is observed to decrease (increase). In these scenarios, it cannot be deduced that it is due to a decrease in technical efficiency, since we assume that technological progress cannot be reversed. What may be actually happening when we observe a reduction in apparent energy efficiency is that the installed equipment is not being used efficiently or that the improvement in technical efficiency, or technological advance, could have lowered the costs or prices of certain energy causing an increase in the consumption of that energy, i.e., the so-called rebound effect.

That is why it is necessary to discern between what is driving the apparent or observed energy efficiency. To do so, as shown in Fig. 3, we subject such observed end-use energy efficiency to a further decomposition and we examine the role played by (1) technical energy efficiency or actual energy savings, (2) rebound effects, and (3) other factors (where the infra-utilization of the installed energy equipment can be a key contributor) in its developments. As a result, we will contribute to the literature by reconciling observed and technical end-use energy efficiency metrics. We will review the technical energy efficiency influences and the potential rebound effects in Sect. 2.5.1 and the influence of other factors like the infra-utilization in Sect. 2.5.2.

2.5.1 Rebound effect

It is not right to analyze the apparent end-use energy efficiency without a deep mention of the induced rebound effect. Usually, one may think that technical efficiency improvements result in providing the same amount of energy service to the consumer using less energy, what would induce positive changes in the observed energy efficiency. However, by having equipment that uses less energy, the energy service becomes less costly (effective price is reduced) for the user than before the energy

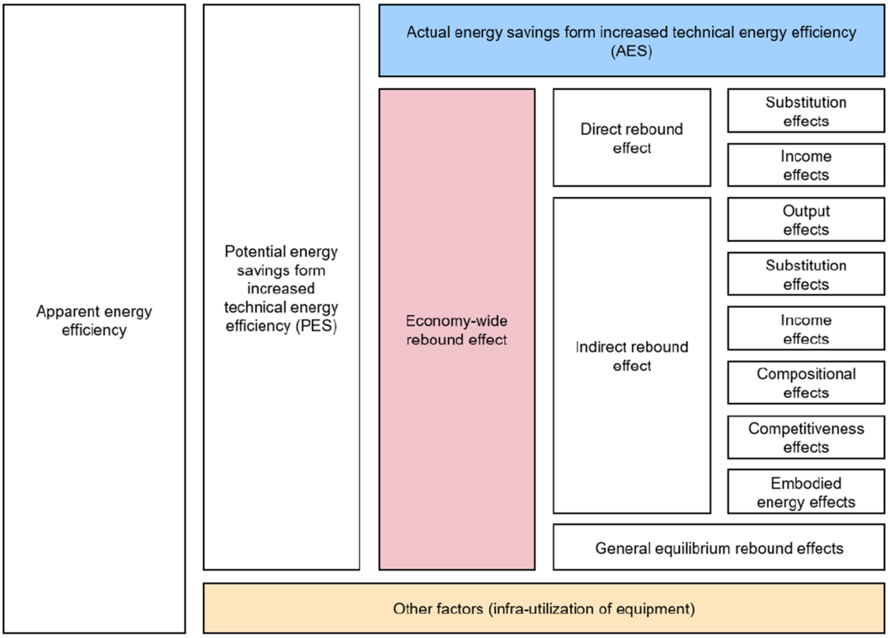

Fig. 3 Decomposition of apparent end-use energy efficiency

efficiency improvement happened. This decrease in the cost of the energy service could provoke increases in energy consumption that can occur through a price-reduction or other behavioral responses. In this way, the observed energy efficiency may not reflect actual changes in the technical energy efficiency. This is one of the main reasons why it is unavoidable to separate the technical efficiency from the observed (or apparent) energy efficiency.

Mathematically, as shown in Eq. 1, we define the rebound effect (RE) as the fraction of the potential energy savings (PES) that is not translated into actual energy savings (AES).

$$\text{RE} := 1 - \frac{\text{AES}}{\text{PES}} \tag{1}$$

The PES are given by the evolution of the technical energy efficiency, which is typically estimated by engineering models that assume no economic responses to improved energy efficiency and non-reversible improvements. The AES are usually depicted by observed changes in the apparent energy efficiency once we have controlled for potential rebound effects and other factors like the infra-utilization of the energy equipment installed. This formula could seem very simple and handy. However, the price- or cost-induced rebound effect is a very complex element. It is the umbrella term for a variety of economic mechanisms that comprises every reaction of the agents when they face an effective price reduction. Every potential reaction can be identified as a different type of rebound effect. Hence, the identification of every type of rebound effect is a very complicated process that depends on many aspects. Here, as shown in Fig. 3 and explained as follows, we provide a classification of the different types of price-induced rebound effect following the influential works of Greening et al. (2000), Sorrell (2007), Azevedo (2014) and Freire-González et al. (2017).

1. *Direct rebound effect* It was first defined by Khazzoom (1980) as the increase in the demand of an energy service caused by improvements in the efficiency of that particular energy service. It encompasses (1) pure substitution effects derived from the incentive to use more energy input of the energy whose effective price has fallen. This effect is typically given by the own-price elasticity of demand for a particular energy service. The direct rebound effect also covers potential (2) income effects. The cost reduction derived from the technical efficiency improvement may increase real incomes, which will positively impact on consumption of all commodities, including that of the energy product whose effective price has fallen as a result of the technical efficiency improvement.
2. *Indirect rebound effect* It is usually defined as the increase in the demand for other goods and services that also require energy for their production and distribution and that are affected by the reduction in the effective cost of the energy service considered and the associated increase in disposable income. This indirect rebound effect can originate from a number of sources. As it can be observed in Fig. 3, it covers: (1) output effects (producers may use the cost savings from energy efficiency improvements to increase output, increasing consumption of capital, labor and materials, which themselves require additional energy to provide); (2) substitution effects (given by the cross-price elasticities of demand for non-energy services); (3) income effects (increased real incomes will impact on consumption of all commodities, which will indirectly enhance an increase in the energy consumption); (4) compositional effects (relatively energy-intensive products benefit more from the fall in the effective energy prices); (5) competitiveness effects (the fall in supply prices of commodities that use energy as an input for production could stimulate their demand, increasing energy needs); and (6) embodied energy, (energy needed to implement the technical efficiency measure that leads to the technical change).
3. *Economy-wide rebound effect* It accounts for every increase in the demand of energy services caused by a higher economic growth and consumption at a macroeconomic level as a consequence of a technical efficiency improvement of the energy service considered. It comprises all sub types of rebound effects. The economy-wide rebound effect takes into account not only direct and indirect rebound effects, but also general equilibrium rebound effects. The latter effects account for the adjustments of prices and quantities of goods and services on the whole economy after an energy efficiency improvement. As the technical efficiency improves, there will be a reduction in the price of the energy services, which in turn will lead to a new overall equilibrium of supply and demand for all goods and services in the economy.

There is a variety of interpretations of the rebound effect depending on the magnitude and sign of the effect. (i) For values below zero, we encounter negative rebound effects or super-conservation effects. It means that the technical energy efficiency improvement is over realized, i.e., the energy consumption declines in a greater proportion than the extent to what the technical energy efficiency improves. (ii) When the value of the rebound effect is zero, we can say that the technical energy efficiency improvement is fully realized, i.e., the energy consumption drops in the same proportion than the extent to what the technical energy efficiency improves. (iii) We find partial rebound effects for values between zero and one hundred. In this case, the technical energy efficiency improvement is partially offset by an increased demand for energy. Finally, (iv) for values of the rebound effect greater than one hundred, we encounter the so-called backfire effect. In this particular case, the technical energy efficiency improvement is outweighed by an increased demand for energy, i.e., the energy consumption increases in a greater proportion than the extent to what the technical energy efficiency improves.

There is an open discussion regarding the actual magnitude of the rebound effect. For the concrete case of the Spanish economy, several research studies estimating direct rebound effects exist. Using panel data from the period 1991–2003, Freire-González (2010) estimates the magnitude of direct rebound effect for all energy services using electricity in households of Catalonia (Spain) using econometric techniques. He finds an estimated direct rebound effect of 35% in the short term and 49% in the long term. Gálvez et al. (2014) estimate the direct rebound effect in the residential sector for Spain. They analyze electricity and natural gas direct rebound effects using data on residential heating and domestic hot water consumption in 2012 and encounter direct rebound effects of 70–80% for electricity and of more than 100% for natural gas. Finally, in the most recent work addressing this topic, Bordon Lesme et al. (2020) estimate short- and long-run direct rebound effects with data on households' electricity consumption in Spain. Using a two-step Error Correction Model through GMM estimation, they find direct rebound effects between 26 and 35% in the short-run and around 36% in the long-run.

After reviewing the literature on rebound effects for Spain one can note how the empirical works do not offer a consensus about the magnitude of the direct rebound effect. Moreover, these studies focus exclusively on the residential sector of the economy and on certain specific energy products. However, for our analysis, we would need to learn what the total rebound effect of the economy is, for every sector (as a whole and separately for each of them) and for every energy product. That is why it is undoubtedly necessary to study what the economy-wide rebound effect is. In this way, we will be able to quantify the rebound effect of the total economy, which will capture the influences not only of direct and indirect rebound effects, but also of general equilibrium rebound effects, as shown in Fig. 3. In other words, we will move the core of this discussion toward the magnitude of the economy-wide rebound effect.

Sorrell and Dimitropoulos (2008) state that the economy-wide rebound effect from energy efficiency improvements may be expected to be larger than the direct rebound effect. However, the mechanisms involved are complex, interdependent, and difficult to conceptualize, and the magnitude of this effect is extremely difficult to estimate empirically. While both direct and indirect rebound effects are microeconomic and can be tested empirically, the magnitude of the economy-wide rebound effect should be estimated by the use of Computable General Equilibrium (CGE) models or macroeconometric models. These models carefully capture the dynamics of a entire economy and, as a consequence, calibrating such models to replicate current conditions and running them under alternate conditions is a daunting task. As pointed out by Azevedo

(2014), these theoretical frameworks rely on assumptions about price, income, substitution elasticities, cost-minimizing behavior from producers, utility-maximizing behavior from consumers. But once these setup conditions for building the theoretical framework are defined, one could perform an analysis of the economy-wide rebound effects which microeconomic or bottom-up analyses may be inappropriate to handle with.

Colmenares Montero et al. (2019) review the state-of-the-art of energy and climate modeling vis-a-vis the rebound literature and they find that worldwide research works report, on average, economy-wide rebound effects around 58%. When we look at the European countries, we encounter the work by Malpede and Verdolini (2016). They estimate the economy-wide rebound effect for 5 major European economies (Germany, France, Italy, the UK and Spain) over the years 1995-2009 and show a range of estimates of 50–60%. Other work reviewing economy-wide rebound effects for a number of countries is Adetutu et al. (2016). They use a combined stochastic frontier analysis (SFA) and two-stage dynamic panel data approach to explore the magnitude of the economy-wide rebound effect for 55 countries over the period 1980 to 2010. They find economy-wide rebound effects of 50–60% for both Spain and Europe.

Finally, placing the focus on the Spanish sphere, we find three important papers that calculate the economy-wide rebound effect. Guerra and Sancho (2010) build a CGE model and show that the use of engineering savings instead of general equilibrium potential savings downward biases economy-wide rebound effects and upward-biases backfire effects. Duarte et al. (2018) also construct a dynamic CGE model, but only covering the residential sector, and estimate economy-wide rebound effects for Spain of the order of 50–70%. Finally, Peña-Vidondo et al. (2012) present a static CGE model describing an open economy disaggregated into 27 production sectors, with 27 consumer goods, a representative consumer, the public sector and a simplified rest of the world and accounting for every group of energy products. This model also has the particular feature of including unemployment in labor markets, given the high level of unemployment in the Spanish economy. With this very complex and complete model, they estimate economy-wide rebound effects in Spain of 60–70%.

One can see how there is a greater consensus on estimates of the economy-wide rebound effect. In this sense, in our work we will use these estimates from the literature to identify the economy-wide rebound effect in Spain and in Europe and thus be able to decompose the effect of technical energy efficiency on the observed evolution of the apparent energy efficiency of the end-use sectors.

2.5.2 Other factors: infra-utilization

Apart from changes in technical efficiency and their possible rebound effects, an observed increase in the unit energy consumption (or decrease in apparent energy efficiency) may be due to other factors. As shown in Fig. 3, the apparent end-use energy efficiency is influenced by other factors that are calculated as a residual from differences between the evolution of the apparent efficiency and the evolution of the technical efficiency and its potential rebound effects.

Among this other-factors category, we find that decreases of the apparent energy efficiency may be due to an inefficient use of the equipment, as it is often observed during economic recessions. This is particularly true in industry or freight transport. For instance, as documented by ODYSSEE-MURE (2020a), in a period of recession, the energy consumption of the industry does not decrease proportionally to the activity as the efficiency of most equipment drops, as they are not used at their maximum rated capacity. It means that part of its energy consumption is independent of the production level. This infra-utilization is also well documented by the Ministerio de Turismo, Energía y Agenda Digital (2017). In that case, the technical energy efficiency does not decrease as such, as the equipment is still the same, but it is used less efficiently. This is another of the main reasons why it is unavoidable to separate the technical efficiency from the observed (or apparent) energy efficiency.

2.6 Overview of the main contributions of this study

In sum, we are convinced that the present work, which

(i) Mixes features and benefits from both IDA and SDA decomposition techniques,
(ii) Provides an allocation diagram scheme for assigning the responsibility of primary energy requirements and CO_2 emissions to the end-use sectors including both economic and non-productive sectors,
(iii) Analyzes more potential influencing factors than those typically examined,
(iv) Proceeds in a way that reconciles energy intensity and energy efficiency metrics,
(v) And distinguishes between technical and observed end-use energy efficiency taking into account potential rebound effects and other factors

represents a novelty and offers clear value added to past studies devoted to the study of the energy-related CO_2 emissions trends both in Spain and in the EU28. In addition, to the best of our knowledge, there is no previous study for Spain and the EU28 that uses such recent and disaggregated data.

3 Methodology and data

In this Section, we first introduce the primary energy conversion factor (K_{PEQ}) in Sect. 3.1 and the primary carbon dioxide emission factor (K_C) in Sect. 3.2. Then, these key parameters are adopted to develop an LMDI decomposition method suitable for analyzing all influencing factors driving the evolution of energy-related CO_2 emissions in Sect. 3.3. Finally, a further decomposition for the apparent end-use energy efficiency is presented in 3.4. All data used for these calculations are briefly introduced in the course of this Section.

3.1 Primary energy conversion factor

Any estimation of primary energy must first establish factors for conversion between energy magnitudes. Here, the primary energy quantity conversion factor (K_{PEQ}), which was suggested by many authors in previous studies, is the key parameter for establishing the connection between final energy consumption and primary energy consumption.[12] K_{PEQ} is defined as the total number of units of primary energy that must be consumed to produce one unit of final energy. There are several methods to calculate this primary energy quantity conversion factor. The European Comission (2016) conducted a survey about some of the methodologies available, applying them to the specific case of electricity, but valid for other types of energy. The purpose of the strategy is to be able to express final energy consumption in both standard quantity (SQ) form and primary energy quantity (PEQ) form. The SQ form denotes the heat value of final energy consumed by the end-use sectors while the PEQ form denotes the total primary energy consumed to produce such final energy by compensating all energy losses upstream. However, the compensating process for energy losses upstream is complex and involves many interacting conversion sub-sectors. Thus, we follow an input–output method in the spirit of the theoretical framework used by Alcántara and Roca (1995) and Ma et al. (2018) to acquire the K_{PEQ} of each energy product.

The input–output method has been widely applied to reveal internal relationships among the economic sectors. The development of an input–output table can reflect the balance of material or capital flows among all sectors while the Leontief inverse matrix of the table can establish the connection between the end-use consumption and the total consumption (which includes both intermediate and end-use consumption) of the flows. Therefore, using the input–output method, we can here construct an energy input–output table of energy sectors to establish the connection between final energy consumption and primary energy consumption by using the Leontief inverse matrix.

3.1.1 Establishment of the energy input–output table

To estimate the primary energy required for final energy consumption, a first approximation (an underestimation, as it will be discussed below) is based on the existing interrelationships in the Spanish energy sector so that each final energy consumption (primary or secondary) corresponds to a primary energy vector containing all primary energy sources that must be consumed to make such final consumption available.[13] For this purpose, making use of the *Complete Energy Balances* of the European countries published by Eurostat (2020c), which provide detailed data on energy supply, energy conversion, and final energy consumption, we can modify such energy balance table into an energy input–output table as shown in Table 1 (all table entries are expressed in SQ form).

The complete energy balance involves 63 energy products (the complete list of products can be shown in Table 13 of Appendix). These energy sources can be either primary or secondary and can be consumed either (1) directly by the end-use sectors to cover their energy needs (final demand of energy i, Y_i) or (2) by the conversion

[12] See Chong et al. (2015a) and Ma et al. (2018) for an application of this concept to China, Chong et al. (2015b) for an application to Malasya, and Alcántara and Roca (1995) for an application to the Spanish case.

[13] We understand as primary energies those directly extracted from the nature and as secondary energies those coming from the transformation of primary (and also secondary) energies.

sector to produce final energy that will be later consumed by the end-use sectors (this refers to the intermediate consumption part, where $Q_{i,j}$ is the quantity of energy i consumed to produce energy j in the transformation sector).

However, we should also take into account that many secondary energy products (oil derivatives and electricity, among others) could be directly imported from abroad. In our analysis, we consider that an imported energy unit is offset by an exported unit, so we only focus on what the net balance is (the difference between imports and exports).[14] When there is a positive net import balance in one secondary energy product, we must obviously consider that this entry of energy means a greater availability of primary energy.[15] To do this, we use the methodology proposed by Alcántara and Roca (1995) and we treat these positive net import balances of secondary products as a primary energy source valued for its energy content. In other words, in addition to the 63 energy types, we must augment our input–output table to incorporate the positive net import balances of secondary products. It means that we would have as many new primary energy sources (denoted by N_s) as secondary products with a positive net import balance.[16] We should note that the final demand of those positive net import balances of secondary products is 0, i.e., $Y_i = 0$, for $i = \{63 + 1, \ldots, 63 + N_s\}$, since such positive net import balances would just enter the input–output table in the intermediate consumption part. For example, if electricity were the energy product 1, the positive net import balance of electricity, say it would be the energy product 63+3, would just appear as an input for production of electricity. It means that $Q_{63+3,1}$ would report such positive net import balance quantity and that the row would be filled with zeros elsewhere.

The final demand of energy i is denoted by Y_i. This quantity includes several elements according to the *Sankey Diagrams for Energy Balances* developed by Eurostat (2020l). It results from the sum of (1) final energy consumption of energy i (including also final energy i consumption of the energy branch, i.e., energy i consumed to operate installations for energy production and transformation), (2) final non-energy consumption of energy i (for instance, oil used as timber preservative), (3) distribution and transmission losses of energy i (energy losses due to transport or distribution of electricity, heat, gas, as well as pipeline losses), (4) energy i consumed by international maritime bunkers (fuel consumption of ships during international navigation), (5) energy i consumed by international aviation (fuels delivered to aircrafts for international aviation), and (6) positive net export balances of energy i (when the quantity

[14] Nevertheless, while electricity can be considered a homogeneous product (and even in this case an electricity Kw/h generated at one point of time is not the same as a Kw/h generated at another moment), oil derivatives are very heterogeneous products. This could explain the strong import and export balances that the oil derivatives experience.

[15] Note that when there is a positive net export balance in a secondary product, the problem mentioned above does not appear and in this case we do not need to consider it since it would not mean a greater availability of primary energy.

[16] Another approach would be to estimate how much primary energy is needed to obtain these energies in the countries of origin or estimate it assuming that the technology in other countries is the same as in Spain, but due to a non-easy access to this information and because the differences between the use of this method and the use of the previous one are irrelevant, as shown by Roca et al. (2007), we perform here the first presented alternative.

Table 1 Energy input–output table

	1	2	3	…	j	…	63	63 + 1	63 + 2	63 + 3	…	$63 + N_s$	Y	Q
1	$Q_{1,1}$	$Q_{1,2}$	$Q_{1,3}$	…	$Q_{1,j}$	…	$Q_{1,63}$	0	0	0	…	0	Y_1	Q_1
2	$Q_{2,1}$	$Q_{2,2}$	$Q_{2,3}$	…	$Q_{2,j}$	…	$Q_{2,63}$	0	0	0	…	0	Y_2	Q_2
3	$Q_{3,1}$	$Q_{3,2}$	$Q_{3,3}$	…	$Q_{3,j}$	…	$Q_{3,63}$	0	0	0	…	0	Y_3	Q_3
…	…	…	…		…		…	…	…	…		…	…	…
i	$Q_{i,1}$	$Q_{i,2}$	$Q_{i,3}$	…	$Q_{i,j}$	…	$Q_{i,63}$	0	0	0	…	0	Y_i	Q_i
…	…	…	…		…		…	…	…	…		…	…	…
63	$Q_{63,1}$	$Q_{63,2}$	$Q_{63,3}$	…	$Q_{63,j}$	…	$Q_{63,63}$	0	0	0	…	0	Y_{63}	Q_{63}
63 + 1	$Q_{63+1,1}$	$Q_{63+1,2}$	$Q_{63+1,3}$	…	$Q_{63+1,j}$	…	$Q_{63+1,63}$	0	0	0	…	0	0	Q_{63+1}
63 + 2	$Q_{63+2,1}$	$Q_{63+2,2}$	$Q_{63+2,3}$	…	$Q_{63+2,j}$	…	$Q_{63+2,63}$	0	0	0	…	0	0	Q_{63+2}
63 + 3	$Q_{63+3,1}$	$Q_{63+3,2}$	$Q_{63+3,3}$	…	$Q_{63+3,j}$	…	$Q_{63+3,63}$	0	0	0	…	0	0	Q_{63+3}
…	…	…	…		…		…	…	…	…		…	…	…
$63 + N_s$	$Q_{63+N_s,1}$	$Q_{63+N_s,2}$	$Q_{63+N_s,3}$	…	$Q_{63+N_s,j}$	…	$Q_{63+N_s,63}$	0	0	0	…	0	0	Q_{63+N_s}

of energy i produced or transformed in the territory which is sent abroad is larger than the quantity of energy i coming from outside the territory).

The energy balances report 27 different types of energy transformation or conversion processes in the transformation sector section (see Table 17 of Appendix for a detailed description of all of them). These processes involve all activities where one energy commodity (either primary or secondary) is transformed into a secondary energy commodity (e.g., natural gas transformed into electricity in a power plant). For these 27 types of energy transformation processes, Eurostat (2020c) reports the energy inputs that they require to produce the energy transformation output. Therefore, the transformation inputs reported in the balances would be the quantities that would fill the intermediate demand part of our input–output table (elements $Q_{i,j}$, for $i, j = \{1, \ldots, 63\}$). However, there is a limitation coming from many of these transformation processes resulting in more than one energy output.[17] Thus, within a unique transformation process, we could not identify exactly which part of the transformation input is dedicated to produce which energy output. To overcome this issue, we assume that the inputs of each transformation process are distributed proportionally to each energy output in case that the transformation process results in more than one energy output. For example, if a transformation process X results in an output of 2 units of energy A, 2 units of energy B and 1 unit of energy C, the inputs of the transformation process X would be assigned in the following way: 40% to produce energy A, 40% to produce energy B, and 20% to produce energy C. In this way, we manage to allocate an intermediate energy demand to each type of energy output, which would allow us to fully identify our input–output table in the intermediate demand part.

Finally, Q_i denotes the total output of energy i, i.e., the total energy i needs. It can be calculated from two perspectives. From the demand side, the total energy needs result from the sum of the intermediate consumption and the final demand. This mathematical relationship is expressed in Eq. (2) for the case of energy i. Further, Eq. (3) shows the matrix form containing all energy products.

$$\sum_{j}^{63+N_s} Q_{i,j} + Y_i = Q_i \tag{2}$$

$$ID + Y = Q, \tag{3}$$

where $Q_{i,j}$ is the i, j-element of the matrix of intermediate demand, ID, Q is the column vector of total output, and Y is the column vector of final demand.

On the other hand, from the supply side, Q_i results from the sum of (1) the primary production of energy i (extraction from natural sources into a usable form), (2) the quantity of energy i recovered or recycled (e.g., the supply of renewable energy commodities produced in other fuel balances or certain petroleum products which are reprocessed and recycled), (3) the stock changes of energy i (difference between the opening stock level and closing stock level for stocks held on national territory), (4) the transformation output of energy i (quantity of energy obtained as a result of all

[17] For instance, while the charcoal production plants produce charcoal as the only energy output, the refineries produce more than 20 energy outputs (e.g., ethane, fuel oil, gasoline, petroleum coke, among others).

transformation processes), and (5) the positive net import balance of energy i (when the energy quantities produced or transformed in the territory which are sent abroad are smaller than the energy quantities coming from outside the territory). Both calculations lead to the same quantity of energy needs, Q_i.[18]

3.1.2 Leontief inverse matrix of energy input–output table

We define the direct consumption efficiency (or transformation coefficient) $a_{i,j}$ as the energy i consumed to produce one unit of energy j, which is shown in Eq. (4).

$$a_{i,j} = \frac{Q_{i,j}}{Q_j} \tag{4}$$

Hence, Eq. (3) can be further expressed as Eq. (5).

$$AQ + Y = Q, \tag{5}$$

where $a_{i,j}$ is the i, j-element of the matrix A.

Further, Eq. (5) can be rewritten as Eq. (6), where $(I - A)^{-1}$ is the Leontief inverse matrix, which is denoted with symbol L', as shown in Eq. (7).

$$Q = (I - A)^{-1}Y \tag{6}$$

$$Q = L'Y \tag{7}$$

In the Leontief inverse matrix, the i, j-element, $L'_{i,j}$, indicates the total number of units of energy i that should be consumed as transformation input in the energy sector in order to provide one unit of energy j for final energy consumption of the end-use sectors. Now, as we are interested in knowing just how much primary energy is necessary to make a unit of energy available for consumption of the end-use sectors, we must ignore the coefficients $L'_{i,j}$ for which i is a secondary energy product. In other words, we must drop the rows of the matrix L' that correspond to secondary energy products. Obviously, it does not refer to the rows included to incorporate positive net import balances of secondary energy products. Thus, we can further calculate the total units of primary energy that should be consumed in the conversion sector in order to provide one unit of energy j for end-use by using Eq. (8).

$$K_{\text{PEQ},j} = \sum_{i=1}^{63+N_s} L'_{i,j} \cdot \mathbb{1}_{i \notin \mathcal{S}} \tag{8}$$

where $\mathcal{S}$ is the subset of secondary energy products, $\mathbb{1}_{i \notin \mathcal{S}}$ is an indicator variable that takes value 1 when the energy product i is not part of the subset of secondary products and 0 otherwise, and $K_{\text{PEQ},j}$ is the primary energy quantity conversion factor

[18] See Table 12 of Appendix for a numerical example of the input–output table. This is done in a fictitious way in order to facilitate the comprehension of the table.

of energy j. In other words, $K_{\text{PEQ},j}$ would represent the direct and indirect primary energy requirements needed to obtain a unit of energy j for consumption of the end-use sectors. Therefore, this elevation factor allows us to transform energy quantities in standard (or final energy) quantity (SQ) form into primary energy quantity (PEQ) form.

This should be taken as a first approximation of the primary energy required by each final-demand energy product. In fact, this could be potentially an underestimation because, as discussed by Alcántara and Roca (1995), a more complete analysis would require the study of the direct and indirect energy demands of the conversion sector on other economic sectors, including transport, to include the energy needed to be able to make this input energy available, i.e., part of which is usually included as final energy consumption is in fact energy consumption necessary to transform the primary sources. In addition, we cannot consider the energy consumed in other countries to provide the energy used in Spain through imports. In this sense, if the primary energy requirements of imported secondary products were higher than the requirements of exported secondary products, we would be underestimating the associated impact. However, despite the relevance of this issue in the assessment of environmental impacts attributable to the Spanish economy, it is beyond the scope of this study. Finally, it should be noted that our approach has an aggregate perspective. We implicitly consider that any electricity user consumes the same primary energy needs for every Kw/h used and this is not the case in reality. For example, industrial plants that produce their own electricity or individual houses with photovoltaic cells have different distribution losses and these are also different according to the voltage at which electricity is distributed. But on top of that, we believe that the method we use allows us to have a fairly accurate approach to analyze the primary energy requirements of an economy and their evolution over time.

K_{PEQ} is further used to derive the primary carbon dioxide emission factor in Sect. 3.2. It is used in Sect. 4 to compute and show the responsibility of the energy-related CO_2 emissions associated to each end-use sector and to each final energy product. In addition, it is adopted to develop the LMDI method to decompose the evolution of energy-related CO_2 emissions in Sect. 3.3.

3.2 Primary carbon dioxide emission factor

After introducing the acquirement of the parameter K_{PEQ} of each energy product to assign the responsibility of the primary energy requirements among the energy products, we further introduce the acquirement of the primary carbon dioxide emission factor (K_C) in this Subsection. This is a key parameter for establishing the connection between energy consumption expressed in PEQ form and CO_2 emissions. Following Ma et al. (2018), $K_{C,j}$ is defined as the total number of units of CO_2 that are emitted when one unit of end-use energy j expressed in PEQ form is consumed. The mathematical expression to acquire this parameter is given by Eq. (9).

$$K_{C,j} = \sum_{m=1}^{63+N_s} \frac{L'_{m,j} \cdot \mathbb{1}_{m \notin S}}{K_{\text{PEQ},j}} \cdot f_m \tag{9}$$

Further, if we would like to compute the total number of units of CO_2 that are emitted when one unit of end-use energy j expressed in SQ form (rather than in PEQ form) is consumed, we would have to calculate the elevation factor $K_{C,SQ,j}$, which is given by Eq. (10).

$$K_{C,\mathrm{SQ},j} = K_{C,j} \cdot K_{\mathrm{PEQ},j} = \sum_{m=1}^{63+N_s} \frac{L'_{m,j} \cdot \mathbb{1}_{m \notin \mathcal{S}}}{K_{\mathrm{PEQ},j}} \cdot f_m \cdot K_{\mathrm{PEQ},j}$$
$$= \sum_{m=1}^{63+N_s} L'_{m,j} \cdot \mathbb{1}_{m \notin \mathcal{S}} \cdot f_m \qquad (10)$$

In Eqs. (9) and (10), $K_{\mathrm{PEQ},j}$, $L'_{m,j}$, and $\mathbb{1}_{m \notin \mathcal{S}}$ are defined as previously in Sect. 3.1. Here, f_m denotes the CO_2 emission factor of the primary energy m. The acquirement of this emission factor will be discussed in what follows.

3.2.1 Carbon dioxide emission factor

We define here the CO_2 emission factor f_m as the kilograms of CO_2 emitted when a human activity (combustion and the upstream, i.e., the production and transport of the energy product) makes use of 1 KTOE of primary energy m. It means that f_m will be expressed as kg-CO_2/KTOE. In order to calculate such parameter, we rely on the methodology and the data presented by the Intergovenmental Panel on Climate ChangeIntergovenmental Panel on Climate Change (2006) and introduce the formula given by Eq. (11).

$$f_m = \mathrm{NCV}_m \cdot v_m \cdot o_m \cdot \frac{44}{12} \qquad (11)$$

where NCV_m is a factor to convert the net calorific value of the energy m into TJ units. In our case, the energy quantities in the energy balances are expressed in KTOE. Hence, we have to multiply the KTOE quantity of each energy product m by $NCV_m = 41.868$ to convert it into TJ. v_m is the carbon content per unit of calorific value of the energy product m, expressed in kg-CO_2/TJ. It can be shown in Table 13 of the Appendix. o_m denotes the oxidation rate of the energy product m when it is used. The value of o_m is usually 1, reflecting complete oxidation of the energy product m. Lower values are used only to account for carbon retained indefinitely in ash or soot. Finally, $\frac{44}{12}$ denotes the molecular weight ratio of carbon dioxide (CO_2) to carbon (C). We should mention that the CO_2 emission factors of the different primary energies are the same for every region.

3.2.2 Estimation of energy-related carbon dioxide emissions

The $K_{C,\mathrm{SQ},j}$ factor (or the $K_{\mathrm{PEQ},j}$ and $K_{C,j}$ factors) can be further adopted to estimate the energy-related CO_2 emissions. By means of applying the aforementioned factors to the final energy demand data that Eurostat (2020c) publishes in its energy balances, we are able to approximate the energy-related CO_2 emissions of an economy. This is the reference approach used in the guidelines of the Intergovenmental Panel on Climate ChangeIntergovenmental Panel on Climate Change (2006). This is a top–down estimation approach, but there is another way to estimate the emissions in a bottom-up fashion, for which we would need to collect data relating to the mileage, energy consumption, and CO_2 coefficients of various types of vehicles at different speeds, as well as the number of each vehicle. We discard here such bottom-up approach because these data on many end-use activities are difficult to obtain and opt for the top–down approach, which is only based on terminal energy consumption easily accessible through the energy balances. Accordingly, we can estimate the energy-related CO_2 emissions by using Eq. (12).

$$C_E = \sum_{j=1}^{63} E_{\mathrm{SQ},j} \cdot K_{C,j} \cdot K_{\mathrm{PEQ},j} = \sum_{j=1}^{63} E_{\mathrm{SQ},j} \cdot K_{C,\mathrm{SQ},j} \tag{12}$$

where C_E denotes the total energy-related CO_2 emissions associated to the energy magnitude E, $E_{\mathrm{SQ},j}$ stands for the quantity of the energy product j being part of the energy magnitude E in SQ form, and $K_{C,j}$, $K_{\mathrm{PEQ},j}$, and $K_{C,\mathrm{SQ},j}$ are the elevation factors calculated in Eqs. (8), (9) and (10).

Then, by changing the energy magnitude that we impute to $E_{\mathrm{SQ},j}$, we can estimate the energy-related CO_2 emissions that different energy magnitudes imply. In addition, the estimated elevation factors, K_C and $K_{C,\mathrm{SQ}}$, are adopted to compute and show the responsibility of the energy-related CO_2 emissions associated to each end-use sector and to each final energy product in in Sect. 4, and to develop the LMDI method to decompose the evolution of energy-related CO_2 emissions in Sect. 3.3.

3.3 LMDI decomposition model

Following the estimation approach for energy-related CO_2 emissions presented in Eq. 12, and using the sectoral final energy consumption data that Eurostat (2020c) publishes in its energy balances (with some adjustments to acquire the sectoral disaggregation that we present, as it will be discussed below), we can derive the total energy-related CO_2 emissions at year t as the sum of the energy-related CO_2 emissions coming from each of the sectors considered at year t, as shown in Eq. 13.

$$\begin{aligned} C^t_{\mathrm{TOT}} &= \sum_s \sum_{j=1}^{63} E^t_{\mathrm{SQ},s,j} \cdot K^t_{C,j} \cdot K^t_{\mathrm{PEQ},j} = \sum_s \sum_{j=1}^{63} E^t_{\mathrm{SQ},s,j} \cdot K^t_{C,\mathrm{SQ},j} \\ &= C^t_{\mathrm{AGRI}} + C^t_{\mathrm{IND}} + C^t_{\mathrm{CPS}} + C^t_{\mathrm{HH}} + C^t_{\mathrm{TRA}} = \sum_s C^t_s \end{aligned} \tag{13}$$

where $s = \{\mathrm{AGRI, IND, CPS, HH, TRA}\}$ indexes the different end-use sectors, C^t_s denotes the energy-related CO_2 emissions associated to the sector s at year t, $E^t_{\mathrm{SQ},s,j}$ stands for the end-use energy quantity of product j consumed by the sector s at year t in SQ form, and $K_{C,j}$, $K_{\mathrm{PEQ},j}$, and $K_{C,\mathrm{SQ},j}$ are the elevation factors calculated in Equations (8), (9) and (10). Three of the five sectors here presented refer to economic sectors, i.e., they refer to economic activities included in the NACE list.[19] These economic sectors are agriculture, denoted by $AGRI$, industry, denoted by IND, and commercial and public services, denoted by CPS. In addition, there are two other sectors responsible for CO_2 emissions which are not economic or business sectors: households, denoted by HH, and transport, denoted by TRA.

We can also use Eq. 12 to compute the energy-related CO_2 emissions identity of each sector separately and extend it to further consider macro-level, technical and other extra details about many type of changes through the complex energy system along stages of the energy supply chain. This means that we follow a multisectoral augmented *Kaya* identity approach to study the contributions of many influencing factors to the evolution of the energy-related CO_2 emissions. In what follows, we present the LMDI decomposition strategy that we follow for each of the five previously mentioned sectors and how we aggregate them to examine the overall changes. It should be noted that decomposition strategy varies for each sector, as the depth of decomposition is highly dependent of the input data availability, especially at finer levels of disaggregation. And reaching very deep levels of disaggregation is what we are seeking, because in that way we ensure that changes in many factors are really due to the change in the factor itself, and not due to structural changes on a larger scale, as demonstrated by Sinton and Levine (1994).

3.3.1 Agriculture

For the agricultural sector, we can apply Eq. 12 to the final energy consumption data of the sector coming from Eurostat (2020c) and extend it as Eq. 14 to express the energy-related CO_2 emissions provoked by the mentioned sector at year t. This extension is designed to consider the following influential factors: population (1), which was considered the most important driver of the original *IPAT* identity; (2) total product per capita as a proxy of the income per capita,[20] which describes the affluence of the population referred to; (3) economic structure, to account for changes in energy consumption and emissions due to changes in the relative importance of the sectors in the economy; (4) intra-structure of the sector, to capture changes derived from the sub-sectoral composition; (5) end-use energy intensity, which pretends to describe changes due to technological improvements and policy effects; (6) energy-mix of final consumption, to observe the influence of fossil or low-carbon energies in the final consumption; and (7) primary CO_2 emission factor, which is intended to explain technical efficiency changes of the transformation sector (measured through changes in

[19] The Statistical Classification of Economic Activities in the European Community, commonly referred to as NACE (from the French term *"nomenclature statistique des activités économiques dans la Communauté européenne"*), is the industry standard classification system used in the European Union. The current version is revision 2 and was established by the Regulation No 1893/2006 of the European Parliament (2006-12-30).

[20] We use the total gross value added of the economy as a proxy of the GDP, since it results from the aggregation of the gross value added of the sectors considered. Activities of households as employers (with NACE code T) is the only economic activity group with no match in our scheme and therefore its value added (0.9% of the total in 2017 for Spain) is not included in our aggregate magnitude for gross value added.

the Leontief inverse matrix previously presented) and changes in the primary energy-mix of the conversion process.

$$C^t_{\mathrm{AGRI}} = \sum_m \sum_{j=1}^{63} \underbrace{P^t}_{(1)} \cdot \underbrace{\frac{V^t_{\mathrm{TOT}} \cdot \chi^t}{P^t}}_{(2)} \cdot \underbrace{\frac{V^t_{\mathrm{AGRI}} \cdot \chi^t}{V^t_{\mathrm{TOT}} \cdot \chi^t}}_{(3)} \cdot \underbrace{\frac{V^t_{m,\mathrm{AGRI}} \cdot \chi^t}{V^t_{\mathrm{AGRI}} \cdot \chi^t}}_{(4)} \cdot \underbrace{\frac{E^t_{\mathrm{SQ},m,\mathrm{AGRI}}}{V^t_{m,\mathrm{AGRI}} \cdot \chi^t}}_{(5)} \cdot \underbrace{\frac{E^t_{\mathrm{SQ},m,\mathrm{AGRI},j}}{E^t_{\mathrm{SQ},m,\mathrm{AGRI}}}}_{(6)} \cdot \underbrace{K^t_{C,\mathrm{SQ},j}}_{(7)}, \tag{14}$$

where m represents the different agricultural sub-sectors ($m = \{\mathrm{AF}, \mathrm{FISH}\}$), AF stands for agriculture and forestry, FISH stands for fishing, V^t_{TOT} denotes the total gross value added of the economy at year t, V^t_{AGRI} represents the gross value added of the agricultural sector at year t, $V^t_{m,\mathrm{AGRI}}$ describes the gross value added of the agricultural sub-sector m at year t, χ^t is a scaling factor to adjust the value added quantities to the purchasing power parity (PPP) of the region analyzed in order to make the magnitudes comparable across regions, and the different final energy products are indexed by j.[21]

Moreover, we can further extend Eq. 14 into 15. With this expression, we can reconciliate end-use energy intensity and end-use energy efficiency metrics in a single framework. This is a recognized issue in the literature related to decomposition analysis, as shown by Belzer et al. (2017) and discussed in Sect. 2. Here, in the spirit of the framework proposed by Torrie et al. (2018), we can disentangle (1) which part of the end-use energy intensity change is due to changes in the apparent or observed end-use energy efficiency (or physical intensity, i.e., energy unit consumption) and (2) which part is due to other influencing structural factors captured by the relation of physical driver to economic output. In addition, following the decomposition strategy presented by Ma et al. (2018), the primary CO_2 emission factor can be further extended to capture the influence of (3) changes in the technical efficiency of the conversion sector (measured through changes in the Leontief inverse matrix) and (4) changes in the energy-mix used in the transformation process (4).

$$\begin{aligned} C^t_{\mathrm{AGRI}} &= \sum_m \sum_{j=1}^{63} P^t \cdot \frac{V^t_{\mathrm{TOT}} \cdot \chi^t}{P^t} \cdot \frac{V^t_{\mathrm{AGRI}} \cdot \chi^t}{V^t_{\mathrm{TOT}} \cdot \chi^t} \cdot \frac{V^t_{m,\mathrm{AGRI}} \cdot \chi^t}{V^t_{\mathrm{AGRI}} \cdot \chi^t} \cdot \underbrace{\frac{D^t_{m,\mathrm{AGRI}}}{V^t_{m,\mathrm{AGRI}} \cdot \chi^t}}_{(1)} \cdot \underbrace{\frac{E^t_{\mathrm{SQ},m,\mathrm{AGRI}}}{D^t_{m,\mathrm{AGRI}}}}_{(2)} \cdot \frac{E^t_{\mathrm{SQ},m,\mathrm{AGRI},j}}{E^t_{\mathrm{SQ},m,\mathrm{AGRI}}} \cdot \underbrace{K^t_{\mathrm{PEQ},j}}_{(3)} \cdot \underbrace{K^t_{C,j}}_{(4)} \\ &= \sum_m \sum_{j=1}^{63} \mathrm{POP}^t \cdot \mathrm{INC}^t \cdot \mathrm{STR}^t_{\mathrm{AGRI}} \cdot \mathrm{INTR}^t_{\mathrm{AGRI},m} \cdot \mathrm{OUT}^t_{\mathrm{AGRI},m} \cdot \mathrm{EFF}^t_{\mathrm{AGRI},m} \cdot \mathrm{MIX}^t_{\mathrm{AGRI},m,j} \cdot \mathrm{CONV}^t_j \cdot \mathrm{EMI}^t_j \end{aligned} \tag{15}$$

where $D^t_{m,\mathrm{AGRI}}$ is the physical activity driver of the sub-sector m at year t and $K^t_{C,j}$ and $K^t_{\mathrm{PEQ},j}$ are the elevation factors calculated in Eqs. (9) and (8) at year t.

The data feeding this equation are gathered from different databases. First, the final energy consumption of the agricultural sector is determined directly by the Eurostat (2020c) energy balances, as they also distinguish the consumption of its sub-sectors. Second, the physical activity drivers are the *Utilised Agricultural Area* and the *Wooded Land* for the AF sub-sector, while the physical driver for the $FISH$ sector is the *Fish-*

[21] See Mendidulce et al. (2010) for an application of the PPP adjustment to make gross value added quantities comparable across regions (Spain and EU28).

ing Fleet.[22] Data are extracted from Eurostat (2020e), Eurostat (2020b), and Eurostat (2020f), respectively. Thus, the apparent or observed end-use energy efficiency will be determined by the energy consumption per thousand hectare of utilized agricultural area and wooded land and by the energy consumption per gross tonne of fishing fleet, respectively, for each sub-sector. Third, the *Gross Value Added* both for the sector and sub-sectors (in chain linked volumes, base 2015, to remove price effects) and for the national total is extracted from Eurostat (2020g) following the economic sector matching scheme presented in Table 16 of the Appendix.[23] Finally, population and PPP data at the national level are extracted from Eurostat (2020i) and Eurostat (2020k), respectively.

Subsequently, applying the additive LMDI decomposition technique to Eq. 15, we can derive the contributions the mentioned factors to the change in the energy-related CO_2 emissions of the agricultural sector from $t = 0$ to $t = T$ by using Eq. 16.[24]

$$\begin{aligned}\Delta C^T_{\mathrm{AGRI}} &= C^T_{\mathrm{AGRI}} - C^0_{\mathrm{AGRI}} \\ &= \Delta C^T_{\mathrm{POP,AGRI}} + \Delta C^T_{\mathrm{INC,AGRI}} + \Delta C^T_{\mathrm{STR,AGRI}} \\ &\quad + \Delta C^T_{\mathrm{INTR,AGRI}} + \Delta C^T_{\mathrm{OUT,AGRI}} \\ &\quad + \Delta C^T_{\mathrm{EFF,AGRI}} + \Delta C^T_{\mathrm{MIX,AGRI}} + \Delta C^T_{\mathrm{CONV,AGRI}} + \Delta C^T_{\mathrm{EMI,AGRI}}\end{aligned} \tag{16}$$

where the factor $\Delta C^T_{\mathrm{EFF,AGRI}}$ for the agricultural sector, as an example, would be constructed as shown in Eq. 17 (and in analogous manner for other factors and other sectors).

$$\Delta C^T_{\mathrm{EFF,AGRI}} = \sum_m \sum_{j=1}^{63} L(C^T_{\mathrm{AGRI}}, C^0_{\mathrm{AGRI}}) \cdot ln\left(\frac{\mathrm{EFF}^T_{\mathrm{AGRI},m}}{\mathrm{EFF}^0_{\mathrm{AGRI},m}}\right) \tag{17}$$

with $L(a, b) = (a - b)/(ln(a) - ln(b))$ being the logarithmic mean of two positive real numbers, which is used as the weighting function in the LMDI decomposition approach.[25] At this point, we must stress that the LMDI method is not defined for zeros or negative values in the dataset (due to logarithmic terms in the formula), hence it is necessary to substitute these to avoid errors in computation. We here use the so-called

[22] The *Utilised Agricultural Area* is only reported for years 1995, 1997, 2000, 2003, 2005, 2007, 2010, 2013, and 2016. Therefore, we interpolate linearly the existing data gaps in-between. The *Fishing Fleet* data is complete for every year, but we replace some missing data of some countries for some years with the linear observed trend. In addition, the EU28 quantity of both data inputs is calculated by aggregation of the different national data.

[23] There are some sectors with missing GVA data for some years. Following the strategy utilized by Economidou and Román-Collado (2019), these gaps are fulfilled assuming that the trend of the magnitude is proportional to the total GDP trend.

[24] See the annex of the work by Ma and Stern (2008) for a complete mathematical derivation of the LMDI decomposition.

[25] It should be noted that $L(a, b)$ separates the arithmetic and the geometric mean, i.e., $\sqrt{a \cdot b} < L(a, b) < \frac{1}{2}(a + b)$.

Small Value Strategy proposed by Ang and Choi (1997) and we substitute the zero values by values smaller than 10^{-20}.[26]

Following this scheme, $\Delta C^{T}_{\text{POP,AGRI}}$ describes the change in the energy-related CO_2 emissions of the agricultural sector from $t = 0$ to $t = T$ that is associated to changes in population, $\Delta C^{T}_{\text{INC,AGRI}}$ is the change associated to the variations in income per capita (or GVA per capita), $\Delta C^{T}_{\text{STR,AGRI}}$ represents the change attributed to the economic structure, $\Delta C^{T}_{\text{INTR,AGRI}}$ provides information about the change related to composition variations of the agricultural sector (or intra-structure), $\Delta C^{T}_{\text{OUT,AGRI}}$ denotes the changes linked to the structural elements influencing the energy intensity (or variations in the ratio of physical activity driver to economic output), $\Delta C^{T}_{\text{EFF,AGRI}}$ stands for changes associated to the physical end-use energy intensity (or apparent end-use energy efficiency), $\Delta C^{T}_{\text{MIX,AGRI}}$ describes the change attributed to variations in the composition of the end-use energy-mix, $\Delta C^{T}_{\text{CONV,AGRI}}$ represents the change linked to the technical efficiency of the conversion sector (or variations in the primary energy requirements), and $\Delta C^{T}_{\text{EMI,AGRI}}$ denotes the change associated to the share of carbon primary energy sources used to make the final energy consumption available.

3.3.2 Industry

Regarding the industrial sector, we can implement the same extension of the energy-related CO_2 identity that we perform for the agricultural sector, since the granularity of the data is the same. In this sense, following Eq. 15, the energy-related CO_2 emissions coming from the industrial sector and the influential factors to be analyzed can be derived from Eq. 18.

$$\begin{aligned} C^{t}_{\text{IND}} &= \sum_{m}\sum_{j=1}^{63} P^{t} \cdot \frac{V^{t}_{\text{TOT}} \cdot \chi^{t}}{P^{t}} \cdot \frac{V^{t}_{\text{IND}} \cdot \chi^{t}}{V^{t}_{\text{TOT}} \cdot \chi^{t}} \cdot \frac{V^{t}_{m,\text{IND}} \cdot \chi^{t}}{V^{t}_{\text{IND}} \cdot \chi^{t}} \cdot \underbrace{\frac{D^{t}_{m,\text{IND}}}{V^{t}_{m,\text{IND}} \cdot \chi^{t}}}_{(1)} \cdot \underbrace{\frac{E^{t}_{\text{SQ},m,\text{IND}}}{D^{t}_{m,\text{IND}}}}_{(2)} \cdot \frac{E^{t}_{\text{SQ},m,\text{IND},j}}{E^{t}_{\text{SQ},m,\text{IND}}} \cdot \underbrace{K^{t}_{\text{PEQ},j}}_{(3)} \cdot \underbrace{K^{t}_{C,j}}_{(4)} \\ &= \sum_{m}\sum_{j=1}^{63} \text{POP}^{t} \cdot \text{INC}^{t} \cdot \text{STR}^{t}_{\text{IND}} \cdot \text{INTR}^{t}_{\text{IND},m} \cdot \text{OUT}^{t}_{\text{IND},m} \cdot \text{EFF}^{t}_{\text{IND},m} \cdot \text{MIX}^{t}_{\text{IND},m,j} \cdot \text{CONV}^{t}_{j} \cdot \text{EMI}^{t}_{j} \end{aligned} \tag{18}$$

where IND stands for industry, $m = \{\text{EEI, FBT, TL}, \ldots, \text{CON}\}$ indexes the industrial sub-sector, EEI stands for energy sector and extractive industries, FBT stands for food, beverages and tobacco, TL stands for textile and leather, WWP stands for wood and wood products, PPP stands for paper, pulp and print, CPC stands for chemical and petrochemical industry, NMM stands for non-metallic minerals, BM stands for basic metals, MAC stands for machinery, TE stands for transport equipment, OI stands for other industry, CON stands for construction, and the rest of notations describe analogous aspects to those shown in Eq. 15.

In this regard, the only difference from the agricultural sector is the definition of physical activity drivers for each of the industrial sub-sectors. Here, following the matching sector scheme presented in Table 16 of Appendix and based on the strategy

[26] There is another strategy called *Limit Strategy* and proposed by Wood and Lenzen (2006), but we decline to use it because it requires more calculation and is not distinguished from the one we use in the results it offers.

proposed by ODYSSEE-MURE (2020a), we compute the physical activity driver of each sub-sector with the *Production Volume Index* for each of them, respectively. This is an index reported by Eurostat (2020j) that approximates the output of each sub-sector in physical terms.[27]

Therefore, applying the LMDI decomposition technique to Equation 18, we can derive the change in the energy-related CO_2 emissions of the industrial sector from $t = 0$ to $t = T$ by using Eq. 19.

$$\begin{aligned}\Delta C_{\text{IND}}^{T} &= C_{\text{IND}}^{T} - C_{\text{IND}}^{0} \\ &= \Delta C_{\text{POP,IND}}^{T} + \Delta C_{\text{INC,IND}}^{T} + \Delta C_{\text{STR,IND}}^{T} \\ &\quad + \Delta C_{\text{INTR,IND}}^{T} + \Delta C_{\text{OUT,IND}}^{T} \\ &\quad + \Delta C_{\text{EFF,IND}}^{T} + \Delta C_{\text{MIX,IND}}^{T} + \Delta C_{\text{CONV,IND}}^{T} + \Delta C_{\text{EMI,IND}}^{T}\end{aligned} \tag{19}$$

where the notations represent analogous aspects to those shown in Eqs. 16 and 17, but now for the industrial sector.

3.3.3 Commercial and public services

The granularity of the data in the commercial and public services sector follows a different perspective. Whereas we were able to gather the energy consumption and the economic output of the different sub-sectors within the agricultural and industrial sectors directly from the Eurostat (2020c) energy balances, in the case of commercial and public services, we are unable to observe a similar breakdown at the sub-sector level. However, within the conglomerate of activities that constitutes the commercial and public services sector (see Table 16 of Appendix), we can impute the fraction of energy consumption that is devoted to each type of energy end-use making use of the ODYSSEE-MURE (2020b) database.[28] In other words, we can see how much of the final energy consumption (with a breakdown by energy product) of the commercial and public services sector is allocated to space heating (SH), hot water (HW), cooking (COOK), air cooling (AC), and lighting (LIGHT). Therefore, given the breakdown of the data for this sector, the extension of the energy-related CO_2 emissions identity for the commercial and public services sector to include the influencing factors would be as shown in Equation 20.

$$C_{\text{CPS}}^{t} = \sum_{u} \sum_{j=1}^{63} P^{t} \cdot \frac{V_{\text{TOT}}^{t} \cdot \chi^{t}}{P^{t}} \cdot \frac{V_{\text{CPS}}^{t} \cdot \chi^{t}}{V_{\text{TOT}}^{t} \cdot \chi^{t}} \cdot \frac{D_{\text{CPS}}^{t}}{V_{\text{CPS}}^{t} \cdot \chi^{t}} \cdot \frac{E_{\text{SQ,CPS}}^{t}}{D_{\text{CPS}}^{t}}$$

[27] The *Production Volume Index* missing data is fulfilled with the linear observed trend.

[28] See Reuter et al. (2019) for a detailed description of the ODYSSEE-MURE (2020b) data imputation and the missing-data filling process.

$$\cdot \underbrace{\frac{E^t_{\mathrm{SQ},u,\mathrm{CPS}}}{E^t_{\mathrm{SQ,CPS}}}}_{(1)} \cdot \underbrace{\left(\frac{\mathrm{HDD}^t}{\mathrm{HDD}_{\mathrm{ref}}}\right)_{u=\mathrm{SH}} \cdot \left(\frac{\mathrm{CDD}^t}{\mathrm{CDD}_{\mathrm{ref}}}\right)_{u=\mathrm{AC}}}_{(2)} \cdot \frac{E^t_{\mathrm{SQ},u,\mathrm{CPS},j}}{E^t_{\mathrm{SQ},u,\mathrm{CPS}}} \cdot K^t_{\mathrm{PEQ},j} \cdot K^t_{C,j}$$

$$= \sum_u \sum_{j=1}^{63} \mathrm{POP}^t \cdot \mathrm{INC}^t \cdot \mathrm{STR}^t_{\mathrm{CPS}} \cdot \mathrm{OUT}^t_{\mathrm{CPS}} \cdot \mathrm{EFF}^t_{\mathrm{CPS}} \cdot \mathrm{USE}^t_{\mathrm{CPS},u}$$
$$\cdot \mathrm{WEA}^t_{\mathrm{CPS},u} \cdot \mathrm{MIX}^t_{\mathrm{CPS},u,j} \cdot \mathrm{CONV}^t_j \cdot \mathrm{EMI}^t_j \quad (20)$$

where CPS stands for commercial and public services, $u = \{\mathrm{SH, HW, COOK, AC, LIGHT}\}$ indexes the particular energy end-use, HDD^t (CDD^t) denotes the heating (cooling) degree days during the year t, $\mathrm{HDD}_{\mathrm{ref}}$ ($\mathrm{CDD}_{\mathrm{ref}}$) stands for the reference value of heating (cooling) degree days for the whole period of analysis (from 1995 to 2017), the ratio $\frac{\mathrm{HDD}^t}{\mathrm{HDD}_{\mathrm{ref}}}$ is 1 for $u \neq SH$ and the ratio $\frac{\mathrm{CDD}^t}{\mathrm{CDD}_{\mathrm{ref}}}$ is 1 for $u \neq AC$, and the rest of notations describe analogous aspects to those shown in Eq. 15.

We can notice that in this sector we do not find the intra-structural component, since there is no disaggregation by sub-sectors as there was in the previous two sectors. However, we find two new influential factors that we did not have before: (1) the share of the different end-uses in the total final energy consumption of the sector and (2) the climate factor. The latter is included so that the magnitudes of both regions (Spain and the EU28, in our case) are comparable and to ensure that the differences between regions are not due to purely climatic systemic differences. In this sense, the final energy consumption for space heating and air cooling is adjusted following Reuter et al. (2019), since variations in weather are a determining factor for this type of end-uses and we must take this into account.[29] For that purpose, we access the data regarding the heating (cooling) degree days published by Eurostat (2020d). Finally, it should be commented that because we do not have disaggregation by sub-sectors, because the data coverage of the production volume index does not include the entire commercial and public services sector, and given that other indicators such as the surface area of the sector's installations, the number of offices or other technical aspects are not available for the sector as a whole, the only statistic that we consider valid to act as a physical activity driver for the sector is the number of employees provided by Eurostat (2020h). Therefore, the apparent end-use energy efficiency (or physical end-use intensity) of this sector will be determined by the energy consumption per employee.

Hence, applying the LMDI decomposition technique to Eq. 20, we can derive the change in the energy-related CO_2 emissions of the commercial and public services sector from $t = 0$ to $t = T$ by using Eq. 21.

[29] Effects of changes in annual average temperature play a minor role in other sectors like industry and transport, as shown by Reuter et al. (2019).

$$\begin{aligned}\Delta C^T_{\mathrm{CPS}} &= C^T_{\mathrm{CPS}} - C^0_{\mathrm{CPS}} \\ &= \Delta C^T_{\mathrm{POP,CPS}} + \Delta C^T_{\mathrm{INC,CPS}} + \Delta C^T_{\mathrm{STR,CPS}} \\ &\quad + \Delta C^T_{\mathrm{OUT,CPS}} + \Delta C^T_{\mathrm{EFF,CPS}} \\ &\quad + \Delta C^T_{\mathrm{USE,CPS}} + \Delta C^T_{\mathrm{WEA,CPS}} + \Delta C^T_{\mathrm{MIX,CPS}} \\ &\quad + \Delta C^T_{\mathrm{CONV,CPS}} + \Delta C^T_{\mathrm{EMI,CPS}}\end{aligned} \tag{21}$$

where the notations represent analogous aspects to those shown in Eqs. 16 and 17, but now for the commercial and public services sector. Furthermore, following this scheme, $\Delta C^T_{\mathrm{USE,CPS}}$ describes the change in the energy-related CO_2 emissions of the commercial and public services sector from $t = 0$ to $t = T$ that is associated to changes in the share of the different end-uses in the total final energy consumption of the sector and $\Delta C^T_{\mathrm{WEA,CPS}}$ is the change associated to the variations in the climate conditions.[30]

3.3.4 Households

For the household sector (denoted by HH), the approach is designed based on the energy end-uses in that sector, a similar strategy to that followed for the commercial and public services sector. In this case, the difference comes from the energy consumption of households not being associated with any economic activity (included in the NACE list), but coming from a private activity. Again, in the case of households, we are not able to observe a breakdown by energy end-uses directly from the Eurostat (2020c) energy balances. However, we can impute the fraction of energy consumption that is devoted to each type of energy end-use making use of the ODYSSEE-MURE (2020b) database. In this sense, we can observe how much of the final energy consumption of the households is allocated to space heating (SH), hot water (HW), cooking (COOK), air cooling (AC), and lighting (LIGHT). In addition, due to a different definition of the apparent end-use energy efficiency factor for each end-use type of the residential final energy consumption and given the breakdown of the data for this sector, the extension of the energy-related CO_2 emissions identity for the household sector to include the influencing factors would be separated in this case into two different expressions, as shown in Eqs. 22 and 23.

Equation 22 displays the extension of the energy-related CO_2 emissions identity for the case of space heating as energy end-use.

$$\begin{aligned}C^t_{HH,SH} &= \sum_{j=1}^{63} P^t \cdot \underbrace{\frac{H^t}{P^t}}_{(1)} \cdot \underbrace{\frac{A^t}{H^t}}_{(2)} \cdot \frac{E^t_{\mathrm{SQ,SH,HH}}}{A^t} \cdot \frac{\mathrm{HDD}^t}{\mathrm{HDD_{ref}}} \cdot \frac{E^t_{\mathrm{SQ,SH,HH},j}}{E^t_{\mathrm{SQ,SH,HH}}} \cdot K^t_{\mathrm{PEQ},j} \cdot K^t_{C,j} \\ &= \sum_{j=1}^{63} \mathrm{POP}^t \cdot \mathrm{SOC}^t \cdot \mathrm{COM}^t \cdot \mathrm{EFF}^t_{\mathrm{HH,SH}} \cdot \mathrm{WEA}^t_{\mathrm{HH,SH}} \cdot \mathrm{MIX}^t_{\mathrm{HH,SH},j} \cdot \mathrm{CONV}^t_j \cdot \mathrm{EMI}^t_j\end{aligned} \tag{22}$$

where H^t denotes the number of dwellings in the region at year t, A^t represents the total area of dwellings in the region (in m^2), and the rest of notations describe

[30] Note that $\Delta C^T_{\mathrm{WEA,CPS},u}$ will be zero for $u \notin \{\mathrm{SH, AC}\}$.

analogous aspects to those shown in Eqs. 15 and 20. In this case, data for A^t and H^t are extracted from the ODYSSEE-MURE (2020b) database. Therefore, the factor $\text{EFF}^t_{\text{HH,SH}}$ is defined as energy consumption for space heating use per m^2 of dwelling in the region. In the case of the household sector, we do not find influencing factors like income per capita, economic structure and intra-structure, structural factors affecting the energy intensity of the sector nor a factor calibrating the share that the different energy end-uses have in the total energy consumption of the sector. However, we discover two new influencing factors that we had not found before: (1) the social factor (i.e., less people living together in one dwelling) and (2) the comfort factor (or factor related to living standards, i.e., an increasing/decreasing area per dwelling).

On the other hand, Eq. 23 displays the extension of the energy-related CO_2 emissions identity for the case of household energy end-uses different from space heating.

$$
\begin{aligned}
C^t_{\text{HH},\overline{\text{SH}}} &= \sum_{u\neq\text{SH}} \sum_{j=1}^{63} P^t \cdot \underbrace{\frac{H^t}{P^t}}_{(1)} \cdot \frac{E^t_{\text{SQ},u,\text{HH}}}{H^t} \cdot \left(\frac{\text{CDD}^t}{\text{CDD}_{\text{ref}}}\right)_{u=\text{AC}} \cdot \frac{E^t_{\text{SQ},u,\text{HH},j}}{E^t_{\text{SQ},u,\text{HH}}} \cdot K^t_{\text{PEQ},j} \cdot K^t_{C,j} \\
&= \sum_{u\neq\text{SH}} \sum_{j=1}^{63} \text{POP}^t \cdot \text{SOC}^t \cdot \text{EFF}^t_{\text{HH},u} \cdot \text{WEA}^t_{\text{HH},u} \cdot \text{MIX}^t_{\text{HH},u,j} \cdot \text{CONV}^t_j \cdot \text{EMI}^t_j
\end{aligned}
\tag{23}
$$

where the factor $\text{EFF}^t_{\text{HH},u}$ is defined here as energy consumption for end-use u per dwelling in the region and the rest of notations describe analogous aspects to those shown in Equations 15 and 20. It can be noticed that we do not incorporate the factor COM^t for energy end-use types different from space heating, but only the factor $\text{SOC}^t(1)$. We should also note that the ratio $\frac{\text{CDD}^t}{\text{CDD}_{\text{ref}}}$ is 1 for $u \neq \text{AC}$.

Therefore, applying the LMDI decomposition technique to Eqs. 22 and 23, we can derive the change in the energy-related CO_2 emissions of the household sector from $t = 0$ to $t = T$ by using Eq. 24.

$$
\begin{aligned}
\Delta C^T_{\text{HH}} &= \Delta C^T_{\text{HH,SH}} + \Delta C^T_{\text{HH},\overline{\text{SH}}} \\
&= (C^T_{\text{HH,SH}} - C^0_{\text{HH,SH}}) + (C^T_{\text{HH},\overline{\text{SH}}} - C^0_{\text{HH},\overline{\text{SH}}}) \\
&= \Delta C^T_{\text{POP,HH}} + \Delta C^T_{\text{SOC,HH}} + \Delta C^T_{\text{COM,HH}} \\
&\quad + \Delta C^T_{\text{EFF,HH}} + \Delta C^T_{\text{WEA,HH}} \\
&\quad + \Delta C^T_{\text{MIX,HH}} + \Delta C^T_{\text{CONV,HH}} + \Delta C^T_{\text{EMI,HH}}
\end{aligned}
\tag{24}
$$

where the notations represent analogous aspects to those shown in Eqs. 16 and 17, but now for the household sector. Furthermore, following this scheme, $\Delta C^T_{\text{SOC,HH}}$ describes the change in the energy-related CO_2 emissions of the household sector from $t = 0$ to $t = T$ that is associated to changes in social factors and $\Delta C^T_{\text{COM,HH}}$ is the change associated to comfort or behavior developments.[31]

[31] Note that $\Delta C^T_{\text{WEA,HH},u}$ will be zero for $u \notin \{\text{SH, AC}\}$ and that $\Delta C^T_{\text{COM,HH},u}$ will be zero for $u \neq \text{SH}$.

3.3.5 Transport

As far as the transport sector is concerned (denoted by TRA), the strategy is based on the final energy demands coming from the different existing transport modes. Again, these energy consumptions are not associated with any economic activity (included in the NACE list), but are taken as energy consumption derived from private activity.[32] In terms of energy consumption data availability for this sector, the Eurostat (2020c) energy balances present a disaggregation by transport mode (rail, road, aviation, navigation, and pipelines), but no distinction is made on the share of the energy consumption of each transport mode that corresponds to freight (FR) and passenger transport (PASS). This distinction is very relevant as the most appropriate indicator to express activity is passenger-kilometers (PKM, hereafter) in the case of passenger transport and tonne-kilometers (TKM, hereafter) in the case of freight transport. As the conversion of PKM to TKM is not possible, alternative sources like the ODYSSEE-MURE (2020b) database must be considered. In this sense, since domestic navigation (NAVI) and pipeline transport (PIPE) are freight transport by definition and domestic air transport + other (AVI) is passenger transport by definition, using the shares offered by the ODYSSEE-MURE (2020b) database, we calculate which part of the road transport (ROAD) and train transit (RAIL) is due to passenger transport and which part is due to freight transport.[33] Once we have defined it, we have a complete disaggregation of the transport energy consumption by transport modes. Therefore, the extension of the energy-related CO_2 emissions identity for the transport sector to include the influencing factors would be given by Eq. 25.

$$
\begin{aligned}
C^t_{\mathrm{TRA}} &= \sum_p \sum_q \sum_{j=1}^{63} P^t \cdot \underbrace{\frac{K^t_p}{P^t}}_{(1)} \cdot \underbrace{\frac{K^t_{p,q}}{K^t_p}}_{(2)} \cdot \frac{E^t_{\mathrm{SQ},p,q,\mathrm{TRA}}}{K^t_{p,q}} \cdot \frac{E^t_{\mathrm{SQ},p,q,\mathrm{TRA},j}}{E^t_{\mathrm{SQ},p,q,\mathrm{TRA}}} \cdot K^t_{\mathrm{PEQ},j} \cdot K^t_{C,j} \\
&= \sum_p \sum_q \sum_{j=1}^{63} \mathrm{POP}^t \cdot \mathrm{SOC}^t_p \cdot \mathrm{STR}^t_{p,q} \cdot \mathrm{EFF}^t_{p,q} \cdot \mathrm{MIX}^t_{p,q,j} \cdot \mathrm{CONV}^t_j \cdot \mathrm{EMI}^t_j
\end{aligned}
\tag{25}
$$

where K^t_p denotes the PKM at year t in the whole passenger transport if $p = PASS$ and the TKM at year t in the whole freight transport if $p = FR$, $K^t_{p,q}$ stands for the PKM of the passenger transport mode q (for $q = \{\mathrm{ROAD, RAIL, AVI}\}$) at year t if $p = \mathrm{PASS}$ and the TKM of the freight transport mode q (for $q = \{\mathrm{ROAD, RAIL, NAVI, PIPE}\}$) at year t if $p = FR$, and the rest of notations describe analogous aspects to those shown in Equation 15. PKM and TKM data are gathered from the ODYSSEE-MURE (2020b) database for every transport mode except for pipeline transport, whose associated TKM

[32] In our analysis, we consider that the energy consumption associated with transportation activities appearing in the NACE list of economic activities is only that consumption related to installations (e.g., lighting in train stations). These energy demands will therefore appear under the consumption associated to the commercial and public services sector.

[33] Road transport consumption includes all energy consumed by cars, motorcycles and buses for the passenger transport and trucks and light vehicles for the case of freight transport. Domestic aviation only includes energy used by all domestic aeroplanes (e.g., private and commercial planes). Domestic navigation only includes energy consumed for river and coastal maritime domestic transport.

are taken from a report published by Eurostat (2020m).[34] Therefore, the apparent end-use energy efficiency of the transport sector is measured as energy consumption per PKM (if passenger transport) or per TKM (if freight transport). We do not find in this sector influencing factors like income per capita, intra-structure, weather, comfort, structural factors affecting the energy intensity of the sector nor a factor calibrating the share that the different energy end-uses have in the total energy consumption of the sector. However, two influencing factors that we have presented above are here redefined: (1) the factor SOC_p^t is here constructed as PKM or TKM per capita and (2) the factor $\mathrm{STR}_{p,m}^t$ describes the modal composition of the passenger or freight transport structure.

Hence, applying the LMDI decomposition technique to Equation 25, we can derive the change in the energy-related CO_2 emissions attributed to the transport sector from $t = 0$ to $t = T$ by using Eq. 26.

$$\begin{aligned}\Delta C_{\mathrm{TRA}}^T = C_{\mathrm{TRA}}^T - C_{\mathrm{TRA}}^0 \\ = \Delta C_{\mathrm{POP,TRA}}^T + \Delta C_{\mathrm{SOC,TRA}}^T + \Delta C_{\mathrm{STR,TRA}}^T \\ + \Delta C_{\mathrm{EFF,TRA}}^T + \Delta C_{\mathrm{MIX,TRA}}^T \\ + \Delta C_{\mathrm{CONV,TRA}}^T + \Delta C_{\mathrm{EMI,TRA}}^T\end{aligned} \tag{26}$$

where the notations represent analogous aspects to those shown in Eqs. 16 and 17, but now for the transport sector.

3.3.6 Factor aggregation scheme and data

After carefully explaining the different LMDI decomposition strategies that we have performed for each of the five sectors presented above and given the aggregation property of the LMDI formulation, the obtained sectoral results are summed up to review the composition of the energy-related CO_2 emissions as a whole. Based on Eq. 13, where it is stated that the total energy-related CO_2 emissions is equivalent to the aggregation of the different sectoral estimates of such magnitude, we can obtain an aggregate LMDI decomposition for the change in the total energy-related CO_2 emissions from $t = 0$ to $t = T$ by using Eq. 27.

$$\begin{aligned}\Delta C_{\mathrm{TOT}}^T = \Delta C_{\mathrm{AGRI}}^T + \Delta C_{\mathrm{IND}}^T + \Delta C_{\mathrm{CPS}}^T + \Delta C_{\mathrm{HH}}^T + \Delta C_{\mathrm{TRA}}^T = \sum_s \Delta C_s^T \\ = \Delta C_{\mathrm{POP,TOT}}^T + \Delta C_{\mathrm{INC,TOT}}^T + \Delta C_{\mathrm{SOC,TOT}}^T + \Delta C_{\mathrm{COM,TOT}}^T \\ + \Delta C_{\mathrm{STR,TOT}}^T + \Delta C_{\mathrm{INTR,TOT}}^T + \Delta C_{\mathrm{OUT,TOT}}^T \\ + \Delta C_{\mathrm{EFF,TOT}}^T + \Delta C_{\mathrm{USE,TOT}}^T + \Delta C_{\mathrm{WEA,TOT}}^T \\ + \Delta C_{\mathrm{MIX,TOT}}^T + \Delta C_{\mathrm{CONV,TOT}}^T + \Delta C_{\mathrm{EMI,TOT}}^T\end{aligned} \tag{27}$$

[34] For the EU28 case, pipeline TKM data is only available until 2015, therefore years 2016 and 2017 are extrapolated from the data.

where the factor $\Delta C^{T}_{\mathrm{EFF,TOT}}$, as an example, would be constructed as shown in Eq. 28 (and in analogous manner for other factors).

$$\Delta C^{T}_{\mathrm{EFF,TOT}} = \sum_{s} C^{T}_{\mathrm{EFF},s} \tag{28}$$

for $s = \{\mathrm{AGRI, IND, CPS, HH, TRA}\}$. However, as we have seen in the above narrative, not all sectors (or sub-sectors) imply a change for the aggregate magnitude. For example, the weather factor at the aggregate level is only determined by how the climate shapes the energy consumption devoted to space heating or air cooling in the services and residential sectors. In any case, an overview of how the factors are aggregated is shown in Fig. 4. Finally, to check the validity of the decomposition, we estimate the annual change of the total energy-related CO_2 emissions from $t = 0$ to $t = T$ and we compare it with the quantity obtained by aggregating the changes in the different factors and sectors. In this regard, our check reveals 0% differences for the vast majority of cases, with the difference never exceeding 2%, which may be due to the problem that the LMDI approach has in dealing with close-to-zero values.

3.4 Further decomposition of apparent end-use energy efficiency

After performing the decomposition presented in the previous Sect. 3.3, we can see how much the apparent end-use energy efficiency contributes to the evolution of energy-related CO_2 emissions in Spain and the EU. However, as we commented in Sect. 2.5, this observed end-use energy efficiency may be driven not only by the technical efficiency itself, but also by other influences such as possible rebound effects resulting from technical efficiency improvements or other factors such as the infra-utilization of installed energy equipment. For this reason, we consider it necessary to develop a methodology of decomposition that allows us to know what is really driving the apparent end-use energy efficiency (the observed energy unit consumption).

Firstly, we define what we understand as apparent end-use energy efficiency. For each sub-sector of the economy previously presented, m, belonging to a sector, s, the apparent end-use energy efficiency at year t, $\mathrm{AEE}^{t}_{m,s}$, is determined by the physical activity driver of said sub-sector, $D^{t}_{m,s}$, divided the final energy consumption of said sub-sector, $E^{t}_{\mathrm{SQ},m,s}$. Note that since a decrease in the specific unit energy consumption is an increase in the apparent energy efficiency, such observed energy efficiency will be given by the inverse of the mentioned specific unit energy consumption. That is,

$$\mathrm{AEE}^{t}_{m,s} = \frac{1}{\frac{E^{t}_{\mathrm{SQ},m,s}}{D^{t}_{m,s}}} = \frac{D^{t}_{m,s}}{E^{t}_{\mathrm{SQ},m,s}}. \tag{29}$$

In order to make the evolution of all these apparent energy efficiency indicators comparable across sub-sectors, we calculate an index with base 100 in 1995 (the beginning of our analysis period), i.e., $\mathrm{AEE}^{1995}_{m,s} = 100$. In addition, once presented for each sub-sector, the apparent end-use energy efficiency index of the sector s as a whole, AEE^{t}_{s}, is determined by the average of whose sub-sector indexes pondered by the

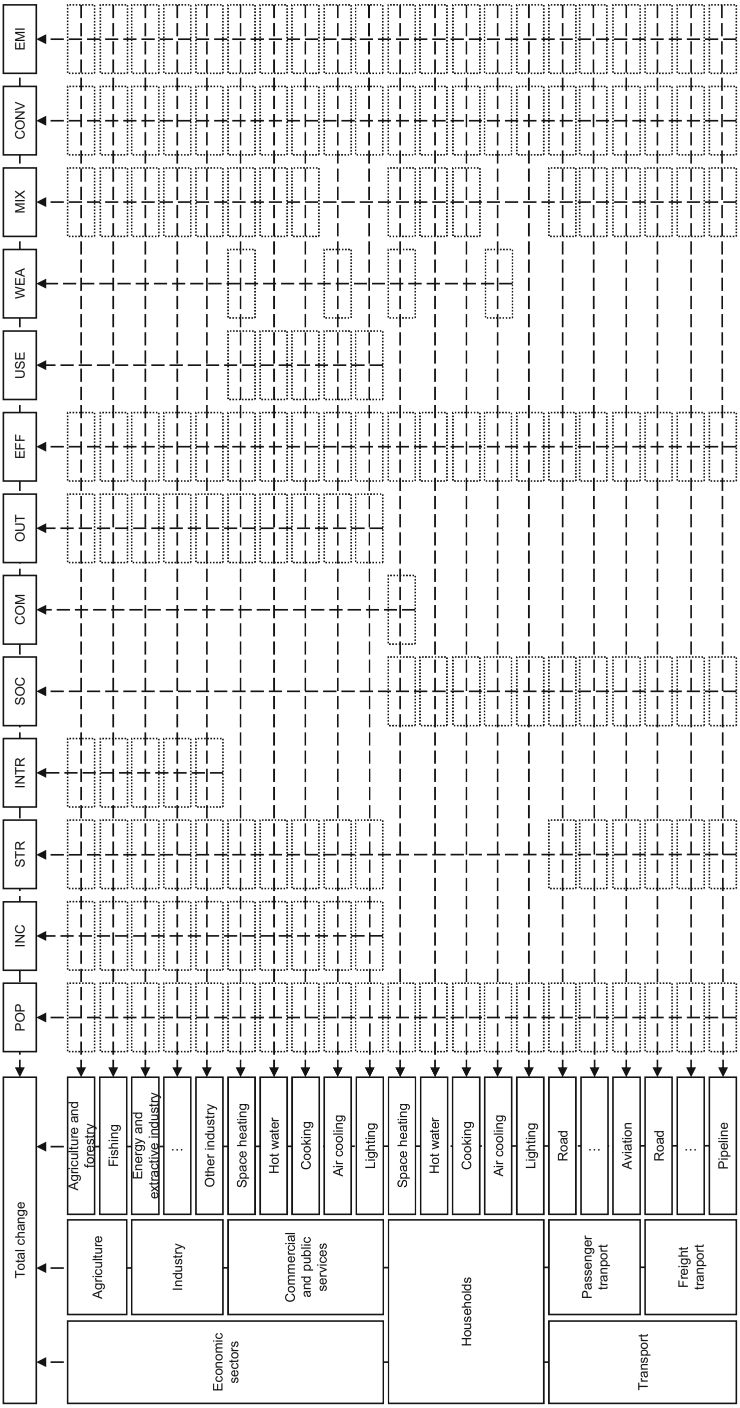

Fig. 4 Aggregation scheme over factors and sectors

weight of each of them in the final energy consumption of the sector, $\omega^t_{m,s} = \frac{E^t_{\mathrm{SQ},m,s}}{E^t_{\mathrm{SQ},s}}$. That is, $\mathrm{AEE}^t_s = \sum_m \mathrm{AEE}^t_{m,s} \cdot \omega_{m,s}$. Analogously, the total or national apparent end-use energy efficiency index will be given by $\mathrm{AEE}^t_{\mathrm{TOT}} = \sum_s \mathrm{AEE}^t_s \cdot \omega^t_s$, with ω^t_s being in this case the share of the sector s in the total final energy consumption, $\frac{E^t_{\mathrm{SQ},s}}{E^t_{\mathrm{SQ,TOT}}}$.

Secondly, we present the calculation of the technical end-use energy efficiency index. Following the definition and calculations provided by ODYSSEE-MURE (2020a), for each sub-sector of the economy previously presented, m, belonging to a sector, s, the technical end-use energy efficiency index (also called *ODEX* index) at year t, $\mathrm{TEE}^t_{m,s}$, will be defined as the apparent end-use energy efficiency index assuming non-reversible efficiency improvements. A decrease in the specific unit energy consumption (an increase of the apparent energy efficiency index) indicates that energy efficiency has been improving. However, in some cases the observed indicator shows an increase (an decrease in the apparent energy efficiency index), resulting in a negative energy efficiency improvement. Since we assume non-reversible technical efficiency improvements, this increase in the specific unit energy consumption may be due to an inefficient use of the equipment (part of the energy consumption is independent of the production level), as it is often observed during economic recession, or due to rebound effects derived from a fall in the effective energy cost. In this case, the apparent energy efficiency index can be replaced by technical energy efficiency index, by considering that if the apparent energy efficiency index for a given sub-sector decreases at year t its value will be kept constant in the calculation of the technical efficiency, i.e., the considered apparent energy efficiency index will be that from year $t-1$. Thus, the technical end-use energy efficiency index of the sub-sector m in the sector s at year t will be depicted by Eq. 30.

$$\begin{aligned}\mathrm{TEE}^t_{m,s} &= \mathrm{TEE}^{t-1}_{m,s} \cdot \frac{E^t_{\mathrm{SQ},m,s} + D^t_{m,s} \cdot \left(\frac{E^{t-1}_{\mathrm{SQ},m,s}}{D^{t-1}_{m,s}} - \frac{E^t_{\mathrm{SQ},m,s}}{D^t_{m,s}} \right)}{E^t_{\mathrm{SQ},m,s}} \\ &= \mathrm{TEE}^{t-1}_{m,s} \cdot \frac{E^t_{\mathrm{SQ},m,s} + D^t_{m,s} \cdot \left(\frac{1}{\mathrm{AEE}^{t-1}_{m,s}} - \frac{1}{\mathrm{AEE}^t_{m,s}} \right)}{E^t_{\mathrm{SQ},m,s}} \\ &= \mathrm{TEE}^{t-1}_{m,s} \cdot \frac{E^t_{\mathrm{SQ},m,s} + \mathrm{PES}^t_{\mathrm{SQ},m,s}}{E^t_{\mathrm{SQ},m,s}}\end{aligned} \tag{30}$$

where $\mathrm{PES}^t_{\mathrm{SQ},m,s}$ denotes the potential energy savings (PES) from $t-1$ to t and is calculated by multiplying the physical activity driver at t by the variation in the specific unit energy consumption between $t-1$ to t, and it is assumed that $PES^t_{\mathrm{SQ},m,s} = 0$ for $\mathrm{AEE}^t_{m,s} \leq \mathrm{AEE}^{t-1}_{m,s}$. It means that the technical end-use energy efficiency index of the sub-sector $m$in the sector s at year t will be obtained by multiplying the index in the previous period, $\mathrm{TEE}^{t-1}_{m,s}$, by the ratio between the final energy consumption of the sub-sector without potential energy savings (PES) at t, $E^t_{\mathrm{SQ},m,s} + \mathrm{PES}^t_{\mathrm{SQ},m,s}$, and the actual energy consumption at t, $E^t_{\mathrm{SQ},m,s}$, assuming that these PES cannot be negative. For example, say that the technical end-use energy efficiency index of the construction sub-sector were 103 in year 2001, the final energy consumption of such sub-sector were 2,1 in 2002, and the PES of said sub-sector were 0,18 in 2002. Then the technical end-use energy efficiency index of the construction sub-sector in year 2002 would be $111,82 = 103 \cdot \frac{2,1+0,18}{2,1}$.

Finally, once presented for each sub-sector, as shown in Eq. 31, the technical end-use energy efficiency index of the sector s as a whole, TEE_s^t, will be computed by multiplying the sectoral index in the previous period, TEE_s^{t-1}, by the average of whose sub-sectoral index changes pondered by the weight of each of these sub-sectors in the final energy consumption of the sector, $\omega_{m,s}^t = \frac{E_{\mathrm{SQ},m,s}^t}{E_{\mathrm{SQ},s}^t}$.

$$\mathrm{TEE}_s^t = \mathrm{TEE}_s^{t-1} \cdot \left(\sum_m \frac{\mathrm{TEE}_{m,s}^t}{\mathrm{TEE}_{m,s}^{t-1}} \cdot \omega_{m,s}^t \right) \tag{31}$$

Analogously, the total or national technical end-use energy efficiency index will be given by Eq. 32.

$$\mathrm{TEE}_{\mathrm{TOT}}^t = \mathrm{TEE}_{\mathrm{TOT}}^{t-1} \cdot \left(\sum_s \frac{\mathrm{TEE}_s^t}{\mathrm{TEE}_s^{t-1}} \cdot \omega_s^t \right) \tag{32}$$

with ω_s^t being in this case the share of the sector s in the total final energy consumption, $\frac{E_{\mathrm{SQ},s}^t}{E_{\mathrm{SQ,TOT}}^t}$. We should note that with our calculations of the technical energy efficiency index, we success to acquire the same numbers as those published by ODYSSEE-MURE (2020a) in its *ODEX* index series, which highlights and shows the adequacy of the method we follow for the estimation of technical efficiency.

After having presented both apparent and technical end-use energy efficiency indexes, we can decompose the index-points change in the apparent end-use energy efficiency index of sector s from $t-1$ to t, $\Delta\mathrm{AEE}_s^t$, as the sum of the apparent index-points changes caused by three influencing components. As shown in Eq. 33, these components will be: (1) the index-points change in the apparent efficiency index caused by technical efficiency index changes in sector s, $\Delta\mathrm{AEE}_{\mathrm{TEE}_s^t,s}^t$; (2) the index-points change in the apparent efficiency index caused by the rebound effect derived from a technical change in sector s, $\Delta\mathrm{AEE}_{\mathrm{RE}(\mathrm{TEE}_s^t),s}^t$; and (3) the index-points change in the apparent efficiency index caused by a variation in other factors in sector s, $\Delta\mathrm{AEE}_{\mathrm{OF}_s^t,s}^t$, where the infra-utilization of installed energy equipment could enter as a key contributor, jointly with other extra non-identifiable factors.

$$\Delta\mathrm{AEE}_s^t := \Delta\mathrm{AEE}_{\mathrm{TEE}_s^t,s}^t + \Delta\mathrm{AEE}_{\mathrm{RE}(\mathrm{TEE}_s^t),s}^t + \Delta\mathrm{AEE}_{\mathrm{OF}_s^t,s}^t \tag{33}$$

for $s = \{\mathrm{AGRI}, \mathrm{IND}, \mathrm{CPS}, \mathrm{HH}, \mathrm{TRA}\}$ if we analyze the sectoral apparent energy efficiency metrics and for $s = TOT$ if we assess the total or national apparent energy efficiency index change.

More precisely, the index-points change in the apparent efficiency index caused by technical efficiency index changes in sector s, will be directly given by the index-points change in the technical efficiency index. That is, $\Delta \mathrm{AEE}^t_{\mathrm{TEE}^t_s,s} = \Delta \mathrm{TEE}^t_s$.

A more detailed explanation is needed when it comes to identify the index-points change in the apparent efficiency index caused by the rebound effect derived from a technical change. As discussed in Sect. 2.5.1, it is not right to analyze the apparent end-use energy efficiency without a deep mention of the induced rebound effect. In this sense, a positive change in the technical end-use energy efficiency could make an energy service become less costly (effective energy price is reduced) for the user than before the technical energy efficiency improvement happened. This decrease in the cost of the energy service could provoke increases in the final energy consumption, which would negatively contribute to the evolution of the observed end-use energy efficiency. This mechanism is known as rebound effect, which is mathematically defined as the fraction, RE, of the index-points change in the technical efficiency index, $\Delta \mathrm{TEE}^t_s$, that is not directly translated into the index-points change in the apparent efficiency index. That is, we identify the index-points change in the apparent efficiency index caused by the rebound effect as $\Delta \mathrm{AEE}^t_{\mathrm{RE}(\mathrm{TEE}^t_s),s} = -\mathrm{RE} \cdot \Delta \mathrm{TEE}^t_s$.[35]

Since we can identify the index-points change in the technical efficiency index, the only remaining aspect to be determined would be the RE fraction itself. For this purpose, we rely on the available academic literature devoted to estimate the magnitude of these rebound effects. More precisely, we use the economy-wide rebound effect estimates from Peña-Vidondo et al. (2012) and Adetutu et al. (2016). As discussed in Sect. 2.5.1, we select academic works that estimate the economy-wide rebound effect, because it is a wider definition of the rebound effect which encompasses all possible sub-types of rebound effects.

One the one hand, we use the economy-wide rebound effect estimates of Adetutu et al. (2016) to be able to compare the evolution of the rebound effect over time both in Spain and in the EU28. They use a combined stochastic frontier analysis (SFA) and two-stage dynamic panel data approach to explore the magnitude of the economy-wide rebound effect for 55 countries over the period 1980 to 2010.[36] The use of their estimates has the advantage of allowing us to have economy-wide rebound effects for both Spain and the EU28 (i) calculated on an equal methodological footing and (ii) for a long period of time. However, these estimates do not allow us to analyze more than the rebound effect of the total economy. In this sense, with these data we cannot

35 Note that the sign of this index-points change depends on the sign of the rebound effect, RE. For rebound effects greater than 0, it would imply a negative index-points change contribution to the evolution of the apparent energy efficiency index. However, for rebound effects smaller than 0 (backfire effects), it would imply a positive index-points change contribution to the evolution of the apparent energy efficiency index. Note also that for non-existent technical efficiency changes ($\Delta \mathrm{TEE}^t_s = 0$) this contribution would be 0.

36 Since our period of analysis covers until year 2017 and the paper only provides estimates until 2010, we assume that the economy-wide rebound effect estimates remain unchanged from 2010 to 2017. In addition, not every EU28 country is included in the paper, but we can only compute the European aggregate magnitude with 19 European countries (calculated as a weighted average of the different country-specific rebound effects using final energy consumption of each of these countries as a weight). In this sense, the EU19 rebound effect would act as a good proxy of the EU28 rebound effect in our analysis since the 19 European countries in the selected paper account for more than 95% of the total EU28 final energy consumption.

reach higher levels of disaggregation and analyze the rebound effects by sector or by type of energy.

To make the latter possible, we refer to the results provided by Peña-Vidondo et al. (2012). They develop a CGE model (i) describing an open economy disaggregated into 27 production sectors, with 27 consumer goods, a representative consumer, the public sector and a simplified rest of the world and (ii) accounting for every group of energy products. In addition, unlike similar models, their model has the particular feature of including unemployment in labor markets, which is key for calculating economy-wide rebound effects given the high level of unemployment in the Spanish economy. The results of these authors are an enormous discovery for us, since they allow us to learn about the economy-wide rebound effect for each sector and for each group of energy products. Moreover, the sectoral structure of this analysis permits us to fully match their sectors and sub-sectors with the sectoral disaggregation available in our work. However, this article only analyzes Spain for the year 2005.[37] Therefore, in Sect. 4 we will only be able to show the sectoral breakdown of this effect for the Spanish case, while for the EU28 case we will only have the total aggregate rebound effect. Finally, another favorable point is that both papers, with different methodologies, estimate similar economy-wide rebound effects for Spain (of the order of 60%), which highlights the validity of the selected literature, albeit different, for acquiring the estimates of rebound effects.

Finally, the index-points change in the apparent efficiency index caused by a variation in other factors in sector s, $\Delta\text{AEE}^t_{OF^t_s,s}$, is the only contributor to the evolution of the apparent end-use energy efficiency index that needs to be identified. This is defined residually as $\Delta\text{AEE}^t_{\text{OF}^t_s,s} = \Delta\text{AEE}^t_s - \Delta\text{AEE}^t_{\text{TEE}^t_s,s} - \Delta\text{AEE}^t_{\text{RE}(\text{TEE}^t_s),s}$. This last contributor is a umbrella term that is determined in a residual way and where the infra-utilization of installed energy equipment could enter as a key contributor, jointly with other extra non-identifiable factors. However, we are not able to reach higher level of detail within this contributor, so we cannot distinguish what part of the other-factors term is actually determined by the infra-utilization of installed resources and what part is not. In any case, we believe that said infra-utilization plays an important role in driving the observed or apparent end-use energy efficiency index. Decreases of the apparent energy efficiency that cannot be explained by rebound effects may be due to an inefficient use of the equipment, as it is often observed during economic recessions. As shown by the Ministerio de Turismo, Energía y Agenda Digital (2017), in a period of recession, the energy consumption of the industry does not decrease proportionally to the activity as the observed efficiency of most equipment drops, as they are not used at their maximum rated capacity. It means that part of its energy consumption is independent of the production level. This is why we believe that infra-utilization is a key component of the other-factors contributor, although we cannot state it with certainty since we cannot decompose further said contributor.

To sum up, we provide an example on how we decompose the index-points change in the apparent end-use energy efficiency of a sub-sector from $t-1$ to t. Let's say that the machinery industrial sub-sector presented an apparent end-use energy efficiency index of 104 at $t-1$ and of 107 at t. We can deduce that the index-points change in

[37] We must assume that the sectoral RE estimates for Spain are constant throughout our period of analysis.

its observed end-use energy efficiency at t is +3. In addition, say that such sub-sector (i) experienced an increase in its technical end-use energy efficiency of 8 index points from $t-1$ to t and (ii) present a rebound effect of 45%. Then, the index-points change in the apparent end-use energy efficiency of the machinery industrial sub-sector can be decomposed as follows: $3 = (8)-(40\%\cdot 8)+(3-8+40\%\cdot 8) = (8)-(3,2)+(-1,8)$. It means that (i) the technical energy efficiency contributes with 8 positive index-points to the index-points change in the apparent end-use energy efficiency of the machinery industrial sub-sector, (ii) the rebound effect contributes negatively with − 3,2 index points to said change, (iii) and other factors contribute also negatively with up to − 1,8 index points to such change.

4 Results

Once the methodology that we adopt to estimate the energy-related CO_2 emissions and to determine the contribution of certain factors to the evolution of said magnitude has been presented, we can now provide a description of the main results found. The assignments of primary energy requirements and CO_2 emissions responsibilities are shown in Sects. 4.1 and 4.2, respectively. Subsequently, the factor and sectoral decomposition results for the evolution of the energy-related CO_2 emissions are shown in an aggregated way in Sect. 4.3. The remaining Subsections are devoted to a separate analysis of each of the most relevant influencing factors in the mentioned evolution.

4.1 Allocation of primary energy requirements

First, we make use of the estimated K_{PEQ} to derive the primary energy requirements associated to each component of the final energy demand, as shown Table 2. We must note that the estimation of the primary energy requirements associated to the final energy demand reveals a number that is equivalent to the gross available energy (calculated from the supply side) reported in the energy balances published by Eurostat (2020c), which proves that our method of estimation is appropriate. We can observe that the total primary energy requirements have increased, both in the EU28 (+ 4.2%) and in Spain (+ 33.5%) from 1995 to 2017, being the increase much higher in the Spanish case. We can also show that the requirements solely associated to final energy consumption are responsible of the greatest fraction of total primary energy requirements, but their weight has experienced a drop both in the EU28 (from 85.3 to 80.9%) and in Spain (from 80.6 to 77.5%). The final non-energy consumption, and to a lesser extent the distribution losses, have also reduced their weight in the total primary energy requirements, which was already small, in favor of the weight gained by the primary energy requirements associated to the consumption dedicated to the international maritime bunkers and aviation, and the positive net export balances. This is an evolution that can be observed both in the EU28 and in Spain.

Moreover, applying the respective $K_{\mathrm{PEQ},j}$ elevation factor to each energy product j, we can obtain the primary energy requirements derived from each energy product. For this purpose, we show in Table 3 how much the primary energy requirements related

Table 2 Total primary energy requirements (Demand perspective)

Concept	Spain		EU28	
	1995	2017	1995	2017
Final demand (MTOE)	111.10	148.30	1739.033	1,812.94
International maritime bunkers	2.97%	4.55%	2.05%	2.41%
International aviation	1.92%	2.96%	1.74%	2.81%
Distribution losses	3.29%	3.09%	3.19%	2.69%
Final energy consumption	80.59%	77.47%	85.27%	80.90%
Final non-energy consumption	7.23%	3.32%	6.33%	5.84%
Positive net export balance	3.41%	8.06%	1.28%	5.03%
Statistical differences	0.60%	0.55%	0.14%	0.31%

Table 3 Primary energy requirements associated to total energy supply

Energy	Spain		EU28	
	1995	2017	1995	2017
Total Energy Supply (MTOE)	101.22	124.39	1,648.43	1,621.40
Solid fossil fuels	1.47%	0.45%	3.79%	1.75%
Manufactured gases	1.32%	0.70%	2.53%	1.47%
Peat and peat products	0.00%	0.00%	0.06%	0.03%
Oil shale and oil sands	0.00%	0.00%	0.01%	0.00%
Oil and petroleum products	49.99%	38.34%	34.73%	31.85%
Natural gas	6.86%	13.79%	15.88%	16.84%
Renewables and biofuels	3.22%	5.25%	2.69%	6.37%
Non-renewable waste	0.08%	0.01%	0.10%	0.25%
Nuclear heat	0.00%	0.00%	0.00%	0.00%
Heat	0.00%	0.00%	5.32%	5.38%
Electricity	37.06%	41.46%	34.89%	36.06%

to each energy product group (a compendium of similar energy products) contribute to the requirements stemming from the total energy supply, a magnitude reported in the energy balances published by Eurostat (2020c) which results from subtracting all energy consumption not directly related to the activity in the territory (i.e., energy consumption for international maritime bunkers and aviation and energy consumption to cover positive net export balances) from the total final energy demand.

Again, the estimation of the primary energy requirements associated to the total energy supply reveals a number that is equivalent to the magnitude reported in the energy balances published by Eurostat (2020c), which highlights the strength of our estimation approach. We can notice how the total energy supply has increased from 1995 to 2017 in Spain, while in the EU28 it not only has not been maintained, but has decreased. We also see how the primary energy needs associated with electricity have increased in both regions, accounting for a higher weight in Spain. At the same time,

Table 4 Primary energy requirements associated to final energy consumption

Sector	Spain		EU28	
	1995	2017	1995	2017
Total (MTOE)	88.36	116.3728	1,486.48	1,470.53
Agriculture	3.33%	2.77%	2.55%	2.27%
Industry	40.82%	33.63%	38.83%	32.85%
Commercial and public services	10.19%	18.18%	13.14%	16.99%
Households	16.37%	18.09%	26.27%	25.16%
Transport	29.29%	27.33%	19.20%	22.72%

we can see that derived heat does not represent a significant weight in Spain, while in the EU28 it has a not insignificant weight. Finally, we can show how the weight of the requirements derived from oil and petroleum products (which accounted for 50% of primary energy needs in Spain in 1995) and the weight associated to natural gas are evolving approaching European values (around 30% for oil products and in the region of 15% for natural gas). However, the weight of the oil derivatives is still relatively large in Spain in comparison with the EU28. Finally, as for the weight of renewable energies in the primary mix, it can be seen that Spain (which accounted for a greater presence of renewables than the EU28 in 1995) is experiencing a much weaker increase than the one observed in the EU28. Consequently, the EU28 has witnessed a greater decarbonization of its national primary mix than Spain from 1995 to 2007.

Further, by applying the K_{PEQ} elevation factor to the final energy consumption, we can compute the responsibility of each end-use sector in the primary energy requirements related to such final energy consumption. We should note that the final energy consumption has been corrected by the heating and cooling degree days of each region in order to make the quantities comparable across regions, i.e., quantities not reflecting asymmetric changes in weather conditions in both regions.

In Table 4, we can notice that the climate-adjusted primary energy requirements derived from final energy consumption increase by 31.7% in Spain from 1995 to 2017, while they remain unchanged in the EU28. The industry is the sector with the highest responsibility of primary energy needs both in Spain and in the EU28. The main differences across regions lie in (i) the household sector, with share of the primary energy requirements being much higher in the EU28 than in Spain, and in (ii) the transport sector, which is more relevant for the Spanish primary energy needs than for those of the EU28. Finally, the share attributed to commercial and public services grows to a greater extent in Spain than in the EU28.

4.2 Allocation of carbon dioxide emissions

Making use of the previous mapping scheme to assign responsibilities of primary energy requirements and the $K_{C,j}$ - $K_{C,\mathrm{SQ},j}$ elevation factors, the estimated energy-related CO_2 emissions derived from the total final energy demand (recall that it does not include only final energy consumption, but also other magnitudes) are shown

Table 5 Energy-related CO_2 emissions associated to total final energy demand

Concept	Spain		EU28	
	1995	2017	1995	2017
Final energy demand (Gg CO_2)	307.06	374.52	4720.11	4719.49
International maritime bunkers	3.29%	5.63%	2.33%	2.85%
International aviation	2.13%	3.57%	1.97%	3.30%
Distribution losses	2.51%	2.16%	2.70%	2.21%
Final energy consumption	79.55%	74.37%	84.54%	78.64%
Final non-energy consumption	7.98%	3.92%	6.94%	6.64%
Positive net export balance	3.78%	9.78%	1.46%	5.96%
Statistical differences	0.76%	0.57%	0.05%	0.40%

in Table 5. We find that the mentioned emissions have increased by 22% in Spain from 1995 to 2017, while they remain in the levels of 1995 in the EU28. We also detect that the emissions derived from final energy consumption account for the largest proportion of the total CO_2 emissions (around 80%), but this proportion has diminished in favor of the weight gained by the CO_2 emissions associated to energy consumption for international maritime bunkers, non-domestic aviation, and positive net export balances. This is an evolution that can be observed both in the EU28 and in Spain.

Moreover, applying our estimated $K_{C,\mathrm{SQ},j}$ elevation factor to the consumption of each energy product j, we can obtain the energy-related CO_2 emissions derived from each energy product in the final energy consumption, which has been adjusted by the heating and cooling degree days of each region in order to make the magnitudes comparable across regions. This is the reference magnitude to study the evolution of the emissions, since it does not incorporate the energy-related CO_2 emissions related to international energy activities, energy distribution losses and positive net energy export balances. In other words, this is the most appropriate magnitude because it solely reflects the energy-related CO_2 derived from national energy activities. For this purpose, we show in Table 6 how much the energy-related CO_2 emissions related to each energy product group (a compendium of similar energy products) contribute to the total energy-related CO_2 emissions stemming from the adjusted final energy consumption. Foremost, we should note that the estimation of the energy-related CO_2 emissions associated to final energy consumption reveals a number that is equivalent to the magnitude reported in the *Air Emission Accounts* published by Eurostat (2020a), which highlights the strength of our estimation approach.[38]

Further on, when reading Table 6 we realize that while the CO_2 emissions related to final energy consumption have increased by 16.2% from 1995 to 2017 in Spain, they have dropped by 7.4% in the EU28. We also observe how the CO_2 emissions associated with natural gas and renewables have increased in both regions (due to a higher use of these energy products), accounting both of them for a smaller weight in Spain than

38 The magnitude in the *Air Emission Accounts* published by Eurostat (2020a) that is equivalent or comparable with our estimate is the aggregate of the CO_2 emissions that takes into account all economic activities (including transport) and households.

Table 6 Energy-related CO_2 emissions associated to final energy consumption (I)

Energy	Spain		EU28	
	1995	2017	1995	2017
Final energy consumption (Gg CO_2)	241.13	280.09	4005.41	3710.42
Solid fossil fuels	2.46%	0.71%	6.19%	2.84%
Manufactured gases	2.22%	1.11%	3.85%	2.29%
Peat and peat products	0.00%	0.00%	0.11%	0.05%
Oil shale and oil sands	0.00%	0.00%	0.01%	0.00%
Oil and petroleum products	54.72%	46.99%	36.87%	35.36%
Natural gas	6.22%	13.59%	14.46%	15.97%
Renewables and biofuels	5.25%	7.32%	4.61%	9.23%
Non-renewable waste	0.20%	0.01%	0.24%	0.59%
Nuclear heat	0.00%	0.00%	0.00%	0.00%
Heat	0.00%	0.00%	6.90%	6.95%
Electricity	28.93%	30.27%	26.74%	26.72%

Table 7 Energy-related CO_2 emissions associated to final energy consumption (II)

Sector	Spain		EU28	
	1995	2017	1995	2017
Final energy consumption (Gg CO_2)	241.13	280.09	4005.41	3710.42
Agriculture	3.31%	3.00%	2.69%	2.38%
Industry	39.96%	32.12%	38.12%	31.94%
Commercial and public services	8.39%	13.98%	11.63%	13.79%
Households	15.75%	16.51%	26.04%	24.68%
Transport	32.59%	34.39%	21.53%	27.20%

in the EU28. At the same time, we can see that derived heat does not represent a significant weight in Spain, while in the EU28 it has a not insignificant relevance. Finally, we can discern how the weight of the CO_2 emissions derived from solid fossil fuels and oil and petroleum products is evolving in a downward direction, but being oil products still more relevant in Spain than in the EU28 in terms of associated CO_2 emissions.

From a different perspective, we can also compute the responsibility of each end-use sector in the energy-related CO_2 emissions associated to the weather-adjusted final energy consumption. In Table 7, we can notice that the industry was typically the sector with the highest CO_2 emissions both in Spain and in the EU28, but its prominent role has been decreasing and we encounter that the transport sector over-passed the weight of the industry in the energy-related CO_2 emissions attributable to the weather-adjusted final energy consumption in Spain. The transport sector has more relevance in Spain than in the EU28, despite the increase of its weight in the latter region. Finally, the share attributed to the commercial and public services has slightly

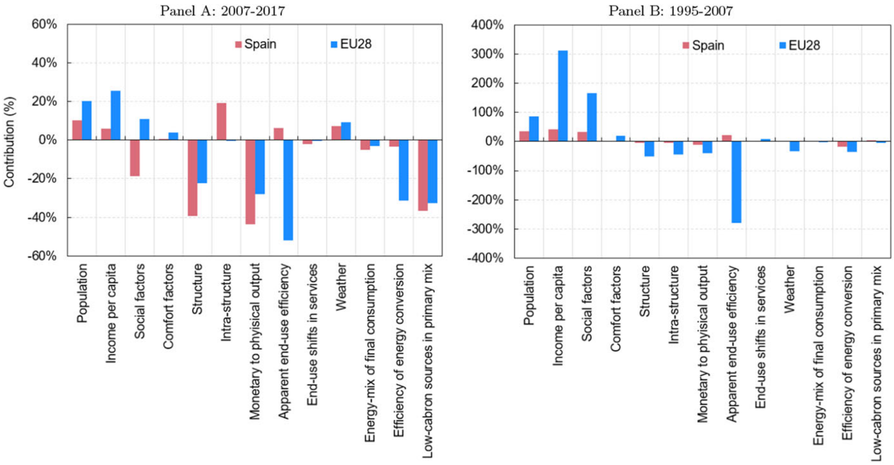

Fig. 5 Factor contributions to the total change in energy-related CO_2 emissions. *Note:* Positive contributions refer to an increase of the energy-related CO_2 emissions associated to the evolution of the factor. Negative contributions refer to a decrease of the energy-related CO_2 emissions associated to the evolution of the factor

increased both in Spain than in the EU28 from 1995 to 2017. The most noticeable differences between the two regions in terms of the sectoral structure of emissions are found in households (with a greater weight in the EU28) and in transport (with a larger share in Spain). This is clearly a result of the weather (Spanish households contributing less to emissions) and the systemic structure of transport (the main mode of transport in Spain is road transport, which is much more carbon-intensive).

4.3 Decomposition of the evolution of carbon dioxide emissions

After having over-viewed the general picture of the energy-related CO_2 emissions estimation, we move on to our decomposition analysis to identify what factors have been the most relevant influences underlying the observed evolution of said total energy-related CO_2 emissions (that shown in Fig. 2 of Sect. 1). To do this, we believe that it would be appropriate to divide our entire analysis period into two sub-periods determined by the outbreak of the 2007 crisis, i.e., we will have a sub-period 1995-2007 and another sub-period 2007–2017. Figure 5 shows the contributions (in %) of each of the thirteen influencing factors considered to the aggregate evolution of the CO_2 emissions associated with final energy consumption. In addition, Table 6 presents the actual evolution of the energy-related CO_2 jointly with the hypothetical evolution that such magnitude would have had if each contributing factor would have acted independently.

The CO_2 emissions associated with final energy consumption increased by 43% in Spain (from 241.12 Gg CO_2 to 345.07 Gg CO_2) and by 4% in the EU28 (from 4005.45

Gg CO_2 to 4171.02 Gg CO_2) from 1995 to 2007.[39] The population growth, a rising per capita disposable income and other social factors were the main drivers behind this development. These effects were much greater in the EU28 than in Spain (in both periods). These large effects in the EU28 reversed the very positive effect on emissions reduction that the increase in the apparent or observed energy efficiency of the end-use sectors had, resulting in an increase of the total emissions during the mentioned sub-period. However, this is not what can be observed in Spain, since despite the first factors mentioned above not contributing to the same extent as in the EU28 to the increase in emissions, the evolution of the apparent energy efficiency in the Spanish end-use sectors, unlike in the EU28, was driving further the increase in total emissions.

On the other hand, from 2007 to 2017 (the last year for which we have disaggregated data), CO_2 emissions associated with final energy consumption fell by 19% in Spain (from 345.07 Gg CO_2 to 280.10 Gg CO_2) and by 11% in the EU28 (from 4005.45 Gg CO_2 to 3710.51 Gg CO_2). At the EU28 level, this evolution is mainly determined by (i) the increase in the apparent end-use energy efficiency and in the improvement of the efficiency in the energy transformation sector (which means that less and less primary energy is required to produce the necessary energy demanded by the end-use sectors), (ii) the evolution of the productive structure toward sectors that generate fewer emissions, and by (iii) a lower use of fossil fuels for energy transformation. These factors offset the increases in emissions related to population growth, increased income and other social factors, resulting in a decrease in aggregate emissions. Spain has experienced a similar evolution, but the gains in the apparent end-use energy efficiency and in the efficiency of the energy conversion sector that can be observed in the EU28 are not detected in Spain. This means that the Spanish emissions have not been reduced from 2007 to 2017 as much as they could potentially have been if the same energy efficiency improvements (both in apparent end-use efficiency and in efficiency of the conversion sector) as in the EU28 had been observed in Spain. In Spain, the main factor behind the reduction of emissions is the economic structural transition toward less emission-generating sectors and its shift toward higher value products (captured by the monetary to physical output relation factor), changes that are not observed to the same extent in the EU28. Finally, we must note that the apparent energy efficiency is influenced by many factors and do not uniquely depend on the actual technical efficiency, hence we must be cautious when interpreting these results. A more detailed explanation in this regard will be presented in Sect. 4.7.

Analyzing these same developments from a sectoral perspective (see Fig. 7), we can note how the transport and services sectors were the main contributors to the increase in emissions that occurred from 1995 to 2007 in the EU28. In Spain, the transportation and the services sector, although to a lesser extent than in the EU28, also contributed to the increase in emissions. Contrarily, despite households and industrial sectors being an inhibitor of the increase in emissions in the EU28, they were a clear driving force of the Spanish emissions during said sub-period. However, during the sub-period 2007–2017, households and especially industry were clear inhibitors and led to a decline in emissions both in Spain and the EU28. In this latter sub-period, the transport sector

[39] Recall that these emissions are computed from a weather-adjusted magnitude. See Fig. 12 of Appendix to check the evolution of the weather factor, which seems to be an upward-driver of the emissions during the sub-period 2007–2017 and an inhibitor of emissions during the sub-period 1995–2007.

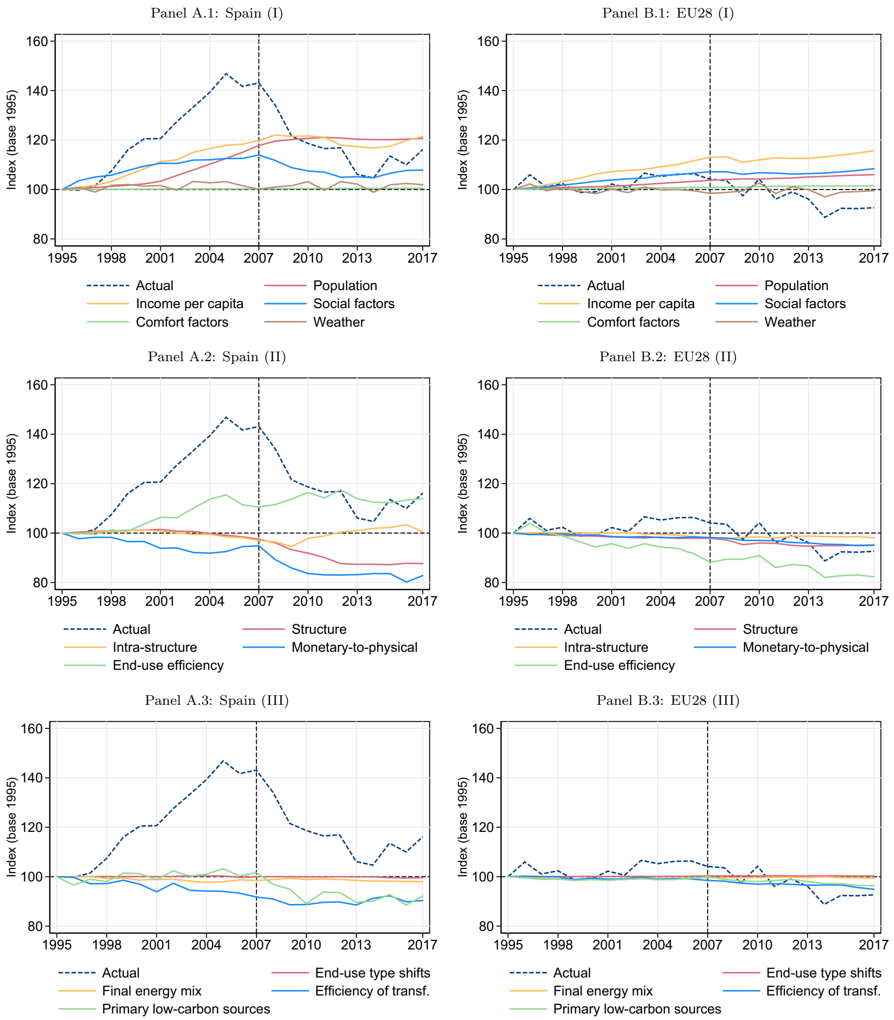

Fig. 6 Evolution of energy-related CO_2 emissions and contributors. *Note:* End-use efficiency refers to the apparent end-use efficiency

also contributed significantly to the fall in emissions, with this contribution being much greater in Spain than in the EU28.

It remains open and what is behind the evolution of each sector, whether structural changes, efficiency changes, final energy-mix, etc.. Thus, after the identification of the most influential factors and sectors in the evolution of the aggregate CO_2 emissions associated to the final energy consumption, we analyze in more detail each of them in the following Subsections.

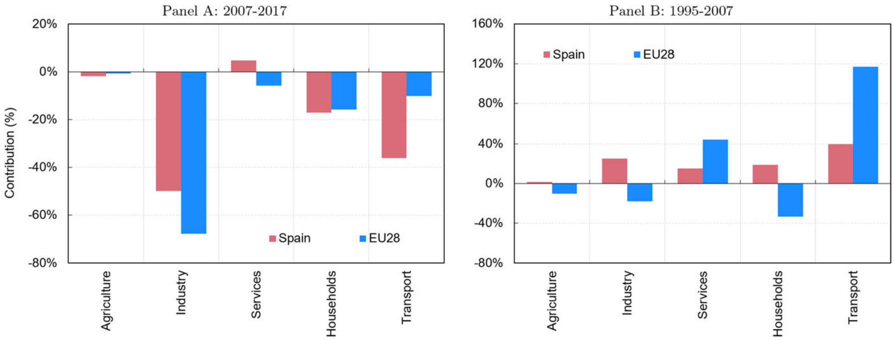

Fig. 7 Sectoral contributions to the total change in energy-related CO_2 emissions. *Note:* Positive contributions refer to an increase of the energy-related CO_2 emissions associated to the evolution of the factor. Negative contributions refer to a decrease of the energy-related CO_2 emissions associated to the evolution of the factor

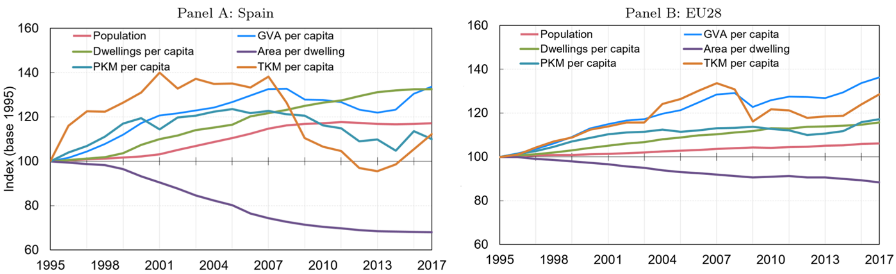

Fig. 8 Population, income and other social/comfort factors

4.4 Population, income and other social factors

We have previously shown in Fig. 5 that the effects of population growth, rising per capita disposable income and other social elements were emission-augmenting factors during both sub-periods considered in Spain and in the EU28. In Fig. 8 we can see how the population grew throughout the period considered, both in Spain and in the EU28, although it is true that this growth is slightly more pronounced in the Spanish case. Obviously, the larger the population, the greater the energy consumption and, consequently, the higher the energy-related emissions. Therefore, the population is a driving force for emissions throughout our period of analysis. When it comes to the GVA per capita, we can notice that it also experiences an upward trend if we analyze the beginning and the end of the period. However, it is true that there are a few years after the 2007 crisis (in Spain until 2014 and in the EU28 until 2009) for which the income per capita fell, which could make households and businesses consume slightly less energy during this sub-period, driving emissions down. But from an aggregate perspective in time, the GVA per capita emerges as a driver of emissions, since the higher the income per capita, the greater the energy consumption by the agents of the economy and the greater the consumption of other goods, which consequently increases the energy demand that is necessary to cover their production.

In terms of social factors, the number of dwellings per capita increased almost steadily throughout the period, which would lead to higher emissions. On the other hand, the comfort factor, which is measured by the area per dwelling, fell during the period analyzed, but this fall does not translate into a significant contribution to the decrease in emissions. Finally, other social factors such as per capita PKM and per capita TKM, which indicate how much we travel per capita or how much goods are moved per capita, are observed to have increased from 1995 to 2007. This means that, for this sub-period, as there is an increasing transit of people and goods, there is a higher energy consumption of transport, which leads to rising emissions, i.e., PKM and TKM per capita being an upward pressure on emissions. However, this trend ceases abruptly with the arrival of the 2007 crisis and, immediately afterwards, the PKM and TKM per capita fall (to a greater extent in the case of goods) for a few years until their posterior recovery, with the fall being much more pronounced and the recovery more delayed in Spain than in the EU28. This discrepancy between regions in the evolution of the aforementioned magnitudes derived from the impact of the 2007 crisis is the reason why, while the social factors were emission inhibitors in Spain during the 2007–2017 sub-period, they were emission driving forces in the EU28.

In aggregate, taking into account all population, income and social factors, we can say that all their related effects offset each other and give rise to a contribution to the emissions that make them increase. In other words, the conglomerate of these factors could be considered as an emission-generating element.

4.5 Economic structure

As we have clearly shown in Fig. 5, the economic structure factor is an inhibitor of energy-related CO_2 emissions for both sub-periods of analysis. The logic behind this result is that the economic structure of both Spain and the EU28 (economically advanced regions) has undergone a process of tertiarization. This mentioned process can be evidently characterized by the changes in the different sectoral shares observed in Table 8. In this Table, the sub-sector shares refer to the weight that each sub-sector has in its particular sector. Analogously, the sector shares refer to the weight that each sector has in the total production. It can be noticed how the industry (a traditionally emission-generating sector) has decreased its weight in favor of the commercial and public services. In this way, activities requiring less energy needs have become more relevant, which leads to a reduction in emissions.

By reading this Table 8 we can also explain why the intra-structural factor is an emission-driving force in Spain for the 2007–2017 sub-period, while in the EU28 this factor drives the pressure down. Within industry (or in the intra-industrial structure), the activities of the energy sector and the extractive industries have increased their share of the total industrial GVA in Spain, while they have reduced it in the EU28. These industries are traditionally very energy-intensive, and therefore very emission-intensive. Hence, as their weight within the industry increases, the intra-structural factor becomes an upward-pressure on emissions for the Spanish case.

Table 8 GVA share

Sector	Spain			EU28		
	1995	2007	2017	1995	2007	2017
Agriculture	2.87%	2.72%	2.93%	1.86%	1.54%	1.56%
Agriculture and forestry	88.31%	94.47%	95.23%	95.06%	96.39%	96.80%
Fishing	11.69%	5.53%	4.77%	4.94%	3.61%	3.20%
Industry	29.05%	27.14%	20.83%	27.03%	25.17%	23.05%
Energy sector and extractive industries	10.47%	10.94%	15.39%	13.60%	11.56%	11.09%
Food, beverages and tobacco	11.32%	10.75%	12.18%	8.92%	8.17%	8.76%
Textile and leather	3.92%	3.42%	4.26%	4.11%	2.65%	2.27%
Wood and wood products	1.32%	1.19%	0.87%	1.38%	1.37%	1.22%
Paper, pulp and print	3.17%	3.01%	2.62%	2.96%	2.72%	2.60%
Chemical and petrochemical	6.22%	5.67%	7.21%	6.93%	8.17%	8.68%
Non-metallic minerals	3.88%	3.59%	2.45%	2.74%	2.65%	2.35%
Basic metals	1.70%	1.37%	2.13%	2.45%	2.09%	2.25%
Machinery	11.08%	12.17%	11.62%	16.87%	20.38%	20.90%
Transport equipment	5.91%	5.89%	7.49%	6.26%	7.78%	10.43%
Other industries	4.78%	4.80%	4.91%	5.84%	6.14%	6.28%
Construction	36.22%	37.20%	28.87%	27.95%	26.33%	23.16%
Commercial and public services	68.09%	70.14%	76.25%	71.11%	73.20%	75.36%

Activities of households as employers (with NACE code T) is the only economic activity group with no match in our scheme and therefore its value added (0.9% of the total in 2017 for Spain) is not included in this table

4.6 Transport sector composition

Performing an analogous exercise to the one carried out on the GVA shares in the previous Subsection, we analyze in Table 9 what the compositional change of the transport sector has been during our analysis period. It should be recalled that modal shifts in the transport sector are included within the contribution of the structural factor to the evolution of emissions, although it is true that changes in the economic structure play a more significant role in the structural factor than what the change in the modal composition of transport plays.

We must recall from Fig. 7 that the transport sector affects the change in aggregate emissions in an augmenting manner during the 1995–2007 sub-period and in a downward way during the 2007–2017 sub-period. This is perfectly consistent with what we learn from Table 9. During the 1995–2007 sub-period, there is an increase in the share of aviation (for passengers) and road transport (for goods), which are typically energy- and emission-intensive transport modes, hence inducing an upward pressure on emissions both in Spain and in the EU28. On the other hand, during the 2007–2017 sub-period, the share of rail transport for passengers increased both in Spain and in the EU28, and since this is a more energy-efficient mode, it leads to downward pressure on emissions.

Table 9 Transport mode composition

Mode	Spain			EU28		
	1995	2007	2017	1995	2007	2017
Passenger transport (% of total PKM)						
Road	90.17%	88.57%	87.37%	90.41%	89.84%	89.04%
Rail	6.37%	6.14%	8.05%	8.52%	8.62%	9.49%
Aviation	3.46%	5.29%	4.58%	1.06%	1.55%	1.46%
Freight transport (% of total TKM)						
Road	80.66%	84.26%	80.76%	67.34%	72.61%	73.54%
Rail	3.95%	2.68%	3.03%	20.28%	17.05%	16.11%
Navigation	13.16%	10.92%	13.42%	6.38%	5.49%	5.64%
Pipeline	2.23%	2.14%	2.80%	6.00%	4.85%	4.71%

4.7 End-use energy efficiency

Consistently with Fig. 5, the influence of the apparent or observed end-use energy efficiency on emissions is one of the major differences between the EU28 and Spain. While in the EU28 the apparent end-use energy efficiency (measured as energy unit consumption, i.e., final energy consumption per physical output/item) is increasing throughout the period under consideration, and is a major inhibitor of emissions, in Spain such apparent efficiency has not improved at all (for any of the sub-periods), which means that emissions are not reduced in Spain as much as they could have been if an apparent end-use efficiency trend such as that observed in the EU28 had been observed.

However, as discussed previously in Sect. 2.5, there are many driving forces driving the apparent energy end-use efficiency from behind. One must note that the observed physical or apparent end-use energy efficiency need not be an accurate measure of the actual technological progress. Therefore, as discussed in Sect. 3.4, it is necessary to discern between what is actually driving the apparent or observed energy efficiency. And to do so, we subject such observed or apparent end-use energy efficiency to a further decomposition and we examine the role played by (1) technical energy efficiency or actual energy savings, (2) rebound effects, and (3) other factors (where the infra-utilization of the installed energy equipment can be a key contributor) in its developments.

Firstly, on the basis of the technical end-use energy efficiency indexes calculated in Sect. 3.4 and the rebound effect estimates of Adetutu et al. (2016), we can analyze the aggregate evolution of the apparent end-use energy efficiency both in Spain and in the EU28 and discover which components are effectively driving this evolution.

What we can observe in Fig. 9 is that, while the apparent or observed end-use energy efficiency has decreased notably in Spain, it has increased considerably in the EU28 from 1995 to 2017. One could think that the EU28 is becoming more energy-efficient than Spain, but this is completely misleading. What we observe is that end-use technical energy efficiency has improved steadily even more in Spain than in the EU28

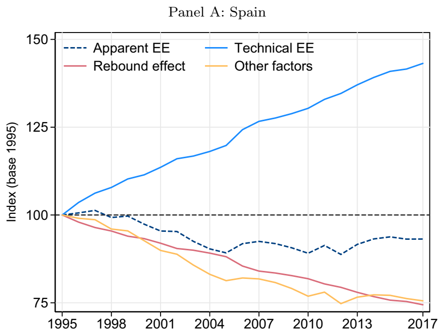

Fig. 9 Contributors to aggregate apparent end-use energy efficiency

as a whole. So what could be making apparent energy efficiency decrease in Spain and increase in the EU28? Our simplest explanation is that this difference is due to a greater infra-utilization of energy equipment installed in Spain, among other factors. Although the observed rebound effect is a somewhat more negative influence in Spain than in the EU28, what really differentiates these regions in their apparent energy efficiency are other factors.[40] Decreases of the apparent energy efficiency that cannot be explained by rebound effects may be due to an inefficient use of the equipment, as it is often observed during economic recessions. This is consistent with the Ministerio de Turismo, Energía y Agenda Digital (2017). They state that, the energy consumption of does not decrease proportionally to the activity in Spain as the observed efficiency of most equipment drops, as they are not used at their maximum rated capacity. It means that part of its energy consumption is independent of the production level. This is why we believe that infra-utilization is a key component of the other-factors contributor, although we cannot state it with certainty since we cannot decompose further said contributor. On the other hand, it can be seen that the influence of other factors on the evolution of apparent energy efficiency is not only non-negative in the EU28, but contributes positively to this evolution. However, we are not able with our analysis to discern what these other possible factors might be.

This makes the Spanish case particular in terms of observed energy efficiency. That is why, since we have more disaggregated data for Spain on the basis of the study by Peña-Vidondo et al. (2012), we analyze which sectors of the economy would be conducting the evolution of end-use energy efficiency, both apparent and technical. In Fig. 10, we can observe the index-points change in the apparent end-use energy efficiency of each sector that is attributed to each factor.

It can be seen that the apparent energy efficiency fell in all sectors in Spain during the period 1995–2007, this fall being especially accentuated in the agricultural and services sectors, with decreases in the apparent energy efficiency of 23 and 18 index points, respectively. However, technical efficiency increased in all sectors. But rebound effects and other factors (mainly, the infra-utilization of energy equipment) lead to a decrease in apparent efficiency, with the influence of these other factors being especially relevant in the agricultural and household sectors. Nevertheless, households are the only ones

40 Rebound effect estimates by Adetutu et al. (2016) for Spain and the EU are around 60% during the whole period of analysis.

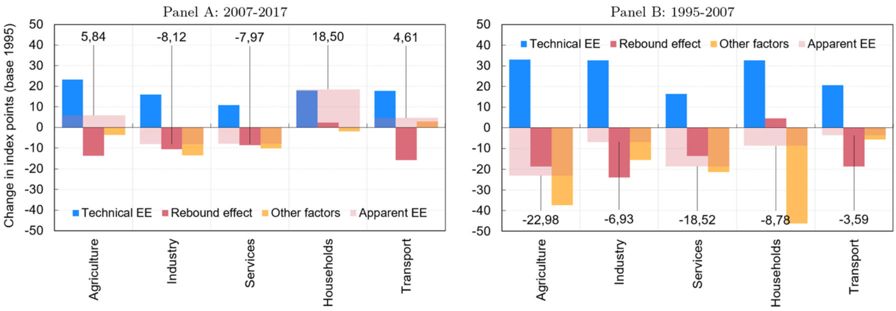

Fig. 10 Contributors to sectoral apparent end-use energy efficiency in Spain

that present a backfire effect, which makes their apparent efficiency losses much lower than, for example, in the case of agriculture. It can also be noted that where there was less infra-utilization was in the industry and transport sectors, but these sectors suffered greater rebound effects.

On the other hand, in the period 2007–2017, the narrative changes. Here, sectors such as agriculture, households or transport experience an increase in their technical efficiency that compensates for the negative effects derived from rebound effects and other factors and leads to increases in their apparent end-use energy efficiency indexes. However, sectors such as industry or the services sector suffer so much from the infra-utilization of equipment caused by the 2007 crisis that they witness how their apparent energy efficiency diminishes despite great advances in their technical efficiency.

After this analysis, we have ascertained what is effectively driving the evolution of the apparent end-use energy efficiency in Spain. However, this does not mean that the apparent efficiency does not need to be taken into account. It is true that apparent efficiency cannot serve us as a proxy for technical energy efficiency due to the reasons previously stated, but this does not imply that the indicators of apparent energy efficiency of the end-use sectors are not relevant anymore. In fact, they are the clearest indicator for policy-makers of where to put the focus when it comes to developing energy efficiency policies or measures. Therefore, an in-depth analysis of this apparent end-use energy efficiency at the sector and sub-sector level is necessary. To this end, we show in Fig. 11 the sectoral sub-drivers underlying the evolution of the aggregate energy efficiency.

For the sub-period 1995–2007, some industrial sub-sectors (basic metals, chemical, and food industries) and freight transportation (especially, the navigation transport mode) are identified as the only players whose improvement in apparent end-use energy efficiency contributes to pushing the emissions down in Spain. When it comes to the EU28 sphere, the economic sectors (especially the chemical industries and the basic metals sub-sector) and households (especially in the use of space heating) were the main performers in downward-pushing the CO_2 emissions due to an apparent energy efficiency improvement. However, these good-performing sectors for the European case not only fail to show an apparent end-use efficiency improvement in Spain, but also worsen it. More specifically, the space heating use by households, the services sector, the road transport of passengers and many industrial sub-sectors (especially the energy and mining industries) were the main protagonists in the apparent end-use

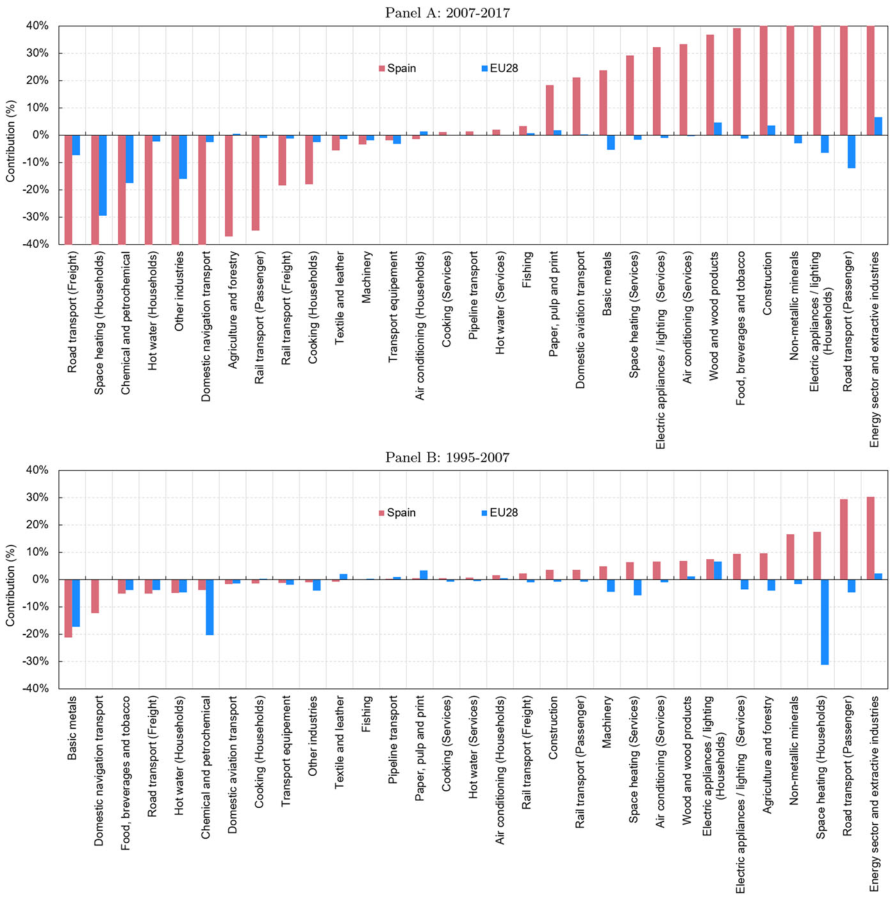

Fig. 11 Sub-sectoral contributions to the apparent end-use energy efficiency. *Note:* Positive contributions refer to an upward pressure of the apparent end-use energy efficiency on the energy-related CO_2 emissions. Negative contributions refer to a downward pressure of the apparent end-use energy efficiency on the energy-related CO_2 emissions. Factors are sorted by contribution to the Spanish apparent energy efficiency contributing factor. There are some contributions in the period 2007-2017 that are greater than 40% (indeed, they are of the order of 200-300%) but the Panel A graph is limited to this region for a better visualization

energy efficiency developments observed in Spain, which not only did not experience an improvement, but also showed a considerable worsening during this sub-period, leading consequently to an increase in emissions.

Looking now at the sub-period 2007–2017, we can observe how the sub-sectors that contribute most to the reduction of emissions in Spain through the channel of improving apparent end-use energy efficiency are: freight transport (especially the road mode), space heating and hot water uses by households, the industrial chemical sub-sector and other industrial sub-sectors. Similar trends can also be observed at the European level, even to a greater extent in the uses of households. Further, passenger road transport, electric appliances in households and space heating use by the services sector must be added to the list of apparent end-use efficiency enhancers at the EU28 level. All this means that, at an aggregate level, the EU28 is experiencing an improvement in the aggregate apparent end-use energy efficiency that makes such efficiency a clear inhibitor of emissions. However, despite the improvements in apparent energy efficiency in some sub-sectors in Spain, there are many other sectors that are experiencing a deep worsening of apparent end-use efficiency. These bad actors in terms of apparent end-use energy efficiency are the energy and mining industry, the road passenger transport, the lighting use by households, the construction sector, and, to a lesser extent, the services sector and other industrial sub-sectors. The poor performance of these latter actors imply that the end-use energy efficiency at the aggregate level is an upward pressure on CO_2 emissions in Spain.

Finally, it is worth remembering that the 2007 crisis hit these economies very severely, but even more so the Spanish economy. This could lead us to believe that many of the worsening of apparent end-use energy efficiency observed in the 2007-2017 sub-period may result from an inefficient use of the production equipment, as previously discussed. For this reason, more disaggregated data at the sub-sector level is needed to separate technical energy efficiency from apparent (or observed) energy efficiency. At this level of sub-sectoral disaggregation, despite the relevance of this matter, our analysis is only able to monitor changes in apparent energy efficiency (or physical intensity).

4.8 Transformation sector

Recalling from Fig. 5, we have shown that (1) the efficiency of the energy conversion sector (measured through changes in the Leontief inverse matrix) and (2) the use of low-carbon primary sources as transformation inputs for this sector are inhibiting factors of the observed energy-related CO_2 emissions.

First, to show the efficiency improvement of the conversion sector, we display the $K_{PEQ,j}$ conversion factor of the main energy products in Spain and the EU28 in Table 10 for the beginning and the end of our period of analysis, 1995 and 2017, respectively.[41] For instance, to make available one unit of electricity in Spain, 2.57 units of primary energy were needed in 1995, while in 2017 the number decreased to 2.13 units. These estimated primary energy quantity conversion factors for electricity are in line with those estimated by the European Comission (2016). In addition, from this Table we can also read that from 1995 to 2017 the weight of oil products, solid fossil fuels, and nuclear heat in the primary energy needs for electricity generation declined in favor of renewable primary sources and natural gas, being this change more pronounced in Spain than in the EU28. On the other hand, heat is another type of final energy that typically requires a large quantity of primary energy, although it is also true that in Spain this type of energy is not consumed. To make a heat energy unit available in the EU28, 1.62 units of primary energy were needed in 1995, while in 2017 that number dropped to 1.49 units. Finally, it should be noted that other final energy products widely consumed both in the EU28 and in Spain, such as primary solid biofuels or natural gas, do not require an additional quantity of primary energy

[41] The mentioned main energy products are those involving more primary energy requirements in both Spain and the EU28.

Table 10 K_{PEQ} of main energy products

Region	$K_{PEQ,j}$ and its structure	Final energy type											
		Electricity		Heat		Solid biofuels		Natural gas		Diesel		Gasoline	
		1995	2017	1995	2017	1995	2017	1995	2017	1995	2017	1995	2017
Spain	$K_{\text{PEQ},j}$	2.57	2.13	–	–	1.00	1.00	1.00	1.00	1.04	1.00	1.04	1.00
	Solid fossil fuels	42.3%	22.6%	–	–	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Oil and petroleum	10.2%	6.3%	–	–	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	Natural Gas	2.0%	19.2%	–	–	0.0%	0.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%
	Renewables	6.0%	20.5%	–	–	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Nuclear	38.1%	29.3%	–	–	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Other	1.4%	2.0%	–	–	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EU28	K_{PEQ}	2.46	2.09	1.62	1.49	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.02
	Solid fossil fuels	36.7%	25.0%	51.8%	34.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Oil and petroleum	8.6%	2.2%	12.7%	4.1%	0.0%	0.0%	0.0%	0.0%	100.0%	99.8%	100.0%	99.7%
	Natural Gas	8.3%	16.0%	23.3%	34.1%	0.0%	0.0%	100.0%	99.8%	0.0%	0.2%	0.0%	0.2%
	Renewables	6.4%	19.0%	4.0%	20.7%	100.0%	100.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	Nuclear	38.8%	35.7%	4.6%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Other	1.3%	2.1%	3.6%	4.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 11 K_C and $K_{C,SQ}$ of main energy products

Region	$K_{C,\mathrm{SQ},j}$ and its structure	Final energy type											
		Electricity		Heat		Solid biofuels		Natural gas		Diesel		Gasoline	
		1995	2017	1995	2017	1995	2017	1995	2017	1995	2017	1995	2017
Spain	$K_{C,j}$ (Mt-CO_2/KTOE)	2.09	1.70	–	–	4.19	4.19	2.35	2.35	3.07	3.07	3.07	3.07
	$K_{C,\mathrm{SQ},j}$ (Mt-CO_2/KTOE)	5.38	3.62	–	–	4.19	4.19	2.35	2.35	3.19	3.04	3.21	3.06
	Solid fossil fuels	80.9%	52.9%	–	–	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Oil and petroleum	14.9%	11.5%	–	–	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	Natural Gas	2.3%	26.6%	–	–	0.0%	0.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%
	Renewables	1.1%	7.9%	–	–	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Other	0.8%	1.1%	–	–	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EU28	$K_{C,j}$ (Mt-CO_2/KTOE)	2.03	1.77	3.35	3.29	4.19	4.19	2.35	2.35	3.08	3.08	3.07	3.07
	$K_{C,\mathrm{SQ},j}$ (Mt-CO_2/KTOE)	4.97	3.70	5.42	4.92	4.19	4.19	2.35	2.35	3.06	3.08	3.11	3.14
	Solid fossil fuels	73.4%	57.4%	62.5%	43.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Oil and petroleum	13.1%	3.9%	11.7%	3.8%	0.0%	0.0%	0.0%	0.0%	100.0%	99.8%	100.0%	99.8%
	Natural Gas	9.6%	21.2%	16.3%	24.4%	0.0%	0.0%	100.0%	99.8%	0.0%	0.1%	0.0%	0.2%
	Renewables	1.6%	12.8%	4.9%	23.2%	100.0%	100.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
	Other	2.2%	4.6%	4.7%	5.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

resources to make them available and fuels like gasoline or diesel are in the vicinity of a K_{PEQ} with value 1 as well. This reinforces the idea of a conversion sector experiencing efficiency improvements and leading emissions to fall both in Spain and in the EU28, as, over the years, it has been realized that this sector needs less primary energy to produce the same quantity of final energy.

Lastly, we use the $K_{C,j}$ and the $K_{C,SQ,j}$ factors of the main energy products to present in Table 11 the evolution of the primary carbon dioxide emission factor in Spain and the EU28 for the beginning and the end of our period of analysis, 1995 and 2017, respectively.[42] For instance, while the consumption of 1 KTOE of electricity by the end-use sectors represented a CO_2 emission of 5.3 megatons in 1995, in 2017 the amount dropped to 3.62 megatons of CO_2 per KTOE due to a more low-carbon-oriented primary energy-mix of the conversion sector. On the other hand, this same value decreased from 4.97 to 3.70 in the EU28. This is a smaller reduction than that observed in Spain, resulting in slightly cleaner electricity in Spain than in the EU28 in 2017. This is the a consequence of an less dependent electricity on fossil fuels and petroleum products in favor of a higher share of natural gas an renewables in the power generation. The mentioned reduction of the fossil fuels weight in the electricity generation was larger in Spain than in the EU28, which explains the observed smaller $K_{C,SQ,j}$ of electricity in Spain. We find that other secondary energy products (as diesel or gasoline) that emit a relevant quantity of CO_2 (in part, because they are the most used) have not changed much in their primary carbon dioxide emission factor. We also observe how derived heat, a product that is not used in Spain, has a very high $K_{C,SQ,j}$ in the EU28, but has decreased greatly from 1995 to 2017. Finally, it can be shown how the $K_{C,j}$ and the $K_{C,SQ,j}$ factors report the same value primary energy products (which are also consumed as end-use energy products) are considered. This Table rationalizes the downward-pressuring contribution made by the primary energy mix utilized by the conversion sector to the observed energy-related CO_2 emission evolution.

5 Concluding remarks

In order to support the most appropriate energy policy decisions, an analytical method to jointly understand the driving forces behind the observed developments of (1) the energy-related CO_2 emissions, (2) the energy consumption and (3) the energy efficiency (the three magnitudes for which the main energy and climate targets are defined) is irremediably needed. In this paper, we develop a methodological framework to investigate the contributions of various influencing factors to the evolution of the energy-related CO_2 emissions between 1995 and 2017 both in Spain and in the EU28. In this way, within one comprehensive methodological framework, we are able to capture the role played by primary energy consumption and the renewable-energy share of the energy-mix in the developments of the energy-related CO_2 emissions.

In addition, the decomposition method that we propose takes into account jointly the effects that (1) the technical aspects of the physical energy system (analyzed through energy input–output models) and (2) the macro-level influencing factors traditionally

[42] In this case, we understand as the main primary energy products those energy products that provoke the highest estimated energy-related CO_2 emissions in both regions.

employed (studied through IDA decomposition methods) have in the evolution of the energy-related CO_2 emissions both in Spain and in the EU28. Thus, we refer to this hybrid integrated approach, which benefits from the advantages of both SDA and IDA techniques, as *input–output logarithmic mean Divisia index* (IO-LMDI, hereafter) decomposition method. Further, with our methodological approach, we also provide an allocation diagram scheme for assigning the responsibility of primary energy requirements and CO_2 emissions to the end-use sectors including both economic and non-productive sectors. Moreover, we are able to (3) analyze more potential influencing factors than those typically examined. In addition, we (4) proceed in a way that reconciles energy intensity and energy efficiency metrics. Finally, we (5) distinguish between technical and observed end-use energy efficiency taking into account potential rebound effects and other factors. Therefore, we believe that our work represents a novelty and offers clear value added to past studies devoted to the study of the energy-related CO_2 emissions trends both in Spain and in the EU28.

To report of our findings, we make a distinction between two clear sub-periods: 1995-2007 and 2007-2017. In the first mentioned sub-period, the CO_2 emissions associated with final energy consumption increased by 43% in Spain (from 241.12 Gg CO_2 to 345.07 Gg CO_2) and by 4% in the EU28 (from 4005.45 Gg CO_2 to 4171.02 Gg CO_2). The population growth, a rising per capita disposable income and other social factors were the main drivers behind this development. These effects were much greater in the EU28 than in Spain. These large effects in the EU28 reversed the very positive effect on emissions reduction that the increase in apparent or observed energy efficiency of the end-use sectors had, resulting in an increase of the total emissions during the mentioned sub-period. However, this is not what can be observed in Spain, since although the first factors mentioned above did not contribute to the same extent as in the EU28 to the increase in emissions, the evolution of apparent end-use energy efficiency in the Spanish end-use sectors, unlike in the EU28, was driving further the increase in total emissions. Nevertheless, we cannot say that Spain experienced a decrease in its technical end-use energy-efficiency. Indeed, Spain witnessed an increase in such technical end-use energy efficiency. However, the infra-utilization of the installed energy equipment and the rebound effects drove down the apparent or observed end-use energy efficiency.

On the other hand, from 2007 to 2017, the CO_2 emissions associated with final energy consumption fell by 19% in Spain (from 345.07 Gg CO_2 to 280.10 Gg CO_2) and by 11% in the EU28 (from 4005.45 Gg CO_2 to 3710.51 Gg CO_2). At the EU28 level, this evolution is mainly determined by the increase in energy efficiency both in final consumption (apparent end-use efficiency) and in the energy transformation sector (which means that less and less primary energy is required to produce the necessary energy demanded by the end-use sectors), by the evolution of the productive structure toward sectors that generate fewer emissions, and by a lower use of fossil fuels for energy transformation. These factors offset the increases in emissions related to population growth, increased income and other social factors, resulting in a decrease in aggregate emissions. Spain has experienced a similar evolution, but the gains in apparent end-use energy efficiency in both final consumption and energy transformation that can be observed in the EU28 are not detected in Spain. This means that the Spanish emissions have not been reduced from 2007 to 2017 as much as they could potentially have been if the same apparent end-use energy efficiency improvements as in the EU28 had been observed in Spain. In Spain, the main factor behind the reduction of emissions is the economic structural transition toward less emission-generating sectors and its shift toward higher value products (captured by the monetary to physical output relation factor), changes that are not observed to the same extent in the EU28. However, as in the previous sub-period, the infra-utilization of the installed energy equipment (mainly in industrial and services sectors) and the rebound effects drove down the apparent or observed end-use energy efficiency resulting in an increase of the CO_2 emissions associated with final energy consumption.

Analyzing these same developments from a sectoral perspective (see Fig. 7), we can note how the transport and services sectors were the main contributors to the increase in emissions that occurred from 1995 to 2007 in the EU28. In Spain, the transportation and the services sector, although to a lesser extent than in the EU28, also contributed to the increase in emissions. Contrarily, despite households and industrial sectors being an inhibitor of the increase in emissions in the EU28, they were a clear driving force of the Spanish emissions during said sub-period. However, during the sub-period 2007–2017, households and especially industry were clear inhibitors and led to a decline in emissions both in Spain and the EU28. In this latter sub-period, the transport sector also contributed significantly to the fall in emissions, with this contribution being much greater in Spain than in the EU28.

As a final conclusion we can say that Spain is on a path toward the decarbonization of the economy. However, despite the fact that this trend is more accentuated than in the EU28, there is still much to be done in order to reverse the huge increases in emissions that occurred in the period of time prior to the 2007 crisis. Furthermore, we can state that the technical energy efficiency of the Spanish economy is improving even more than that of the EU28, although all these gains are exceeded by the losses that the country suffers due to the installation of energy equipment above its potential. That is, there is an energy infrastructure that does not yield its maximum potential, but which has very high fixed energy costs that reduce the observed energy efficiency and puts at risk the achievement of the emissions and energy consumption targets set by the European institutions.

The results that we present give interesting information related to the drivers and inhibitors of the energy-related CO_2 emissions both in Spain and in the European economy as a whole. These results are useful not only for researchers, but also for private utility companies and policy-makers, as they can contribute to construct and implement the optimal saving and efficiency measures to achieve the mentioned climate and energy targets.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Compliance with ethical standards

Conflict of interest This article is entirely the author’s own work and no sources or aids other than the ones listed have been employed. This article has not been published before and it is not under consideration for publication anywhere else. The author declares that he has no conflict of interest.

Informed consent This article does not contain any information that requires informed consent.

Human and animal rights This article does not contain any studies with human participants or animals performed by the author.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Appendix

See Tables 12, 13, 14, 15, 16 and Fig. 12

Table 12 Example of energy input–output table

		$Q_{i,j}$										Mar_i	Av_i	FEC_i	$FNEC_i$	DL_i	$Diff_i$	Exp_i	Y_i	Q_i (demand)
		1	2	3	4	5	6	7	8	8+1	8+2									
Coal and coal products	1	0.5	0	0	1.2	0	0	0	0	0	0	0	0	1	0.1	0	0	1	2.1	3.8
Crude, LNG and raw materials	2	0	0.3	12.3	0	0	0	0	0	0	0	0.1	0	0	0.2	0	0	0	0.3	12.9
Oil derivatives	3	0	0	0.4	0.1	0	0	0	0	0	0	0.3	0.2	16	0.1	0.1	0	0	16.7	17.2
Electricity	4	0	0	0	0.7	0	0	0	0	0	0	0	0	6	0	1	0	0	7	7.7
Hydroelectric power	5	0	0	0	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.2
Renewables	6	0	0	0.1	0.2	0	0.1	0	0	0	0	0	0	3	0	0	0	1.5	4.5	4.9
Natural gas	7	0	0	0	2.9	0	0	1.1	0	0	0	0	0	12	0	0	0	0	12	16
Nuclear	8	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1	1.4
Refined oil imports	8+1	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
Electricity imports	8+2	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
Primary production $_j$	–	3	9.6	0	0	3.2	4.9	10	1.3	0	0	–	–	–	–	–	–		–	32
Recycled and recovered $_j$	–	0.5	0.1	0	0	0	0	0	0	0	0	–	–	–	–	–	–	–	–	0.6
Stock change $_j$	–	0	0.2	−0.4	0	0	0	0	0	0	0	–	–	–	–	–	–	–	–	−0.2
Transformation output $_j$	–	0.3	1	17.4	7.4	0	0	0	0	0	0	–	–	–	–	–	–	–	–	26.1
Positive net import balance $_j$	–	0	2	0.2	0.3	0	0	6	0.1	0.2	0.3	–	–	–	–	–	–	–	–	9.1
Q_j (supply)	–	3.8	12.9	17.2	7.7	3.2	4.9	16	1.4	0.2	0.3	–		–	–	–	–	–	–	67.6

Q_i denotes the total energy needs of energy i, $Q_{i,j}$ denotes the intermediate consumption of each energy i to produce energy j, Mar_i denotes the consumption of energy i for international maritime bunkers, Av_i denotes the consumption of energy i for international aviation, FEC_i denotes the final consumption of energy i (including final consumption of the energy branch), FNEC_i denotes the final non-energy consumption of energy i, DL_i denotes the distribution losses of energy i, Diff_i denotes the statistical difference between Q_i calculated from the supply side and Q_i calculated from the demand side, Exp_i denotes the positive net export balance of energy i, and Y_i denotes the final demand of energy i

Table 13 List of energy products and their carbon content

i	Product	Group	v_i
1	Anthracite	Solid fossil fuels	26.8
2	Coking coal	Solid fossil fuels	25.8
3	Other bituminous coal	Solid fossil fuels	25.8
4	Sub-bituminous coal	Solid fossil fuels	26.2
5	Lignite	Solid fossil fuels	27.5
6	Patent fuel	Solid fossil fuels	26.6
7	Coke oven coke	Solid fossil fuels	29.2
8	Gas coke	Solid fossil fuels	29.2
9	Coal tar	Solid fossil fuels	22.0
10	Brown coal briquettes	Solid fossil fuels	26.6
11	Gas works gas	Manufactured gases	12.1
12	Coke oven gas	Manufactured gases	12.1
13	Blast furnace gas	Manufactured gases	70.9
14	Other recovered gases	Manufactured gases	14.9
15	Peat	Peat and peat products	28.9
16	Peat products	Peat and peat products	28.9
17	Oil shale and oil sands	Oil shale and oil sands	24.6
18	Crude oil	Oil and petroleum products	20.0
19	Natural gas liquids	Oil and petroleum products	17.5
20	Refinery feedstocks	Oil and petroleum products	20.0
21	Additives and oxygenates	Oil and petroleum products	49.6
22	Other hydrocarbons	Oil and petroleum products	21.0
23	Refinery gas	Oil and petroleum products	15.7
24	Ethane	Oil and petroleum products	16.8
25	Liquefied petroleum gases	Oil and petroleum products	17.2
26	Motor gasoline	Oil and petroleum products	18.9
27	Aviation gasoline	Oil and petroleum products	19.1
28	Gasoline-type jet fuel	Oil and petroleum products	19.1
29	Kerosene-type jet fuel	Oil and petroleum products	19.5
30	Other kerosene	Oil and petroleum products	19.6
31	Naphtha	Oil and petroleum products	20.0
32	Gas oil and diesel oil	Oil and petroleum products	20.2
33	Fuel oil	Oil and petroleum products	21.1
34	White spirit	Oil and petroleum products	20.0
35	Lubricants	Oil and petroleum products	20.0
36	Bitumen	Oil and petroleum products	22.0
37	Petroleum coke	Oil and petroleum products	26.6
38	Paraffin waxes	Oil and petroleum products	20.0
39	Other oil products n.e.c.	Oil and petroleum products	20.0
40	Natural gas	Natural gas	15.3

Table 13 continued

i	Product	Group	v_i
41	Hydro	Renewables and biofuels	0.0
42	Tide, wave, ocean	Renewables and biofuels	0.0
43	Wind	Renewables and biofuels	0.0
44	Solar photovoltaic	Renewables and biofuels	0.0
45	Solar thermal	Renewables and biofuels	0.0
46	Geothermal	Renewables and biofuels	0.0
47	Primary solid biofuels	Renewables and biofuels	27.9
48	Charcoal	Renewables and biofuels	30.5
49	Biogases	Renewables and biofuels	14.9
50	Renewable municipal waste	Renewables and biofuels	27.3
51	Pure biogasoline	Renewables and biofuels	19.3
52	Blended biogasoline	Renewables and biofuels	18.9
53	Pure biodiesels	Renewables and biofuels	19.3
54	Blended biodiesels	Renewables and biofuels	20.1
55	Pure bio jet kerosene	Renewables and biofuels	19.3
56	Blended bio jet kerosene	Renewables and biofuels	19.5
57	Other liquid biofuels	Renewables and biofuels	21.7
58	Ambient heat (heat pumps)	Renewables and biofuels	0.0
59	Industrial waste (non-renewable)	Non-renewable waste	39.0
60	Non-renewable municipal waste	Non-renewable waste	25.0
61	Nuclear heat	Nuclear heat	0.0
62	Heat	Heat	0.0
63	Electricity	Electricity	0.0

The list of products is that appearing in the energy balances published by Eurostat (2020c). v_i is the carbon content per unit of calorific value of the energy product i, expressed in kg-CO_2/GJ, and is extracted from the Intergovenmental Panel on Climate ChangeIntergovenmental Panel on Climate Change (2006). The v_i associated to oil shale and oil sands is the mean of the v_i for shale oil and oil shale and tar sands. The v_i associated to primary solid biofuels is the mean of the v_i for wood (and wood waste), sulphite lyes (black liquor), and other primary solid biomass. Finally, the v_i associated to blended biofuels is calculated assuming that 90% of the value is given by the carbon content of conventional fuel and 10% of the value is given by the carbon content of the pure biofuel

Table 14 Annual total change of emissions CO_2 and its influencing factors (in KTOE) in Spain

Year	Total	POP	INC	SOC	COM	STR	INTR
1996	– 0.57089	0.977923	2.133976	8.439514	0.074566	0.877572	– 0.85301
1997	4.217855	1.038496	1.758623	3.735246	0.072389	0.790313	1.751609
1998	14.42058	0.997271	3.84462	1.785072	0.074529	0.441027	0.354878
1999	21.27917	1.088614	6.442058	4.525198	0.096206	0.585414	1.052812
2000	11.32436	1.36754	5.990556	4.291115	0.09868	0.207863	0.487957
2001	0.378722	2.604685	7.002508	2.80018	0.099789	0.674091	– 0.8573
2002	16.7021	5.628298	1.735142	– 0.17505	0.040184	– 1.71855	– 1.44396
2003	14.00605	5.32808	7.367625	3.259047	0.037436	– 0.21626	– 1.81705
2004	14.50217	5.669869	3.667058	0.301037	0.045451	– 2.13189	0.114553
2005	18.25691	5.59958	3.110804	1.269109	0.05476	– 1.62132	– 2.41935
2006	– 12.3097	6.015616	1.147315	0.129558	0.049727	– 1.53684	– 0.84673
2007	3.380313	6.688847	3.508711	3.308696	0.046628	– 2.35154	– 2.6347
2008	– 21.7683	4.132925	5.491006	– 5.36107	0.051359	– 3.45298	– 1.48687
2009	– 28.8785	1.63411	– 1.36701	– 6.98107	0.051066	– 6.81982	– 4.52604
2010	– 7.02718	1.115428	0.434884	– 3.26922	0.047804	– 3.23759	8.017159
2011	– 5.00705	0.910755	– 1.33279	–1.14252	0.038391	– 4.32005	2.295485
2012	1.227012	– 0.53827	–7.65934	– 4.95822	0.045652	– 5.98065	3.922819
2013	– 25.9982	–1.23103	– 1.40452	0.525003	0.041614	– 0.62327	1.246895
2014	– 3.54988	– 0.34154	– 1.45966	– 0.9979	0.040155	0.030052	2.275833
2015	21.25216	– 0.05316	1.79948	4.335375	0.038067	– 0.42413	0.859243
2016	– 8.56551	0.50846	5.541196	2.749434	0.037597	1.394246	2.638563
2017	14.88578	0.761135	3.972913	0.445944	0.038149	– 0.26939	– 6.77186

Year	OUT	EFF	USE	WEA	MIX	CONV	EMI
1996	– 5.47709	– 0.2488	0.033838	2.207881	0.041264	– 0.59201	– 8.18652
1997	1.358993	– 1.05467	0.078376	– 4.71392	0.060313	– 6.29808	5.640164
1998	0.000318	4.326382	0.053743	6.56696	– 1.90976	0.137305	– 2.25177
1999	– 4.19961	– 1.25093	– 0.01448	0.833054	0.489081	3.285742	8.346014
2000	0.100046	6.988206	– 0.03254	– 1.69302	– 2.02124	– 3.89675	– 0.56405
2001	– 6.59002	6.689092	– 0.06315	0.685032	0.745956	– 7.40629	– 6.00585
2002	0.277748	– 0.42473	0.146934	– 4.4999	0.048431	8.381744	8.705813
2003	– 4.36544	9.156711	0.596855	8.474452	– 1.73521	– 6.90104	– 5.17916
2004	– 0.70014	8.839238	– 0.0135	– 1.36603	– 1.22468	– 0.71666	2.017847
2005	1.559912	4.22147	– 0.07223	1.189202	0.418171	– 0.28427	5.231076
2006	4.768466	– 9.64875	– 1.47655	– 4.02787	1.973498	– 1.83976	– 7.01741
2007	0.921259	– 2.24513	0.593257	– 3.39057	– 0.60567	– 3.74075	3.281269
2008	– 13.5392	2.516414	0.17381	2.273922	0.868287	– 1.93181	– 11.504
2009	– 8.20418	5.288846	– 0.12586	1.189062	1.319104	– 5.60236	– 4.7344
2010	– 5.3461	6.513455	– 0.10805	3.987472	– 1.21364	0.222256	– 14.191
2011	– 1.34947	–5.37416	– 0.10641	–8.51115	0.47094	2.158318	11.2556
2012	– 0.07935	8.009776	0.253437	8.519753	– 0.39211	0.346412	– 0.26291
2013	0.300082	– 8.81855	– 0.1374	– 2.50927	– 0.88733	– 2.95221	– 9.54822
2014	1.055807	– 3.27937	0.023094	– 7.81771	– 0.74986	6.519039	1.152182
2015	– 0.01951	– 0.53873	– 0.74693	7.151668	0.003283	2.439702	6.407794
2016	– 8.27973	2.394104	– 0.40087	1.379293	– 0.4182	– 5.82534	– 10.2843
2017	6.33422	1.583135	0.267753	– 1.21506	– 0.20436	1.249768	8.693434

Table 15 Annual total change of emissions CO_2 and its driving factors (in KTOE) in the EU28

Year	Total	POP	INC	SOC	COM	STR	INTR
1996	238.1859	6.619692	32.4255	18.82297	5.428458	−19.6768	2.123793
1997	−194.711	20.20656	42.01313	24.07666	2.462667	−8.37472	9.374708
1998	51.52232	5.862608	54.41516	28.28837	2.642897	−11.3007	−7.46749
1999	−144.159	5.629107	50.81539	28.16658	3.059867	−4.86625	2.839164
2000	11.23863	7.962826	68.95427	32.61742	3.705448	−4.77716	−8.02215
2001	127.2738	5.950427	41.83606	22.28843	2.419093	−13.8093	−1.49202
2002	−65.2608	14.32531	18.5426	19.69544	2.273714	−8.21993	5.826487
2003	240.5691	15.69937	17.02448	9.160892	2.758919	−8.03006	−18.7642
2004	−53.562	17.53439	43.6581	46.00667	1.902231	14.38634	−7.62641
2005	36.95267	15.69573	35.47033	10.70141	2.589056	−20.9884	−8.69967
2006	6.458884	15.94102	59.7578	25.42597	4.262218	2.489451	−25.9133
2007	−88.6637	16.83316	58.11647	21.66927	1.258312	−1.28395	−15.0002
2008	−21.9231	14.86762	7.213549	−1.0821	1.779377	−27.15	−14.7542
2009	−244.62	8.640492	−91.0741	−40.1201	1.08125	−75.1633	18.96444
2010	268.8639	−1.6495	41.60523	26.22048	11.26409	25.5327	5.623849
2011	−323.967	8.605468	32.82243	−6.29369	2.202521	−4.6967	−15.418
2012	117.3094	8.623308	−10.4338	−15.7536	1.744806	−32.81	25.51959
2013	−115.603	15.98759	−0.56431	7.435797	3.759218	−14.5583	4.982199
2014	−296.494	9.350781	26.34362	9.127094	−0.93058	9.787204	−7.72821
2015	146.4297	11.81807	29.31857	19.72769	0.926677	−0.53102	−4.50732
2016	−4.76435	8.654791	30.84689	22.43054	0.528465	7.20809	0.951889
2017	14.19114	7.184669	40.50846	28.66168	−0.67499	5.188793	−16.6166

Year	Total	OUT	EFF	USE	WEA	MIX	CONV	EMI
1996	238.1859	−25.3244	157.8292	−1.50417	89.25372	−18.4454	8.948447	−18.3152
1997	−194.711	7.907139	−150.19	2.311971	−108.183	−4.06257	−7.42021	−24.8336
1998	51.52232	4.785894	−51.7745	0.967348	39.83442	−13.8982	−5.40895	4.575565
1999	−144.159	−17.4421	−93.6559	0.656572	−46.7834	−6.29877	−44.1169	−22.1625
2000	11.23863	0.283031	−86.8499	3.648241	−42.4988	−0.00664	24.70678	11.51532
2001	127.2738	−25.7618	52.59604	−3.77281	73.44724	−1.86531	−17.0517	−7.51061
2002	−65.2608	−9.40715	−75.93	3.197478	−54.9415	3.016273	5.016098	11.34431
2003	240.5691	9.199883	76.11225	−1.28505	92.2456	4.353734	25.7537	16.3396
2004	−53.562	−19.2259	−56.0335	0.593244	−49.7137	6.464886	−30.7124	−20.796
2005	36.95267	1.763631	−19.633	0.98623	5.570676	−1.9314	10.33633	5.091802
2006	6.458884	11.58578	−87.326	0.216632	−18.1294	10.37654	−8.1247	15.89699
2007	−88.6637	−11.7445	−138.429	7.558154	−42.1978	6.785569	−22.1727	29.94356
2008	−21.9231	−6.86816	49.64785	−2.17602	14.20892	−0.7833	−12.8956	−43.931
2009	−244.62	−37.2138	0.702598	0.902307	26.2053	1.365501	−32.1886	−26.7217
2010	268.8639	−2.51741	59.60244	−1.38025	128.2929	0.600412	−15.2259	−9.10508

Table 15 continued

Year	Total	OUT	EFF	USE	WEA	MIX	CONV	EMI
2011	− 323.967	− 4.27679	− 195.819	3.24699	− 172.369	6.442389	6.821793	14.7651
2012	117.3094	− 28.3081	50.9394	− 2.03061	109.678	− 0.71502	− 9.43263	20.28819
2013	− 115.603	− 8.12284	− 23.5995	− 1.7896	− 46.0613	− 3.35182	− 14.9633	− 34.7571
2014	− 296.494	−20.1963	− 186.825	2.613144	− 116.342	7.827374	3.045326	− 32.5665
2015	146.4297	− 3.86455	28.93652	− 0.58847	75.68251	− 9.11639	2.407016	− 3.77961
2016	− 4.76435	− 18.9427	10.26233	− 0.89885	8.435162	− 5.10129	− 42.6591	− 26.4805
2017	14.19114	5.347963	− 27.5449	− 1.12335	15.89771	− 8.54656	− 28.5034	− 5.58827

Table 16 Sector matching scheme

Sector group	Sector	Sub-sector	NACE	Final consumption
Economic sectors	Agriculture	Agriculture and forestry	A01, A02	Agriculture and forestry consumption from energy balances
		Fishing	A03	Fishing consumption from energy balances
	Industry	Energy sector and extractive industries	B, C19, D	Energy branch + mining and quarrying consumption from energy balances
		Food, breverages and tobacco	C10 - C12	Food, beverages and tobacco consumption from energy balances
		Textile and leather	C13 - C15	Textile and leather consumption from energy balances
		Wood and wood products	C16	Wood and wood products consumption from energy balances
		Paper, pulp and print	C17, C18	Paper, pulp and printing consumption from energy balances
		Chemical and petrochemical	C20, C21	Chemical and petrochemical consumption from energy balances
		Non-metallic minerals	C23	Non-metallic minerals consumption from energy balances
		Basic metals	C24	Iron and steel + non-ferrous metals consumption from energy balances
		Machinery	C25, C26, C27, C28	Machinery consumption from energy balances
		Transport equipement	C29, C30	Transport equipment consumption from energy balances
		Other industries	C22, C31, C32	Not elsewhere specified industry consumption from energy balances
		Construction	F	Construction consumption from energy balances
	Commercial and public services	Space heating	C33, E, G - S, U	Commercial and public services + not elsewhere specified consumption from energy balances and end-use shares
		Hot water		Commercial and public services + not elsewhere specified consumption from energy balances and end-use shares
		Cooking		Commercial and public services + not elsewhere specified consumption from energy balances and end-use shares
		Air Conditioning		Commercial and public services + not elsewhere specified consumption from energy balances and end-use shares
		Electric appliances / lighting		Commercial and public services + not elsewhere specified consumption from energy balances and end-use shares
Households	Households	Space heating	-	Households consumption from energy balances and end-use shares
		Hot water	-	Households consumption from energy balances and end-use shares
		Cooking	-	Households consumption from energy balances and end-use shares
		Air Conditioning	-	Households consumption from energy balances and end-use shares
		Electric appliances / lighting	-	Households consumption from energy balances and end-use shares
Transport	Passenger	Road transport	-	Road transport consumption from energy balances and mode-shares
		Rail transport	-	Rail transport consumption from energy balances and mode-shares
		Domestic aviation transport	-	Domestic aviation consumption from energy balances
	Freight	Road transport	-	Road transport consumption from energy balances and mode-shares
		Rail transport	-	Rail transport consumption from energy balances and mode-shares
		Domestic navigation transport	-	Domestic navigation consumption from energy balances
		Pipeline transport	-	Pipeline transport consumption from energy balances

Activities of households as employers (with NACE code T) ise the only economic activity group with no match in our scheme

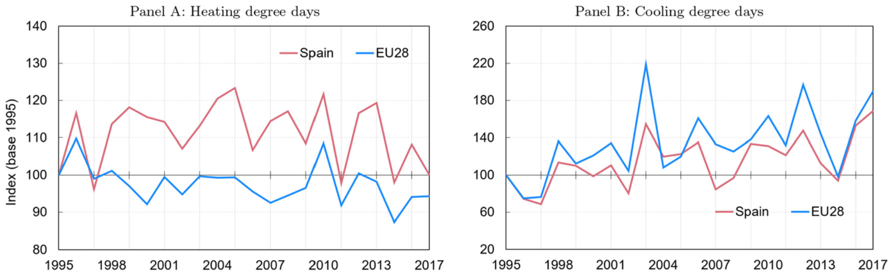

Fig. 12 Heating and coolind degree days

See Table 17 and Figs 13 and 14.

Table 17 Intermediate sectors in the energy input–output table

Transformation sector	Description
Electricity & heat generation (10 sub-sectors)	Production of electricity and/or heat, including renewable energies, like hydro power, wind power and solar photovoltaic, which are transformed into electricity, or the energy transformed in nuclear or thermal power plants (e.g., burning of oil, coal, gas and biofuels) to produce electricity and/or heat, or district heating plants, which are central locations used to produce district heat that is distributed through a network and may be used for processing or space heating purposes
Coke ovens	Transformation of coal into coke oven coke, which is the most important raw material for blast furnaces
Blast furnaces	Transformation of coke oven coke into blast furnace gas
Gas works	Transformation of fuels into gas works gas, which is a flammable gas
Refineries & petrochemical industry (6 sub-sectors)	Transformation of crude oil and other intermediary products into refined petroleum products (like gasoline, diesel oil, fuel oil, lubricants, etc.). Input to refineries consists of crude oil and intermediary products (feedstocks) treated in the refineries, including treatment on behalf of foreign countries. The quantities of oil products re-treated in the refineries (recycling) are also included. It also covers the petrochemical industry, which is the transformation of energy carriers during the production of petrochemicals (chemical products derived from petroleum) in the petrochemical industry. The backflows are considered as an input as well, i.e., all energy commodities obtained as outputs from transformation processes but used as an input to other transformation processes, for example, fuels returned from the petrochemical sector to refineries for further processing/blending. Although the real backflow is not known from the energy balance, a minimal backflow can be inferred by consistency: any amount of a given product that is present at the transformation input node, but not provided by energy available from all sources, must be a backflow
Patent fuel plants	A composition fuel manufactured from hard coal fines with the addition of a binding agent. The amount of patent fuel produced may, therefore, be slightly higher than the actual amount of coal consumed in the transformation process
BKB & PB plants	Plants used to produce brown coal briquettes and peat briquettes. These are bricks composed of shredded peat or brown coal, compressed to form a slow-burning, easily stored and transported fuel
Coal liquefaction plants	Quantities of coal, oil shale and tar sands used to produce synthetic oil
Blended in natural gas	Quantities of coal gases or petroleum gas products blended with natural gas
Liquid biofuels blended	Quantities of conventional and pure biofuels to produce blended biofuels
Charcoal production plants	Charcoal is a manufactured fuel from solid biofuels, i.e., the solid residue of the destructive distillation and pyrolysis of wood and other vegetal material
Gas-to-liquids plants	Quantities of natural gas used as feedstock for the conversion to liquids, e.g., the quantities of fuel entering the methanol production process for transformation into methanol
Not elsewhere specified	Transformation input/output is reported under Non-specified only as a last resort, if a final breakdown into the above sub-sectors is not available

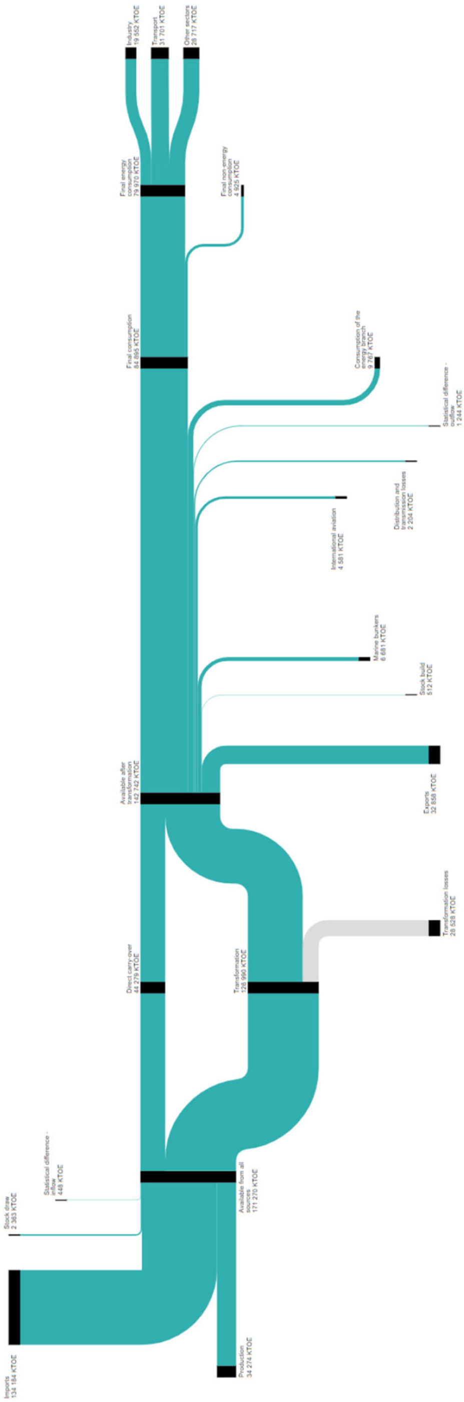

Fig. 13 Sankey diagram of the energy flow in Spain (2017). *Source:* Picture directly taken from the Eurostat Sankey drawing tool

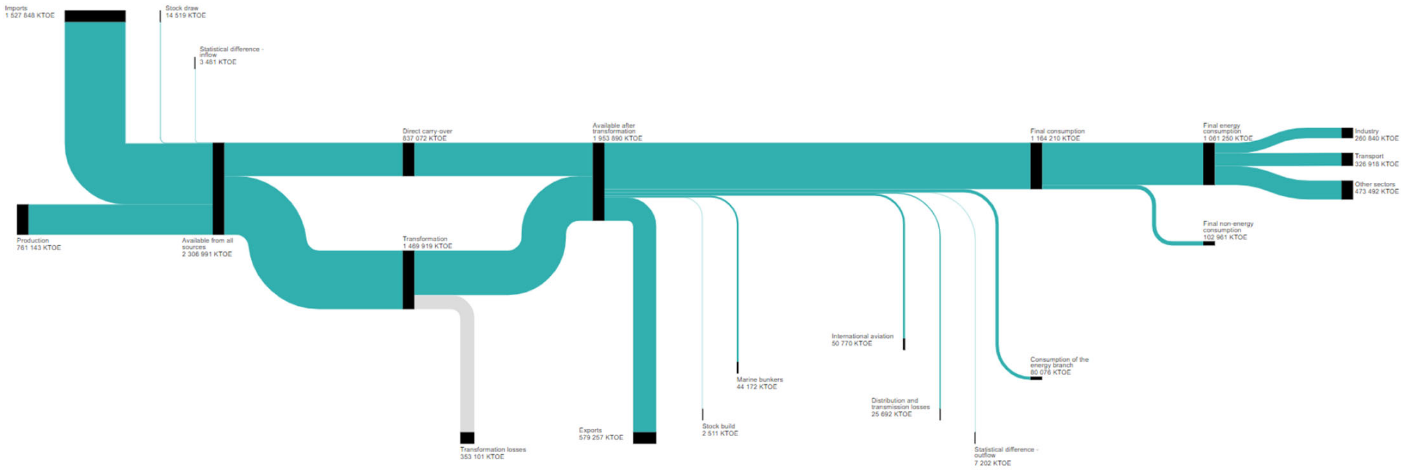

Fig. 14 Sankey diagram of the energy flow in the EU28 (2017). *Source:* Picture directly taken from the Eurostat Sankey drawing tool

References

Adetutu MO, Glass AJ, Weyman-Jones TG (2016) Economy-wide estimates of rebound effects: evidence from panel data. Energy J. https://doi.org/10.5547/01956574.37.3.made

Alcántara V, Duarte R (2004) Comparison of energy intensities in European Union countries, results of a structural decomposition analysis. Energy Policy 32:177–189. https://doi.org/10.1016/S0301-4215(02)00263-X

Alcántara V, Roca J (1995) Energy and CO2 emissions in Spain: methodology of analysis and some results for 1980–1990. Energy Econ 17:221–230. https://doi.org/10.1016/0140-9883(95)00014-L

Ang BW (2015) LMDI decomposition approach: a guide for implementation. Energy Policy 86:233–238. https://doi.org/10.1016/j.enpol.2015.07.007

Ang BW, Choi K-H (1997) Decomposition of aggregate energy and gas emission intensities for industry: a refined divisia index method. Energy J 18:59–73. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol18-No3-3

Ang BW, Su B, Wang H (2016) A spatial-temporal decomposition approach to performance assessment in energy and emissions. Energy Econ 60:112–121. https://doi.org/10.1016/j.eneco.2016.08.024

Ang BW, Xu X, Su B (2015) Multi-country comparisons of energy performance: the index decomposition analysis approach. Energy Econ 47:68–76. https://doi.org/10.1016/j.eneco.2014.10.011

Ang BW, Zhang FQ (2004) A survey of index decomposition analysis in energy and environmental studies. Energy 25:1149–1176. https://doi.org/10.1016/S0360-5442(00)00039-6

Azevedo IM (2014) Consumer end-use energy efficiency and rebound effects. Annu Rev Environ Resour 39:393–418. https://doi.org/10.1146/annurev-environ-021913-153558

Bartoletto S, del Mar Rubio-Varas M (2008) Energy transition and CO2 emissions in Southern Europe: Italy and Spain (1861–2000). Global Environ 1:46–81. https://doi.org/10.3197/ge.2008.010203

Belzer DB, Bender SR, Cort KA (2017) A comprehensive system of energy intensity indicators for the US: methods, data and key trends, Pacific Northwest National Lab. (PNNL), Richland, WA (USA), PNNL-22267 Rev 2 PG0300000. https://doi.org/10.2172/1373003

Bordon Lesme M, Padilla E, Freire-González J (2020) The direct rebound effect of electricity energy services in spanish households: evidence from error correction model and system GMM estimates, Working Paper-Universitat Autònoma de Barcelona-Departament d'Economia Aplicada, 20.02. https://ddd.uab.cat/record/232627

Butnar I, Llop M (2007) Composition of greenhouse gas emissions in Spain: an input-output analysis. Ecol Econ 61:388–395. https://doi.org/10.1016/j.ecolecon.2006.03.005

Cansino JM, Cardenete MA, Ordóñez M, Román R (2012) Economic analysis of greenhouse gas emissions in the Spanish economy. Renew Sustain Energy Rev 16:6032–6039. https://doi.org/10.1016/j.rser.2012.06.033

Cansino JM, Román R, Ordóñez M (2016) Main drivers of changes in CO2 emissions in the Spanish economy: a structural decomposition analysis. Energy Policy 89:401–415. https://doi.org/10.1016/j.enpol.2015.11.020

Cansino JM, Sánchex-Braza A, Rodrí-Arévale M (2015) Driving forces of Spain's CO2 emissions: a LMDI decomposition approach. Renew Sustain Energy Rev 48:749–759. https://doi.org/10.1016/j.rser.2015.04.011

Cazcarro I, Duarte R, Sánchez-Chóliz J (2013) Economic growth and the evolution of water consumption in Spain: a structural decomposition analysis. Ecol Econ 96:51–61. https://doi.org/10.1016/j.ecolecon.2013.09.010

Chong CH, Ma L, Li Z, Ni W, Song S (2015a) Logarithmic mean Divisia index (LMDI) decomposition of coal consumption in China based on the energy allocation diagram of coal flows. Energy 85:366–378. https://doi.org/10.1016/j.energy.2015.03.100

Chong CH, Ni W, Ma L, Liu P, Li Z (2015b) The use of energy in Malaysia: tracing energy flows from primary source to end use. Energies 8:2828–2866. https://doi.org/10.3390/en8042828

Colmenares Montero G, Loschel A, Madlener R (2019) The rebound effect and its representation in energy and climate models, CAWM Discussion Paper, p 106. http://hdl.handle.net/10419/193664

Directorate-General for Climate Action (European Commission), Eclareon, ICF International, Umweltbundesamt GmbH, and ZEW (2016) Decomposition analysis of the changes in GHG emissions in the EU and Member States. https://op.europa.eu/en/publication-detail/-/publication/ceb0fb6c-f4e2-11e6-8a35-01aa75ed71a1

Duarte R, Sánchez-Solís J, Sarasa C (2018) Consumer-side actions in a low-carbon economy: a dynamic CGE analysis for Spain. Energy Policy 118:199–210. https://doi.org/10.1016/j.enpol.2018.03.065
Economidou M, Román-Collado R (2019) Assessing the progress towards the EU energy efficiency targets using index decomposition analysis in 2005–2016. JRC Science for Policy Report. https://doi.org/10.2760/61167
European Comission (2012-10-25, later modified in 2013) Europe 2020: a European strategy for smart, sustainable and inclusive growth. https://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf. Accesed 18 Sep 2019
European Comission (2016) Review of the default primary energy factor (PEF) reflecting the estimated average EU generation efficiency referred to in Annex IV of Directive 2012/27/EU and possible extension of the approach to other energy carriers, Energy Studies. https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf
European Comission (2019-10-31) REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Preparing the ground for raising long-term ambition EU Climate Action Progress Report 2019, COM/2019/559. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0559
European Environment Agency (2015) Energy and non-energy related greenhouse gas emissions, Indicator Assessment, ENER 001. http://www.eea.europa.eu/pressroom/newsreleases/why-did-greenhouse-gas-emissions
European Parliament (2006-12-30) Regulation (EC) No 1893/2006 of the European Parliament and of the Council of 20 December 2006 establishing the statistical classification of economic activities NACE Revision 2 and amending Council Regulation (EEC) No 3037/90 as well as certain EC Regulations on specific statistical domains Text with EEA relevance, OJ, L 393, pp 1–39, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006R1893
Eurostat (2020a) Air Emission Accounts. https://ec.europa.eu/eurostat/web/environment/air-emissions. Accesed 28 May 2020
Eurostat (2020b) Area of wooded land (source: FAO-FE). http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=for_area&lang=en. Accesed 28 May 2020
Eurostat (2020c) Complete energy balances. https://ec.europa.eu/eurostat/web/energy/data/energy-balances. Accesed 28 May 2020
Eurostat (2020d) Cooling and heating degree days by country - annual data. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_chdd_a&lang=en. Accesed 28 May 2020
Eurostat (2020e) Farmland: number of farms and areas by size of farm (UAA) and NUTS 2 regions, Accesed: 28/05/2020, https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ef_lu_ovcropaa&lang=en
Eurostat (2020f) Fishing fleet by type of gear and engine power. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=fish_fleet_gp&lang=en. Accesed 28 May 2020
Eurostat (2020g) National accounts aggregates by industry (up to NACE A*64). https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a64&lang=en. Accesed 28 May 2020
Eurostat (2020h) National accounts employment data by industry (up to NACE A*64). https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a64_e&lang=en. Accesed 28 May 2020
Eurostat (2020i) Population on 1 January by age and sex. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_pjan&lang=en. Accesed 28 May 2020
Eurostat (2020j) Production in industry - annual data. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sts_inpr_a&lang=en. Accesed 28 May 2020
Eurostat (2020k) Purchasing power parities (PPPs), price level indices and real expenditures for ESA 2010 aggregates. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_ppp_ind&lang=en. Accesed 28 May 2020
Eurostat (2020l) Sankey diagrams for energy balance. https://ec.europa.eu/eurostat/statistics-explained/index.php/Sankey_diagrams_for_energy_balance. Accesed 28 May 2020
Eurostat (2020m) Statistical pocketbook 2017 on transport. https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2017_lt. Accesed 28 May 2020
Fernández-González P, Landajo M, Presno MJ (2014) Multilevel LMDI decomposition of changes in aggregate energy consumption. A cross country analysis in the EU-27. Energy Policy 68:576–584. https://doi.org/10.1016/j.enpol.2013.12.065
Freire-González J (2010) Empirical evidence of direct rebound effect in Catalonia. Energy Policy 38:2309–2314. https://doi.org/10.1016/j.enpol.2009.12.018

Freire-González J, Puig-Ventosa I (2015) Energy efficiency policies and the Jevons paradox. Int J Energy Econ Policy 5:69–79
Freire-González J, Vivanco DF, Puig-Ventosa I (2017) Economic structure and energy savings from energy efficiency in households. Ecol Econ 131:12–20. https://doi.org/10.1016/j.ecolecon.2016.08.023
Gálvez P, Mariel P, Hoyos D (2014) Green energy and efficiency, green energy and technology, chap. Estim Direct Rebound Effect Resid Energy Sec Appl Spain 165–182:1997
Goh T, Ang BW (2019) Tracking economy-wide energy efficiency using LMDI: approach and practices. Energy Eff 12:829–847. https://doi.org/10.1007/s12053-018-9683-z
Greening LA, Greene DL, Difiglio C (2000) Energy efficiency and consumption–the rebound effect–a survey. Energy Policy 28:389–401. https://doi.org/10.1016/S0301-4215(00)00021-5
Guerra A-I, Sancho F (2010) Rethinking economy-wide rebound measures: an unbiased proposal. Energy Policy 38:6684–6694. https://doi.org/10.1016/j.enpol.2010.06.038
Hoekstra R, van den Bergh JC (2003) Comparing structural decomposition analysis and index. Energy Econ. https://doi.org/10.1016/S0140-9883(02)00059-2
Intergovenmental Panel on Climate Change (2006) 2006 IPCC Guidelines for national greenhouse gas inventories, energy, p 2, https://www.ipcc-nggip.iges.or.jp/public/2006gl/
Intergovenmental Panel on Climate Change (2007) Fourth assessment report: climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK
Kaya Y (1990) Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, Energy and Industry Subgroup, Response Strategies Working Group. IPCC, Paris., https://ci.nii.ac.jp/naid/10021966297/
Khazzoom JD (1980) Economic implications of mandated efficiency in standards for household appliances. Energy J 1:21–40. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol1-No4-2
Ma C, Stern D (2008) China's changing energy intensity trend: a decomposition analysis. Energy Econ 30:1037–1053. https://doi.org/10.1016/j.eneco.2007.05.005
Ma L, Chong CH, Zang X, Liu P, Li Z, Ni W (2018) LMDI decomposition of energy-related CO2 emissions based on energy and CO2 allocation sankey diagrams: the method and an application to China. Sustainability 10:344. https://doi.org/10.3390/su10020344
Malpede MM, Verdolini E (2016) Rebound effects in Europe. In: Conference paper: Italian Association of environmental and resource economists. https://www.researchgate.net/publication/303665672_Rebound_effects_in_Europe
Medina A, Ángeles C, Monrobel JR (2016) Measuring the socioeconomic and environmental effects of energy efficiency investments for a More Sustainable Spanish Economy. Sustainability 8:1039. https://doi.org/10.3390/su8101039
Mendidulce M, Pérez-Arriaga I, Ocaña C (2010) Comparison of the evolution of energy intensity in Spain and in the EU15. Why is Spain different? Energy Policy 38:639–645. https://doi.org/10.1016/j.enpol.2009.07.069
Ministerio de Medio Ambiente (2005) Evaluación preliminar de los impactos en España por efecto del cambio climàtico. https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/evaluacion_preliminar_impactos_completo_2_tcm30-178491.pdf. Accesed 18 Sep 2019
Ministerio de para la Transición Ecológica (2017) Plan Nacional Integrado de Energía y Clima, 2021–2030. https://www.miteco.gob.es/es/prensa/pniec.aspx. Accesed 18 May 2020
Ministerio de Turismo, Energía y Agenda Digital (2017) Plan Nacional de Acción de Eficiencia Energética, 2017–2020. https://ec.europa.eu/energy/sites/ener/files/documents/es_neeap_2017_es.pdf. Accesed 18 Sep 2019
ODYSSEE-MURE (2020a) Definition of ODEX indicators in ODYSSEE data base. https://www.odyssee-mure.eu/publications/archives/odex-indicators-database-definition.html
ODYSSEE-MURE (2020b) ODYSSEE database. https://www.indicators.odyssee-mure.eu/. Accesed 28 May 2020
Our World in Data (2020) Annual total CO? emissions, by world region, 1751 to 2017. https://ourworldindata.org/grapher/annual-co-emissions-by-region. Accesed 28 May 2020
Ozturk I, Acaravci A (2010) CO_2 emissions, energy consumption and economic growth in Turkey. Renew Sustain Energy Rev 14:3220–3225. https://doi.org/10.1016/j.rser.2010.07.005
Patiño IL, Alcántara V, Padilla E (2019) Driving forces of CO2 emissions and energy intensity in Colombia, Documento de trabajo UAB. https://hdl.handle.net/2072/364987

Peña-Vidondo S, Arocena P, Gómez-Plana AG (2012) The impact of increased efficiency in the use of energy: a computable general equilibrium analysis for Spain, EcoMod2012 Paper, p 4317. https://www.semanticscholar.org/paper/The-impact-of-increased-efficiency-in-the-use-of-A-Vidondo-Arocena/d566ac8bd17df3902d93e359fa13bdebf1bf057a

Reuter M, Patel MK, Eichhammer W (2019) Applying ex post index decomposition analysis to final energy consumption for evaluating European energy efficiency policies and targets. Energy Eff 12:1329–1357. https://doi.org/10.1007/s12053-018-09772-w

Roca J, Alcántara V, Padilla E (2007) Actividad económica, consumo final de energía y requerimientos de energía primaria en Cataluña, 1990-2005. Análisis mediante el uso de los balances energéticos desde una perspectiva input-output, Documento de trabajo UAB. http://hdl.handle.net/2072/4806

Román-Collado R, Colinet MJ (2018) Is energy efficiency a driver or an inhibitor of energy consumption changes in Spain? Two decomposition approaches. Energy Policy 115:409–417. https://doi.org/10.1016/j.enpol.2018.01.026

Sessler M (1987) Net energy as an energy planning tool. Energy Policy 3:5–10

Sinton JE, Levine MD (1994) Changing energy intensity in Chinese industry: the relatively importance of structural shift and intensity change. Energy Policy 22:239–255. https://doi.org/10.1016/0301-4215(94)90162-7

Sorrell S (2007) The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, UK Energy Research Center (UKERC). https://ukerc.ac.uk/publications/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency/

Sorrell S, Dimitropoulos J (2008) The rebound effect: microeconomic definitions, limitations and extensions. Ecol Econ 65:636–649. https://doi.org/10.1016/j.ecolecon.2007.08.013

Su B, Ang B (2012) Structural decomposition analysis applied to energy and emissions: aggregation issues. Econ Syst Res. https://doi.org/10.1080/09535314.2012.677997

Sun J (2000) Is CO2 emission intensity comparable? Energy Policy 28:1081–1084. https://doi.org/10.1016/S0301-4215(00)00098-7

Torrie RD, Stone C, Layzell DB (2018) Reconciling energy efficiency and energy intensity metrics: an integrated decomposition analysis. Energy Eff. https://doi.org/10.1007/s12053-018-9667-z

United Nations (2015) The 2030 Agenda for Sustainable Development. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E. Accesed 18 Sep 2019

Vivanco DF, Kemp R, van der Voet E (2016) How to deal with the rebound effect? A policy-oriented approach. Energy Policy 94:114–125. https://doi.org/10.1016/j.enpol.2016.03.054

Waggoner PE, Ausubel H (2002) A framework for sustainability science: a renovated IPAT identity. Proc Natl Acad Sci USA 11:7860–7865. https://doi.org/10.1073/pnas.122235999

Wang H, Ang B, Su B (2017) Assessing drivers of economy-wide energy use and emissions: IDA versus SDA. Energy Policy 107:585–599. https://doi.org/10.1016/j.enpol.2017.05.034

Wood R, Lenzen M (2006) Zero-value problems of the logarithmic mean divisia index decomposition method. Energy Policy 34:1326–1331. https://doi.org/10.1016/j.enpol.2004.11.010

World Bank and ClimateWorks Foundation (2014) El desarrollo adaptado al cambio climático. La suma de los beneficios derivados de las medidas que contribuyen a generar prosperidad, poner fin a la pobreza y combatir el cambio climático. http://documents.worldbank.org/curated/en/437961468154489915/text/889080WP0v20Bo0ment0Summary0SPANISH.txt

Xie S-C (2014) The driving forces of China?s energy use from 1992 to 2010: an empirical study of input-output and structural decomposition analysis. Energy Policy 73:401–415. https://doi.org/10.1016/j.enpol.2014.05.035

Zeng L, Xu M, Liand S, Zeng S, Zhang T (2014) Revisiting drivers of energy intensity in China during 1997–2007: a structural decomposition analysis. Energy Policy 67:640–647. https://doi.org/10.1016/j.enpol.2013.11.053

Zhang S, Wang J, Zheng W (2018) Decomposition analysis of energy-related CO2 emissions and decoupling status in China's logistics industry. Sustainability 10:1340. https://doi.org/10.3390/su10051340

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.