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Decoupling efficiency from electricity intensity: An empirical assessment in the EU

Frederico Perillo [a,*], Patrícia Pereira da Silva [a,b,c], Pedro A. Cerqueira [b]

[a] Energy for Sustainability Initiative, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal
[b] University of Coimbra, CeBER, Faculty of Economics, Av. Dias da Silva, 165, 3004-512, Coimbra, Portugal
[c] INESC Coimbra, Rua Sílvio Lima, Polo II 199, 3030-030, Coimbra, Portugal

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ABSTRACT

A naive analysis of electricity intensity is not very informative since deviations in this indicator entail the consequences of changes in its components. The objective of this paper is to address these components, decomposing the electricity intensity in the European Union from 1995 to 2019. Complementing the LMDI method (Ang, 2015), this paper proposes an improvement by adding a new element to the decomposition methodology. Subsequently, three components of electricity intensity are explored: structure, efficiency, and electrification. This enhancing innovative feature is fundamental to distinguish the actual influence of energy efficiency on electricity intensity from that of the other elements. Results demonstrated that the efficiency component impact was greater than it first appeared. As the goals of public policies such as 20-20-20 EU have been intensified, policy makers need to keep promoting technological innovations since the relevant contribution of the efficiency component was supported by reasonable evidence and the adopted strategies have generated solid results regarding the electricity intensity indicator.

Also, the structural element displayed minor influence, although the economic activity profile of the EU has changed. Additionally, the electrification component contributed to increase electricity intensity, since the electricity consumption has grown at a higher rate than the output of the economy.

As values were distinct between the EU-28 countries and each one has its particularity that influences the electricity intensity, a country-specific efficiency policy could also be considered.

1. Introduction

In the current scenario of energy transition toward renewable sources and in order to achieve the sustainable development goals adopted by all United Nation Member States (UN, 2015), there is a clear need to balance economic growth, energy consumption and the exploitation of energy resources. Aspects related to the energy industry transcends its borders and impacts not only the energy sector of a country, but also other important areas such as the economy, the environment, social relations, and international affairs, among others.

Therefore, policy makers need to consider many factors to support their choices. Among all the elements that underpin these decisions, one of the greatest challenges is to maintain high levels of economic activity while reducing energy consumption. Electricity intensity represents the relationship between electricity consumption and Gross Domestic Product (GDP) and is an important indicator of efficiency related to economic productivity (European Environment Agency, 2012).

Considering that electricity has an increasing share in the total final energy consumption (International Energy Agency, 2019b) and taking into account that the concern for the implementation of energy efficiency measures has increased, whether on the supply or the demand side, the electricity intensity indicator has been used in the analysis of the countries' economic behavior, as evidenced by Liddle (2009), Inglesi-Lotz and Blignaut (2012) and Herrerias and Liu (2013). In the European Union (EU-28), the electricity intensity has declined by 38.9% from 1995 to 2019, and this deviation may indicate an increase in efficiency in the EU-28 economy.

Although the intensity indicator and its changes seem to have the answer for everything, it is still not meaningful (Löschel et al., 2015). We need to understand the factors that dictate its evolution and although electricity intensity is influenced by energy efficiency, this is not the sole influencing factor. Therefore, the objective of this study is to decompose

* Corresponding author.
E-mail address: fredericoperillo@efs.uc.pt (F. Perillo).

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the electricity intensity indicator into its components. Departing from the decomposition methodology of Ang and Choi (1997), an advancement is proposed by adding a new component not yet used in other studies, as far as we know. In addition to the structural and the efficiency factors, previously implemented by authors such as Fisher-Vanden et al. (2004), Metcalf (2008) and Song and Zheng (2012), we will consider a third element: the electrification factor.

As defined by Sugiyama (2012), electrification is the replacement of other energy sources by electricity on the demand side. Electrification, as stated by Williams et al. (2012), is a key factor in the reduction of GHG emissions, being a complement to other alternatives such as energy efficiency and the decarbonization of the energy supply. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change – IPCC exclusively dedicates a topic to the importance of electrification in climate change mitigation and stresses that "the electricity sector plays a major role in mitigation scenarios with deep cuts of GHG emissions." (IPCC, 2014). In this context, electrification is highly representative, since the replacement of the final energy source modifies the consumption profile and changes the energy and electricity intensity indicators, contributing to a positive final balance.

Analyzing the components of change in electricity intensity figures is essential at a time when improvements in energy efficiency are being made at a fast pace and electricity assumes an increasing share in the total final energy consumption. Assessing the behavior of these components also proofs to be relevant, because the analysis of electricity intensity is not a trivial matter, and the variation of any of its drivers can have a direct impact not only on the way in which electricity intensity should be evaluated, but also on the evolution and effectiveness of energy efficiency measures.

The EU-28 has presented a reduction in electricity intensity values from 1995 to 2019. The average values of all EU countries in 1995 were almost two times higher than the 2019 values, as shown by Fig. 1. During this period, energy efficiency was increasingly important on the sustainability agenda, but this was not the only reason for changes in electricity intensity. In addition to the efficiency factor, two other components were part of these variations.

The first factor that contributed to this variation refers to the structural profile of the economy. Different economic activities have different levels of electricity consumption and generate distinct financial results. Sectors such as industry, for example, tend to be more energy intensive while others such as services tend to have reduced electricity consumptions, resulting in deviations in the intensity indicator.

The second component was electrification. The increasing electricity share in the total final energy consumption in recent years and the projection that it will account for 49% by 2050, according to the International Renewable Energy Agency – IRENA (2019), also influence the electricity intensity index.

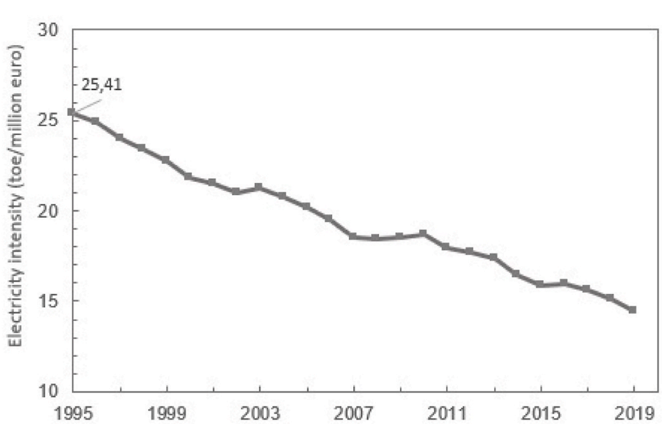

Fig. 1. EU-28 electricity intensity from 1995 to 2019 - Based on Eurostat (2020a).

With energy transition plans becoming more relevant mainly due to energy price volatility, especially for oil and natural gas, decoupling electricity intensity components is fundamental for any political assessment in line with the set of measures to tackle rising energy prices (European Comission, 2021a) and pursuant to a recent Energy Efficiency Directive (European Comission, 2021b).

By detailing electricity intensity and its components in the EU-28 and understanding the real impact of energy efficiency on the intensity index, this assessment contributes not only to the scientific community, but also to policy regarding electricity consumption, electricity intensity and energy efficiency.

This introduction to the article contextualizes the topic and presents the objectives of this study. Section 2 comprises the relevant literature review, divided into energy and electricity intensity studies (Section 2.1), and a review of the decomposition methodology literature (Section 2.2). Section 3 describes the methodology and the components of electricity intensity (Section 3.1), the traditional logarithmic mean Divisia index (LMDI) approach and its characteristics (Section 3.2) and the collected data (Section 3.3). In Section 4, we present the proposed methodology to obtain a more detailed breakdown into three factors: the structural, the electrification and the efficiency components, and discuss the results in Section 4. Section 5 presents the key results and conclusions, provides insights on energy efficiency policies and suggests alternatives for future work.

2. Literature review

Aspects associated with the energy sector have always gone beyond the traditional relationship between supply and demand. In addition to critical topics such as energy security, increasing renewables in the energy matrix and reducing energy poverty rates, the variation of energy and electricity intensity must also be considered as essential constituents of the energy policy agenda. Thus, research on intensity indicators has grown in recent years, even if most of them are focused only on energy intensity. Electricity intensity is the main point in only a few of the studies.

2.1. Energy and electricity intensity roles in an energy transition scenario

Besides the International Energy Agency (IEA) definition that focused only on primary energy (International Energy Agency, 2019a), some important authors, such as Fisher-Vanden et al. (2004) and Cornillie and Fankhauser (2004) defined energy intensity as being the ratio of real energy consumption to real GDP. These authors emphasize the importance of the intensity indicator since they consider it not only a measure of how efficient the economy of a country or a region is, but also how it behaves in relation to socioeconomic and environmental circumstances. Filippini and Hunt (2010, 2015) pointed out that, although the energy intensity indicator is widely used in public energy efficiency policies, the results may not be accurate since the indicator is a function of various factors, and other appropriate economic methods should be applied.

Liddle (2012) highlighted the importance of this indicator for energy studies and explored the convergence of OECD countries. Considering three measures of energy consumption and two ways of GDP calculation, the author laid out the versatility and insights that the correct analysis of energy intensity can generate.

Belzer (2014) also explored the particular significance of the energy intensity indicator when he considered that the ratio of energy consumption to GDP is not only affected by technological changes that allow more energy-efficient processes, but also by structural changes in the mix of activities of the economy, which is divided into different sectors.

Then, Löschel et al. (2015) furthered the research and raised several hypotheses for the reduction of energy intensity values, such as the shift in the composition of the European economy, sectoral improvements in energy efficiency, economic and political drivers, and the individual analysis of the performance of each of the member countries. These authors made a great contribution to this topic and, additionally to structural and efficiency analysis, as they revealed a deep insight into the way in which economic variables affected energy intensity (Löschel et al., 2015).

Grubler et al. (2018) described changes in the energy intensity indicator that would lead to a potential energy demand reduction scenario to limit global warming to 1.5 °C and other sustainable development goals.

Regarding electricity intensity, the existing literature evaluated the convergence of this indicator in various countries or regions. A study by Liddle (2009) explored the IEA/OECD countries, while Herrerias and Liu (2013) focused on assessing data from Chinese provinces data, finding a dominant behavior of moderate reduction in electricity intensity across regions.

In some of these studies, however, the energy efficiency variation over time is confused with energy intensity analysis. Although these are similar concepts and both are considered sustainable development indicators (Verbič et al., 2015), they must be distinguished, and the decomposition methodology plays a fundamental role in this regard.

2.2. Prior work on decomposition analysis in energy field

Most of the literature that assessed intensity indicators and its causes used a traditional strategy to decompose the main index into several specific components (Ang, 1994, 1995). This decomposition methodology was applied to different areas of the energy sector, such as in the evaluation of greenhouse gas emissions (Bhattacharyya and Matsumura, 2010), energy efficiency changes (Inglesi-Lotz and Pouris, 2012) and energy vulnerability (González and Moreno, 2015).

Regarding energy intensity, the decomposition methodology seeks to understand which are the forces that drive changes in aggregate energy intensity values over time (Ang, 1994, 1995). This is one of the main approaches of authors such as Cornillie and Fankhauser (2004), Fisher-Vanden et al. (2004), Metcalf (2008), Song and Zheng (2012) and Wu (2012).

Cornillie and Fankhauser (2004) accessed data from 1992 to 1998 of the economies of Central and Eastern Europe and the former Soviet Union to identify factors that contributed to the dramatic reduction in energy intensity in this historical period. These authors were among the firsts to use a decomposition methodology in an energy intensity study and, although different patterns were found, a strong link between the efficient use of resources and the reduction of energy intensity was verified (Cornillie and Fankhauser, 2004).

Fisher-Vanden et al. (2004) stated that there are three determinants of changes in energy intensity - changes in economic activity, energy efficiency improvements and another factor called ‘inaccurate statistics’. This last component was used to include other political, economic, and social deviations that might have an effect on energy intensity, in addition to changes in economic activity and energy productivity.

Metcalf (2008) simplified the decomposition analysis proposed by Fisher-Vanden et al. (2004) and contemplated two responsible causes of alterations in energy intensity - changes in economic activity and improvements in energy efficiency. The author used these factors to assess how each one influenced the decrease of the index values in the United States from 1970 to 2003 and concluded that energy efficiency played a key role contributing up to three-quarters of the verified energy intensity reduction (Metcalf, 2008).

Song and Zheng (2012) focused their research on China and used the decomposition methodology to assess which were the forces that led to the abrupt reduction of the energy intensity value of the Chinese economy in recent years. Although there was an impact from other economic variables such as energy prices, the authors concluded that the main reason for the sharp fall in Chinese energy intensity was the increased energy efficiency of its industry, which now needs less energy to generate the same wealth values as it did previously. Wu (2012) focused his analysis on regional China and also found a reduction in energy intensity in the country from 1981 to 2007, mainly due to the influence of the efficiency factor. The author further concluded that the intensity indicator has a range in which it may be reduced, if the structure of the Chinese economy changes and the share of less energy-intensive activities increases (Wu, 2012).

Parker and Liddle (2016) also used decomposition to identify the behavior of energy-intensity factors in OECD countries. The authors also used regression techniques to identify the influence of energy prices on efficiency and structural elements and concluded that, in general, increasing prices implies efficiency improvements.

In general, the approaches gathered in the literature achieved similar results in the decomposition of energy intensity, pointing to a significant participation of the efficiency factor in the reduction of this indicator regardless of the country or region addressed.

On the other hand, regarding electricity intensity, no research has been found so far using this decomposition methodology, even though the principles are similar to those used for energy intensity. Considering that this is a fundamental subject that has not been detailed in existing literature, the focus of this paper is to fill this gap with an innovative approach, considering that variations in the electricity intensity indicator are the result of structural, efficiency and electrification changes.

3. Methodology

This section describes the adopted methodology for this research, followed by the description of the chosen method and the collected data.

3.1. Decomposition methodology

Since the main objective of this study is to analyze the behavior of the electricity intensity indicator and its causes, this study adopts the decomposition methodology to assess the actual influence of each of these elements in the total intensity index. In addition to the traditional approach that considers structural and intensity factors as the only components of an intensity indicator, this research also proposes a new way to visualize the intensity factor, splitting it into efficiency and electrification elements and totaling the three components mentioned before: structure, efficiency, and electrification.

3.2. LMDI decomposition method

From an extensive study describing the most-widely used methods in decomposition analysis research and seeking to find out what is the preferred method for policymaking in energy, LMDI is considered the most appropriate method for the analysis of an index decomposition because of its theoretical foundation, adaptability, ease of use and the interpretation of results interpretation, as concluded by Ang (2004, 2005). On the other hand, this method can give a large residual term and it is not good for analyzing data sets containing a zero value. Therefore, considering that it is already well consolidated, the LMDI was the decomposition method chosen for this study.

Additionally, Ang (2004, 2005), says the LMDI method requires the definition of factors contributing to changes in the variable that it is intended to control. Considering that V represents the electricity-related aggregate value (electricity intensity) and assuming that there are n factors that contribute to the changes in V, the index decomposition analysis is given by Equation (1):

$$V = \sum_i V_i = \sum_i x_{1,i} x_{2,i} \ldots x_{n,i} \tag{1}$$

where V = index decomposition analysis (IDA), V_i = sub-category of the aggregate for which structural changes in this index and $x_1, x_2, \ldots, x_n$ are variables that contribute to the changes in each sub-category.

However, the analysis of intensity indicators requires a greater detail of Equation (1) components. Considering that the wealth generation of a country is formed by the sum of the GDP of all sectors of the economy and considering that the components of electricity intensity are three (n = 3), namely changes in economic activity, energy efficiency and electrification, the index decomposition analysis can be detailed using Equation (2). This is an adaptation of what was proposed by Ang (2015):

$$V = \frac{El}{Q} = \sum_i \left(\frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{El_i}{E_i} \right) = \sum_i S_i F_i K_i \quad (2)$$

where V = electricity intensity index, El = total electricity consumption, Q = total activity level (GDP), E_i = energy consumption of sector i, El_i = electricity consumption of sector i and Q_i = activity level of sector i. Components of total electricity intensity are represented by variables S, F and K and describe the activity share in economy, energy efficiency and electrification, respectively. Therefore, in the decomposition of an aggregate intensity indicator, S_i = activity share of sector i, F_i = energy efficiency of sector i and K_i = electrification of sector i.

Considering that 0 and T are respectively the start and end periods of evaluation of intensity index variation, these changes of electricity intensity can be summarized using Equation (3) adapted from Ang (2015).

$$U_{tot} = \frac{V^T}{V^0} = U_{str}\, U_{eff}\, U_{kwh} \quad (3)$$

where U_{str} = the structure effect, U_{eff} = the energy efficiency effect and U_{kwh} = the electrification effect. The U_{str}, U_{eff} and U_{kwh} components are indices in this multiplicative case. When multiplied (Equation (3)), they will result in U_{tot}, thereby indicating the weight and real importance of each of the components (U_{str}, U_{eff} and U_{kwh}) in changes in the electricity intensity index between periods 0 and T. Finally, components U_{str}, U_{eff} and U_{kwh} are given by Equations (4)–(6) respectively.

$$U_{str} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}{\sum_i L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}\, ln\left(\frac{S_i^T}{S_i^0}\right) \right) \quad (4)$$

$$U_{eff} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}{\sum_i L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}\, ln\left(\frac{F_i^T}{F_i^0}\right) \right) \quad (5)$$

$$U_{kwh} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}{\sum_i L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}\, ln\left(\frac{K_i^T}{K_i^0}\right) \right) \quad (6)$$

Results achieved for U_{str} , U_{eff} and U_{kwh} represent, on a percentage basis, how the electricity intensity indicator (U_{tot}) would behave if all other components remained unchanged during the entire period.

3.3. Data

To apply the method presented in Section 3.2, we collected data from Eurostat on energy consumption, electricity consumption, activity level and electricity intensity.

Regarding variables related to economic activity, this study incorporated Gross value added (GVA) as the economic variable used in the calculation of electricity intensity. GVA is measured net of taxes and subsidies on products and adjusts gross domestic product (GDP). Therefore, it is the best suited for this research, considering that each country has its own tax rate rules. GVA data were taken from Eurostat, which contains records of total activity level and activity level by sector measured in million euro and considering current prices and its implicit deflator that allowed us to build the GVA series at constant prices.

To match the electricity consumption data with the GVA data, we aggregated the latter into three sectors: Industry; Commerce (commercial, services, transport, and others); and Agriculture (agriculture, forestry, and fishing). Although a more detailed breakdown would provide additional information, this study is based on the division of economic activity used by the World Bank (2019). Such aggregation is justified by the fact that the electricity consumption data are only available for the three mentioned groups. Inputs for above variables were calculated on an annual basis starting in 1995 and ending in 2019 (we opted to not include the most recent years in order to not have the results influenced by the COVID19 pandemic).

The household sector was not considered in this paper because it adds relatively low value to the financial sum of goods and services produced in the EU countries. Such irrelevance in economic productivity coupled with considerable electricity consumption would distort the electricity intensity index in these cases and could complicate the interpretation of the results.

Data for total energy consumption, total electricity consumption and electricity consumption by sector data were taken from Eurostat (2020a), which contains energy and electricity consumption information measured in thousand tons of oil equivalent (ktoe).

Total electricity intensity and electricity intensity by sector were calculated by dividing electricity consumption values by the economic activity level based on the indicator definition and measured in toe/million euro.

4. Results and discussion

The EU-28 has dramatically reduced electricity intensity values in 21 years. The intensity index figures for 2019 represent only 61.10% of the 1995 initial value. This 38.90% reduction indicates that, in general, countries of the economic bloc reduced their electricity consumption and increased value-added ratio during the period evaluated. The decomposition analysis details the contribution of the components year by year. Each one of the three components had completely different behaviors and influenced the total electricity intensity in a different way, as shown by Fig. 2.

When comparing the electricity intensity components, we see that the efficiency (U_{eff}) and structure factors (U_{str}) curves declined, while the electrification factor (U_{kwh}) increased. However, the distance between the three elements to the curve that represents the total electricity intensity value (U_{tot}) is not the same. The greater proximity of the efficiency curve to the total intensity graph indicates that energy efficiency was more relevant and had a greater participation in the reduction of the total electricity intensity values in the period 1995–2019. The following Sections 4.1, 4.2 and 4.3 provide the results achieved for the structure, electrification, and efficiency components in all EU-28 countries.

4.1. Structure component (U_{str})

Considering the structural element and analyzing results presented in Fig. 3, if there were no changes in efficiency or electrification from 1995 to 2019, total electricity intensity in 2019 would represent 95.62% of the 1995 amount, and therefore a reduction of 4.38% due to changes in economic activities composition.

Service sector share expansion in the economy may explain the decrease in electricity intensity values caused by changes in structural composition. According to the World Bank (2020), the increase of the service sector share (5.12%) was accompanied by the decline of the industry share (decrease of 4.72%) and agriculture, forestry, and fishing (decrease of 1.21%) from 1995 to 2019. The remaining amount consists of other less relevant activities. It must be emphasized that this movement refers to sectoral growth rates relative to the total economy, which does not mean that only the service sector has grown during this interval. The volume of goods supplied by the EU manufacturing industry, for example, has continued to increase even with all this structural change,

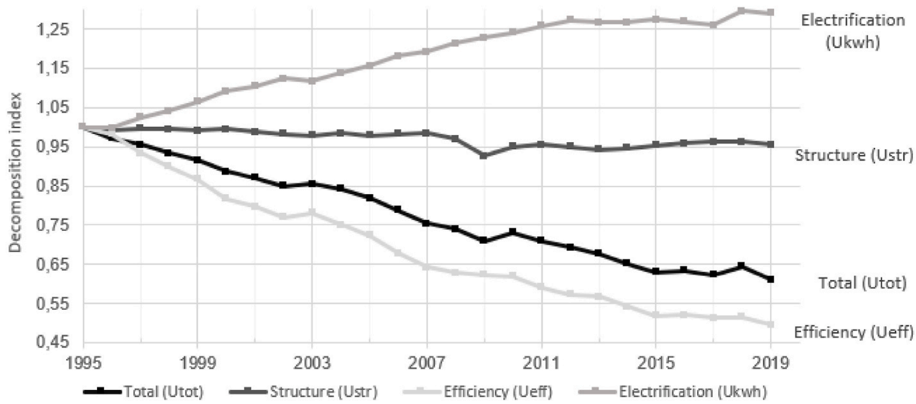

Fig. 2. EU-28 evolution of the three components of electricity intensity (1995–2019).

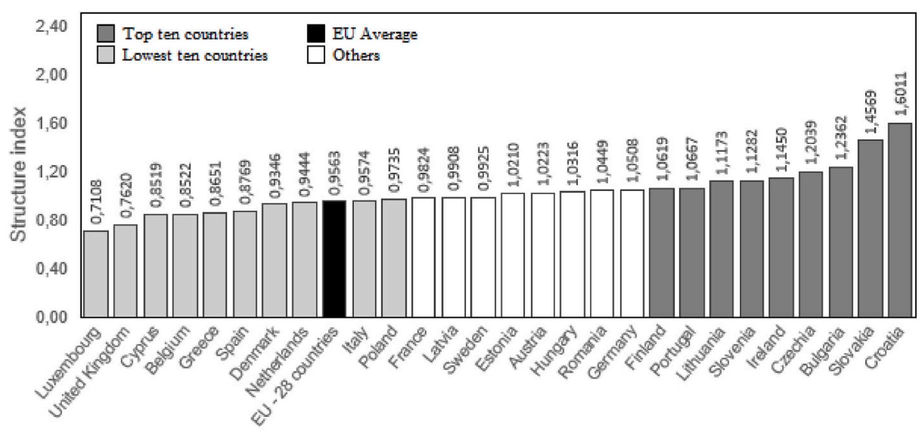

Fig. 3. Structure component in EU-28 countries (1995–2019).

as highlighted by the EC Directorate General for Enterprise and Industry (2015), and only reduced its share of overall economic activity.

Services activities are less energy intensive than industry, as they generally do not depend on heavy machinery and do not consume much electricity in relation to the potential economic value generated, explaining the reduction in electricity intensity caused by changes in economic structure.

Results for the structure component were uniform across the EU countries. Despite the dynamic nature of the economy, structural changes that caused variation in electricity intensity were rather similar and the structural index was close to 1.00 in the EU-28 countries. Croatia, Slovakia, Bulgaria, Czechia, Ireland, Slovenia, Lithuania, Portugal, Finland, Germany, Romania, Hungary, Austria and Estonia were the countries that had structural indices above 1.00, showing that changes in the economic activity of these countries would increase total electricity intensity values if there were no changes in the efficiency or electrification field.

Furthermore, we see that the among the countries with a higher variation from one in this index are a number of East European countries, (as Croatia, Slovakia, Bulgaria, Czechia, Slovakia or Lithuania) which is not surprising as these economies went through a deep economic transformation while they were transitioning from communist regimes to democracies (Gevorkyan, 2018).

4.2. *Electrification component* (U_{kwh})

The electrification factor curve shows an increasing trend over the years and, except for 1996, this component always presented values above 1.00. The value achieved for this index in the 1995–2019 period ($U_{kwh} = 1.2909$) implies that, if there had been no variation in structural and efficiency factors during this period, the total electricity intensity in 2019 would have been 29.09% higher than in 1995.

The electrification component increase was practically constant from 1996 to 2012, and since then this index has stabilized at around 1.27 up to the end of 2019. Considering that these values have always remained above 1.00 in the period evaluated, we see that GVA growth in EU did not occur at the same pace as the increase in electricity consumption, causing an increase in the electricity intensity value.

Extending the granularity of the decomposition analysis illustrated in Fig. 3, a breakdown of the electrification indices obtained across the EU-28 over the period 1995–2019 is given in Fig. 4. The only country with an electrification index lower than 1.00 was Austria.

Although Austria had a 47% growth in electricity consumption (Eurostat, 2020a), it also had an economic growth of almost 100% in the same period (Eurostat, 2020b), thus contributing to the reduction in total electricity intensity. All other countries had economic growth rates below the rate of increase of electricity share in the total final energy consumption, justifying most of the electrification indices above 1.00.

Even though the electrification factor contributed to the increase of electricity intensity, the greater participation of electricity in the energy consumption profile may be a major contributor to achieving sustainability goals and the final result of these energy policy definitions can be positive. A study carried out by the American Council for an Energy-Efficient Economy – ACEEE (2019) demonstrated that the electrification and energy efficiency processes are not conflicting factors, since energy efficiency plays a central role in many electrification strategies. If designed in parallel, both are capable of saving energy (final energy consumption), saving money, and reducing GHG emissions (ACEEE, 2019).

Finally, regarding country differences, we see from Fig. 4 that the

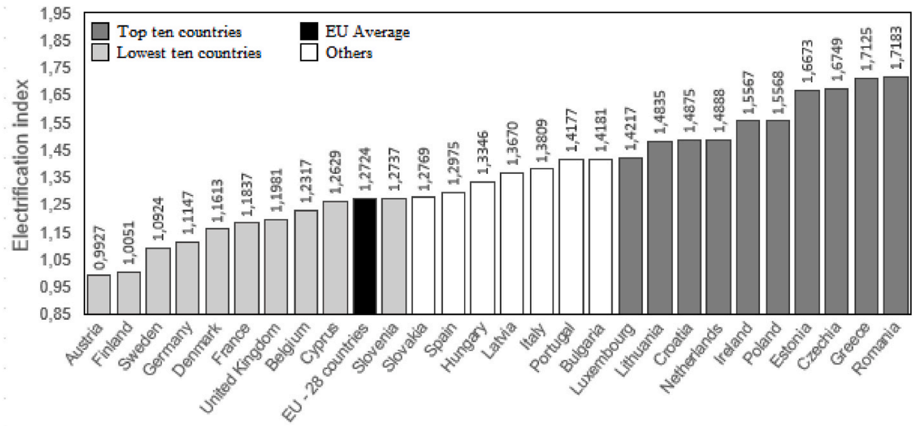

Fig. 4. Electrification component in EU-28 countries (1995–2019).

countries that have a higher electrification component are mostly in East Europe. This may be the result of their economy transitioning, as well as their integration with the Western Europe Electric Market.[1]

4.3. *Efficiency component (U_{eff})*

The efficiency factor had more representative results than the other components, having contributed to the reduction of electricity intensity in all the EU-28 countries (Fig. 5). Even though structure, and especially the electrification factor, was important in the variation of the electricity intensity, the results provide empirical evidence that the efficiency factor was the key influencer of this indicator.

If there had been no changes in the economic structure and the electricity maintained its share in the total final energy consumption, the electricity intensity indicator in 2019 would represent 49.50% of the value recorded in 1995, and, therefore, would indicate a reduction of 50.50% due exclusively to efficiency improvements throughout the electricity consumption chain. The value achieved is higher than the actual reduction (38.90%) and, therefore, taking all three components into account confirms that energy efficiency played a fundamental role in optimizing the consumption of electricity over those years.

Furthermore, as shown in Fig. 2, since 2012 the structural and electrification components have stabilized, with no increase or decrease in their curves. In the 2012–2019 period, it was verified that these components achieved indices very close to 1.00 ($U_{str} = 0.9969$ and $U_{kwh} = 0.9998$), and, therefore, had no influence on the electricity intensity indicator. So, we have evidence that, in recent years, the reduction in the intensity index was only due to efficiency improvements, further increasing the relevance of energy efficiency measures and plans.

From Fig. 5 we can also see a split between West and East Europe in terms of efficiency increase, being that in east European countries it has been much higher which may reflect the fact, as pointed earlier, that under the initial part of this period these countries were under an economic transformation from a planned economy (where efficiency gains were not a priority) towards a market economy. The case of Ireland is somewhat different as its GDP is inflated due to the tax policy that attracted the headquarters of more than 1500 multinationals and distorted the statistics as shown by Honohan (2021).

5. Conclusion and policy implications

Despite being an enlightening indicator, deviations in electricity intensity may also be difficult to support clear conclusions, as factors influencing it arise and need to be accounted for. In addition to energy efficiency, electricity intensity can also be changed by variations in the economic activity profile or by the increase of the electricity share in the total final energy consumption.

This study helps to understand which forces that drive changes in electricity intensity and what is the importance of each one of these components was in the EU-28 from 1995 to 2019. In order to answer these questions, an adaptation of the LMDI method was proposed. This method was first developed by Ang and Choi (1997) and, in this study, it was upgraded by adding a component called the electrification factor, a feature never used before, to the best of our knowledge.

The decomposition analysis carried out with in this research work is a complementary contribution to the evaluation of the effectiveness of energy efficiency measures in the EU since it established the distinctive influence of the efficiency factor. In this way, if there were merely improvements in energy efficiency, and simultaneously no changes in either in electrification, or in the economic structure of the EU-28 (from 1995 to 2019), electricity intensity values would have decreased by 50.50% due exclusively to energy efficiency measures. The results obtained advocate that EU efficiency measures focused on the electricity sector had an even greater positive impact than expected, since the electricity intensity decrease recorded before the decomposition was 38.90%.

The methodology and method applied can be easily replicated in other countries constituting an opportunity for future research, only restricted by data availability. In addition to the reproduction of the method, there is an opportunity to relate the achieved results obtained from the decomposition to other economic variables, such as energy or electricity prices. That association can generate forecasts of energy efficiency and electrification components variation based on the prices applied in a dynamic energy market. Also, the EU-28 countries have their particularities that influences the electricity intensity, and a country-specific efficiency policy could also be considered.

Deviations in electricity intensity may also be difficult to support clear conclusions, as factors influencing it arise and need to be accounted for. In addition to energy efficiency, electricity intensity can also be changed by variations in the economic activity profile or by the increase of the electricity share in the total final energy consumption.

Seeing that the goals of public policies such as 20-20-20 EU (EC, 2015) have been intensified, it is crucial to highlight the policy implications of our findings.

First, policy makers should continue to promote technological innovations since the relevant contribution of the efficiency component proved to be evident, and the adopted strategies generated solid results considering the electricity intensity indicator. Theses incentives encourage effectiveness and can contribute for an even greater reduction in the efficiency factor.

[1] For an assessment of the European single market in electricity see Pollitt (2019).

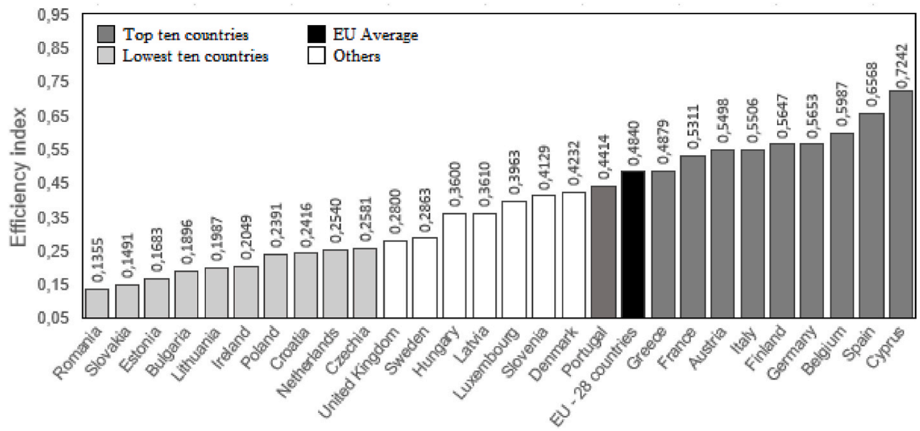

Fig. 5. Efficiency component in EU-28 countries (1995–2019).

Second, since U_{eff} values were diverse across EU-28 countries and each one has its particularity that influences the electricity intensity, a dedicated country-specific efficiency policy could be designed, particularly in those Member-States that presented an efficiency index above the EU average.

Finally, seeing that the real contribution of the efficiency factor to the electricity intensity was accounted for, a future policy measure could encompass the coupling of the decomposition results presented here with outputs of an assessment on the public sector energy efficiency policies. This association could determine how successful the energy efficiency plans in electrical systems are, complementing the contribution of this research and guiding future public policies in the energy sector.

CRediT authorship contribution statement

Frederico Perillo: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Patrícia Pereira da Silva:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Pedro A. Cerqueira:** Conceptualization, Methodology, Data curation, Writing – review & editing.

Declaration of competing interest

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

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References

ACEEE, 2019. Electrification and efficiency: crafting an enduring relationship. Retrieved December 29, 2019, from ACEEE Blog website: https://aceee.org/blog/2019/01/electrification-and-efficiency.

Ang, B.W., 1994. Decomposition of industrial energy consumption: the energy intensity approach. Energy Econ. 16 (3), 163–174.

Ang, B.W., 1995. Decomposition methodology in industrial energy demand analysis. Energy 20 (1), 1081–1095.

Ang, B.W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method. Energy Pol. 32, 1131–1139. https://doi.org/10.1016/S0301-4215(03)00076-4.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Pol. 33, 867–871. https://doi.org/10.1016/j.enpol.2003.10.010.

Ang, B.W., 2015. LMDI decomposition approach: a guide for implementation. Energy Pol. 86, 233–238. https://doi.org/10.1016/j.enpol.2015.07.007.

Ang, B.W., Choi, K.-H., 1997. Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. Energy J. 18 (3), 59–73.

Belzer, D.B., 2014. A Comprehensive System of Energy Intensity Indicators for the U.S.: Methods, Data and Key Trends. Retrieved from. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22267.pdf.

Bhattacharyya, S.C., Matsumura, W., 2010. Changes in the GHG emission intensity in EU-15: lessons from a decomposition analysis. Energy 35 (8), 3315–3322. https://doi.org/10.1016/j.energy.2010.04.017.

Comission, European, 2021a. Communication from the Comission - tackling rising energy prices: a toolbox for action and support. Retrieved October 24, 2021, from EUR-Lex website: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A660%3AFIN&qid=1634215984101.

Comission, European, 2021b. Directive of the European parliament and of the Council on energy efficiency. Retrieved October 24, 2021, from EEA website: https://ec.europa.eu/info/sites/default/files/amendment-energy-efficiency-directive-ambition-2030-climate-target-with-annexes_en.pdf.

Cornillie, J., Fankhauser, S., 2004. The energy intensity of transition countries. Energy Econ. 26, 283–295. https://doi.org/10.1016/j.eneco.2004.04.015.

EC, 2015. EU industrial structure 2015. In: The Directorate General for Enterprise and Industry. https://doi.org/10.2769/28487.

Energy Agency, International, 2019a. Energy intensity - glossary. Retrieved May 18, 2019, from International Energy Agency - IEA website: https://www.iea.org/about/glossary/e/#tabs-2.

Energy Agency, International, 2019b. World energy outlook. Retrieved from. https://www.iea.org/reports/world-energy-outlook-2019.

Environment Agency, European, 2012. Electricity intensity and electricity consumption per employee in services. Retrieved May 20, 2019, from European Environment Agency website: https://www.eea.europa.eu/data-and-maps/figures/electricity-intensity-and-unit-consumption-1.

Eurostat, 2020a. Complete energy balances. Retrieved March 25, 2022, from Eurostat - Your key to European statistics website: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en.

Eurostat, 2020b. Gross value added and income by A*10 industry breakdowns. March 25, 2022, from Eurostat - Your key to European statistics website: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a10&lang=en.

Filippini, M., Hunt, L.C., 2010. Energy Demand and Energy Efficiency in the OECD Countries: a Stochastic Demand Frontier Approach. Guildford.

Filippini, M., Hunt, L.C., 2015. Measurement of energy efficiency based on economic foundations. Energy Econ. 52, S5–S16. https://doi.org/10.1016/j.eneco.2015.08.023.

Fisher-Vanden, K., Jefferson, G.H., Liu, H., Tao, Q., 2004. What is driving China's decline in energy intensity. Resour. Energy Econ. 26, 77–97. https://doi.org/10.1016/j.reseneeco.2003.07.002.

Gevorkyan, A.V., 2018. Transition Economies: Transformation, Development, and Society in Eastern Europe and the Former Soviet Union. Routledge.

González, P.F., Moreno, B., 2015. Analyzing driving forces behind changes in energy vulnerability of Spanish electricity generation through a Divisia index-based method. Energy Convers. Manag. 92, 459–468. https://doi.org/10.1016/j.enconman.2014.12.083.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., et al., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527. June 2018, Retrieved from. https://www.nature.com/articles/s41560-018-0172-6.

Herrerias, M.J., Liu, G., 2013. Electricity intensity across Chinese provinces: new evidence on convergence and threshold effects. Energy Econ. 36, 268–276. https://doi.org/10.1016/j.eneco.2012.08.026.

Honohan, P., 2021. *Is Ireland Really The Most Prosperous Country In Europe?* (No. 1/EL/21). Central Bank of Ireland.

Inglesi-Lotz, R., Blignaut, J.N., 2012. Electricity intensities of the OECD and South Africa : a comparison. Renew. Sustain. Energy Rev. 16 (7), 4491–4499. https://doi.org/10.1016/j.rser.2012.04.004.

Inglesi-Lotz, R., Pouris, A., 2012. Energy efficiency in South Africa: a decomposition exercise. Energy 42 (1), 113–120. https://doi.org/10.1016/j.energy.2012.04.002.

Intergovernmental Panel on Climate Change, 2014. Climate change 2014 mitigation of climate change. In: Climate Change 2014 Mitigation of Climate Change. https://doi.org/10.1017/cbo9781107415416.

IRENA, 2019. Global energy transformation: a roadmap to 2050 (2019th ed.). https://www.irena.org/DigitalArticles/2019/Apr/-/media/652AE07BBAAC407ABD1D45F6BBA8494B.ashx.

Liddle, B., 2009. Electricity intensity convergence in IEA/OECD countries: aggregate and sectoral analysis. Energy Pol. 37, 1470–1478. https://doi.org/10.1016/j.enpol.2008.12.006.

Liddle, B., 2012. OECD energy intensity: measures, trends, and convergence. Energy Effic. 5 (4), 583–597. https://doi.org/10.1007/s12053-012-9148-8 PM.

Löschel, A., Pothen, F., Schymura, M., 2015. Peeling the onion: analyzing aggregate, national and sectoral energy intensity in the European Union. Energy Econ. 52, S63–S75. https://doi.org/10.1016/j.eneco.2015.09.004.

Metcalf, G.E., 2008. An empirical analysis of energy intensity and its determinants at an empirical analysis of energy intensity and its determinants at the state level. Energy J. 29 (3), 1–26.

Parker, S., Liddle, B., 2016. Energy efficiency in the manufacturing sector of the OECD: analysis of price elasticities. Energy Econ. 58, 38–45. https://doi.org/10.1016/j.eneco.2016.06.003.

Pollitt, M.G., 2019. The European single market in electricity: an economic assessment. Rev. Ind. Organ. 55 (1), 63–87.

Song, F., Zheng, X., 2012. What drives the change in China's energy intensity : combining decomposition analysis and econometric analysis at the provincial level. Energy Pol. 51, 445–453. https://doi.org/10.1016/j.enpol.2012.08.044.

Sugiyama, M., 2012. Climate change mitigation and electrification. Energy Pol. 44, 464–468. https://doi.org/10.1016/j.enpol.2012.01.028.

UN, 2015. Transforming our world: the 2030 agenda for sustainable development. https://doi.org/10.1163/157180910X12665776638740.

Verbič, M., Filipović, S., Radovanović, M., 2015. Determinants of energy intensity in the European Union: a panel data analysis. Energy 92, 547–555. https://doi.org/10.1016/j.energy.2015.07.011.

Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R., et al., 2012. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. Science 335 (6064), 53–59. https://doi.org/10.1126/science.1208365.

World Bank, 2019. World development indicators. Retrieved September 26, 2019, from World Bank website: https://databank.worldbank.org/reports.aspx?source=2&series=NV.AGR.TOTL.ZS&country=#.

Wu, Y., 2012. Energy intensity and its determinants in China's regional economies. Energy Pol. 41, 703–711. https://doi.org/10.1016/j.enpol.2011.11.034.