1 2 9 0

UNIVERSIDADE Ð COIMBRA

Frederico Loureiro Perillo

BEYOND THE EFFICIENCY CONTRIBUTION

A DECOMPOSITION ANALYSIS OF ELECTRICITY INTENSITY IN EUROPEAN UNION

Master Dissertation in Energy for Sustainability, developed on the specialization branch in Energy Systems and Energy Policies, supervised by Professor Patrícia Pereira da Silva and co-supervised by Professor Pedro André Cerqueira, presented to the Faculty of Science and Technology of the University of Coimbra as part of the requirements for the award of the Master Degree

March 2020

Dissertação dedicada a Celso, Alice e João,

que inspiram e representam passada, presente e futura geração.

ACKNOWLEDGMENTS

Experiencing the historic University of Coimbra in its 730th anniversary was quite special. Fortunately, this academic step was not achieved alone, and those who contributed to this important milestone must be acknowledged.

Firstly, I would like to recognise Professor Patrícia Pereira da Silva, Ph.D. and Professor Pedro André Cerqueira, Ph.D., for supervising this dissertation. I am very grateful for the autonomy received, perfectly balanced with the availability to support the research process. The guidance and critical analysis were also crucial on determining the research ambition.

I would like to appreciate the support given by the Energy for Sustainability (EfS) initiative of the University of Coimbra. Professors and students were always available to provide academical support and share experiences.

Furthermore, I am also thankful to the professors from the Energy Engineering undergraduate course at Pontíficia Universidade Católica de Minas Gerais, who inspired and encouraged me to follow my academic path.

Finally, I express my sincerely thanks to my family and friends, unconditional supporters of my decisions and understanding at times when exclusive dedication to this research was necessary.

ABSTRACT

The energy sector is fundamental for sustainable development. Maintaining high levels of economic activity while reducing electricity consumption is still one of the main challenges to overcome.

In this context, electricity intensity is a key indicator in assessing the economic efficiency because it is a measure of the economy output related to the electricity demanded. However, a simplistic analysis of the electricity intensity index does not reveal much, since the deviations in this indicator are the result of changes in its different components. Therefore, the objective of this dissertation is to address these components influence in detail, decomposing the electricity intensity indicator in European Union.

Complementing the logarithmic mean Divisia index (LMDI) method introduced by Ang (2015), an upgrade is proposed, by breaking down the intensity component and adding a new element to the decomposition methodology. Consequently, the components of the electricity intensity are three: structure, efficiency and electrification. This enhancing feature, innovative to the best of our knowledge, is fundamental in distinguishing the real influence of the efficiency component from other elements, considering that energy efficiency goals are becoming more stringent and have to be perfectly measured.

Results from the upgraded decomposition demonstrated that the impact caused by the efficiency component was, in fact, greater than it appeared. If there had been merely improvements in energy efficiency, and simultaneously no changes neither in the economic structure, nor in the electrification rate, the electricity intensity index would have decreased 48.64% from 1995 to 2017, a result 8.75% greater than what actually occurred.

The structural factor displayed minor influence in electricity intensity, even though the service sector increased its shared by 5.12% and the economic activity profile of EU has changed. Additionally, the electrification component contributed to increase the intensity indicator, since the electricity consumption has grown at a higher rate than the economy output.

Finally, a partitioned analysis demonstrated that the reduction in electricity intensity was solely caused by efficiency improvements in the 2012-2017 cycle, suggesting positive evidence regarding the success of energy efficiency measures in the EU.

Key words: Electricity intensity; Energy efficiency; Electrification; Economic activity; Decomposition

RESUMO

O setor de energia é fundamental para o desenvolvimento sustentável. Manter os níveis de atividade econômica enquanto reduz-se o consumo de eletricidade é um dos principais desafios a ser superado.

Neste contexto, a intensidade elétrica é um indicador chave na avaliação da eficiência econômica por ser uma medida da produção da economia relacionada à eletricidade demandada. No entanto, a análise simplista do índice de intensidade elétrica não é muito reveladora, uma vez que os desvios neste índice são resultado de mudanças nos seus diferentes componentes. Desta forma, o objetivo desta dissertação é abordar detalhadamente a influência destes componentes, decompondo o indicador de intensidade elétrica na União Europeia.

Complementando o método *logarithmic mean Divisia index* (LMDI) introduzido por Ang (2015), é proposta uma atualização que decompõe o componente de intensidade e adiciona um novo elemento à metodologia de decomposição. Consequentemente, os componentes da intensidade elétrica são três: estrutura, eficiência e eletrificação. Este aprimoramento, inovador de acordo com o nosso conhecimento, é fundamental para distinguir a real influência do componente de eficiência dos outros elementos, considerando que as metas de eficiência energética têm se tornado mais rigorosas e precisam ser perfeitamente mensuradas.

Os resultados da decomposição atualizada demonstraram que o impacto causado pelo componente de eficiência foi, na verdade, maior do que aparentava. Se houvesse apenas melhorias de eficiência energética e, simultaneamente, nenhuma mudança na estrutura econômica e na taxa de eletrificação, o índice de intensidade elétrica teria diminuído 48,64% entre 1995 e 2017, valor 8,75% maior ao que realmente ocorreu.

O fator estrutural apresentou menor influência na intensidade elétrica, embora o setor de serviços tenha aumentado a sua participação em 5,12% e a estrutura econômica da UE tenha mudado. Adicionalmente, o componente de eletrificação contribuiu para aumentar o indicador de intensidade, já que o consumo de eletricidade cresceu a taxa superior à produção econômica.

Por fim, uma análise particionada demonstrou que a redução na intensidade elétrica foi causada exclusivamente por melhorias de eficiência no ciclo 2012-2017, sugerindo evidências positivas a respeito do sucesso das medidas de eficiência energética na UE.

Palavras-chave: Intensidade elétrica; Eficiência energética; Eletrificação; Atividade econômica; Decomposição

LIST OF ABBREVIATIONS AND ACRONYMS

ACEEE	American Council for an Energy-Efficient Economy
ADEME	*Agence de l'environnement et de la maîtrise de l'énergie*
AT	Austria
BE	Belgium
BG	Bulgaria
CEC	Commission of the European Communities
CEECs	Central and Eastern European Countries
CRES	Centre for Renewable Energy Sources and Saving
CY	Cyprus
CZ	Czechia
DE	Germany
DK	Denmark
EC	European Commission
ECB	European Central Bank
ECEEE	European Council for an Energy Efficiency Economy
EE	Estonia
EEA	European Environment Agency
EED	Energy Efficiency Directive
EL	Greece
EMCC	European Monitoring Centre on Change
ERM	European Restructuring Monitor
ES	Spain
EU	European Union
EU-28	European Union 28 countries
FI	Finland
FR	France
GDP	Gross domestic product
GVA	Gross value added
HR	Croatia

HU	Hungary
IE	Ireland
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IT	Italy
ITRE	European Parliament's committee on Industry, Research and Energy
KTOE	Thousand tonnes of oil equivalent
LMDI	Logarithmic mean Divisia index
LT	Lithuania
LU	Luxembourg
LV	Latvia
MNEs	Multinational enterprises
MT	Malta
NL	Netherlands
OECD	Organisation for Economic Co-operation and Development
PL	Poland
PT	Portugal
RES-E	Renewable energy source electricity generation systems
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
TFC	Total final consumption
TOE	Tonnes of oil equivalent
UK	United Kingdom
US	United States

List of figures

TABLE OF CONTENTS

1. Introduction

Broadly, in a current scenario of energy market transition and having sustainable development goal achievement in mind, there is a clear need to balance economic growth, energy consumption and exploitation of energy resources. Aspects related to the energy sector range from the definition of strategies concerning the energy matrix to the way by which fuels and electricity are consumed. Consequently, energy policy is an area of politics that transcends its borders and impacts not only the energy sector of a country, due to the importance that energy industry has acquired over time, but also several important areas such as economy, environmental, social, foreign relations, among others.

Therefore, policy makers need to consider many preponderant factors to support their choices. Among all the elements that underpin these decisions, one of the greatest challenges is to maintain the levels of productivity and economic capacity by reducing the energy resources input. This relationship between resources exploitation and the amount of wealth produced is commonly termed as intensity. In this sense, energy intensity is a measure of total primary energy use per unit of gross domestic product (GDP), as defined by the International Energy Agency, IEA (2019a).

Considering that in some cases the definitions of energy and electricity may be unclear, it is important to highlight a basic distinction. In 2016, the electricity consumption corresponded to 18.8% of the world total final energy consumption (IEA, 2018a). The perception that electricity corresponds to a higher amount of total energy consumption is due to the great relevance of electrical energy in routine activities. The electricity share is in fact increasing every year and is expected to represent 31% of global final energy needs by 2040 (IEA, 2019b). Nevertheless, it is still far from corresponding to the total energy consumption, reinforcing the need to clearly distinguish the concepts.

On the one hand, the significance of electricity cannot be considered big enough to correspond to the total final energy consumption, since other forms such as oil, coal and natural gas are still more representative. On the other hand, the electricity share is sufficiently large to be exclusively investigated.

Given these important differences, a similar and equally representative indicator can be obtained if the constituent energy is replaced by electricity. As defined by the European Environment Agency, EEA (2012), electricity intensity represents the ratio of electricity consumption to GDP added value, thus being an important indicator of efficiency in electricity consumption related to economic productivity. This definition is also used by the *Agence de l'Environnement et de la Maîtrise de l'Énergie*, ADEME (2019) and some authors such as Liddle (2009), Inglesi-Lotz & Blignaut (2012) and Hien (2019).

As the concern for implementation of energy efficiency measures has increased, whether on the supply or demand side, the electricity intensity indicator has been more frequently used in the analysis of the countries' economic behaviour, not only by the aforementioned Liddle (2009) and Inglesi-Lotz & Blignaut (2012), but also by Herrerias & Liu (2013). In European Union (EU-28), the electricity intensity has declined 39.86% from 1995 to 2017 (Eurostat, 2019a), and this deviation could indicate an efficiency increase in the economy.

However, as well described by Löschel et al. (2015), the intensity indicator seems to have the answer to all questions, but it still not meaningful. Even though electricity intensity is influenced by energy efficiency, and since this indicator is a measure of maintaining the economic activity while reducing electricity consumption, this is not the single influencing factor. The evaluation of this intensity index goes far beyond just a numerical analysis and must be detailed to explain the reasons that caused this decrease over the years.

Analysing the components of change in electricity intensity values is fundamental at a time when energy efficiency improvements are happening at a fast pace and electricity assumes an increasingly share in the total final energy consumption. Assessing the behaviour of these components also proofs relevant, considering that the analysis of electricity intensity is not trivial, and the variation of any of the elements 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.

Considering that this is a fundamental subject that has not been detailed in existing literature, this dissertation proposes a decomposition analysis of the electricity intensity indicator in EU-28. Departing from the decomposition methodology by Ang & Choi (1997), an upgrade 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 & Zheng (2012), the electrification factor is the other considered component in this electricity intensity decomposition. As defined by Sugiyama (2012), electrification is the replacement of other energy sources by electricity on the demand side and, therefore, it is highly representative in this context.

Besides assessing the historical profile of electricity intensity in the EU, the objective is to decompose this indicator and evaluate the influence of its components, answering the following questions:

- What are the forces that drive changes in electricity intensity and what is the importance of each one of these components?
- How have these components behaved in EU recently?
- Based on the decomposition results, what is the actual impact of energy efficiency in total electricity intensity index?
- Considering only variations in electricity intensity values and the results of the decomposition analysis, how effective were the proposed energy efficiency plans and measures?

At the end of this research, it is expected to have an assessment of electricity intensity, as well as the relationship of important economic and technical variables. In addition, a detailed analysis of the behaviour of each of the electricity intensity components in all EU countries is to be accounted for, contributing to the understanding of the real impact of energy efficiency on the intensity index. Finally, this assessment can contribute not only to the scientific community, but also to policy makers, regulatory agencies, environmental bodies and utilities companies in their issues about electricity consumption, electricity intensity and energy efficiency.

The dissertation document is organized as follows, starting with Chapter 1 that contextualizes the topic. This introduction presents the motivation to go further, reveals the objectives of this study and punctuates the research main questions.

Chapter 2 comprises the relevant literature review, divided into energy and electricity intensity studies (Section 2.1), decomposition methodology literature (Section 2.2) and a review of the decomposition analysis methods (Section 2.3).

In Chapter 3 the methodology is described, defining strategies and the components of electricity intensity (Section 3.1). The following Sections 3.2, 3.3 and 3.4 detail each of these components, elucidating their importance and behaviour in the EU in recent years.

Chapter 4 describes the adopted method and the accessed data. Section 4.1 discusses the traditional LMDI approach and its characteristics, followed by Section 4.2 which presents the upgrade proposed by this dissertation. Section 4.3 is an important description of how to interpret the achieved results and Section 4.4 details collected data.

In Chapter 5, results are presented and discussed. Firstly, Section 5.1 reviews the achieved results in the first decomposition methodology. The following Section (5.2) explores the achieved results in the second decomposition methodology, considering the addition of a new component. Complementing this analysis, a more detailed breakdown is proposed across Section 5.3 by dividing the 1995-2017 period into shorter cycles, following a chronological order organized in sections 5.3.1, 5.3.2, 5.3.3 and 5.3.4.

Finally, Chapter 6 presents the key achievements and research conclusions, in addition to suggesting alternatives for future work.

2. Literature Review

In order to assess the main issues raised by this research, it is fundamental to evaluate the prior work which is somehow connected to the decomposition of electricity intensity. Chapter 2 is a literature review, starting with an analysis of studies on energy and electricity intensity (Section 2.1) and further analysing other studies related to the methodology and method defined for this dissertation (Sections 2.2 and 2.3).

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

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 fundamental constituents of the energy policy agenda. Given these pillars that sustain current trends in energy guidelines around the world, energy and electricity intensity stand out for being measures of the structural and technological profile of the economy.

Naturally, considering that this is a recurring subject in political and economic forums, research on intensity indicators in the energy sector has grown in recent years, although most of them are focused only on energy intensity and a barely few have electricity intensity as the main topic. Relevant authors such as Fisher-Vanden et al. (2004) and Cornillie & Fankhauser (2004) defined energy intensity as being the ratio of real energy consumption to real GDP, going beyond the IEA (2019a) definition that focused only on primary energy. The authors went further and considered energy intensity not only an indicator of how efficient the economy of a country or a region is, but also how it behaves in relation to socioeconomic and environmental aspects.

As mentioned by Cornillie & Fankhauser (2004), a country's energy consumption depends on socio-economic and environmental factors - such as the composition of its economic activity, resource endowment, population density and climate - and the analysis of pure values of energy intensity cannot be used to evaluate the efficiency of a region. Therefore, the comparison of energy or electricity intensity values between different countries is not always correct.

Löschel et al. (2015) deepened 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 EU member countries. These authors had a great contribution to this topic and, in addition to structural and efficiency analysis, they were able to have a deep insight in the way in which economic variables affected energy intensity (Löschel et al., 2015).

Belzer (2014) also 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. The IEA Energy Efficiency Report (International Energy Agency, 2018b) also separated the economies of the associated countries into different sectors and assessed energy intensity under structural and technological aspects, adding that a shift from one energy-intensive economic activity to another less-intensive can cause representative changes in the index values.

Some authors such as Kaufmann (2004), Hang & Tu (2007) e Verbič et al. (2017) sought a new proposal by correlating energy intensity with other economic variables, looking for external elements that influence this indicator. These authors achieved similar results, having found a negative influence of energy prices on the intensity indicator.

Considering the electricity intensity, the existing literature evaluated the convergence of this indicator in some countries or regions, such as the approach of the IEA/Organisation for Economic Co-operation and Development (OECD) countries carried out by Liddle (2009). However, the comparison between countries must be carefully evaluated since they have different climatic conditions and economic structure, and these are elemental factors for the definition of the electricity consumption profile. Herrerias & Liu (2013) headed the same way, despite the fact they focused on accessing Chinese provinces data, having observed a moderate reduction in electricity intensity across regions.

Nevertheless, energy and electricity intensity assessment must be distinguished from energy efficiency analysis, and the decomposition methodology plays a fundamental role in this regard.

2.2. Decomposition analysis methodology

Most of the literature that assessed intensity indicators and its causes used a traditional strategy to relate several specified components and the main index. This methodology is called decomposition of an intensity indicator and can be applied to different areas of the energy sector, such as in the evaluation of greenhouse gas emissions (Bhattacharyya & Matsumura, 2010), energy efficiency changes (Inglesi-Lotz & Pouris, 2012) and energy vulnerability (González & Moreno, 2015).

Regarding energy intensity, the decomposition methodology aims to understand which are the forces that drive changes in aggregate energy intensity values over time (Ang, 1994). This is one of the main approaches of authors such as Cornillie & Fankhauser (2004), Fisher-Vanden et al. (2004), Metcalf (2008), Song & Zheng (2012) and Wu (2012). On the other hand, concerning electricity intensity, no research has been found so far using this methodology to decompose this index, even though the principles are similar to those used for energy intensity.

Cornillie & 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. The authors were pioneers in using a decomposition methodology in an energy 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 & Fankhauser, 2004).

Fisher-Vanden et al. (2004) considered that there were three determining factors of changes in energy intensity - changes in economic activity, energy efficiency improvements and another factor termed ‘inaccurate statistics’. This last component was used to include other political, economic and social deviations that might have some 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 for variations in energy intensity - changes in economic activity and energy efficiency improvements. 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 & Zheng (2012) focused their research on China and used the decomposition methodology to evaluate what were the forces that led to the abrupt reduction of the energy intensity value of Chinese economy in recent years. Although there were impacts 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 efficiency increase of its industry, which now needs less energy to generate the same wealth values as years ago. 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 considerable scope to reduce if the structure of the Chinese economy changes, increasing the share of less energy intensive activities (Wu, 2012).

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

2.3. Decomposition analysis methods

The 1974 world oil crisis prompted authors to search for answers to energy sector problems. Since the end of 1970s, the index decomposition methodology became very common in the analysis of the impacts of economic and environmental variables on energy demand (Ang & Zhang, 2000).

Huntington & Myers (1987) were the first authors to list the decomposition methods that were being used around the world in the late 1980s. Years later, Ang (1995) listed 51 studies that were being used in energy and environmental analysis. In the early 2000s, Ang & Zhang (2000) went further on their research, identifying 124 authors who used the methodology of index decomposition and classifying the employed methods in two different groups: Laspeyres and Divisia indexes.

Bossanyi (1979) and Hankinson & Rhys (1983) sought to assess the structural changes in UK industry in relation to energy and electricity consumption and used the Laspeyres method as an intuitive and straightforward tool (Ang & Zhang, 2000). Then, Boyd (1987) proposed the idea of using the consolidated Divisia index approach (1925) as an alternative to the Laspeyres method, being favourable mainly for dividing the applied weights between the base year and the target year. This feature was adopted in 1987 to evaluate the US industrial energy consumption, as described by Ang & Zhang (2000), and formed the basis for further adaptations and refinements to the method, proposed by Liu et al. (1992) and Ang (1994).

Finally, after the evolution of decomposition analysis studies and based on Tornquist (1935) and Sato (1976), Ang & Choi (1997) proposed a refined method to decompose energy and gas emissions intensity for industry. This method is the well-known logarithmic mean Divisia index (LMDI), that uses specific logarithmic weight functions instead of the weights used in the Laspeyres method or in the method introduced by Boyd (1987). The LMDI was the first logarithmic mean Divisia index method used by researchers, much for its pioneering approach with no residual in the decomposition result.

The LMDI method developed by Ang & Choi (1997) was widely explored in the literature and was applied by relevant authors such as Fisher-Vanden et al. (2004), Bhattacharyya & Matsumura (2010), Inglesi-Lotz & Pouris (2012), González & Moreno (2015), as well as being used by the governments of Australia (2008) and Canada (2013) in some energy sector studies.

3. Methodology

Since the main objective is to analyse the contribution of the electricity intensity components, this dissertation adopts the decomposition methodology to answer the questions presented in Chapter 1. The considered components of electricity intensity are structure factor and intensity factor (subdivided into another two components, namely efficiency and electrification factor).

Initially, a traditional decomposition analysis is proposed, aiming to determine the influence of the elements that could cause changes in the electricity intensity values. This first decomposition analysis is expected to result in two different components: one that measures intensity improvements (intensity factor) and another that measures changes in economic activity profile (structure factor).

Following this first approach, a second and more detailed decomposition analysis is proposed. This second step is expected to break down the intensity component in another two (efficiency and electrification factors mentioned above), resulting in three components that have a contribution in electricity intensity variation: changes in energy efficiency (efficiency factor), changes in electricity consumption share over total energy consumption (electrification factor) and changes in economic activity profile (structure factor already mentioned).

The chosen methodology was defined to seek the relation between electricity intensity and its components, in addition to assessing the real influence of each of the elements on the total intensity index. This chapter discusses the structural, efficiency and electrification components and their relationship with the electricity intensity indicator, in Sections 3.1, 3.2 and 3.3 below.

3.1. Economic activity

3.1.1. Structural economic composition

World economic activity is commonly divided into different sectors for the analysis of their contribution to GDP. Segregation can also be used for the assessment of other economic, structural, social and environmental indicators contributing to better data interpretation and more accurate decision making. While large institutions such as the US Central Intelligence Agency (CIA) and World Bank segregate the economy into three sectors, namely agriculture, industry and services, other renowned groups such as the OECD and EC, through Eurostat, subdivide economy into 21 or even 64 different activities, respectively.

Although a more detailed breakdown provides additional information, this study is based on the division of economic activity used by the World Bank, which split the economy into three sectors. Such definition is justified by the fact that the data will be correlated with electricity consumption data, which are only available for the following grouping: Industry; Commercial (commercial, services, transport and others) and Agriculture (agriculture, forestry and fishing). Therefore, economic activity, electricity consumption and electricity intensity will be analysed under the scope of these three distinct sectors detailed in Table 1 below.

Table 1 - Economic activity breakdown by sector

Economic activity breakdown	Description of included sub activities
Industry	Industrial activities, including construction and manufacturing
Commercial, Services, Transport and Others	Wholesale and retail trade, transport, accommodation and food service activities
	Information and communication
	Financial and insurance activities
	Real estate activities
	Professional, scientific and technical activities; administrative and support service activities
	Public administration, defence, education, human health and social work activities
	Arts, entertainment and recreation
	Other
Agriculture, Forestry and Fishing	Agriculture
	Forestry
	Fishing

Source: Adapted from Eurostat (2019c)

Household sector was not considered in this dissertation because it has a small contribution to the economic activity and aggregates 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 hinder the results interpretation.

3.1.2. Changes in economic structure

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 as may involve uninterrupted and heavy machinery activities, while others such as agriculture, fishing and forestry tend to have reduced electricity consumptions. Therefore, the evolution of electricity intensity is not only dependent on the evolution of energy efficiency, as reported in Chapter 1, but also on the EU economy profile that has been undergoing structural changes over the last few years. Clarifying and quantifying the relevance of each of the activities is elementary in order to determine what is the importance of this economic factor in the intensity index.

According to the World Bank (2019), the EU service sector accounted for 66.03% of GDP composition in 2017, while industry and agriculture accounted for 21.86% and 1.48% respectively. The remaining amount consists of other less relevant activities. However, economic activity is quite dynamic and can react very quickly to economic crises, supply and demand variations, technological changes and other elements. Since 1995, the service sector has been increasing its share when compared to the industry and the agriculture sectors. Fig. 1 shows the evolution of the value added (% of GDP) of each of the three highlighted sectors in EU based on World Bank data (2019).

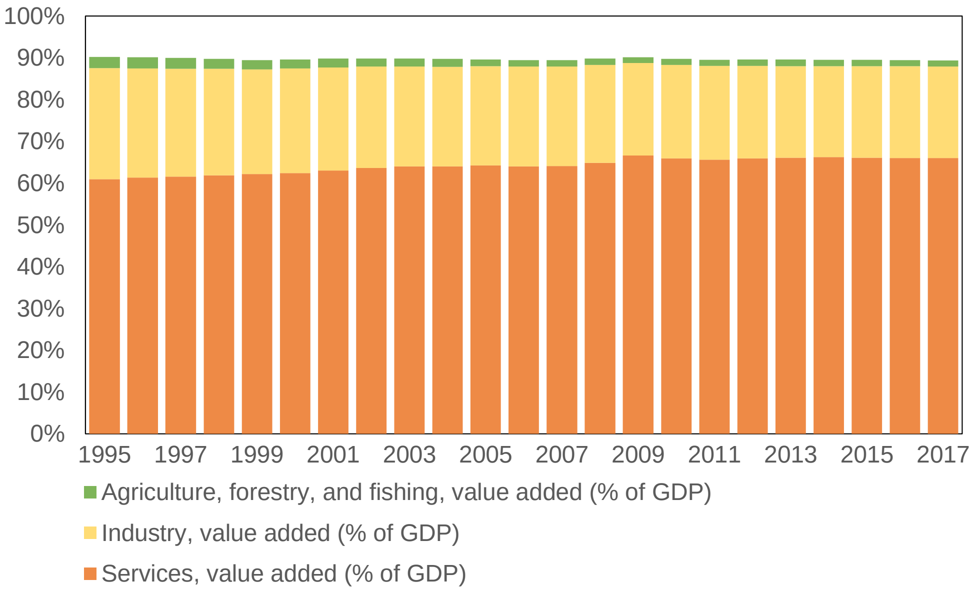

Fig. 1 - Value added (% of GDP) in EU by sector (1995-2017)
Source: Adapted from World Bank (2019)

Considerable increase can be seen in the service sector from 1995 to 2017, which goes beyond the whole economic growth in EU. According to World Bank (2019), this evolution

(5.12% over 23 years) was accompanied by the decline industry share (decreased 4.72% in 23 years) and agriculture, forestry and fishing (decreased 1.21% in 23 years). 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 had 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, as highlighted by the EC Directorate General for Enterprise and Industry (2015), and only reduced its share of overall economic activity.

Still, according to the Directorate General for Enterprise and Industry (2015), the rising trend of service activities in developed countries is explained by the Baumol's effect (Baumol, 1967) which identified that technological advancement in progressive sectors generates a response effect in non-technological sectors, and makes the relative price of services higher. This increase has made the service sector more attractive to the labour force and increased its share in economic activity, a trend observed in all developed economies (EC, 2015).

Structural changes are not only influenced by technological development and prices variation, but also by other factors such as financial crisis, globalization, outsourcing and the recent phenomenon of relocating certain activities to lower labour-cost regions, inside or outside the EU, as EC has detailed (2019). The real importance of this relocation to the economic activity, and consequently to the electricity intensity index, is discussed in Section 3.1.3.

3.1.3. EU economic relocation

To assess the impact of relocation on the EU economy, it is necessary to understand the reason for an economic activity to take place in a specific location. According to Capik & Dej (2018), the decision of setting up an activity in a certain region began to be discussed for the analysis of agricultural production from the perspective of the location theory precursor, Johann Heinrich von Thünen (1826). Von Thünen concluded that there was a relationship between land use for agricultural activities and the distance from the central marketplace (Capik & Dej, 2018). The industrialization and the society development for the city-based model made Alfred Weber perceive an evolution of Von Thünen's model and create a theory of the industries location in 1929 (Wood & Roberts, 2011). Weber identified that the installation of an industry or a company depended basically on the transportation cost, whether it is from raw materials to the manufacturing plant or from finished products to the market (Capik & Dej, 2018).

The evolution of business models and the introduction of globalization concept have reinvented the economy, introducing a new value chain with different concepts, opportunities and challenges. However, the basic ideal of most economic activities remains to be reducing production costs as much as possible to increase profit margins. Seeking competitive alternatives and internationalization, so-called multinational enterprises (MNEs) looked for new positioning strategies and expanded beyond their borders in a process that involves moving a company from one place to another or expanding installations to new locations (Capik & Dej, 2018). As pointed out by Kim & Aguilera (2016), the decisions to choose a new location to take place evaluates several characteristics, the main ones being: transport and communication infrastructures, the size of the local market, tax rates applied at that location and availability of human capital. All these considerations seek to increase productivity and income. Although technology has strongly advanced and nowadays allows communication anywhere in the world, the location decision still critical and can create alternatives to optimize all types of economic activity.

Activities displacement is highly justified concern and can cause changes in employment, energy and electricity statistics, investments, education, among others. However, there are few studies about the real impact of relocation.

One of the official EU documents assessing this issue was requested by the European Parliament's Committee on Industry, Research and Energy (ITRE). The report entitled ‘Relocation of EU industry: An overview of literature’, noted that there is no data available in Europe to quantify the real impact of relocation, but presented a set of studies that give an idea of how the economic bloc reacts to relocations and showed that industry is the main economic activity taking place in other countries (ITRE, 2006). Still according to ITRE (2006), gathered data suggested that relocation in the EU appears to be limited and the impacts on the economy are relatively small. In terms of changes in job vacancies, the European Monitoring Centre on Change (EMCC) showed through the European Restructuring Monitor (ERM) that relocation, outsourcing and offshoring represent 7.2% of planned job reductions. On the other hand, internal restructuring accounts for 76.8% of planned job reductions (EMCC, 2005). This study was conducted between 2002 and 2004 and demonstrated that, until then, the restructuring of economic activity has generated more socio-economic impacts than relocation.

ITRE also presented relocation forecasts in EU through a survey based on “1019 interviews with decision makers across the range of industries, regions and business models” (ITRE, 2006). Results showed that 24% of the interviewed have intentions to displace industry activities. However, the majority (35%) intend to maintain business within the EU by moving to Central and Eastern Europe, while another 14% intend to move facilities to China and just 3% to India.

Mentioned studies have shown an insignificant interference from relocation, outsourcing and offshoring activities in the EU economy so far, apart from the trend to remain minimal as most of the industry intending to relocate in the coming years expect to move to other countries inside EU area. Therefore, relocation impacts on electricity intensity are not relevant enough to be considered in this decomposition analysis.

3.2. Energy efficiency

3.2.1. Clarifying the concept and its benefits

Energy efficiency began to be widely discussed in the world after the 1974 oil crisis. Reducing energy supply meant that it was necessary to find ways to meet demand and ensure that supply was enough to the consumption pattern of that time (Ruffa et al., 2012). Although it has been an important concept since then, the term energy conservation is often mistakenly used to refer to energy efficiency. Schiller (2007) has well distinguished these two concepts and defined energy conservation as a reduction in energy consumption or energy-using services to save energy, while energy efficiency consists in maintaining or increasing outputs of a given activity using less energy. Oikonomou et al. (2009) have enriched energy efficiency definition by considering that the technological aspect is a key factor to reduce energy consumption without change consumer’s behaviour. The World Energy Council (2010) also defined energy efficiency improvement as being a reduction in the energy used in a particular service or activity.

As one of the electricity intensity components, energy efficiency allows economy growth using less energy resources and still providing the same service or level of comfort. Such reduction in electricity consumption, together with the wealth generation growth, results in the reduction of the intensity indicator values. The whole macroeconomic scenario mentioned comes from a sustainable development guideline that, recently, has been increasing in line with technological advances. Although not the only factor responsible for the electricity intensity variation as described in Chapter 1, the results of energy efficiency measures must be analysed in detail in order to assess their real impact on the economy.

According to Ryan & Campbell (2012), on a report published by the IEA and illustrated by Fig.2 of this dissertation, the benefits created by energy efficiency measures are the most diverse and go beyond just reducing electricity consumption. In general terms, such measures have the objective of maximizing social benefits by promoting environmental improvements and maximizing cost effectiveness, influencing household consumers, industries, utilities and regulatory agencies (Lazar & Colburn, 2013).

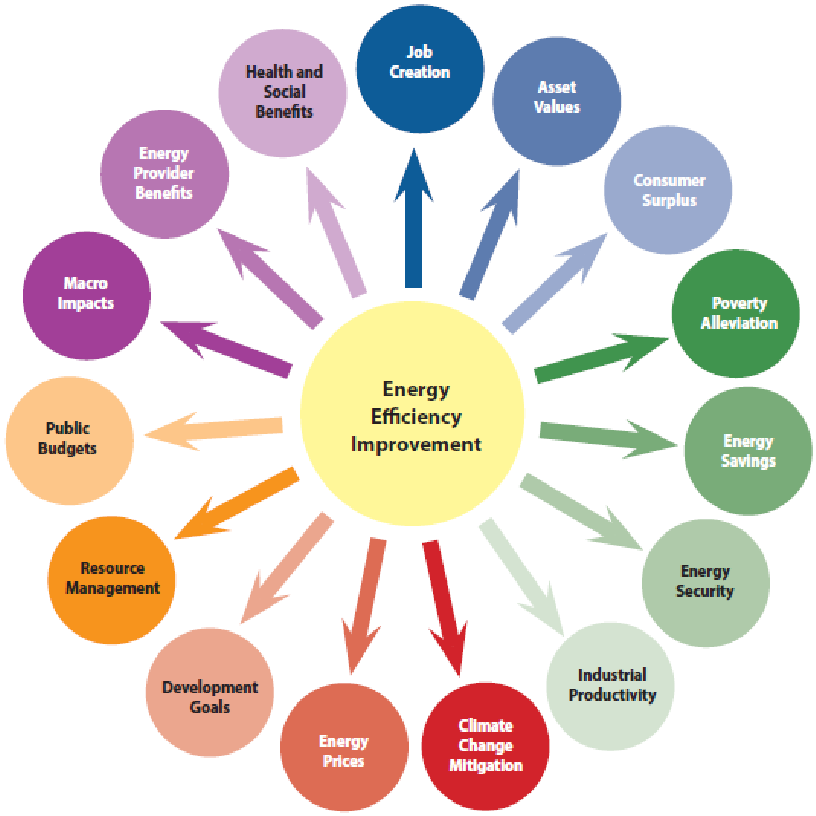

Fig. 2 - The Multiple Benefits of Energy Efficiency
Source: Ryan & Campbell (2012)

The document divulged by the IEA also presented a proposal for classifying these benefits into two different groups: direct and indirect. According to this division and as well organized by Pereira (2014), the direct benefits are those related to the energy system, while the indirect ones may be of international, national, sectoral or individual interest. This classification has reinforced the importance that energy efficiency has been taking and has put this theme on the agenda of the most diverse areas.

3.2.2. Energy efficiency evolution in EU

EU can be considered the government organization that most introduces and acts on energy and sustainability development measures. The action plans support this concern by setting goals and ambitions that guide EU countries. The energy and climate measures agenda for the future consist of three key milestones set by the European Commission (EC). The first one has become known as 20-20-20 EU-targets and aims to reduce primary energy consumption by 20%, reduce greenhouse gas emissions by 20% and increase the share of renewable energy sources generation systems (RES-E) by 20% in 2020, always comparing to 1990 levels (EC, 2010). The second imposed milestone proposes a 40% reduction in greenhouse gas emissions, an increase of 27% of the share of RES-E and a target of 27% improvements in energy efficiency by 2030 (EC, 2013). The final goal in the EU's perspective in terms of energy, climate and sustainability actions proposes a reduction of 80-95% in greenhouse gas emissions, with a safe and competitive energy system by the year 2050 (EC, 2011b). Although these three action plans have become the most important as they guide sustainability policies, efficiency measures in EU have been developed since the beginning of the 21st century. Those goals set for the future are not isolated actions and are supported by other preliminary initiatives that have made the scenario conducive to more ambitious plans.

Starting in 2000, the former Commission of the European Communities (CEC) and current EC launched the 'Action Plan to Improve Energy Efficiency in the European Community' (2000). This plan outlined simple energy efficiency initiatives to be implemented in the transportation, manufacturing and building sectors, and cited an economic potential for energy efficiency improvement of more than 18%. One of the objectives, according to the text, was "to establish the foundation for a continuous and long-term improvement in energy efficiency through the use of market forces and market transformation, with accelerated development and diffusion of new energy-efficient technologies" (EC, 2000).

In 2006, EC proposed a more detailed plan to reach the full potential identified in Europe, criticizing the EU's inability to implement energy efficiency measures until that date. The 'Action Plan for Energy Efficiency: Realizing the Potential' stressed that this potential value could reach a 20% reduction in energy consumption, in addition to the €100 billion financial potential that could be saved by taking the ten suggested measures (EC, 2006). The described expectative in this plan foresaw effects in the three to six years after its publication and evolved to underpin a very important directive in 2011, considered another major step towards an overarching effort by countries (Pereira, 2014).

This was called the 'Energy Efficiency Plan 2011' and reconsidered the efficiency measures adopted so far, including guidelines for households in addition to transport, industry and buildings (EC, 2011a). The EC, concern of reaching only half of the 2020 objectives, reinforced the role of EU, member states and other stakeholders, and restructured some actions as well described by Pereira (2014). This plan is one of the most important in the recent history of the EU energy sector as it considered energy efficiency as being the most effective solution to meet carbon and energy reduction goals, besides presenting the picture that the EU was experiencing at the time. However, some organizations such as the European Council for the Energy Efficiency Economy (ECEEE) criticized the plan for not containing technical information and not describing in detail how the program implementation could contribute to the expectations set for 2020 and 2050 (ECEEE, 2011).

Energy efficiency evolution should not only be evaluated by these plans, as the success of the measures involves the most distinct variables such as the price of electricity and other forms of energy, economic performance, technology development and market barriers. In addition to these variations, energy efficiency is also characterized by being difficult to measure due to its very characteristic problems such as rebound effect and free riders, as explained by Geller & Attali (2005) and Hossein & Khawaja (2012), respectively. In any case, dividing this analysis into distinct cycles using the plans published by the EC as milestones facilitates the overview and allows comparison between different periods. Fig. 3 illustrates the key measures taken and strategies for the future on the EU energy agenda.

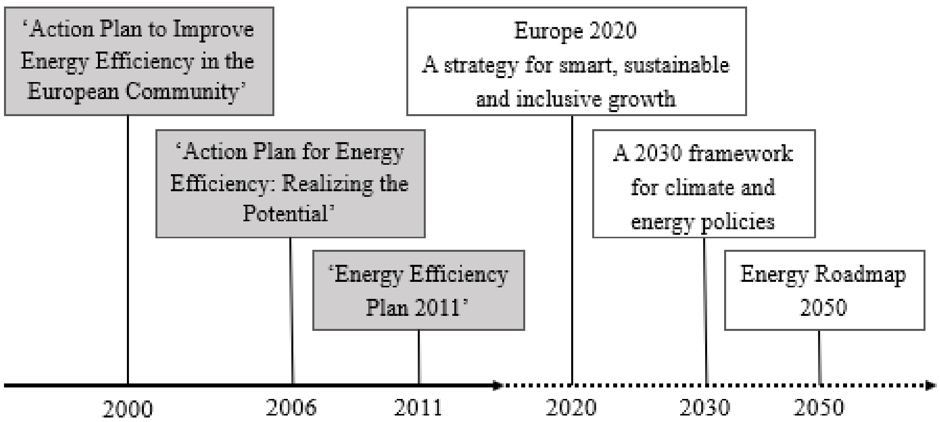

Fig. 3 - EU energy efficiency agenda
Source: Adapted from EC (2000, 2006, 2010, 2011a, 2011b, 2013)

3.2.3. Electricity intensity in EU

Despite being a well-organized and politically strong institution, the EU is also characterized by being a quite varied economic bloc because of the natural diversity of its member states. It is a huge geographical area with variety of cultural, linguistic and institutional expressions, as well as considerable climatic, economic, environmental and political diversity. This heterogeneity is reflected in the electricity intensity indicator, which widely varies across

EU countries, as shown in Table 2. Values were calculated in tonnes of oil equivalent (toe)/million euro.

Table 2 - Electricity intensity in EU countries (toe/million euro) - 2017

Country	Electricity intensity (toe/million euro)
European Union - 28 countries	12.52
Euro area (19 countries)	12.53
Belgium (BE)	14.02
Bulgaria (BG)	36.02
Czechia (CZ)	21.07
Denmark (DK)	7.26
Germany (DE)	11.53
Estonia (EE)	22.16
Ireland (IE)	5.55
Greece (EL)	18.80
Spain (ES)	13.50
France (FR)	11.70
Croatia (HR)	20.67
Italy (IT)	12.73
Cyprus (CY)	14.63
Latvia (LV)	17.57
Lithuania (LT)	16.39
Luxembourg (LU)	9.39
Hungary (HU)	22.31
Malta (MT)	13.49
Netherlands (NL)	10.81
Austria (AT)	11.86
Poland (PL)	22.36
Portugal (PT)	17.48
Romania (RO)	16.26
Slovenia (SI)	23.51
Slovakia (SK)	23.50
Finland (FI)	26.06
Sweden (SE)	16.81
United Kingdom (UK)	8.06

Source: Based on Eurostat (2019a, 2019c)

While countries such as Ireland (5.55), Denmark (7.26), United Kingdom (8.06) and Luxembourg (9.39) presented low values in 2017, other countries such as Finland (26.06) and Bulgaria (36.02) were above the average of all listed countries. Although the intensity indicator must not be superficially evaluated and should consider distinct aspects, the divergent figures show how versatile the EU area can be.

However, those presented indexes were much higher at a time when energy efficiency was scarcely considered. Average values of all EU countries in 1995 were almost two times higher than in 2017, as illustrated by Fig. 4. During this period, energy efficiency has become a very hot topic on sustainability agenda, as highlighted by Section 3.2.2, and the electricity intensity indicator has been declining year after year.

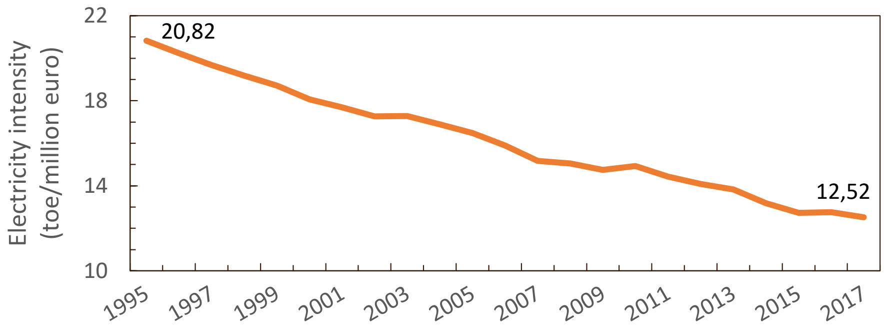

Fig. 4 - EU-28 electricity intensity from 1995 to 2017 (toe/million euro)
Source: Adapted from Eurostat (2019a)

In addition to the economic, efficiency and climate contributors, another factor that may be relevant to a country's electricity intensity is the energy policy adopted by its government. Ideologies and political-economic systems can contribute to an electricity intensity variation, since they have a direct influence on economic activity and can influence energy prices and long-term electricity demand.

Former Soviet states, for example, were always identified by being very electric-intensive, an aspect justified by the abundant supply of generation resources and the lack of concern with energy use. In addition, these governments were characterized by a high level of interventionism, maintaining low electricity prices and encouraging an exacerbated consumption (Kozlova, 2012). Years after the dissolution of Soviet Union, which ended in 1991, electricity intensity values have sharply decreased. This positive reduction could be explained by two main factors: the decrease of the economic activity of these countries (Cornillie & Fankhauser, 2004) and the greatest concern for energy security and energy efficiency.

Baltic states (EE, LT, LV) are former representatives of the Soviet Union who are currently part of the EU. These countries did not deviate from this decrease trend as they had high electricity intensity values in the early 1990s and reduced more than EU average from 1995 to 2017. The same is true for most countries in a group defined by OECD (2001) as Central and Eastern European Countries (CEECs), which comprises the following former communist states: Bulgaria, Croatia, Czechia, Hungary, Poland, Romania, Slovakia, Slovenia and Baltic countries. Fig. 5 illustrates the reduction (%) of the electricity intensity of EU member countries from 1995 to 2017. Countries with the highest percentage showed the biggest decrease in electricity intensity over this period. Considering CEECs, only Croatia, Hungary and Slovenia are not on the top ten countries.

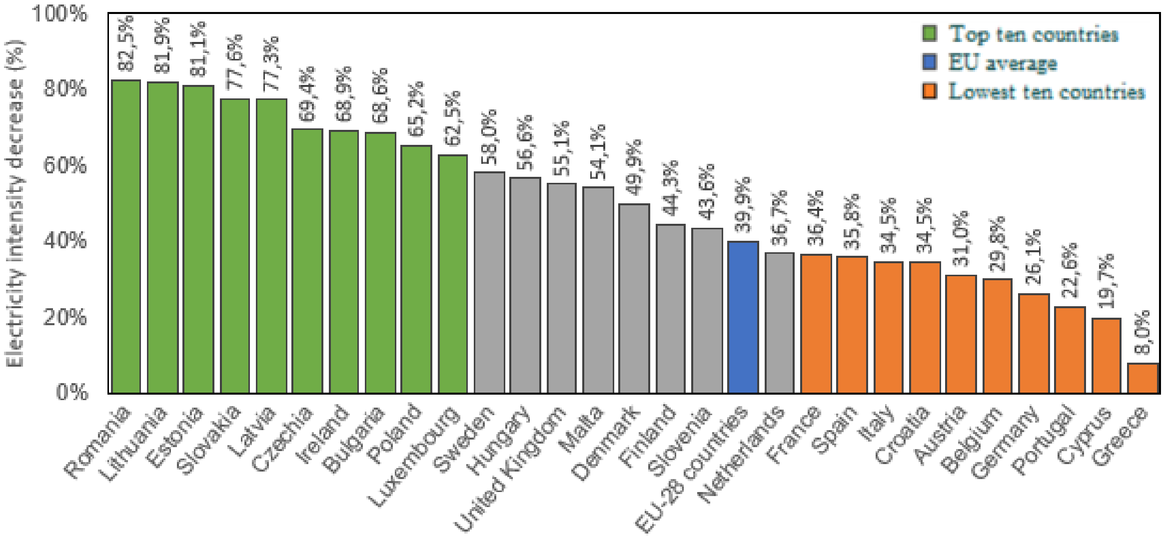

Fig. 5 - Electricity intensity decrease from 1995 to 2017 (%)

The drastic reduction in electricity intensity values by the CEECs compared to the rest of the EU-28 countries from 1995 to 2017 is also shown in Fig. 6. The map distinguishes EU-28 countries by colour intensity, enlightening that the reduction in countries geographically located in eastern Europe was higher than the average. The darker the country's plot on the map, the higher was the electricity intensity decrease.

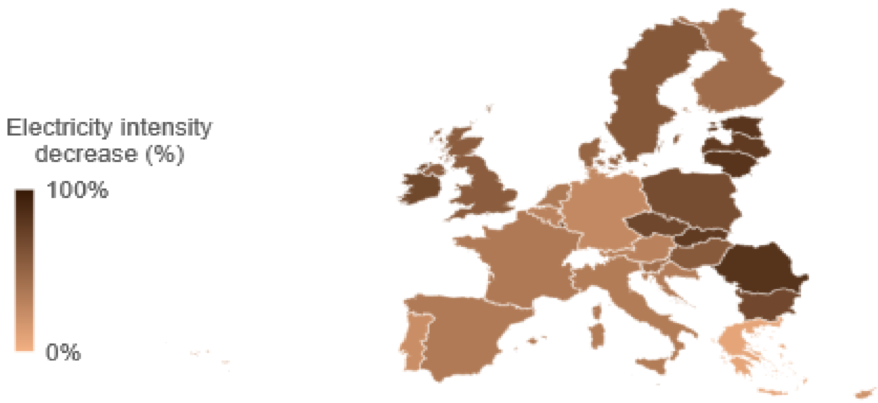

Fig. 6 - Map of electricity intensity decrease in Europe from 1995 to 2017 (%)

As shown in Figs. 4, 5 and 6, the EU has presented a reduction in electricity intensity values since 1995. Therefore, it is clear that the evolution of energy efficiency is one of the determining factors that made possible for countries to produce more goods and services by consuming the same amount of electricity (or keep GDP stable by consuming less electricity). It remains to be seen how important this contribution was and its relationship with another component: the electrification of the economy.

3.3. Electrification

3.3.1. Electricity role in total final energy consumption

Over the last few years, electricity has become increasingly present in the routine of industries, agriculture and services in general. Activities that once used fossil fuels as final energy have been replaced by technologies that use electricity. According to IEA (2018a), electricity share as a final energy source ranged from 9.4% in 1971 to 18.8% in 2016 across the world. Fig. 7 illustrates the total final consumption variation by fuel.

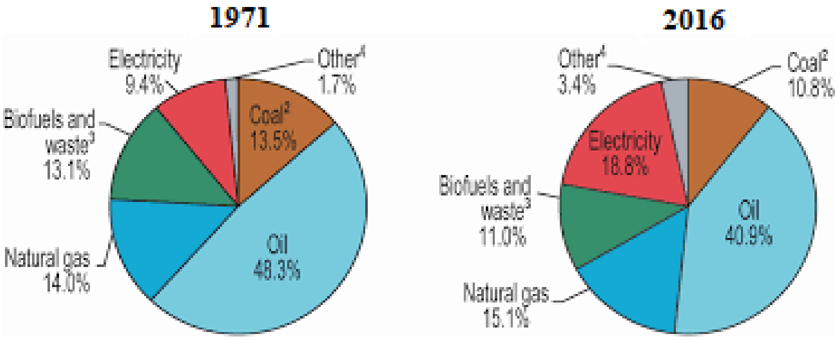

Fig. 7 - World total final consumption (TFC) from 1971 to 2016 by fuel
Source: Adapted from International Energy Agency - IEA (2018a)

2. In these graphs, peat and oil shale are aggregated with coal.
3. Data for biofuels and waste final consumption have been estimated for a number of countries.
4. Includes heat, solar thermal and geothermal.

Whereas it is expected that sustainability and greenhouse gas emissions policies are becoming more aggressive and considering the efficiency improvements of electrical products, it is projected that the participation of electricity in final energy consumption will increase. According to an optimistic report, defined as 'Sustainable Development Scenario' and published by International Renewable Energy Agency, IRENA (2019), by 2050 electricity will account for 49% of total final energy consumption, as illustrated by Fig. 8.

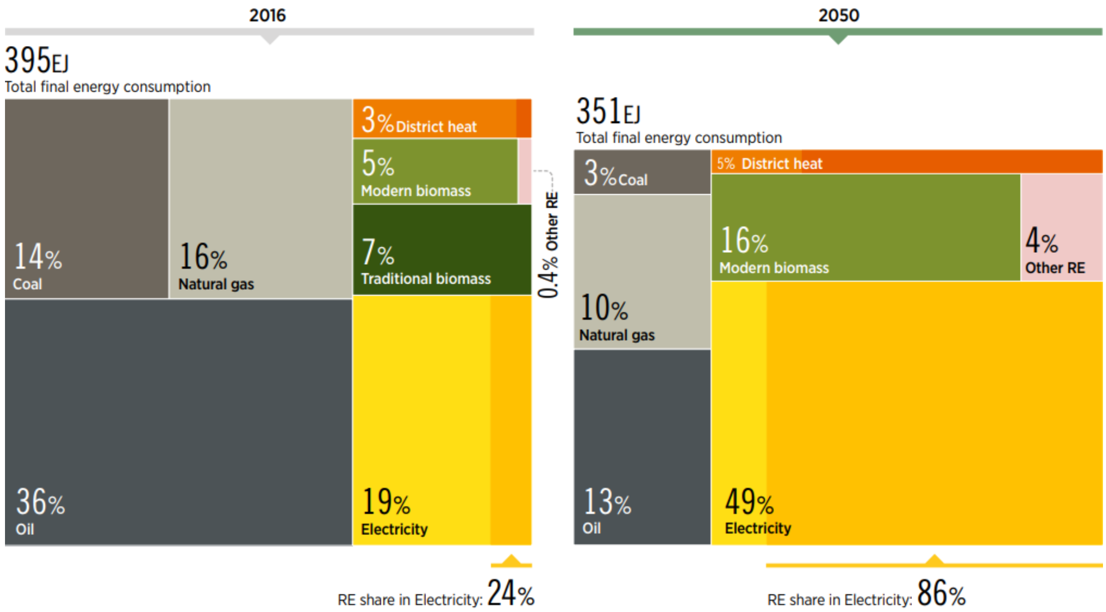

Fig. 8 - Total final energy consumption breakdown by energy carrier (%)
Source: Adapted from IRENA (2019)

Although the greater participation of electricity in the world energy consumption profile may be a major contributor to the achievement of sustainability goals, it should be noted that this increase does not necessarily mean a reduction in greenhouse gas emissions, since the fundamental fuel used for electricity generation can still be a fossil fuel. The more environmentally friendly alternative can only be defined after the life cycle assessment of each of the power generation projects, and the optimal scenario is usually the one that uses renewable technologies such as wind and solar. The projection carried out by IRENA (2019) points out that RES-E will be fundamental to the process of increasing electricity participation, representing about 86% of the total technologies used for generation and making this a positive scenario for sustainability, as shown in Fig. 8.

IEA (2019b) also noted that electricity will grow at a higher rate than the overall energy demand, surpassing more traditional forms of energy consumption, such as oil. According to The World Energy Outlook (International Energy Agency, 2019b), this change is led by the rise of electric industrial motors, as well as the increased share of electric vehicles and household appliances. The 'Sustainable Development Scenario' (IRENA, 2019) also classified electricity as one of the few sources of energy that will increase its consumption by 2040.

3.3.2. Electrification concept and its relationship with efficiency

The upward movement of the electricity share in the total final consumption illustrated by Fig. 8 is known as electrification. As introduced in Chapter 1, electrification in this context should be understood as being the increase of the ratio of electricity to final energy demand (Sugiyama, 2012).

The American Council for an Energy-Efficient Economy (ACEEE) also defined electrification as being a switch process from technologies that use fossil fuel for those that use electricity (ACEEE, 2019). ACEEE has performed a research exploring the relationship between electrification and energy efficiency. According to the organization, while electrification causes an increase in electricity consumption and energy efficiency measures seek to optimize electricity consumption, these two processes are not conflicting, since energy efficiency plays a central role in many electrification strategies. If designed in parallel, both strategies have the power to save energy (final energy consumption), save money, and reduce emissions (ACEEE, 2019).

Regarding the possibility to achieve efficiency, abundance and affordable energy supply, Tsao et al. (2018) pointed out the different characteristics that make electricity the most viable form of energy. In addition to being easily transported and easily converted to other forms of energy, electricity cost is low considering a free-fuel electricity generation scenario. Therefore, by classifying electrification as the change from a diversity of energy forms to one that predominantly uses electricity, Tsao et al. (2018) argued that the increase of electricity share combined with free-fuel electricity generation sources and grid flexibility can bring environmental, economic and geopolitical benefits.

Electrification is interpreted by the scientific community as a positive process. It should not conflict with energy efficiency measures, and both strategies should be complementary ways of achieving sustainability goals. Owing to the increase in electricity consumption and possible changes in countries' economy, the greater participation of electricity in total energy consumption directly impacts the electricity intensity index. Thus, electrification is one of the components of the decomposition method described in Chapter 4.

4. Methods and Data

Chapter 4 details the defined method and accessed data. Firstly, Section 4.1 describes the traditional LMDI decomposition method, followed by an upgraded method proposed by this dissertation (Section 4.2). Section 4.3 is a tutorial on how to interpret the obtained results and Section 4.4 is an overview of the collected data.

4.1. Traditional LMDI decomposition approach and its characteristics

From an extensive study describing the most used methods in decomposition analysis research and seeking to find out what is the best one for policymaking in energy sector, LMDI was considered the most appropriate, as concluded by Ang (2004). The author emphasised its theoretical foundation, adaptability, ease of use and facility in results interpretation. In this way and considering that it is already well consolidated, the LMDI was the decomposition method chosen for this dissertation.

However, there are several variations in this method, and it is crucial to define the most adequate so that the results are as accurate as possible. According to Ang (2015), the LMDI decomposition approach can be defined from the combination of three aspects: the method according to the weight of the formula used (LMDI-I or LMDI-II), the formulation of the decomposition procedure (additively or multiplicatively) and the variable type (quantity or intensity).

Considering that the objective of this dissertation is to decompose an intensity indicator and taking into account technical aspects addressed by Ang (2015), such as the adaptability to this scenario and the ease of interpretation of the results, the LMDI-II using a multiplicative decomposition was defined as being the ideal method for this research.

According to Ang (2005), the LMDI method requires the definition of contributing factors to changes in the variable that is intend 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 Eq. 1:

$$V = \sum_i V_i = \sum_i x_{1,i} x_{2,i} \dots x_{n,i}. \quad (1)$$

where V = index decomposition analysys (IDA), V_i = sub-category of the electricity-related aggregate and x_1, x_2, ..., x_n = variables that contribute to the changes in each sub-category.

However, the analysis of intensity indicators requires a greater detail of the Eq. 1 components. These type of index represent the change of a given variable in relation to another, giving the idea of productivity. By definition (Chapter 1), electricity intensity represents the ratio between electricity consumption and an economic output added value. Considering that the wealth generation of a country is formed by the sum of the economic output of all sectors and considering that the components of electricity intensity are only two (n = 2 in Eq. 1), namely changes in economic activity and other improvements that influence electricity intensity, the index decomposition analysis can be written in a more elaborated way. Adapting what was proposed by Ang (2015) and replacing energy terms by electricity terms, the index decomposition analysis can be detailed using Eq.2.

$$V = \frac{El}{Q} = \sum_i \frac{El_i}{Q} = \sum_i \left(\frac{Q_i}{Q}\frac{El_i}{Q_i}\right) = \sum_i S_i\, I_i \quad (2)$$

where V = electricity intensity index, El = total electricity consumption, Q = total economic activity level, El_i = electricity consumption of sector i and Q_i = economic activity level of sector i. The electricity intensity components are represented by variables S and I which describe the activity share in economy and the intensity factor, respectively. Therefore, in the decomposition of an aggregate intensity indicator, S_i = activity share of sector i and I_i = electricity intensity of sector i (Ang, 2015).

Considering that the multiplicative analysis procedure was chosen and *0* and T are, respectively, the initial and final periods of evaluation of the intensity index, it is possible to summarize these changes of electricity intensity using Eq. 3 adapted from Ang (2015).

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

where U_{tot} = total electricity intensity variation following the multiplicative analysis, V^0 = electricity intensity at the time *0*, V^T = electricity intensity at the time T, U_{str} = electricity intensity effects associated with activity structure and U_{int} = electricity intensity effects associated with the intensity element. The U_{str} and U_{int} components are indexes in this multiplicative case. When multiplied (Eq. 3), they will result in U_{tot}, thereby indicating the weight and real importance of each of the components (U_{str} and U_{int}) in changes in the electricity intensity index between periods *0* and T.

Finally, factors U_{str} and U_{int} are given by Eq. 4 and Eq. 5, respectively. These equations were first described by Ang & Choi (1997) and organized by Ang (2015) in a paper that is a guide for implementing the LMDI decomposition approach.

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

$$U_{int} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T},\frac{El_i^0}{El^0}\right)}{\sum_j L\left(\frac{El_j^T}{El^T},\frac{El_j^0}{El^0}\right)}\ ln\left(\frac{I_i^T}{I_i^0}\right)\right) \quad (5)$$

Still according to Ang (2015), L(*x*,*y*) is the logarithmic average of positive numbers *x* and *y*, given by: L(*x*,*y*) = $\frac{x-y}{lnx-lny}$, if $x \neq y$ or L(*x*,*y*) = *x*, if $x = y$.

4.2. Breaking down the intensity component

Section 4.1 detailed and adapted a method proposed by Ang (2015) that results in the structural and intensity components and allows to distinguish the contribution of factors related to the economic structure from the factors related to changes in electricity consumption and conservation. However, constant changes regarding the increase of electricity share in the total final energy consumption, or simply electrification as described in Section 3.3.2, make it difficult to identify the real influence of energy efficiency on total electricity intensity variation. The electrification process, which is predicted to be increasing as seen in Fig. 8, may advance more than the wealth generation growth, and so the analysis of the electricity intensity index variation may not be accurate.

In this way, an even more detailed analysis is proposed, in which the contribution of energy efficiency and electrification are distinguished in two different indexes. These two indexes are components of the intensity factor (U_{int}), and will replace it in this new decomposition analysis. In order to add the new energy efficiency and electrification elements as components of the decomposition of the total electricity intensity index, a variation of the method developed by Ang (2015) is proposed.

By breaking the intensity element into these two other factors, and considering that the components of electricity intensity are now three (*n* = 3), namely changes in economic activity, energy efficiency and electrification, new elements are introduced to Eq. 2 which can be rewritten as Eq. 6:

$$V = \frac{El}{Q} = \sum_i \left(\frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{El_i}{E_i} \right) = \sum_i S_i \, F_i \, K_i \tag{6}$$

where V = electricity intensity index, El = total electricity consumption, Q = total economic activity level, E_i = energy consumption of sector i, El_i = electricity consumption of sector i and Q_i = economic activity level of sector i. In this case, the components of total electricity intensity are represented by variables S, F and K and describe the economic activity share, 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.

The multiplicative analysis procedure continues to be used for this decomposition into three different components, and Eq. 3 describing the real importance of each of the components can now be written as Eq. 7 described below:

$$U_{tot} = \frac{V^T}{V^0} = U_{str} \, U_{eff} \, U_{kwh} \tag{7}$$

where U_{str} = electricity intensity effects associated with activity structure, U_{eff} = electricity intensity effects associated with energy efficiency and U_{kwh} = electricity intensity effects associated with electrification. Intensity component (U_{int}) detailed in Eq. 5 is partitioned into indexes U_{eff} and U_{kwh} which, if multiplied, will result in U_{int}. Components U_{eff} and U_{kwh} are given by Eq. 8 and Eq. 9, respectively.

$$U_{eff} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}{\sum_j L\left(\frac{El_j^T}{El^T}, \frac{El_j^0}{El^0}\right)} \; ln\left(\frac{F_i^T}{F_i^0}\right) \right) \tag{8}$$

$$U_{kwh} = exp\left(\sum_i \frac{L\left(\frac{El_i^T}{El^T}, \frac{El_i^0}{El^0}\right)}{\sum_j L\left(\frac{El_j^T}{El^T}, \frac{El_j^0}{El^0}\right)} \; ln\left(\frac{K_i^T}{K_i^0}\right) \right) \tag{9}$$

4.3. LMDI-II results interpretation

LMDI-II decomposition analysis method developed and proposed by Ang & Choi (1997), and widely used in studies of indexes decomposition related to the energy sector as discussed in Section 2.3, gives as a product two decimal numbers which, if multiplied, result in the total electricity intensity index variation (U_{tot}) without leaving a residual term. Thus the results of the applied numerical method are indexes that represent the importance of each of the components, namely electricity intensity effects associated with activity structure (U_{str}) and electricity intensity effects associated with intensity factors (U_{int}).

The U_{str} and U_{int} indexes represent, in percentage, how the electricity intensity indicator (U_{tot}) would behave if one of these elements remained unchanged during the analysed period. Supposing a fictitious scenario that, after applying the decomposition method, results in U_{str} = 0.95, it should be understood that if there is no change in energy efficiency (U_{int} = 1.00), the U_{tot} value will also be 0.95. These figures are given as an example and would indicate a final electricity intensity of 95% of the initial value and, therefore, a 5% reduction caused exclusively by changes in the structure of economic activity (U_{str}). In this described scenario, energy efficiency and other factors had no influence on electricity intensity.

In the same way, when applying the decomposition method described in Section 4.2 that results in three different components, U_{eff} and U_{kwh} represent, in percentage, how the total electricity intensity indicator (U_{tot}) would behave if all other components remained exactly the same during the analysed period. Assuming that U_{kwh} = 1.15, for example, it is understood that, if there is no change in the structural or energy efficiency scope, U_{tot} will also be equal to 1.15. In this hypothetical case, electrification would be responsible by 15% of the variation in total electricity intensity.

Isolating and individually analysing the impact of the components on the total electricity intensity shows the real influence of each one of the factors. This assessment clarifies the influence of energy efficiency measures and the influence of changes in structural activity on the evolution of the intensity indicator over time, and can answer whether the variations on the electricity demand side were actually from efficiency improvements.

4.4. Data

To assess the electricity intensity components in EU, data were selected from Eurostat - the organization of the European Commission which is the EU statistical office (Eurostat, 2019b). Eurostat is widely used by decision makers and the academic community for different types of research, being an extremely reliable data source that contains statistical information on economics and finance, population and social conditions, industry and services, international trade, transport, energy and environment, among others. This database is also characterized by allowing comparison and statistical analysis between member countries, having evolved over the years and increasing its importance with the growing relevance of the EU in the world economy.

To apply the method presented in Section 4.1, data on total electricity consumption, electricity consumption by sector, total activity level, activity level by sector, total electricity intensity and electricity intensity by sector were required. To include the electrification factor explained in Section 4.2 as one of the electricity intensity components, total energy consumption data are required in addition to the total electricity consumption already mentioned. These two variables allow the calculation of electricity share in the final energy consumption.

Energy consumption and electricity consumption data were taken from 'Complete energy balances (nrg_bal_c)' (Eurostat, 2019a) which contains energy and electricity consumption information measured in thousand tonnes of oil equivalent (ktoe). This data source contains records of each member country in addition to aggregations made for the Euro area (19 countries) and EU-28 (28 countries).

Regarding variables related to economic activity, Gross value added (GVA) data were taken from the 'Gross value added and income by A*10 industry breakdowns (nama_10_a10)' (Eurostat, 2019c) which contains records of total activity level and activity level by sector, measured in million euro and considering current prices. According to the European Central Bank, ECB (2003), GVA is measured net of taxes and subsidies on products and adjusts the GDP. Therefore, the use of that economic variable works best in this study which contemplates different countries, considering that each country has its own tax rate rules. This data source also contains records from each member country and aggregations made for the Euro area (19 countries) and EU-28 (28 countries). Although Eurostat has classified economic activity into ten different categories, aggregation into three different sectors has been defined for this research: Industry; Commercial (services, transport and others) and Agriculture (agriculture, forestry and fishing). As indicated in Section 3.1.1, this classification is justified by the fact that GVA data will be correlated with electricity consumption data, which are only available for these three sectors mentioned above.

Total electricity intensity and electricity intensity by sector were calculated by dividing electricity consumption values by the economic activity level, based on the definition given in Chapter 1 and measured in toe/million euro.

Data for above variables were calculated on an annual basis starting in 1995 and ending in 2017. A division in different cycles is proposed, based on the key energy efficiency measures taken by EC recently and illustrated in Fig. 3. The first cycle covers the period from 1995 to 2000, the second cycle from 2001 to 2006, the third from 2007 to 2011 and the fourth cycle from 2012 to 2017. An assessment from the whole cycle that covers the period from 1995 to 2017 is also proposed. It is crucial to emphasise that it is not intended to evaluate the success of each of the EC directives that serve as milestones for the suggested cycles. The purpose of this division is to provide an analysis of the evolution of the electricity intensity components in the EU at different periods, enabling comparisons between the distinct cycles.

5. Results and Discussion

The decomposition analysis proved to be a meaningful procedure for electricity intensity, since its components contributed in different ways to the deviations of this indicator in the EU. Section 5.1 reports the achieved results in the first decomposition, which considers structural and intensity factors as the two components of electricity intensity. Subsequently, Section 5.2 presents and discusses the achieved results in the upgraded decomposition, which is more detailed and breaks down the intensity component in the efficiency and electrification factors. Finally, a detailed analysis of the defined periods is given in section 5.3, which was split into easily understandable subsections 5.3.1, 5.3.2, 5.3.3 and 5.3.4.

5.1. Considering structure and intensity as the electricity intensity components

EU-28 has dramatically reduced electricity intensity values in 22 years. The intensity index figures for 2017 represent only 60.11% of the 1995 initial value. This 39.89% reduction indicates that, in general, countries of the economic bloc reduced the ratio of electricity consumption to the economic value-added during the evaluated period. In this section, the decomposition analysis details the contribution of each of the two considered components year by year and proved that most of the reduction was caused by advances in the intensity factor, as illustrated in Fig. 9.

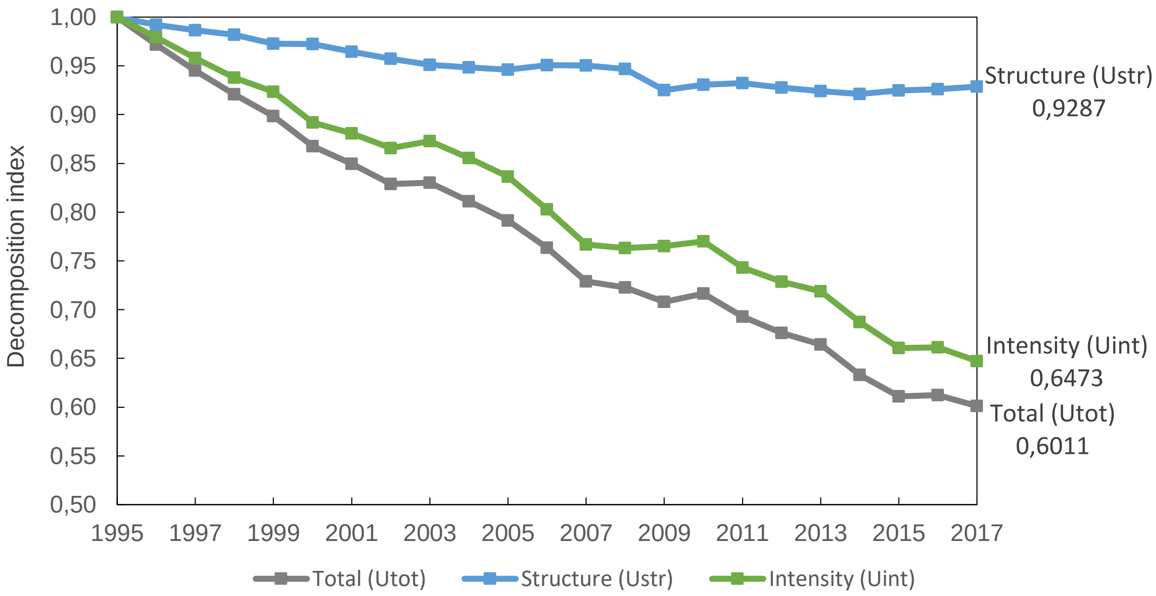

Fig. 9 - EU-28 evolution of the two electricity intensity components (1995-2017)

These results are in line with those reported by authors such as Metcalf (2008) and Löschel (2015), although they have addressed energy intensity instead of electricity intensity and the figures are not directly comparable. These authors found more expressive results, with a strong influence of the intensity factor. Metcalf (2008) accessed data from the United States in the 1970s and concluded that 75% of the energy intensity decrease was due to energy efficiency improvements. On the other hand, Löschel (2015) investigated the EU and concluded that the variation in energy intensity had a similar influence from the structure and the intensity effects until 2003. From 2004 to 2009, the intensity effect increased its relevance and had a greater influence on the energy intensity reduction.

Regarding the components of this electricity intensity decomposition, it is noted that the intensity (U_{int}) and activity structure (U_{str}) curves had falling behaviour. However, the decrease level of these elements is different, as is the distance of each of them in relation to the curve that represents the total intensity index (U_{tot}). The greater proximity of the intensity curve to the total electricity intensity curve indicates that energy efficiency and other intensity elements were more relevant and had a greater participation in the reduction of the total electricity intensity values in the period 1995-2017. During this interval, if there had been no changes in the economic structure and the activities maintained their respective share in the economy, the total electricity intensity indicator in 2017 would represent 64.73% of the value recorded in 1995. Therefore, a reduction of 35.27% exclusively due to intensity improvements throughout the electricity consumption chain. Results for each of the EU-28 countries is shown in Table 3.

Greece was the only EU-28 country in which, if there had been no structural changes in the economy, the electricity intensity would have increased in 2017 compared to 1995. According to Centre for Renewable Energy Sources and Saving, CRES (2018), until 2007 the country showed high indications of economic growth and industry modernization, leading to an increase in electricity consumption and an even greater increase in economic growth, as a result of efficiency improvements and consequently decreasing electricity intensity values. However, Greeks were severely impacted by the global economic crisis that began in 2008 and, despite directives to encourage end-use efficiency, the economic recession and unstable electricity prices shifted their focus and delayed the evolution of energy efficiency in the country.

Table 3 - Intensity component (U_{int}) and total electricity intensity (U_{tot}) variation (1995-2017)

Country	**Intensity** U_{int}	**Total** U_{tot}
Lithuania	0.1907	0.1813
Romania	0.1931	0.1754
Estonia	0.2020	0.1892
Slovakia	0.2279	0.2239
Latvia	0.2415	0.2269
Bulgaria	0.2573	0.3144
Ireland	0.3013	0.3106
Czechia	0.3131	0.3061
Poland	0.3699	0.3476
Hungary	0.4373	0.4344
Sweden	0.4701	0.4205
United Kingdom	0.5066	0.4491
Luxembourg	0.5397	0.3746
Denmark	0.5398	0.5014
Malta	0.5536	0.4545
Slovenia	0.5724	0.5644
Finland	0.6166	0.5565
European Union - 28 countries	0.6473	0.6011
Croatia	0.6671	0.6549
France	0.6938	0.6363
Spain	0.7047	0.6420
Italy	0.7150	0.6547
Netherlands	0.7330	0.6331
Austria	0.7383	0.6897
Germany	0.7625	0.7394
Belgium	0.8270	0.7019
Cyprus	0.8476	0.8029
Portugal	0.8517	0.7736
Greece	1.0190	0.9202

Considering the structure scope and still analysing results presented in Fig. 9, if there had been no improvements in the intensity field, total electricity intensity in 2017 would represent 92.87% of the 1995 amount, and therefore a reduction of only 7.13% due to changes in economic structure. Service sector expansion in the economy was presented in Section 3.1.2 of this dissertation and may explain the decrease in electricity intensity values caused by changes in structural composition. According to the World Bank (2019), the service sector is taking market share of the industrial sector in EU since 1995. Services activities are less energy intensive than industry, explaining the reduction in electricity intensity caused by changes in economic structure.

Contrary to the intensity component, results for the structure element were more uniform across EU countries. Despite the dynamism of the economy, structural changes that caused variation on electricity intensity were rather similar and the structural index was close to 1.00 in most of the countries. Ireland and Bulgaria were the only countries that had structural indexes above 1.00, indicating that changes in the economic activity would increase total electricity intensity values if there had been no changes in the intensity field. Greece stood out as the only country in the EU in which structural changes were more influential and had a greater impact on the intensity indicator than variations caused by efficiency and other improvements. Table 4 presents the calculated structure component for all countries.

Table 4 - Structure component (U_{str}) and total electricity intensity (U_{tot}) variation (1995-2017)

Country	**Structure** U_{str}	**Total** U_{tot}
Luxembourg	0.6941	0.3746
Malta	0.8210	0.4545
Belgium	0.8486	0.7019
Netherlands	0.8637	0.6331
United Kingdom	0.8866	0.4491
Sweden	0.8945	0.4205
Finland	0.9026	0.5565
Greece	0.9031	0.9202
Romania	0.9081	0.1754
Portugal	0.9083	0.7736
Spain	0.9110	0.6420
Italy	0.9157	0.6547
France	0.9171	0.6363
European Union - 28 countries	0.9287	0.6011
Denmark	0.9290	0.5014
Austria	0.9341	0.6897
Estonia	0.9366	0.1892
Latvia	0.9395	0.2269
Poland	0.9397	0.3476
Cyprus	0.9473	0.8029
Lithuania	0.9510	0.1813
Germany	0.9696	0.7394
Czechia	0.9778	0.3061
Country	**Structure**	**Total**

	U_{str}	U_{tot}
Croatia	0.9818	0.6549
Slovakia	0.9826	0.2239
Slovenia	0.9861	0.5644
Hungary	0.9933	0.4344
Ireland	1.0309	0.3106
Bulgaria	1.2221	0.3144

In addition to the varied range of results obtained depending on the country in which the decomposition method was applied, there was also a variation in the influence of structure and intensity factors depending on the period evaluated. The 1995-2017 period breakdown into four distinct cycles (1995-2000, 2001-2006, 2007-2011 and 2012-2017), as defined in Section 4.4, proved to be fundamental as the evolution of efficiency measures in EU did not always occur at the same pace. Fig. 10 shows the difference between total electricity intensity and its components in the four covered cycles, relating the index in the last year of each cycle with the index in the first year. In this way, the achieved value for 1995-2000 represents the electricity intensity of 2000 compared to the electricity intensity of 1995, and so on.

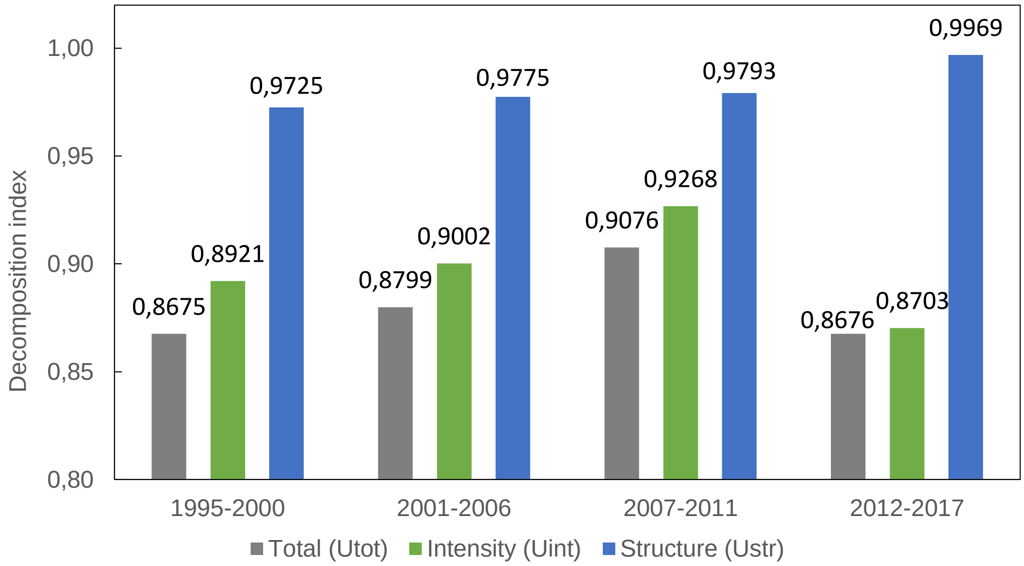

Fig. 10 - EU-28 Electricity Intensity decomposition by cycle (two components)

5.2. Breaking down the intensity component – Considering structure, electrification and efficiency as the electricity intensity components

Electricity intensity decomposition into three components contributed to a more complete analysis of the real behaviour of this index. It is essential to note that both total electricity intensity variation and structural component variation from 1995 to 2017 maintained the same results discussed in Section 5.1. The intensity factor, however, was decomposed into two other components, namely efficiency and electrification, generating new results that allowed distinguishing the contribution of energy efficiency improvements from the other elements.

Each one of the three components had completely different behaviours and influenced the total electricity intensity index in a different way. While the efficiency and the structural factor contributed to the reduction of the electricity intensity index, the electrification factor acted in the opposite direction and contributed to an increase (or decrease at a slower rate) of this index. Fig. 11 shows the variation of the three considered components in the decomposition analysis from 1995 to 2017.

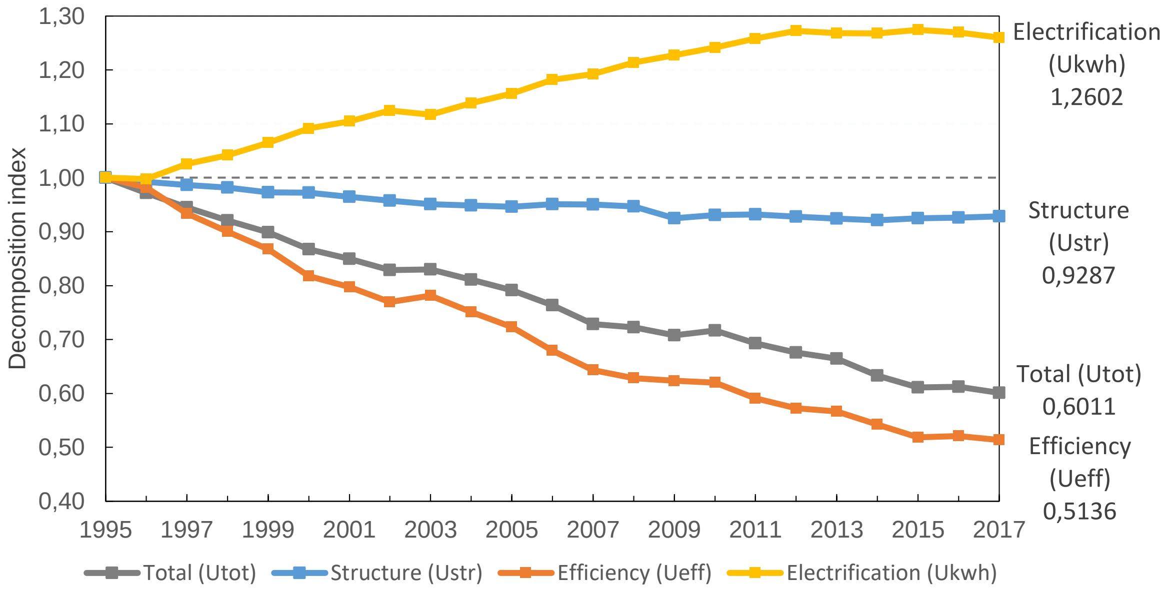

Fig. 11 - EU-28 evolution of the three electricity intensity components (1995-2017)

The electrification factor curve had an increasing behaviour over the years and, except for 1996, this component always presented values above 1.00. It is noteworthy that the electrification curve in Fig. 11 evidences the increase of the electrification component in relation to the electricity intensity index, and not simply an increase of electricity consumption. The achieved result for this index in the 1995-2017 cycle (1.2601) implies that, if there had been no variation in structural and efficiency factors and these components remained unchanged during this period, the total electricity intensity in 2017 would have been 26.02% higher than in 1995.

The electrification factor increase was practically constant from 1996 to 2012, and since then this index has stabilized at around 1.26 until the end of 2017. Considering that the results were almost always above 1.00 in the evaluated period, it is possible to verify that GVA growth in EU did not occur at the same pace as the increase in electricity consumption, provoking an increase in the electricity intensity index.

However, in order to have a more detailed picture of the impact of substituting other energy sources for electricity, an integrated analysis would be necessary. In addition to electricity intensity and its components, other factors that are beyond the main theme of this dissertation should be considered, such as energy intensity and other economic, environmental, social and political aspects.

Extending the granularity of the decomposition analysis illustrated in Fig. 11, a breakdown of the electrification indexes obtained across the EU-28 over the period 1995-2017 is given in Table 5. The only country with an electrification index lower than 1.00 was Austria. Although Austria had a 47% growth in electricity consumption (Eurostat, 2019a), it also had an economic growth of almost 100% in the same period (Eurostat, 2019c), and thus contributing to the reduction in total electricity intensity. All other countries had economic growth rates below the electrification rate, justifying most of the indexes above 1.00.

Sweden was the only country that reduced absolute electricity consumption in 2017 when compared to 1995 (Eurostat, 2019a). Although it was a slightly variation, at around 0.07%, it was still less than the decreased of 4.51% in total energy consumption at the same period. Therefore, even though electricity consumption has decreased in absolute terms, electricity share in the final energy consumption has increased, justifying an electrification factor of 1.0942 for this country.

Table 5 - Electrification component (U_{kwh}) and total electricity intensity (U_{tot}) variation (1995-2017)

Country	**Electrification** U_{kwh}	**Total** U_{tot}
Austria	0.9199	0.6897
Finland	1.0171	0.5565
Sweden	1.0942	0.4205
Denmark	1.1420	0.5014
Germany	1.1622	0.7394
United Kingdom	1.1873	0.4491
Belgium	1.1993	0.7019
Latvia	1.2222	0.2269
Hungary	1.2234	0.4344
Country	**Electrification** U_{kwh}	**Total** U_{tot}

France	1.2309	0.6363
Poland	1.2580	0.3476
European Union - 28 countries	1.2602	0.6011
Bulgaria	1.2703	0.3144
Lithuania	1.2744	0.1813
Slovenia	1.2769	0.5644
Ireland	1.2892	0.3106
Slovakia	1.2916	0.2239
Croatia	1.3171	0.6549
Netherlands	1.3332	0.6331
Luxembourg	1.3495	0.3746
Spain	1.3561	0.6420
Malta	1.3761	0.4545
Czechia	1.4091	0.3061
Estonia	1.4312	0.1892
Italy	1.4353	0.6547
Portugal	1.4491	0.7736
Cyprus	1.4729	0.8029
Greece	1.7003	0.9202
Romania	1.7605	0.1754

Results achieved for the efficiency component were different and contributed to the reduction of total electricity intensity in all EU countries, as detailed in Table 6. In contrast to what was observed in the first decomposition, in which the intensity factor was not always very significant in the total intensity index, in this more detailed process the influential participation of the efficiency element was highlighted. In 17 of the 28 analysed countries, electricity intensity values in 2017 would have decreased by more than 50% compared to 1995 if they had only been influenced by efficiency improvements and the other components had remained unchanged.

Another aspect that demonstrated the evolution of energy efficiency in EU over these years was the increasing proximity of this element to the total electricity intensity index. In all EU-28 countries the efficiency index was the closest factor to the total index, supporting that this component was the most influent in electricity intensity variation. This proximity must be perceived as a positive indicator as the optimization of electricity use has been taking place across all EU countries and the mobilization around this topic has been producing effective results.

Table 6 - Efficiency component (U_{eff}) and total electricity intensity (U_{tot}) variation (1995-2017)

Country	**Efficiency** U_{eff}	**Total** U_{tot}
Romania	0.1097	0.1754
Estonia	0.1411	0.1892
Lithuania	0.1496	0.1813
Slovakia	0.1764	0.2239
Latvia	0.1976	0.2269
Bulgaria	0.2025	0.3144
Czechia	0.2222	0.3061
Ireland	0.2337	0.3106
Poland	0.2941	0.3476
Hungary	0.3574	0.4344
Luxembourg	0.3999	0.3746
Malta	0.4023	0.4545
United Kingdom	0.4267	0.4491
Sweden	0.4296	0.4205
Slovenia	0.4483	0.5644
Denmark	0.4726	0.5014
Italy	0.4982	0.6547
Croatia	0.5065	0.6549
European Union - 28 countries	0.5136	0.6011
Spain	0.5197	0.6420
Netherlands	0.5499	0.6331
France	0.5636	0.6363
Cyprus	0.5755	0.8029
Portugal	0.5877	0.7736
Greece	0.5993	0.9202
Finland	0.6062	0.5565
Germany	0.6561	0.7394
Belgium	0.6680	0.6841
Austria	0.8026	0.6897

Although electrification and efficiency curves had well-defined profiles, as shown in Fig. 11, variations have not always been the same over the years. Thus, the decomposition method was applied for each of the cycles defined in Section 4.4. Results showed a different behaviour between electrification and efficiency elements in all four evaluated cycles, as illustrated in Fig. 12.

The efficiency component index remained between 0.8173 and 0.8705 in all periods, excepting for the last one, in which it presented an index value slightly higher than the total electricity intensity. The electrification element had results above 1.00 in almost all cycles, contributing for the increase of the total electricity intensity in the first three periods. However, in the fourth and last period, electrification was for the first time below 1.00 (0.9998) and had virtually no influence on the total intensity index. Therefore, and considering that the structural component index was also nearly 1.00 (0.9969) in the 2012-2017 cycle, almost all the electricity intensity reduction in this period was a result of energy efficiency improvements.

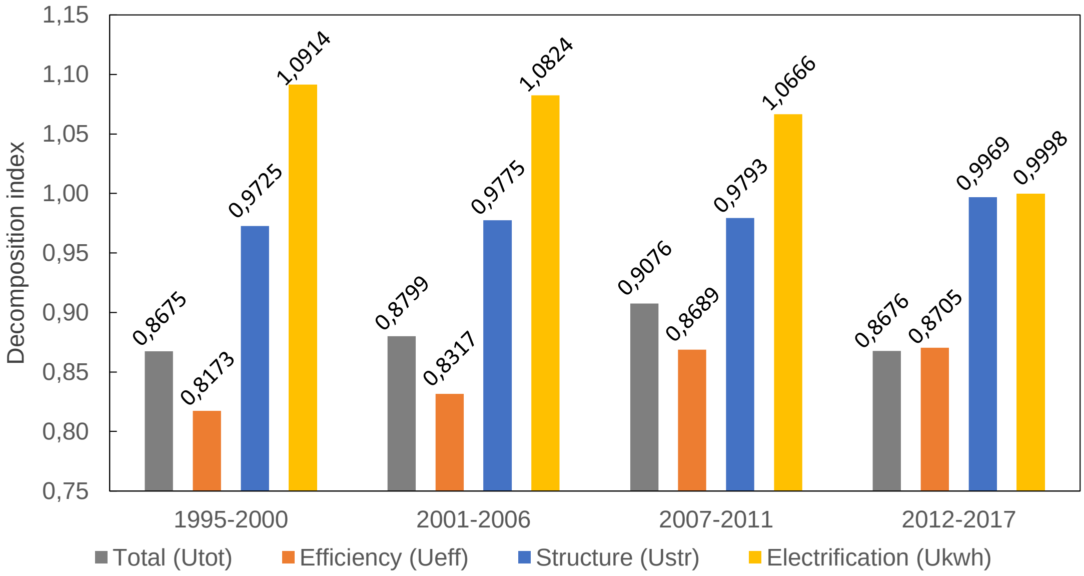

Fig. 12 - EU-28 Electricity Intensity decomposition by cycle (three components)

Another interesting way to analyse the evolution of the efficiency factor and its role in reducing electricity intensity over the years is by comparing it to the intensity component, detailed in Section 5.1. The intensity factor is formed by the product of efficiency and electrification components. Thus, the greater proximity between the efficiency and the intensity indexes determines greater relevance of the efficiency factor and lower participation of the electrification factor. As shown in Fig. 13, the difference between intensity and efficiency has been decreasing over the four cycles. In the last one, these two indexes were practically the same and, therefore, efficiency assumed full prominence, transforming electrification in a marginal element.

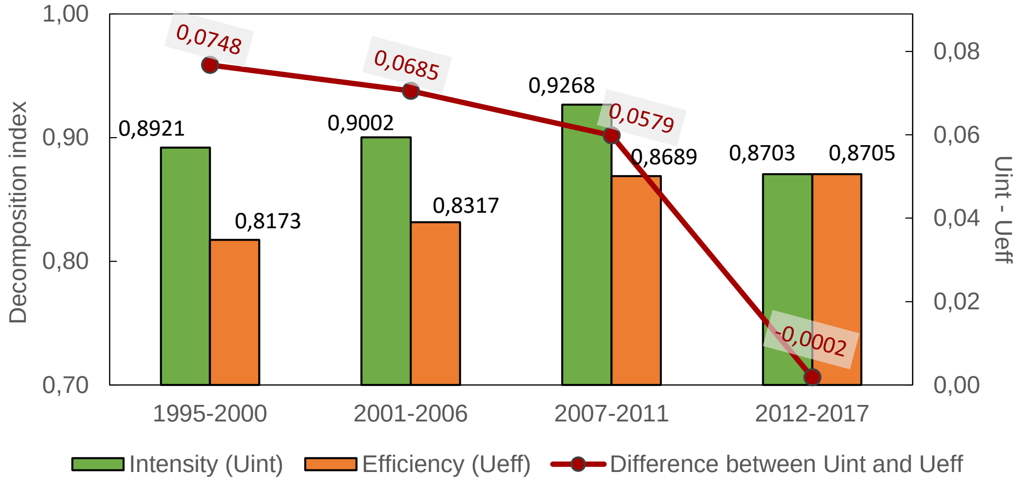

Fig. 13 - Difference between Intensity and Efficiency components by cycle

Detailed discussion of structure, electrification and efficiency components in all four cycles is given in Sections 5.3.1, 5.3.2, 5.3.3 and 5.3.4 below.

5.3. Results of the detailed decomposition in the distinct cycles

Section 5.3 presents and discusses the obtained results of the upgraded decomposition in the different cycles, namely 1995-2000 (Section 5.3.1), 2001-2006 (Section 5.3.2), 2007-2011 (Section 5.3.3) and 2012-2017 (Section 5.3.4). Results were not the same over the years. The 2012-2017 period stood out, as the efficiency component was virtually the only responsible for the electricity intensity decrease.

5.3.1. First cycle (1995-2000)

After decomposing the electricity intensity index in the four defined cycles, it is evidenced that the first one presented the greatest divergence results in terms of total electricity intensity. Between 1995 and 2000, the European situation was still quite troubled in a post-collapse of communism scenario across central and eastern Europe. Furthermore, European countries were still seeking to be better organized after the Maastricht Treaty, which would be a milestone for the consolidation of the EU (European Parliament, 2019). Countries reality was completely different and, while the major powers sought to reinvent their activities and increase participation in global economy, other less representative were still in the process of building their economic profile.

This reconstruction redefined the participation of each of the economy sectors. Therefore, the electricity intensity decomposition could not result otherwise than in the relevant participation of the structure component (U_{str}). The period of 1995-2000 had the greatest structural changes in the composition of economic activity in the EU (U_{str} = 0.9725) and was also the one with the highest electrification factor index (1.0914) and lowest efficiency factor (0.8137). The composition of these three elements resulted in the lowest value of total electricity intensity index among the four cycles.

If in terms of total electricity intensity there was a discrepancy between the EU-28 countries, the decomposition analysis showed that the same did not apply to the structure element. Although 1995-2000 had the lowest structure factor among all the four cycles, there was some convergence between EU countries. This uniformity is a result of the economic situation of each country at that time and can be explained by two main reasons.

The first one is justified by the fact that the eastern countries were still forming their manufacturing activities and, therefore, did not have a consolidated industry. Industrial activity is highly energy intensive, and the low level of industry development in eastern Europe at that time contributed to low values of structure indexes after the electricity intensity decomposition. The exception to this rule was Bulgaria, which disclosed the structure component values (1.1637). The Bulgarian political and economic crisis in the post-communist period was so significant that, although industrial sector wealth generation declined in 2000 compared to 1995, its economic activity share increased, replacing part of the service sector. This increase in industry participation influenced electricity intensity and would increase its values if there had been no efficiency or electrification changes in this period.

At the same time, developed countries were starting to make the opposite path and had a reduction of the industry share in economic activities, naturally being replaced by the service sector. This fact contributed to structure indexes below 1.00 in several countries, including Netherlands, United Kingdom, Italy, Germany, Belgium, France and Sweden. The achieved result for each country is detailed on Fig. 14, which differentiates the top ten countries as being those that obtained as a result a structure component with the greatest positive influence by contributing to the decrease of electricity intensity, and the lowest ten countries as being those in which the structural factor had the least influence or even contributed to the increase of the total intensity index.

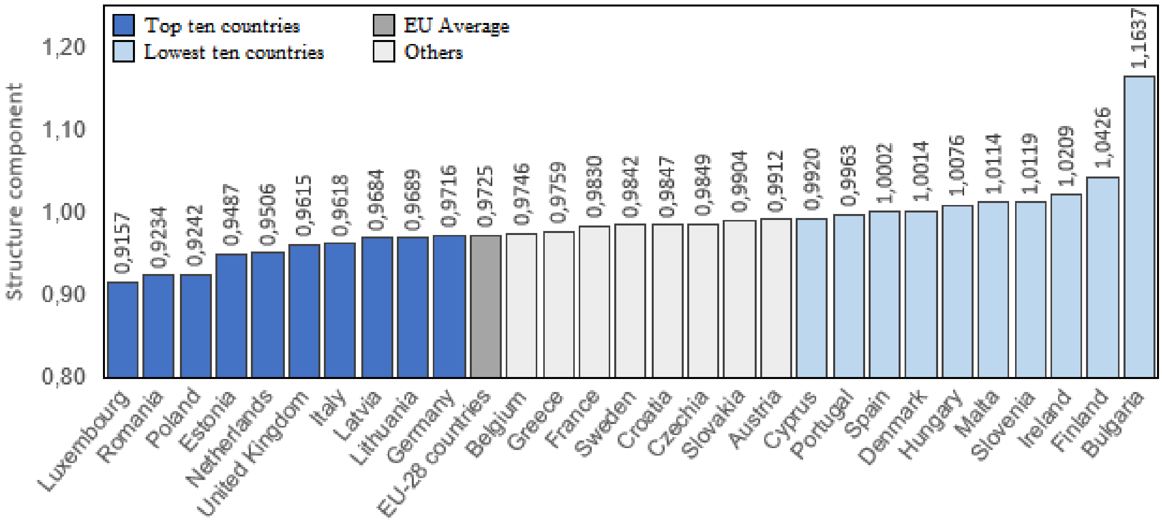

Fig. 14 - Structure component (U_{str}) in EU-28 (1995-2000)

During the first cycle, the electricity share of total energy consumption increased by 1.46% (Eurostat, 2019a), representing the greatest increase of all periods. Such growth in electricity consumption did not occur at the same pace as the EU economic output, contributing to a greater influence of the electrification factor. Thus, if it were considered that there was no interference from structural and efficiency factors during the years 1995 to 2000, the total electricity intensity would have increased by 9.14% due to the electrification component.

The lowest ten countries had indexes above 1.11, representing an increase of, at least, 11% in total electricity index and showing a decrease in the efficiency of electricity use in these countries. On the other hand, Austria (0.9566), Croatia (0.9735), Finland (0.9962) and Belgium (0.9996) were at the top ten group and were the only countries that resulted in an electrification factor that contributed to the reduction of the total intensity index, although the values were quite close to 1.00. Fig. 15 shows the achieved indexes for each country.

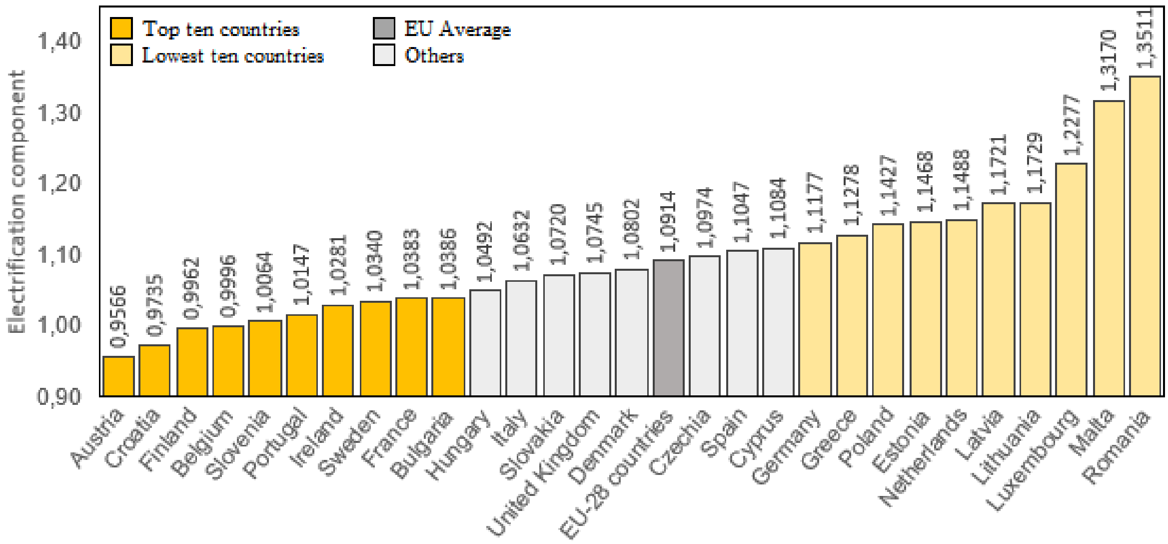

Fig. 15 - Electrification component (U_{kwh}) in EU-28 (1995-2000)

Considered as a period in which some economies sought to structure their economic activities, the 1995-2000 cycle had the lowest achieved values for the efficiency component. The first cycle was also the one in which the efficiency factor index differed most from the intensity factor, obtained in the first decomposition. The divergence between the efficiency and intensity indexes shows the importance of the decomposition resulting in three components. Concepts of efficiency and intensity, which initially appear to be similar, proved to be completely different mainly in situations where the electrification factor is as representative as it was in the period 1995-2000.

However, the high representativeness achieved for the efficiency component was not a result of strategic measures and can be justified by two main factors. The first one was the reduction of the participation of energy-intensive activities in the economy, making the production of the same amount of goods and services possible through activities that consume less electricity. The second factor was the unusual variation of GVA in less economically representative countries such as the Baltic States, which have experienced an economic growth of over 100% in five years. Fortunately, electricity consumption has not increased at the same pace, enabling greater economic efficiency which has resulted in a significant reduction in total electricity intensity, even though it was a natural movement from countries that previously had low GVA values.

At the other end of the 1995-2000 efficiency component ranking were Austria (1.0125) and Belgium (1.0285), the only countries in which the lack of energy efficiency would cause an increase in the total intensity index if the structural and electrification components had remained unchanged during the first cycle. The obtained index for each country is detailed in Fig. 16.

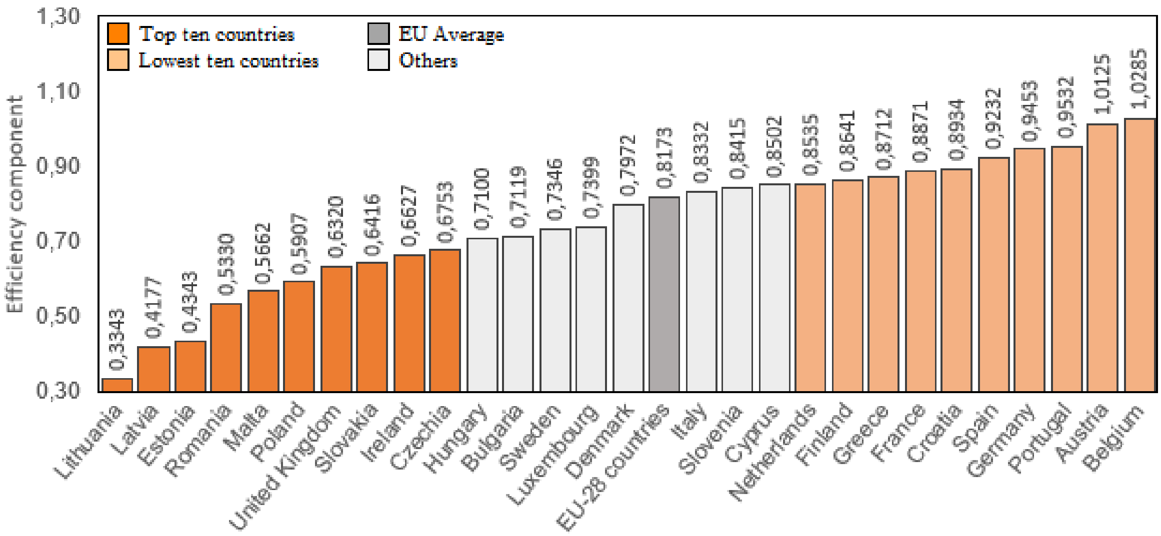

Fig. 16 - Efficiency component (U_{eff}) in EU-28 (1995-2000)

5.3.2. Second cycle (2001-2006)

The period from 2001 to 2006, defined in this dissertation as the second cycle, presented very similar results to the first cycle. Without major changes in electrification (1.0824) and structure (0.9777) factors compared to the first cycle, the total electricity intensity index was slightly higher than the values obtained in the first years mainly due to the decrease of the influence of the efficiency factor. The product of the three components was 0.8799, indicating that the electricity intensity in 2006 was 12.01% lower than in 2001.

Succeeding the first major European energy efficiency plan named 'Action Plan to Improve Energy Efficiency in the European Community', released in 2000, this cycle brought an optimistic view that could expect an immediate response to the measures that were part of the plan. These measures could cause effects on the electricity consumption profile and directly reflect on the decomposition of the total electricity intensity index. However, the product of the decomposition method showed that structural, efficiency and electrification components were practically the same as those obtained in the previous period, making it difficult to understand the real immediate contribution from this plan.

The structural component was also very similar to the first cycle (U_{str} = 0.9775) proving that, if technological advances, energy efficiency measures and electrification process remained unchanged during this cycle, the total 2006 electricity intensity would be 2.25% lower compared to 2001. Overall, the structural component behaviour indicated that the contribution of each of the EU's economic activities remained stable over this period. However, when the analysis is detailed at country level, the stability scenario is slightly different.

In a disaggregated analysis of the structure component of each of the EU-28 countries illustrated in Fig. 17, it was possible to notice a variation of some members in relation to the first cycle. Although countries at the extremities of the ranking were the same, namely Luxembourg with the lowest value (0.8855) and Bulgaria with the highest value (1.0913), there was an even greater movement from the former Soviet states to the group of countries with a structure index greater than 1.00 (CZ, PL, HR, EE, SK, LT, RO, BG) and, therefore, with a structural component that caused an increase in total electricity intensity.

All the above countries experienced an increase in industrial activity over the period 2001-2006, except for Croatia which basically had minor changes in the participation of the commercial and agriculture sectors. Spain, Denmark, Malta, Finland and Ireland moved in the opposite direction, reducing the structure index to less than 1.00 and indicating a reduction in the participation of more energy-intensive activities.

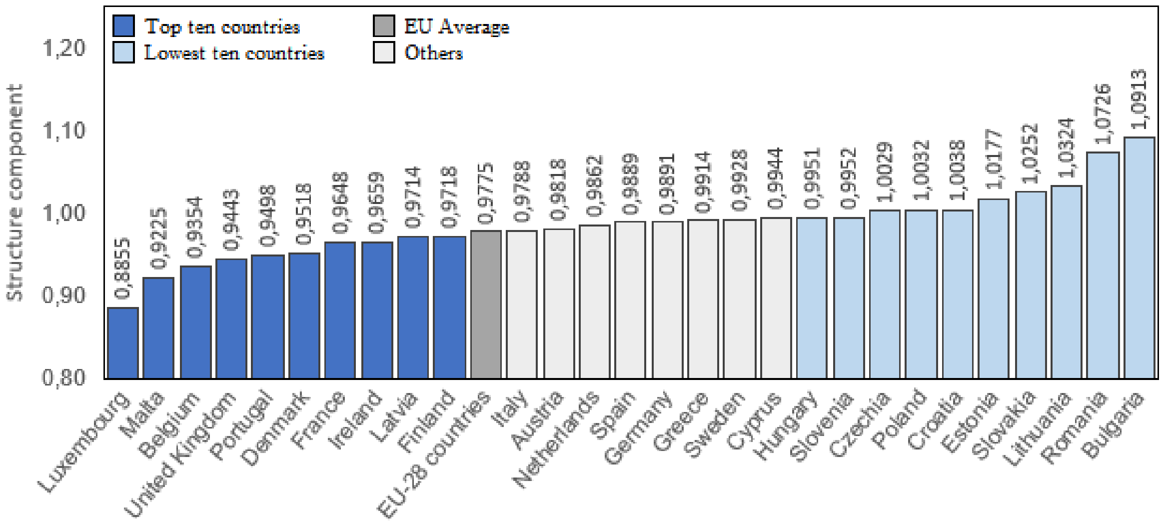

Fig. 17 - Structure component (U_{str}) in EU-28 (2001-2006)

While electricity intensity decreased over the years, the electrification has continued to contribute in the opposite direction. Once again, the increase in electricity consumption occurred at a faster pace than economic growth, causing a reduction in the efficiency of electricity use in relation to the economic productivity.

The electrification index average for EU-28 in this period was 1.0824, being Cyprus (1.2186) and Portugal (1.2066) the countries in which electrification contributed most to the increase of the total electricity intensity index. Italy and France were two other countries that incorporate the list of lowest ten countries considering only the electrification element, even though they were two of major EU economies at that time. In the top ten countries, only Austria (0.9259), Malta (0.9490), Luxembourg (0.9585), Latvia (0.9762) and Lithuania (0.9838) had indexes below 1.00, as shown in Fig. 18.

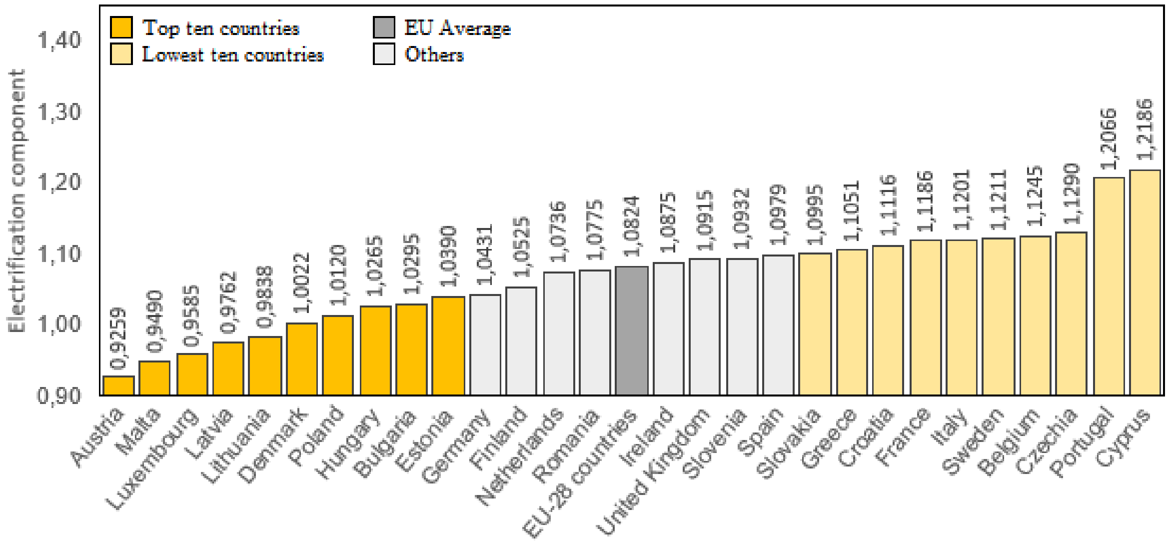

Fig. 18 - Electrification component (U_{kwh}) in EU-28 (2001-2006)

Determining the effectiveness of an efficiency plan is a difficult task by several factors, including the possible presence of free riders, defined as consumers predisposed to conservation with or without any incentive available (Haeri & Khawaja, 2012), or the occurrence of rebound effect, defined by Maxwell et al. (2011) as increases in energy consumption due to energy efficiency interventions. In this cycle, assessing the success of measures dispatched by EC was even more difficult as the results were very similar to the first cycle.

However, considering only the efficiency component, results showed that it remained quite relevant although it did not influence the total electricity index as positively as it was in the 1995-2000 period. In the 2001-2006 cycle, the efficiency index resulted in 0.8317, being the second lowest value among the four evaluated cycles. These results should not be understood as a consequence of the public policies launched by EC, precisely because there was not enough time to achieve the desired effect. Both the intensity component variation in the first decomposition method and the efficiency component variation in the second method occurred due to a natural evolution of technology from electricity demand side.

Another worth mentioning movement was the reduction of the difference of intensity and efficiency index values. The distance between these indexes decreased in relation to the first cycle and, as illustrated in Fig. 13, the two factors would be even closer in the following cycles. Regarding the efficiency factor, it can be highlighted the positive fact that only 1 of the 28 countries in the EU presented an index above 1.00. Results for each country are shown in Fig. 19.

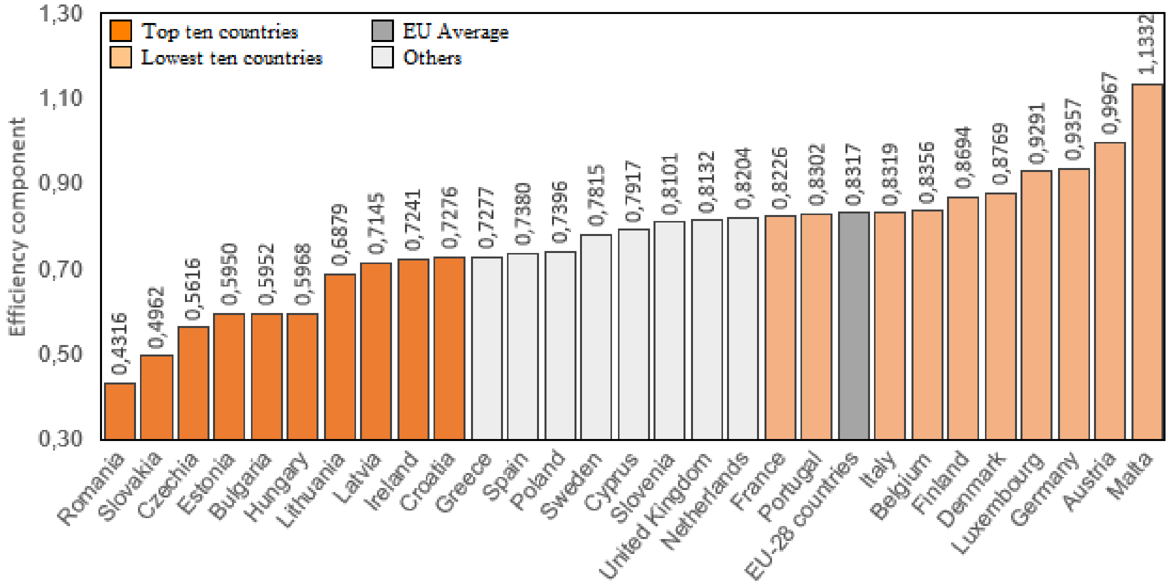

Fig. 19 - Efficiency component (U_{eff}) in EU-28 (2001-2006)

5.3.3. Third cycle (2007-2011)

The third cycle presented the lowest variation of electricity intensity among the four evaluated cycles. In the period 2007-2011 the total electricity intensity index was 0.9076, considerably higher than the first and second cycles, which resulted in 0.8675 and 0.8799, respectively. This figure indicates that in 2011 the total electricity intensity corresponded to 90.76% of the 2007 value, resulting in a reduction of only 9.24% in this period. Although the third cycle has occurred after the 'Action Plan for Energy Efficiency: Realizing the Potential' (Section 3.2.2), created in 2006 by EC and expecting significant results in the near future, the outcome was greatly influenced by the macroeconomic scenario that emerged after the global crisis of 2008.

An unstable environment prevailed in the world economy, and what was seen was a stagnation in all sectors that ended up influencing not only EU's economic activity, which grew only 1.76% from 2007 to 2011 (Eurostat, 2019c), but also the electricity consumption, which fell by only 3.25% over the same five-year period (Eurostat, 2019a). This scenario contributed to a slight variation in the total electricity intensity, and the decomposition analysis showed that impacts of the three components behaved differently from previous periods. While on the one hand the structural component remained almost the same as in the first two cycles, on the other hand the efficiency factor increased significantly and was the main responsible for the reduction in the decrease rate of the total electricity intensity index.

The structural component was quite uniform, ranging only 0.1182 among 27 of EU-28 countries. The greater proximity between countries indexes can be explained by two factors. The first one points to a trend towards stabilization of the EU economic structure, having achieved a homogenization in the share of the industrial, commercial and agriculture sectors in all countries of the economic bloc. The second and more likely is due to the fact that in a period of economic recovery, there is no expectation of a change movement in the participation of each of the economic activities, since they tend to decrease their wealth generation in a similar way. The exception in this cycle was Romania, which had a significant increase of 18.29% in industry share and was the only country with a structure component index higher than 1.00 (U_{str} = 1.0992). Fig. 20 details the obtained values for the structural component in each country.

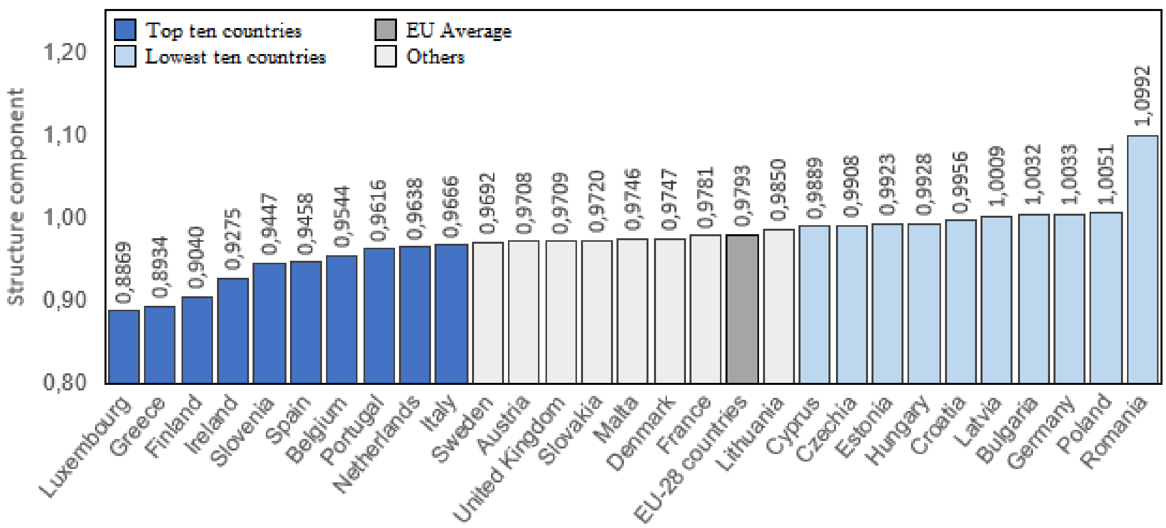

Fig. 20 - Structure component (U_{str}) in EU-28 (2007-2011)

The electrification factor behaved similarly to the previous two cycles, although the reasons for this performance were different. The average value of 1.0666 indicated that, if there had been no variation neither in structural, nor in the efficiency factor and these components remained unchanged during this period, the total electricity intensity would have increased by 6.66% over the 2007-2011 period. Differently from 1995-2000 and 2001-2006 periods, in the third cycle electricity consumption decreased 3.26% over the years, and, therefore, the electricity demand in 2011 was only 96.74% of 2007 demand (Eurostat, 2019a). Total energy consumption also varied in the same direction and had a further decline of 6.61% in the same period. In this way, even though electricity consumption has dropped over this period, the share of electricity in the total energy consumption has increased, contributing to the increased of electrification index in this decomposition analysis.

Regarding the individual analysis of each country, only Sweden (0.9538) and Finland (0.9870) had electrification indexes below 1.00, indicating a contribution to the reduction of the total electricity intensity. The ranking of the achieved value for EU-28 countries is shown in Fig. 21.

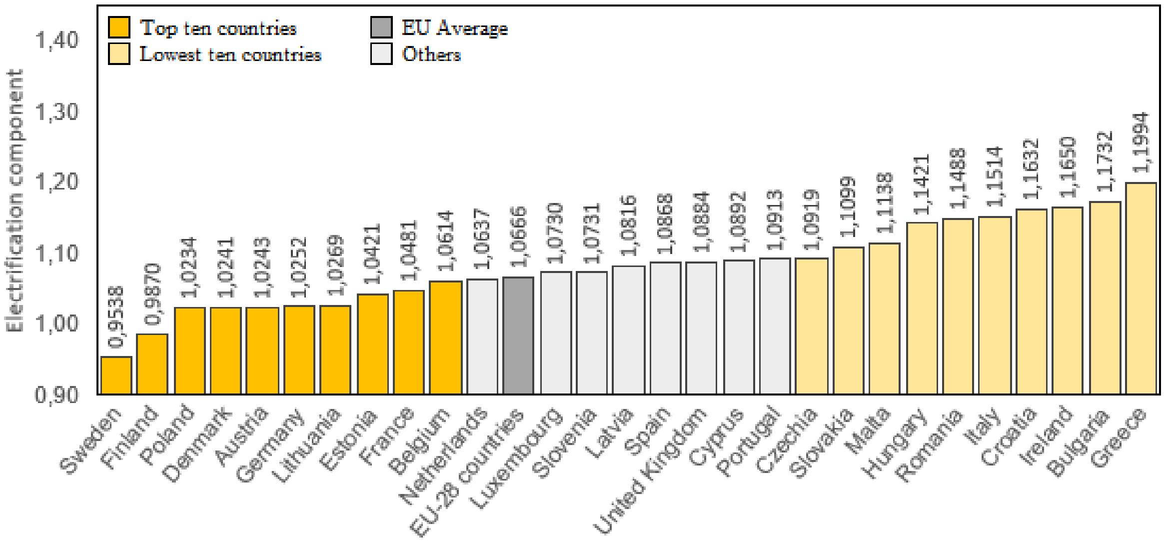

Fig. 21 - Electrification component (U_{kwh}) in EU-28 (2007-2011)

Considering the efficiency factor, a greater uniformity between EU countries results can be highlighted, as shown in Fig. 22. The gap between top and lowest ten countries indexes has considerably narrowed, and the United Kingdom (1.0144) was the only one above 1.00.

Even though it was a period of economic stagnation, all energy efficiency measures developed since the release of the 'Action Plan to Improve Energy Efficiency in the European Community', in 2000, maintained the third cycle with relevant results regarding the efficiency factor. Although the average index value was slightly higher than the previous periods, showing less influence on the total electricity intensity, the efficiency factor value was even closer to the intensity factor, and remained fundamental for the reduction of the total indicator.

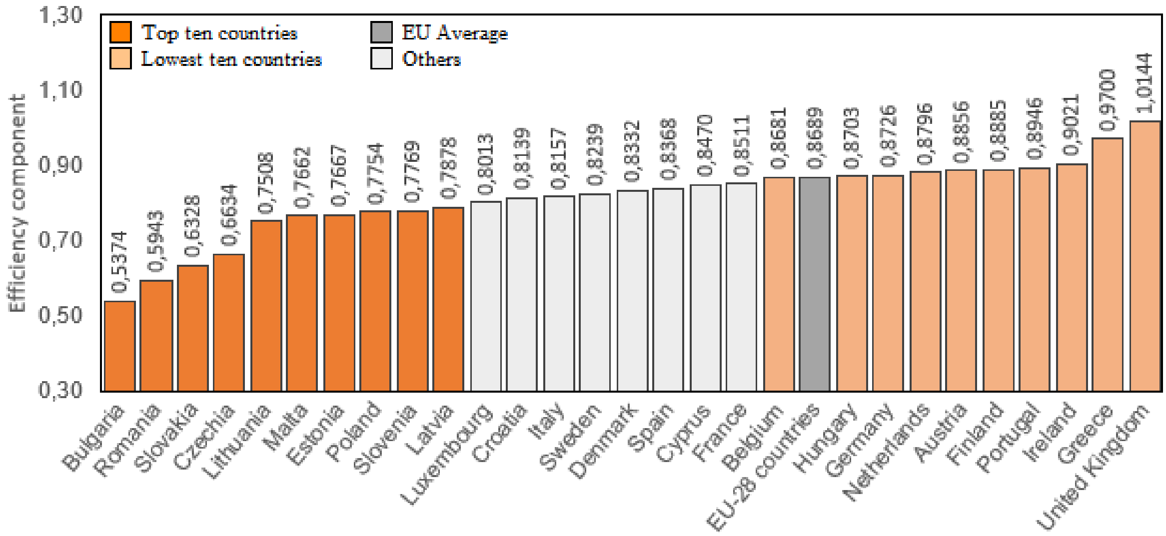

Fig. 22 - Efficiency component (U_{eff}) in EU-28 (2007-2011)

The benefits of plans and measures adopted so far were mainly seen in the last evaluated cycle, enabling an almost ideal scenario of electricity intensity reduction caused basically by advances in energy efficiency field, discussed in Section 5.3.4 below. In addition to the adopted measures, increasing awareness of energy efficiency significance also helped to achieve sustainability, economic and financial objectives in the following years.

5.3.4. Fourth cycle (2012-2017)

The fourth and last analysed cycle was the one that presented the most desired results in terms of energy efficiency influence in a current scenario of sustainable development goal achievement. Following the 'Energy Efficiency Plan', which triggered several strategic measures with targets for the 2020, 2030 and 2050 plans established by the EC, what was seen was a prominence of the energy efficiency component. One of the most important programs was the Energy Efficiency Directive (EED), approved by the European Parliament on 11 September 2012. The EED was marked by having applied stricter rules to meet the European target of 20% energy efficiency by 2020, involving the entire energy chain and including decision makers, energy companies and consumers (EC, 2012). As early as 2014, the follow-up of the objectives set allowed the EC to affirm that "...(EU) has managed to decouple economic growth from energy consumption through increased energy efficiency" (EC, 2014).

The increase in energy efficiency role could be proven after the decomposition of the total electricity intensity index, illustrated in Fig. 11. It is not clear what was the contribution of each of the implemented directives, but all the mobilization around this theme contributed to an optimization in the electricity use in this post 2011 period. As shown in Section 5.2, after the decomposition of the total electricity intensity, structural (0.9969) and electrification (0.9998) indexes were practically equal to 1.00, showing that the total intensity decrease was only due to improvements in energy efficiency field. Results obtained for the last cycle were extremely useful for evaluating the effectiveness of energy efficiency programs, as the use of electricity and its respective economic productivity can be evaluated without any interference from other electricity intensity components.

Moreover, the results also showed that, even though a restructuring of the EU economic profile is taking place recently, it has occurred very gradually during this last cycle. The service sector increased its share in total GVA by 0.23%, while industry and agriculture have decreased 0.19% and 0.04%, respectively (Eurostat, 2019c). This variation did not influence the electricity consumption profile and did not affect electricity intensity.

Individualized analysis of each country's structure component showed a small influence of the structural aspect on the total electricity intensity index and, as detailed in Fig. 23, most EU countries were very close to the average value. Considering the EU-28 group, 13 countries had a structural component between 0.99 or 1.01, making results for the last cycle the most uniform among the four evaluated.

By assessing countries that have deviated from the standard behaviour, Romania has reduced industry participation in GVA by 11% during this 6-year period. Although the country has developed its industrial activity after a period of economic crisis during the third cycle, the industry participation varied from 43.80% to 32.43%. Sweden and Malta also reduced the industry share in the economy (Eurostat, 2019c), considerably contributing to reduce the electricity intensity.

Contrary to the growth bias of the service sector, Ireland had an 11% growth in its industry share in the economy. Much driven by the impressive reconstruction after the 2008's global crisis, the Irish economy showed a consistent recovery mainly after 2014, being the European country with the highest economic growth in that year, according to the World Bank (2019). The reestablishment of Ireland's economy was only possible due to the rapid development of the industry and, although this growth has pushed the total electricity intensity index to increase over the period 2012-2017 (U_{str} = 1.1383), it occurred in parallel with technological advances in the energy efficiency field that allowed reaching a total electricity intensity index of 0.6024 in the fourth cycle.

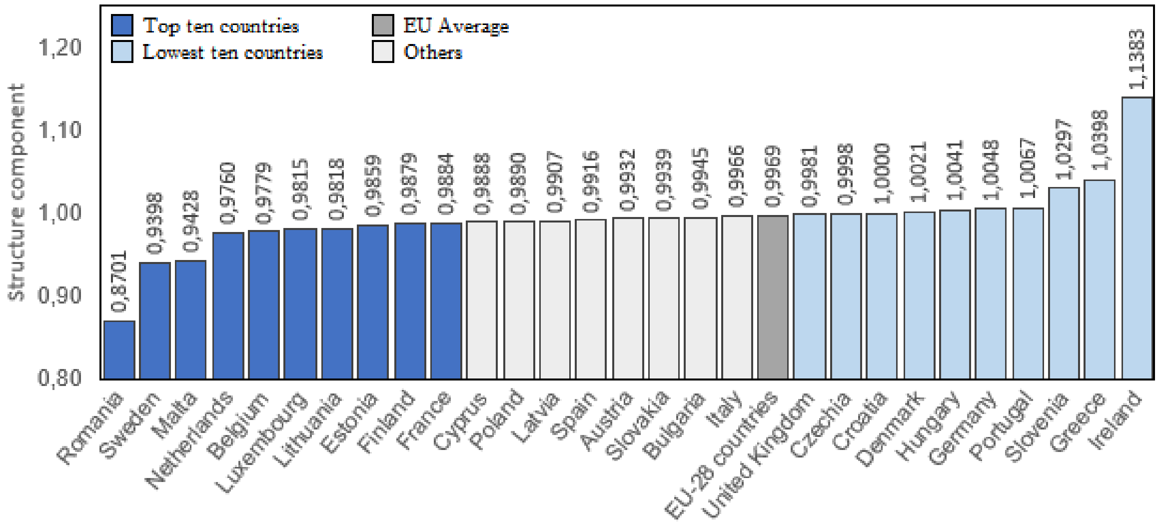

Fig. 23 - Structure component (U_{str}) in EU-28 (2012-2017)

Given that the average electrification factor in the EU was 0.9998 in the fourth cycle, many countries with indexes below 1.00 were accounted in this period. Considering all EU-28, 10 countries were in the group in which electrification contributed for reducing electricity intensity, including major economies such as United Kingdom (0.9317) and Germany (0.9732). The last cycle was also highlighted by the uniformity of the electrification index obtained for all countries. Estonia (1.1936) was an outlier that considerably contributed to the unwanted increase in the electricity intensity index. Fig. 24 details the achieved values for the electrification component in each country.

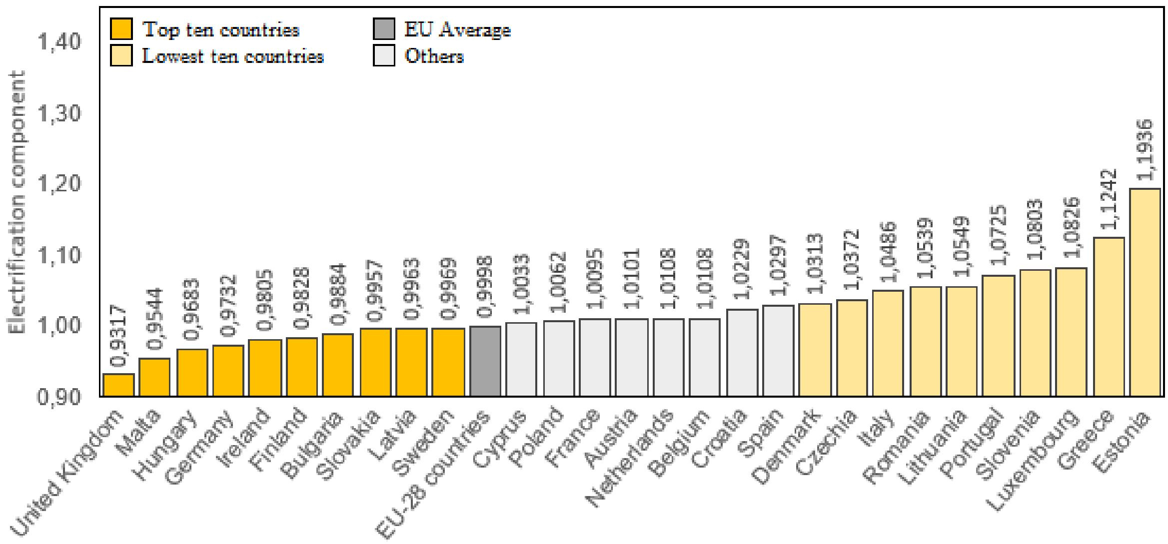

Fig. 24 - Electrification component (U_{kwh}) in EU-28 (2012-2017)

Considering the efficiency component of the intensity factor, it was already noted that this element was basically the only one that caused changes in the electricity intensity index during the 2012-2017 cycle. In addition to being relevant in the optimization of electricity consumption during this period, the efficiency index was, for the first time, below 1.00 in all countries and, therefore, changes in energy efficiency caused a reduction in the total intensity index across the EU. Although achieved results were not as great as expected in numerical terms, the uniformity achieved is undoubtedly a standout factor. This characteristic demonstrated that, in one way or another, the rigor and ambition of EC directives in the energy efficiency field has been causing positive effects in all 28 countries.

EU-28 countries had no tendency to be organized by economic strength, geographical location or predominant political regime. In this way, even though all countries had positives efficiency indexes, contributing to the reduction of electricity intensity, there was no well-established standard of group organization. Probably because of the economic reasons, Greece continued to be the country in which energy efficiency was least influential in this last cycle (0.9908). In addition to the Greece, Croatia, Cyprus and Hungary also did not have significant developments in energy efficiency field, having been the lowest countries in terms of efficiency indexes (0.9771, 0.9891 and 0.9895, respectively).

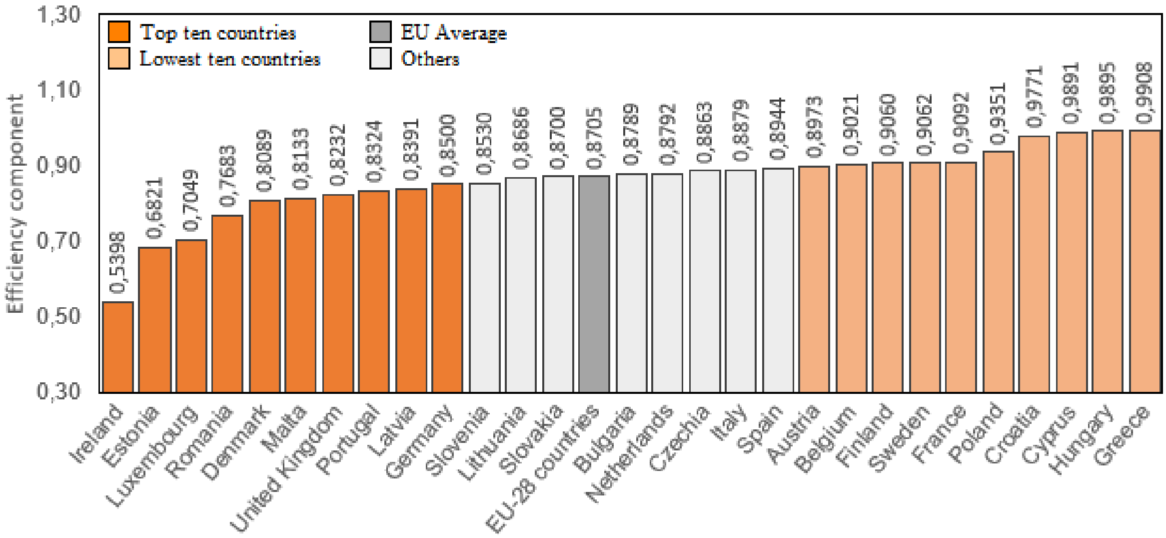

Fig. 25 - Efficiency component (U_{eff}) in EU-28 (2012-2017)

From achieved results in the last cycle, it is concluded that the challenge from then on is to increase the impact that energy efficiency plans have on the intensity indicator, decreasing the efficiency index compared to other electricity intensity components. The optimization of these measures, combined with the prominence achieved by the energy efficiency initiatives in the 2012-2017 period, will contribute to an efficient economic growth in terms of electricity consumption.

6. Conclusion

The imminent plea for sustainable development has broadened the necessity of initiatives that seek to balance economic growth and electricity consumption. Although some actions such as energy efficiency plans and the electrification of the economy are already a reality, the specific relation between electricity consumption and economic productivity has not yet been thoroughly addressed.

Despite being an enlightening indicator, deviations in electricity intensity may be weak in supporting clear conclusions, as its influential factors arise and need to be accounted for. It is important to have a detailed assessment of the indicator components for more conclusive analysis. In addition to the energy efficiency, electricity intensity can also be changed by variations in the economic activities profile or by the increase of electricity share in the final energy consumption. This dissertation explored how influential were structural, efficiency and electrification components in the electricity intensity and what was the actual contribution of energy efficiency to the decrease of this indicator in EU.

In order to answer these questions, a complement of the LMDI method was proposed. This method was first developed by Ang & Choi (1997) and it has been being widely used by the scientific community in the decomposition of intensity indicators. In this dissertation, Ang & Choi (1997) method was upgraded by adding a first-hand component, a feature never used before, to the best of our knowledge, that proved to add new evidence to the literature.

Besides providing inputs to the energy sector stakeholders, this dissertation can be highlighted by two main contributions. Firstly, an enhancement over the definition on the real impact of energy efficiency in the reduction of the electricity intensity index. Secondly, the novelty of incorporation of the electrification element as one of the electricity intensity components. This step was taken motivated by the recognition that the electricity share in the total final energy consumption has been boosting sharply so it is to reach 49% by 2050, according to IRENA (2019). In addition to the efficiency and electrification elements mentioned above, the structural factor of countries' economic activities composition was also considered as an electricity intensity component.

The electricity intensity decomposition enabled rating in detail the variation of the components of this indicator in EU from 1995 to 2017. Apart from analysing the behaviour of these parameters over the whole period, a division into four distinct cycles revealed to be crucial. Therefore, energy efficiency directives proposed by the EC were used as milestones.

It was possible to provide empirical evidence that all three components had completely different behaviours. Even though the structure, and especially the electrification element, were significant in the variation of the total electricity intensity, it was found that the efficiency component was the key influencer of this indicator, highly contributing to its reduction.

As the energy efficiency actions have enlarged over the years and the goals of public policies such as 20-20-20 EU (EC, 2010) have been intensified, the relevant contribution of the efficiency component to the reduction of the electricity intensity index should be considered a positive evidence.

The decomposition analysis carried out with this research work is a complementary contribution to the evaluation of the effectiveness of energy efficiency measures in EU, since it determined the distinctive influence of the efficiency factor. In this way, if there had been merely improvements in energy efficiency, and simultaneously no changes neither in electrification, nor in the economic structure of EU-28 (from 1995 to 2017), electricity intensity values would have decreased by 48.64% exclusively due to energy efficiency measures. The value achieved surpasses the reduction that actually occurred (39.89%), and, therefore, considering all three components we were able to confirm that energy efficiency played a fundamental role in optimizing the consumption of electricity over those years.

Furthermore, the electrification factor contributed most of the time to the increase of the electricity intensity index. Except for the 2012-2017 cycle, it was attained that the increase in electricity consumption occurred at a higher rate than the development in GVA. For this reason, electrification was the only one of the three components that would cause an increase in the electricity intensity values, if the other two elements remained unchanged. However, the verified enhance in electricity intensity does not necessarily represent an effective increase in the total energy consumption, since electrification may have caused an improvement of the energy consumption in general and may have provided reductions in the total energy intensity. For a deeper analysis of the economic benefits of electrification, a decomposition of the total energy intensity index could be carried on, considering electrification as one of its components. Despite having been focused on the evaluation of the electricity index, relating the results achieved in this dissertation to the decomposition of energy intensity is an approach believed to generate an interesting debate and could be considered for future research.

The structure factor displayed minor variation when compared to the other components, with no relevant interference in the electricity intensity indicator. Although there were small variations, the structural element was on average below 1.00 in the first three cycles, contributing to the reduction of electricity intensity. Such behaviour can be mainly explained by the increased share of service sector share in the economy. Overall, this sector has less energy-intensive activities than other sectors such as the industry, for example.

In the 2012-2017 cycle, the structural factor remained practically unchanged (0.9998). Consequently, and as the electrification factor index was also very close to 1.00 (0.9969), the entire reduction in electricity intensity was only possible due to the energy efficiency improvements.

Considering the individual analysis of EU-28 countries in the indexes ranking of electricity intensity components, no standard behaviour stood out as having persistently been maintained to generate a relevant conclusion. In the first cycle (1995-2000), former Soviet countries and Baltic states revealed more significant values of the intensity index, mainly because of the quite low level of efficiency in electricity consumption at the beginning of this period. However, in the other cycles, an interchange of countries was significantly evidenced in structural, efficiency and electrification components rankings. Such diversification is enlightening because it indicates that political and economic divergences were not meaningful and energy efficiency initiatives have been taking place in all countries, not only in major economies.

The methodology and method applied can be easily replicable to other countries constituting an opportunity for future research, only restricted to data availability. In addition to the reproduction of the method, there is an opportunity to relate the decomposition components to other economic variables, such as energy or electricity prices. Such an association can generate forecasts of energy efficiency and electrification components variation based on the prices determined by the energy market.

Going beyond the demand-side assessments and considering the electrification reality, an evaluation of generation sources deployed to meet this increase in electricity demand would be valuable. Electrification may be positive if, in a life cycle assessment, for instance, it is confirmed to generate less environmental impacts than the former energy source that have been replaced.

Finally, once the real contribution of the efficiency component to the electricity intensity was accounted for, another opportunity for future research would be to associate the decomposition results with critical analysis of the energy efficiency directives. This combination could determine how successful the efficiency plans in electrical systems were, intensifying the impact of the current research and guiding for future public policies in the energy sector.

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

ADEME. (2019). Electricity intensity trends in EU countries. Retrieved May 19, 2019, from Odyssee-Mure/Eurostat website: http://www.odyssee-mure.eu/publications/efficiency-by-sector/services/electricity-intensity-trends-eu-countries.html

Ang, B. W. (1994). Decomposition of industrial energy consumption: The energy intensity approach. *Energy Economics*, *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 Policy*, *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 Policy*, *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 Policy*, *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. *The Energy Journal*, *18*(3), 59–73.

Ang, B. W., & Zhang, F. Q. (2000). A survey of index decomposition analysis in energy and environmental studies. *Energy*, *25*, 1149–1176.

Baumol, W. J. (1967). Macroeconomics of unbalanced growth: The anatomy of urban crisis. *The American Economic Review*, *57*(3), 415–426. Retrieved from http://piketty.pse.ens.fr/files/Baumol1967.pdf

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

Bossanyi, E. (1979). UK primary energy consumption and the changing structure of final demand. *Energy Policy*, *7*(3), 253–258.

Boyd, G., Mcdonald, J. F., Ross, M., & Hanson, D. A. (1987). Separating the changing composition of U.S. manufacturing production from energy efficiency improvements: A Divisia Index approach. *The Energy Journal*, *8*(2), 1–22.

Capik, P., & Dej, M. (2018). *Relocation of Economic Activity - Contemporary theory and practice in local, regional and global perspectives* (Springer; P. Capik & M. Dej, Eds.). Cham.

Centre for Renewables Energy Sources and Saving. (2018). Energy Efficiency trends and policies in Greece. In *Odyssee-Mure/Eurostat*. Retrieved from http://www.odyssee-mure.eu/publications/national-reports/energy-efficiency-denmark.pdf

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

Divisia, L. (1925). L'indice monetaire et al theorie de la monnaie. *Revue Divisia Economic Politique*, *9*(2), 109–135.

EC. (2000). *Action plan to improve energy efficiency in the European Community*. Brussels.

EC. (2006). *Action plan for Energy Efficiency: Realising the potential*. Brussels.

EC. (2010). Europe 2020 - A strategy for smart, sustainable and inclusive growth. In *European Commision*. https://doi.org/10.1016/j.resconrec.2010.03.010

EC. (2011a). *Energy Efficiency Plan 2011*. Brussels.

EC. (2011b). *Energy Roadmap 2050*. Brussels.

EC. (2012). Directive 2012/27/UE. *Jornal Oficial Da União Europeia*, 1–56.

EC. (2013). Green Paper - A 2030 framework for climate and energy policies. In *European Commision*. Retrieved from http://ec.europa.eu/clima/policies/strategies/2030/documentation_en.htm

EC. (2014). Questions and answers on the Energy Efficiency Communication. Retrieved November 30, 2019, from https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_494

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

EC. (2019). Developments for GDP in the EU-28: growth since 2013. Retrieved October 1, 2019, from National accounts and GDP website: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=National_accounts_and_GDP#Gross_value_added_in_the_EU_by_economic_activity

ECEEE. (2011). ECEEE on the Energy Efficiency Plan 2011: "New concrete measures needed to meet the 2020 savings target." Retrieved September 23, 2019, from European Council for an Energy Efficiency Economy website: https://www.eceee.org/all-news/press/Energy_Efficiency_Plan_2011/

EMCC. (2005). *European Restructuring Monitor*. Dublin.

European Central Bank. (2003). What is behind discrepancies between growth in GDP and gross value added? *Monthly Bulletin*, 1–2. Retrieved from https://www.ecb.europa.eu/pub/pdf/other/mb200312_focus06.en.pdf

European Environment Agency. (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

European Parliament. (2019). Treaty on European Union (TEU) / Maastricht Treaty. Retrieved November 17, 2019, from European Parliament website: https://www1.europarl.europa.eu/about-parliament/en/in-the-past/the-parliament-and-the-treaties/maastricht-treaty

Eurostat. (2019a). Complete energy balances. Retrieved September 25, 2019, from Eurostat - Your key to European statistics website: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en

Eurostat. (2019b). Eurostat - Overview. Retrieved September 25, 2019, from Eurostat - Your key to European statistics website: https://ec.europa.eu/eurostat/about/overview

Eurostat. (2019c). Gross value added and income by A*10 industry breakdowns. Retrieved September 25, 2019, from Eurostat - Your key to European statistics website: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a10&lang=en

Fisher-Vanden, K., Jefferson, G. H., Liu, H., & Tao, Q. (2004). What is driving China's decline in energy intensity ? *Resourse and Energy Economics*, *26*, 77–97. https://doi.org/10.1016/j.reseneeco.2003.07.002

Geller, H., & Attali, S. (2005). The experience with energy efficiency policies and programmes in IEA countries: Learning from the critics. *IEA Information Paper*, 1–43.

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 Conversion and Management*, *92*, 459–468. https://doi.org/10.1016/j.enconman.2014.12.083

Haeri, H., & Khawaja, S. M. (2012). The trouble with freeriders. *Public Utilities Fortnightly*, 1–9.

Hang, L., & Tu, M. (2007). The impacts of energy prices on energy intensity: Evidence from China. *Energy Policy*, *35*(5), 2978–2988. https://doi.org/10.1016/j.enpol.2006.10.022

Hankinson, G. A., & Rhys, J. M. W. (1983). Electricity consumption, electricity intensity and industrial structure. *Energy Economics*, *5*(3), 146–152.

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

Hien, P. D. (2019). Excessive electricity intensity of Vietnam: Evidence from a comparative study of Asia-Pacific countries. *Energy Policy*, *130*(April), 409–417. https://doi.org/10.1016/j.enpol.2019.04.025

Huntington, H. G., & Myers, J. G. (1987). Sectoral shift and industrial energy demand: what have we learned. *Battelle Press*, 353–388.

Inglesi-Lotz, R., & Blignaut, J. N. (2012). Electricity intensities of the OECD and South Africa : A comparison. *Renewable and Sustainable Energy Reviews*, *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

International Energy Agency. (2018a). Key world energy statistics. https://doi.org/10.1002/art.1780270204

International Energy Agency. (2018b). *Market Report Series - Energy Efficiency 2018*. Retrieved from https://webstore.iea.org/download/direct/2369?fileName=Market_Report_Series_Energy_Efficiency_2018.pdf

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

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

IRENA. (2019). *Global Energy Transformation: A Roadmap to 2050* (2019th ed.). Retrieved from https://www.irena.org/DigitalArticles/2019/Apr/-/media/652AE07BBAAC407ABD1D45F6BBA8494B.ashx

ITRE. (2006). *Relocation of EU industry - An overview of literature*. Retrieved from http://www.europarl.europa.eu/document/activities/cont/201109/20110906ATT26029/20110906ATT26029EN.pdf

Kaufmann, R. K. (2004). The mechanisms for autonomous energy efficiency increases: A cointegration analysis of the US energy/GDP ratio. *The Energy Journal*, *25*, 63–86.

Kim, J. U., & Aguilera, R. V. (2016). Foreign location choice: Review and extensions. *International Journal of Management Reviews*, *18*(2), 133–159. https://doi.org/10.1111/ijmr.12064

Kozlova, A. (2012). *Responde of residential electricity demand to price changes in Ukraine*. Kyiv School of Economics.

Lazar, J., & Colburn, K. (2013). *Recognizing the Full Value of Energy Efficiency*. Montpelier.

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

Liu, X. Q., Ang, B. W., & Ong, L. H. (1992). The application of the Divisia index to the decomposition of changes in industrial energy consumption. *The Energy Journal*, *13*(4), 161–177.

Löschel, A., Pothen, F., & Schymura, M. (2015). Peeling the onion: Analyzing aggregate, national and sectoral energy intensity in the European Union ☆. *Energy Economics*, *52*, S63–S75. https://doi.org/10.1016/j.eneco.2015.09.004

Maxwell, D., Owen, P., McAndrew, L., Muehmel, K., & Neubauer, A. (2011). Addressing the Rebound Effect. *European Commission DG Environment*.

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. *The Energy Journal*, *29*(3), 1–26.

Natural Resources Canada's Office of Energy Efficiency. (2013). *Energy Efficiency Trends in Canada 1990 to 2013*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/trends2013.pdf

OECD. (2001). Glossary of statistical terms. Retrieved March 1, 2020, from Agricultural Policies in OECD Countries: Monitoring and Evaluation 2000: Glossary of Agricultural Policy Terms, OECD. website: https://stats.oecd.org/glossary/detail.asp?ID=303

Oikonomou, V., Becchis, F., Steg, L., & Russolillo, D. (2009). Energy saving and energy efficiency concepts for policy making. *Energy Policy*, *37*(11), 4787–4796. https://doi.org/10.1016/j.enpol.2009.06.035

Pereira, G. I. (2014). *Connecting energy efficiency progress and job creation potential*. Universidade de Coimbra.

Ruffa, D., Maia, E., Gonçalves, J., Coelho, M., Abadi, M. B., Figueiredo, N., … Miguel, R. (2012). *Energy efficiency and market transformation policies: an appraisal based on case-studies*. São Miguel.

Ryan, L., & Campbell, N. (2012). *Spreading the net: The multiple benefits of energy efficiency improvements*. Paris.

Sandu, S., & Syed, A. (2008). *Trends in energy intensity in Australian industry*. Retrieved from http://apps.olin.wustl.edu/faculty/Zhang/Energy/Australia - Energy Trends.pdf

Sato, K. (1976). The Ideal Log-Change Index Number. *The Review of Economics and Statistics*, *58*(2), 223–228.

Schiller, S. R. (2007). *National action plan for energy efficiency (2007). Model energy efficiency program impact evaluation guide*. (December). Retrieved from www.epa.gov/eeactionplan

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 Policy*, *51*, 445–453. https://doi.org/10.1016/j.enpol.2012.08.044

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

Thünen, J. H. von. (1826). *The Isolated State* (2nd ed.). Jena,G. Fischer,1910.

Törnqvist, L. (1935). *A memorandum concerning the calculation of Bank of Finland consumption price index*. Helsinki: unpublished memo.

Tsao, J. Y., Schubert, E. F., Fouquet, R., & Lave, M. (2018). The electrification of energy: Long-term trends and opportunities. *MRS Energy & Sustainability*, *5*, 1–14. https://doi.org/10.1557/mre.2018.6

Verbič, M., Filipović, S., & Radovanović, M. (2017). Electricity prices and energy intensity in Europe. *Utilities Policy*, 58–68. https://doi.org/.1037//0033-2909.I26.1.78

Wood, A., & Roberts, S. (2011). *Economic geography - places, networks and flows* (Routledge). Abingdon.

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=#

World Energy Council. (2010). *Energy efficiency: A recipe for success*. Retrieved from https://www.worldenergy.org/assets/downloads/PUB_Energy_Efficiency_-A_Recipe_For_Success_2010_ExecSummary_WEC.pdf

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