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The energy metabolism of countries:

energy efficiency and use in the period that followed the global financial crisis

Abstract

This paper discusses how the deceleration of economic growth, that followed the financial crisis of 2008, influenced the energy efficiency, allocation and use of 18 European countries. By using a Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), the relationships between energy requirements, economic trends and population are investigated for the years 2008 and 2015. The analyses are performed for the entire society (Level N), for the household and the paid sectors (Level N-1) and for the agricultural, the industrial and the service activities (Level N-2). Results show that two main groups of countries performed the largest energy reductions, namely: the country most affected by the global financial crisis, such as Greece, Romania and Spain, where the total energy throughput decreased by -19.6%, -15.8% and -12.1%, respectively; and the countries, such as Ireland and United Kingdom, that experienced the largest energy intensity reductions (-38.7% and -19.2%), together with the highest GDP increases (+44.8% and +10.2%). By providing an overview of the relationships existing between socio-economic and energy variables, this paper contributes to the debate around growth and efficiency and can support the design of policies oriented to promote the achievement of a more sustainable and competitive economy.

Keyword: Economic growth; Financial crisis; Energy efficiency; Energy metabolism; Energy policies

1. Introduction

The increased awareness on climate change-related issue together with the instabilities related to energy dependency and supply, have encouraged the academic and political debate around strategies oriented to promote economic growth while reducing the energy intensity of societies [1-9]. The Energy Efficiency Directive (2012/27/EU), the related revisions, and the definition of the 2030 targets, are examples of policies oriented to reduce the dependency form energy import and to promote a more sustainable, efficient and competitive economy. In addition, the increased policy attention devoted to sustainable production and consumption, together with the recent definition of the Sustainable Development Goals have highlighted the need for integrated energy strategies oriented to take into account the specific characteristics of countries and the interrelated relationships existing between socio-economic and energy variables [10-13]. Within this context, the European Member States, characterized by different socio-economic and energy profiles, represent an interesting case study to investigate the sustainability transition of countries.

During the last few years, the extensive implementation of energy efficiency strategies together with increased consumer responsibility, have contributed to reduce the energy consumption of EU [14,15]. However, when analysing the individual Member States, large differences exist both in relation to energy efficiency and use. The countries characterized by the highest GDP increases, such as Ireland and United Kingdom, have for example experienced some of largest energy intensity improvements, together with some of the highest energy consumption drops. On the contrary, the countries most affected by the global financial crash, such as Greece, Romania and Spain, have performed some of the lowest energy efficiency gains.

The possible impacts of economic growth trends, on energy intensity and use, have been largely debated from theoretical and empirical perspectives [16-19]. Despite the large number of studies, however, a general agreement does not seem to exist around the impacts that energy

efficiency and economic growth could generated on the overall level of energy demand. On the one side, the technological progress and the efficiency gains have supported the idea that decoupling trends can reduce the energy demand, while maintaining a growing economic output; On the other side, the scale and the rebound effects have highlighted the potential role that price reduction and income increase could have on the overall level of demand [20-24].

Most of the empirical studies published so far, mainly analyse the relationships between economic and energy variables during period of GDP growth, and limited analysis have been specifically focused in the period that followed the global financial crash [25-27]. As previously reported by other studies, the possible impacts that economic crisis could generate on energy demand are not always straightforward. On the one side, the deceleration of growth could reduce the pressure on resources by reducing the level of demand. On the other side, the GDP drop and the consequent reduction of investments in cleaner and efficient technologies, could result in energy consumption increases [28, 29].

Within this context, the present paper aims to investigate how the deceleration of growth, that followed the global financial crash of 2008, has influenced the energy efficiency, allocation and use of 18 European countries. To this purpose, the Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is used. Previously applied to complement analysis on energy intensity and use, the MuSIASEM approach has been proven to be an effective methodology to investigate how socio-economic and energy variables relate over time [30, 31].

The present paper contributes to the existing literature in different ways: *i)* it uses, for the first time, the MuSIASEM approach to compare the metabolic profile of 18 European countries in a period of economic downturn; *ii)* it investigates the existing relationships between economic growth, energy efficiency and energy use, by analysing how the energy requirements of countries have changed in the first year of the crisis (2008) and seven years after the global

financial crash (2015). From a theoretical perspective, the 2008 crisis represents an opportunity to investigate the relationships between energy and economy not in a framework of growth, as it has been mainly done previously, but in a framework of decelerated growth; *iii)* by comparing the metabolic profiles of countries characterized by different socio-economic conditions, the present paper contributes to the academic and political debate around socio-economic structures, sustainability and growth; in addition, *iv)* by considering the performance of the different European countries, policy implications are discussed.

The paper is structured as follows: Section 2 introduces the methodology. Section 3 presents the geographical scope and data. Section 4 discusses the main results, limitations and possible developments of research. Section 5 includes conclusions and policy implications.

2. Methodology

2.1 Theoretical framework

The Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is a transdisciplinary approach that has been developed to investigate the existing relationships between environmental elements, economic variables and human time allocation. Based on the concept of metabolism, generally defined as the way in which energy and materials are used by systems to keep running and develop, the MuSIASEM approach investigates the process of material and energy transformations that are functional to sustain the structure of societies [32-35]. Developed through the integration of various theoretical concepts, such as: *i)* the flow-fund model, that analyses how energy and materials are transformed, used and combined [36, 37]; *ii)* the complex system theory, that investigates how metabolic systems evolve across different spatial and temporal scales [38-43] and *iii)* the post-normal science, that highlights the importance of using various dimensions and multiple scale of analysis [44]; the

MuSIASEM approach has advantages over other methodologies used to investigate the metabolism of societies, such as emergy, ecological footprint and input-output analysis (for a detailed description see [45]). By providing integrated descriptions across different levels of analysis, the MuSIASEM approach does not collapse the information into a single numerical index and analyses the energy used in relation to the specific socio-economic structure. In addition, the inclusion of various dimensions (such as GDP, human time and energy use) together with the use of various scale of analysis (such as the sectoral and the national level) is able to: *i)* provide information about processes taking place inside the system, and to *ii)* analyse how external variables (such as economic crisis and resource shortage) can affect resources allocation and use [46, 47].

During the last decade, a large number of studies have been oriented to investigate how the increasing use of energy relates to changes in economic activities, human time and demographic structures [30, 48-52]. Previous studies have been focused on analysing the metabolic profile of countries over periods of time or in relation to specific production activities. [53], for example, investigated the recent economic history of Ecuador, [54] and [42] focused on the Peruvian mining and oiling sector and [55] investigated the energy metabolism of Balearic island. Analysis have also been focused on cross-regional comparisons, such as [56] that compared the metabolism of Romania, Bulgaria, Poland and Hungary, [57] that used the MuSIASEM approach to investigate the energy metabolism 28 world countries, and in [49] that provided a comparative analysis of urban metabolism for four megacities. Previous analyses have also been focused on regional and urban scale dimensions. Published studies include Shanghai [46], Barcelona [58], Catalonia [59], Campania [60], Naples [61] and Italian regions [62]. Specific studies have also been developed to investigate the water and the land use metabolism [63, 48] and to include end-use matrix oriented to take into account different

level of human activities and to investigate how energy is used to perform different end-uses [49, 58, 64].

During the last decade, the MuSIASEM approach has proven to be an effective methodology to investigate how resource allocation, technological development and economic structure can influence the variations of the metabolic structure of societies. Within this context, the MuSIASEM approach can then be particularly useful to investigate the effectiveness of strategies oriented to promote a more sustainable production and consumption. Generally defined as the possibility of doing more and better with less [65], the sustainable production and consumption strategies are strictly related to the idea of decoupling, according to which, economic growth can gradually be disconnected from material and energy use. The existing distinctions between absolute and relative decoupling, together with the contrasting arguments reported above, make however difficult to have a clear overview of the relationships existing between growth, efficiency and energy use. With this in mind, the MuSIASEM approach can provide useful information to investigate the relationships existing between energy profiles and socio-economic characteristics of countries. The evidence provided can be used to support the development of efficient energy strategies designed in line with the characteristics of the considered areas.

2.2 Analytical Framework

To investigate the impacts that the deceleration of economic growth has generated on the energy efficiency, allocation and use of the 18 European countries considered in this paper, the following variables, indicators and levels of analysis, have been used:

- Level N – National level, that considers the entire society. Data related to GDP, population and total energy throughput are used at this level of analysis. Eurostat data

on GDP and population are used together with the total energy throughput provided by the energy balances.

- Level N-1 – Disaggregates society between production and consumption activities and includes the paid sector and the household sectors. Data related to the human time devoted to the paid and to the household activities are considered based on the information included in the EUKLEMS database. The energy throughput of the paid and of the household sectors are also used based on the disaggregation included in the energy balances of Eurostat.

- Level N-2 – Disaggregates the paid sector into different subsector, such as agriculture (including agriculture, hunting, forestry, fishing and mining and quarrying), industry (including manufacturing, construction) and services (including commercial and public services). Eurostat data on sectoral GDP and sectoral energy throughput are used at this level of analysis, together with the information on sectoral time allocation provided by the EUKLEMS database.

For every level reported above, the existing relationships between energy use, GDP and human time are investigated based on: *i)* extensive variables, that summarize the size of the system (Figure 1) and based on *ii)* intensive variables which characterize the changes of the system (Figure 2) and that can be used to describe the social metabolism at different levels of analysis.

Figure 1. MuSIASEM extensive variables.

Figure 2. MuSIASEM intensive variables.

3. Geographical scope and data

As reported above, this paper focuses on 18 European countries. Due to data availability and consistency, not all the 28 EU Member States have been considered. However, by including

both western and eastern European countries, this paper takes into account a range of EU Member States characterized by different socio-economic and energy structures. In particular, ten of the countries have been classified as western European countries, while the other eight have been considered as eastern European countries. The EU Member States included in this paper are:

Western European Countries	Eastern European Countries
Germany (DE)	Czech Republic (CZ)
Denmark (DK)	Estonia (EE)
Greece (EL)	Lithuania (LT)
Spain (ES)	Latvia (LV)
Finland (FI)	Poland (PL)
France (FR)	Romania (RO)
Ireland (IE)	Slovenia (SI)
Italy (IT)	Slovakia (SK)
Sweden (SE)	
United Kingdom (UK)	

The data provided by Eurostat have been used as the main data sources. In particular, the energy balances providing information on the total final energy consumption (TEC), energy sector own use (ESOU) and losses (L) have been used to estimate the energy consumption of the paid and household sectors. In addition, based on [30], the following adjustments have been adopted to quantify the energy consumption of the sectors considered in this paper:

- For Level N, the total energy throughput is quantified as the total final energy consumption, plus the energy sector own use plus losses (TET = TEC + ESOU + L). The energy balances provided by Eurostat have been used as main source of information.

- For Level N-1 the energy consumption has been allocated based on the information included in the energy balances provided by Eurostat, that disaggregates the final energy consumption between the paid and the household sectors. In addition, the energy sector consumption and the transformation losses have been allocated to the paid and to the household sectors based on their share in the final energy consumption. Since

specific data related to transport activities are not consistently available across the countries considered in this paper, the following assumption (previously used in [66, 67] and in [30]) has been adopted: 25% of the transport energy consumption has been allocated to the household sector and the remaining 75% to the service sector. This allocation assumes that 50% of the mobility is distributed to the transport of goods and that the remaining 50% is equally distributed between the commuting mobility (allocated to the service sector) and the voluntary mobility (allocated to the household sector). The lack of specific data and the adoption of a general approach, represent an element of uncertainty impacting on the accuracy of results. However, by adopting the same approach previously used by other studies, consistency on methodology is maintained.

- For Level N-2, the information included in the energy balances provided by Eurostat have been aggregated according to the following sectoral classification:
  - The agricultural sector includes agriculture, forestry and fishing;
  - The industrial sector includes all the activities classified in the Eurostat energy balances as industrial activities (namely: iron and steel, chemical and petrochemical, non-ferrous metals, non-metallic minerals, transport equipment, machinery, mining and quarrying, food, beverages and tobacco, paper, pulp and printing, wood and wood products, construction, textile and leather and not elsewhere specified);
  - The service sector includes all the activities classified in the Eurostat energy balances as commercial and public services.

In addition, in line with the approach adopted for Level N-1, the energy sector consumption, the transformation losses and the transport energy consumption has been allocated based on the sectoral share in the final energy consumption.

Eurostat data have also been used for population and GDP. The harmonized index of consumer prices (HICP 2015=100) has been applied to harmonize the GDP reported by Eurostat at current prices. Data provided by the EU KLEMS database has been used for the total hours worked per persons engaged. At sectoral level, the classification reported above for the energy throughput have also been used for the sectoral aggregation of GDP and human time data The time period considered is between 2008, that was the year of the global financial crash, and 2015 that is the most recent year for which EU KLEMS data are available.

4. Results

4.1 Level N – Country Level

As reported above, the Level N of analysis refers to the national level, and investigates the metabolic performance of the 18 European countries. According to data reported in Figures 3 and in Table A.1 of the Appendix, between 2008 and 2015 the total energy throughput (TET) decreased for all the countries.

Figure 3. THA, TET and GDP - % variation (2008-2015)

The largest variations have taken place in three groups of countries, namely:

- The countries most affected by the global financial crisis, such as Greece, Romania and Spain, where a reduction of the TET (-19.6%, -15.8% and -12.1%, respectively), is associated to a large drop in GDP production (-31.9%, -15.7%, -11.71%, respectively).

- The countries with a negative GDP variation that during the period considered have been able to reduce the energy intensity of production (TET/GDP). In Italy and Slovenia, for example, the total energy throughput (-13.7% and -10.6%, respectively) has reduced more than the GDP production (-8.9% and -7.9%, respectively). Based on

data reported by [68,69], Italy experienced energy efficiency increase across the agriculture, the industrial and the service sectors. Industrial activities performed the largest energy intensity reductions, with efficiency improvements that have taken place across all the industrial branches. The implementation of market-based instruments, such as white certificate scheme and the tax relief on energy efficiency upgrades largely contributed to reduce the energy intensity of production [14]. In the years that followed the global financial crisis, however, the energy efficiency improvements have slowed down especially in the energy intensive branches, due to unused production capacity. Slovenia also performed energy intensity reductions across the agricultural, the industrial and the service sectors. The introduction of financial mechanisms, such as the financial incentives for the replacement of inefficient heating structures, together with the introduction of the motor vehicles tax act, largely contributed to increase the energy efficiency across the industrial, the residential and the transport sectors [70].

- The countries, such as Ireland, United Kingdom and Slovakia, that during the period considered experienced some of the highest GDP increases (+44.8%, +10.2% and 7.3%, respectively) together with some of the largest energy intensity reduction (TET/GDP: -38.7%, -19.2%, -16.8%, respectively) (see Table A.2 of the Appendix and Figure 4). According to data reported in Table A.8 of the Appendix, the increased contribution of the service sector and the energy efficiency improvements have been the main factors contributing to reduce the energy intensity of United Kingdom and Slovakia. During the period considered, these countries, together with Estonia and Sweden, experienced some of the largest energy efficiency increase. The United Kingdom, for example moved from being, in 2003, the least energy intensity economy in the G7 to being 33% below the G7 average and 23% below the EU28 average in 2012. The industrial and the service sectors performed the largest energy intensity reduction (-57% and -45%,

respectively since 1980). The chemicals, the food, drink and tobacco sectors together with the iron and steel sectors had the largest energy efficiency increases (82%, 49% and 34%, respectively) [71]. In Estonia, the energy intensity of production remains above the EU average. However, energy efficiency improvements have taken place across the agricultural and the industrial sectors. In particular, between 2008 and 2015, the industrial sector recorded a 32.5% energy intensity drop, significantly higher than the average energy intensity reduction of the EU28. The process of European integration, the related technological transfer and the modernisation of the energy infrastructures largely contributed to the energy efficiency increase [72]. In Ireland, the implementation of the national energy efficiency plans, together with structural changes that have taken place in the industrial sector, such as the increased contribution of high value production of the pharmaceutical and electronic compartment, have largely contributed to reduce the energy intensity of production [73].

Figure 4. Energy intensity - Absolute values (TJ/Million€) and % variations (2008-2015)

The gross domestic product (GPD) increased for 10 of the considered countries (Figure 3 and Table A.1 of the Appendix). The largest percentage variations have taken place in Ireland (+44.8%), Sweden (+18.6%) and United Kingdom (+10.1%). As reported above, these countries also performed the largest reduction of energy used per unit of GDP produced (-38.7%, -18%, -19.2%, respectively). Greece has been the only country to significantly increase the energy used per quantity of GDP produced (+18%). According to [74] the energy intensity in Greece is now slightly above the EU average and the energy intensity increase can be seen as a consequence of the recession as the volume of output fell faster than the energy use. Due

to running costs and structural constraints, the reduction of the energy used is not directly proportional to the production decrease.

The total human time (THA), that provides information on the population size, has decreased in seven of the countries considered in this paper (Figure 3 and Table A.1 of the Appendix). The largest percentage variations have taken place in Latvia (-9.2%) and Lithuania (-9.2%) that according to Eurostat had some of the highest emigration rate in the EU (together with Estonia). The largest THA percentage increases have taken place in the countries with some of the highest fertility and GDP growth rate, such as Sweden, United Kingdom and Ireland.

4.2 Level N-1 – Household and Paid Sector Level

The Level N-1 disaggregates the variables considered in the previous section between the household (HH) and paid (PW) sectors.

According to data reported in Table A.3 of the appendix, all the considered countries, exception for Germany, Poland, Sweden and United Kingdom reduced the human time devoted to the productive sector (HA_{PW}). The largest reductions have taken place in:

- the countries most affected by the global financial crisis, such as Greece (-19.9%), Spain (-12.8%) and Romania (-11.0%);

- Ireland, that according to Eurostat has been the country with the highest labour productivity increases;

- the countries that experienced the largest emigration rates (namely: Latvia, Lithuania and Estonia). These countries, together with Germany, Poland and Romania also have reduced the human time allocated to the household sector.

In all the other countries, exception of Germany, Poland and United Kingdom, the variation of the time allocated to the household sector has been higher (or have been reduced less) than the variation of the time allocated to the productive sector. This indicates that the dependency ratio

of the non-working population has increased. Aging population and increased unemployment rate can have been the main factors affecting this trend.

When considering the energy used per unit of time spent in the household sector (EMR$_{HH}$) all the considered countries, with exception of Czech Republic, reduced the EMR$_{HH}$ (see Figure 5 and Table A.4 of the Appendix). In addition, for all the countries, with exception of Czech Republic, the percentage increase of the time spent in the household sector (HA$_{HH}$) has been higher (or has been reduced less) than the percentage increase of the energy consumed (ET$_{HH}$). Since previous studies [75-78] have used the energy throughput per hour of human activity in the household sector (EMR$_{HH}$) as a proxy of the material standard of living, the evidence provided suggests that the energy used alongside the home appliances, that usually increase the overall comfort of non-working time, have reduced. This is consistent with the expected impact of the global financial crisis and with the deceleration of growth experienced by the considered countries. The Member States with the greatest reduction of the energy throughput of the household sector (ET$_{HH}$) have been Latvia (-21.6%), Greece (-13.9%) and Lithuania (-13.5%). According to [74], the energy consumed by households in Greece decreased at a higher pace than the EU average as a consequence of global financial crisis and personal income reduction. In Latvia and Lithuania, the reduction can mainly be explained by the high migration rate that reduced the time spent in the household sector, and by the implementation of EU and national policies for energy efficiency increase that have taken place both in the service and in the household sectors [79,80].

Figure 5. Exosomatic metabolic rate of the household sector (EMR$_{HH}$ = ET$_{HH}$/HA$_{HH}$). Absolute values (MJ/h) and % variations (2008-2015)

Based on data reported in Table A.4 of the Appendix, all the countries, exception for Germany, Latvia, and Poland also reduce the energy throughput of the paid sector (ET_{PW}). The largest reductions have taken place in two sets of countries, namely: the countries most affected by the global financial crisis, such as Greece (-22.7%), Romania (-18.8%) and Spain (-14.4%); the countries with structural changes or with the largest energy efficiency increases (Ireland -14.4%, Estonia -14.8%, Denmark -12.9%, Italy -18.1%, Slovenia, -13.7%, Slovakia -11.6% and United Kingdom -10.8%). In terms of exosomatic metabolic rate (EMR_{PW}) (see Figure 6 and Table A.4 of the Appendix), almost all the countries reduced the energy consumed per hour of labour. Latvia and Lithuania have been the only countries to increase the EMR of the paid sector, while Germany and Poland have remained almost constant. In addition, Latvia, that performed the largest EMR percentage increase (+27.1%), has been the only country to increase the energy throughput both in the agricultural and the industrial sectors (see Table A.6 of the Appendix). According to data provided by previous studies [81,82] Latvia has been one of the EU countries that mostly increased the energy consumption in the industrial and in the transport sectors. For all the other countries, the percentage reduction of the hours worked (HA_{PW}) has been higher than the percentage reduction of the energy throughput of (ET_{PW}). The EMR_{PW} mostly decreased in the countries that performed the largest energy efficiency increase, such as United Kingdom, Italy, Sweden, Slovakia and Slovenia. These countries, had the highest percentage reduction of the energy throughput in comparison to the percentage reduction of the worked hours.

Figure 6. Exosomatic metabolic rate of the paid sector ($EMR_{PW} = ET_{PW}/HA_{PW}$). Absolute values (MJ/h) and % variations (2008-2015)

4.3 Level N-2 – Economic Sectors Level

The analysis of the metabolic performance of the paid sector can be disaggregated between the agricultural, the industrial and the services activities. The changes that have taken place across the sectors can be useful to explain the metabolic trends reported in the previous sections. According to data reported in Table A.5 of the Appendix, all the considered countries reduced the human time allocated to the industrial sector (HA_{PWi}). The largest reductions have taken place in the countries most affected by the global financial crisis, namely Greece (-33.3%) and Spain (-28.0%) and in the countries with the highest emigration rate, such as Latvia (-29.9%), Lithuania (-20.6%) and Estonia (-18.3%) plus Ireland, that according to data provided by Eurostat, has been the EU country with the highest labour productivity increase. Most of the countries also reduced the time allocated to the agriculture and increased the hours spend in the service sector. Czech Republic, Denmark, Estonia, Greece, Spain, Ireland, Italy and Latvia are the only countries that reduced the human time allocated to all the three economic sectors considered in this paper. According to data reported in Table A.7 of the appendix, in all the countries (with exception of Latvia and Lithuania) the exosomatic metabolic rate of the service sector (EMR_{PWs}) has been reduced or left almost unchanged. Latvia, that increased the EMR_{PWs} by 27.1%, has been the country that mostly reduced the human time devoted to the service activities (-15.3%). Latvia also performed the largest percentage increase of the exosomatic metabolic rate of industry (+65.9%) and it has been the only country to increase the exosomatic metabolic rate of all the considered sectors. According to data reported in Tables A.1-A3 of the Appendix, the large reduction of the time devoted to the productive sector (-20.6%), generated by the high emigration rate and by the drop in the level of production (GDP reduced by 11.2% between 2008 and 2015) together with the second largest energy intensity increase, have been the main factors responsible for to the variation of the exosomatic metabolic rate (EMR_{PW} +27.1%). Romania has been the country that mostly reduced the EMR of the industrial

sector (-19.3%) and that mostly increased the EMR of agriculture (+77.0%) (Table A.7 of the Appendix). According to data provided by [82,83] the implementation of the Common Agricultural Policy in Romania, the provision of consistent financial EU investments, and the implementation of energy efficiency policies, largely contribute to increase the mechanization rate of agriculture and to reduce the energy intensity of industries.

4.4 Summary of results, limitations and research developments

Based on the analysis reported above, a summary of results is reported in Table 1. In this section the main limitations and the possible research developments are also discussed.

Table 1. Summary of results

In line with previous studies [84,85], the results provided in this paper highlight that the global financial crisis and the related income and production drop, have been able to reduce the quantity of energy used both in the paid and in the household sectors. In addition, the energy intensity reductions that have taken place in the countries that experienced the largest economic growth rate (such as Ireland, Sweden, United Kingdom, Germany and Slovakia) highlight the role of economic growth in promoting technological development, energy efficiency and shifts of production toward less energy intensive products. In line with the sustainable production and consumption theories, energy efficiency increase has mainly taken place in the countries characterized by the largest economic growth rate. The overall reduction of the total energy throughput, together with the reduction in the quantity of energy used per unit of GDP produced have highlighted that in these countries an absolute and relative decoupling has taken place. On the contrary, the countries characterized by the largest GDP reductions, have experienced an absolute decoupling without experiencing an energy efficiency increase.

Despite the large amount of information provided by the MuSIASEM approach, the analyses included in this paper does not provide specific information around the drivers of energy changes. In particular, the MuSIASEM technique is not able to fully determine if the energy efficiency variations are a direct cause or a consequence of the socio-economic changes taking place in a specific country during a specific period of time. To this purpose decomposition analysis should be used to complement the MuSIASEM analysis performed in this paper. In addition, the impossibility to account for the quantity of energy embedded into imported and exported products, represent a further limitation and an element of uncertainty. By considering the energy used within a national territory, and by excluding the information related to international trade, the MuSIASEM approach leave uncertainty around the overall amount of energy that is need to sustain the consumption of societies. To provide a more consistent pictures of the overall sustainability trends, the information provided by the MuSIASEM approach, would then need to be complemented by studies investigating the energy footprints of countries. As previously reported by [3], the economic development of nations and the related technological progress can contribute to energy efficiency increase. However, the structural changes taking places across sectors of production can lead to displace the most pollutant and energy intensive activities to developing countries. Based on data reported in Table A.7 and A.8 of the Appendix, most of the countries that experiences the largest GDP growth rate also had a reduction in the contribution played by the industrial sector and an increased role of the less energy intensive activities of the service sector. As highlighted by previous studies [86-4] an accounting approach investigating the energy used to support consumption, together with the energy used to support production, can provide a more exhaustive picture of the energy requirements of countries. Future analysis could also be oriented to investigate the metabolic trends of Member States during the years included between 2008 and 2015. In line with previous studies [57] the comparative analysis presented

in this paper have been focused on data for two specific years. This approach allows to compare countries in specific points of time and to investigate the metabolic performance at the beginning of the crisis and seven years after the crash. The analysis of the adjustment trends that have taken place between 2008 and 2015 could however complement the present study by providing detailed information on the recovery process of countries. The case of Latvia, Lithuania and Estonia, for example, would benefit from detailed year to year analysis. In spite of experiencing some of the highest GDP drops, these countries have been some of the first areas in the EU zone to return to GDP growth. A detailed analysis of the recovery process could provide useful information to investigate the adjustments measures that have taken place in the national and in the sectoral metabolism. In a similar way, the metabolic profile of Poland and Ireland would need to be further investigated. Poland has been the only EU country to avoid a recession through the 2008 financial crisis and Ireland had in 2015 an outliner year, with an economic growth largely higher than in the previous years [27].

In spite of the possible research developments reported above, the MuSIASEM approach adopted in this paper contributes to identify how the energy metabolism of countries, characterized by different socio-economic conditions, have changed during a period of economic downturn. The results can contribute to the debate around growth and efficiency and can be used to support the design of sustainable energy policies.

5. Conclusion and policy implications

By considering the metabolic profiles of 18 European countries, this paper investigates the relationships between energy requirements, economic trends and population in the period that followed the global financial crash. Results show that two main two groups of countries performed the largest energy reduction, namely: the country most affected by the global financial crisis, such as Greece, Romania and Spain, where the total energy throughput

decreased as a consequence of production and consumption drop; and the countries, such as Ireland and United Kingdom, characterized by the highest GDP increases together with the largest energy efficiency improvements.

The large differences existing between the energy performances of Member States, have highlighted how the different socio-economic conditions have impacted on energy profiles of countries. In spite of the extensive European policies oriented to reduce the energy intensity of societies, the geographical areas most affected by the global financial crash have not been able to achieve the same progresses obtained by the countries with the highest GDP growth rates. The costs related to the unused production capacity, the lowest investments and the low expectations of GDP growth have contributed to slow down the energy efficiency improvements and the implementation of the 2030 targets. On the contrary, the rapid economic recovery of Ireland and UK, together with structural economic changes and ambitious national energy plans, have contributed to reduce the energy intensity of the household and of the paid sectors. In addition, the process of European integration, characterized by technological transfer and modernization of the energy infrastructures, has contributed to increase the energy efficiency of the eastern European areas.

From a policy perspective, the results of this paper, highlight that the European policies oriented to support the achievement of the 2030 targets have contributed to reduce the energy throughput of EU. In particular, the implementation of the energy targets, together with the promotion of structural economic changes and technological improvements have been able to move the European area toward a more sustainable energy structure. The socio-economic conditions, characterizing every specific country, have however impacted on the achievement of the national targets. As reported above, the financial constraints of the global financial crash together with the diverse recovery process experienced by countries have affected the achievements of more sustainable, efficient and competitive economy.

Within this context, the European policies oriented to support the 2030 targets should be designed to take into account the specific opportunities and constraints characterizing the countries. The definition of national targets, together with periodic revisions and adjustments, are evidence of existing strategies oriented to consider the wide diversities existing across the EU. The recent assessment of the National Energy and Climate Plan for Greece (SWD(2019)261final), conducted by European Commission in 2019 has, for example, specifically highlighted how the economic situation of the country has been taken into account in evaluating the insufficiently ambitious energy efficiency goals. On the opposite side, Ireland has recently strength the commitment to the 2030 targets by revising the renewable electricity target up from 55% to 70% in 2030.

Integrated European policies should then be further promoted to compensate the structural and economic differences of countries. This recommendation is strictly in line with the principles included in the Lisbon and Sustainable Development EU strategies, that identify integration and support as fundamental pillars of EU. Within this context, the largely debated "energy union", devoted to transform the European energy system through integrated energy markets, diversification of energy sources and promotion of technological development, could largely contribute to reduce the efficiency gaps and to promote a more sustainable, efficient and competitive economy.

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List of Figures and Table

Level N

- 1- **THA:** Total human activity: Accounts the time available to a countries' population for one year (Population*24hours*365days). It is measured in hours (h)
- 2 -**TET:** Total energy throughput: Quantifies the total primary energy used in one year to support the production and consumption activities that have taken place in the considered country. It is measured in megajoule (MJ)
- 3 - **GDP:** Gross domestic product: Quantifies the value added generated in one year in the considered country. It is measured in euro (€)

Level N-1

- 1 - THA can be disaggregated in:
- **HA$_{PW}$**: Human activity paid work: Accounts for the hours allocated to the production activities, classified as paid sector
- **HA$_{HH}$**: Human activity household: Accounts for the hours allocated to the cosumption activities, classified as household sector
- 2 - TET can be disaggregated in:
- **ET$_{PW}$**: Energy throughput paid work: Accounts for the energy used in the paid sector
- **ET$_{HH}$**: Enery throughput household: Accounts for the energy used on the household sector

Level N-2

- 1 - HA$_{PW}$ can be disaggregated in:
- **HA$_{PWa}$**: Accounts for the hours allocated to the agricultural sector
- **HA$_{PWi}$**: Accounts for the hours allocated to the industrial sector
- **HA$_{PWs}$**: Accounts for the hours allocated to the service sector
- 2 - ET$_{PW}$ can be disaggregated in:
- **ET$_{PWa}$**: Accounts for the energy allocated to the agricultural sector
- **ET$_{PWi}$**: Accounts for the energy allocated to the industrial sector
- **ET$_{PWs}$**: Accounts for the energy allocated to the service sector
- 3 - GDP can be disaggregated in:
- **GDP$_a$**: Accounts for the value added generated by the agricultural sector
- **GDP$_i$**: Accounts for the value added generated by the industrial sector
- **GDP$_s$**: Accounts for the value added generated by the service sector

Figure 1. MuSIASEM extensive variables. Adapted from [51]

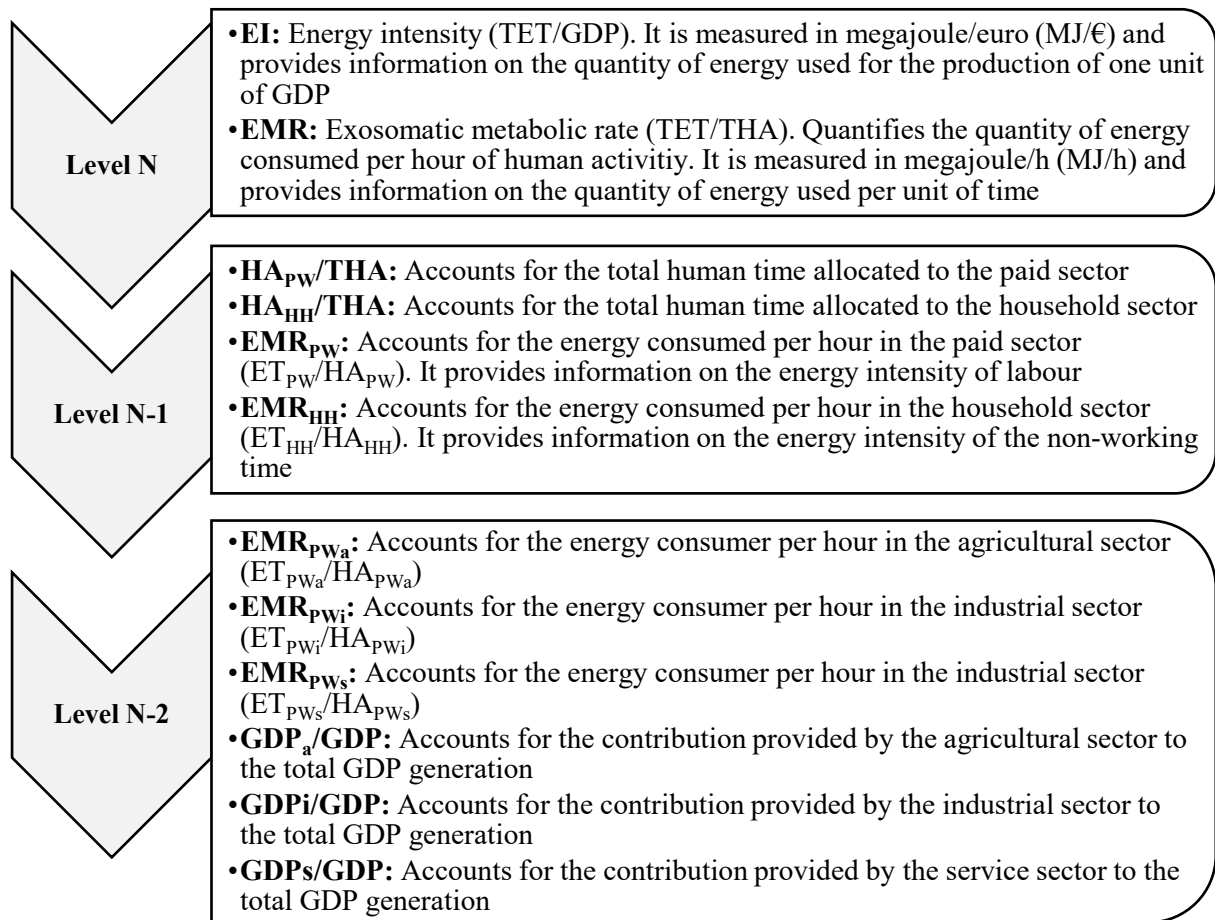| Level N	•**EI:** Energy intensity (TET/GDP). It is measured in megajoule/euro (MJ/€) and provides information on the quantity of energy used for the production of one unit of GDP •**EMR:** Exosomatic metabolic rate (TET/THA). Quantifies the quantity of energy consumed per hour of human activitiy. It is measured in megajoule/h (MJ/h) and provides information on the quantity of energy used per unit of time
Level N-1	•**HA_{PW}/THA:** Accounts for the total human time allocated to the paid sector •**HA_{HH}/THA:** Accounts for the total human time allocated to the household sector •**EMR_{PW}:** Accounts for the energy consumed per hour in the paid sector (ET_{PW}/HA_{PW}). It provides information on the energy intensity of labour •**EMR_{HH}:** Accounts for the energy consumed per hour in the household sector (ET_{HH}/HA_{HH}). It provides information on the energy intensity of the non-working time
Level N-2	•**EMR_{PWa}:** Accounts for the energy consumer per hour in the agricultural sector (ET_{PWa}/HA_{PWa}) •**EMR_{PWi}:** Accounts for the energy consumer per hour in the industrial sector (ET_{PWi}/HA_{PWi}) •**EMR_{PWs}:** Accounts for the energy consumer per hour in the industrial sector (ET_{PWs}/HA_{PWs}) •**GDP_a/GDP:** Accounts for the contribution provided by the agricultural sector to the total GDP generation •**GDPi/GDP:** Accounts for the contribution provided by the industrial sector to the total GDP generation •**GDPs/GDP:** Accounts for the contribution provided by the service sector to the total GDP generation

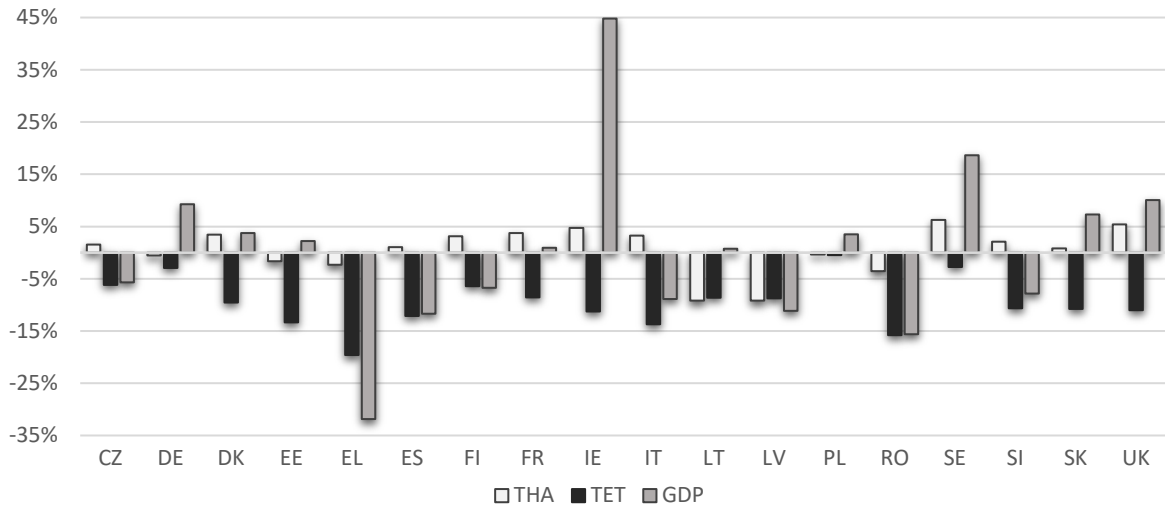**Figure 2. MuSIASEM intensive variables. Adapted from [51]**

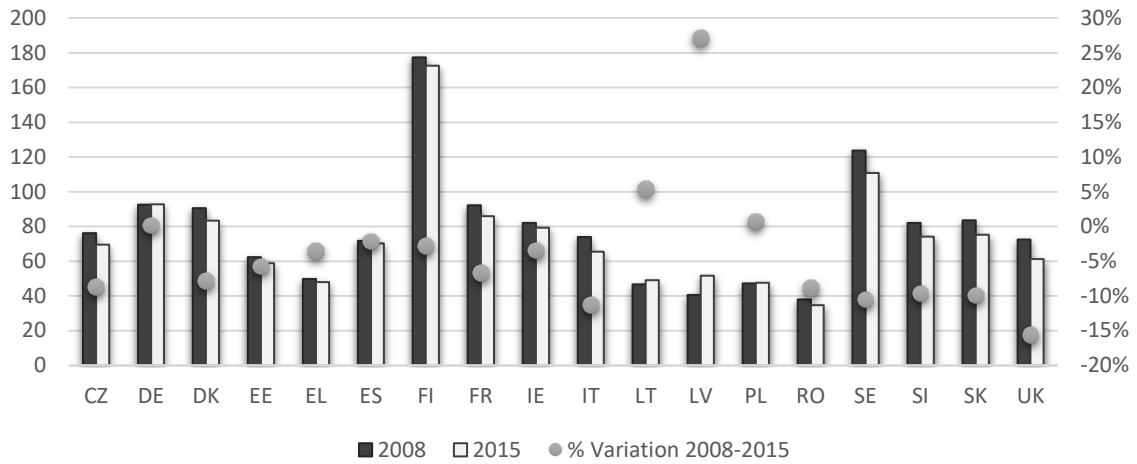**Figure 3. THA, TET and GDP - % variation (2008-2015)**

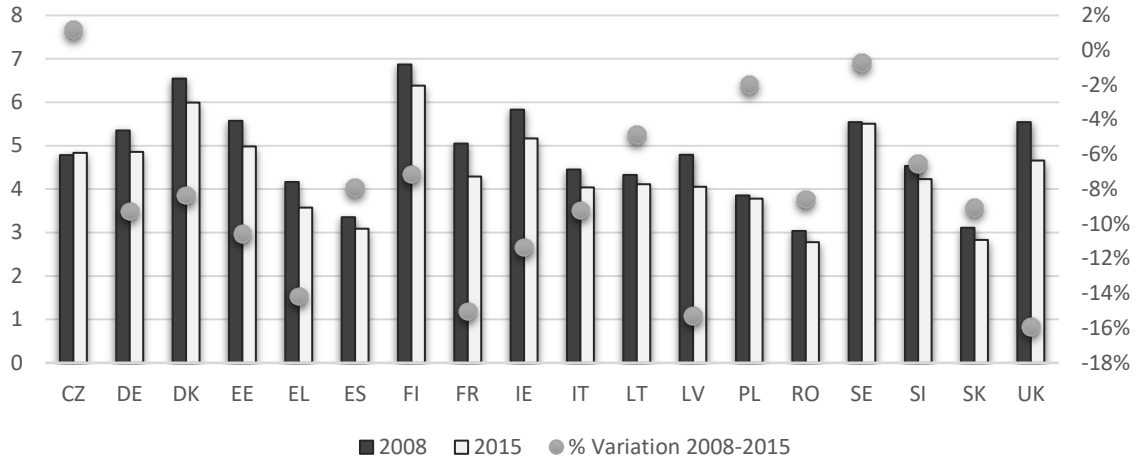**Figure 4. Energy intensity - Absolute values (TJ/Million€) and % variations(2008-2015)**

Figure 5. Exosomatic metabolic rate of the household sector (EMR$_{HH}$ = ET$_{HH}$/HA$_{HH}$). Absolute values (MJ/h) and % variations (2008-2015)
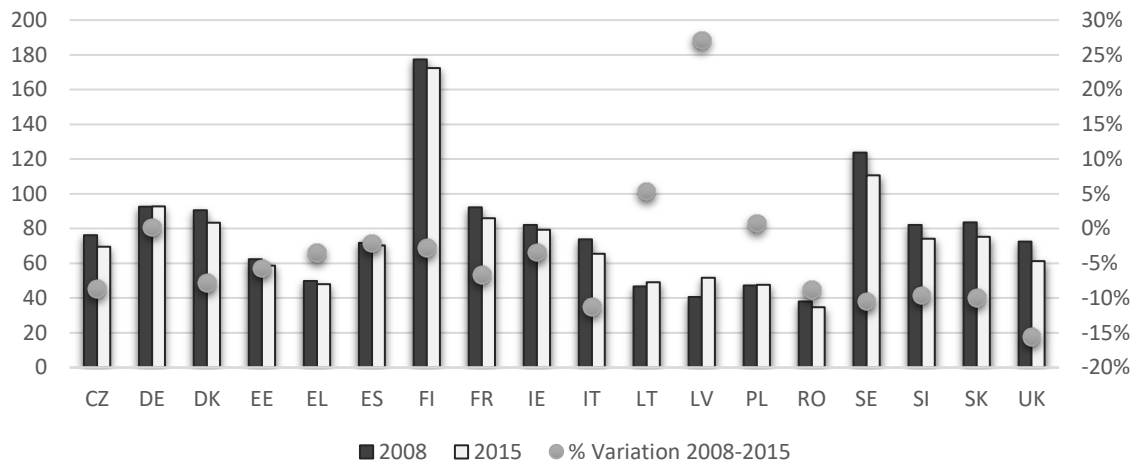

Figure 6. Exosomatic metabolic rate of the paid sector (EMR$_{PW}$ = ET$_{PW}$/HA$_{PW}$). Absolute values (MJ/h) and % variations (2008-2015)

Table 1. Summary of results

Level N	▪ Between 2008 and 2015 the TET decreased for all the considered countries.
	▪ The largest reductions have taken place:
	  ○ in the countries that reduced the overall production as a consequence of the global financial crisis;
	  ○ in the countries that have been able to reduce the energy intensity of production. These countries have been characterised by the higher percentages of GDP increases.
	▪ All the 18 countries (except Greece and Latvia) reduced (or kept almost unchanged) the quantity of energy used per unit of GDP produced.
	▪ The percentage reduction of the energy throughput has been generally higher than the percentage variation of the total human time (THA). Consequently, the per capita energy consumption decreased.
	▪ The only countries that slightly increased the per capita energy use have been the countries with the highest emigration rate, such as Latvia and Lithuania. Due to structural factors and long-term constraints, the percentage reduction of energy use has resulted to be lower than the percentage reduction of population.

Level N-1	▪ Between 2008 and 2015 most of the countries have increased the dependency ratio of the non-working population. This means that the time allocated to the household sector has been higher (or have been reduced less) than the variation of the time allocated to the productive sector. This trend is in line with the impact of an aging population and increased unemployment rate that characterise most of the European countries during the last decade. ▪ Most of the countries have also reduced the time allocated to the productive sector. The largest reductions have taken place in the areas most affected by the global financial crisis and in the eastern European countries with the highest emigration rate. ▪ Most of the countries reduced both the energy used in the paid sector as well as the energy used in the household sector. In both of the cases, the largest variations have taken place in the countries most affected by the crisis. ▪ The overall reduction of the GDP or the slow-down of the GDP growth rate, together with the negative expectations that characterised consumption in most of the European countries [77] largely contributed to reduce the quantity of energy used in the household sector. ▪ The energy intensity improvements together with the drop of production have been the main factors influencing the reduction of the energy used.
Level N-2	▪ All the countries reduced the human time allocated to the industrial sector. ▪ Most of them also reduced the time allocated to agriculture and increase the hours spent in the service sector. ▪ Most of the countries also reduced the exosomatic metabolic rate of the service sector and the energy intensity of the industrial and service activities. ▪ The increased role played by the service sector and the reduction of the energy intensity of the industrial activities highlight that structural changes and energy improvements have taken place across the countries.