

Received:
31 August 2018
Revised:
18 October 2018
Accepted:
20 October 2018

Cite as: Jarmo Vehmas,
Jari Kaivo-oja,
Jyrki Luukkanen. Energy
efficiency as a driver of total
primary energy supply in the
EU-28 countries —
incremental decomposition
analysis.
Heliyon 4 (2018) e00878.
doi: [10.1016/j.heliyon.2018.e00878](https://doi.org/10.1016/j.heliyon.2018.e00878)



Energy efficiency as a driver of total primary energy supply in the EU-28 countries — incremental decomposition analysis

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Abstract

Energy efficiency is a common element in European energy and climate policies. In the EU energy policy, energy efficiency is a policy target, and in the EU climate policy, energy efficiency is a means to achieve the CO₂ targets. In this paper, energy efficiency trends in the European Union and its 28 countries are analyzed during the period 1990–2015 by using the data provided by international Energy Agency (IEA). Total primary energy supply is decomposed into the effects of change in population, economic activity, final energy intensity, and the ratio between primary and final energy use. This paper introduces an incremental decomposition analysis method based on the Sun-Shapley method. Incremental decomposition provides information about annual changes. Information for longer periods can be obtained by summing up the necessary annual results. The empirical analysis carried out for the EU-28 countries clearly shows the effects of financial crisis 2008–09. When the whole period 1990–2015 is considered, despite of significant decrease in energy intensity, total primary energy supply has decreased only slightly in the EU. Differences between the countries are significant.

Keywords: Information science, Economics, Energy

1. Introduction

Energy efficiency has been a very common and actual policy objective since the 1970s. At a first glance, energy efficiency seems very handy to offer a win-win situation: improving energy efficiency decreases energy use and energy costs, and at the same time, negative impacts related to energy use such as carbon dioxide (CO₂) and other emissions in the air decrease. Thus, improving energy efficiency is considered as an important means to reach climate policy targets as well as other policy goals related to energy use, directly or indirectly.

Energy efficiency is one of the most studied phenomenon in the field of energy and energy policy studies. In the Elsevier ScienceDirect service, keyword “energy efficiency” can be found in the title, abstract and/or keywords of more than 70,000 peer-reviewed research articles, review articles, or book chapters.

Energy efficiency, however, is a relative concept, and as such far from being without problems (Patterson, 1996; Herring, 2006; Proskuryakova and Kovalev, 2015). This is one of the reasons to its popularity both in scientific and political discussions. The win-win solution mentioned above assumes decreasing energy consumption, but actually per unit of production only. Improvements gained by increasing energy efficiency per unit are often lost in additional energy consumption, caused either by increase in amount of the units (direct rebound effect), or consumption elsewhere (indirect rebound effect). This is the Jevons paradox (Polimeni et al., 2009).

In general systems perspective, efficiency refers to a relationship between the input and output of a defined system. Change of efficiency over time brings out the common efficiency idea of getting more from less, which explains the fact that improving energy efficiency has been a common energy policy goal all over the World from the 1970's oil shocks. The idea is that using less energy for a certain task decreases energy consumption and gives better possibilities to use energy sources with a predictable price development, which in practice meant domestic energy sources especially in those countries depending on imported crude oil and imported liquid fuels.

When energy use is chosen as an input of a system, energy efficiency refers to a relationship between energy use and the output. This kind of definition is valid in all systems, and it is not dependent on any scale or type of system *per se*. However, in practice, the system boundary must be clearly defined. In large systems, the energy input usually consists of different energy sources such as electricity, heat, or different types of fuels. Energy efficiency of a system requires that the total energy input to the system is considered. In large systems, the use of aggregate energy units is relevant for this reason. On the other hand, also the output should be considered in total terms, which makes the use of monetary units as an alternative if the physical units cannot be easily aggregated. One can argue for focusing on systems with only

one energy source and one output product only, but the question how to select the systems for analysis remains.

The IPAT identity emerged out of the Ehrlich & Holdren/Commoner debate in the early 1970s about the driving forces of global environmental impacts (York et al., 2003). The IPAT identity identifies the major drivers of environmental impact (I) at the global level: the amount of population (P), the affluence of that population (A), and level of technology (T). Waggoner and Ausubel (2002) added a new term, consumption (C) in the identity and called the result as an ImPACT identity. Kaya (1990) applied the idea of IPAT identity to identify the drivers of climate change and carbon dioxide emissions. His application has been called as Kaya identity (Eq. (1)), which is a common starting point of many empirical studies:

$$CO_2 = \frac{CO_2}{TPES} \times \frac{TPES}{FEC} \times \frac{FEC}{GDP} \times \frac{GDP}{POP} \times POP \quad (1)$$

To analyze and understand changes in socioeconomic or environmental indicators, it is useful to assess the drivers that underlie these changes (Hoekstra and van den Bergh, 2003). Energy consumption at the macro level of the society is a result of three basic drivers: activity, intensity and structural change. The structural change can refer to different economic sectors, but also to the energy mix. Energy efficiency deals directly with only one of these effects, the intensity effect. Changing energy intensity is not the same as changing energy efficiency (IEA, 2014, 2017a). The intensity effect is, however, essential at the macro level and is thus in the focus of this article.

The structure of this article is the following: In the following chapter, the methodology belonging to index decomposition analysis (IDA) will be described. In the empirical part, first the trends of two macro level energy efficiency related indicators, the ratio between primary and final energy use and energy intensity in the EU-28 countries will be described. After that, results from the empirical analysis of total primary energy supply (TPES) will be presented. The final chapter concludes and gives policy recommendations.

2. Methodology

Decomposition analysis is a common approach in energy analysis, and energy efficiency is one of the drivers included in practically all empirical analyses. In the Elsevier ScienceDirect service, a combination of keywords “energy efficiency” and “decomposition analysis” can be found in the title, abstract, or keywords of more than 600 peer-reviewed research articles, review articles, and book chapters.

There are two main categories of decomposition analysis (Hoekstra and van den Bergh, 2003; Wang et al., 2017), index decomposition analysis, which uses

aggregated time series data (IDA) and structural decomposition analysis, which uses disaggregated sectoral data from the input-output tables (SDA). The popularity of index decomposition analysis has been increasing since the 1980's when the first studies were published. Approach in the early IDAs were mainly based on the Laspeyres index, in the 1990's the Divisia index gained more popularity, and in the 2000's the most popular IDA approach based on the logarithmic mean Divisia index (LMDI) (Ang, 2015). According to Ang (ibid.), the dominance of LMDI is likely to further increase over time.

Major focus in energy-related IDAs has been change in energy consumption, change in energy intensity, and especially in the recent years, change in energy-related CO₂ emissions (Ang, 2015). The scope of IDA varies from sectoral analyses (such as selected industry, agriculture, transport, service sector or residential sector) to entire national economies and comparative analyses between different countries.

Energy-related IDA studies for the European Union have been made for aggregate energy consumption (either primary or final energy), CO₂ emissions, and energy intensity. European Union as an aggregate, selected countries, and economic energy-consuming sectors have been analysed. Examples from EU-wide analyses include the following: Kaivo-oja and Luukkanen (2004) used the Sun/Shapley method in decomposing CO₂ emissions of the EU-15 countries in 1973–1998. Saikku et al. (2008) analysed CO₂ emissions in different groups of countries selected from the EU-27 countries in 1993–2004 and forecasted meeting of the 2020 target based on results from a logarithmic decomposition. Fernández Gonzales et al. have used LMDI method for energy intensity, energy consumption and CO₂ emissions in a set of EU-wide studies in 2013–2015 (Fernández Gonzales et al., 2013, 2014a, 2014b, 2014c, 2015). Moutinho et al. (2015) studied CO₂ emissions 1995–2010 in 21 European countries by using the LMDI method. Löschel et al. (2015) carried out a multi-level LMDI decomposition analysis of energy intensity 1995–2009 in the EU-27 countries. Recently, EU-wide IDAs have been carried out also at sectoral level mostly with the LMDI method, e.g. for electricity generation, energy-intensive cement industry, and agriculture (Karmellos et al., 2016; Branger and Quirion, 2015; Li et al., 2016; Yan et al., 2017). Europe has been analysed as a part of comparative IDA of CO₂ emissions using the Sun/Shapley method (Kaivo-oja et al., 2014) and the LMDI method (Henriques and Borowiecki, 2017).

In this article, an incremental IDA method based on the Sun-Shapley decomposition method will be used to study the drivers of total primary energy supply 1990–2015 in the EU-28 countries. The methodology was introduced by J.W. Sun (1996, 1998), and was first called as the Sun method and then as the refined Laspeyres method in the literature. After Albrecht et al. (2002) published their decomposition analysis of carbon emissions based on the Shapley value method, Ang et al. (2003) showed that

the method used by Albrecht et al. (2002) was exactly the same as the Sun method. Since then, the term Sun/Shapley method has been used in the literature.

The Sun/Shapley method has been included in the recommended decomposition methods by Ang (2004), because it provides a perfect decomposition by allocating the residual term with a principle “jointly created, equally distributed” to the identified drivers. Since then, methods based on the Divisia index gained more popularity and the Sun/Shapley method has been used much less. Early examples of using the Sun/Shapley method for forecasting include the studies by Sun (2001) who developed a forecasting model for energy demand in the EU and Luukkanen et al. (2005) who made a forecasting analysis for CO₂ emissions in the aggregates of OECD and non-OECD countries.

Decomposition analysis allocates the observed change in environmental, social or economic phenomenon to pre-defined drivers. Identifying the drivers may be challenging, because selection of potential drivers should be supported by theoretical or empirical evidence. The approach itself does not give tools for driver identification. Eq. (2) defines the drivers of total primary energy supply, and likewise the Kaya identity (Eq. (1)), it is based on assumed causal relationship between the included variables:

$$TPES = \frac{TPES}{FEC} \times \frac{FEC}{GDP} \times \frac{GDP}{POP} \times POP \quad (2)$$

In Eq. (2), TPES is total primary energy supply, FEC is final energy consumption, GDP is gross domestic product in real prices, and POP is the amount of population. New drivers are this “chained”, many times as needed in order to get all the identified factors included. It should be noted that the order of entrance of new factors in the chain is determined by the theory, or assumptions, behind factor identification.

Decomposition analysis is usually carried out for relatively long periods between two selected years. In this article, decomposition will be made for annual changes so a moving base year will be used. This is called as incremental decomposition analysis. Longer periods can then be analyzed by summing up the incremental results. Incremental analysis reveals the dynamics during the studied period. The dynamics has been studied earlier by (Luukkanen & Kaivo-oja 2002), who made a dynamic analysis of CO₂ emissions in Denmark, Finland, Norway, and Sweden during a period 1960–1997 with a fixed base year 1990.

Eq. (2) includes four drivers of total primary energy supply (TPES). Driver TPES/FEC (total primary energy supply divided by final energy consumption) represents the efficiency of the energy transformation system. That efficiency changes when a change in the energy transformation process take place, e.g. when fuel use is replaced by electricity. If that electricity is produced in condensing power plants,

the transformation process becomes more inefficient. This is because in condensing power plants, only 35–40 % of the fuel's energy content is transformed into electricity and the rest is waste heat. Thus, a drop in the efficiency of the energy transformation process increases the need of primary energy (TPES). If combined heat and power (CHP) production is used, the overall efficiency change is smaller, because the heat is used for heating purposes either in industrial processes or as district heat (which is common e.g. in Finland).

Driver FEC/GDP (final energy consumption divided by gross domestic product) describes energy intensity of the economy, which is an inverse of energy efficiency at national level, i.e. GDP productivity of energy use. Changes in this driver are due to changes in the structure of the economy, such as change from energy intensive to lighter industrial branches and services or vice versa. Technology improvements are another reason for change of energy intensity. Economic growth via financial transactions may decrease energy intensity without any structural change or technology improvements. Driver GDP/POP (gross domestic product divided by number of population), GDP per capita, describes affluence of the population referred to in the original IPAT identity. Driver POP (number of population) was considered as the most important driver in the original IPAT identity which focused on global environmental issues. In energy analysis of industrial countries it is less significant, but defends its position in the driver identification.

The decomposed effects of the drivers identified in Eq. (2) are calculated by chaining the variables follows (Eqs. (3), (4), (5), (6), (7), and (8)). Each equation provides the effect how the driver in the left side of an equation contributes to the TPES change.

$$TPES/FEC = (FEC_{t-1} + \lambda_1 \Delta FEC_{t-1}) \times \Delta \left(\frac{TPES}{FEC} \right)_{t-1} \quad (3)$$

$$FEC = \left[\left(\frac{TPES}{FEC} \right)_{t-1} + (1 - \lambda_1) \Delta \left(\frac{TPES}{FEC} \right)_{t-1} \right] \times \Delta FEC_{t-1} \quad (4)$$

$$FEC/GDP = \left[\left(\frac{TPES}{FEC} \right)_{t-1} + (1 - \lambda_1) \Delta \left(\frac{TPES}{FEC} \right)_{t-1} \right] \times (GDP_{t-1} + \lambda_2 \Delta GDP_{t-1}) \times \Delta \left(\frac{FEC}{GDP} \right)_{t-1} \quad (5)$$

$$GDP = \left[\left(\frac{TPES}{FEC} \right)_{t-1} + (1 - \lambda_1) \Delta \left(\frac{TPES}{FEC} \right)_{t-1} \right] \times \left[\left(\frac{FEC}{GDP} \right)_{t-1} + (1 - \lambda_2) \Delta \left(\frac{FEC}{GDP} \right)_{t-1} \right] \times \Delta GDP_{t-1} \quad (6)$$

$$\begin{aligned}
 GDP/POP = & \left[\left(\frac{TPES}{FEC} \right)_{t-1} + (1 - \lambda_1) \Delta \left(\frac{TPES}{FEC} \right)_{tt-1} \right] \times \left[\left(\frac{FEC}{GDP} \right)_{t-1} \right. \\
 & \left. + (1 - \lambda_2) \Delta \left(\frac{FEC}{GDP} \right)_{tt-1} \right] \times (POP_{t-1} + \lambda_3 \Delta POP_{tt-1}) \\
 & \times \Delta \left(\frac{GDP}{POP} \right)_{tt-1}
 \end{aligned} \tag{7}$$

$$\begin{aligned}
 POP = & \left[\left(\frac{TPES}{FEC} \right)_{t-1} + (1 - \lambda_1) \Delta \left(\frac{TPES}{FEC} \right)_{tt-1} \right] \times \left[\left(\frac{FEC}{GDP} \right)_{t-1} \right. \\
 & \left. + (1 - \lambda_2) \Delta \left(\frac{FEC}{GDP} \right)_{tt-1} \right] \times \left[\left(\frac{GDP}{POP} \right)_{t-1} + (1 - \lambda_3) \Delta \left(\frac{GDP}{POP} \right)_{tt-1} \right] \\
 & \times \Delta POP_{tt-1}
 \end{aligned} \tag{8}$$

Parameters λ_1 , λ_2 and λ_3 determine how the allocation is made to the two drivers in each of the decompositions. Following the principle “jointly created, equally distributed” of the Sun-Shapley method, $\lambda_1 = \lambda_2 = \lambda_3 = 0.5$ in all analyses carried out for this article. Subscript $t-1$ refers to a moving base year (previous year to t), and subscript $tt-1$ refers to a difference (Δ) between the current year t and the previous year $t-1$.

Time series data on all the variables in Eqs. (3), (4), (5), (6), (7), and (8) for the selected years 1990–2015 is available in the IEA World Energy Balances and Statistics (IEA, 2017b), which have been used in the analyses of this article.

3. Results

Fig. 1 shows the trend of TPES/FEC ratio during the years 1971–2015 for the Mediterranean EU countries Cyprus, Greece, Italy, Malta, Portugal, and Spain. The trends are rather stable in all countries. Italy and Portugal show the most efficient energy transformation systems, where the TPES/FEC ratio is around 1.2–1.3 during the whole period.

The trend of Malta is exceptional. The efficiency of the energy transformation system in Malta varies a lot but is much more inefficient than in the other Mediterranean countries during the whole period. While the TPES/FEC ratio in other Mediterranean countries varies between 1.2 and 1.6, in Malta the variation takes place between 1.4 and 2.8. The reason can be found in changes in the very few large units of either energy production or industrial consumption.

Fig. 2 describes the same trend in the three largest EU countries, i.e. France, Germany, and the United Kingdom. These countries differ from each other. France, highly relying on nuclear power, shows an increasing trend of TPES/FEC ratio (from 1.3 to 1.6), which means that the efficiency of the energy transformation system is decreasing. Nuclear electricity is calculated in the IEA statistics as primary

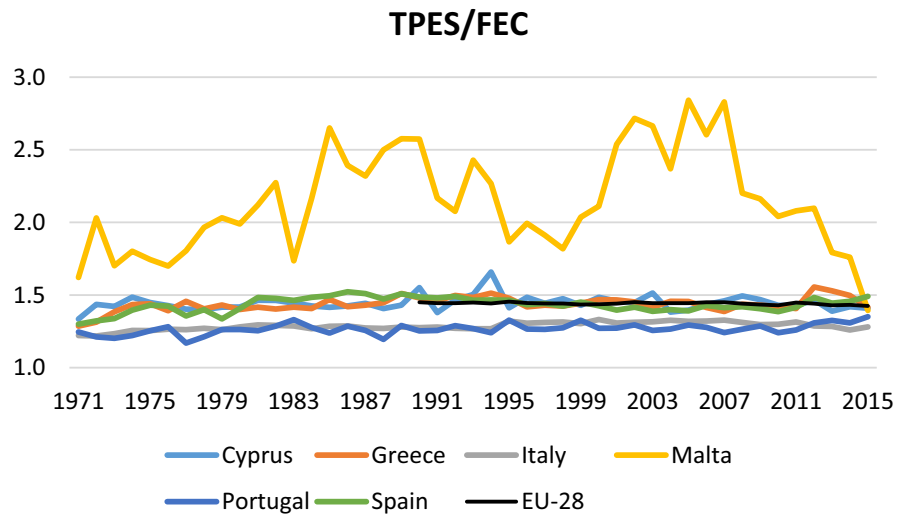


Fig. 1. Trend of TPES/FEC ratio in Cyprus, Greece, Italy, Malta, Portugal and Spain, 1971–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: IEA 2017b.

energy by dividing the amount of produced electricity by 0.33, and the increasing use of electricity is the major reason for the bad trend of energy transformation efficiency in France. The long period trend of Germany is quite stable with some annual variation (1.4–1.5), and the trend of the UK is slightly decreasing. This reflects a slight improvement in the efficiency of the energy transformation system over time in the UK.

In the Northern EU countries, Denmark, Finland and Sweden (Fig. 3), the TPES/FEC trend varies quite a lot. One obvious reason for this kind of trend is the variation

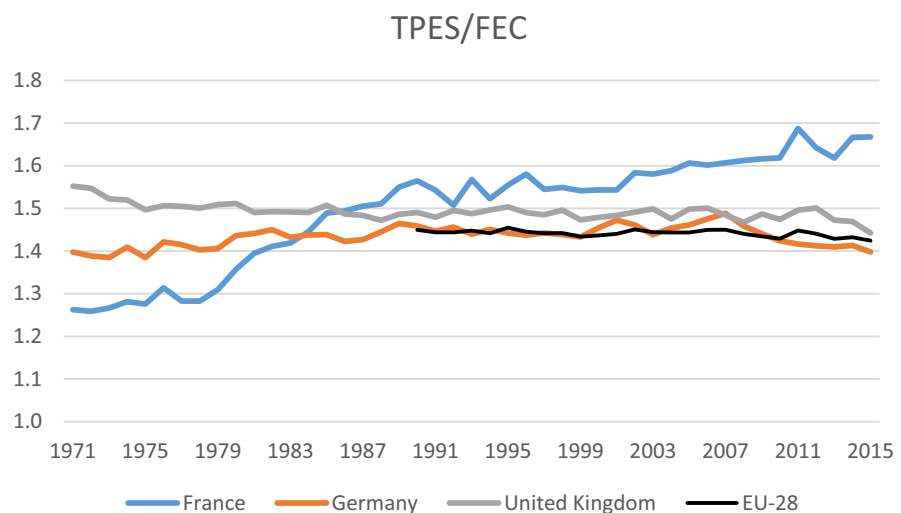


Fig. 2. Trend of TPES/FEC ratio in France, Germany and the United Kingdom, 1971–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: IEA 2017b.

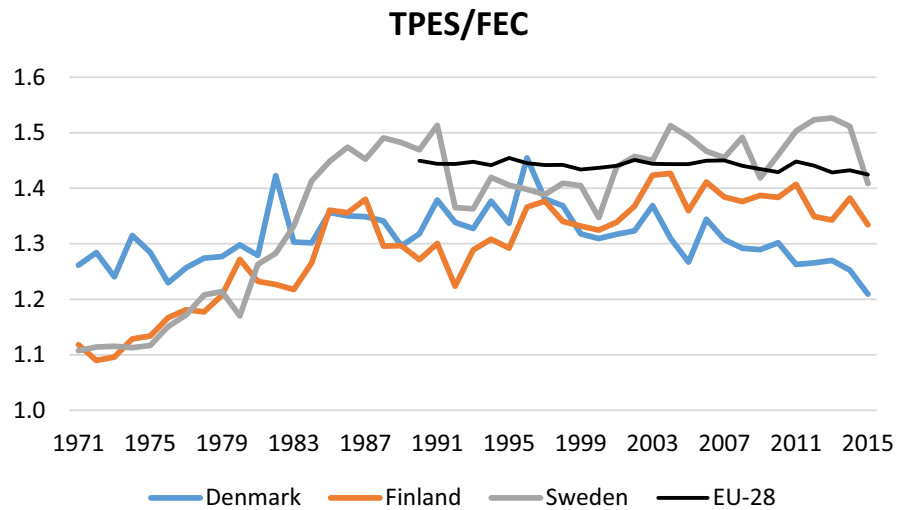


Fig. 3. Trend of TPES/FEC ratio in Denmark, Finland and Sweden, 1971–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: [IEA 2017b](#).

in imported electricity and hydropower availability (due to changes in precipitation). The long-term TPES/FEC trend of Denmark has turned into a decreasing one while the trends of Sweden and Finland are still increasing. A major reason to the increasing trend is, as in all Western economies, is the increasing use of electricity produced with a relatively low efficiency. Thus, the share of electricity in final energy consumption increases, and the value of TPES/FEC ratio increases, i.e. the energy transformation system becomes more inefficient.

In [Fig. 4](#), the trends of TPES/FEC for the Benelux countries Belgium, Luxembourg and the Netherlands, as well as for Austria and Ireland are presented. In general, a slightly decreasing trend can be observed from the 1990s onwards, Luxembourg is an exception because changes in one factory may change the whole system because of the extremely small size of the economy. In the 2000s, the TPES/FEC ratio of Luxembourg is closest to the minimum value 1.0 among all EU-28 countries.

The Baltic countries Estonia, Latvia and Lithuania show very different trends of TPES/FEC ([Fig. 5](#)). Based on the [IEA \(2017b\)](#) data, Latvia has the most efficient energy transformation system of the Baltic countries. The TPES/FEC trend of Estonia and Lithuania varies quite a lot, which is a common feature in small EU countries. However, the energy transformation system of Estonia is among the most inefficient ones in the EU.

The East European EU countries Czech Republic, Hungary, Poland and Slovakia have performed in two different ways regarding their TPES/FEC trends ([Fig. 6](#)). When the old Czechoslovakia collapsed, the TPES/FEC trend of Czech Republic started to increase, and the trend of Slovakia decreased rapidly. Shortly after that,

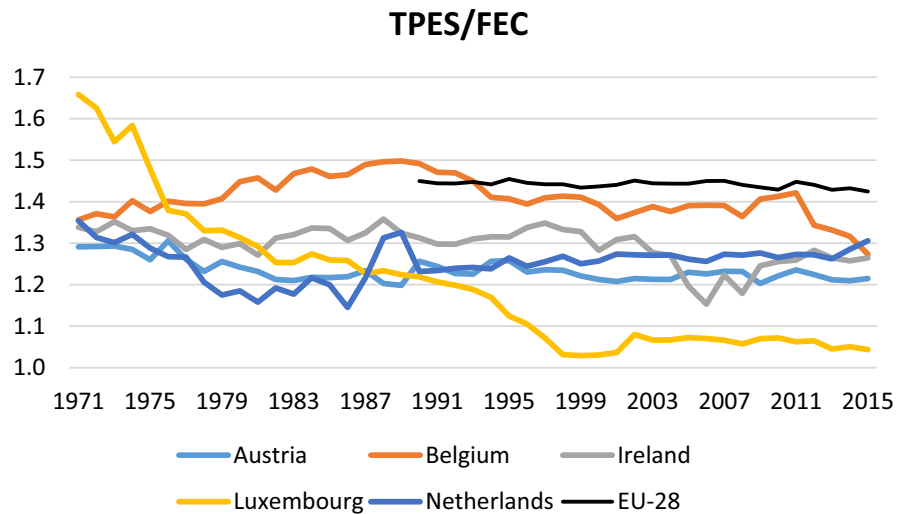


Fig. 4. Trend of TPES/FEC ratio in Austria, Belgium, Ireland, Luxembourg and the Netherlands, 1971–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: [IEA 2017b](#).

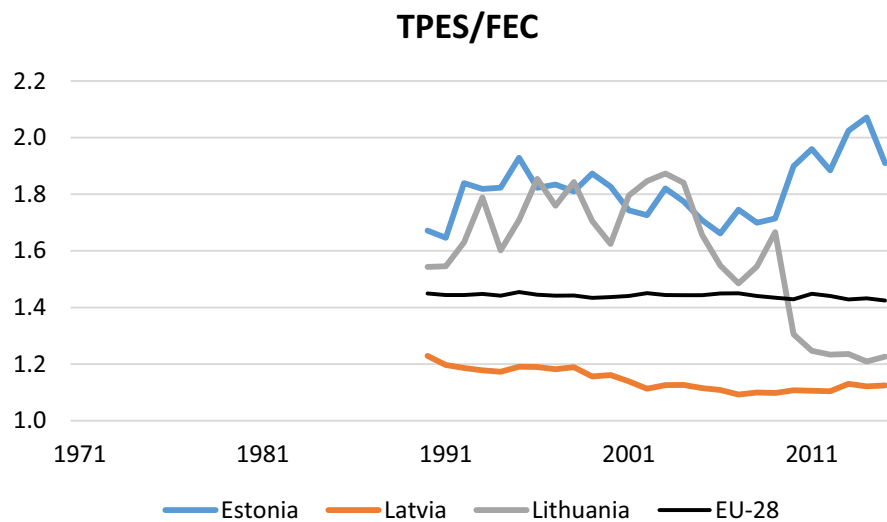


Fig. 5. Trend of TPES/FEC ratio in Estonia, Latvia and Lithuania, 1990–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: [IEA 2017b](#).

the trend of Slovakia started to increase again. Hungary and Poland, on the other hand, have had decreasing TPES/FEC trends since the 1990s. As such, the energy transformation systems of all these EU countries are not among the efficient ones.

[Fig. 7](#) shows the TPES/FEC trends of four countries recently joining the European Union. The trends of Croatia and Slovenia are decreasing during the period of their data availability (1990–2015). During the same period, also the trend of Romania is

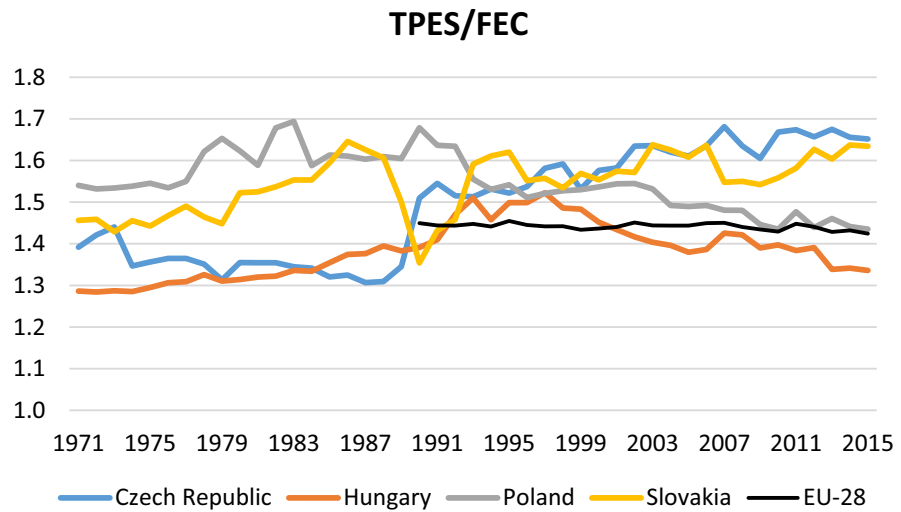


Fig. 6. Trend of TPES/FEC ratio in Czech Republic, Hungary, Poland and Slovakia, 1971–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: IEA 2017b.

a decreasing one while Bulgaria still tends to increase its trend. Bulgaria has quite an ineffective energy transformation system in the light of the IEA (2017b) data.

When the trends of energy intensity, an inverse of energy efficiency, are looked at, there are not so many differences as in the case of the trend of TPES/FEC above. In practice, all EU-28 countries show a decreasing trend of energy intensity (FEC/GDP), the major difference is in the rate and starting time of the decrease. Because trends of 28 countries do not fit well into a same figure, the same clusters of countries

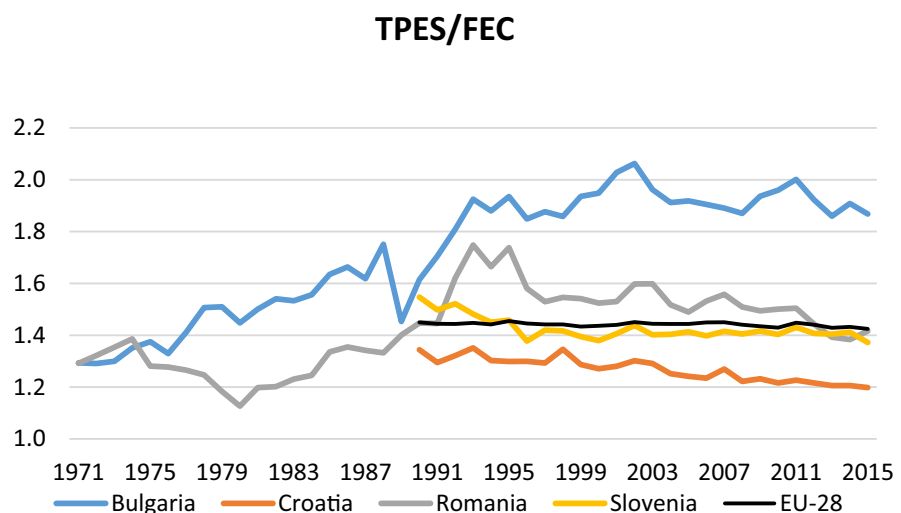


Fig. 7. Trend of TPES/FEC ratio in Bulgaria, Croatia, Romania and Slovenia, 1971/1990–2015. Total primary energy supply (TPES in Mtoe) divided by final energy consumption (FEC in Mtoe). The lower the ratio, the better the efficiency. Data source: IEA 2017b.

as above. Energy intensity is quite a poor indicator of energy efficiency at the macro level, because there are so many possible reasons for change, starting from structural change in the economy (from energy intensive industrial branches to lighter branches and services) and ending in technological improvements in a part of energy consuming activities of the society.

Fig. 8 shows how energy intensity has changed in the Mediterranean countries. The change in energy intensity is rather small, and in some countries such as Greece, Portugal and Spain the decrease has started quite recently. Italy has a nice slightly decreasing trend of energy intensity from the early 1970s, while in the energy intensity trend of small island countries Malta and Cyprus there is quite a lot of variation.

Fig. 9 shows the long-term decreasing trend of energy intensity in the large EU countries France, Germany and the United Kingdom. The level of energy intensity recently reached by the UK, 0.05 Mtoe/1000 USD₂₀₁₀, is one of the lowest in the whole European Union. Denmark (Fig. 10 below) and Ireland (Fig. 14 below) are the closest competitors. In these countries, one Mtoe of consumed energy produces GDP worth 20 000 USD₂₀₁₀.

In the Nordic countries Denmark, Finland and Sweden (Fig. 10), a clear decreasing trend of energy intensity can be observed. Only during the recession periods the decreasing trend has been shortly interrupted in Finland and Sweden. As noted above, Denmark has reached a level of energy intensity among the lowest in the whole EU.

Fig. 11 describes the energy intensity trends in the Benelux countries Belgium, Luxembourg and the Netherlands, and also in Austria and Ireland. The trends are

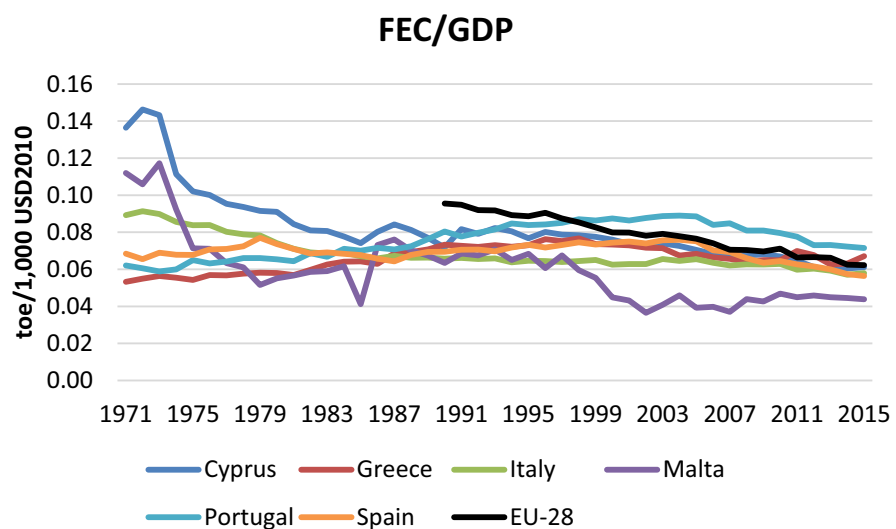


Fig. 8. Trend of energy intensity in Cyprus, Greece, Italy, Malta, Portugal and Spain, 1971–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

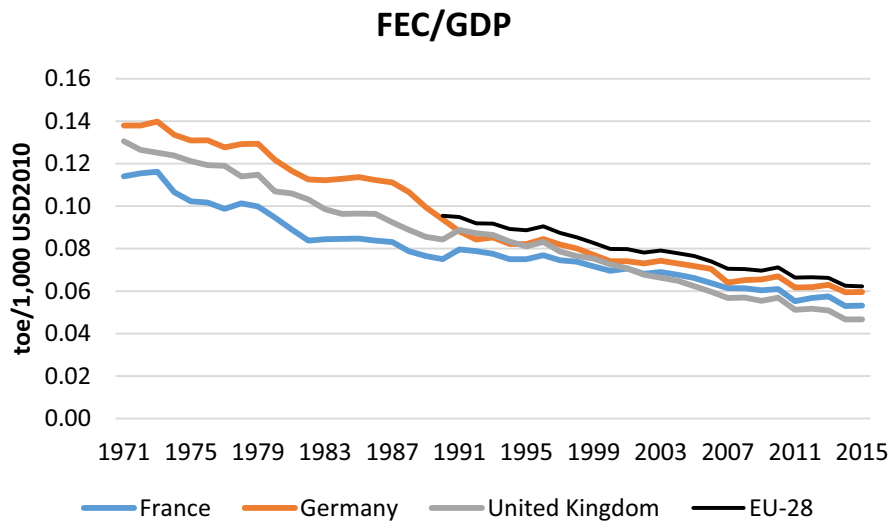


Fig. 9. Trend of energy intensity in France, Germany, and the United Kingdom, 1971–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

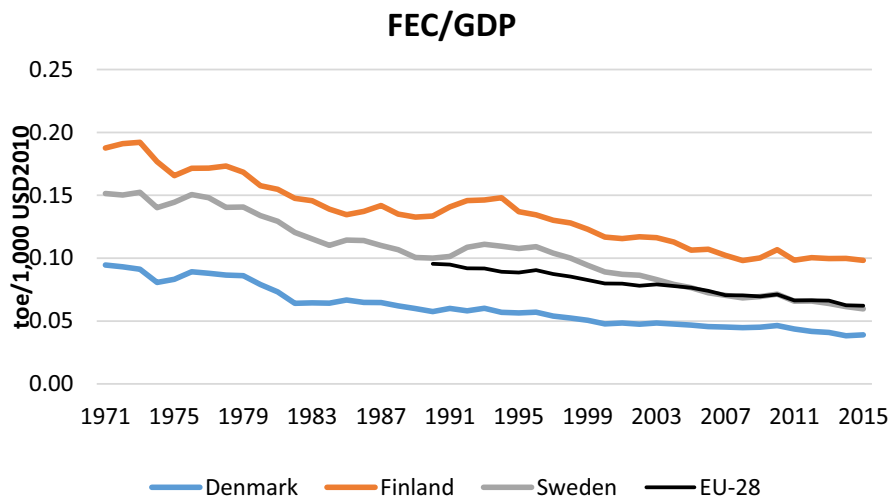


Fig. 10. Trend of energy intensity in Denmark, Finland and Sweden, 1971–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

decreasing ones, and Ireland together with Denmark (Fig. 10 above) and the UK (Fig. 9 above) has had one of the lowest energy intensities in the European Union during the recent years.

The Baltic countries have data in the IEA (2017b) database from the year 1990 onwards. In these countries, however, the decrease of energy intensity has been quite a rapid one (Fig. 12). However, these countries still have quite a high energy intensity, clearly above the EU-28 average.

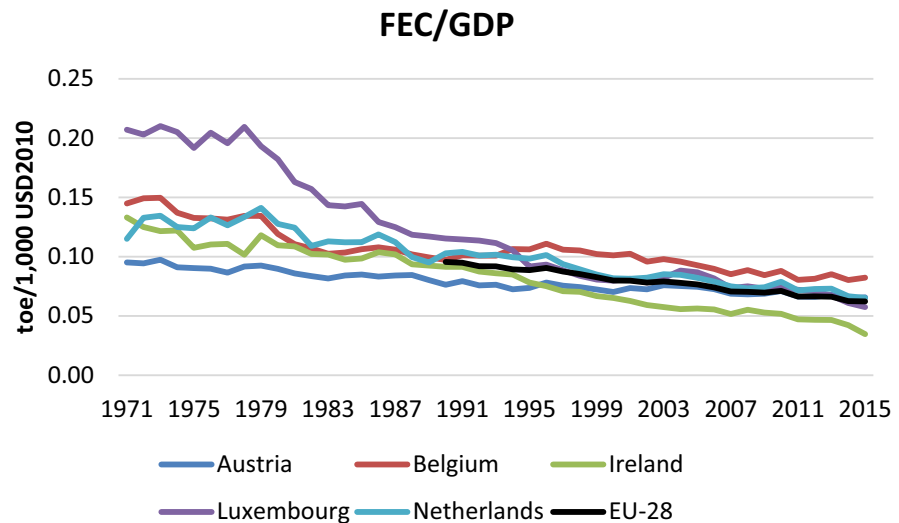


Fig. 11. Trend of energy intensity in Austria, Belgium, Ireland, Luxembourg and the Netherlands, 1971–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

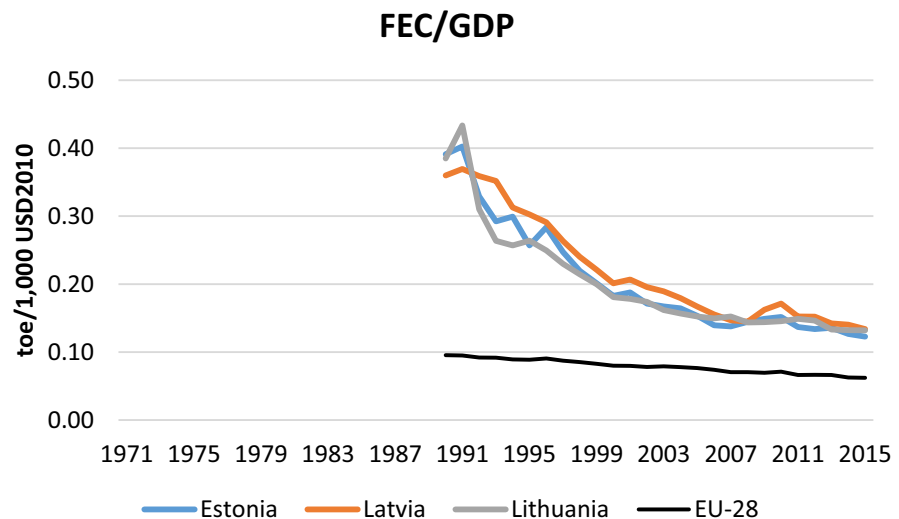


Fig. 12. Trend of energy intensity in Estonia, Latvia and Lithuania, 1990–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

The East European countries Czech Republic, Hungary, Poland, and Slovakia also have a decreasing trend in energy intensity (Fig. 13). The trends have turned into continuous decrease in the 1990s, before that there have been several increasing phases too. The most recent values are still clearly above the EU-28 average.

Fig. 14 shows how the energy intensity trends of Bulgaria and Romania have come down from the high values in early 1970s towards the level of 0.2 Mtoe/1000 USD₂₀₁₀. In comparison, the trends of Croatia and Slovenia are quite flat, but their

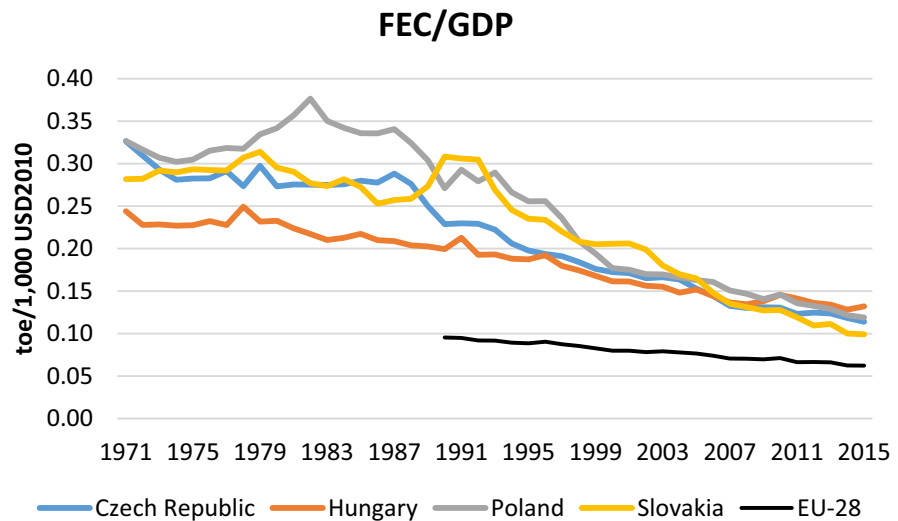


Fig. 13. Trend of energy intensity in Czech Republic, Hungary, Poland and Slovakia, 1971–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

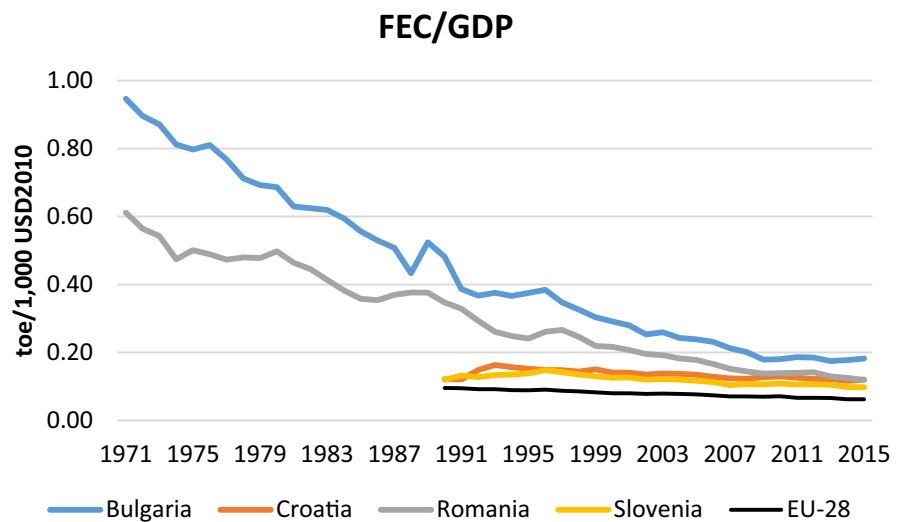


Fig. 14. Trend of energy intensity in Bulgaria, Croatia, Romania and Slovenia, 1971/1990–2015. Final energy consumption (FEC) divided by gross domestic product (GDP), toe/1000 USD₂₀₁₀. Data source: IEA 2017b.

nicely decreasing trends during the 2000s are hidden by the scale of Fig. 14 caused by the high 1970s values of Bulgaria and Romania.

After looking at the trends of TPES/FEC and FEC/GDP, the effects of these energy efficiency related indicators to total primary energy supply (TPES) will be analysed. The justification for this kind of analysis is, that in addition to keeping increasing energy efficiency as a policy target *per se*, energy efficiency can be considered as

a means to reach more concrete policy targets such as reducing energy use, or decreasing CO₂ and other emissions directly caused by energy use.

One of the major policy targets of improving energy efficiency is to reduce energy use without a need to limit the activities where energy is used in the society. Nowadays energy efficiency is taken as a policy target as such, but from the era of oil crises in the 1970s “energy saving” was commonly used instead up to the 1990’s. Energy efficiency can be improved in the energy consumption side (final energy consumption) and in the energy production side (transforming primary energy into energy carriers). It is worth noting here, that the EU energy efficiency target is not related to energy efficiency per se, but energy consumption in relation to projected future consumption.

The decomposition analysis gives an insight to what extent these policy targets have been reached, and also an insight to the role of the Jevons paradox (cf. Polimeni et al., 2009). In the following, change total primary energy supply will be decomposed into the relative contributions of the drivers described in Eq. (2). Data used in this decomposition activity is taken from the International Energy Agency (IEA, 2017b). This data includes total primary energy supply (TPES), final energy consumption (FEC), gross domestic product (GDP) in real prices ((in USD₂₀₁₀), adjusted by exchange rates), and number of population. The data used in the analyses covers the years 1990–2015 and it is the most recent data available from International Energy Agency (IEA, 2017b).

The results presented in the Supplementary Table are based on decomposition analysis of incremental (annual) changes, and they are presented as percentage of a selected base year value of the decomposed indicator, total primary energy supply (TPES). The analysis has been carried out for the years 1990–2015. The main results include relative contributions of the energy efficiency related drivers TPES/FEC and FEC/GDP as well as the contributions of other drivers defined in Eq. (2) above, i.e. GDP/POP and POP, to the change of total primary energy supply (TPES). The summary of decomposition results in the Supplementary Table are based on sums of incremental changes, and they are presented as percentage of the absolute TPES value of the first year of the period, 1990.

For the incremental effects of energy efficiency related drivers TPES/FEC and FEC/GDP, basic statistical info, i.e. median (Md), average (Av), standard deviation (Stdev) and minimum (Min) and maximum (Max) values, are given as well to show the variation in annual results. These numbers are percentages of the previous year’s absolute TPES value. Fig. 15 shows the incremental results for the EU-28 aggregate.

Between the years 1990 and 2015 (Supplementary Table), total primary energy supply increased in 14 EU countries and at the aggregate level of EU-15 (1.6 %). Large

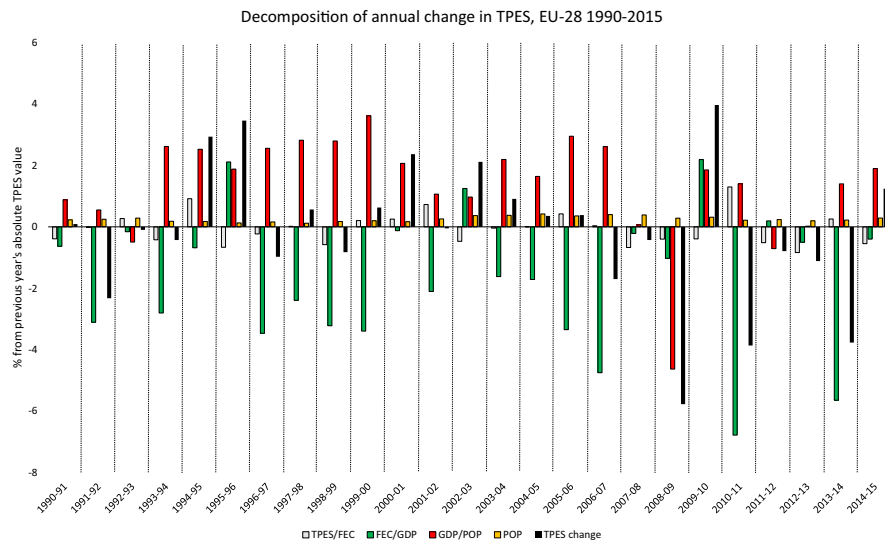


Fig. 15. Results of incremental decomposition analysis of total primary energy supply in the EU-28 aggregate, 1990–2015.

increase took place in Latvia (50 %), Cyprus (48 %), Ireland (34 %), Spain (32 %), Austria (32 %) and Portugal (31 %). Total primary energy supply decreased in 14 countries and at the aggregate level of EU-28 (−3.7 %). Large decreases took place in Lithuania (−55 %), Romania (−49 %), Estonia (−45 %) and Bulgaria (−34 %). Generally speaking, TPES increased in most of the Mediterranean countries and decreased in most of the Baltic (except Latvia) and East European countries. Among the large EU countries, TPES increased in addition to Spain (32 %) also in France (10 %) and Italy (4 %), and decreased in Germany (−12 %), the UK (−12 %) and Poland (−8 %).

In terms of energy savings and energy efficiency, the performance of a national state can be considered as good, if (i) the change of TPES is a decreasing one, and (ii) both energy efficiency related drivers (TPES/FEC and FEC/GDP) have a decreasing effect to TPES. With this criteria, performance between the years 1990 and 2015 was good in nine out of 28 EU countries: Croatia, Denmark, Germany, Hungary, Lithuania, Malta, Poland, Sweden and the UK, and in the EU-28 aggregate. Energy intensity (FEC/GDP) was the most significant driver with a decreasing effect in all EU countries except Malta, where TPES/FEC had a larger decreasing effect than FEC/GDP. Two additional things are worth noting: Firstly, in Bulgaria, Croatia, Estonia, Hungary, Latvia, Lithuania and Romania, also change in population had a decreasing effect to TPES. Secondly, change in GDP per capita had an increasing effect all over the EU, but in many countries, its effect was less significant than the decreasing effect of energy intensity.

When looking at the annual changes during the period 1990–2015, some interesting observations can be made. The financial crisis 2008-09 is clearly visible in the

incremental results for the EU-28 aggregate (Fig. 15), and it can be identified in practically all countries as well. Total primary energy decreased overall of the EU, and GDP per capita had a decreasing effect, which often was the most remarkable driver of decreasing TPES. The “normal”, and in practice the most common annual performance in the EU-28 is that GDP per capita (GDP/POP) and population (POP) have an increasing effect to TPES, and energy intensity has the most significant decreasing effect. 16 out of the 25 increments has this kind of performance, but the effect of TPES/FEC varies annually and does not have any clear trend. The same holds for total primary supply as well, there are shorter periods of annual decreases and periods of annual increases. As a result of all this, the change in TPES during 25 years in the EU-28 aggregate is only a slight reduction (−3.7 %; Supplementary Table).

There is a significant variation between the annual changes among the EU countries, both in the absolute trends of energy efficiency drivers FEC/GDP and TPES/FEC, as well as in the decomposed effects of these drivers on total primary energy supply. The variation is large especially in small EU countries and in the new EU countries. In general, energy intensity (FEC/GDP) has a decreasing trend but its effect to total primary energy supply is usually balanced by the effect of increasing economic growth (GDP/POP). The effects of other drivers (TPES/FEC and POP) are usually less significant in the longer run. However, among the results of incremental decomposition analysis (Annex1) several examples can be identified where the effects of these drivers also play a major role in changing TPES.

The trend of energy intensity is decreasing in most of the EU countries, but in practice it depends not only on good performance in energy efficiency, but also on poor economic performance which is directly reflected into the indicator FEC/GDP. This is important to keep in mind when looking at the studied period 1990–2015 which includes the financial crisis in 2008–2009. During that time, the driver GDP/POP had a decreasing effect to TPES in almost all EU countries. On the other hand, the effect of FEC/GDP had a decreasing effect in a few countries only during the same period. As a result, total primary energy supply decreased in many EU countries.

4. Discussion & conclusions

In this article, energy efficiency of EU-28 countries has been studied. Focus has been on macro level indicators of energy efficiency, their long-term historical trends and their decomposed effects on energy consumption (total primary energy supply TPES). In the empirical analyses, the most recent data from the International Energy Agency (IEA, 2017b) has been used. Because decomposition analysis is sensitive to the studied period and other empirical choices, different studies are difficult to

compare to each other. The major differences between IDA methods are mathematical differences, which fully explain the differences in results.

The indicators of energy efficiency used in this study are energy intensity of the economy (final energy consumption divided by gross domestic product in fixed USD₂₀₁₀ prices; FEC/GDP) and efficiency of the energy transformation system (ratio of total primary energy supply and final energy consumption; TPES/FEC). Energy intensity has decreased significantly in most of the EU-28 countries, but the trend of TPES/FEC ratio is not so clear and varies a lot between different countries. Increasing use of electricity affects the TPES/FEC ratio very differently, depending on the used primary energy sources (fossil, nuclear, renewables) and modes of electricity production (CHP, condensing power). In the IEA energy statistics, electricity produced by hydro, wind and solar is calculated as primary energy with a coefficient 1, but for nuclear and geothermal electricity, coefficient imitating thermal efficiency is assumed. This makes the use of aggregated energy indicators and their international comparison problematic. EU countries relying on nuclear power and fossil fuels may have a stronger increasing trend in the TPES/FEC ratio than countries relying more on energy sources where the statistical TPES/FEC ratio equals to 1.

The effect of energy efficiency on total primary energy supply (TPES) was studied by incremental Sun/Shapley decomposition analysis. The analysis was made for the period 1990–2015 using incremental decomposition with a moving base year for the first time. The method provides an exact decomposition, and the incremental results can be summed up to look at longer periods and there is no information loss. This makes the incremental Sun/Shapley decomposition very applicable to the exact analysis of annual changes.

The trend of TPES/FEC ratio reflects the efficiency of the energy transformation system from primary energy to final energy consumption. In some countries, the trend is a decreasing one, but also increasing trends have been identified. Change in the TPES/FEC ratio may partly be caused by changes in technical efficiencies, but also by fuel switch and other changes in the energy mix. Moreover, energy statistics do not treat different energy sources used in electricity production in a similar way. Furthermore, the TPES/FEC ratio does not take into account the efficiency of appliances consuming the final energy, and providing the actual energy service.

The incremental decomposition analysis clearly shows that the annual differences are large in terms of change in TPES and the effects of the identified drivers. Usually decomposition analyses are made between two years with several years in between. The strength of the incremental analysis is that it reveals what happens during the whole period, and does not focus only on the difference between the starting and ending year. Choice of the starting and ending year of the studied period also may affect the results. Thus, incremental decomposition with a moving base year

(and a dynamic analysis with a fixed base year) can be highly recommended for energy-related decomposition analyses.

Declarations

Author contribution statement

Jarmo Vehmas: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jari Kaivo-oja: Conceived and designed the experiments; Wrote the paper.

Jyrki Luukkanen: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by the EU Horizon 2020 project 649342 EUFORIE.

Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2018.e00878>.

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