THE DETERMINANTS OF THE ENERGY EFFICIENCY IN THE EUROPEAN UNION

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Abstract

With the rise of energy insecurity, and volatile energy prices, the previously under-prioritized energy efficiency targets of the European Union became urgent and critically important. The improvement of energy efficiency is an excellent and undisputable way to increase energy independence, which is currently a crucial challenge for the member states in the short and medium term. This research focuses on the main determinants of energy efficiency. The first part covers the theoretical background, with an overview of the energy efficiency-related regulations in the European Union. The second part summarizes the relevant literature and analyzes data on energy efficiency in Europe. As a measurement of energy efficiency, energy intensity measures were applied. A panel data analysis on the total country level, and on the residential energy intensity level in the period between 2000-2021 is conducted on the dataset of the EU member states, UK, Norway, and Serbia. The following potential factors are examined: level of energy intensity that current and past electricity and gas prices, economic development, EU membership, population growth, energy poverty, the years of major economic or health crises, and the climate conditions are affecting the level of energy intensity. Based on the main findings of the analysis, economic development, and EU membership positively influence total energy efficiency. On the residential level, the climate circumstances and the years of major economic or health crises significantly influence energy efficiency. The effects of energy prices and economic development vary based on the model form.

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Chapter 1

Introduction

This thesis's main goal is, to analyze the relationship between energy efficiency and its key determinants. It is an important topic due to various reasons, among others energy efficiency is affecting climate changes, human health, economic development of given countries, and geopolitics too.

This thesis covers the necessary theoretical background along with the historical and future regulations of the European Union, and expanded the literature with data analysis on the key influential factors of energy efficiency in Europe. More specifically, the tested hypotheses included the examination of current and past electricity and gas prices, economic development, EU membership, energy poverty, the years of major economic or health crises, climate conditions, and their relationship with energy efficiency.

As global economic activity increases, the energy demand and the related CO_2 emission are increasing too. This higher pollution has harmful consequences on the human health and the environment. If we would like to keep or even improve the current economic growth and avoid the serious consequences of climate change energy usage has to be reformed. Energy efficiency is a very broad concept, which covers the relationship between energy consumption and the related economic output too.

This thesis focuses on the topic of energy efficiency from the different countries' point of view. More specifically, the thesis analyses the total country-level and residential-level energy efficiency. The majority of the well-performing countries in the field of energy efficiency are economically developed. The top performers are also member states of the European Union.

The existing literature on energy efficiency is flourishing, especially on residential energy efficiency. The existing literature covers extensively the planned interventions from the past too. In these papers, the context, the performance, and the reasons behind the interventions are discussed broadly. Some paper also covers the determinants of energy efficiency too, among others energy prices, economic development, globalization, and regulatory changes. However, only a minor share of these papers are analyzing the key determinants of energy efficiency with econometric methodology. The main contribution of this methodology is that could estimate the effect of certain changes in the economy or the regulation. The European countries have been studied previously with econometric models. Although these models in the literature are well constructed, they could be improved in several ways. These models studied previous time periods, which did not cover the recent year's major crises. The majority of the studies examines only developed member states, due the data availability issues. Besides the covered dataset, the applied statistical methodology and the examined set of factors could be also improved.

The most important contribution of this research is the analysis of a broader and more recent dataset. The broader dataset means a wider selection of countries, so besides the member states European Union, the UK, Norway, and Serbia are also covered. The timeframe of the dataset already includes the first year of COVID-19, which means the analyzed period is between 2000 and 2021. In the set of examined factors, more relevant measures are used. As an example, for price indicators, residential and industrial electricity, and gas prices are applied separately. Residential energy consumption per residential area was used, as an indicator of energy efficiency. This metric is reflecting more on the energy intensity of the buildings. Residential electricity and gas prices were used during the analysis of the residential energy intensity, to achieve more consistent results. Based on the review of the relevant literature, the controls on EU membership and energy poverty in a regression context were newly introduced in this literature.

In the data analysis fixed effect are built, and first difference models are applied as a robustness check of the results.

Based on the analysis of the total energy intensity, the beneficial effect of economic development and EU membership is statistically significant in every model. The electricity prices can also improve the energy intensity, based on the fixed effect models. Based on the analysis, there is significant statistical proof for the effects of population growth, the years of major economic or health crises, and the previous prices.

In the residential energy intensity analysis, additional factors are also examined, such as energy poverty, and climate circumstances.

Based on the residential level models, the economic development, which was measured with the growth of the GDI, showed a statistically significant effect on the residential energy intensity in fixed effect models. As the models show the years of the major economic crises also affect the residential intensity, but in a harmful way. According to the model's output, there is no indisputable statistical proof for the effect of current and previous energy prices, EU membership, and population growth. The results on energy poverty were slightly unambiguous, with different directions in different models. In the fixed models, its coefficients were negative, but not significant. In the first difference model, it was significant with a positive coefficient. In line with the literature, the climate circumstances significantly effects the energy efficiency, meaning that countries with more extreme weather conditions has higher energy intensity on average.

Based on the literature review and the data analysis policy implications could be derived. . A proper economic strategy, including trade openness (Liu et al, 2023) in a country could create the positive side effect of improved energy efficiency. Being part of the EU is also beneficial, which could be interpreted as the long term regulatory targets are also beneficial.

In this introductory chapter, the structure of the thesis is presented with their main purpose and results. After the Introduction, Chapter 2 presents a brief overview of the main global topics of energy efficiency along with the motivation that led to the research topic of this thesis. The brief summary of the global energy efficiency ranking of the countries shows, that the countries of the EU has dominant position in this field. The second part of this Chapter investigate the reasons behind this from a regulatory point of view. This section collects the key milestones of the regulations in the EU from 1990, which resulted in the current level of energy efficiency in the member states. The published plans on the future targets and directions until 2050 are also covered in this section.

The purpose of Chapter 3 is to lead to the data analysis part from the theoretical summary by presenting the review of the relevant literature on two essential topics. The first topic that is covered includes the research papers on overall energy efficiency and its key determinants on a country level. In this subsection, those papers presented more details, which applied econometric techniques. The second topic which is described in this chapter is the literature on residential energy efficiency. Similarly, to the general energy efficiency literature review, the papers with econometrics were described more extensively.

The research question of the data analysis and the applied methodology are presented in details in Chapter 4. This research is focused on the key determinants of the total country level and the residential county level energy efficiency. Besides the theoretical summary, the thesis also present a panel data analysis to support the answer on the research question. This section also covers the source of the examined dataset and the definitions and calculation methods for the applied metrics. During the data analysis energy intensity metrics were applied as an indicators for both the total and residential level energy efficiency. The data analysis part builds on fixed effect and first difference econometric models. To help the understanding, the methodology of these econometric model were briefly presented in this chapter. The statistical research broadly builds on the relevant literature but also extends it in several ways. The lists of the specific methods which were from the literature and were added as a novelty are also collected at the end of this chapter.

The econometric modeling of the total and residential level energy efficiency with the discussion of the results is documented in Chapter 5. In this section similarly to the literature, the research question was studied with fixed effect and first difference models. These models contained energy intensity indicators explained variables and current and lagged energy prices, economic development metrics, indicators on EU membership, economic or health crisis, energy poverty, and climate circumstances as explanatory variables. Models on total and residential level energy intensity were run and interpreted separately. The end of the chapter contains a summary and an evaluation of the statistical results.

The policy implications of the presented theoretical and statistical research are collected in Chapter 6. After the last chapter, a brief summary of the research question, applied methodology, the main results, and the derived policy recommendations are described in the Conclusion.

Chapter 2

Energy efficiency in the European Union

In this Chapter, the theoretical background of the topic of energy efficiency is discussed along with the necessary definitions. The summary of the most important topics of energy efficiency is presented in a global context. These topics include a summary of the latest global ranking of countries along with the evaluation criteria. This part aims to describe the motivation behind the research question of this thesis. In the second half of the chapter, the focus is on the energy efficiency of the European Union. The historical evolution, the current status, and the future directions of the most important energy efficiency-related policies are presented.

2.1 What is energy efficiency and why is it important?

The demand for affordable, constantly available, and possibly clean energy is constantly growing. Only a big crisis, such as the economic crisis in 2008-2009 or the diminished economic activity due to COVID-19 in 2020 could temporarily halt this growth (IEA 2022). Preliminary data in 2022 suggest significant changes in energy consumption as in the case of the previous crises, so a demand contraction (IEA, 2022b) Figure 1. This energy was used for various kinds of economic activities, among others those which are contribute to the GDP production. On the preliminary data on 2022 it can be seen that to create the same amount of GDP in 2022 as in 2021 less amount of energy was sufficient. This improvement in the usage of energy is what is usually referred to as energy efficiency and the ratio between the GDP and the used energy is the energy intensity. In this chapter the crucially related phenomena these terms are presented in detail, and in a global context along with some useful examples.

Energy efficiency is a very broad topic and has very extensive literature, analyzing questions on energy consumption, savings, and the related policies to nudge the transition toward the desirable outcome (Springer, 2023). Erbach defined energy efficiency as basically the improvement in energy usage to create the same amount of output (Erbach, 2015). Energy efficiency could be analyzed on many levels, such as on household, producer, industry, country, or regional level (Erbach, 2015). In this thesis, energy efficiency was analyzed at the country level.

The interest in energy efficiency significantly increased in recent years. By decreasing energy consumption the countries save money and mitigate GHG emissions (Subramanian et al, 2022). Energy efficiency is a broader concept and can be measured with complex and less complex indicators to scale the savings in energy. As a complex measure researchers tend to use indexes which could reflect to energy consumption, the spread of advanced technologies, useful information, and practices (Odyssee-Mure, 2023). As a simplified measure, the energy intensity measures are widespread. The indicators could be observed, so it is ”directly calculated from observed values of consumption, i.e. without any corrections” (Odyssee-Mure, 2023). Alternatively, the indicators could be corrected as well based on some circumstances. In most of the cases, the energy efficiency indicators are calculated based on climate circumstances, so “their variation from one year to the other is independent of climatic influences (such as a colder winter implying a higher consumption of heating)” (Odyssee-Mure, 2023). In other category systems, energy efficiency can be measured on a total level or partial level (Hu and Wang, 2006). The partial level is usually measured with energy intensity measurements, as it is not covering anything else beyond the ratio of the energy input and output.

Energy intensity is a very similar phenomenon to energy efficiency and is often used as a synonym. This term refers to the ratio between some measurement of the required energy usage, such as primary or final energy consumption, and the resulting output in the gross domestic product (GDP) (Verbič et al, 2017). If an industry requires more energy to produce the same amount of output in GDP, it is considered more energy intensive, and less efficient. However, it is very complicated to compare different countries in terms of energy intensity, since there may well be a lot of structural differences with significant influence, such as the climate, political status, or the economic and technological development of the countries (IEA, 2022). If the United Kingdom and Russia are compared, it can be seen, that the former could produce the same amount of GDP with only a quarter of the energy, which would be necessary for the latter. We could also observe high volatility in the energy intensity levels of the countries in the latest years due to the effect of COVID-19 and the energy crisis. Despite the unstable economic environment, improvements in energy efficiency were still visible in some countries. For example, the best performer was the United Kingdom with a 2.8% advancement per year between 2015 and 2020 (IEA, 2022). Numerous studies use energy intensity measures as an indicator of energy efficiency (Liu et al, 2023). However, it is important to highlight that the structural differences such as climate conditions or the difference between the mix of energy sources cannot be accurately expressed with energy intensity (IEA, 2009). Energy intensity is also not able to show what should be improved exactly to increase the energy efficiency of given technologies or devices (Proskuryakova & Kovalev, 2015). Energy intensity rather describes the level of the countries or industries on a high level (Proskuryakova & Kovalev, 2015). Other more complex measurments such as the one that Proskuryakova and Kovalev presented in their study in 2015, the thermodynamic measurement could show the possible improvement options as well. This metrics is useful, but it is quite hard to calculate, so it could not spread in the practice. Moreover, if we are using GDP to calculate energy intensity, the derived measurement will still carry the deficiencies of the GDP. GDP is a quite good measurement to capture economic output, but missing to count the value of the non-market transaction and externalities such as environmental pollution during production which are relevant factors for the current and future energy demand. These should be taken into account when deriving further policy recommendations.

Overall, the energy efficiency seems to have improved in 2022, experts expect a further 2% improvement in energy intensity in this, and the next year (IEA, 2022). However, the fact that the fossil fuel consumption subsidies increased significantly would darken the picture (IEA, 2022c). With this subsidized fossil fuel usage, we could improve the energy intensity, but also increase the CO2 emission at the same point. Unfortunately, detailed data for 2022 is not available at the time of writing this thesis. However, we already know the important question of these years. Was this crisis able to bring a permanent and favorable improvement in energy efficiency (IEA, 2022). To reach the desired outcomes with less emission, and a healthy standard of living we have to break the link between the increasing energy demand, and the economic growth. These future targets and along with the exact meaning of energy efficiency and intensity was discussed in this chapter. The significance of this topic is also explained.

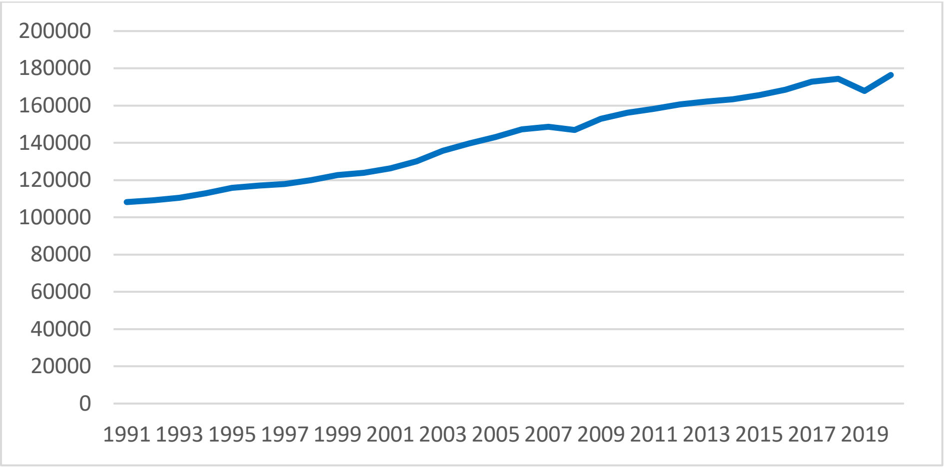

Figure 1.: Global primary energy consumption (TWh)

Source: Ritchie et al (2022))

Currently, the differences are very high between the countries in terms of per capita energy demand, as we can observe in the world map Figure 2. As their incomes grow, people tend to consume more energy. We can see in the map that the citizens of Emerging Markets, and Developing Economies are currently consuming significantly less energy than in developed countries. An average person in a developed country is using four times more energy for transport and three times more energy for residential buildings (IEA, 2022).

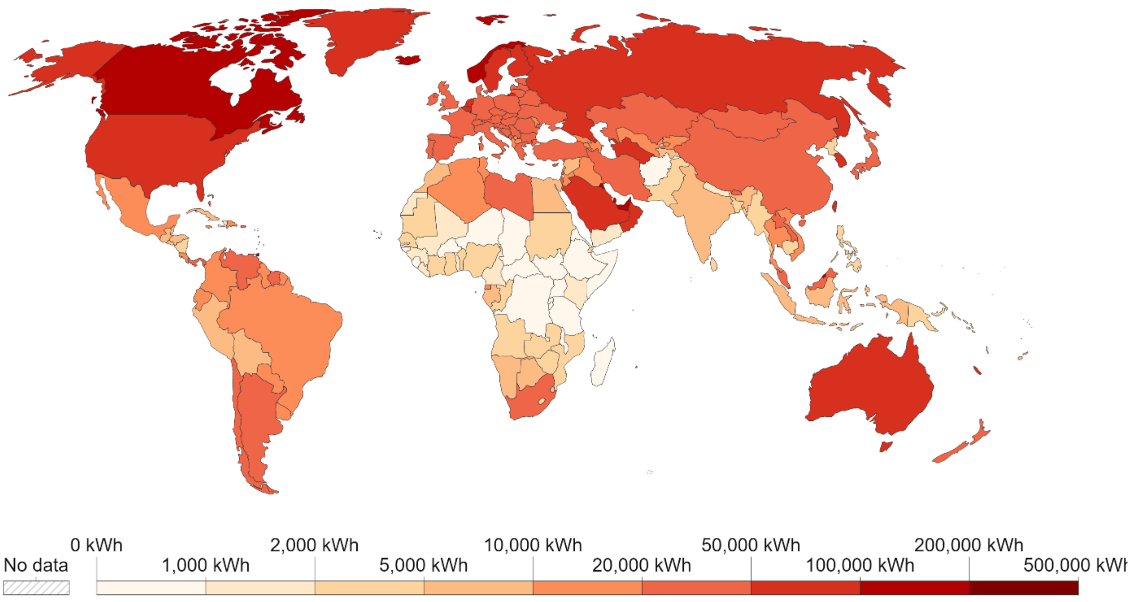

Figure 2.: Energy use per person, Energy use not only includes electricity, but also other areas of consumption including transport, heating and cooking.

Source: (Ritchie et al, 2022)

However, energy production comes with a cost. In the last 50 years, the amount of CO2 emission due to energy production was increasing as we can see in Figure 3. Even its share in the total global CO2 emission was increasing and it reached 38% by 2020 (EDGAR/JRC, 2022). While the CO2 emission is increasing more and more, researchers are working on analyzing its effect on the human health. They found a lot of evidence that exposure to higher CO2 creates a direct risk to our health, and could cause, among other diseases, inflammations, kidney calcification, and oxidative stress (Jacobson et al, 2019). In this sense, in urban areas, the higher outdoor atmospheric CO2 could be a potential stressor.

Besides its direct effect on human health, CO2 emission accounts for the majority (76% in 2015) of the greenhouse gas emission(C2ES, 2023). Many scientists found evidence that these gases are responsible for accelerated climate change (NASA, 2023). The climate change is creating a significant direct and indirect risk to human health from various angles (Costello et all, 2009). We can expect among others, extreme climatic events, and as a consequence of these, changing patterns of diseases, water, and food insecurity, and increased migration. The biggest negative impact would hit the poorer harder, those who contributed the least to this process Reference

To satisfy the growing energy needs of the less developed regions without further increasing pollution through energy production is a very difficult task. The key would be to improve the efficiency of how we use this produced energy and cover our need from less primary energy sources. Between 1980 and 2019, energy consumption as a consequence of the energy-related emission increased drastically (IEA, 2021). As scientists estimate, the global CO2 emissions would be 30% higher without the improvement in energy intensity between 2000 and 2020 (IEA, 2022). In recent years due to COVID-19 the energy demand has dropped significantly and so has the CO2 (Subramanian et al, 2022).

Experts expect further expansion in economic activity and energy consumption in the coming years which could result in even higher emissions. To mitigate the harmful effects of this process, but not at the cost of slowing down the development of emerging countries, energy efficiency improvements have a big potential. (IEA, 2022). Improved energy efficiency can boost economic development, and create new jobs in parallel. As the International Energy Agency estimate, the right policies to increase energy efficiency could boost the creation of 2 million jobs in the next two years (IEA, 2022)

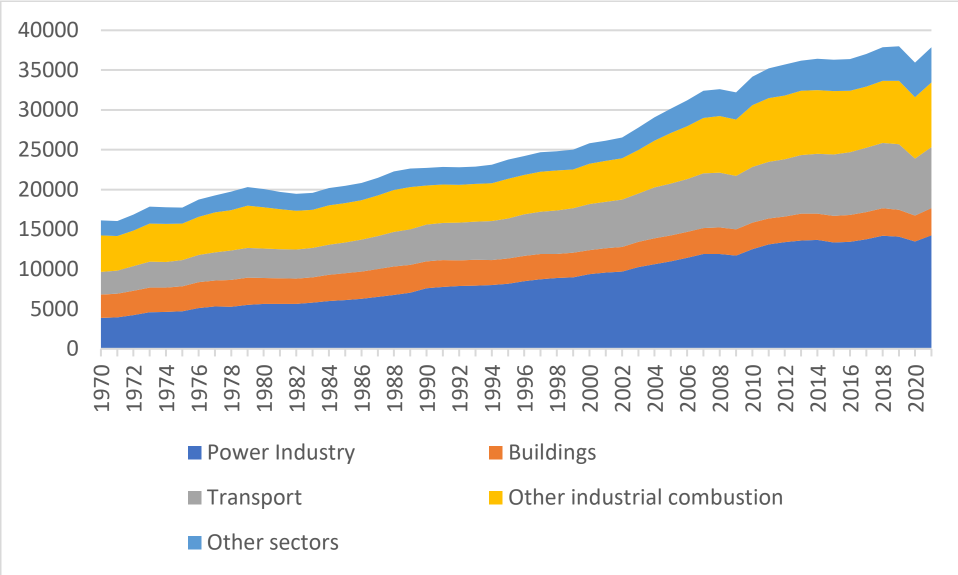

Figure 3.: Global carbon dioxide emissions from 1970 to 2021, by sector (in billion metric tons of carbon dioxide)

Source: (EDGAR/JRC, 2022)

One of the most important effects of improved energy efficiency is its potential to mitigate emissions. However, it is not the only one. Energy poverty could be also diminished with policies targeting energy efficiency. *Energy poverty* is referred to a situation when the financial burdens of accessing sufficient energy for a household are so high, that it can not maintain its healthy standard of living e.g. in terms of heating or cooling (European Commission, 2023d). The higher the share of income that a household has to spend on essential energy, the higher the probability of the household would fall into the category of energy poverty. It is commonly accepted to measure energy poverty with the share of households, who are unable to keep their home adequately warm. In the European Union this ratio was around 8% in 2020 (European Commission, 2023d). The right policies to improve energy efficiency could tackle energy poverty as well. If households can decrease the actual amount of energy that would be necessary for a healthy comfort level, then the level of their energy-related bills could also drop.

Last but not least, the high energy dependence could be decreased with the right investments in energy efficiency (EUROSTAT, 2023b). The *energy dependency* on a specific country depends on the weight of the fuels in the energy mix and the dependency on imports of those fuels from a specific origin (EUROSTAT, 2023b).. For the countries in the European Union, we are usually talking about the energy dependency on Russia. In 2020 57.5% of the consumed energy in the 27 EU countries was imported, from this, 24,4% comes from Russia and 33.1% from other countries (EUROSTAT, 2023b).

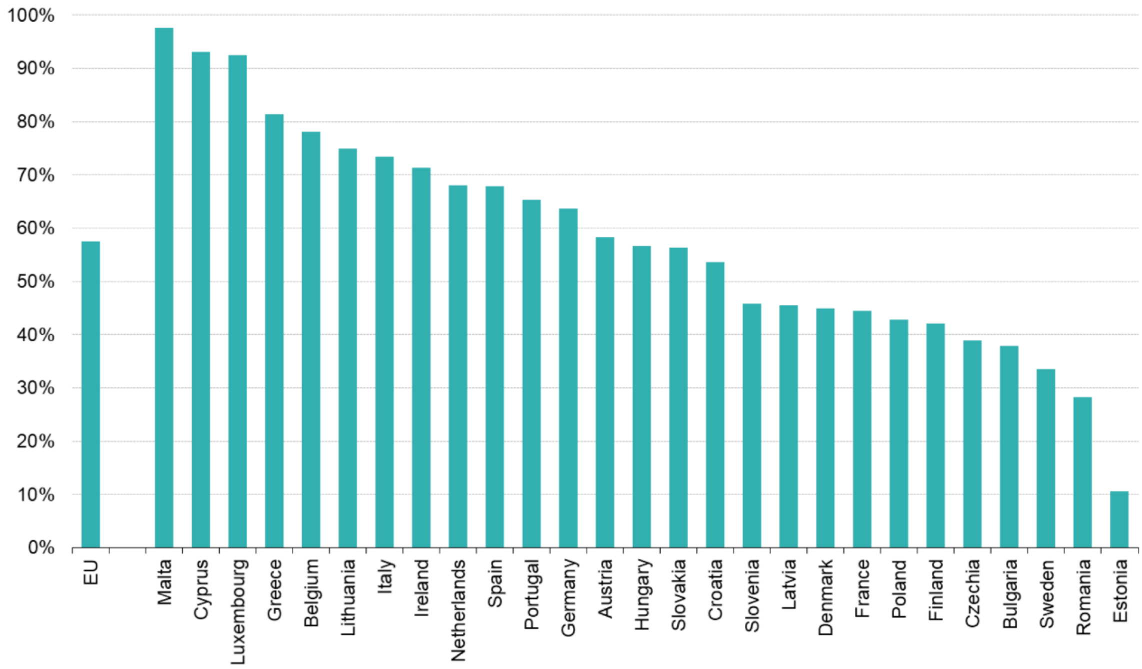

Figure 4.: Energy import dependency, European Union

Source: 2020 (EUROSTAT, 2023b)

There are many famous research topics and related phenomena that exist under the umbrella of energy efficiency. Among others, it is worth mentioning the energy paradox or the energy efficiency gap (Gerarden, 2017). These two expressions are used for the same phenomena. We could observe in many cases in history that some energy-efficient technological solutions did not spread as fast as they should have based on rational calculations. These settings are not optimal for society for many reasons, including energy usage and related emissions. Many scientists did research in this field to find the root causes of the energy paradox. Some were looking for the reasons for the measurement and model errors, behavioral anomalies, and market failures (Gerarden, 2017).

Another frequently studied topic related to intensity is the existence of the environmental Kuznets curve. According to the theory, this curve could illustrate the relationship between environmental degradation and energy intensity (Grytten, 2020). The shape of this curve is an inverted U since it assumes that the emission will increase until a certain point and will decrease as the GDP or income rises.

2.1.1 Current topics of the energy efficiency around the World

If we would like to get a complete picture of the main topic areas under the title of energy efficiency, the scoring structure of the International Energy Efficiency Scorecard report.

The presented Figure 5 could help (Subramanian et al, 2022). This report gives scores to countries based on four broader categories, which include further subcategories. The four categories are national efforts, buildings, industry, and transportation. In the subcategories, countries are given points based on certain requirements. Each year the rank of the countries based on the points has been published annually since 2017. This section, briefly touch on these categories and the corresponding subcategories to introduce the key factors of energy efficiency.

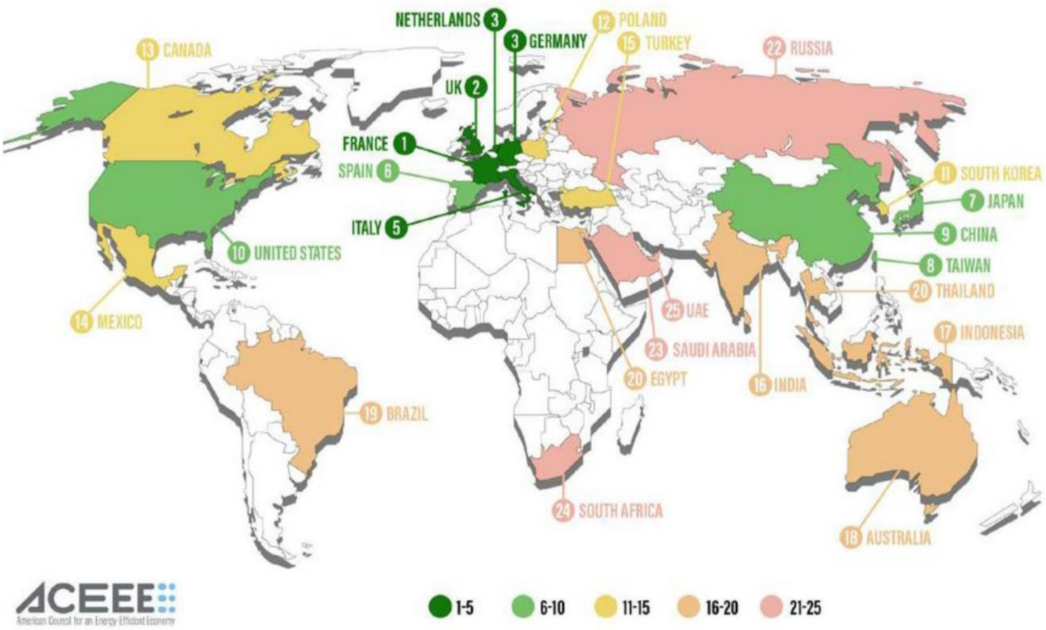

Figure 5.: The 2022 International Energy Efficiency Scorecard

Source: (Subramanian et al, 202).

The category of the *national efforts* is collecting measurements on the overall energy efficiency of the given country (Subramanian et al, 2022). This is covering most importantly the change in energy intensity and the spending on energy efficiency. The spending on research and development on energy efficiency appears separately. This category gives a point based on the criteria if the country can meet its own energy savings and climate goals. Countries can gain points in this category based on their tax incentives and loan programs which are aiming to support energy efficiency. Points are given also based on the efficiency of the thermal power plants, water efficiency policies, and also based on the size of the ESCO market. *ESCOs* are those firms that are specialized to offer services to improve energy efficiency (Subramanian et al, 2022). Last, but not least data availability is also a key evaluation factor in this category.

In terms of national efforts the Netherlands and Germany had the highest scores in the latest IEES report (Subramanian et al, 2022). In the second place, there was a tie between Japan, France, and Taiwan. In the EU the member states have to set national goals in line with the EU targets. The Netherlands got the first place in terms of national efforts thanks to various policies. They set bold targets for GHG emissions (by 2030 49% and by 2050 95%) and for energy efficiency improvements (32.5% by 2030) (Subramanian et al, 2022). According to the Dutch National Energy and Climate Plan (NECP) they are setting the right policies in the building and industrial sectors to reach these goals as well. Germany set a 32.5% decrease by 2030 and 50% by 2050 in primary energy use and accepted a meaningful plan for energy efficiency (National Action Plan on Energy Efficiency, NAPE 2.0) (Subramanian et al, 2022).

This plan is covering the energy efficiency of the buildings, industry, and the transportation sector, among others using tax incentives to improve the energy efficiency of the buildings.

Under the topic of energy efficiency, it is crucial to cover the energy efficiency of *buildings.* As recent publications show, 34% of the global energy consumption was coming from buildings, and the construction sector in 2021. This was accompanied by around 37% of the energy and process-related CO2 emissions (UNEP, 2022). In the International Energy Efficiency Scorecard report (Subramanian et al, 2022) the subcategories under the buildings category could be divided into two main areas. One is on the energy efficiency codes, labeling ,and standards of the buildings, such as residential and commercial building codes, the standards and labeling of the appliances and equipment, and building rating and disclosure. The second area covers more general areas, related to the energy efficiency of creating grid-interactive efficient buildings (IEA, 2022)). The report gives points here based on the retrofit policies of the buildings and the energy intensity of the residential and commercial buildings. The importance of the latter is crucial since they are able to reduce energy consumption significantly. The latest technological improvements are even highly affecting commercial buildings. These buildings with smart technologies are able to actively optimize the usage of the grid services, which helps to reduce distribution costs. Experts predict that the number of these smart buildings will increase dynamically in the coming years.

In terms of the building's energy efficiency, the Netherlands got first, France second, and Spain, Germany, and UK got the third, fourth, and fifth place in the ranking (Subramanian et al, 2022). The Netherlands and the US can serve with many good policy examples which are targeting the energy efficiency of the buildings (Subramanian et al, 2022). In the Netherlands, all buildings, both residential and commercial have to have a certificate on energy efficiency with A-G ratings, and 42 products have to have appliance standards and 25 appliance labels. Since 2021 the newly built buildings have to be „Almost Energy Neutral”. Although, the states of the US could be different based on their regulations, overall, the building codes, and the appliance and equipment standards of the US are among the strictest ones in the World. These codes are covering both heating, cooling, lighting, and the building envelope.

Probably the most important category to study under energy efficiency is the *industry*, since it is the biggest final energy consumption in the world (Subramanian et al, 2022). The industrial activity is the third largest sector in terms of final energy consumption in the European Union and is responsible for more than 26%, with agriculture and forestry for 29% (EUROSTAT (2023)). In terms of industrial energy efficiency, the key term is energy intensity, which is as we already explained, the ratio between the required energy usage and the resulting output in the gross domestic product (GDP) (Verbič et al (2017)). However, there are other important topics, that require attention under industrial energy efficiency. In the International Energy Efficiency Scorecard report (Subramanian et al, 2022) the countries can gain points based on participation in voluntary agreements and mandatory energy audits based on the mandate for energy managers. The *CHPs*, the combined heat and power plants are those very energy-efficient systems, which produce electricity and use the heat which is generated as a side product to create thermal energy as well. Since these technologies are favorable in terms of energy efficiency, countries can gain points based on their policies to boost CHPs and their installed CHP capacity. The regulation of motor standards can also have beneficial effects on energy usage, so this is also an important subcategory to earn a point for energy efficiency under the industry category. EnMS policies, the measures which are supporting energy management systems are also welcomed under the topic of energy efficiency. These policies are made to create management methods, which can improve the energy efficiency of industrial productions and industrial systems (Subramanian et al, 2022). The energy intensity of agriculture represents a separate subcategory due to its strong relation to climate circumstances. It is extremely important to pay attention to this sector since it is very energy intensive. However, the level of this intensity varies based on a lot of factors such as crop mix or level of mechanization (Subramanian et al, 2022).

According to the latest IEES report, Japan earned the first place in term of industrial energy efficiency. UK, Germany, Italy and France also got a place in the top five (Subramanian et al, 2022).

The energy efficiency of the industries could be boosted with many measures on country level. For good examples we can take a look at Italy (Subramanian et al, 2022), where the Nuova Sabatini subsidy is designed for small and medium enterprises to improve the energy efficiency, and the competitiveness of their production via investing in less carbon-intensive tools and machines. They are also supporting research and development of companies for newer industrial technologies with tax credits.

Germany, among others is using the power of energy audits and management, special taxes, and exemptions to boost the energy efficiency of the industry (Subramanian et al, 2022). The industrial electricity tax is an effective measure in Germany to target better industrial energy efficiency. If a company has proof that they comply with certain national standards or set energy management system to meet with the ISO 50001 standard, then it can get a 90% discount on their tax liability.

The United Kingdom is targeting industrial energy efficiency from a different angle. They are even investing with public resources to create net-zero carbon industrial clusters by 2040. These clusters are the groups of manufacturing facilities that are important for their economy and heavy energy users, so the improvement of their efficiencies decreases the CO_2 emission too.

Finally, the *transportation* sector itself represents a separate category under energy efficiency. In 2020 in the European Union, the transportation sector accounted for 28%, the biggest share of the final energy consumption (EUROSTAT, 2023). This sector should be treated carefully since it has high energy demand accompanied with high emissions (Subramanian et al, 2022). Fortunately, this sector has great potential to improve its energy usage. Under this category, the International Energy Efficiency Scorecard report (Subramanian et al, 2022) lists various subcategories as ways to increase energy efficiency. Light Duty fuel economy standards and Heavy duty fuel economy standards are very important ones. These standards on fuel economy are made to boost both the producers and as a consequence the buyers towards vehicles that are more efficient. These standards could focus on more metrics such as CO_2 emission or miles per gallon. In this sense, the lower quantity of LD vehicles are also preferred and treated as a separate subcategory in the International Energy Efficiency Scorecard report. Under the subject of transportation, it is also important to track the distance that the vehicles travel annually (VMT, vehicle miles travel). Besides VMT, it is important to track Tons-mile per dollar of GDP. Another important subcategory is the share of electric vehicles in sales, it is increasing in a lot of countries, and bringing a solution to decrease pollution. In this way, this is also a subcategory under transportation. Besides electric vehicles to transport goods, and a higher number of people in an energy-efficient way, the ratio of rail to road investment is also a key metric to track in the long term. For other transportation methods than trains, the smart freight initiatives are suggesting logistic practices to lower the required transportation and to increase fuel efficiency (Subramanian et al, 2022). Finally, the percentage of transit passengers is also a good indicator of the status of the given country in global transportation, as transit hubs tend to use more energy for transportation. Usually, buses and trains are more energy-efficient ways of transportation for people, so a higher share in the total transit is also preferred. Only European countries are ranked in the top 5 in terms of transportation in the IEES report. France had the highest score, followed by UK, Italy, Netherlands, and Spain (Subramanian et al, 2022).

Netherlands and France could serve as good examples on transportation-related energy efficiency policies. The Netherlands is first in terms of new vehicle sales of EV with 25%, which is way higher than other countries' shares (eg. 2% in the US). The Netherlands is also taking steps to meet the EU targets on emission reduction for new cars by meeting the required standards. However, France performed even better in the field of transportation energy efficiency. France set impressive GHG reduction targets, which required various policies. Among others, they used a bonus-malus program to support investments in more-efficient vehicles. France significantly improved its railroad system to boost the clean and effective transportation of passengers and goods.

In the total ranking based on the previous four categories, France arrived in first place. France was followed by the United Kingdom, Germany and the Netherlands in a tie, and Italy (Subramanian et al, 2022). We can observe the further ranks in Table 1 .It might be not a coincidence that European countries earned top places for their national efforts to boost energy efficiency. EU, where the UK was also a former member state, set common targets for 2020, 2030, and 2050 and obliged its member states to set national targets and plans to contribute to the common goals.

If we want to rank the top five countries based on the GDP per capita in 2022, which is commonly considered as the chief indicator of the economic development, we would have a very different order (from highest to the lowest), as the first will be the Netherlands, followed by Germany, UK France, and Italy (IMF, 2023). A similar ranking based on residential electricity prices in the first half of 2022 would be (from highest to the lowest) Germany, Italy, France, and Netherlands (data is not available for the UK) (EUROSTAT, 2023c). These conflicting orders sprung up the idea to the thesis on the relationship between energy efficiency, economic development, and energy prices.

(here maybe I can show only the top 10)

Table 1.: Energy Efficiency Scorecard Ranking 2022 and GDP 2021 ranking, GDP per capita on PPP (current international $)

Countries	**Energy efficiency ranking**	**GDP ranking**
France	1	7
United Kingdom	2	8
Netherlands	3	3
Germany	3	4
Italy	5	11

Spain	6	13
Japan	7	12
Taiwan	8	NA
China	9	18
United States	10	2
South Korea	11	10
Poland	12	14
Canada	13	6
Mexico	14	17
Turkiye	15	16
India	16	24
Indonesia	17	22
Australia	18	5
Brazil	19	20
Egypt	20	23
Thailand	20	19
Russia	22	15
Saudi Arabia	23	9
South Africa	24	21
United Arab Emirates	25	1

Sources: (Subramanian et al, 2022) and (Worldbank, 2023)

As we compare further rankings with GDP Table 1, we can conclude, that there is no visible linear relationship between GDP and energy efficiency in the upper half of the table. (For data availability reasons, the table shows GDP data for 2021). According to the International Energy Efficiency Scorecard Report (Subramanian et al, 2022), the countries with the lowest ranks were Egypt, Russia, Thailand, Saudi Arabia, South Africa, and UAE. However, for the last two countries, the very limited data availability might distort the results. In the lower half of Table 1, we can see, that there might be some relationship between economic development and energy efficiency, but probably not explicitly linear. Understanding this potential relationship between economic development and energy prices with energy efficiency and studying the well-functioning policies from highly ranked countries could help to design the best policies for countries with lower energy efficiency ranks to catch up.

2.2 Historical summary on the energy efficiency policies in the European Union

In this section, the major energy efficiency policies in the European Union are discussed in a historical context. Besides the policies which explicitly focus on the topic of energy efficiency, major measures related to energy prices until 2023 would be described, since the data analysis in the next chapter would also contains them.

In the previous section we could see, that the countries of the European Union tend to have higher ranks in the energy efficiency ranking lists (Subramanian et al, 2022). This is partially due to the common targets and policies to handle energy-related questions and problems. The differences are significant between the countries (Mussini, 2020), but the leading countries could support and show good examples to less efficient countries. The legally binding common targets are also nudging those countries, which originally would deprioritize the question of energy efficiency.

Before 2020, the total level of energy efficiency and the energy intensity of the European Union were highly influenced by three important factors. The first one is the composition of the European Union. From the foundation of the European Union, the countries tried to improve the efficiency of their energy usage, which slowed down by the first half of the ’90 along with slower economic growth (Verbich et al, 2017). In the years 1995-2004 the European Union with its 15 member states improved the energy intensity significantly as the energy prices increased (Verbich et al, 2017) In 2004, with the enlargement Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, and Slovenia joined the EU. These countries had higher energy intensity levels (so they were less energy efficient) than the old member states (Mussini, 2020). In 2007 Bulgaria and Romania and in 2013 Croatia also joined. These countries also had very low energy efficiencies (European Commission, 2023e; Burcea et al, 2012). This energy inefficiency in the majority of these countries originates from the Soviet regimes, where the countries were directed to have energy-intensive industries (Burcea et al, 2012). Although some of the new members such as Bulgaria, Lithuania, Romania, and Slovakia took successful steps to improve their energy usage, the differences were still very significant in 2015. On the extreme ends of the energy intensity, there was Ireland with 62 kgoe per 1000 EUR and Bulgaria with 448 kgoe per 1000 EUR (Verbich et al, 2017). The second important factor which is influencing the energy efficiency of the EU is the actual status of the economy. As an example, due to the financial crisis in 2007, the economies of the new members of the EU significantly shrank. As a consequence, the demand for energy also decreased (Mussini, 2020). This led to a reduction in the energy intensity (Burcea et al, 2012).

The third factor is the legal environment which is pushing the member states to set energy efficiency targets and create effective measures to reach them. The late joiner countries did not put a lot of emphasis on energy efficiency right after their accession (Mussini, 2020). Regardless, with the help of the EU structural funds, they could set the foundations of the change. Among other measures, tax reductions and subsidies were developed to pursue energy efficiency, energy performance standards and labels were introduced (Verbich et al, 2017). In 2010 the 2010/31/EU Energy Performance of Buildings Directive was published (IEA, 2019). This directive introduced various regulations on the energy efficiency of buildings. Among others, the directive set the minimum achievable energy performance level for new buildings and also gave a calculation method to calculate these metrics for any building or building unit. Based on this Directive, the member states had to create plans to boost the building of zero-energy buildings. The obligation of the energy certifications, inspections of the heating and cooling systems and their independent control and inspection was also introduced. The Energy Efficiency Directive 2012/27/EU was only published in 2012, its aim was to achieve higher energy efficiency in the member states (Mussini, 2020). This directive contained the goal to reach a 20% reduction in primary energy consumption by 2020 compared to the projections (European Parliament, 2012).

The European Union is trying to influence the energy efficiency of its neighboring countries as well (Verbich et al, 2017). In light of this, in 2003 they signed the Energy Community Treaty with Albania, Bosnia and Herzegovina, Montenegro, Serbia, North Macedonia, Kosovo, Moldova, and Ukraine. In these countries, the energy prices tend to be lower, while the energy intensity is higher than in the EU. This treaty helped to liberalize the energy market and enforce payments to effectively incentivize consumers to be careful about energy consumption.

The famous EU 20-20-20 targets were set in 2017, which set three important targets for the European Union to reach by 2020 in order to slow down climate change (European Commission (2023)). First, the member states should achieve a 20% cut in greenhouse gas emissions compared to the level of 1990. Secondly, 20% of the energy consumption has to come from renewable resources. Thirdly, the member states have to improve their energy efficiency by 20%. Of the three targets, this latest one was the most vaguely defined, which meant a significant risk of not bringing efficient measures to reach

As the European Environment Agency published in 2021, (European Environment Agency (2021)), the 20-20-20 targets were met. Actually, the first target on the reduction of greenhouse gases was highly exceeded. Compared to the level in 1990, the greenhouse gas emission was 31% lower. It is important to add, that the drop in economic activity in 2020 due to the COVID-19 virus, resulted in a major decrease. Individually, not all of the member states reached their goals. Bulgaria, Cyprus, Finland, Germany, Ireland, and Malta met the targets only by purchasing emission quotas from other states.

The second target was also attained with 21.3% of energy consumption from renewable sources (European Environment Agency (2021)). Here, the improvement was the result of the change in energy sources for heating, cooling, and energy production. The transportation sector could barely reach a 10% share of renewables.

The third target for energy efficiency improvement could be measured by the reduction in energy consumption (European Environment Agency 2021). This target was only achieved due to the effect of the COVID-19 virus. To push consumption to the desired lower level, further measures are indispensable.

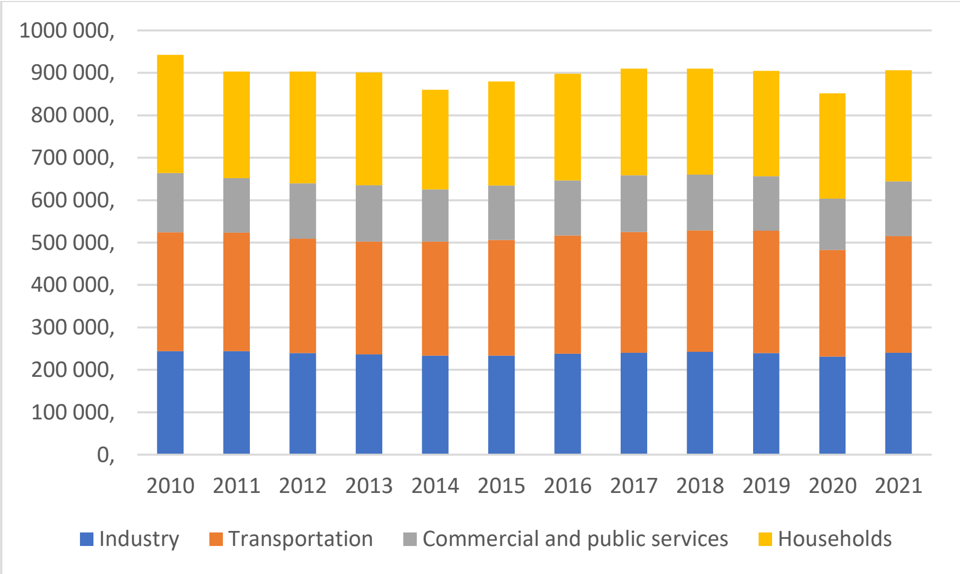

Figure 6.: Final energy consumption by sector in the 27 countries of EU (Thousand tonnes of oil equivalent)

Source: (EUROSTAT, 2023d)

After 2020, as preliminary data shows, economic activity rebounded along with primary energy consumption (European Environment Agency, 2022) Figure 6. Due to the lifted restrictions, the flow of people and goods bounced back, and caused the biggest annual growth of 6.7% in the consumption of final energy in the transport sector. The growth in the primary energy consumption of the buildings was also significant in 2021. It was 4.8%, which was partially due to the unusually cold winter. The primary energy usage of the industrial sector also increased by around 4.8% due to the restarted production. Although the rise in the primary energy demand was significant, it could still stay below the pre-pandemic level as we can see in Figure 7-

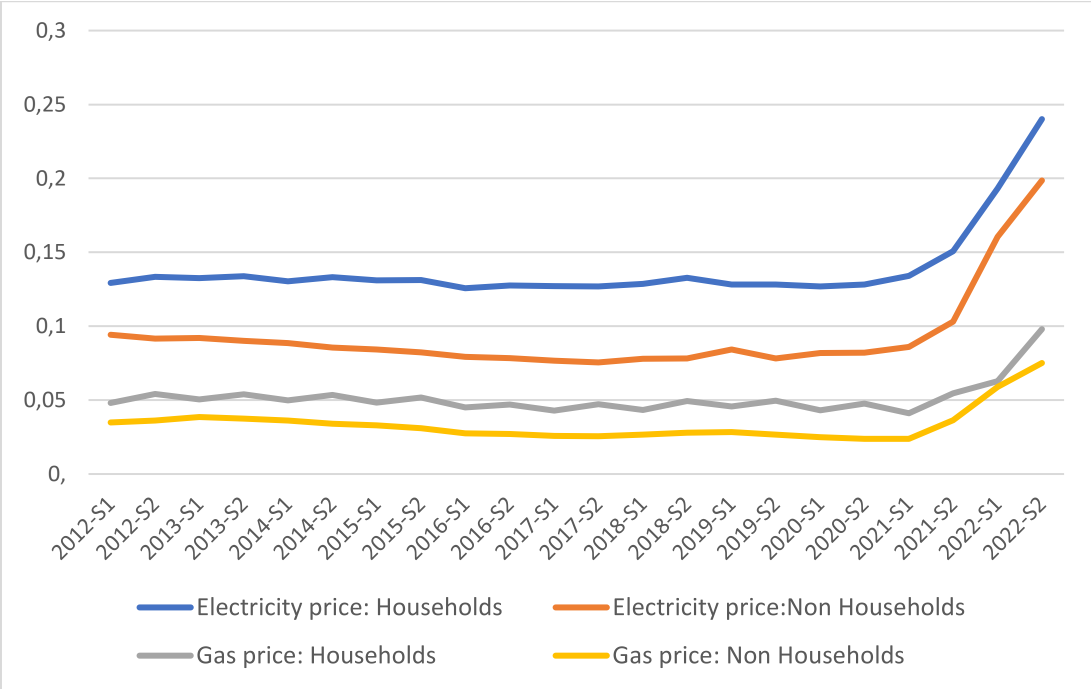

Figure 7.: Electricity and gas prices in the EU, euro/ Kilowatt-hour, without taxes and levies

Source: (EUROSTATc, e,f,g,, 2023)

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In 2022 February Russia attacked Ukraine which was the start of the ongoing war. The countries of the European Union strongly disapprove of (a condemn job) the aggressive act of Russia (European Council, Council of the European Union, 2023) and have supported Ukraine with various measures (European Commission, 2023f), among others, legal and economic sanctions against Russia and the Russian citizens.

In Russia a high share of export revenues are coming from primary energy export, more precisely the share of crude oil, and natural gas related revenues was 45% in the 2021 federal budget (IEA, 2022d). As it was shown in the previous section, the member states of the European Union are highly dependent on Russian energy sources (EUROSTAT, 2023b). In this sense, Russia is trying to use this dependence as a political weapon against the EU (Giles, 2023), to mitigate their support for Ukraine. Unfortunately, it is out of the scope of this thesis, to analyze in detail the geopolitical situation. The research would be limited to the effect of the energy crisis on the energy efficiency of the European Union.

As we can see on the graph above, energy prices increased dramatically since the war started. The war and the economic slowdown after the COVID-19 affected almost every person and every industry in the European Union. In the last year, way more households had to face the danger of energy poverty. In 2020, 35 million, so 8% of the European citizens could be classified as energy poor, but this number was further increasing in 2021, and 2022 (European Commission, 2023d). This brought the need for further measures, to decrease energy poverty by improving energy efficiency. In 2021 the *Fit for 55 packages* was suggested to put more emphasis on the Energy Efficiency Directive. This package also lists the most important factors which determins the frequency of energy poverty. These factors include the low income of the households, the high energy prices, and the lack of proper, efficient appliances and buildings.

The *Fit for 55 package* was followed by a document created by the Commission in 2021, titled *Tackling rising energy prices: a toolbox for action and support* (European Commission, 2023d). This was a list of national-level, short and long-term policies to reduce energy efficiency

2.3 Future Directions of the EU's energy efficiency

To successfully reach the 20-20-20 target for the member states, was a significant achievement. However, the future targets are even more ambitious, and create the need to even decrease energy consumption faster than in the previous fifteen years (European Environment Agency (2021b)). The next milestone in the energy policy of the European Union is based on a directive that came into force in 2018 (Energy Efficiency Directive ((EU) 2018/2002)) and its aim was to set targets for 2030. This directive, set at least a 32.5% energy efficiency improvement compared to the projections for 2030 (European Commission (2023)). This efficiency improvement means 1273 Mtoe primary, and/or 956 Mtoe in final energy consumption in practice. In 2021, these targets were revised, and set to a stricter level at 1023 Mtoe in primary energy and 787 Mtoe in final energy usage. This would be a 9% energy efficiency improvement, compared to the reference values projected in 2020. Based on this common target, the countries of the European Union have to set their own individual goals. These are based on a formula that takes into consideration the different levels of energy intensity, gross domestic product per capita, and energy savings potential of the countries. The increase of the 2030 target continued in 2022, when the Commission suggested a significantly stricter, 13% energy efficiency target, so 980 Mtoe in primary and 750 Mtoe in final energy consumption.

To meet the established targets, the member states are legally obliged to create a 10-year plan, which contains the necessary steps to reach their national goals, in line with the EU 2030. These plans are called the national energy and climate plan (NECP) for 2021-2030.

The mid targets, like the ones for 2030 are set to meet with the long-term strategy for 2050 (European Commission (2023b)). In 2050 the countries of the European Union are aiming to reach net-zero greenhouse gas emissions, as the realization of their commitments under the European Green Deal. The European Green Deal is the EU's long-term strategy package to deal with climate change, and its unfavorable consequences. The main goal of this is to reach zero net emission in greenhouse gases by 2050, while the economy and the health of people should be also improved, and no regions or people should be left behind (European Commission (2019)) (European Commission (2023c)).

As the European Commission states, the energy efficiency measures of the European Union try to focus on those areas, where they have the most significant saving potential (European Commission (2023)). These areas include the buildings, the industrial sector, transportation, and inevitably the energy supply sector. It is important to mention, that the EU pursues energy labeling as well, which could also support energy savings in an effective way, without major market distortion.

In this Chapter, the main definitions and phenomena of energy efficiency were described along with the most important global topics. This is a meaningful topic to study since it strongly relates to the question of climate change. As the global demand for energy increases, the emission related to its production also escalates. Moreover, energy efficiency is also important in human health, economic development, and geo-political context too. A brief summary of the latest global ranking of countries was also presented in this Chapter. In this ranking, the countries of the European Union have outstanding ranks. The second part of this Chapter focuses only on these countries. From the regulation point of view, the past 30 years were described and the planned targets and actions for the 30 years were also summarized. These subchapters illustrate well that a regulatory environment could result in higher energy efficiency, than in other economically developed countries.

Chapter 3

Energy efficiency and economic development- Literature Review-

In this chapter, the literature on the research in the field of energy efficiency, economic development, and energy prices would be briefly introduced. After the literature review, my own data analysis is presented.

The literature on energy efficiency research in terms of its relation to economic development is varied and far-reaching. In this chapter, an overview of this literature is grouped into some categories that are created based on the patterns that I noticed in these publications, and which topics are especially relevant to my thesis.

The relevant literature in this presentation is grouped into the categories of general literature, country case studies, policy-focused, emission focused. Under the umbrella of the general keywords, papers are cited, that use statistical methods to examine the main factors, which influence energy efficiency. The case studies and the policy-focused papers are very relevant to this thesis, since they served as a significant input during the policy recommendations based on the results of the data analysis. The papers on the topic of the relationship between emission and energy efficiency is out of the focus of this thesis.

The papers on the energy efficiency of the residential buildings, and the households, in the focal points, are discussed with more details, due to their particular relevance for my later data analysis.

3.1.1 General papers

Among the general papers on the relationship between energy efficiency and economic development, one of the most recent ones (Liu et al, 2023) examines, if globalization is hindering or boosting energy efficiency. For this purpose, they used advanced statistical modeling techniques, such as parametric stochastic frontier analysis on the sample of 141 counties. They have found, that calculated energy efficiency is highly affected by globalization, and the direction of this relationship is positive. They analyzed this result in detail and showed that it is biased due to various factors like heterogeneity bias and the effect of the business cycles. With the help of further calculations, they identified that energy efficiency is increased by globalization, particularly in medium-income countries, such as, lower-middle and upper-middle-income countries. The authors emphasized the policy relevance of their results, among others globalization comes with various advantages and from an energy efficiency point of view it is especially favorable for middle-income countries. In this sense, their government should support the opening process.

Similarly to the effect of globalization, the effect of energy prices, openness in terms of trading, and technological development on energy intensity are also studied (Samargandi, 2019). With the help of panel econometrics, the autoregressive distributed lag model Nahla Samargandi analyzed this question on the sample of the OPEC countries between 1990-2016. Her results were in line with the previously discussed paper (Liu et al, 2023), as trade openness favorably influences energy intensity. On this dataset, she could not find statistically significant evidence, that innovation reduces energy intensity. On the effect of the energy prices, she found an interesting result, which is the opposite of the traditional hypothesis. Based on her calculations, the energy prices increase the energy intensity. She explains this as the possible effect of the increased revenues in the OPEC countries from oil export if the energy prices are higher.

Probably the most important paper for the thesis was published by Miroslav Verbič, Sanja Filipović, and Mirjana Radovanović in 2017 (Verbič et al, 2017). In this paper, the authors used panel econometric methods with numerous control variables, to identify how the changes in electricity prices affect energy intensity. They did their analysis on the sample of 29 European countries, including Norway and the 28 countries of the European Union in the years 1990-2015. As their results show, if the demand for energy increases the energy intensity tends to be lower. Their calculation also showed that higher energy prices are related to lower energy intensity in the sample and the relationship between these two is statistically significant. Belgium, Denmark, and Germany were examples for this. They found also that in countries where the prices are lower, and probably subsidized, the energy intensity was higher.

The same group of researchers published other important papers from the thesis point of view. (Filipović et al 2015). In their earlier paper Miroslav Verbič, Sanja Filipović, and Mirjana Radovanović investigated what could be the main factors which are influencing the energy intensity of the 28 countries of the European Union between 1990 and 2012. They used panel econometrics methodology to calculate the effect of the GDP as the measurement of economic development, energy consumption, energy prices, and the related taxes on energy intensity. For the measurement of energy prices, they used electricity prices. According to their results, it can be proved statistically that electricity prices and the related taxes could decrease energy intensity. GDP also had a significant advantageous influence on energy intensity, but its magnitude was very low. However, the demand for energy rather influences energy intensity in an unfavorable way. From these results, they derived the conclusion that appropriately constructed taxes could be used as adequate policy tools to influence energy intensity. The author's study sprung the main idea for this thesis. However, in the data analysis part, further improvement is needed of their methodology, which would help to design, more accurate policies to improve energy efficiency in the European Union.

The effect of the energy price changes in the context of energy efficiency is studied with different research questions too. In a 2011 paper, the authors ((Yoon & Ratti, 2011) used statistical models, namely error correction models and GARCH models, to investigate how the uncertainty around energy price changes influences the investments of the firms. The authors analyzed the dataset of manufacturing companies from the US. As their result showed, if the expectations on future energy prices are more vague, firms tend to invest less, despite their sales growth. From this they deducted, that the ambiguous future energy prices could hinder investment in more energy-efficient technologies.

Investing in green technologies could also be a way to decrease energy intensity. Researchers analyzed this statement with the help of time series econometrics on the dataset of OECD countries between 1975-2014 (Chakraborty & Mazzanti, 2020). They found, that there is possibly a long and short-term relationship between green technology investments and energy intensity, also, their magnitude is very variable among different countries. However, they did not find evidence of statistical causality.

3.1.2 Households

The economic literature on the energy efficiency of households, especially in the European Union is particularly relevant for this topic. In this section, I am going to briefly summarize the main characteristics of the literature of residential energy efficiency, and present some particularly relevant papers with more details.

Numerous papers have been published on this broad topic, along with literature review papers to organize, and analyze them (De Boeck et al, 2015; McAndrew et al, 2021). For a brief overview of the literature on residential energy efficiency, it is very useful to catalog the papers based on “area of application and design variables, objectives and performance measures, type of analysis, solution methodology, software tools, case study location and type of building” (De Boeck et al, 2015, p1). In a literature review paper, the author reviewed 78 papers based on these criteria (De Boeck et al, 2015). This paper is very useful to identify some specific sets of papers from different angles around residential energy efficiency based on such factors as location such as France or methodology as linear programming or regression. The paper even helps to find interesting gaps in the literature.

A more recent literature review paper from Ryan McAndrew, Rory Mulcahy, Ross Gordon, and Rebekah Russell-Bennett is even more helpful to get an overview of the topic of household energy efficiency (McAndrew et al, 2021). In their paper, the authors collected and reviewed papers on household-related energy efficiency interventions ″including setting, target households, types of interventions, intervention tools used, theories and models, study design, quality rating, outcome measures, and effectiveness″ (McAndrew et al, 2021). From a policy maker point of view, this paper offers a more suitable grouping structure.

The collected papers covered countries across the globe from Japan to the EU countries, such as Sweden, and Greece. However, a greater number of studies are written in the US (46), Australia (27), the UK (16), and Sweden (10). After the summary of the findings, they derived further conclusions on the related policy measures. The reviewed papers focused mainly on electricity usage, behavioral changes, technological development, and cost reduction, and only two of them were related to gas consumption. This sprung the idea to develop the data analysis with gas-related calculations as well. The presented papers are mainly focusing on all the households in the geographical context (121 paper). Only a limited number of studies covered more specific target groups like low-income households or households with elderly or children. Based on their literature review, the authors found that the presented 153 interventions were mainly advantageous, more specifically 133 created improvement. Of the others only 7 were harmful and 13 had no significant result. It was also highlighted in the article that improving energy efficiency was not and should not be the goal in every circumstance. Better comfort levels, especially for those people who cannot afford a sufficient level before any policies should be considered as successful. The change from energy sources that produce more emissions to less harmful ones, should be also classified as improvements. In the evaluation of a policy, the multiplicative and the indirect effects should be also collected, such as improved health of the member of the households, air quality, and decreased energy poverty.

The papers with econometrics techniques, like the one from Erdal Aydin and Brounen Dirk (Aydin & Brounen, 2019), are particularly relevant to this paper. Similarly to this thesis, they also used a panel econometric approach to study residential energy consumption. The focus of their analysis is the per capita energy consumption (Aydin & Brounen, 2019). They analysis is made on the dataset covering 1980-2016 with 13 European countries, such as Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, and the UK. With their model, the authors studied the consequences of the aggravation in standards of the national buildings, and the compulsory labels for residential appliances. As the dataset covered a relatively small number of cross-sectional units (countries) and a longer timeframe, the first differences models are applied. In their models, besides the mentioned regulation changes, controls on GDP, Heating and Cooling Degree-days, and the share of the population over age 65 were included. Different models were built for electricity and non-electricity consumption, and they included electricity and non-electricity prices. According to their results, both policies led to a decrease in energy usage. Additionally, based on their calculations these beneficial impacts lasts for more years. The authors also concluded, that those countries benefit more from these policies, which have faster growing construction sector and quicker consumer durables changing habits.

A good example for papers that studied the residential energy consumption and intensity in the European Union with data on the period of 2000-2015 was published in 2019 by a large group of authors (Tsemekidi Tzeiranaki et al, 2019). In their analysis, the authors used descriptive statistics, correlations, and index decomposition analysis, to process and analyze their data. The analysis covered the topics of total energy consumption, energy intensity (calculated as the ratio between total energy consumption and GDP), energy consumption per capita, and energy consumption per square meter. With their graphs and chart, the authors examined the effect of population, GDP per capita, Gross Disposable Household Income, and Heating degree days on a high level. The study included the examination of the Percentage of people without the ability to keep their homes adequately warm in the population too. Their result shows, that the climate conditions are very important factors in energy consumption, but household and building socio-economic attributes and characteristics of the dwellings are also influential. After filtering out the effects of these circumstances, the authors found that the energy demand was still decreasing, while the GDP did not. These as a combination, could be a sign of improved energy efficiency. The analysis with the decomposition technique also verified this result, as the prime determinant of the energy consumption was the shrinking residential energy intensity. This paper also contributed to the data analysis in this thesis, as the authors highlighted that further analysis with econometric models would be beneficial to understand the underlying processes among these factors better.

Finally, studying residential energy efficiency with experiment and analyzing it with data and models is very important. Among the latter topic, the post-intervention or post-policy impact analysis is just as important as the prior ones. To design the most appropriate policies, the policymakers have to know the intended and the unintended consequences of the previous interventions. A relevant paper for this topic, was carried out on the dataset from Latvia in the period between 2008 and 2020 (Blumberg et al, 2021), which could present as an example of what could grow wrong. During the study the authors used a system dynamics simulation model, to analyze the effect of two policy interventions on the residential buildings. The first intervention was financial support from the European Union, the second policy helped to spread the information. The applied technique allowed them to simulate human behavior under different circumstances. According to the results of the paper, the intervention brought unforeseen negative consequences, due to the high volatility in the support funding, which brings uncertainty. These negative effects appeared among others in the construction sector in the form of price and quality fluctuation, due to the lack of equilibrium between supply and demand. This sector could be adapted slowly to the different regulatory environments, which materialized in a constrained capacity. The latter pushed the prices higher and the demand lower for these kinds of investments, resulting in an unwanted fall in the projects. The higher prices attracted inexperienced construction companies to enter the market and resulted in deficient execution, and decreased customer willingness to start these projects. As the authors proved the opposite with their analysis, the common belief on the usefulness of financial support, and information support for energy efficiency investment has to be treated carefully.

Among Among the literature on household energy efficiency, it is very common to study the behavioral, and psychological factors behind the individual's decision on energy consumption, energy efficiency-related investments, and the relevant influential policies. Some politicians strongly encourage the application of practices based on behavioral sciences, while others argue that these should be studied more thoroughly before (Jiefang et al, 2017). The potential in the behavioral economics findings is very high for residential energy efficiency, since with them the irrational behaviors, biases, and motivations could be utilized for more careful energy usage. As an example, a paper documented a small-scale field experiment on residential energy efficiency (Suter et al, 2013). In the presented experiment, the treatment was randomized. According to the results, with financial incentives and insulation 20% savings were achievable in the annual natural gas consumption. These energy savings were achieved easier if the households had a programmable thermostat.

The households mainly consume energy for transportation or through their residents, via heating, cooling, cooking, lighting, and the usage of electrical appliances. In this sense, the energy efficiency of residential buildings, and household appliances is particularly for this thesis. Transportation is out of the scope of this thesis. A well-researched area in the literature on residential buildings' energy efficiency is the energy efficiency labels and their impact. The energy efficiency standards and labels are very helpful in general since they decrease the information asymmetry between the buyers and sellers on the building's energy efficiency. However, sometimes their effect could be ambiguous. As an example, in Ireland, the energy efficiency labels of the residential buildings resulting in less strict evaluation by the assessors (Hyland et al, 2016). This means, that if the building was close to the pass category, but just below, the assessors tended to be more lenient, just build positive relations and earn future business.

Numerous papers studied residential energy efficiency within specific countries with case studies. The majority of these studies focus on the US and Japan, which allows the rest of the world to observe the outcomes of the newly introduced policies in these countries (Im et al, 2017). As an example, in the US researchers studied the effect of 30 energy efficiency-related investments e.g. more efficient lighting, and appliances on rental prices. They used propensity score matching and conditional mean comparison techniques. According to the results, these investments were notably useful for the owners of the properties, since the rental prices increased significantly. However, the success of any energy efficiency policy highly depends on the country's context, so copying them in other countries carries a lot of risks.

The relationship of the residential energy efficiency to the energy prices is usually studied from the point of price, or demand elasticity point of view. These papers are rather focusing on energy consumption as a result of energy prices and derive some inferences for energy efficiency only indirectly.

The paper by Massimo Filippini, Lester C. Hunt, and Jelena Zorić (Filippini, 2014) used econometric techniques, similar to this thesis, to estimate demand elasticity. In their analysis the authors stochastic frontier framework on the dataset of the 27 member states of the European Union between 1996 and 2009. This approach allowed us to estimate the minimum amount of energy input, which is required for the households for different levels of output. Based on their results the EU residential energy demand was price and income inelastic in the examined period. From the other examined factors, climate circumstances, population growth, and dwelling size had a significant effect on the energy demand, surprisingly, the latest had a negative coefficient. The authors explained this with the correlation between household size and dwelling size.

Finally, the last important topic of residential energy efficiency is the retrofit measures. These papers are usually covering case studies that happened in the past, and their results are already visible. Even the energy efficiency gap, so the distance between the current and the better energy efficiency, which is still real, could be assessed in these papers (Coyne & Denny, 2021).

This chapter presented the literature on the topic of energy efficiency, more precisely on total and residential energy efficiency. The overview is grouped into two categories, general and household-focused literature.

Under the umbrella of the general keywords, papers are cited, that use statistical methods to examine the main factors, which influence energy efficiency. Based on the literature, economic development, and trade openness could boost innovation and investments in energy-efficient technologies.

The papers on the energy efficiency of households, particularly residential buildings are presented with the help of literature review papers. Only papers with econometric methodology are described in detail. Based on the literature, economic development, climate circumstances, population growth, regulations, and energy prices are the potential key determinants of residential energy efficiency.

Chapter 4 Research question and methodology

As it can be seen in the previous sections, energy efficiency tends to be higher in economically developed countries. However, it cannot be observed in a linear relationship, if GDP is used as a measurement of economic development. In the European Union, the common binding regulations are representing strong incentives to push the member states to develop energy efficiency policies. Setting up national targets is both mandatory, and crucial for the member states to commit to long-term goals to improve energy efficiency. As in the case of almost any goods, products, or services the prices also strongly determine the demand for energy as well.

In this chapter, the detailed research question is discussed. This question focuses on the key determinant of energy efficiency in the European Union. The data analysis methodology which helps to answer this question will be also described in a nutshell. This means a short introduction to panel econometrics with the presentation of the fixed effect and first difference model is also part of this chapter.

The presented analysis broadly builds on the existing literature but improves the existing models too. The end of this chapter collects the points which are based on the literature, and where this analysis improves them.

If a policymaker would like to improve the energy efficiency in a country, an analysis of the total energy efficiency level could bring only limited insights. As it was seen in the previous section, the main areas of energy efficiency are national efforts, buildings, industries, and transportation. From these topics, the building could be regulated independently the most. Around 75% of the buildings in the EU are residential buildings, and households are one of the biggest energy consumers in the EU (European Commission, 2023j). The majority of the household's energy consumption is mainly due to housing. These houses have strong energy savings potential.

In the second part of the 5. Chapter, the analysis was taken one step further, and examined which factors are influencing the household energy efficiency level and how strong is their effect. The size of the residential spaces could be very different in countries, such as an average house is more than two times larger space in Ireland than in Romania (ODYSSEE, 2023A). Consumer habits tend to be very diverse as well across countries. Some countries are using electricity mainly for residential purposes, while others use it only for lighting. As this thesis focuses in the state of the buildings, the energy usage per residential area was chosen as the focus of the analysis.

The focus of this thesis are the main determinants of energy efficiency on a country level in the European Union. As it could be seen in the previous section, the number of policies and regulations which are aiming to improve energy efficiency are growing in the European Union. In this context, it is very important to understand which factors and measures are increasing and which are decreasing the energy efficiency. As it can be seen, the relationship between economic development and energy efficiency probably exists, but not in a linear way. Researchers argue that the role of energy prices is also crucial (Verbich et al 2015; Verbich et al 2017);. In this section, it was analyzed, how energy prices, economic development, and regulations are influencing energy efficiency. In this analysis, besides the general country-level relationship, it was also of interest, if there can be seen similar relationships in the case of household energy efficiencies. This sector was chosen since this energy consumption is representing a very high share of the total consumption of the countries, and could be regulated quite independently from other counties, and could be improved with a more general approach than the industry energy efficiency, since the latter is highly depends on the structure of the different industries in the given country.

Figure 8.: Electricity prices and taxes in Europe in 2020, eurocent/KWh

Source: own compilation Data source (Enerdata, 2023)

The effect of the electricity and gas prices were analyzed, more specifically the effect of residential electricity Figure 8 and gas prices Figure 9. Since there are significant differences between these two prices, in order to design proper policies it is important to know, which are more influential. The thesis also focused on, how the previous prices and the different taxes and charges are influencing energy efficiency. The analysis also covers the effect of the economic development the outcome of the EU membership, and climate circumstances among other important external factors. It can be sad, that is critical to study the effects of the relevant factors, prices, and taxes before designing any well-established policy to improve energy efficiency. The upcoming data analysis results could help to choose the right areas to intervene, such as raising taxes on certain prices.

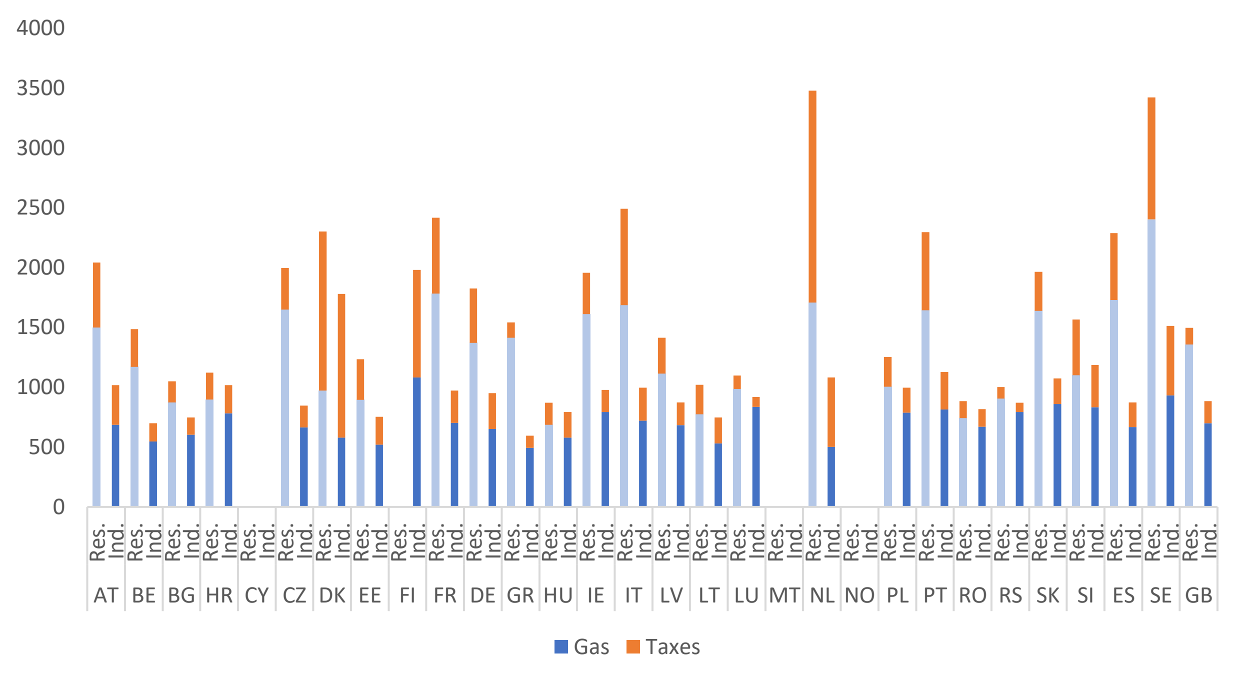

Figure 9.: Gas prices and taxes in Europe in 2020, eurocent/GJ

Source: own compilation, Data source (Enerdata, 2023)

As it could be seen in the previous section, the economic literature on the energy efficiency topic is flourishing. Among these research papers, more and more are using statistical and econometric methods to analyze data in order to examine their research question. This thesis follows a similar approach. The answer to the research question is pursued, with the help of country-level data and a panel econometric approach.

This research is focusing on the period between 2000 and 2021, and covers the countries of the European Union, Norway, the UK, and Serbia. The main sources of the data are the Odyssee and the Enerdata database. (For further details on the dataset please see the Dataset description section).

The analysis follows a top-down approach. Based on the relevant literature, the analysis starts with the determinants of total country-level energy efficiency. Energy intensity measurement was used as the measurement of energy efficiency. In line with the relevant literature, energy intensity was calculated as the ratio of the total final energy consumption in Ktoe/GDP in constant prices in Billion Eur. In this calculation, the numerator is summing up all the energy which was consumed in the given country in the given year converted into the measurement of oil equivalent Ktoe. This energy consumption was corrected based on the climate differences between the countries. In this sense, this consumption is calculated as it would be with average climate for a long period in the past (ODYSSEE-MURE, 2023). The GDP is measured in constant prices to filter out the effect of inflation. As energy prices indicators, gas and electricity prices were used. The energy prices are calculated as the simple average of the relevant form of energy for the specific sector. As an example, the residential electricity price for Hungary in 2020 was calculated as the average of the residential electricity prices in Eurocent/KWh for the different consumer groups. Unfortunately, the consumptions of the different price ranges were not available to calculate weighted averages. The industrial electricity price for Hungary in the same year was calculated with a similar method. It is the simple average of the electricity prices for the different sectors and consumer groups. Detailed definitions of the different sectors of the countries with consumptions were not available in the dataset. Additionally, in the total energy intensity analysis per capita GDP data, population, and an indicator on EU membership was used. For the summary of the applied measurement please see the Table 2,

Table 3, and Table 4 below.

For the analysis of the energy intensity of the residential buildings, a similar approach was followed. The energy intensity of the residential buildings was the ratio between Household energy consumption in Ktoe and the residential area in m2. The denominator was the average area of dwellings multiplied by the total stock of dwellings. For this analysis, household consumption with climate correction was not available. In this sense, besides the GDP, population, and the indicator on EU membership, indicators on the climate circumstances, such as the Cooling and Heating degree days were used. These indicators measure able to capture those weather conditions which highly influence the amount of energy used for heating or cooling purposes.

Additionally, a variable on energy poverty was added. To measure energy poverty, the indicator, which shows the ratio of those in the population, who are unable to keep their households warm due to its financial consequences was used (European Commission, 2023h).

The dataset used for the analysis was covering the same 30 countries originally for 31 years, from 1990 to 2021. However, a lot of observations were missing before 2000, especially for the less developed countries of Europe. To mitigate the overrepresentation of the developed countries in the early years, the analysis was limited to the period of 2000 to 2021. The original dataset covered Switzerland as well. Unfortunately, energy price data were not available for this country, so it was left out of the analysis. Since this dataset contained observations on the same cross-sectional units for the countries, for a longer timeframe, it was suitable for panel econometrics analysis. However, it is important to note that the final dataset still contained missing values, so it was unbalanced panel data. In the panel data framework, it is beneficial to have numerous observed units and a very long timeframe, in this sense this dataset is limited, which could affect the results.

In line with the relevant literature (Verbich et al 2015, Verbich et al 2017), fixed effect models were used , FE models, to study the relationship between the energy intensity, the energy prices, and the relevant confounders. The first difference model is preferred in the methodology, as it is able to control for serial correlation, so the correlation between the specific variables past and current versions. Unfortunately, the unbalanced nature of this dataset did not support the use of first differences. With the differencing between years, many observations would have been lost. It was preferred to study the statistical relationships on levels due to the rather complex dependent variables as well. In the analysis, the research focused on, which factor determines the level of energy efficiency, and not its changes in time.

$$y^{E}_{it} = \alpha_i + \beta x_{it}$$

$$y_{it} = \beta_1 x_{it} + a_i + u_{it} \text{ , } t = 1, 2, \ldots, T.$$

The equations above represent simple examples of a fixed effect model, where y E it or y it is the dependent variable (with other names right-hand side variable, response variable, predicted variable), while the E abbreviation notes estimation in the first equation. The x_{it} is the independent variable (with other names left-hand side variable, explanatory variable, predictor variable) and β is the coefficient of the x_{it} variable. The αi is the fixed effect (or with other names, the intercept for cross-sectional units, in my case they are the country-specific constants). The u_{it} is the error term in the second equation. In the fixed effect model with the help of the country-fixed effects, those circumstances can be controlled which are country-specific, but stable through time. With the interpretation of the β coefficients in the FE regression, we can see how bigger or smaller is the dependent variable on average compared to its mean, if the relevant independent variable is higher by one unit compared to its mean within the cross-sectional unit (Békés, 2020).

To evaluate the different models the R square should be used for fixed effect models. The within R square is calculated based on the mean differenced dependent and independent variable, so it is more meaningful (Bekes, 2020).

The fixed effect model has a strict exogeneity assumption, which means the independent variables should not correlate with the error term u_{it}, otherwise the estimation is biased (Wooldridge, 2013).

As a robustness check for the fixed effect regression, fixed effect model with yearly dummies and first difference models were built too. In the fixed effect models with yearly dummies, the goal of the yearly dummies is to capture those effect which are effecting the cross sectional unit similarly in the same time period, but changing over time.

$$\Delta y^{E}_{it} = \alpha + \beta \Delta x_{it}$$

$$\Delta y^{E}_{it} = \alpha_i + \theta_t + \beta_0 \Delta x_{it} + \beta_1 \Delta x_{i(t-1)} + ... + \beta K \Delta x_{i(t-K)}$$

The equations above represent simple examples of a first difference model, where Δ y E it or Δy it is the dependent variable, which is a difference between the current value y it and the previous value y it-1. The time trend is represented by the α variable, so the average change in the independent variable from period to period, when there is no change in the other explanatory variables (Bekes, 2020). The θt is the coefficient of dummies of the time periods. The Δxit, Δxit-1, are the changes in the explanatory variables between the current and the previous, the previous and the period before.

The coefficient of the Δxit, is noted with β0, and shows the magnitude of the relationship between the changes in x and y. If there is a unit change in x is between t-1 and t period than β shows the change in y on average. Similarly, the β1 coefficient shows, if x changes by 1 unit from t-2 to t-1 period, how the y change on average in the t period.

During the calculations, clustered standard errors were reported, since the observations by countries are not independent from each other. As the dataset was not broad, it was decided to 10% significance level to evaluate the coefficients. The significance level is defining the level of probability when the hypothesis is true but is rejected (Wooldridge, 2013). The smaller the significance level the smaller the chance that a true hypothesis is rejected.

As the regressions output tables in the next section show, the regressions with different control variables were run, which could be potential confounders. The purpose of these potential confounders was to eliminate the omitted variable bias, which could bias the estimated coefficients both upward and downward (Wooldridge, 2013).

Finally, it is important to add, that many omitted factors can affect both the independent and dependent variables, and the counterfactual state was not observes. In this sense, the regression result should not be interpreted as sure proof of causality.

A detailed description of the models along with the interpretations could be found in the next section.

Table 2.: Energy consumption and price data in the analysis

Name	Unit	Definition	Source
Energy consumption			
Total final consumption ventilated with climatic corrections	Mtoe	"An energy consumption with climate corrections is a consumption at normal climate. A consumption at normal climate is the consumption which would have occurred, with a normal climate over the heating and cooling periods. The normal climate is defined as the average climate observed over a certain period over the past (20 years or more). The primary energy consumption includes the consumption and conversion losses in the energy transformations, i.e. in the energy industries (e.g. power generation, refineries) while the final energy consumption is the sum of the consumption in industry (excluding the energy sector), transport, buildings (residential and services) and agriculture, excluding the fuels used for power generation by autoproducers." (ODYSSEE-MURE, 2023)	ODYSSEE, 2023A
Final consumption of residential sector	Mtoe		
Gas final consumption in residential sector	Mtoe		
Electricity final consumption in residential sector	Mtoe		
Gas final consumption in industry sector	Mtoe		
Electricity final consumption in industry sector	Mtoe		
Energy Prices			
Price of electricity for household	Eurocent / Kwh	Simple average of the unit electricity prices for different residential consumption levels, without taxes and VAT.	Own calculation based on Enerdata, 2023
Price of electricity in industry	Eurocent / Kwh	Simple average of the unit electricity prices for different industry sectors, without taxes and VAT.	
Price of natural gas for household	Eurocent / GJ	Simple average of the unit electricity prices for different residential consumption levels, without taxes and VAT.	
Price of natural gas in industry	Eurocent / GJ	Simple average of the unit gas prices for different industry sectors, without taxes and VAT.	
Price of electricity for household with taxes	Eurocent / Kwh	Simple average of the unit electricity prices for different residential consumption levels, with taxes and VAT.	
Price of electricity in industry with taxes	Eurocent / Kwh	Simple average of the unit electricity prices for different industry sectors, with taxes and VAT.	
Price of natural gas for household with taxes	Eurocent / GJ	Simple average of the unit electricity prices for different residential consumption levels, with taxes and VAT.	
Price of natural gas in industry with taxes	Eurocent / GJ	Simple average of the unit gas prices for different industry sectors, with taxes and VAT.	

Source: (ODYSSEE-MURE, 2023, Enerdata, 2023)

Table 3.: Additional raw data for the analysils

Name	Unit	Definition	
Additional variables			

Unable to keep the household warm	%	Indicator to measure energy poverty. Represent the ratio of populations of the countries, who "represents the share of the population who declare if they can afford or not to keep their homes at a suitable temperature" (European Commission, 2023h)	European Commission, 2023i
GDP (constant EUR)	Billion EUR	Gross Domestic Product on 2015 EUR	Enerdata, 2023
GDP per capita (constant EUR)	Thousand EUR	Gross Domestic Product on 2015 EUR	
GDI	Billion EUR	Adjusted gross disposable income of households per capita	Eurostat, 2023h
Population	Thousand person	Population of the countires	
Floor area of dwellings (average)	m2	The average residential area in m2 of one household unit. Missing data is estimated based on assuming linear trend between years. For 2020, where the data was missing, the estimation was the value of 2019, due to Covid 19.	ODYSSEE, 2023A
Total stock of dwellings	k unit	The number of residential dwellings in the given country. For 2020, where the data was missing, the estimation was the value of 2019, due to Covid 19. For Luxemburg, the total stock of permanently occupied dwellings was used, due the missing total stock of dwellings.	
Cooling degree-days	degree	"The number of cooling degree days (CDD) is the sum over each day of the cooling period of the difference between the average outside temperature and a reference indoor temperature. The higher this number the warmer is the cooling period. The CDD value depends on the level of the reference indoor temperature (between 20°C and 23°C depending on the sources)."(ODYSSEE-MURE, 2023)	
Heating degree-days	degree	"The number of heating degree days (HDD) is an indicator of winter severity, and thus of heating requirement. It is calculated as the sum over each day of the heating period (e.g. October to April) of the difference between a reference indoor temperature and the average outside temperature. The higher this number the colder is the heating period. The HDD value depends on the level of the reference indoor temperature (typically 18°C). The national value should be a population weighted average of meteorological stations, so as to be representative of national heating or cooling consumption rather than an arithmetic average. Example: if the average temperature of a day is 5°C, HDD= 13 (18-5)" (ODYSSEE-MURE, 2023)	
EU	0 / 1	Indicator if the given country in the given year is a member state	Own calculation
Crisis	0 / 1	Indicator for the years of 2008, 2009 and 2020	Own calculation

Source: Own calculation, data source (ODYSSEE, 2023A, Enerdata, 2023; EUROSTAT, 2023h)

Table 4.: Calculated variables in the analysis

Name	Unit	Definition	
Calculated variables			
Average electricity price	Eurocent / Kwh	Average of the residential and industrial gas price with taxes	Own calculation based on Enerdata, 2023
Average gas price	Eurocent / GJ	Average of the residential and industrial electricity price with taxes	
Residential area	k m2	Floor area of dwellings (average) multiplied by the Total stock of dwellings	Own calculation based on ODYSSEE, 2023A
Total energy intensity	Mtoe / Billion EUR	Total final consumption ventilated with climatic corrections divided by the GDP in Billion Eur in constant prices	
Residential energy intensity	toe / m2	Final consumption of residential sector divided by the Residential area	
Taxes on electricity for household	Eurocent / Kwh	Price of electricity for household with taxes minus Price of electricity for household without taxes	Own calculation based on Enerdata, 2023
Taxes on electricity in industry	Eurocent / Kwh	Price of electricity in industry with taxes minus Price of electricity in industry without taxes	
Taxes on natural gas for household	Eurocent / GJ	Price of natural gas for household with taxes minus Price of natural gas for household without	
Taxes on natural gas in industry	Eurocent / GJ	Price of natural gas in industry with taxes minus Price of natural gas in industry without	

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

The presented data analysis builds on the previous studies in the literature, but it can be taken one step further, with the analysis of the residential level energy intensity. According to the literature review, the main novelties of this thesis are listed below. Overall, this thesis added value to the literature mainly through the broader dataset, the effect of the residential and the industrial electricity and gas prices separately, and the improvement of the control variables. The currently existing papers are either focusing on high-level energy efficiency with general price averages, or consumption prediction, and both offer limited or different information for policymakers.

My research builds on preexisting literature in the following ways:

- The analysis of the EU countries (Verbič et al, 2017; Filipović et al 2015): The authors studied different timeframe and a different set of countries (Serbia was not included)
- The application of the fixed effect model (Verbič et al, 2017; Filipović et al 2015): The authors studied different timeframe and different sets of countries (Serbia was not included
- Control on the climate circumstances with Cooling and Heating degree days (Aydin & Brounen, 2019): The authors studied different research question, on different timeframes (1980 -2016) and a different set of countries (only 13 EU countries were included)
- Analysis of prices from the previous years (Aydin & Brounen, 2019): The authors studied different research question, on different timeframe (1980 -2016) and a different set of countries (only 13 EU countries were included)
- Robustness check with the help of first difference models (Aydin & Brounen, 2019): The authors studied different research question, on different timeframe (1980 -2016) and a different set of countries (only 13 EU countries were included)

Ways in which my models extend the literature:

:

- European countries with the time period of 2000-2021: different dataset than in the literature, including the first year of COVID-19 and covering the UK, Norway, and Serbia besides the member states
- More precise price indicators: Residential electricity and gas prices, Industrial electricity and gas prices
- Residential energy consumption per residential area as an indicator of energy efficiency, which is reflecting more on the energy intensity of the buildings
- Analysis of the residential energy efficiency, with residential electricity and gas prices
- Control on EU membership, control on energy poverty

The research question of this thesis focuses on the key determinant of energy efficiency in the European Union. This question addressed with the help of panel econometric methodology This means a short introduction to panel econometrics with the presentation of the fixed effect and first difference model is also part of this chapter.

The presented analysis broadly builds on the existing literature but improves the existing models too. This chapter also presents the points which are based on the literature, and where this analysis improves them.

Chapter 5

Panel data analysis of the energy efficiency

In this section data analysis on the total energy efficiency and the residential energy efficiency is presented. The aim of these analysis to determine the key influential factors of the total energy efficiency and the residential energy efficiency. The tested hypotheses were that current and past electricity and gas prices, the economic development, the EU membership, the energy poverty, the years of major economic or health crisis, and the climate conditions are effecting the level of energy intensity. For the interpretation of the statistical outputs presented in this section, please see the following table for the applied abbreviations of the variables.

Figure 10.: Variable names and contents during the data analysis

Variable Name	Variable content
T intensity	Total energy intensity
R intensity	Residential energy intensity
TPEt	Total price of electricity with taxes, average of the residential and industrial price
TPnGt	Total price of natural gas with taxes, average of the residential and industrial price
PEHt	Price of electricity for households with taxes
PEIt	Price of electricity for industry with taxes
PGHt	Price of gas for households with taxes
PGIt	Price of gas for industry with taxes
lnGDPcapco	Natural logarithm of the Gross Domestic Product per capita on constant prices
lnGDI	Natural logarithm of the Gross Disposable Income
UKHW	Unable to Keep the Houshold Warm, indicator for energy poverty
EU	EU membership
lnpopulation	Natural logarithm of the population
Crisis	Crisis
lnGDPcapco	Natural logarithm of the GDP per capita on constant prices
EU	EU membership
lnpopulation	Natural logarithm of the population
Crisis	Dummy for the years of economic or health crisis
Heatingdd	Heating Degree Days
Coolingdd	Cooling Degree Days
L_, L2_	1 period lagged version, 2 period lagged version of the given variable
d, d2, d3	First, second, and third differences of the given variable

Source: Own compilation

5.1 Determinants of the total country level energy intensity

5.1.1 Dataset description

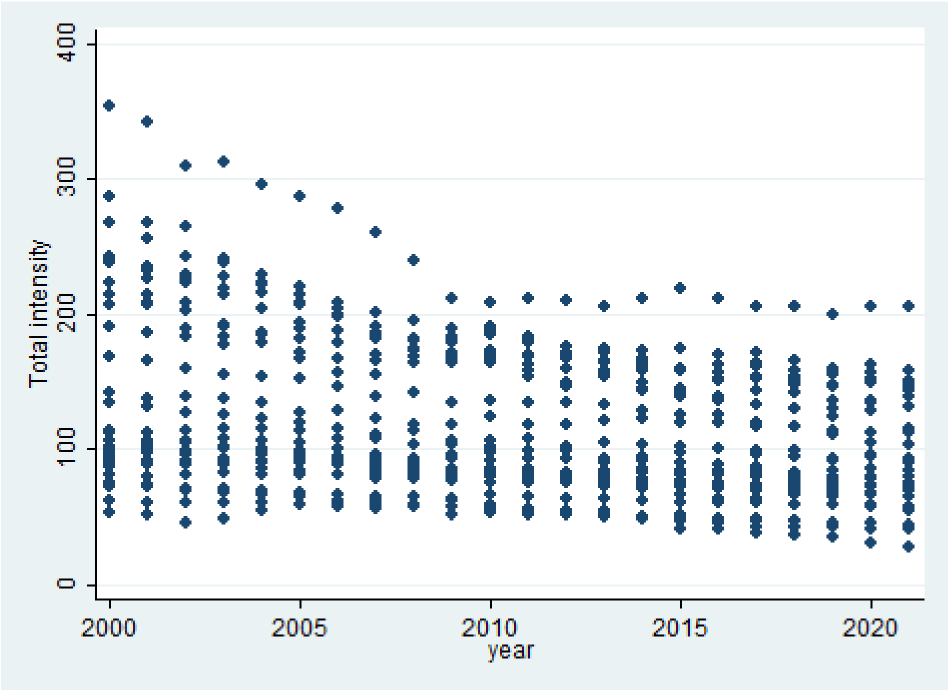

Figure 11.: Historical total energy intensity of the countries in the European Union, ktoe/ Billion EUR

Source: Own calculation, data source (ODYSSEE, 2023A, Enerdata, 2023

In this section, the key determinants of energy efficiency on the total country level were examined. As an indicator for energy efficiency, the energy intensity of the countries were used, which was calculated as the ratio between the climatically corrected total energy consumption (toe) and the GDP on constant prices (Billion euro) in the given country. In this sense, it is important to highlight that countries having lower energy intensity level, are considered to be more efficient. As we can see in the graph above (Figure 11), the energy intensity slightly decreased between 2000 and 2021. In the examined period the maximum, the minimum the standard deviation decreased. The dataset contains mainly the countries of the EU plus Norway, Serbia, and Great Britain. This means that the common energy efficiency targets of the EU could be an important reason behind this convergence. The table (Table 5) shows the descriptive statistics of the variables that are going to be used in the regressions. From this table, we can also see that the highest energy intensity was more than 10x higher than the lowest in the dataset.

Table 5.: Summary statistics for the total energy intensity regressions

	N	Mean	Std. Dev.	min	Max
T intensity	660	116.97	55.429	28.495	353.817
TPEt	627	14.537	4.657	5.533	28.614
TPnGt	512	1370.191	512.716	353.833	4441.4

lnGDPcapco	704	3.056	0.731	1.058	4.618
EU	704	.81	0.393	0	1
lnpopulation	698	9.175	1.640	5.963	13.149
crisis	704	.136	0.343	0	1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

From the correlation table (Table 6), it can be seen that there is quite a strong negative correlation between the energy prices (TPEt, TPGt) and the total energy intensity. This suggests that higher energy prices tend to occur together with lower total energy intensity. The natural logarithm of the GDP per capita on standard prices is negatively correlated with the total energy intensity even stronger (-0.828). From the correlation table it can be seen that although the population is a common explanatory variable in the literature, for energy consumption or energy intensity modeling, it is weakly correlating in this case with the total intensity.

Table 6.: Pairwise correlations for the total energy intensity regressions

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) T_intensity	1.000						
(2) TPEt	-0.586	1.000					
(3) TPnGt	-0.512	0.621	1.000				
(4) lnGDPcapco	-0.828	0.429	0.430	1.000			
(5) EU	-0.359	0.207	0.295	0.325	1.000		
(6) lnpopulation	-0.072	0.142	0.111	0.059	-0.021	1.000	
(7) crisis	-0.043	0.038	0.018	0.022	0.077	-0.007	1.000

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 7 below shows the summary statistics of the residential and industrial electricity and gas prices separately, while (Table 8Table 8) presents the correlation between these prices and the total energy intensity. Based on this data, the household energy prices, both the electricity and the gas prices have a stronger negative correlation with the total energy intensity than the industrial prices. Since the majority of the countries in the sample, can be considered developed ones, the weaker correlation between the industrial energy prices and the energy intensity could be a sign of a more developed industry with less energy demand or a higher share of the service sector. The table also shows that the prices are correlated positively with each other.

Table 7.: Summary statistics of the energy prices

	N	Mean	Std. Dev.	min	Max
PEHt	631	17.248	6.067	5.4	33.8
PEIt	630	11.791	4.130	3.667	46
PGHt	530	1659.712	681.405	448.667	6651
PGIt	552	1096.147	407.846	259	2883

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 8.: Pairwise correlations for the total energy intensity regressions, with price breakdown

Variables	(1)	(2)	(3)	(4)	(5)
(1) T_intensity	1.000				
(2) PEHt	-0.642	1.000			
(3) PEIt	-0.379	0.652	1.000		
(4) PGHt	-0.550	0.658	0.455	1.000	
(5) PGIt	-0.367	0.497	0.490	0.761	1.000

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

5.1.2 Models

Table 9 shows the first set of regressions, were the dependent variable was the total energy intensity and the explanatory variables were the average prices. The natural logarithm of the GDP per capita, the EU membership, the natural logarithm of the population, and the indicator for the years of any crisis were added step by step as independent variables. The regressions (6) and (7) included the average prices from the previous (1 year lagged) and the year before the previous year (2 year lagged) besides the current prices. The lagged prices were included to examine, if the previous prices have any effects on the current energy intensity. The hypothesis was, that the previous high prices could serve, as an incentive to invest in energy efficiency investments, which takes more years to fully realize, such as changing technologies in the industry.

Table 9.: Regression

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	T_intensity	T_intensity	T_intensity	T_intensity	T_intensity	T_intensity	T_intensity
TPEt	-2.155***	-0.840**	-0.940***	-0.818**	-0.817**	-0.730*	-0.749*
TPnGt	-0.013***	-0.007**	-0.006**	-0.005*	-0.005*	-0.003	-0.003
lnGDPcapco		-94.354***	-83.464***	-84.996***	-84.995***	-82.977***	-81.152***
EU			-14.116**	-14.983**	-14.972**	-12.362**	-9.949**
lnpopulation				-28.187	-28.132		
Crisis					-0.097		
L_TPEt						-0.165	0.018
L_TPnGt						-0.004	-0.002
L2_TPEt							-0.144
L2_TPnGt							-0.003
Constant	167.287***	433.382***	412.551***	674.655***	674.151***	410.557***	403.184***
R-squared	0.420	0.778	0.804	0.809	0.809	0.799	0.790

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 10 shows similar regressions as Table 9. The main difference is that instead of the average prices, the residential and industrial electricity and gas prices were included as independent variables. From the control variables, only the natural logarithm of the GDP per capita, and the EU membership were included, as these had significant coefficients in the first set of the regressions.

As a robustness check of the presented models, fixed effect models with year dummies, and first difference models were built. Due the size of the tables, Table 22, and Table 23 yre in the Appendix. It shows the fixed effect model with the yearly dummies. Table 10 below shows the first difference models.

Table 10.: Regression

	(1)	(2)	(3)
VARIABLES	T_intensity	T_intensity	T_intensity
PEHt	-0.916**	-0.850***	-0.905***
PEIt	0.361	0.459	0.587
PGHt	-0.005**	-0.005**	-0.005**
PGIt	-0.001	0.003	0.003
L_PEHt		-0.087	0.080
L_PEIt		-0.005	0.004
L_PGHt		0.001	0.001
L_PGIt		-0.007***	-0.005**
L2_PEHt			-0.255
L2_PEIt			0.118
L2_PGHt			0.001
L2_PGIt			-0.005
lnGDPcapco	-82.625***	-83.366***	-81.017***
EU	-14.438**	-12.249**	-9.458*
Constant	409.762***	410.855***	401.306***
R-squared	0.811	0.809	0.805

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 11 shows the first difference regressions, so (1) with the energy prices, the natural logarithm of the GDP per capita, EU membership and with 1 period lagged prices, and with 1 and 2 period lagged prices.

Table 11.: First different regressions on total energy intensity

	(1)	(2)	(3)
VARIABLES	d_T_intensity	d_T_intensity	d_T_intensity
d_TPEt	-0.158	-0.074	-0.044
d_TPnGt	-0.001	-0.001	-0.001
d2_TPEt		0.209	0.209
d2_TPnGt		-0.003*	-0.003*
d3_TPEt			-0.048
d3_TPnGt			-0.001
d_lnGDPcapco	-44.026***	-43.005***	-40.934***
d_EU	-2.700	-3.308	-2.501

Constant	-1.421***	-1.425***	-1.412***
R-squared	0.179	0.184	0.159

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

5.1.3 Interpretation

Table 9 and Table 10, summarizes the results of the regressions on the total energy intensity. As the stars show next to the coefficient of the different variables, the coefficient of the electricity price was significant in every regression. However, the magnitude of this coefficient decreased as I added potential confounders to the regressions. All of the coefficients were negative, which meant that if electricity prices are higher on average, then ceteris paribus the total energy intensity is lower, so the energy efficiency is higher. For an example in the (7) regression if the electricity price is higher by 1 euro cents on average, then the total energy intensity is lower by -0.749 ktoe/ Billion Eur. This means, to produce 1 million Eur GDP, 749 ktoe less energy is sufficient on average. We can compare the explanatory power of the different models with the help of the within R squared. The value of this measurement was between 42% and 81% in the models. This means in the Table 9 for regression (3) 80% of the variation in the total energy intensity was explained with the average prices, ln GDP per capita, and the EU membership

In the Table 9 (1)-(5) regressions the average gas prices were not significant. From the potential confounders, the lnGDPcapco, the EU was significant in every regression. These independent variables also had negative coefficients in every regression, which EU membership and higher GDP per capita, on average occurs together with lower energy intensity. As an example based on Table 9 (3) regression if ceteris paribus the GDP per capita is larger by 1% on average, than the total energy intensity is lower by 83,5 ktoe/ Billion Eur. However, it is important to note, that the exact value of this coefficient is slightly volatile.

In this sense, based on this dataset, there is statistically significant relationship between the energy prices, economic development, and EU membership. The results for the energy prices and economic development are in line with the relevant literature (Verbich et al, 2015; Verbich et al, 2017)

Based on these regressions, any statistically significant relationship between the total energy intensity and the population, the crisis indicator, and the lagged values of the average electricity and gas prices could not be found.

In similar regressions with the breakdown of the energy prices to residential and industrial electricity and gas prices, similar results were found (Table 10). The coefficients of the current prices, the natural logarithm of GDP per capita, and the EU were significant. From the different prices, only the residential electricity and gas price coefficients were significant. The direction and the magnitude of the coefficients are similar in both regressions, which suggests, that the electricity prices, especially residential, the economic development, and the EU membership both positively influence energy efficiency.

From these regressions with different control variables, the results from the relevant literature could be replicated. Such as, the electricity prices and the GDP per capita significantly influence the energy intensity. However, it is important to note that the addition of further relevant potential confounders resulted in decrease of the magnitude of the coefficients.

As a robustness check, fixed effect models with yearly dummies and first difference models (FD) were built. The fixed effect models with the yearly dummies are presented in the Appendix. Table 11 shows the first different version of the regressions. These regressions shows slightly different results than the previous ones. The coefficients of the natural logarithm of the GDP per capita was significant in every model, but its magnitude decreased significantly. In the first difference model, it is -40,9. which means that ceteris paribus if the changes in the natural logarithm GDP is higher by 1% than the changes in total energy intensity is lower by -40,9 ktoe/ Billion Eur. Based on these models, the current electricity and gas prices were not significant. The FD models shows, that the second lag of the gas prices differences were significant. The coefficient of the EU membership was significant only in the fixed effect models, even with yearly dummies, but its magnitude decreased with the expansion of the models with further control variables and year dummies.

Together the results of the fixed effect models, with the results of the first difference model and the fixed effect regression model with yearly dummies, suggest smaller or no significant relationship between total energy intensity and energy prices. Based on these regressions, statistical proof only found for the influence of economic development on the energy intensity.

It is important to add, that since we cannot observe the counterfactual state, and there could be many omitted factors that are driving energy intensity, thus the results cannot be interpreted as 100% proof for causality.

5.2 Determinants of the residential energy efficiency

In this section, the data analysis is continued with the examination of the residential level energy intensity. This topic was chosen due to several reasons. As we saw in the first section, households are responsible for around a quarter of the final energy consumption. In this consumption, they have a very high savings potential (reference). Moreover, from the analysis on the total level energy intensity, it can be seen, that the residential energy prices might significantly influence the total energy intensity. Further analysis was chosen in the residential sector, since it could be fairly independently influenced by the policymakers of the given countries. The transportation sector significantly relates to other countries and the industry is quite heavily dependent on natural resources, historical circumstances, and long-term economic strategy.

5.2.1 Dataset description

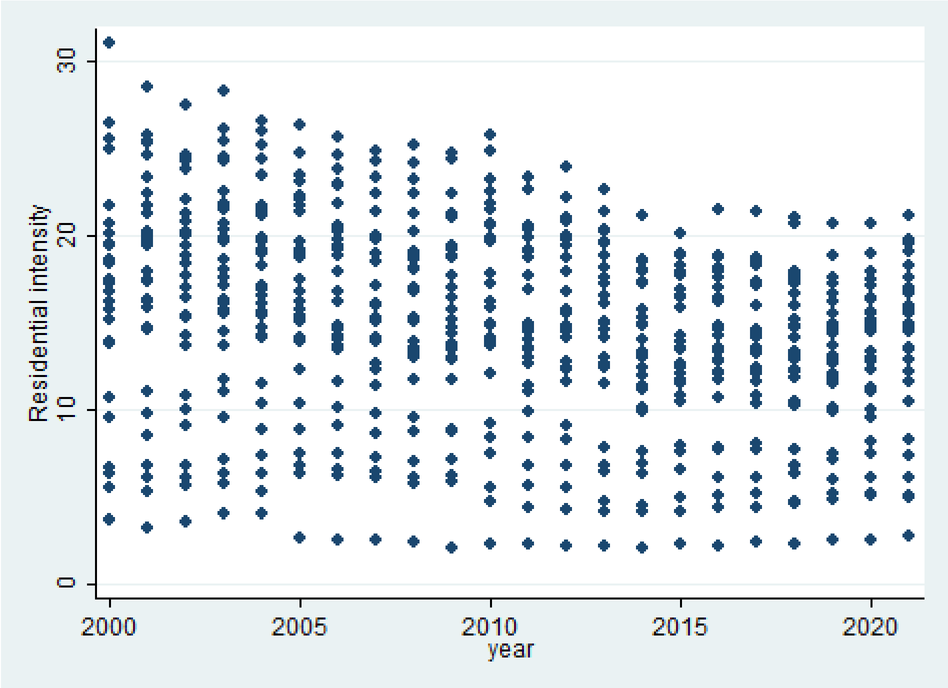

Figure 12.: Historical residential energy intensity in the European Union, toe/ 1000 m2

Source: Own calculation, data source (ODYSSEE, 2023A, Enerdata, 2023)

As the residential sector is the second largest energy consumer after the transportation sector, it made sense to proceed the research towards the analysis of residential energy efficiency. In this section the residential energy efficiency was measured with an energy intensity indicator, the ratio between the residential energy consumption and the total residential area, so in ktoe/m2.

As Figure 12 represent, the residential energy intensity slightly decreased in the period between 2000 and 2021. However, it is also visible, that while the yearly maximum of this residential energy intensity decreased, the minimum almost remained stable.

Data on energy poverty was only available from 2003, thus in this section, the examined period was limited to 2003-2020.

Table 12.: Summary statistics for the residential energy intensity regressions

	N	Mean	Std. Dev.	Min	Max
R intensity	660	14.856	5.710	1.994	31.061
PEHt	631	17.248	6.067	5.4	33.8
PGHt	530	1659.712	681.405	448.667	6651
EU	704	.81	0.393	0	1
lnGDPcapco	704	3.056	0.731	1.058	4.618

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 12 shows, that overall both the prices and the residential energy intensity has relatively high standard deviation and differences are sizeable between the maximum and minimum prices. In this section, the set of potential confounder variables were expanded. Besides the natural logarithm of the per capita GDP, population, years of crisis, and the EU membership, the Gross Disposable Income (GDI), an indicator on energy poverty (Unable to keep the household warm, UKHW), and indicators on climate circumstances, the Heating and the Cooling degree days were also added.

Table 13.: Summary statistics for the residential energy intensity regressions

	N	Mean	Std. Dev.	Min	Max
lnGDI	595	9.708	0.387	8.26	10.5
lnpopulation	698	9.175	1.640	5.963	13.149
crisis	704	.136	0.343	0	1
UKHW	522	9.682	11.186	.3	69.5
Coolingdd	616	116.751	179.396	0	812.18
Heatingdd	635	2878.397	1080.059	322.36	6179.75

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

From the correlation Table 12 it can be seen, that the residential energy intensity moderately and negatively correlated with the residential electricity and gas prices. The correlation of the residential energy intensity of the newly introduced potential confounders is presented in Table 15. From this table it can be seen that the residential energy intensity strongly correlates with the Cooling and Heating degree days. The table shows a stronger correlation with the natural logarithm of the Gross Dispensable Income than with the natural logarithm of the GDP per capita. This suggest that, it can be better indicator for economic development in the residential energy intensity regressions. The indicator of the energy poverty (UKHW) moderately and positively correlates with the residential energy intensity.

Table 14.: Pairwise correlations for the total energy intensity regressions, with price breakdown

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) R_intensity	1.000						
(2) PEHt	-0.315	1.000					
(3) PGHt	-0.483	0.658	1.000				
(4) EU	-0.151	0.176	0.211	1.000			
(5) lnGDPcapco	-0.066	0.548	0.462	0.325	1.000		
(6) lnpopulation	0.027	0.214	0.226	-0.021	0.059	1.000	
(7) crisis	-0.022	0.031	0.019	0.077	0.022	-0.007	1.000

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 15.: Pairwise correlations for the total energy intensity regressions, with price breakdown

Variables	(1)	(2)	(3)	(4)	(5)
(1) R_intensity	1.000				
(2) lnGDI	-0.184	1.000			
(3) UKHW	-0.308	-0.554	1.000		
(4) Coolingdd	-0.671	-0.045	0.325	1.000	
(5) Heatingdd	0.646	-0.039	-0.315	-0.745	1.000

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

5.2.2 Models

Table 16.: Regression

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	R_intensity	R_intensity	R_intensity	R_intensity	R_intensity	R_intensity
PEHt	-0.284***	-0.155**	-0.154**	-0.112*	-0.134**	-0.143**
PGHt	-0.001	-0.000	-0.000	0.000	0.000	0.000
lnGDI		-5.485***	-5.620***	-6.296***	-6.572***	-5.908***
EU			0.199	0.032	-0.651	-0.369
lnpopulation				-8.120	-9.350	-8.466
crisis				0.412***	0.359***	0.763***
UKHW					-0.008	-0.008
Coolingdd						0.003**
Heatingdd						0.003***
Constant	21.304***	71.441***	72.540***	152.606**	167.126**	144.021**
R-squared	0.408	0.528	0.529	0.559	0.529	0.644

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 17.: First different regressions on residential energy intensity

	(1)	(2)	(3)
VARIABLES	R_intensity	R_intensity	R_intensity
PEHt	-0.171**	-0.089*	-0.100*
PGHt	0.000	0.001***	0.001***
L_PEHt		-0.049	-0.008
L_PGHt		-0.001**	-0.001
L2_PEHt			-0.031
L2_PGHt			-0.001
lnGDI	-4.690***	-5.277***	-5.041***
EU		-0.327	-0.823
lnpopulation		-7.767	-8.588
crisis	0.810***	0.742***	0.688***
UKHW		-0.008	-0.012
Coolingdd	0.002*	0.003**	0.003*
Heatingdd	0.003***	0.003***	0.003***
Constant	55.561***	131.457*	137.236**
R-squared	0.631	0.656	0.664

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 18.: First different regressions on residential energy intensity

	(1)	(2)	(3)
VARIABLES	d_R_intensity	d_R_intensity	d_R_intensity
d_PEHt	0.003	0.019	0.022
d_PGHt	0.000	0.000	0.000
d2_PEHt		-0.022	-0.022
d2_PGHt		-0.001*	-0.001*
d3_PEHt			-0.023
d_EU	-0.040	0.029	0.019
d3_PGHt			0.000
d_lnGDI	2.073	1.880	2.120
d_crisis	0.288*	0.330**	0.328*
d_UKHW	0.010***	0.011***	0.011***
d_Coolingdd	0.002**	0.001**	0.001**
d_Heatingdd	0.003***	0.003***	0.003***
Constant	-0.304***	-0.265***	-0.265***
R-squared	0.531	0.541	0.553

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, *
p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 16 summarizes the results of the regressions on the residential energy intensity without any lags in the explanatory variables.

Table 16 shows the first set of regressions were the dependent variable was the total energy intensity and the average prices, the natural logarithm of the GDI, the EU membership, the natural logarithm of the population, the indicator for the years of any crisis, the indicator on energy poverty, and the Heating and Cooling degree days were added step by step as independent variables. The regressions (2) and (3) included the average prices from the previous (1 year lagged) and the year before the previous year (2 year lagged), besides the current prices. The lagged prices were included to examine, if the previous prices have any effects on the current energy intensity. Similarly, to the case of the total energy efficiency, the hypothesis was, that the previous high prices could serve as an incentive to invest in energy efficiency investments, which takes more years to fully realize, such as changing technologies in the industry.

Similarly, to the case of the total energy efficiency, as a robustness check of the presented models on residential energy intensity, fixed effect models with year dummies and first difference models were built. Due the size Table 24 (showing the fixed effect model with the yearly dummies) is in the Appendix, it shows the fixed effect model with the yearly dummies.

Table 18 shows the first different version regressions, so (1) with the energy prices, the natural logarithm of the GDP per capita, EU membership and with 1 period lagged prices, and with 1 and 2 period lagged prices.

5.2.3 Interpretation

Table 16 summarizes the results of the regressions on the residential energy intensity. It can be seen, that the coefficient of the residential electricity price was significant in every regression. However, the magnitude of this coefficient decreased as potential confounders were added to the regressions. All of the coefficients were negative, which meant that if electricity prices are higher on average, then ceteris paribus the residential energy intensity is lower, so the energy efficiency is higher. So as an example in the (6) regression if the electricity price is higher by 1 euro cents on average, then the residential energy intensity is lower by -0.143 toe/ m2. In these regressions, the residential gas prices were not significant. From the potential confounders, the lnGDI, the crises, and the Cooling and Heating Degree Days were significant. Based on these regressions, I could not find any statistically significant relationship between the residential energy intensity and the population, the EU membership, and the indicator of energy poverty.

The explanatory power of the different models can be compared with the help of the within R squares. The value of this measurement was between 40% and 65% in the models. This means in Table 16(6) regression 80% of the variation in the total energy intensity was explained with the average prices, ln GDI, ln population, crisis, EU membership, energy poverty and by climate circumstances.

Based on, table, it can be seen, that the coefficients of the residential gas prices are already significant along with the electricity prices. However, the gas coefficients are positive. This could be explained by consumer habits. The gas is usually used for heating in the household. If the price of the gas increases, then it will affect the heating habits. If the prices are rising, the household starts to look for alternative sources e.g. wood, oil, and coal. However, these are less efficient for heating than gas, which can lead to a slight increase in the amount of consumed energy.

As a robustness check for the residential energy intensity models, fixed effect models with yearly dummies and first difference models were built. The fixed effect models with the yearly dummies are presented in the Appendix. The (table) shows the first different version of the regressions. These regressions shows slightly different results than the previous ones. The coefficients of the current electricity prices were not significant anymore. For gas prices the coefficient were positive and significant in the fixed effect model with yearly dummies.

The coefficients of the natural logarithm of the GDI was only significant in the fixed effect models without yearly dummies, with the magnitude between -4,69 and -6,57. Interestingly, the coefficient of the crisis were significant in every model, with positive sign and magnitude between 0,288-0,763. This means in crisis period the energy intensity is higher in average. This could be explained, mainly with heating habits. In the case major economic downturn, those who are in the lower income segments tends to switch to other energy sources for heating purposes such as wood, coal, oil. The coefficient of the energy poverty was only significant in the fixed effect model with yearly dummies, which suggest if the goal is to improve residential energy efficiency, the treatment of the energy poverty cannot be an effective tool.

From the climates circumstances the coefficients of the Heating degree days were always significant, while the coefficients of the Cooling degree days were not significant in the models with yearly dummies.

Together the results of the fixed effect models, with the results of the first difference model and the fixed effect regression model with yearly dummies, suggest smaller or no significant relationship between total energy intensity and electricity prices, and a vague relationship with gas prices. Based on these regressions, statistical proof only found for the influence of climate circumstances, and the years of crisis.

Due to mixed outcomes in this section, and since we cannot observe the counterfactual state, the results should be interpreted with caution.

5.3 Results and discussion

In this section, the panel data analysis of the key determinants of energy intensity was presented. The focus of the research was the total energy intensity including all sectors with all of their consumption and outputs and the energy intensity of the residential sector. The analyzed dataset covered the period between 2000 and 2021 in the European Union, Norway, and Serbia.

Fixed effects models were built to analyze the key factors of the total and residential energy intensity. To check the model's robustness confounders and yearly dummies were added to the models. First differences regressions were also run, to cross-check the results of the fixed effect models.

The tested hypotheses on the total level energy intensity covered the effects of the current and past residential electricity and gas prices, economic development, the EU membership, population growth, the years of major economic or health crises.

Based on the fixed effect models, there exist statistically significant relationship between the electricity prices, economic development, and EU membership.

Together the results of the fixed effect models and the first difference model and the fixed effect regression model with yearly dummies, suggest smaller or no significant relationship between total energy intensity and energy prices. Based on these regressions, statistical proof only found for the influence of economic development on the energy intensity.

The tested hypotheses on the residential level energy intensity covered the effects of the current and past residential electricity and gas prices, economic development, the EU membership, population growth, energy poverty, the years of major economic or health crises, and climate circumstances were also studied.

The fixed effect models also showed that in countries where the current electricity prices are higher on average, the energy intensity is lower on average. On the effect of the gas prices the result was ambiguous, in some models they showed that higher prices occur together with higher energy intensity. This could be explained by the replacement effects, if the price of gas which is mainly used for heating goes up, people use other less efficient energy sources like wood, coal, and oil. According to the model's output, there is no indisputable statistical proof for the energy prices of the earlier years.

Based on the presented models, the economic development, which was measured with the growth of the GDI, showed a statistically significant effect on the residential energy intensity in FE models. As the models show the years of the major economic crises also affect the residential intensity, but in a harmful way.

The coefficients of EU membership and population growth were not significant in the case of residential energy intensity regressions.

The results on energy poverty were slightly unambiguous. In the FE models, its coefficients were negative, but not significant. In the FD model, it was significant with a positive coefficient. This could be examined with the unambiguous nature of energy poverty. On the one hand, due to their financial burdens, people in energy poverty consume less energy than the sufficient level, which could appear as energy efficient consumption in the data. On the other hand, these people tend to live in houses with worse insulation and with fewer insufficient appliances, and for heating purposes, they tend to use less efficient energy sources such as wood or coal. These habits rather push their consumption higher. This is the trap of energy poverty, which means an even higher amount of consumed energy cannot provide a sufficient comfort level.

In line with the relevant literature, the coefficients of climate circumstances were significant. However, it is important to add that despite the literature, the coefficient of the Cooling degree days was similarly significant in the majority of the models as the Heating degree days. This means that countries with more extreme weather conditions has higher energy intensity on average.

Before inferring any conclusion from the presented results, it is important to highlight that the significant relationship cannot be interpreted as explicit proof of causality due to many reasons. The counterfactual state cannot be observed, and the threat of omitted factors or endogeneity issues could distort the results. In spite of this, the presented analysis could be used to support policy design with careful application. .

Chapter 6

Policy implications

In this section, further policy implications are derived from the presented data analysis. However, it is important to note, that the performance of policies highly depends on the social and cultural environment, and the starting level of energy consumption (Heiskanen et al., 2020). The main influencing factors for the policy tools include the national and international environment and institutional context. However, the “practice as context” (Heiskanen et al., 2020) should be taken into consideration inevitably. This means that successful policies should be transferred cautiously, with careful consideration on country specific circumstances, such as social habits (McAndrew et al, 2021).

During policy recommendations, it is important how the achievable targets are defined. By focusing exclusively on energy efficiency measures, other important outcomes could be easily overlooked. These outcomes could be an acceptable level of comfort, especially for those who are in energy poverty, or a change in fuel mix (McAndrew et al, 2021). The transfer toward renewable energy sources is also advantageous due to less emission, even if it does not appear as a decrease in energy demand.

Based on the data analysis and the literature review, it can be seen, that residential energy prices could be considered as policy tools to improve overall energy efficiency and residential energy efficiency as well. However, it was also visible, that economic development is also a very important factor that determines energy efficiency. In this sense, a proper economic strategy, including trade openness (Liu et al, 2023) in a country could create the positive side effect of improved energy efficiency.

In general, being part of EU is beneficial for the total energy efficiency as both the theoretical and the analytical part of this thesis confirmed. The mandatory directives along with the national action plans are impactful tools to implement long term energy efficiency goals.

From the data analysis it cannot be explicitly deduced, that if the target is to increase residential energy efficiency, decreasing energy poverty could be considered as an impactful solutions or not. However, this does not mean, that we should not aim to decrease energy poverty. At this point, it is very important to highlight the main limitation of this thesis. The examined period only covers 2000-2021. In this sense, the extreme increase in energy prices due to the war did not appear in the data. It is reasonable to assume, that the share of households who are not able to keep their households warm increased significantly due to the rise in energy prices. In this sense, my policy suggestion would be first to treat energy poverty with targeted policies.

Based on the literature (Verbich et al, 2017), previous real world examples and also the result form the data analysis, artificial price decrease via subsidized prices, or low level fixed prices should not be applied. These measures could lead to excessive energy consumption, and decreased incentives to invest in energy efficiency improvement such as insulation, as it happened in Hungary due to the regulated residential energy prices.

Direct transfers and/or one-time deductions from the energy bills could be good examples of targeted policies as happened in the Netherlands (ODYSSEE, 2023A). These policies should explicitly target the most vulnerable groups such as older people and other low-income groups.

Subsidies on long-term energy efficiency investments should be carefully designed or avoided, since they could lead to market distortion and even decreased demand, as it could be seen in the example of Latvia (Blumberg et al, 2021),

Performance and other standards for already existing and new buildings could be beneficial since they could achieve long-term positive results, as an example in the USA, Netherlands (Subramanian et al, 2022), (Aydin & Brounen, 2019) The regulatory support of the spread of smart meters and programmable thermostat also useful on residential level (Suter et al, 2013).

Finally, it is very important to highlight, that only consistent and stable regulation could be efficient tools on long terms to achieve energy efficiency targets. The uncertainties around regulations due to frequent changes put significant risk on investors and decrease the motivation to invest in more expensive improvements.

Nevertheless, consumer behavior should be further studied as well, to avoid excessive consumption if the economic situation is better and prices are lower. The ultimate goal is to consume less energy and create less emission, not to reduce cost.

Conclusion

This research aimed to analyze the relationship between energy efficiency and some potential determinants. More specifically, the tested hypotheses included the examination of current and past electricity and gas prices, economic development, EU membership, energy poverty, the years of major economic or health crises, climate conditions, and their relationship with energy efficiency.

The thesis covered the necessary theoretical background, with an overview of the energy efficiency-related regulations in the European Union and its future direction, and a panel data analysis of the key determinants of energy intensity. Additionally, policy implications were deducted from the results.

The theoretical introduction gave a brief overview of the most important global topics of energy efficiency, based on the latest Energy Scorecard report (Subramanian, 2022). These were the national efforts, buildings, transportation, and industries. From the presented results, the derived conclusion was, that economic development could influence the level of energy efficiency, but on a global level, this relationship is probably not linear.

The subchapters of the “Historical Summary on the energy efficiency policies in the European Union” and the “Future Directions of the EU’s energy efficiency” collected the most important milestones from the past and the future, in the energy efficiency-related regulations and targets. These subchapters also aimed to understand, why the member states tend to have higher energy efficiency than other economically developed countries.

This research extensively builds on the preexisting literature, but presents several novelties mainly in the second half of the thesis. The output tables presents the panel econometric data analysis on total and residential level energy efficiency and its relevant literature.

Similarly to the literature, fixed effect and first difference models were built with current and lagged energy prices, with controls on potential confounders, such as economic development and climate circumstances. The total level energy efficiency analysis was presented along with research on the residential level energy efficiency.

The most important development of this research, the dataset covered a wider selection of countries with a time frame that already included the first year of COVID-19. This analysis covers the period between 2000 and 2021 in the European Union, UK, Norway, and Serbia. More precise price indicators were applied, than in the majority of the literature. In this sense, residential and industrial electricity and gas prices were applied separately. Residential energy consumption per residential area was used, as an indicator of energy efficiency. This metric is reflecting more on the energy intensity of the buildings. Residential electricity and gas prices were used during the analysis of the residential energy intensity, to achieve more consistent results. According to my knowledge, the controls on EU membership and energy poverty in a regression context were newly introduced in this literature.

Based on the presented research, to improve energy efficiency, the overall economic development should be targeted with carefully designed regulations. Although energy prices could significantly influence energy demand, the regulation should avoid using them as policy instruments, due to possible market distortion effects.

However, the problem of energy poverty should be treated carefully. The very low, regulated energy prices should not be applied, since these can hinder the investment in energy efficiency and boost over-consumption. Energy poverty should be rather treated with direct transfers and deductions for the properly identified vulnerable groups.

The regulations should support sufficiently strict standards and labels to improve the energy efficiency of the buildings and residential appliances since these create beneficial effects for everyone. Additionally, consumer behaviors should be further studied too, to avoid excessive consumption if the economic situation is better and prices are lower. The ultimate goal should not be forgotten, that energy efficiency is aiming to create less emissions, not to reduce cost.

Probably, the main limitation of the presented research is the data availability. The dataset covered the years 2000 to 2021. This means, 2022 which brought a major increase in energy prices due to the war, was not covered in the analysis. The dataset did not cover the year before 2000, because the less developed countries did not have proper data coverage before. Further research directions would be beneficial to cover the year of 2022 and the years before 2000 with a larger set of countries with different regions.

Appendix

Appendix A

Additional figures and tables

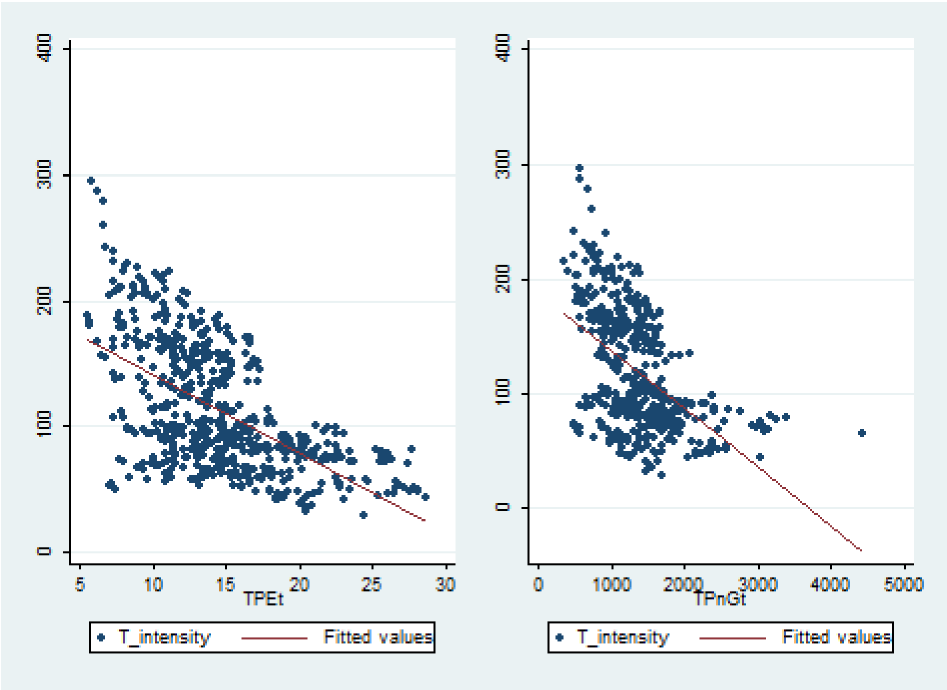

Figure 13.: Figure

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

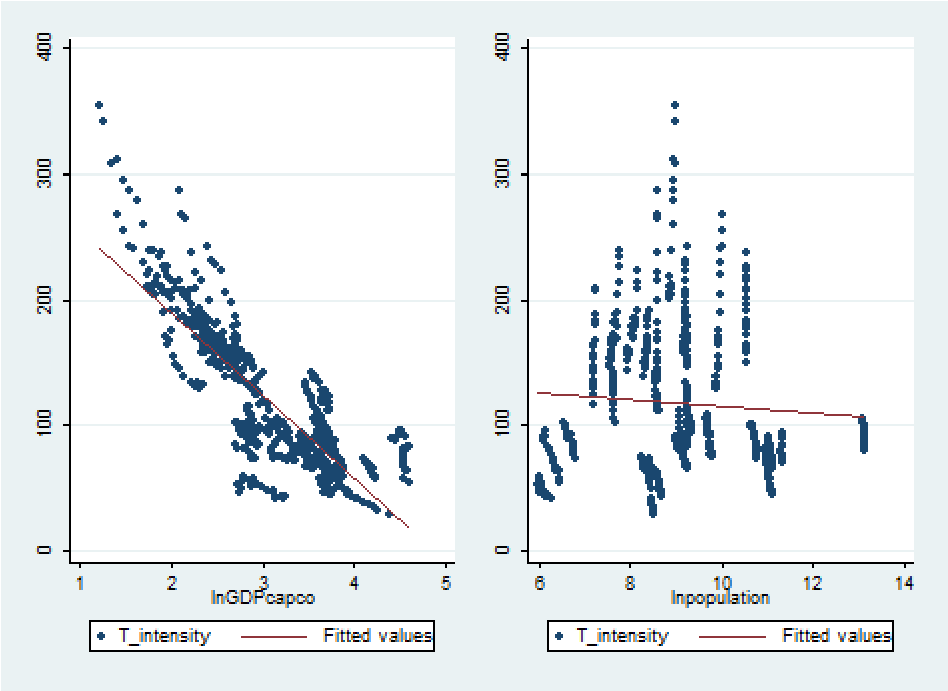

Figure 14.: Figure

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 19.: Summary statistics

	N	Mean	Std. Dev.	min	max
tax PEH	629	4.588	3.769	-8.917	19.8
tax PEI	628	3.054	3.593	-18.5	20.333
tax PGH	530	407.759	341.627	7.667	1848
tax PGI	537	279.839	269.639	-1000.667	1466.8

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 20.: Summary statistics

	N	Mean	Std. Dev.	min	max
Stax PEH	629	.371	0.304	-.42	1.98
Stax PEI	628	.397	0.435	-.673	3.588
Stax PGH	530	.323	0.239	.008	1.533
Stax PGI	537	.34	0.288	-.702	2.081

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 21.: Summary statistics

	N	Mean	Std. Dev.	min	max
PEH	629	12.64	4.046	4.6	25.6
PEI	628	8.724	3.352	2.833	46
PGH	530	1251.953	446.373	335.333	4969.667
PGI	552	816.269	233.894	199.167	1777

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Figure 15.: Figure

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

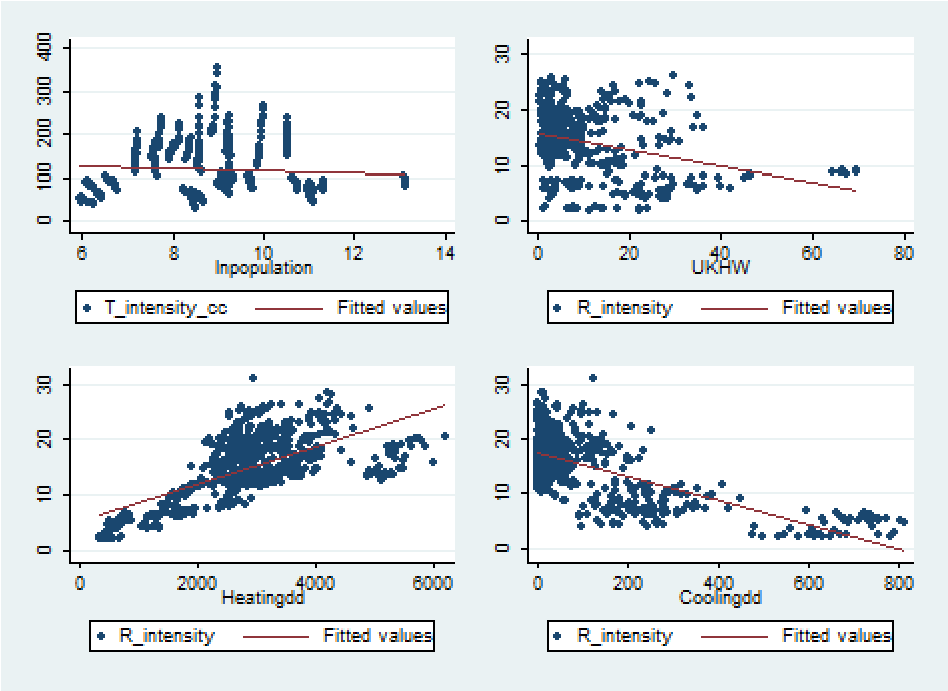

Figure 16.: Figure

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 22.: Regressions on total energy intensity average prices with yearly dummies

	(1)	(2)
VARIABLES	T_intensity	T_intensity
TPEt	0.070	-0.023
TPnGt	-0.003	-0.003
L_TPEt		0.112
L_TPnGt		-0.000
L2_TPEt		0.269
L2_TPnGt		0.001
lnGDPcapco	-68.206***	-62.795***
EU	-14.218**	-8.989*
year = 2001	-0.624	-0.677
year = 2002	-0.979	2.163
year = 2003	-1.952	1.727
year = 2004	4.157	3.972
year = 2005	3.008	3.385
year = 2006	1.217	3.376
year = 2007	0.827	1.918
year = 2008	-1.056	-0.286
year = 2009	-8.085**	-7.403**
year = 2010	-6.986*	-6.749**
year = 2011	-7.798*	-7.678**
year = 2012	-10.318**	-10.362**
year = 2013	-11.754**	-12.085***

year = 2014	-12.648**	-13.699***
year = 2015	-12.639**	-14.006***
year = 2016	-13.733***	-15.224***
year = 2017	-12.353**	-14.000***
year = 2018	-11.797**	-13.290**
year = 2019	-13.160**	-14.687***
year = 2020	-16.121***	-17.625***
year = 2021	-14.012**	-15.782**
Constant	353.204***	326.504***
R-squared	0.854	0.850

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 23.: Regressions on total energy intensity sectoral prices with yearly dummies

	(1)	(2)
VARIABLES	T_intensity	T_intensity
PEHt	-0.223	-0.427*
PEIt	0.334	0.589
PGHt	-0.002	-0.002
PGIt	0.000	-0.000
L_PEHt		0.133
L_PEIt		-0.008
L_PGHt		0.001
L_PGIt		-0.003*
L2_PEHt		0.082
L2_PEIt		0.153
L2_PGHt		0.000
L2_PGIt		0.002
lnGDPcapco	-73.610***	-66.800***
EU	-15.204**	-9.715*
lnpopulation	-18.061	-9.350
crisis	1.358	0.821
year = 2001	-0.442	-1.990
year = 2002	-0.458	1.892
year = 2003	-1.119	1.380
year = 2004	5.784*	4.074
year = 2005	4.911	3.600
year = 2006	3.386	3.982
year = 2007	3.240	3.078
year = 2008, omitted	-	-
year = 2009	-7.257***	-7.188***
year = 2010	-4.575	-5.784
year = 2011	-5.276	-6.562
year = 2012	-7.710	-8.932
year = 2013	-9.034	-10.461*
year = 2014	-9.634	-11.896*
year = 2015	-9.158	-11.874*
year = 2016	-9.880	-12.932*
year = 2017	-8.167	-11.579

year = 2018	-7.366	-10.478
year = 2019	-8.424	-11.585
year = 2020	-12.933***	-15.909***
year = 2021	-9.945	-14.224*
Constant	535.426	425.918
R-squared	0.857	0.854
Robust standard errors in parentheses		
*** p<0.01, ** p<0.05, * p<0.1		

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

Table 24.: Regressions on residential energy intensity with yearly dummies

	(1)	(2)	(3)
VARIABLES	R_intensity	R_intensity	R_intensity
PEHt	-0.009	-0.045	-0.032
PGHt	0.001***	0.001***	0.001***
L_PEHt		0.042	-0.009
L_PGHt		-0.000	0.000
lnGDI	0.251	0.390	0.602
EU	-0.080	-0.100	-0.521
crisis	-3.081***	-2.786***	-3.346***
Coolingdd	0.003*	0.004	0.003
Heatingdd	0.002***	0.002***	0.001***
UKHW	-0.004	-0.004	-0.008
year = 2004	-1.520***	-1.511***	-1.471***
year = 2005	-1.388**	-1.386**	-1.632***
year = 2006	-1.965***	-2.019***	-2.072***
year = 2007	-2.711***	-2.742***	-2.911***
year = 2008, omitted		-	
year = 2009		-0.347**	
year = 2010	-3.221***	-3.303***	-3.501***
year = 2011	-4.165***	-4.255***	-4.576***
year = 2012	-4.749***	-4.830***	-5.102***
year = 2013	-4.920***	-5.034***	-5.294***
year = 2014	-5.698***	-5.816***	-6.315***
year = 2015	-5.702***	-5.836***	-6.287***
year = 2016	-5.392***	-5.510***	-5.938***
year = 2017	-5.489***	-5.625***	-6.042***
year = 2018	-5.735***	-5.883***	-6.299***
year = 2019	-6.073***	-6.227***	-6.657***
year = 2008	0.321**		0.345**
year = 2009, omitted	-		-
L2_PEHt			0.047
L2_PGHt			0.000
Constant	9.694	8.219	6.911
R-squared	0.737	0.738	0.750
Robust standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

Source: Own calculation, data source (ODYSSEE, 2023a; Enerdata, 2023; EUROSTAT,2023h)

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