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Cost function for the electricity market in the European Union

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RESUMEN

El mercado de la electricidad en la Unión Europea ha sido y será una cuestión de vital importancia para todos los poderes implicados. En los últimos tres años se ha visto como sucesos externos como la pandemia y la Guerra de Ucrania han trastocado enormemente el precio de la electricidad. A consecuencia de ello, desde las instituciones de la Unión Europea se ha decidido que la mejor forma para conseguir esa independencia energética es una apuesta total y abierta por las energías renovables.

Por ello, en el presente Trabajo de Fin de Grado se va a tratar de analizar la función de costes del mercado eléctrico desde 2021 hasta 2021. A través de los diferentes tipos de energía utilizados para la creación de electricidad y en relación a diferentes variables independientes, se intentará analizar cuáles son los principales impulsores del precio final de la electricidad.

En este sentido, se tratará de crear una función que tome en consideración el avance de la tecnología en forma de renovables, shocks internos y externos, los riegos geopolíticos y la volatilidad del precio de la electricidad. De esta forma se consigue obtener una imagen muy realista y veraz del mercado eléctrico europeo.

Dicho modelo puede ser de gran utilidad para todos los implicados en el proceso, desde productores de electricidad hasta las comercializadoras, las diferentes autoridades, los legisladores y, por último, los consumidores finales.

PALABRAS CLAVE

Unión Europea, función de costes, electricidad, energías renovables, combustibles fósiles, mercado eléctrico, energía.

ABSTRACT

The electricity market in the European Union has been and will continue to be an important matter for all the powers involved. In the last three years, external events such as the pandemic and the war in Ukraine have greatly affected the price of electricity. As a result, the European Union institutions have decided that the best way to achieve energy independence is a total and open commitment to renewable energies.

Therefore, in this Final Degree Project we will try to analyze the cost function of the electricity market from 2010 to 2021. Through the different types of energy used for the creation of electricity and in relation to different independent variables, we will try to analyze which are the main drivers of the final price of electricity.

In this sense, an attempt will be made to create a cost function that takes into account the advancement of technology in the form of renewables, internal and external shocks, geopolitical risks and the volatility of the price of electricity. In this way, a very realistic and accurate picture of the European electricity market can be obtained.

This model can be of great use to all those involved in the process, from electricity producers to retailers, the different authorities, legislators and, final consumers.

KEY WORDS

European Union, cost function, electricity, renewable energies, fossil fuels, electricity market, energy.

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1. INTRODUCTION

The present Final Degree Project consists of the creation of cost function for the electricity market in the European Union from 2010 to 2021. It will include the different inputs used for electricity production such as gas, oil and coal and many other independent variables such as technology, geopolitical risk factor, producer price index and volatility that have an effect on the formation of the electricity price.

The present work is innovative compared to past investigations in the sense that it offers a more complete cost function with the inclusion of the impact of renewables, price volatility or the geopolitical risk index. It will, without a doubt, provide a clearer and more thorough picture of the energy market in the EU.

The principal methodology used has been quantitative investigation. Based on past literature, and on his investigation, the tutor, Yannis Paraskevopoulos, was able to construct a cost function for the electricity market. Using python, he was able to regress the data plugged in the function to derive the results. Data consisted mostly of prices and quantities of the different variables and were retrieved from different sources such as Eurostat and Bloomberg.

Secondly, a systematic review methodology which aims to analyze and synthesize existing research studies on a certain topic. In the present work, prominent past literature has been examined to understand the state of the investigation of the cost function for the electricity market. In addition, numerous papers gathered from Google Scholar or Comilla´s Digital Library have been reviewed to understand the electricity market structure and history.

The work is centered around the cost function of the European electricity market. In order to provide a clearer picture, a wider framework is used in the paper. Past literature will be analyzed, as well as the history of energy in the EU, the present structure and future trends. In the following paragraphs the structure will be presented.

Firstly, a brief introduction about the purpose of the investigation and its targets. It will be followed with an analysis of past researchers, how they have studied the matter in depth. These studies have been used to laid the foundation of cost function investigation for the electricity market.

Secondly, the European Union electricity market will be studied. Staring with its past history which shaped its foundation and its pillars. The market structure and how the electricity price is settled will be analyzed too as it is crucial to understand how fossil fuels and renewables affect pricing. Lastly, the expansion of renewables throughout the European Union.

Thirdly, a description of the model. Starting with a step-by-step analysis of the theoretical model with detailed explanation for a better understanding. Lastly, the model to estimate, in which the parameters to calculate will be introduced.

Next, a section describing the data used. Each individual data set will be portrayed, mentioning its source and its role on the cost function. Furthermore, a detailed explanation on how these data sets were retrieved and the difficulties encountered.

Finally, a results section where the model will be estimated including one by one the different independent variables considered. In the present section, the different parameters estimated will be discussed, analyzing its impact on the model and pondering the different inputs elasticities.

Lastly, a conclusion section to evaluate the results from all the different point of views, such as companies, regulators and consumers as the cost function affects many interested agents and sectors in our society.

2. COST FUNCTIONS IN ELECTRICITY

The European Union´s electricity market has undergone significant changes in the past few decades, with the introduction of renewable energy sources, market liberalization and integration across borders. Given the present context, the creation of a cost function that accurately reflects the underlying costs of electricity production and distribution is of crucial importance. Such a cost function will help market participants, regulators, and policy-makers make informed decisions about pricing, investment, and infrastructure development.

2.1 PURPOSE OF THE RESEARCH

The object of this Final Degree Project is the creation of a cost function for the electricity market in the European Union. The mentioned cost function is constructed based on series of inputs such as coal, gas and oil and independent variables, for example, the electricity output and technology. The model will also take into consideration external shocks and idiosyncratic effects for each country to account for different legislations and economic conditions. The parameters to be estimated will be capturing the price elasticities between the different sources of energy creation. The objective is to produce substitutive elasticities that show the easiness of switching from one input to another.

The model will analyze the European electricity market as a whole and each member state in particular. This analysis will enrich the discussion as each member has some particularities in their electricity market ranging from intensive use of a certain energy source, Germany with coal for example, to the degree of renewable energies deployment. The model also encompasses a fascinating period of time in the European Union as it ranges from 2010 to 2021. During this period, there are many geopolitical factors influencing the model, the main being the all-in bet of the EU with respect to renewable energies and the Ukrainian war started in 2021 which shook the energy market.

The data retrieved for the model has been mostly collected from the statistical office of the European Union (Eurostat). This data includes prices and quantities of oil, natural gas and coal for each country. It also contains the different electricity price and quantity generated for each state member. Producer Price Index is also considered to measure the average change in the prices that domestic producers receive for the goods and services they produce over a period of time. Renewables will be factor as a technology variable, meaning that an increase of renewable energy quantities is due to the improvement of technology thus reducing the cost of electricity production. Geopolitical risk index is included to account for political and social situations around the European Union. Lastly, volatility is included to capture the risk associated with fluctuations in the electricity prices.

This model is multidimensional in the sense that it can provide with precious intel for many interested parts such as regulators, consumers or companies operating in the electricity market. It comes under a time of great change and uncertainty as the European Union is trying to gain energy independence through renewables energies as a result of realizing its vulnerability to Russia´s gas imports. The skyrocketing rise in gas prices has boosted electricity companies margins as a result of the market configuration which will be discussed later. This has raised some itches around final consumers as their electricity bills have increased substantially and around regulators who have wandered what the real earning margins of these energy companies have been.

Realizing how impactful the price of gas, oil and coal is in the final electricity price is of the most importance to quantify the impact of renewables sources, understand the viability of the current energy market or asses the role of electricity generators between many other matters.

The starting point of the present work was the creation of a cost function proceeded by a series of estimations to derive the conclusions. The cost function used for the estimations is a theoretical model which comprises a system of equations for a flexible cost function with volatility and two types of shocks. In the present work, a reduced function is used as Chung proved that is the same than a system of equations. Here, a regression is run to calculate the parameters using panel for the selected countries: Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Latvia, Lithuania, Luxembourg, Hungary, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden. Moreover, including idiosyncratic effects to account for the different legislations and economic conditions. The estimated parameters capture the price elasticities which will enable the production of the substitutive elasticities that show the easiness to switch from one input to another.

The present paper is innovative to the discussion as it factors the impact renewable sources have on the cost function and the electricity market. Nevertheless, this area of study has been examined before by researchers and some of the most representative papers will be discussed in the following epigraph.

2.2 PROMINENT PAST LITERATURE

There have been several papers discussing or approximating the cost function of electricity. Each one of them has its own particularity and some of them have contributed to some degree to the study of cost functions in the electricity market.

Firstly, Economies and Diseconomies: Estimating Electricity Cost Functions by Michael T. Maloney in 2001. Prior to this article, all of the research had focused on average total cost, meaning the sum of capital and operating expenditures. On the other hand, this paper questions how expanded capacity utilization of existing plants affect the cost of production and the equilibrium price. Basically, instead of examining capital costs, it focuses on the operating costs. Moreover, it utilizes another dimension of cost that had not been studied by other researchers. Instead of using a one-dimensional definition of capacity utilization, it uses two main components. These are the ensuing, one is the misused capacity of plants when load demand decreases, and the other is "load following" which occurs when plants are connected to the load all week as demand varies. This paper proves with its estimated cost function that both dimensions increase average costs as plant capacity utilization decreases[1] .

The primary components of the cost model are the following:

- Economies of scale: the model examines the relationship between output of electricity and costs, both variable and fixed. By analyzing the relationship, it arrives at the optimal scale of production which minimizes average total costs.
- Capacity utilization: represents the degree in which plants are being utilized. If it increases implies greater efficiency thus lesser costs. It helps identifying potential inefficiencies in the production process.
- Input prices: the model considers the impact of input prices such as fuel costs and labor expenses. This enables calculating how fluctuations of these necessary inputs affect the cost structure.
- Technological advancements: how developments in new technologies affect production costs.
- Other factors: environmental regulations, market competition and territorial differences are also taken into account.

As mentioned before, the paper proved the increase of costs that came with the underutilization of the plants. It also provided greater understanding of economies of scale, as well as valuable insights in the electricity sector.

[1] T. MALONEY, M. (2001). Economies and Diseconomies: Estimating Electricity Costs Functions. Clemson University.

The second paper discussing the matter is Identification and Estimation of costs functions using observed bid data: an application to electricity markets by Frank A. Wolak in 2002. The primary use of this paper is to measure the degree of market power controlled by a market player using only bid information and market prices and quantities. As for market power, it is understood as the leverage power a generation firm has to increase the market price by using a bidding strategy, and its ability to gain a profit from it[2] .

The author´s mathematical and econometric approach will be discussed next. First, a theorical framework is developed in order to relate observed bid data to the cost function. It is assumed that electricity producers set forth bids based on their marginal costs, taking into consideration production capacity, fuel costs and other variable costs. Second, the development of a cost function. It should seize the relationship between total costs and electricity output, including fixed and variable costs. It also accounts for inputs prices and other factors that determine cost, such as the mentioned before. Third, model the relationship between the bid data and the cost function, assuming that the bid data is an approximate representation of the true marginal cost function. It also includes an error term to account for the approximation. Next, use of econometric techniques such as instrumental variables and generalized method of moments to estimate the parameters of the cost function using the overserved bid data. After the estimated parameters are derived, they are used to obtain an approximate cost function. This final function is best approximation of the real underlying cost structure[3] .

As a result, the investigation provides a more precise depiction of the underlying cost structure of electricity generation by analyzing the bids, offers to buy or sell, put forward by electricity producers. It also displays an estimation of the amount of variable profit earned by the electricity firms.

The next paper is called Cost functions and the electric utility industry. A contribution to the debate on deregulation written by Francisco Javier Ramos-Real in 2005.

This paper examines previous studies regarding costs function in the electricity markets supporting the competition and vertical disintegration. It analyzes the cost structure of

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[2] A. WOLAK, F. (2001). Identification and Estimation of costs functions using observed bid data: an application to electricity markets. National Bureau of Economic Research.

[3] *Ibid.*

electricity generation, transmission and distribution in the context of deregulation. The papers suggest the need of a proper regulation for the deregulation process as the improvements in productivity from the reform has not translated into benefits for customers[4] .

The mathematical and econometric approach begins with the formulation of separate cost functions for electricity generation, transmission and distribution, portraying the relationship between total output and total cost. These functions also include fixed and variable costs, as well as input prices and factors that influence cost. The model introduces economies of scale by modelling the relationship between costs and output with a scaling factor ranging from 0 to 1. Using econometric techniques such as panel data regression the author estimates the parameters of the cost functions using data from electric utilities. Lastly, an examination of the estimated cost functions helps identify economies of scale and inefficiencies with regard the new deregulation outlook[5].

Lastly, in 2021 a group of university researchers wrote a paper called Estimating electricity distribution costs using historical data.

The paper focus on understanding the relationship between distribution costs, which they claimed that previous investigations have forgotten about, and factors such as population, urbanization and electricity consumption. The data used is derived from reports by the 101 major U.S. investor-owned utilities regarding capital investments and operations and maintenance expenses[6] .

The model approach is similar as the mentioned before, the cost function includes the relationship between distribution costs and the factor mentioned such as population, etc. The authors model the cost function using a functional form that enables flexibility and interaction between the factors. Then, with the historical data gathered, they run a regression to estimate the parameters of the cost function. Lastly, with the parameters, an

[4] RAMOS-REAL, F. (2005). Cost functions and the electric utility industry. A contribution to the debate on deregulation. University of La Laguna.

[5] *Ibid.*

[6] RAUSCHKOLB, N; LIMANDIBHRATHA, N; MODI, V; MERCADAL, I. (2021). Estimating electricity distribution costs using historical data. Columbia University and University of Florida.

estimated cost function that represents the relationship between distribution costs and the factors is obtained[7] .

All these studies examine the same topic but using slightly different approaches and, above all, investigating different aspects. Some of the place their focus on distribution costs. Others encompass a wider spectrum such as transmission and generation costs too. As mentioned before all of these papers have had some importance in the study of cost functions for the electricity market.

3. ELECTRICITY MARKET

The electricity market in Europe stands at the forefront of the global energy landscape, undergoing profound transformations driven by technological advancements, environmental concerns, and evolving policy frameworks. This final degree project aims to provide a comprehensive analysis of the European electricity market, encompassing its historical backdrop, present market structure, electricity pricing dynamics, and the transition towards sustainable and renewable energy sources.

This section is divided into four different parts: it will start with a brief introduction of the past history of energy in the European Union, it will continue with a description of the present market structure and how the clearing electricity price is set. Lastly, an epigraph discussing the green energy transition the EU is experiencing.

3.1 HISTORY OF ENERGY IN EUROPE

The European Union energy outlook is distinguished by great heterogeneity due to some structural differences related to population, economy and energy sources by each country. This heterogeneity is also reflected in the energy systems, policies and resources of every country thus affecting production and consumption structures. The European Union encompass more than 4 million squares kilometers and as a result has a wide variety of natural resources within every member state. Not only resources vary, policies too, for example some countries are intensive in nuclear energy whereas others are completely

[7] *Ibid.*

against it. Lastly, energy structures differ around the EU, one of the most recent and up to date examples is the "Iberian exception".

In order to understand this intricate landscape, it seems necessary to flashback in time to the beginning. The genesis of the European Union came in the aftermath of the Second World War as an intent to create a joint control of the French and German coal and steel mines. As a result, the European Coal and Steel Community (ECSC) was created in 1951. Later on, in 1957, the same two countries created the European Atomic Energy Community (EAEC). These two treaties, apart from the energy, had the goal to integrate countries through legislation and international agreements in order to obtain future peace in Europe. Despite the efforts of integration, national policies still had much importance than common energy legislation. In 1973, the oil crisis shook the economies of the European countries and made them realize their vulnerability to imported energy sources such as oil. As a consequence, security of supply became a number one priority for the upcoming European Union. After the crisis, the measures implemented to guarantee energy supply were adopted mostly at a national level. At a European level, the European Community, integrated by Belgium, France, Italy, Germany, Luxembourg and the Netherlands, which later evolved into the EU, attempted but failed to elaborate a common energy policy. Consequently, for almost thirty years energy supply was relied on maintaining minimum strategic stocks for oil and oil products and by national and uncoordinated policies[8] .

It was only after the signing of the Treaty of Lisbon in 2005 that a common energy policy was deployed. The three pillars of the energy market were laid down: security of supply, competitiveness (affordable prices) and sustainability (clean energies). The pillar of competitiveness had already been discussed in the 80s and 90s as the EU institutions started to have some mandates regarding economic aspects in effort to construct an internal market. As a result, these principles were applied to the energy sector which had always been dominated by large and vertical integrated national monopolies. In an effort to stimulate competition and liberalization two crucial EU directives were approved in the late 90s regarding the electricity and gas market. These two directives had the

[8] HAFNER, M; LUCIANI, G. (2022). The Palgrave Handbook of International Energy Economics. Paris SciencesPo. p. 735.

objective of making the energy market more cost efficient and affordable for consumers as well as introducing fair market competition[9]

Lastly, the third pillar, sustainability, started to materialize worldwide after the 1992 Earth Summit in Rio de Janeiro and the 1997 Kyoto Protocol. At an EU level, the fight against climate change really took a turn in 2009 with the launch of the 2020 objectives "Green Package—A European strategy for Sustainable, Competitive and Secure Energy".

3.2 PRESENT STRUCTURE

As explained in the previous epigraph, before liberalization, the electricity sector in most of the European countries was dominated by a small number of large, vertical integrated utilities that owned the entire electricity value chain, from generation to distribution. These monopolistic companies had remarkable market power and were often safeguarded by regulations that prevented limited competition. This disposition resulted in higher prices, few to none innovation and, as a result, lower efficiency. Nevertheless, a series of events including the oil crisis, the integration of the European markets and the principles of liberalization and competition changed the spectrum radically.

The liberalization process policies undertook by the European Union included separating the ownership and control of generation and transmission assets. As a result, generators and distributors were not the same company, allowing the entrance of new competitors and improving the transparency of the market. It also improved supply as distribution was only mandated to a specific company. Another important factor was the introduction of retail competition as it allowed customers to choose between different distributors thus pushing electricity prices down. Also, with the liberalization came a privatization of publicly owned companies. Lastly, another impactful policy was the establishment of independent regulators at a national and supranational level[10] .

[9] *Ibid.*
[10] JAMASB, T; POLLITT, M. (2005). Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration. Center for Energy and Environmental Policy Research. p. 2-4.

The electricity system of the European Union is a complex and intricated structure of vast extension. In the following section, a superficial and brief explanation will be given focusing just on the elements which relate closely to the present Final Degree Project.

The EU electricity market is divided into different market segments including wholesale, retail and balancing, each of one having its own regulations. The wholesale segment is where electricity is traded in large quantities between generators, traders and large consumers. The wholesale prices are determined through auctions organized by the different transmission system operators (TSOs) in every country. The retail segment is where electricity is sold to final consumers such as households or industrials. Finally, the balancing segment is also managed by TSOs which ensure that electricity demand and supply is balanced at all times[11].

The market participants which play different roles in the market and regulated by various bodies. The most prominent ones are the following:

- Generators: companies which produce energy and afterwards sell it to the market. They use different energy sources such as coal, natural gas, nuclear or renewables. These companies can also participate in the market with capacity mechanisms to ensure electricity supply at given periods in exchange for a payment, different from the regular sale to suppliers.
- Transmission system operators (TSO), who are in charge for the long-distance transport and system stability thereby getting paid for it. They supply the electricity from generation plants to local electricity distribution operators (DSO) via high voltage electrical grid.
- Distribution network operators (DSO): they operate with low or medium voltage distribution networks and organize the local market of electricity which supplies to the final consumers.
- Suppliers: these are the companies that buy the electricity from generators to then commercialize it to households and businesses. These suppliers can also participate in other parts of the value change, such is the case of Iberdrola, which acts as a generator, supplier and TSO.

[11] POLLITT, M. (2022). The European wholesale electricity market: from crisis to net zero. Centre on Regulation in Europe. p. 21-31.

- Regulators: national and supranational public authorities that over watch the proper functioning of the electricity market. Regulators look after the interest of consumers and ensure fair competition between companies. At a EU level the main regulatory entities are the European Commission and the Agency for Cooperation of Energy Regulators (ACER).

Lastly, it is important to understand the different markets in which energy is traded. The bilateral market which is an over-the-counter transaction between two parties to agree on the terms of a purchase or sale of electricity. Secondly, the spot market, the intra-day and day-ahead market in which electricity is traded in advanced for a future time that could be the same or the following day. Price allocation works as explained before with a system of auctions and the intersection of supply and demand curves. Finally, the futures market in which electricity is traded for future delivery in order to hedge against possible volatility of prices[12].

3.3 ELECTRICITY PRICE IN THE EUROPEAN UNION

The European Union electricity market is established on a marginal price also known as "pay-as-clear" market. The particularity is that price is settled by the marginal cost, meaning the cost of producing and additional MWh of electricity. Megawatt-hour is the unit of measure commonly used for energy generated and equals to a thousand kilowatts per hour. Generators are placed on the market ranked by a merit order beginning with the least costly to the most expensive power generator plant. Therefore, the last plant required to satisfy the demand for electricity within the defined time period sets the price and all the other generators are paid the same amount [13].

The way the clearing price is retrieved is the following: buyers submit demand bids and seller also submit supply offers. Then, an auctioneer, which is usually a government agency or private company, balances the supply and demand curves to find the point

[12] POLLITT, M. (2022). *Op. cit.* p. 25.

[13] Preliminary Assessment of Europe's high energy prices and the current wholesale electricity market design. Main energy drivers, outlook, and key markets characteristics. (2021). European Union Agency for the Cooperation of Energy Regulators. p. 11.

where they cross. Therefore, all demand bids above the clearing price and all bid offers below it are accepted [14].

A great advantage of the "pay-as-clear" model is that all electricity producers in the same bidding zone are encourage to bid their real costs in order to get into the merit order and latter get their offer settled. This model benefits technologies with higher capital expenditures but lower operational costs, as they are at the beginning of the merit order (least expensive to produce) and get paid a higher price set by the most expensive plants. This incentives competition as generators tried to run as efficient as possible to expand the gap between marginal costs and clearing price. Additionally, it guarantees security of supply covering the operating expenses of the costliest energy plant in the market. Finally, it contributes to the development of renewable energies as it allows greater returns to finance the expensive deployment of capital expenditures[15] .

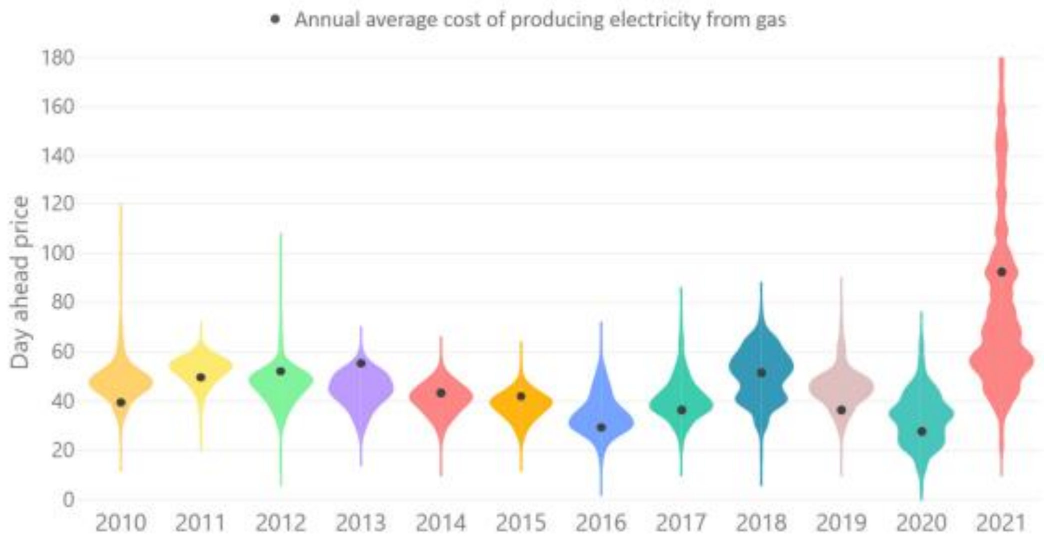
In the following paragraphs, the past energy outlook of the European Union will be discussed, explaining price drivers and geopolitical factors.

Firstly, it is important to point out that the main driver for electricity price has been natural gas. There is a strong correlation between the price of gas (most of it imported) and the final electricity bill.

Figure 1: Electricity day-ahead prices distribution compared to the cost of producing electricity with gas in Europe (2010-2021) (EUR/MWh)

[14] BALDICK, R. (2009). Single clearing price in electricity markets. University of Texas at Austin. p. 2.

[15] European Union Agency for the Cooperation of Energy Regulators. (2021). *Op. cit.* p. 11.



Source: ACER calculations based on ENTSO-E and Platts data

Figure 1 indicates the day-ahead prices with the cost of producing electricity from gas in Europe. For each year, a violin shaped figure represents the distribution of the electricity prices. The height of the figure represents the span of prices at a given year while the width, the frequency of a certain price. The black dot represents the annual average cost of producing electricity with gas.

EU wholesale electricity market prices have a strong correlation with gas prices, driving the electricity bill. It can be seen that during the Covid pandemic electricity prices dropped as result of a lesser demand for gas.

Secondly, electricity prices across different EU member varies considerably due to two different reasons, the level of gas dependency and the level of electricity interconnections with adjoining countries. The higher the level of gas dependency and lower deployment of electricity networks, the higher the wholesale price of electricity. Countries with neighboring states that have access to cheap energy benefit the most from transnational trade, provided that they have an efficient electrical grid.

For example, during the month of September 2021 Spain recorded one of the highest electricity prices in Europe due to its dependence on gas and its finite interconnection grid. Only 4% of its electricity demand was covered with imports. On the other side of the spectrum, the Nordic countries had a 4% dependency on gas while the rest was covered with renewables and as a result had the lowest electricity prices for the period[16].

[16] *Ibid.* p. 6.

3.4 TOWARDS A GREEN ENERGY IN EUROPE

The European Union is in the process of converting its economy with the goal of reducing the emission of greenhouse gases. The key element for this transformation is set to be electricity. The main areas in which it is going to play a crucial goal are two: firstly, a more efficient use, and a shift in the sources towards renewable energy, overall, it will reduce the greenhouses emission for electricity production. Secondly, its share in the total energy consumed is expected to grow especially in the transport sector (electric vehicles) and in heating and cooling (electric heat pumps).

The challenge the UE is facing comprises making all the sufficient investments to bring changes in electricity generation, transport and distribution, while keeping electricity prices affordable for both industries and households.

The energy industry is in the turning point of a transition towards a net zero carbon economy, as part of the necessity to fight climate change and to reduce carbon emissions. For the past forty years there has been a growing concern around developed countries with regards to the climate change. This preoccupation has led to the signing of international treaties regarding climate by the world powers. Some of the most the most influential treaties that have been ratified over the last decades are the following:

- The first important climate change treaty is the United Nations Framework Convention on Climate Change (UNFCCC). Adopted in Rio de Janeiro, it is the first international treaty to recognize the existence and potential impacts of human-induced climate change and to establish a framework for international cooperation to address it. It also established the Conference of the Parties (COP), which is the supreme governing body of the treaty that meets annually to review progress.
- The Kyoto Protocol, adopted in 1997 and entered into force in 2005, aimed to reduce greenhouse gas emissions. The key element of the agreement was for industrialized countries to reduce emissions in accordance with agreed individual targets. It required developed countries to reduce their greenhouse gas emissions by an average of 5% below 1990 levels over the period 2008-2012 [17].

[17] Kyoto Protocol to the United Nations Framework Convention on climate change. (1998). United Nations.

- The Paris Agreement adopted in 2015 aimed to limit global warming to well below 2 degrees Celsius above pre-industrial levels and ambitions to limit the temperature increase even further to 1.5 degrees Celsius. As opposed to the Kyoto Protocol, the Paris Agreement has a broader scope and includes legally binding emission reduction targets for both developed and underdeveloped countries [18].

Regarding the European Union, it has made an all-in debt for renewable energies.
The green energy transition history of the European Union is the following:

- The original Renewable Energy Directive (RED I) adopted in 2009 determined that a mandatory 20% share of the energy consumption must come from renewable sources. It was latter amened in July 2021 by RED II, which was passed in order to align with the new energy targets set by the ambitious European Green Deal. The new directive increased the binding targets of renewable energy share to 40% by 2030. Following, in May 2022 as a consequence of the Ukrainian war and as a part of the REPowerEU plan, RED III was endorsed, which augmented the sustainable sources share to 45%. Lasty, RED IV was adopted to accelerate the deployment of renewable energy, naming them of public interest and speeding the procedures of the licenses [19].
- On December 2019, the European Commission presented the European Green Deal. Its main objective is to make the EU climate neutral, net zero greenhouse gas emissions, by 2050. Nevertheless, is far more ambitious, as it plans to transform the economy of the Union its industry, agriculture, transport and many others [20].

The core plan is to produce electricity from mostly renewable sources. In order to achieve this goal, the EU has set targets to increase clean energy capacity, which are the following:

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[18] BODANSKY, D. (2021). Paris Agreement. United Nations Audiovisual Library of International Law.

[19] REPowerEU Plan. (2022). Communication from the Commission to the European Parliament, the European Council, the Council, the European economic and social Committee and the Committee of the Regions. European Commission.

[20] *Ibid.*

- Offshore renewable energy: the sea offers many different energy sources that are available, abundant and clean like wind wave and tidal. The target is to achieve installed capacity of at least 60 GW of offshore wind and 1 GW of ocean energy by 2030 and 300 GW and 40 GW, sequentially, by 2050 [21].
- Onshore wind energy: one of the pivotal green energy supplies, according to Eurostat it accounted for over one third of the total electricity generated from renewable sources in the EU by 2021. At the moment, it has 255 GW of capacity installed and from 2022 to 2026 it is expected to be installed 116 GW of new wind farms [22].
- Solar energy: currently the fastest growing source of energy in the EU as its costs have decreased by 82% over the last decade. Solar capacity installed at the moment amounts to 209 GW and it is projected to escalate to 320 GW by 2025 and close to 600 GW by 2030 [23].
- Bioenergy: biomass derived from organic waste such as plants or animals is then transformed to biofuel. Biomass for energy holds the first position as a source of renewable energy in the EU with close to 60%. Biofuels are expected to amount to 14% of energy consumption in transportation by 2030 [24].
- Hydropower: derived from flowing of water that powers a turbine, as of 2021 it has an installed capacity of 255 GW and it is expected to grow around 8% per year until 2030 [25].

Overall, the European Union has and will be investing billions of euros to the deployment of green energies in order to reduce greenhouses gasses emissions and to achieve energy

[21] An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. (2020). European Commission.

[22] *Ibid.*

[23] EU Solar Energy Strategy. (2022). European Commission.

[24] Brief on biomass for energy in the European Union. (2019). Joint Research Centre. European Commission.

[25] Directive (EU) 2018/2001 of the European Parliament and the Council of December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union.

independence. Later in the model, it shall be assessed how these technologies impact the cost of producing electricity and the substitutive elasticities.

4. DESCRIPTION OF THE MODEL

This section presents a comprehensive description of the cost function used in this study to analyze the electricity market in the European Union. The cost function is a mathematical representation that quantifies the relationship between various parameters and the total cost of electricity production.

By describing the cost function equation and its components, this section aims to provide a clear and transparent framework for understanding the underlying mechanics of cost estimation in the EU electricity market. It sets the foundation for subsequent analyses and interpretations of the cost function results, enabling a deeper understanding of the factors driving costs in the electricity market and their relative contributions.

4.1 THEORETICAL MODEL

The electricity production in Europe will involve primary inputs such as gas, oil and coal. Let input price vector be p = $[p_1, p_2, \ldots, p_n]$. If inputs quantities used are q = $[q_1, q_2, \ldots, q_n]$, then the total cost of producing electricity, y, will be

$$C = \sum_{i=1}^{n} p_i q_i = p \cdot q \qquad (1)$$

The total value of output produced will be generating C total cost of emissions.

Output will be subject to total random uncertainty, ϵ, produced by internal and external shocks that are unrelated between them in the sense

$$\epsilon = p\boldsymbol{\epsilon}_I + \sqrt{(1 - p^2)}\epsilon_E \qquad (2)$$

with $Cov\ (\epsilon I, \epsilon E) = 0$.

p is a coefficient that represents the relative importance or weight assigned to the internal and external shocks.

One critical assumption in this equation is that the covariance between the internal shocks and external shocks is zero. This means that there is no correlation or relationship between the internal and external shocks. They are considered to be independent of each other.

The total uncertainty in the economy is given by

$$Var\ (\epsilon) = p^2\sigma_I^2 + (1 - p^2)\ \sigma_E^2 = \sigma^2 \quad (3)$$

The equation concludes that the total variance, denoted as σ^2, captures the combined effect of both internal and external shocks on the overall uncertainty in the economy.

The economy output price unit is also uncertain due to shocks in the economy

$$p_y = \mu_y + \sigma \cdot e$$

The equation provides a way to incorporate uncertainty into the price unit of the economy's output. By combining the mean price unit with a random variable scaled by the overall uncertainty, it captures the potential deviations from the expected value due to shocks in the economy. This equation acknowledges that the price unit is not fixed but rather subject to fluctuation, reflecting the inherent uncertainty and volatility present in economic systems.

The economic agents will maximize the expected utility of the benefit given the current technology $F\ (q)$ as

$$Max_y E\ [U\ (\pi) : y\ \leq F\ (q)] = c\ (p, y) \quad (4)$$

where $\pi = p_y \cdot y - p \cdot q$

Economic agents aim to maximize the expected utility of the benefit, denoted as $Max_y E\ [U\ (\pi) : y\ \leq F\ (q)]$

The technology function $F\ (q)$ represents the current technology's relationship with the quantity of output (q). It is important to highlight that renewable energy deployment will account for the technology advancements.

The expression $c\ (p, y)$ represents a function that determines the optimal decision or choice c made by economic agents based on the price unit p and the quantity of output y.

The benefit π is calculated as the difference between the product of the price unit p_y and the quantity y and the product of the price p and the quantity q.

By maximizing the expected utility of the benefit, subject to the condition that y is less than or equal to the technology function $F\ (q)$, economic agents make decisions that optimize their welfare or utility.

Using the profits equation, the expected maximization problem is stated as

$$max_y E\left[\left(\mu_y + \sigma_\epsilon \cdot e\right) y - c\ (p, y)\right] \equiv V\ (p, \mu_p, \sigma_y) \qquad (1)$$

The objective function combines the expected benefit $\left(\mu_y + \sigma_\epsilon \cdot e\right)$ multiplied by the quantity of output y and subtracts the cost function $c\ (p, y)$. The objective function is denoted as $V\ (p, \mu_p, \sigma_y)$, which represents the value of the expected profits. The objective function captures the agents' utility or satisfaction derived from maximizing their expected profits, considering the expected value of the price unit of the electricity output, costs, and the associated uncertainty.

The first order conditions for this maximization problem are

$$Eu'\ (\pi)\left[\left(\mu_y + \sigma_\epsilon\right) - c'\ (p, y)\right] = 0 \qquad (2)$$

The first-order conditions represent the necessary optimality conditions for the maximization problem. It states that for an optimal solution, the derivative of the expected utility with respect to the benefit, multiplied by the difference between the expected benefit and the derivative of the cost function, should equal zero. This condition ensures that agents maximize their expected utility by equating the marginal utility of the benefit to the marginal cost of production.

$Eu'\ (\pi)$ represents the derivative of the expected utility function with respect to the benefit π. This term captures the marginal utility or the rate of change of utility with respect to changes in the benefit.

$c'\ (p, y)$ represents the derivative of the cost function with respect to the price unit p and the quantity of output y. This term captures the marginal cost or the rate of change of costs with respect to changes in price and quantity.

Taking the expectation in the expression and rewriting we have

$$\mu_y Eu'(\pi) + \sigma_\epsilon \epsilon\, E\,(u'(\pi\epsilon)) = Eu'(\pi)\,\frac{\partial c}{\partial y} = \mu_y + \frac{\sigma_y Eu'(\epsilon)}{Eu'(\pi)} = \frac{\partial_c}{\partial_y} \quad (3)$$

The equation states that the expected marginal utility of the benefit, combined with the expected derivative of the utility function evaluated at different realizations of the random variable, is equal to the expected derivative of the cost function with respect to the quantity. This equation establishes a relationship between the market clearing price μ_y, the overall uncertainty $\sigma_\epsilon E$, and the rates of change in utility and cost functions.

mu_y, will be for us the market clearing price for electricity, where

$$\sigma_\epsilon = \sqrt{p^2\sigma_I^2 + \sqrt{(1-p^2)}\sigma_E^2.}$$

The market clearing price is the price at which the quantity of electricity supplied by producers equals the quantity demanded by consumers, resulting in a state of equilibrium in the electricity market.

p is a parameter that represents the correlation coefficient between internal shocks σ_I^2 and external shocks σ_E^2. The correlation coefficient measures the degree to which these shocks are related or move together.

Then we rewrite the above question as

$$\frac{Eu'(\pi e)}{Eu'(\pi)} = \frac{c'(p,y) - p_y^*}{\sqrt{p^2\sigma_I^2 + \sqrt{(1-p^2)}\sigma_E^2}} = g \qquad (4)$$

This expression shows the additional cost to the marginal cost that the representative electricity producer will have to charge, depending on the attitude towards risk. If $g \leq 0$, then the producer is risk averse and considers the growth in production above a certain level is damaging. The representative electricity producer will buy less because of the higher cost.

The producer will be willing to sacrifice higher expected utility from using $q1$ and $q2$ to eliminate uncertainty in produced output and get with certainty $E\,(\pi)$.

4.2 MODEL TO ESTIMATE

Following Paraskevopoulos et al., (2023) we can recuperate all parameters of an implied flexible cost function as, using Chung, (1987)

$$c = \sum_{i=1}^{N} \eta_{c,i} s_i + \eta_{c,y} \qquad (5)$$

c represents the cost function, which represents the relationship between the cost of production and the input factors. It quantifies the expenses incurred in producing a certain level of output.

$\eta_{c,i}$ represents the parameter associated with the *i*-input factor s_i. These parameters capture the cost elasticity or the responsiveness of the cost function to changes in the corresponding input factor. Each $\eta_{c,i}$ value provides insights into how changes in the *i*-input factor affect the overall cost of production.

s_i represents the *i*-input factor. These input factors are oil, gas and coal that contribute to the production process. The summation $\sum$ notation implies that we consider the cumulative effect of all input η factors on the cost function.

$\eta_{c,y}$ represents the parameter associated with the output level *y*. This parameter captures the cost elasticity or the responsiveness of the cost function to changes in the output level. It indicates how changes in the level of output influence the overall cost of production.

The parameters beta are then calculated by the estimated elasticities of the cross variation

$$\beta_{i,j} = -\frac{s_i s_j}{\eta_{c,i} + \eta_{c,j}}$$

$\beta_{i,j}$ represents the parameter associated with the cross-variation between input factors *i* and *j*. These parameters capture the relationship between the two input factors and their joint impact on the cost function.

$s_i s_j$ represent the values of the respective input factors i and j. These values quantify the levels or quantities of the input factors used in the production process.

$\eta_{c,i} + \eta_{c,j}$ represent the elasticities associated with input factors i and j, respectively. These elasticities measure the responsiveness or sensitivity of the cost function to changes in the corresponding input factors. The elasticities capture the percentage change in the cost function resulting from a one percent change in the input factor.

Lastly, the negative sign indicates the inverse relationship between the cross-variation of the input factors and the parameters in the cost function.

Then we can write the cross-substitution elasticities as

$$\sigma_{i,j} = 1 - \frac{1}{\eta_{c,i} + \eta_{c,j}} \quad (6)$$

The formula calculates the cross-substitution elasticity as the difference between 1 and the inverse of the sum of the respective input factor parameters. The inverse represents the ratio of the price or availability elasticities, indicating the relative responsiveness of the cost function to changes in the input factors.

This elasticity provides insights into the substitutability or complementarity between input factors i and j in the production process. A positive value indicates that the input factors are substitutes, meaning that an increase in the price or scarcity of one input factor leads to a higher allocation or usage of the other input factor. Conversely, a negative value suggests complementarity, where an increase in the price or scarcity of one input factor results in a lower allocation or usage of the other input factor.

The theoretical model we have is a system of equations for a flexible cost function with uncertainty and two types of shocks. Therry (1987) has proved that this system of equations is represented exactly by a reduced equation

$$\hat{c} = \sum_{i=1}^{n-1} \eta_i s_i + \eta_{gas} \cdot \sigma + T + \eta_y y$$

Where the small letters $\hat{c}$, $\widehat{s_i}$ indicate growth variables.

Panel estimations including all European countries where we shall include idiosyncratic effects which are fixed effects to account for different legislations and economic conditions.

The parameters to be estimated $\eta_i = \{\eta_{gas}, \eta_{coal}, \eta_{oil}\}$ are capturing the price elasticities. Once we have estimated η_s we can then recover all the parameters of the system of equations given in the paper.

We want to produce substitutive elasticities ($G_{i,j}$) that show the easiness of switching from one input to another.

5. DATA

The data section of this final degree project emphasizes the significance of robust and comprehensive data for estimating parameters, running models, and achieving accurate results in the analysis of the cost function in the European Union's electricity market. By utilizing various datasets that capture different dimensions of the market, a deeper understanding can be gained of the factors influencing cost dynamics, contributing to informed decision-making and the development of effective strategies for a sustainable and efficient electricity market. Data is used in the present work for quantitative analysis and modeling, enabling to gain insights into the cost drivers, trends, and interdependencies within the electricity market. By utilizing various datasets, such as gas, coal, oil, renewables, electricity, geopolitical risk index, and price volatility, the research can capture a broad spectrum of factors that influence the cost function.

The data used for the model comprises different member states of the European Union. In particular, the countries analyzed are the following: Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Latvia, Lithuania, Luxembourg, Hungary, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden.

Th period of time considered for the model ranges from 2010 to 2021. For the present study, the last few years of the time period (2020, 2021) are remarkably insightful due to the geopolitical turbulences. The covid pandemic in 2020 switched all industries activity off and as a result the electricity demand decreased as it was only needed for households and some strategic industries. On the other hand, in February 2021 the Ukrainian war started and turned the European electricity market upside down. As a consequence of this war, the European Union imposed heavy sanctions against Russia and gas imports from the former USSR, which accounted for 40% of natural gas consumed in the EU, ceased. For the purpose of the study, including data for 2022 would have been of the most relevance but, unfortunately, much of the needed data was only published until 2021.

Most of the data has been gathered from Eurostat and indexes such as the Brent. The inputs used in the model are the gas, coal, oil, electricity output and technology in the form of renewables.

Gas prices and quantities were collected from Eurostat. Quantity represents annual final energy consumption by country in terms of thousand tons of oil equivalent. On the other hand, gas prices account for household consumers, excluding taxes and levies, measured in Kilowatt-hour and the currency being Euro.

Oil prices and quantities were compiled from Eurostat and the Brent. Quantities amount to annual energy consumption measured in thousand tons of oil equivalent for each country. Oil prices were retrieved from the Brent, the European price benchmark, in terms of dollars per barrel with an annual time frequency.

Coal prices and quantities were collected from Eurostat and API2 Rotterdam. Quantities amount to annual energy consumed measured in thousand tons of oil equivalent for every country. Price was derived from the European coal price benchmark API2 Rotterdam measured in dollars per ton for the Europe.

Electricity prices and quantities were collected from Eurostat. Prices are for households' annual consumption for each country, measured in Kilowatts-hour, excluding taxes and levies and the currency being Euro. The output is measured in Gigawatt-hour for gross electricity production for every country.

Producers price index for the industry total excluding construction, sewerage, waste management and remediation activities. It represents the total output price index in euros and was collected from Eurostat. Including the Producers Price index is important for the following reasons: as it captures the changes in the prices producers receive for their goods and services, we can capture the effects of changes in input prices in the costs of electricity production. In addition, changes in the Producers Price index reflect changes in the macroeconomic environment such as inflation or economic growth. In conclusion, including PPI is necessary to identify the factors that drive changes in the cost of producing electricity.

Renewables energies quantities accounts for the technology advancements. It represents final energy consumption, encompass renewables and biofuels and the unit of measure is thousand tons of oil equivalent. It was also retrieved from Eurostat. Including renewables energy as technology independent variable is groundbreaking in the estimation of cost functions for the electricity market. Firstly, it assesses the effect green energy policies are having in the final deployment of this type of renewable energies over a significant period of time where a lot of investment has been made. Secondly, it captures clean energy sources competitiveness, as renewable energy deployment needed an enormous amount of capital which has been reducing over the past decade. Finally, to analyze the impact technology is having on green sources, making them less expensive and more efficient.

Geopolitical risk factor is included as an independent variable to account for the geopolitical risk on the electricity costs. The past few years have offered great examples on how pandemics, bottlenecks and armed conflicts have disturbed electricity prices around the world. Including such variable helps to identify the extent to which these risks affect electricity costs and, therefore, provide a more accurate cost estimate. Given the European Union is highly dependent on Russian gas it is crucial to include this variable to have a better understanding on how gas is an electricity cost driver. It is important to notice that the common geopolitical risk factor used was from Belgium due to the lack of data.

Finally, electricity price volatility is calculated to measure the degree of volatility for the period of time. It is essential for the model for accurately assessing the costs of electricity production and supply. Moreover, it is crucial to include volatility in the panel regression to help control for unobserved heterogeneity across individuals or entities in a panel dataset. Fixed effects models are usually employed to control for unchanging in time heterogeneity, but they may not entirely capture all sources of heterogeneity. By including volatility measures, such as the standard deviation of the electricity price, we can better capture and control for any remaining unobserved heterogeneity. Including volatility also helps measuring the effects external shocks have on the cost function. External effects events such as geopolitical issues, monetary policies, etc.

In order to calculate annual volatility, wholesale daily electricity prices were needed. Nevertheless, price electricity mentioned before could not be used because Eurostat only showcases biannual data not daily. There is an organization called Ember which is an independent think tank that has wholesale electricity daily prices data available for very EU state member. The issue was that the data ranges from 2015 to 2023, not the period estimated in the present work. After some inquiries, we found out through an employee that daily data publication was not mandatory until 2015 so there were no publicly available data sets. The only way to retrieved the data was through the exchanges companies that operated the market. Epex-spot is the main exchange operator for some European countries such as Netherlands, Belgium or Germany. Again, after some phone calls we were provided with an email account to which we wrote petitioning for the data for academic courses but received no answer. Lastly, we tried deriving the data from Spanish public entities; the National Statistics Institute, the Ministry of Industry and the Ministry of Ecological Transition. They were contacted and referred us an email account to which we addressed and, again, received no answer. The ultimate option left was Bloomberg, were the only data available was supplied by Epex-spot, the previously mentioned exchange operator. The operator offered Belgium´s daily electricity price but, instead of being wholesale, it was spot day-ahead peak load electricity price. Peak load refers to the cost of electricity during times when the demand for electricity is highest. After some ponderation, it was decided it is the best proxy in order to calculate volatility. In general, higher demand drives both wholesale and peak load electricity prices upwards, and lower demand do the opposite.

6. RESULTS

The results section of this study presents the outcomes obtained from running the cost function data through Python-based analysis. By applying the cost function model to the gathered data, a set of parameters has been derived, providing valuable insights into the dynamics and characteristics of the European Union's electricity market. The analysis aims to quantify and evaluate the relationships between various factors that influence the cost dynamics in the EU electricity market. The derived parameters offer valuable information on the key drivers of costs within the electricity market. They provide insights into the relative impact of different energy sources, such as gas, coal, oil, and renewables, on the overall cost structure. Also, they provide quantitative evidence on the interplay between supply and demand factors, the influence of geopolitical risks, and the pricing mechanisms that shape the cost function.

The utilization of Python allows for the implementation of complex algorithms, statistical techniques, and visualization tools, enabling a rigorous examination of the cost function and the derivation of meaningful parameters.

Panel regression is a statistical technique used to analyze data sets that include observations of numerous individuals, firms, or other units over a specific period of time. Panel regression models consider both cross-sectional and time-series variations in the data which allow for a more complete analysis of the factors that influence the cost function.

Cross-sectional and time-series refer to the two different type of data sets that are used in econometric analysis. The first one refers to data which is collected at a certain point in time from a sample. The second one is the data which is retrieved for a certain period of time. Panel regression combines these two types of data to comprehensively estimate the relationship between different variables over time.

The regression is a method for modelling the relationship between the dependent variable and the independent variables. The objective of regression is to derive the parameters of a mathematical equation which explain the relationship between the inputs and the final outputs. These parameters denote the rate of change in the cost of production associated with a unit change in each independent variable, while maintaining all the other independent variables constant.

The econometric method used for the panel estimation is fixed effects as they are used to control for time-invariant heterogeneity, which are factors that affect the output but remain constant over time and are particular to each individual country. By controlling these factors, we compare each country´s output to its own average output providing a more unbiased and accurate estimates. Thus, gaining better understanding of the true causal-effect relationship between inputs and output[26].

Given the present work is the optimization of a cost function, we shall minimize the cost function in order to find the lowest costs of producing the electricity output. In order to achieve so, we run a regression to estimate the parameters that minimize the sum of the

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[26] M. WOOLRIDGE, J. (2001). Econometric analysis of cross-section and Panel Data. Massachusetts Institute of Technology. p. 248.

square errors, which is the sum of the squared differences between the actual values and the predicted values for each observation in the sample.

In the following paragraphs an explanation is given on how the data was run through a Panel0LS estimation. In order to structure the data for the regression, we collapsed the countries to one column so as to have two indexes for the data, one representing time and the other countries.

Firstly, regressing the total cost change from year to year of electricity on a constant (1), by including a constant term in the regression, we are assuming there is a fixed cost that remains constant regardless of the of inputs. We also add share of gas change in the total cost year after year, the share of coal change in the total cost year after year, the share of renewables as a technology independent variable and, lastly, entity effects to account for each country´s idiosyncratic effects.

Figure 2: Panel0LS regression formula

```
PanelOLS.from_formula('TC_ch ~ 1  +  S_G_ch + S_coal_ch + S_ren + EntityEffects'
```

It is a general formula for a panel data regression with fixed effects. It is important to emphasize that this formula does not yet include electricity output, volatility nor geopolitical risk factor. As the research progresses, these independent variables shall be included to analyze how the marginal costs are affected in relation with the total cost of producing electricity and the latter independent variables.

Figure 3: Panel0LS estimations without output, volatility, producer price index and geopolitical risk factor

```
                          PanelOLS Estimation Summary
================================================================================
Dep. Variable:                   TC_ch   R-squared:                        0.8020
Estimator:                    PanelOLS   R-squared (Between):              0.8571
No. Observations:                  272   R-squared (Within):               0.8020
Date:                 Mon, Apr 24 2023   R-squared (Overall):              0.8054
Time:                         20:19:04   Log-likelihood                    495.99
Cov. Estimator:             Unadjusted
                                         F-statistic:                      330.82
Entities:                           24   P-value                           0.0000
Avg Obs:                        11.333   Distribution:                   F(3,245)
Min Obs:                        9.0000
Max Obs:                        12.000   F-statistic (robust):             330.82
                                         P-value                           0.0000
Time periods:                       12   Distribution:                   F(3,245)
Avg Obs:                        22.667
Min Obs:                        17.000
Max Obs:                        24.000
```

Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
Intercept	-0.0007	0.0025	-0.2867	0.7746	-0.0056	0.0042
S_G_ch	0.7305	0.0594	12.304	0.0000	0.6135	0.8474
S_coal_ch	0.0070	0.0028	2.4670	0.0143	0.0014	0.0125
S_ren	-0.1472	0.0058	-25.246	0.0000	-0.1587	-0.1357

The Panel0LS estimations derived are the following. R-squared which measures the proportion of the variance in the dependent variable that is explained by the independent variables is 0.8020 which reassured that the investigation was effective. The parameters derived display how the different inputs affect the total cost of electricity. The intercepts are the parameter estimated for each gas, coal and technology. The share of gas is the biggest contributor in the cost of electricity with 0.7305 meaning that if share of gas increases by 1% cost of electricity changes by 0.7305%. On the other hand, share of coal is 0.0070 which is small compared to gas but still has a significant impact. Lastly, the renewables parameter is -0.1472 having a negative correlation with total cost meaning that an increase in renewables reduces total costs and vice versa. Thereby, renewables are gas saving. Having a negative parameter for renewables is crucial as it reduces the total cost of producing the same output of electricity. Meaning lower traditional inputs such as gas and oil to produce the same level of output.

In the following estimations, we shall be including the rest of the independent variables; electricity output, volatility and geopolitical risk factor to analyze how these impact the total cost and the parameters.

Figure 4: Panel0LS estimations including output and without volatility, producer price index and geopolitical risk factor

```
                          PanelOLS Estimation Summary
================================================================================
Dep. Variable:                  TC_ch   R-squared:                        0.8391
Estimator:                   PanelOLS   R-squared (Between):              0.8803
No. Observations:                 272   R-squared (Within):               0.8391
Date:                Thu, Apr 27 2023   R-squared (Overall):              0.8417
Time:                        10:57:55   Log-likelihood                    524.22
Cov. Estimator:            Unadjusted
                                        F-statistic:                      318.18
Entities:                          24   P-value                           0.0000
Avg Obs:                       11.333   Distribution:                   F(4,244)
Min Obs:                       9.0000
Max Obs:                       12.000   F-statistic (robust):             318.18
                                        P-value                           0.0000
Time periods:                      12   Distribution:                   F(4,244)
Avg Obs:                       22.667
Min Obs:                       17.000
Max Obs:                       24.000

                             Parameter Estimates
==============================================================================
            Parameter  Std. Err.     T-stat    P-value    Lower CI    Upper CI
------------------------------------------------------------------------------
Intercept     -0.0002     0.0023    -0.0825     0.9343     -0.0046      0.0043
S_G_ch         0.8623     0.0564     15.281     0.0000      0.7512      0.9735
S_coal_ch      0.0057     0.0026     2.2278     0.0268      0.0007      0.0107
S_ren         -0.0762     0.0108    -7.0324     0.0000     -0.0975     -0.0549
Y_ch           0.0789     0.0105     7.5025     0.0000      0.0582      0.0996
==============================================================================
```

In the present panel regression, electricity output change, meaning electricity quantities produced by each country during 2010 to 2021, is included. It has a positive value and it means that a 1% increase in the electricity output produced in Europe is associated with an expected increase of 0.0789% in the total cost of producing electricity. It is also noticeable that share of gas has increased its impact on the total cost meaning that a 1 percent increase in the share of gas soars electricity costs by 0.8623%. Share of coal has dropped slightly and technology has a lesser but still cost saving impact. Lastly, it is important to highlight that the R-squared value has increased thus making the regression further accurate.

Figure 5: Panel0LS estimations including output, technology and geopolitical risk factor

PanelOLS Estimation Summary

Dep. Variable:	TC_ch	R-squared:	0.8418
Estimator:	PanelOLS	R-squared (Between):	0.8875
No. Observations:	272	R-squared (Within):	0.8418
Date:	Tue, May 23 2023	R-squared (Overall):	0.8446
Time:	21:02:50	Log-likelihood	526.46
Cov. Estimator:	Clustered		
		F-statistic:	258.52
Entities:	24	P-value	0.0000
Avg Obs:	11.333	Distribution:	F(5,243)
Min Obs:	9.0000		
Max Obs:	12.000	F-statistic (robust):	146.49
		P-value	0.0000
Time periods:	12	Distribution:	F(5,243)
Avg Obs:	22.667		
Min Obs:	17.000		
Max Obs:	24.000		

Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
Intercept	−0.0210	0.0115	−1.8290	0.0686	−0.0437	0.0016
S_G_ch	0.8191	0.0820	9.9914	0.0000	0.6576	0.9805
S_coal_ch	0.0087	0.0051	1.7026	0.0899	−0.0014	0.0187
S_ren	−0.0739	0.0274	−2.6963	0.0075	−0.1278	−0.0199
Y_ch	0.0809	0.0287	2.8190	0.0052	0.0244	0.1374
Geo	0.0513	0.0262	1.9578	0.0514	−0.0003	0.1030

Finally, the last panel regression includes the geopolitical risk factor. It is important to highlight that a regression was also run with volatility but the results retrieved were not significant. In the upper image it can be seen how the parameters have varied slightly. Gas has lowered its impact on the total cost with its parameter totaling to 0.8191. Renewables have not varied with the inclusion of geopolitical risk. The impact of total output has increased mildly. The most interesting feature of the present regression is how impactful the geopolitical risk is to the cost of electricity. Around 5% of the total cost can be attributed to social and political factors. Given the shortage of available data the geopolitical risk of Belgium was applied to all the different countries. For future estimations in which, hopefully, data is more accessible, it would be interesting to analyze how the parameters changes when lesser stable geopolitical risk are used for every country.

7. CONCLUSIONS

Given the magnitude of the results, they can be analyzed from multiple perspectives. The outcome affects all the agents involved in the electricity market in the European market. From final consumers to energy retailers, the cost function impacts regulations, margins, renewable energy policies, etc. The three main conclusions are the following: the current state of the energy market with regard to regulators and policies, the role of gas in the electricity market and, lastly, the vast field of study of cost functions in the electricity market.

Firstly, the current situation of regulators and energy policies. It is one of the current burning issues; the role regulators have in order to build the energy structure of the future. There are many factors they have to take into consideration such as geopolitics, climate change, internal energy market or emerging technologies.

One of the most up to date and controversial issues are the so-called windfall profits. This makes reference to the "profits that do not stem from direct and planned actions of a firm but from unanticipated external changes in the market conditions" [27]. They are unexpected profits that arouse from the present structure of the electricity market. Given the current merit of order and the clearing price, energy retailers that produce electricity from sources with low marginal costs such as renewables and nuclear they are receiving vast amounts of money as they are getting paid the same price of the least efficient electricity producer. During the past two years as gas has skyrocketed the final price of electricity, many companies which produce electricity from alternative sources have benefitted enormously from these unexpected profits. The studied cost function helps regulators understand how dependable is electricity price to gas fluctuations. The first natural reaction of politicians and regulators is to penalize this excess of profits in the form of extraordinary taxes. Spain is a perfect example of these type of excess profit levies. The goal is to balance the higher final price consumers are paying by imposing a higher tax to these enterprises. Nevertheless, the issue is far more complex and should be studied more carefully.

[27] NICOLAY, K; STEINBRENNER, D. (2023). The effectiveness and distributional consequences of excess profit taxes or windfall taxes in light of the Commission's recommendation to Member States. European Parliament. p. 13.

Renewable energy deployment is in need of immense amounts of capital in order to have an efficient green energy transition. That capital can only can form either two sources; public and private. Public funding is vital but also short-legged as an entity such as the European Union can not just squander money without a limit and time frame. That is why private capital is crucial to the energy transition and windfall profits play a huge role. By imposing levies to energy retailers, it is true that money is being retrieved back to the citizens but, on the other side, private companies have less capital to pursuit investments in infrastructure of green energies. Solving this dilemma is essential given the time of uncertainty and the future prospect of the energy transition in the Eurozone.

It is also convenient to analyze the current market structure. With the present order of merit and clearing price, regulators seek to assure security of supply by setting the pool price in the least efficient marginal cost of producing electricity. That way less efficient energy producers do not go bankrupt and the market seizes the precious security of supply. The issue comes with the increasing growth of renewable sources that a have a minimum marginal cost and the predicted non fossil fuel future. How is the market going to readjust fifteen years from now when, hopefully, most of our electricity is going to come from green sources? How is the clearing price going to be set?

Secondly, the impact gas has on the cost function. The European Union is still reliant on coal and oil for electricity production but what is astonishing is the reliability the EU has on gas and how impactful it is on the final electricity price. In the present study, gas dependance has been portrayed numerous times but after combining the model with different independent variables it is observable how gas impacts the final price. It can be seen that the biggest explain ability of the electricity price with gas is in Figure 4 when the inputs are combined with the independent variable of electricity output. It means that when taking into account in the regression the total electricity quantities if the share of gas increases one percent it impacts electricity costs by 0.8623%. If we compare it with Figure 3 where the share of gas is 0.7305 the big difference is the inclusion of electricity output. About 7% of electricity costs can be accounted to electricity output, if we produce more is natural that the costs are higher. The reason why share of gas rises with the inclusion of electricity output is that gas is the latest in the order of merit. So, in case more electricity is needed, all renewable sources have already been consumed and the only available source of energy is gas. Scarcer resources drive gas prices up thus affecting the final clearing price. Figure 5 is also of much interest. With the addition of geopolitical risk factor the parameters shift completely. Geopolitical risk contributes to around 5% of the total cost of electricity. The final output of electricity contributes to around 8% thus rising from the previous estimations. Finally, the share of gas lowers to 0.8191. It is interesting to notice how impactful geopolitical conditions can drive the price of electricity where tensions drive the price up. It is also amusing how the total electricity production also rises with the inclusion of geopolitical risk. It is natural that in an environment of political, social and economical stress producing more electricity generates more costs.

The relation between gas and electricity prices has been study deeply. A recent study of the University of Barcelona showed that the main factor in the transmission of gas shocks to electricity prices is market integration[28].

Lastly, it is of much fascination trying to comprehend how many different variables have an effect on the price of electricity. Even though during the whole process of the study there was a growing suspicion that gas was going to have a big impact on the final cost, the results proved that there are other variables that also have a significant impact on the final cost. Renewables as an example, they have negative impact on the total cost, meaning that an increase in renewables output drives the total cost down. The time estimations are calculated up to 2021 which was the latest year for all the available data. 2022 was the year where the green transition truly commenced when the EU realized how vulnerable they were to Russian gas. It is intriguing to think how impactful will renewables be to total cost if we flash forward ten years. Given that the technology parameter is negative it means that it reduces the amount of fossil fuels needed to produce the same output of electricity.

Also, if the clearing price and order of merit system will be changed with the takeover of renewable energies and a more secondary role of fossil fuels.

This study lays the foundations to future investigations around the cost function for the electricity market. The field of study is vast as many other independent variables could be included to gain better understanding of the topic. For instance, including weather

[28] URIBE, J; MOSQUERA-LÓPEZ, S; ARENAS, O. (2017). Assessing the relationship between electricity and natural gas prices in European markets in times of distress. Research Institute of applied economics. Universidad de Barcelona.

patterns such as average temperature or annual precipitations could be of much interest to capture the impact of climate change and renewables sources efficiencies. Other possible variables could include the sophistication of our technology variables that includes the output of renewable energies. In the future, as data more data will be available the technology factor could be separated into different independent variables. For example, infrastructure costs, energy storage or the impact of hydrogen. Another interesting factor could be to include the emissions allowances or carbon pricing schemes to account for the penalization of the use of fossil fuels.

In conclusion, this topic is of much importance given current uncertainty and the future prospects. Cost functions have proved to be a magnificent way to gain better understanding on how different factors affect the electricity price. It is crucial to maintain an ongoing investigation to prevent possible future crisis and to monitor the impact of renewable energies on the pricing of electricity. The European Union is taking on a huge gamble with its Green Deal and it is decisive to study how well the policies are being implemented.

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