Norwegian School of Economics
Bergen, Spring, 2023

The European electricity market over the last 10 years

Which major changes occurred in the electricity markets, in particular in the electricity production of the European Union, in the past 10 years and what are the implications for the future?

Rauecker Robin, Bsc
Reinisch Leopold, Bsc

Supervisor:

Professor Linda Orvedal

Master thesis in Energy, Natural Ressource, and the Environment

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

Electricity forms the backbone of modern society and is vital for powering industries, fostering innovations and guaranteeing the functioning of essential services and technologies.

Throughout the last few decades, the usage of electricity has risen exponentially and is forecasted to grow for the foreseeable future. This underscores the need for functioning electricity markets all around the globe. In the European context, electricity markets have been moving towards integration and the ultimate goal is to create a common European electricity market.

This thesis aims to investigate the major changes undergone by European electricity markets over the last 10 years and showcase some of the recent events that have had a major impact on the European electricity markets. Consequently, implications for the future of European electricity markets will be discussed.

Both a literature review aimed at evaluating shifts in the overall market design and mechanisms as well an analysis showing the changes in price and electricity production over the last 10 years were performed.

Our findings suggest that during the analysed timeframe major changes occurred in the type of electricity produced. The introduction of new market mechanisms such as flow-based market coupling and a trend towards decentralization and utilizing IT technologies to leverage data such as the smart grid have changed the face of the European electricity markets. Major increases in electricity prices, further enforced by the current Russian invasion of Ukraine have moved the focus of market actors towards security of supply and affordability. It is likely that these developments will substantially impact the current market design and the way the EU transitions to a carbon-neutral market.

Avenues for further research might include:

- Research that goes further back in time
- Evaluating the ideal market design for the European electricity market
- Performing in-depth regression analysis of price coupling between electricity prices and other variables such as gas prices, ETS prices, …

Keywords: European electricity markets, energy markets, market design, market integration, Russian invasion, electricity price developments

Table of Contents

List of Figures

1. Introduction

Europe is currently facing a grave energy crisis that is undermining the livelihoods of people and businesses alike. Strangled by skyrocketing prices and supply issues not witnessed in decades, the European energy markets are undergoing profound changes to adapt to a situation that was unthinkable even a couple of years ago.

Like any other good, electricity prices are dependent on the costs associated with producing it. To meet the demand and supply of energy, electricity markets have been established where generators sell electricity to suppliers for a particular period of time. To always guarantee electricity, supply has to meet demand at any moment (Shaw, 2022).

Over the last 10 years, Europe´s energy market[1]has undergone profound changes both in terms of its market structure with the expansion of the European Trading Scheme (ETS) for greenhouses gases and an increased focus on sustainability and security with the introduction of a "European Green Deal" which aims to reduce emission by 55% in 2030 and make Europe the first climate-neutral continent by 2050(European Commission, 2020).

In terms of supply and production, this trend has been influenced by geopolitical factors such as the Russian invasion of Crimea in 2014 (European Parliament, 2022) which led to calls for a more active European energy policy. Moreover, since 2020 gas and electricity prices in the European Union have been soaring due to growing demand ("energy shock") after the global Covid-19 pandemic which forced many economic sectors to close down. Moreover, Russia´s invasion of Ukraine followed by its decision to cut natural gas supplies has further exacerbated the situation (Petcu, 2022).

All these factors influenced electricity prices continent-wide because every electricity generation type is available to meet demand via a merit order which ranks generative sources from cheapest to most expensive. Due to constraints of other energy sources such as renewables and nuclear (in terms of availability, seasonality, or capacity), which usually operate at a lower cost, gas power plants are being utilized due to them meeting the marginal

[1] While there is currently not one, common European electricity market, we use this denomination as the sum of the individual European electricity markets

cost of the last generating unit (Shaw, 2022) even though the costs of running them have increased massively. Depending on the exact energy mix and the availability of energy generators in one energy market, the impact of gas prices can vary on the electricity market of a specific region or country.

While inflationary trends have been observed worldwide, Europe´s dependency on foreign providers(the degree to which an economy relies upon imports in order to meet its energy needs) in 2020 amounted to 58 % and thus particularly exposed the content to rising international prices (Eurostat, 2022a).
All these factors have led to physical and institutional stress not seen since the 1970s oil shocks and are contributing to major changes in the way the EU deals with its energy policy.
On the one side, only a few common European policies such as the aim of reducing gas use by 15 % or an obligation of a 5 % reduction in electricity demand during peak hours have been implemented by February 2023 (European Commission, 2022a).
On the other side, the EU is rapidly reframing its energy policy, broadening its focus from just climate goals such as climate neutrality by 2050 to also consider geopolitics, global industrial competitiveness, and energy poverty (Maaskant & Bogaert, 2023)

List of Abbreviations

Abbreviation	Definition
BA	Balancing market
BRP	Balancing Responsible Party
BSP	Balancing service providers
DA	Day-ahead (spot market)
DSM	Demand-side management
DSO	Distribution system operator
EC	European Commission
EEA	European Economic Area
ENTSO-E	European Network of Transmission System Operators for Electricity
FBMC	Flow-based market coupling
ETS	European Trading Scheme
GHG	Greenhouse gases
IB	Imbalance settlement
ID	Intra Day (Market)
LMP	Locational marginal pricing mechanism
MCO	Market Coupling Operator
MWh	Megawatt per hour
NTC	Net Transfer capacity

OFC	Off-The-Counter Market
PCR	Price Coupling of Regions
PEMS	Prosumers based Energy Management and Sharing
PV	Photovoltaic
RCC	Regional coordination centre
RES	Renewable Energy Sources
TSO	Transmission System Operator
TTF	Title Transfer Facility (Dutch gas hub)

2. Research question

The research question will be twofold and consist of the following elements:

1. Which major changes occurred in the electricity markets, in particular in the electricity production of the European Union, in the past 10 years?

2. Which implications for the future do these changes have on the electricity market, particularly the market supply curve?

This paper aims to evaluate both the major factors affecting European electricity markets over the last 10 years as well as give a future-driven outlook. The analysis will consist of past and current crises, trends, and proposed European solutions. In specific, we will focus on the EU and, by extension, on the European Economic Area (EEA) since its member countries Norway, Iceland, and Liechtenstein play a role as well due to their participation in common European policy by means of e.g., the ETS for CO2 allowances.
While we are primarily dealing with the electricity market as such, we will also include the overall energy market since it indirectly influences the electricity market via gas prices for instance. We will both analyse the European energy mix in terms of costs and volumes but also incorporate proposed policy measures and assess the role that the EU is playing in it.

At the beginning of the thesis, some theoretical input will be given so as to how electricity markets work, how they evolved, how electricity is produced and stored, and how the European markets are set up. Following that, concrete market data will be used to showcase the history of the European electricity markets with a special focus on the impact that Covid-19 and the Russian war in Ukraine are having on different European countries and market segments. The following parts are dealing with current shifts in European energy policies where we will incorporate geopolitics and how Europe can get less dependent on Russian gas in the future.

3. An Overview and Background on European electricity markets

This chapter serves to provide an overview of how European electricity and gas markets are structured and how they work in practice.

In the European Union, a wide-ranging sequence of electricity markets starts years before the actual delivery and continues up to real-time. Due to regulatory processes driven by the European Union, most countries now possess a very similar sequence of electricity markets. Some operate on an interstate level, while others remain national or regional.

The reason for the existence of different layers of electricity markets can be explained by the physical characteristics of electricity:

- Time: As of now it is not possible to store large volumes of electricity. Therefore, electricity prices vary over time
- Location: Electricity flows are difficult to control, and transmission components must be kept under safe flow limits (otherwise, there is a risk of failures and/or blackouts)
- Flexibility: Demand and energy generation must always match each other. However, demand and availability of for instance renewable energy resources like wind can vary sharply over time while other generators can take many hours to start up. This means that the ability to change the generation/consumption of electricity at short notice has a value (Florence School of Regulation, 2020)

When it comes to electricity network levels, there are two dimensions: transmission system operators (TSO) and distribution system operators (DSO). The former connects electricity networks across borders and larger distances and runs at a higher rate of Volt while the latter connects smaller electricity generators and consumers to the electricity system itself (IRENA, 2020).

Figure 4 illustrates the sequence of current electricity markets by type of product and delivery time.

First, there are wholesale markets for the pricing of electrical energy commodities. These include forward markets (which last for months or years), as well as day-ahead and intraday markets, which have the highest volumes of electricity.

Second, there are markets that set prices for transmission capacity. These markets are only short-term integrated with the commodity markets.

Thirdly, there are separate markets for reserves or balancing services, ranging from year-ahead balancing capacity markets to near real-time balancing energy markets.

Finally, there are markets to correct the results of the wholesale and balancing markets. Corrections are necessary because wholesale and balancing markets do not yet fully take into account transmission and distribution constraints. While some of the markets like the day-ahead market (DA) are integrated into a European level, others like the balancing markets are still national or regional, and transmission rights cross-border are allocated in specific auctions (Meeus, 2020).

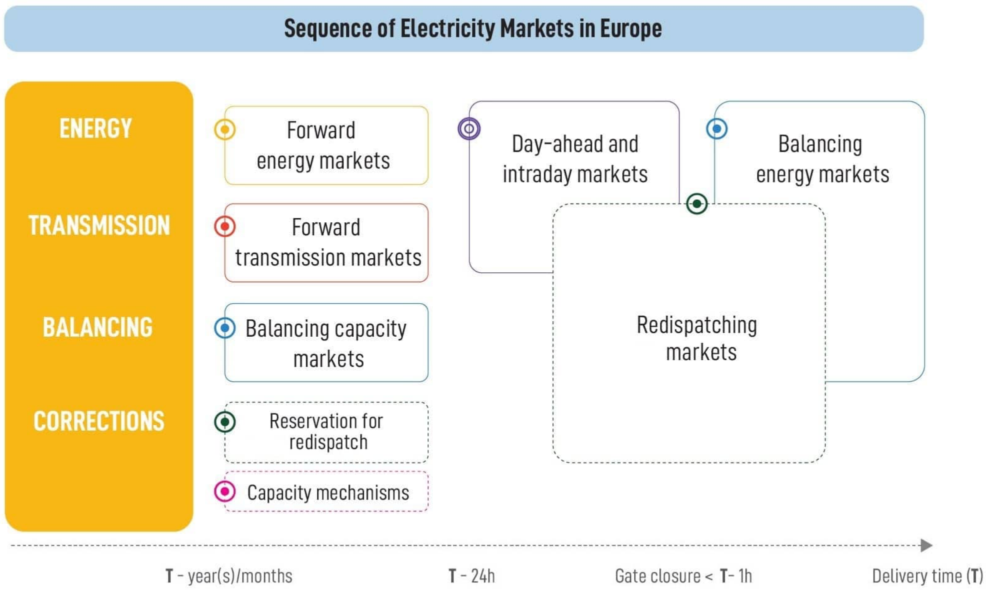

Figure 1: The Evolution of Electricity Markets in Europe (Meeus, 2020)

Concretely, there exist two distinct markets for gas and electricity.
The aim of the EU has been to create a homogenous market for both sectors, a goal that has not yet been achieved.
On the side of electricity markets, the individual European states have both different sizes as well as resources. France is dominated by nuclear; Germany has historically had a significant share of coal; the UK, Spain, and Italy have relatively more gas in their energy mix and Norway has considerable hydro capacity (Pollitt, 2019).

Since transmission constraints do not apply within countries, trade borders are defined within national borders where the prices are the same and trade is unlimited. In order to take trade constraints across borders into account, TSOs created regional coordination centers (RCCs) which are to allocate flows over different borders to maximize welfare from cross-border trade (Meeus, 2020).
In the following, a brief overview of the market design of a submarket will be described as well as its main functions.

Day-ahead spot market

The DA spot market is used to trade hourly wholesale electricity products for the following day. A single DA spot price, calculated in €/MWh, is set by short-run marginal costs if the market is able to clear. If the market cannot clear because there is insufficient generation capacity to meet demand, the spot price is referred to as the scarcity price. The scarcity price approximates the marginal cost of providing an additional unit of electricity and represents the average willingness of consumers to pay to avoid involuntary curtailment of electricity consumption. Winning bidders commit to ex-ante operational scheduling of electricity generation or consumption on a time basis varying from one hour (e.g. Spain) to fifteen minutes (e.g. Belgium, Germany). They also have to be assigned to a balancing responsible party (BRP), which is financially responsible for the real-time net imbalance of the DA operations it manages. The gate closure for DA trading is usually 12:00 noon one day ahead.

Intraday market

The Intraday (ID) market allows parties to obtain a better-balanced position based on updated information about the closing of the DA market. It offers flexibility to reduce the need for more expensive resources with high flexibility for real-time balancing. ID trading can be based on either discrete auctions (e.g. Italy or Portugal) or continuous trading (e.g. Nordic countries), where bids and offers are matched on a first-come, first-served basis, resulting in a "pay as bid" price settlement. In contrast, discrete auctions aggregate all bids and offers within each trading period into a single auction. Price determination follows uniform marginal pricing, similar to the DA. Both types of auctions typically trade electricity products on an hourly basis and the gate closure times are currently 5-60 minutes (continuous trading) or 135-160 minutes before delivery (discrete auctions).

Balancing market

Due to the remaining uncertainties between ID and real-time delivery and sub-hourly variations, a balancing market (BA) is established by the TSO for the reservation and activation of balancing capacity from balancing service providers (BSPs). BSPs must commit to a certain level of generation in the DA to ramp up or ramp down when called upon to provide energy. The TSO determines the amount of balancing capacity needed based on predefined requirements. The auction itself consists of a capacity price bid (€/MW-h of capacity product) and an energy price bid (€/MW-h of energy product) based on pay-as-bid or uniform pricing (based on marginal or average costs). When the system is short, the activated reserves receive the energy price of the bid, while when the system is long, the activated downward reserves pay the energy price due to saved operating costs. The time resolution ranges from annual to hourly for capacity products and from hourly to quarter-hourly for energy products. As for the gate closure time, it ranges from year-ahead to day-ahead before delivery for capacity products and from hour-ahead to quarter-hour before delivery for energy products.

Imbalance market

Imbalance Settlement (IS) is used to allocate ex-post the costs associated with the reservation and activation of balancing capacity in the BA to imbalanced BRPs that deviate from their DA commitment. The settlement price mainly consists of the energy price for the activation of balancing capacity in the BA. As a result, the products traded in the IB settlement are the imbalance energy between a BRP's real-time delivery and its DA commitment. The time resolution is the same as the DA. Some countries also include penalty components (e.g. Germany) to strengthen the incentives for BRPs to reduce imbalances. The IB settlement can be either a one-price or a two-price system, the difference being that in a one-price system, the same imbalance prices apply to BRPs that counteract and exacerbate system imbalance. In the two-price model, there are two corresponding price signals (system imbalance price and DA price). Nevertheless, in both systems short BRPs pay while long BRPs are paid.

Locational marginal pricing mechanism

The locational marginal pricing mechanism (LMP) is utilized to represent grid constraints at different locations on the electricity networks to properly use the transmission capacity at disposal. Electricity prices at two different locations are the same if there is sufficient transmission capacity (for instance if the markets are coupled) while prices differ if grid

congestion occurs between the locations (if markets are split).
Zonal pricing as in the EU takes into account the capacity of the interconnector between two different price zones, without any constraints within each zone (Hu et al., 2018).

As for the gas markets, Europe is currently divided into 12 different gas hubs all across Europe with varying high degrees of integration which means that each hub price cannot be seen as a reliable benchmark for the whole European gas market due to different amounts of market volume and price differentials.
A hub for natural gas can be defined as a trading platform for physical and/or financial transactions of gas with integrated services that allow producers, suppliers, and buyers to trade short, both medium and long-term(Jotanovic & D'Ecclesia, 2021)
These services include futures which are agreements to buy or sell gas at a certain future time for a pre-agreed price, forwards which are customized and sold on a different market, options which give the holder a right to buy or sell the underlying futures contract at a certain date for certain prices and swaps which allow two parties to exchange payments related to market gas price (Chestney, 2022).
While the first gas hub was created by the British in 1996 (NBP; National Balancing Point), due to political reasons such as Brexit and a steady increase in volumes, the Dutch Title Transfer Facility(TTF), founded in 2003, is now Europe´s most relevant gas hub, while the NBP is still seen as the most mature institution in terms of market operations.
As a result, the Dutch TTF gas hub is often identified as the European price leader (Jotanovic & D'Ecclesia, 2021). This role has been underscored by the increased trading occurring in European gas hubs that in 2022 amounted to 62% despite gas derivatives also being traded on other exchanges and Off-The-Counter (OTC) markets where trading can take place bilaterally for instance (Chestney, 2022). Furthermore, when the European Commission (EC) proposed a natural gas price cap of €275 for the month-ahead derivates market in late 2022, the measure applied to the TTF only due to its leading role as a price benchmark. While it has since then expanded to cover all natural gas hubs in Europe to prevent distortions to the overall energy markets, it reflects the position of TTF being the de facto price setter of European gas markets (Reuters, 2023).

3.1 Historical development

In the following chapter, a short historic overview of the evolution of the European electricity market is provided with a focus on market players, institutions, and the creation of a common framework for the successful market integration.

Historically speaking energy policy has been a core issue for European institutions ever since its inception in 1951 when six countries decided to join forces in two key areas of the economy, coal and steel. The European Coal and Steal Community was formed (ECSC) and cross-jurisdictional control on energy resources was imposed in order to pave the way for greater economic collaboration. It was clear at the time that nuclear energy would eventually become the driver of economic growth and, as a result, the European Atomic Energy Community Treaty (Euratom) was introduced in 1957, aiming to control radioactive materials and promote the peaceful development of nuclear energy. Similarly, the Treaty of Rome (1957) sought to reduce trader barriers.

Different visions on the use of nuclear energy led to a focus on national policies in the 19060s before a push for common energy policy was undertaken in the early 1970s as a consequence of the 1973 oil crisis (Kanellakis et al., 2013).

Until that moment, the supply of electricity was deemed as a strategic tool of economic interest and consequently not subject to the usual rules of competition as established by EU treaties. The electricity industry was organized as a vertically integrated monopoly that often was under state control.

With the ongoing process of creating a common internal market of the EU (via the Single European Act of 1987) with a free flow of persons, goods, services, and capital, electricity was initially believed to be a service and treated as such. However, the European Court of Justice ruled on several occasions that electricity must be considered a good, thus ending the consideration of electricity as a service (Meeus et al., 2005). In 1988 the EC published its first document on the internal energy market, which evaluated that significant barriers to trade in energy products persisted. When the common European Single Market became a reality in 1993, the energy sector was still nowhere near ready to operate functionally on a European

level (Meeus, 2020). In the following years, European Directives from the EC strived to liberalize European energy markets which followed a common trend since the 1980s to liberalize industrial sectors worldwide and states withdrawing from running national infrastructure single-handedly. These changes affected both the electricity and gas markets.
The liberalization aimed to create a more competitive and efficient market by separating generation, transmission, and distribution activities and allowing new entrants to participate.

The first steps included introducing a separation between the regulated part of the sector (networks) and the competitive parts (generation and supply), making third-party access the standard for all existing infrastructure, unbundling TSOs from energy generation, legally separating the two, and integrating energy and environmental objectives through the use of market-based measures such as the European Emissions Trading System (ETS)(Dorsman et al., 2011)

In addition, TSOs should create the European Network of Transmission System Operators for Electricity (ENTSO-E) and cooperate in this new institution at the European level. Similarly, an entity of distribution system operators (EU DSO entity) was established to increase efficiency and cooperation in electricity distribution networks.

National Regulatory Authorities (NRAs) have also been made more independent of industry and government.

The Florence Electricity Forum was set up in 1998 and has been meeting once or twice a year since then. The same applies to the Madrid Forum for Gas, which was set up in 1999. The aim of these fora was to improve the dialogue between the EC, national actors such as governments, and market players.

The next step was the creation of the Council of European Energy Regulators (CEER) in 2000. The CEER brought together the national regulators. Although informal in nature, it was established as a more formal setting for regulators' interaction. Regular meetings were to facilitate the exchange of information.
In 2003, the process was institutionalized with the creation of the European Regulators Group for Electricity and Gas (ERGEG), which advises the EC about implementation measures. This was followed by another formalization move in the internal energy market: the creation of ACER (Agency for the Cooperation of Energy Regulators). Its tasks include coordinating and complementing the activities of national regulators, contributing to the establishment of the

European network and market rules, and monitoring the functioning of electricity and gas markets as well as the work of ENTSO-Es (Jegen, 2014).

In an intermediary step, the EU introduced regional bidding zones as areas within which market participants can exchange energy without capacity congestion. Bidding zones were mostly defined by national borders, but some zones comprise areas larger than national states (e.g. Germany and Luxembourg) and some are smaller zones within individual countries (e.g. Italy, Norway, or Sweden). There currently are 31 regional bidding zones in the EEA area (Ofgem, 2014).
In combination with national bidding zones, the EU thought that the final aim of a single electricity market could be achieved by fostering inter-national via regional markets, which were introduced in 2004. European electricity and gas markets were separated into seven and four different regional initiatives respectively. As a result, the markets have been moving towards regional segmentation via adapting the common electricity grid or launching joint pilot projects. It was thought that this bottom-up regional approach would enable the involvement of the relevant stakeholders more than would be possible if implemented on the European level directly. Additionally, the regional approach was meant to consider regional specificities where divergences from the European standards would be needed on an exceptional basis. At the same time, the regional approach enabled a step-by-step development towards an integrated European energy market (Dorsman et al., 2011).
Overall, the regional bidding zone and the European gas and electricity initiatives were introduced to work together to facilitate the integration of national energy markets into a single, more efficient, and more sustainable European energy market.

What is noteworthy in these early legislative actions is the focus on setting the conditions and creating the institutions necessary for electricity markets to function but not the actual market design or rules (Meeus, 2020).

Only in more recent years, between 2015 and 2017, were more precise market rules stipulated via EU network codes (more detailed than guidelines) and guidelines that were entrusted to TSOs who possessed the necessary level of detail and technical complexity. This allocation of powers was however challenged by European institutions as it resulted in insufficient stakeholder engagement and effective solutions and was changed in the 2019 Clean Energy Package which reduced the strong role of TSOs and forced distribution system operators (DSOs) to be included as well.

Instead of prescribing standard market designs these rules simply reduce the degree of freedom that countries have in designing their markets and thus provide an implicit structure (Meeus, 2020).

3.2 Electricity: origin, production, technologies

In the following part, the origin of electricity will be explained as well as the most common ways of producing it and the technologies which are being implemented.

Electricity is a secondary energy source derived from other sources of energy such as coal, natural gas, oil, nuclear power, etc (hence also the close correlation between electricity and overall energy markets). These resources are known as primary resources and can be classified as renewable or non-renewable, but electricity in itself is neither. Electrical energy can be converted and used into other forms of energy such as mechanical energy, heat, light, etc.

At the very basic level, electricity is created by a combination of atoms and electrons. The nucleus in the center of the atom is made up of particles called protons and neutrons while electrons flow around the nucleus in shells. Protons and electrons are attracted to each other, and each carries an electrical charge, with protons possessing a positive one and electrons a negative one while neutrons do not have an electrical charge. An atom is balanced when it possesses an equal number of protons and electrons while the number of neutrons can vary. Electricity is generated when electrons in the atom´s outermost shell are pushed out of the orbit and shift from one atom to another (Just Energy, 2023). This change is caused by an external force (electric field) that makes the atom gain or lose electrons. When electrons are lost from an atom, the free electrons move toward the electrical field. Due to this free movement of these electrons, electric current flows through the conductor on the opposite side of the flow of the electron.

The unity of charge is measured in Coulomb, which is a measure for the package of electrons and protons (Just Energy, 2023). As a measure of work or energy of electricity Joule is used. To facilitate real-world use, a watt-hour was established. One watt-hour is equivalent to 3,600 joules or the total energy in one watt which is being supplied for one hour. Electricity is almost exclusively traded in Wh on the market (Etheredge, 2023).

While it occurs naturally in the world in the form of static electricity(lightning), it can also be manufactured, created by a generator in an electrical power plant, and transmitted through the transmission network to the final consumer.

There are two types of electricity: static and current.

Static electricity is created when electrical charges of opposite signs build up on an object separated by an insulator. Static electricity exists until the two groups find a path between each other to balance the system out. A classic example of static electricity includes lightning: when a cloud system gathers enough charge relative to other clouds or the ground, the charges will try to balance it out. As the cloud discharges, massive quantities of charges run through the air in what we witness as a lightning bolt.

The second form of electricity is called current electricity and exists when charges are able to constantly flow. While static electricity also has real-world uses such as in printers or photocopiers, it has mostly been current electricity that has allowed our modern world to successfully leverage the use of electricity. Current electricity is dynamic, and charges are always on the move within a circuit. A circuit consists of a closed, never-ending loop of conductive material. There are different sources of current electricity including the chemical reactions that take place within a battery, but most of them include some kind of electricity generator (Electricity Forum, 2023).

In terms of technologies used to produce energy, they can be classified according to their primary resources(“renewable/non-renewable”). Renewable energy sources include solar, hydro, geothermal, tidal, wind, and biomass energy while non-renewable energy sources compromise petroleum, coal, and natural gas. While there is considerable debate about whether nuclear is to be considered renewable, for the purpose of this introduction we will classify it as not renewable due to some elements as uranium (which is needed for nuclear energy production) being finite and not reusable (Elavarasan, 2019).
In the following, a short overview of the functioning of the different main technologies produced in Europe will be provided, as well as an estimate of energy efficiency (see figure 2 which gives an overview of primary energy production in Europe in 2020). While the purpose of this thesis is to investigate the European electricity markets as such, a fundamental understanding of the dynamics at work serves to better understand some of the dynamics at work.

Energy efficiency represents a ratio of output to energy input. For instance, an efficiency rate of 85 % means that 85 % of the energy value of the fuel/steam has been converted into useful energy production(and the sum of various losses amounts to 15 %) (United Nations Industrial Development Organization, 2009).

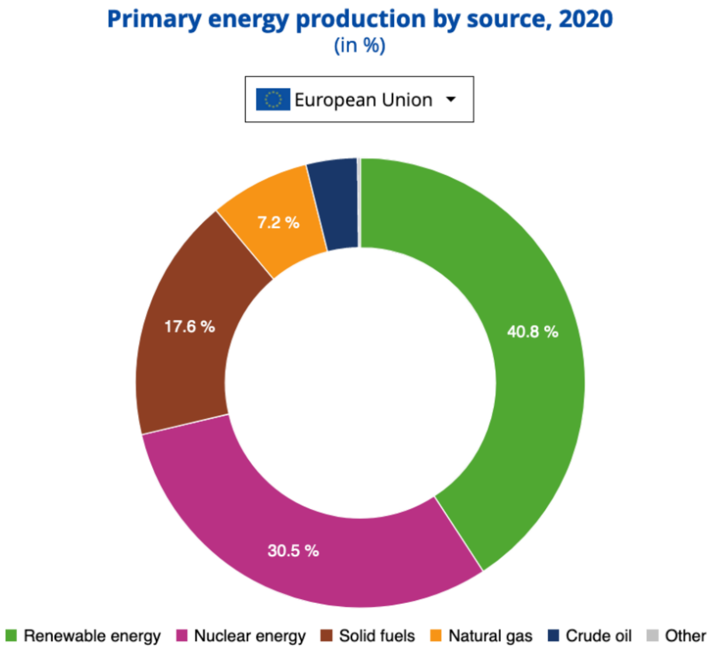

Figure 2: Primary energy production in EU by source, 2020 (Eurostat, 2022b)

Coal

Coal-generated electricity is created using "pulverized coal" (PC) technology where powdered coal is blown into a combustion chamber and burned at a high temperature in order to convert water into steam which then passes a turbine containing thousands of propellers. At the end of these propellers, a generator sits and creates electricity (Just Energy, 2023).

The average efficiency rate of "subcritical" technologies is around 35% while supercritical plants which operate with higher pressures and temperatures can achieve up to 40 % due to the high pressure forcing the water to remain liquid instead of turning into vapour.
A third distinct, the "integrated gasification combined cycle"(IGCC) relies on turning coal into a synthetic gas before combustion (RITE Systems Analysis Group, 2023; United Nations Economic Commission For Europe, 2021).

Petroleum

Oil-fired power can be generated in three different power plant systems: conventional steam, the combustion engine, or the use of a diesel engine.
Oil-fired power plants based on a conventional steam system work very similarly to coal-fired power plants using boiler technology. Oil hereby replaces coal as a fuel.
Oil-fired power plants use a combustion turbine: Oil is sprayed into a combustion chamber where it is ignited by a spark and heats up the water to create steam which powers a steam turbine that creates electricity.
Diesel engine-based power plants: In diesel engine-based power plants an air-fuel mix is introduced into a cylinder and set on fire. This causes a controlled explosion within, and the high-pressure impulse forces the gas in the cylinder to expand, which moves a piston. The engine is directly connected to a generator that converts the mechanical energy into electricity. The efficiency of these technologies ranges between 30 and 48 % (Schinke et al., 2017).

Natural Gas

The main technology of power plants used today is the gas-cycle turbine (GCT), in which heat is recovered from a gas turbine to run a steam turbine. Most gas-fired plants use natural gas while other gas like hydrogen, distillate fuel oil, and gasification gas can also be used. The gas turbine consists of a compressor, a combustion chamber, and a turbine stage that functions as a thermodynamic heat engine. The compressor draws in and compresses air which is mixed in the combustion chamber with gas and burned. This process heats the air up to 1,600°C. The hot gas then enters the turbine stage and spins the turbine. The exhaust gas which is still at a relatively high temperature of 400 to 500°C can be reused like in a combined-cycle gas turbine(CCGT) where it is used to create additional steam or simply discharged into the atmosphere (open cycle gas turbines (OCGT)).
Efficiency can range from 20% to 60% depending on the typology of the turbine with CCGTS outperforming OCGT (United Nations Economic Commission For Europe, 2021)

Nuclear

A nuclear reactor produces energy by splitting atoms of certain elements (most prominently, uranium). This energy is then released to make steam generate electricity either via gas or water very similar to a conventional steam-based thermal power plant (World Nuclear Association, 2023).

There are multiple generations and applications of nuclear reactors, which can be classified according to their energy level, the coolant applied(water, gas, or metal), or their moderator type(water, heavy water, graphite).

The following three types are the main ones currently in use:
Light water reactors, either boiling water reactors (BWRs) or pressurized water reactors (PWRs).
The main differentiators are that PWRs keep water under pressure to prevent it from boiling as well as implementing two separated water circles, wherein the heat from the primary water-cooling system is transferred via a heat exchanger to heat the water in the secondary cycle.
Compared to fossil-fuel power plants, the temperature of the steam is lower, thus reducing the efficiency of these plants to about 30-34%.
Pressurized Heavy Water Reactors (PHWR) use unenriched uranium to drive the reactor as well as heavy water as a coolant. These reactors have higher capital costs, due to heavy water being applied just once, but lower operational costs and an efficiency rate of about 30%.
Gas-cooled reactors (GCRs) use gas as a coolant and graphite as a moderator while uranium is used as fuel. Within this type, temperatures can be significantly higher than in water-cooled reactors, hence they possess an increased efficiency range of 33-36%(Schinke et al., 2017)

Solar

Two main groups of technologies are implemented to generate electricity based on solar radiation: photovoltaic (PV) cells directly convert solar radiation to energy aided by auxiliary components such as racking and mounting structure, cabling, power, and monitoring controls. Based on the material employed PV can currently reach an efficiency rate of up to 30%, with a projected rate of 50% that will be reached by 2035.

Concentrating solar power plants (CSP) capture radiation to generate heat which is then turned into electricity through a steam turbine. Because high temperatures are needed to operate efficiently, solar radiation must be concentrated, and they need a high solar exposition which in turn reduces efficiency to about 10-25%. By implementing thermal storage these plants can also provide power after the sun goes down and add flexibility to the grid (Logan et al., 2017; Schinke et al., 2017).

Hydro

Hydropower covers a wide array of technologies harnessing the potential energy of the natural water cycle and is the largest provider of renewable electricity both in Europe and globally (United Nations Economic Commission For Europe, 2021).

While hydropower cannot be divided into clear boundaries of production types since some applications overlap, they can be separated into three broad categories: Run-of-River Hydroelectric power plants (HPPs), reservoir or storage HPPs and pumped storage HPPs.

Run-of-River HPPs leverage the river's natural flow, which is used to drive a turbine that creates current. Since they are usually without storage possibility, they are subject to variations and might be unable to properly reach their capacity limits.

Storage or reservoir HPPS tackle this issue by creating artificial lakes used to efficiently store electricity making them less prone to variability. On the negative side, they usually require the construction of a dam with high capital costs and a significant environmental/topological impact.

Lastly, pumped storage HPPs (PSPs) work as energy storage devices wherein water is pumped from a lower reservoir into an upper reservoir during off-peak hours and then released during peak hours when demand usually exceeds production. While the pumping often means that this type is a net-electricity consumer it provides stability and flexibility to the grid. Overall, the efficiency of hydropower plants is highest overall at around 70 to 85%.(Logan et al., 2017; Schinke et al., 2017).

Wind

Wind turbines utilize the kinetic energy of wind to turn a rotor and then transform it into energy.

A typical wind turbine consists of the following components: the blades, the nacelle, which is a protective housing unit; the rotor hub, which transfers the rotational energy into mechanical movement; the gearbox, which converts the low-speed rotation of the rotor to high-speed rotation for input to the generator; the generator, which converts the mechanical energy from the rotor to electrical energy; the controller, which monitors the turbine and collects information so that the turbine constantly faces the wind; the tower, which can be made out of steel or concrete; and the transformers, which transform the electricity from the generator to meet the requirements of the grid.

The amount of electricity is proportional to the wind speed which also influences the capacity

factor. On average, modern wind power plants reach efficiency rates between 42 and 45 % with peaks of 56% and lows of 34%.
Additionally, energy storage is often difficult making wind energy plants a relatively fluctuating energy source (Logan et al., 2017; Schinke et al., 2017).

3.3 Drivers, Benefits & Barriers of European market integration

In the following chapter, the main drivers of the common European electricity market will be analysed to give the reader a proper understanding of which forces are affecting the creation of a continent-wide electricity market and how they are impacting it.

These drivers have brought about a range of benefits which will also be discussed as well as current barriers that still inhibit a flawless market with free competition and access in Europe.

3.3.1 Drivers of market integration

On an institutional level, it must be acknowledged that the reform process of market integration is mostly dependent on the driving force of the EC.
Without the efforts of the EC as a policymaker, the pace of reform in many member states would have been considerably slower. The main advantage of the EC over individual Member States is that it takes a broader view of the process and is free from national interests(Dorsman et al., 2011).
One of the primary drivers of the common European electricity market has been the liberalization of energy markets since the 1990s which has aimed to promote competition, reduce energy costs, achieve higher standards of service, and increase overall welfare for participants. A common European electricity and gas market was the goal in order to facilitate this liberalization process and allow for the free movement of electricity across borders(Böckers et al., 2013).
The aim is to create a market with free choice and accessibility where actors can freely switch between multiple providers, new providers enter and overall prices are lowered (Jegen, 2014). This goes hand in hand with economic theory that suggests that electricity trade is welfare enhancing compared to autarkic supply since it is more efficient in resource allocation. Additionally, electricity is a homogenous good that, if traded freely and unconstrained, should follow the law of one price wherein the spot prices between two or more markets become equalized (Gugler et al., 2018).

The aim of the EC is to achieve this by creating a more integrated market, reducing barriers to entry, and allowing more companies to freely enter the market and compete (European Commission, 2015).

The integration of renewable energy sources into the power grid has been another incentivize for the common market, especially when considering the increased need for flexibility that comes with it due to the system always having to ensure load-generation balance.

Considering the variation in output generated by renewable energy sources (daily, monthly, seasonally) the need for greater flexibility in supply can be enhanced by allowing renewable energy to be transported from where it is produced at the lowest cost to where it is needed most. When transmission and interconnection capacity are sufficient, a pan-European electric super grid can aggregate the renewable energy production of the whole continent (Verzijlbergh et al., 2017).

Similarly, the goal of climate neutrality has driven the integration process. If the EU is to reach its goal of complete climate neutrality by 2050 the decarbonization of the energy sector is of pivotal importance and will not be possible to achieve unless energy efficiency will be improved or large-scale investments in renewable power generation will take place Europe-wide. A common European market with clear rules, regulations, and a common energy policy is often depicted as a necessary tool for this goal (Capros et al., 2019).

All in all, we can summarize that the integration of the European markets has been driven by European institutions, primarily the EC and that core issues in this process have been liberalization with the aim of a free concurrence market, security of supply, and sustainability concerns.

3.3.2 Benefits of market integration

One of the main benefits of a common energy market since the inception of European energy integration has been increased security of supply. As the EU depends to a varying degree on energy imports, some member states may be self-sufficient while others are not; thus, potentially harming the functionality of the common internal market. This has in the past led to a considerable lack of agreement between countries that have different energy mixes, different suppliers, and different political allies on how to pursue the goal of creating a common electricity market (Jegen, 2014).

A wide arrange of policies in terms of efficiency and both inner and inter-market mechanisms have been adopted over the years to safeguard the energy supply by the EC.

For instance, percentage targets when it comes to renewable energy both to decarbonize and diversify energy production were established. A 2007 resolution requiring 20% of energy consumption in 2020 to be renewable or grid-priority access to renewable energy production are examples of how the EU tried to steer energy production unionwide towards a safe energy supply.
Member countries are also obliged to hold emergency oil reserves, national emergency plans, and safeguard their internal markets to properly ensure the functioning of natural gas and electricity supply Europe-wide.
Similarly, energy efficiency has been identified as a cornerstone in the common market with multiple directives aimed at for instance rendering European buildings more energy-efficient and incentivizing the implementation of renewables through harmonization of energy taxation Europe-wide (Kanellakis et al., 2013).

Next, a larger power system can benefit from the advantages of scale and is more stable as it has a higher level of inertia which facilitates other system operators providing electricity.
Inertia represents the energy stored in large rotating generators or industrial motors, mostly from coal and gas-fired generators, which can inject their kinetic energy into the system if needed. These parts will continue to rotate even if the generator has lost power. Inertia therefore helps to slow down a drop/spike in frequency immediately after a sudden mismatch between supply and demand (e.g. a power station outage or an unexpected change in the load connected to the network). If the inertia of the system is low, a small sudden difference between load and generation will cause a high-frequency deviation. In a stand-alone (national) system, reserves typically need to be large enough to cope with the most severe event, which is usually the loss of the largest generator in a TSO's control area. A major advantage of interconnecting power zones to form a large synchronous area is that reserves can be pooled and the relative importance of the most severe incident decreases with increasing system size (Meeus, 2020).

Lastly, the outcome of complete market integration where demand is met securely by the most economic resources is likely to bring about significant economic benefits such as lower prices. It has been estimated that the potential increase in social welfare of fully integrating Europe´s electricity markets could lie in the range of 16 billion to 43 billion annually by 2030, depending on the degree to which Europe´s generation portfolio is optimized, interconnector capacity expanded and the response in electricity demand managed (Baker et al., 2018).

3.3.3 Barriers to market integration

Interconnection capacity limitations are one of the main reasons that stand in the way of complete market integration. Since electricity markets were initially designed to meet national demands, complications often arise when interconnecting different markets due to a lack of infrastructure (Gugler et al., 2018).
Even when there would be sufficient infrastructure, interconnector cross-border capacity is often time-limited, with only about a third offered to the market. A significant factor behind this is national states' measures to curtail internal congestion without coordinating with other nations, thus limiting the flow of electricity between nations(Baker et al., 2018).
Additionally, market design imperfections such as differences in auction design, pricing rules, or closing hours hinder price convergence Europe-wide. While the use of market coupling (a mechanism that optimizes the allocation of cross-border capacities between countries) is now widespread, differences persist between bidding zones (Gugler et al., 2018).

Another limit is the balancing and integration of renewable resources considering their intermittent nature and spread-out position throughout Europe. It has been shown that price differentials can be attributed to different energy policies adopted on a national level. If one country incentivizes renewable energies via feed-in tariffs like Germany, this effect will be "transported" throughout the border due to market coupling and creating lower revenues for Dutch or Belgium producers which operate under other conditions. This is strongly correlated with the absence of a union-wide energy approach overall, but specifically in terms of sustainability which has been driven mainly by singular member states (Verzijlbergh et al., 2017).

In conclusion, we can summarize that the creation of a common European electricity market has been driven by a need to increase competition, reduce costs, improve the security of supply, leverage economies of scale and promote environmental concerns.
This has led to a range of benefits, including reduced prices due to higher competition, greater efficiency, and improved security of supply for industry and consumers.
However, there also are also barriers that must be addressed, including the lack of a common regulatory framework, the need for greater physical interconnections and the challenges associated with integrating renewable energy sources into the energy mix.

4. Methodology

This chapter serves to outline and underscore the methodological approaches undertaken in the following chapters 5, 6, and 7. We have employed both a traditional literature review aimed at collecting and synthesizing existing literature as well as a comparative analysis of secondary energy market data.

Literature review

The aim of the literature review in chapter 5 is to collect existing literature concerning the research question stipulated previously, thus providing an underpinning for future analysis and theory.

The literature review is targeted to highlight changes in the European electricity market over the last 10 years in order to evaluate the impact they have had on the market and which future implications might arise.

The literature research was conducted by utilizing search terms such as “European energy market integration”, “changes in European electricity markets”, and “European electricity market reform” in order to filter for relevant papers and academic articles.

While a majority of literature is from academic and scientific backgrounds, political publications such as directives from the EC and similarly relevant articles from newspapers and industry partners were collected as well in order to give the reader a broader view of the issues at hand. Finally, all content was sorted based on relevancy towards contributing to the research question at hand, thus focusing on the European market and the electricity market itself, not on other aspects such as energy technology developments even though some aspects will be incorporated if deemed to substantially contribute to the overall market development.

Analysis

The methodology employed in chapters 6 and 7 involves analysing and describing the European energy market and the challenges it has faced in the past decade. Graphs were both created but also adapted from published papers if deemed fitting. The following steps were undertaken for the figures created:

Data Collection: Comprehensive and reliable data on gas and electricity prices, gross electricity production, and total energy supply in Europe were collected from authoritative sources, ensuring high quality and high reliability.

Data Pre-processing: The collected data was validated, cleaned, and transformed into a suitable format for analysis.

Graphical Analysis: Suitable graphing techniques, such as line graphs and maps, were used to visually represent changes in gas and electricity prices over time.

Comparative Analysis: The graphs were compared to identify similarities, differences, and factors influencing the market dynamics.

Investigation of Gross Electricity Production and Total Energy Supply: Graphs were developed to depict changes in these indicators over the past decade, considering different energy sources and data availability.

Interpretation and Discussion: Insights were drawn from the analysed graphs, and the implications of the findings were discussed.

Limitations and Assumptions: Any restrictions or presumptions made when gathering and inspecting the data were mentioned, along with any potential effects they may have had on the validity of the study.

This methodology provides a systematic approach to examining the European energy market, aiming to contribute to the understanding of its dynamics and challenges.

5. Literature review

Over the last decade, the European electricity market has undergone significant changes, including a shift towards renewable energy sources, increased cross-border trade, the introduction of new market mechanisms, the expansion of the ETS, and new technological innovations. This literature reviews provides an overview of the major changes that have occurred during these 10 years. While the effects of Corona will be mentioned, the analysis of the pandemic will be discussed in greater detail in chapters 6 and 7. Additionally, some topics such as smart grid technology, capacity mechanisms and flexibility markets would have fit in several of the chapters but have been sorted due to relevance to the broader change issue.

5.1 Shift towards Renewable Energy Sources (RES) at varying speed

Throughout the last 10 years, Europe has experienced a steady increase in the use of renewables in line with ambitions of becoming the globe´s first climate-neutral continent while at the same time witnessing a multi-speed approach to the willingness of countries to move toward RES.

Since 2010, the share of RES in the European consumption electricity mix increased from 14.4% to 22.2% in 2021, mostly driven by an increase in solar and wind power production (European Environment Agency, 2023). In fact, the two RES contributed more electricity than gas for the first time in history in 2022 (Ellerbeck, 2023). On the contrary, the energy resource that has plummeted over the same time is coal which decreased from 23.8 % in 2010 to 14.5% in 2021 (Jones, 2023).

When looking at the overall production of electricity from RES in EU countries, Germany was found to be the largest producer (on about 22 %), followed by France, Italy, and Sweden(Brodny & Tutak, 2020).

The need for clean energy consumption is especially high in the sectors of electricity, transport, and housing which account for the majority of emissions.

In terms of individual states, figure 3 depicts the changes in renewable energy sources over the last 15 years. It is noteworthy to mention that all countries of the EEA increased their share of renewable energy sources. The biggest increases were recorded in Malta (10,403.9%) and Luxemburg (1201.3%) which benefit from a small population, good conditions for PV in the case of Malta as well as low starting points. The smallest percentage rise was observed in

Latvia (28.5%), Croatia 32.6%), and Slovenia (35.9%).

Eventually, the goal of 20 % RES consumption within the EU in 2020 was reached with 20.1 % (Bórawski et al., 2022).

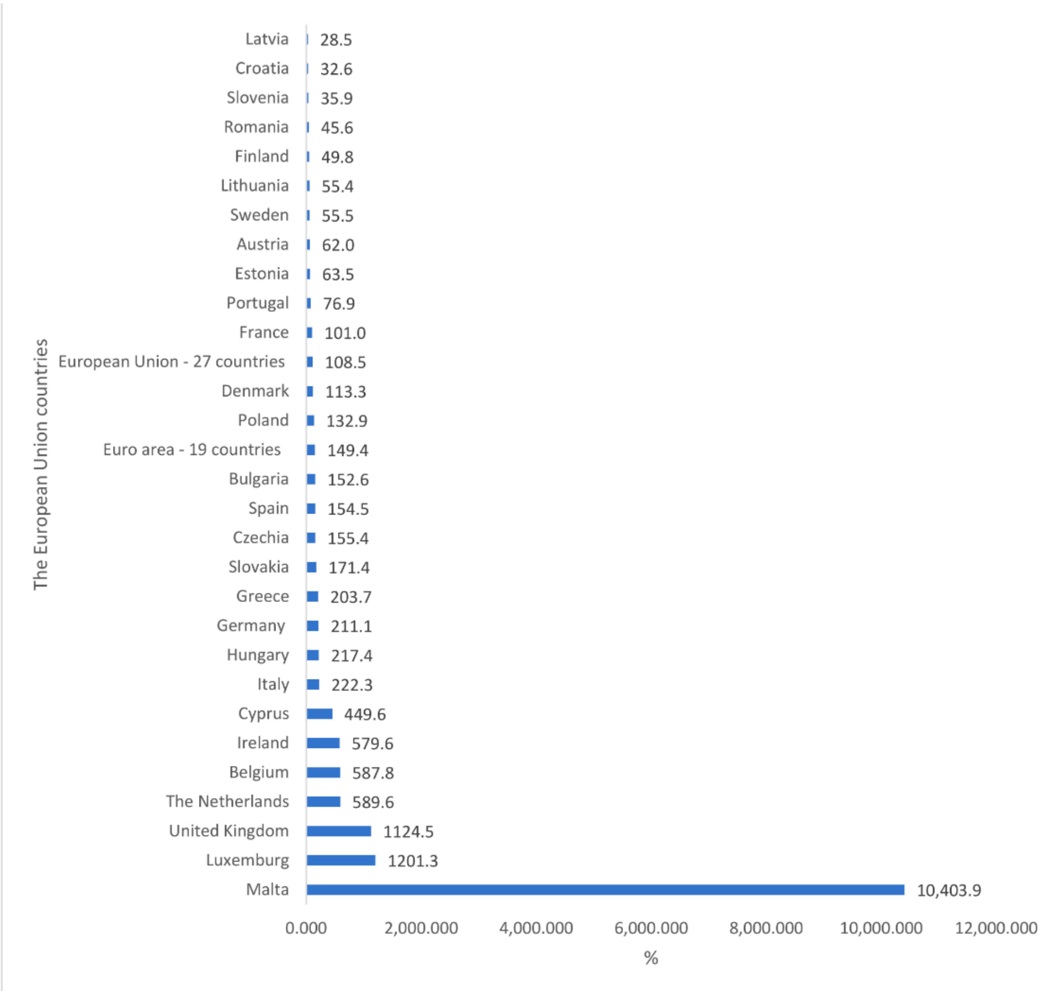

Figure 3: Changes in the share of energy from renewable sources in the European Union in 2004–2020 (%)(Bórawski et al., 2022)

Behind this trend stand multiple commitments by the EC to significantly decrease carbon emissions and/or increase goals for renewable resources such as the 2017 decision to reach 32% of RES in the energy mix by 2030 or the decarbonization of the economy and the cut of GHG emissions by at least of 80% by 2050 (Energy Efficiency Directive 2016/0376). Preceding this, in the 2030 Climate and Energy Policy Framework (adopted in 2014) the European Council introduced binding targets of a 40 % reduction of greenhouse gases (GSG) compared to 1990, a 27% share of RES (thus, further increased by the 2017 directive) in the energy mix and a 27 % increase in energy efficiency, all to be reached within 2030 (Veum & Bauknecht, 2019). In the last years, especially since 2019, an acceleration of initiatives can be

noted with a range of directives and proposals that have been adopted by the EC and the European Council such as the European Green Deal and the Clean Energy Package adopted in 2019 and the European Energy Law which incorporated many concepts from the Green Deal into legislation.
In the Green Deal, all 27 EU member states agreed to become climate neutral by 2050 and reduce emissions by 2030 by at least 55% compared to 1990 (from the previous target of 40%) levels while at the same time aiming to decouple economic growth from emissions, eliminate energy poverty and boosting job creation union-wide (European Commission, 2023a). The Clean Energy package includes binding targets such as an increase of energy efficiency by at least 32,5% by 2030 and other measures to improve energy performances of buildings (European Commission, 2019).

Moreover, the EU possesses key powers in crucial arias of the energy transition such as creating and setting standards for the energy performance of buildings, appliances and emission levels for vehicles, writing rules for energy efficiency, and in implementation of the circular economy and the emissions trading system which will be analysed in chapter 5.3. These areas allow the EU to actively and directly influence and direct actions.

On the other hand, the introduction of concrete measures has been mostly in the hand of individual states who have committed themselves to a different set of short to medium-term goals despite all European countries signing the Paris Agreement in 2015 or the Green Deal (Pellerin-Carlin & Vinois, 2018). Some countries like Germany, Sweden, and Finland have been leading the way in terms of climate neutrality with a date as early as 2045 while other member states like Poland, Hungary, and Romania are very hesitant to move boldly due to lack of finance, expertise or short-term national interests. Then again, countries like Norway and Denmark are for instance examples of countries that can shape their energy system based almost exclusively on RES due to substantial hydro and wind capacities.

Most (Western European) countries see renewable energy as an industrial opportunity that simultaneously diversifies their energy portfolio and reduces greenhouse gas emissions. For these countries, European cooperation is a means to address these challenges together, which implies greater interconnection of their transmission networks and joint policy actions. Other countries, mostly in Eastern Europe, perceive the efforts of their peers as a nuisance that both jeopardises supply at affordable prices and brings grid problems and price volatility without any additional revenue or employment benefits. Especially the historic dependency on Russia

as a provider of gas, an aging infrastructure, a large workforce in fossil-fueled industries together with consumers that have on average less disposable income has prompted these nations to focus primarily on the development of the internal market and the creation of trans-European (gas)connectors.
Especially notable in this context has been the discussion around the Russo-German North-Stream 2 natural gas pipeline which has been criticized as promoting German energy dependence on Russia (before its eventual shutdown over the Ukrainian invasion of Russia in 2022) or China`s 16+1 Cooperation Platform aimed at closer energy collaboration with 16 central and eastern European nations, further underscoring the dilemma of (national) economic and political interests and the urgency of transition towards renewables(Bórawski et al., 2022; Mata Pérez et al., 2019).

As previously stated, energy independence and security of energy supply are among the main key drivers for the implementation of RES as they are crucial for economic growth, development, and social cohesion. Countries that aim to reach proper levels of energy security are faced, in the short term, with issues related to a) the dependency rate (on other countries) b) energy prices (and volatility), c) energy source shortages, and d) environmental protection; in the long-term issues related to the political stability of supplier countries, investments, and policies to support domestic renewable energy sources.
As many EU countries have been dependent on energy imports to a large degree, the EC and national states have tried to foster energy independence by reducing foreign energy independence, even before the Russian invasion of Ukraine, focusing on RES development.
Similarly, increasing RES production has been shown to lead to green growth that is more resilient to external factors and has also proven to be more effective than a non-RES generation, thus strengthening energy security (Carfora et al., 2022).

Since there persist such wide discrepancies in terms of policy interventions, technology, and past trends it is generally not possible to evaluate countries' measures homogenously but they can be clustered, for instance, according to different criteria. The study of Brodny & Tutak (2020) analyses the structure and volume via the electricity production of 8 different types of RES (hydro, wind, solar, physical biofuels, biogas, renewable waste, liquid biofuels and geothermal) on a European level. The greater the distance of a given EU country from the center of the cluster in which this country was located, the greater its discrepancy from countries whose distance from the mean of the cluster was smaller. For instance, Finland with a value of 5144 is the country in cluster 3 which is the most different from the overall mean (see figure 4).

Cluster 1	Distances from Centre of Cluster 1	Cluster 2	Distances from Centre of Cluster 2	Cluster 3	Distances from Centre of Cluster 3	Cluster 4	Distances from Centre of Cluster 4
Spain	3850.46	Germany	0.0	Belgium	1565.13	France	3520.82
United Kingdom	3850.46			Bulgaria	1180.17	Italy	7469.39
				Czech Republic	1615.02	Austria	5466.60
				Denmark	4256.70	Sweden	6575.79
				Estonia	1848.61		
				Ireland	1574.96		
				Greece	1357.56		
				Croatia	1455.91		
				Cyprus	2053.82		
				Latvia	1611.55		
				Lithuania	1479.99		
				Luxembourg	1780.10		
				Hungary	1745.87		
				Malta	2109.29		
				Netherlands	2749.05		
				Poland	3963.60		
				Portugal	3166.95		
				Romania	4185.19		
				Slovenia	1674.17		
				Slovak Republic	1609.99		
				Finland	5144.29		

Figure 4: Elements of clusters of RES accounting for structure and volume with distances from centers (Brodny & Tutak, 2020)

Germany was found to be a homogeneous cluster, not showing enough similarities to be compared with other EU countries, further underscoring the role of Germany as leading in RES infrastructure. Spain and the UK were found to possess a similar structure and volume in RES production. Much smaller amounts of energy from RES were shown to be produced in other countries, with cluster 3 scoring the lowest source. On the other hand, when converting the amount of energy produced from RES to the GDP of a given country (utilized as a measure of wealth, the hypothesis being that richer countries should have an advantage in the transition due to better infrastructure, more investment possibilities and more advanced technology), great similarities between countries such as Germany, Poland, Estonia, Greece, Lithuania, Portugal and Denmark emerged. This means that when accounting for the value of GDP, the amount of energy produced from RES is very similar in these countries, despite the fact that in terms of the absolute values, these quantities significantly differ.

Additionally, when accounting for other factors such as demographics (the ratio of the amount of energy produced from RES to the number of inhabitants of a given country) or land area (on the presumption that the size of a given country should have an impact on the structure and amount of energy produced from RES) other countries such as Finland, Austria or

Luxembourg were found leading.
Finally, the study clearly underscores the diversity of speed and actions undertaken by European nations over the course of the last years and the difficulty to rank them "objectively" (Brodny & Tutak, 2020).

5.2 Increased Cross-border trade and infrastructure construction due to new market Mechanisms

Another macro movement over the last 10 years has been the move toward an increase in cross-border electricity trade. In 2022, more than 15 % of European power was traded between nations with a clear majority being net importers and France(which historically was leading but in recent years underwent renovations of its nuclear reactors lowering its production) Norway, Bulgaria, Sweden, and the Czech Republic being the major exporters (Hook & Thomas, 2022, see figure 5 for a more detailed country-specific list).
This is due to multiple reasons, one of them being the use of coupling mechanisms that facilitates efficient price formation and maximizes social welfare by allocating electricity flows based on price differentials and smart grid technologies which will be analyzed in chapter 5.4. Market coupling allows for electricity to flow from areas with low electricity prices to areas with higher electricity prices. In the 2019 European Clean Energy package a 70 % transmission capacity for cross-zonal trading was introduced which means that TSOs have to offer 70 % of their transmission capacity to inter-country trade (ACER, 2023b).
Ideally, this exchange leads to an equalization of the electricity prices of the coupled markets. Likewise, the expansion of RCCs as a way of coordinating and sharing data in the last 10 years has served to facilitate cross-country collaboration for the DA and ID markets. Not only do they calculate capacity but also perform security analysis, outage planning, adequacy forecasts, and facilitate regional balancing capacity.
Currently, there are six of these centers spread around Europe, most of them established after 2014(Meeus, 2020).

Moreover, an increase in transmission capabilities allows for electricity to flow throughout and within multiple countries at an unprecedented range. Indeed, the effective allocation of cross-border trading capacities has been identified as one of the central challenges for the implementation of a pan-European internal energy market. It is expected that energy bottlenecks in the electricity grid will constitute the most significant barrier to achieving the 2050 climate goals (Cullinane et al., 2022).

In addition, capacity mechanisms were maintained to ensure adequate investment in power plant infrastructure. These mechanisms are called so because they allow national governments to give out payments to electricity providers for capacity (MW) in addition to wholesale markets that remunerate energy (MWh). They serve as temporary support schemes by national governments to safeguard enough electricity supply in the medium to long term and are one of the most discussed topics in the European electricity market.
Supporters argue that they are necessary tools to achieve security of supply and point to the recent electricity crisis as an example of insufficient domestic supply, while opponents criticise them for distorting the single European market and indirectly affecting neighbouring countries markets. In 2019, the EU declared capacity mechanisms to be measures of last resort to address residual concerns about the adequacy of resources. States will have to carry out a study on the potential impact of capacity mechanisms on neighbouring countries before implementing them. Capacity mechanisms should also be temporary and approved by the European Commission for a maximum of ten years (Meeus, 2020).

Until 2030, the EU has further set a goal of at least 15 % interconnectivity of the installed electricity production capacity. This means that each country should have electricity connectors such as cables which allow 15 % or more of the electricity produced to be transported across its borders a (European Commission, 2018; for a comparison see figure 6 for comparison between 2010 and 2020).

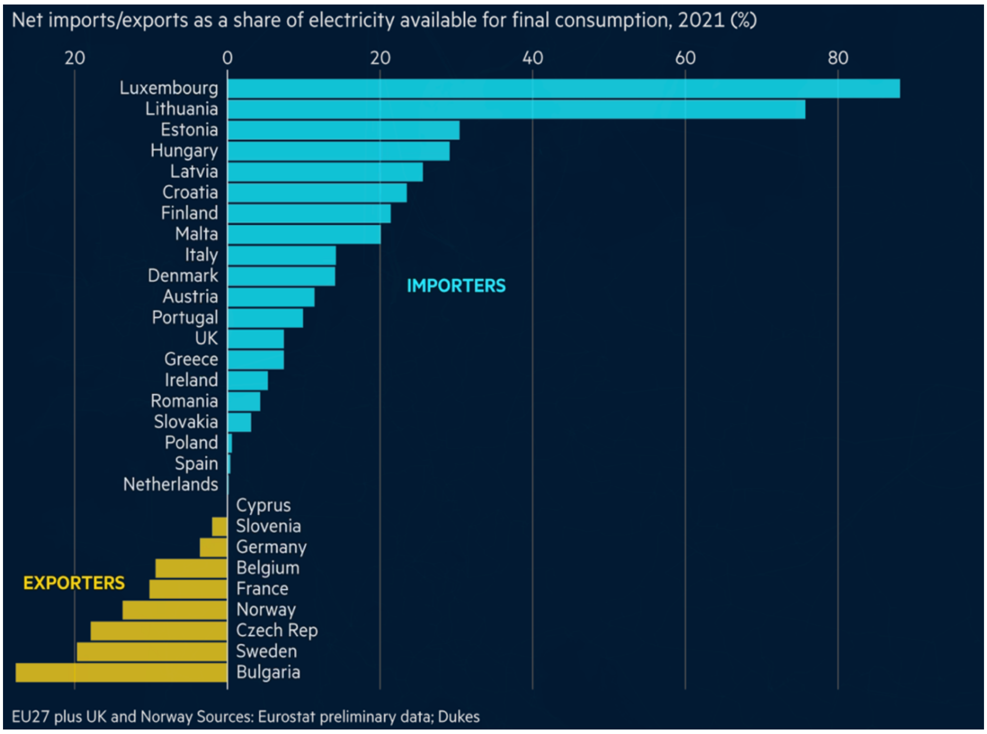

Figure 5: Net imports/exports as a share of electricity available for consumption, 2021(Barnard, 2022)

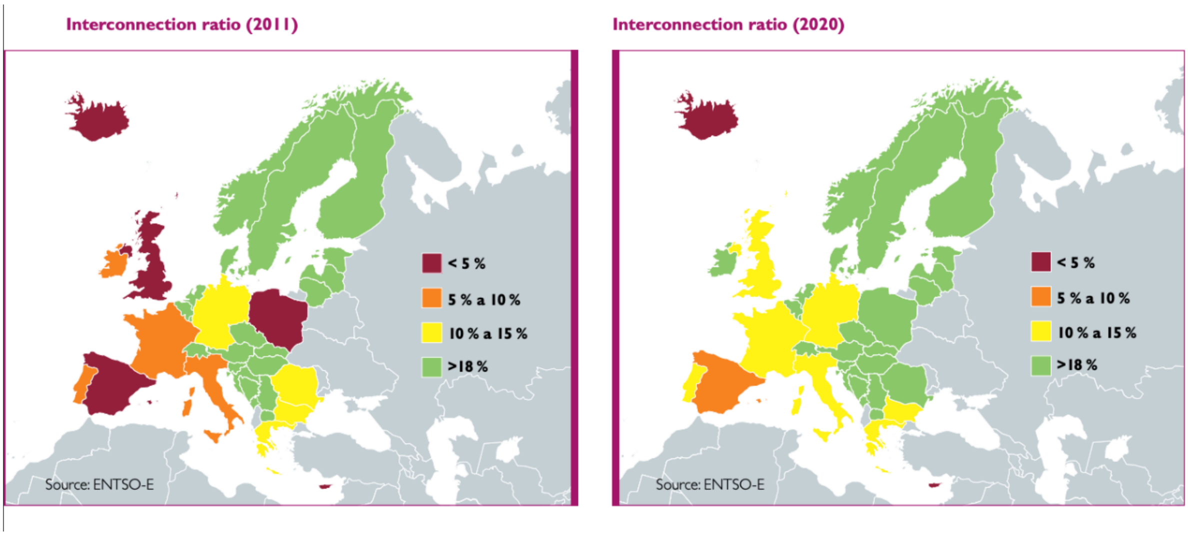

Figure 6: Interconnection ratio of electricity transmission in 2010 and 2022 (ENTSO E, 2019)

In light of zonal electricity markets such as the current European ones which can produce electricity flows that exceed available capacity on transmission lines(thus forcing TSOs to take remedial action that costs billions of euros each year in the EU) flow-based market coupling (FBMC) was introduced in six central European countries (Austria, Germany, Belgium, France, Luxembourg and the Netherlands) in 2015 (Poplavskaya et al., 2020).

Initially only employed in the DA market, it was a move away from the traditional net-transfer capacity (NTC) employed in the rest of the European markets at the time which calculates the maximum exchange of active power between two zones whiles at the same time satisfying overall operational limits (European Commission. Directorate General for Energy. & Tractebel Impact., 2020).

One of the main goals of the implementation of the FBMC mechanism in the region was to optimize social welfare across the region by improving market integration. Specifically, FBMC was introduced only in the DA market but represented nonetheless a major change in European energy market design due to the size of the markets and its geographic position in the heart of Europe. The aim was to achieve price convergence throughout the different zones through a complex and sophisticated mechanism(Corona et al., 2022). Concretely, the FBMC ensured greater cross-border transport capacity through the closer integration of capacity allocation and market activity.

In 2022, FBMC was expanded to cover the CORE region (Austria, Belgium, Croatia, the Czech Republic, France, Germany, Hungary, Luxembourg, the Netherlands, Poland, Romania, Slovakia, and Slovenia), with intraday capacity calculation. A further expansion of the mechanism to the Nordic market and Eastern European markets is planned and it now constitutes the dominant mechanism for the allocation of cross-border electricity trade (ACER, 2023a).

What is more, the EU has since 2010 made use of the price coupling of regions (PCR) to incentivize the market coupling of regions which has since then continuously been enlarging, now including more than 20 countries comprising close to 90 % of European electricity consumption. The PCR includes seven European electricity exchanges (APX-ENDEX, Belpex, EPEX SPOT, GME, Nord Pool Spot, OMIE, and OTE) agreeing on creating a power exchange mechanism based on the best possible calculation and most efficient utilization of cross-border allocations. The PCR was based on three assumptions:

i) a uniform algorithm for calculating electricity prices which ensures transparency
ii) data being collected decentrally
iii) the individual power exchanges have their own responsibility for the respective markets.

A PCR-matcher and a broker service then calculate the different market and reference prices. Afterward, the TSOs send their cross-border capacities to a Market Coupling Operator (MCO). The MCO serves as the interface between the TSOs and the power exchanges. The MCO then models centrally and independently the capacity values with constant monitoring of cross-border capacities. Following this, the MCO communicates the capacity values to the

respective electricity exchange. Once this process is finished, traders can start submitting their offers. The actual coupling is then carried out by the relevant electricity exchanges by settling supply and demand using an algorithm (Next Kraftwerke, 2023).
The technical functioning of the algorithm is subject to debate as well as the overall governance of the MCO which is currently run by a different exchange operator each day (Meeus, 2020).

When it comes to transmission rights, there are ongoing discussions on how to divide long-term transmission Europe-wide rights in different time horizons (such as year-ahead and month-ahead auctions). This is relevant since these forward markets are the biggest ones in overall volume. While traders want to have as many rights as possible allocated far ahead of delivery to leverage them on the market, TSOs generally propose dividing rights more equally over the timeframes. Historically, on most borders physical transmission rights (where owners had the right or priority to use a particular transmission path) were in place but we are currently witnessing a transition from physical to financial transmission rights(where the owner receives real-time price for transmitting power from a particular transmission line)in Europe (Meeus, 2020).

Everything considered, significant barriers to electricity trade persist. For instance, tensions on the electricity grid occur between regions in Europe where the potential for RES is high (e.g., hydro and wind in Scandinavia; wind in Spain Italy to the UK and Ireland; solar in Southern countries such as Greece and Cyprus) and densely populated, power-consuming areas in between. These barriers emerge mostly where geographical conditions have set natural barriers such as mountain ranges and seas which are more difficult to connect (ENTSO-E, 2019, see figure 7 for an overview of the major barriers in Europe).

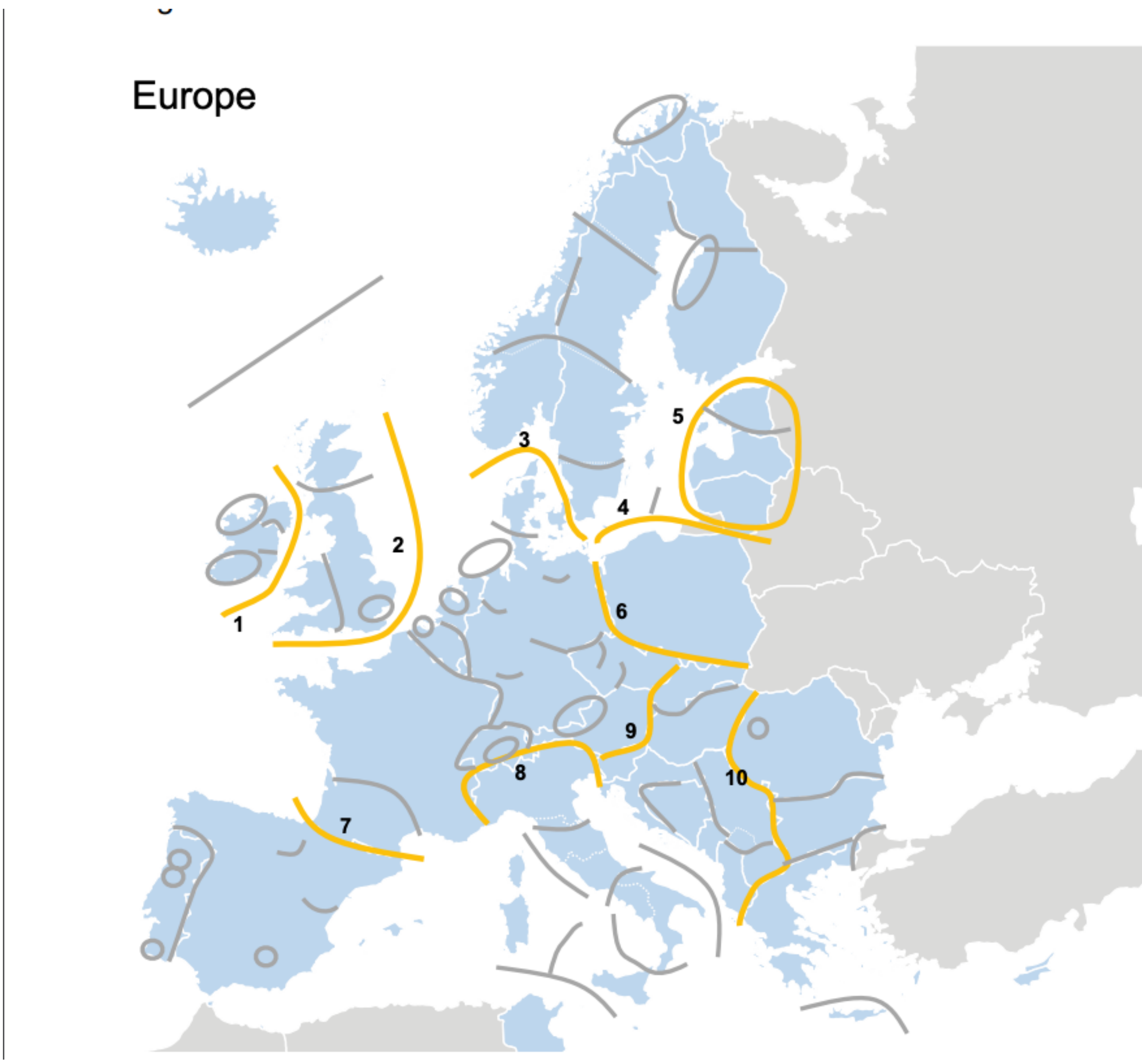

Figure 7: Map of major market boundaries in Europe (ENTSO E, 2019)

Lastly, to enhance and supplement the capability of electricity markets and make use of the increasing digitalization of networks, especially TSOs, and DSOs, a plethora of flexibility markets have emerged over the last years. These are mostly digital platforms that differ in terms of services, functions, coordination, ownership, and interrelations with existing markets. Two main categories have emerged: market platforms (where flexibility is offered and TSOs/DSOs procure it) and aggregator platforms (where flexibility is offered through an independent aggregator or a supplier (Valarezo et al., 2021).

It must also be stated that while interconnectivity infrastructure such as electricity corridors are being developed at a fast pace, it would need to be significantly upscaled in order to meet demand and supply in such a Europe-wide market (ENTSO E, 2019).

All in all, electricity trade between countries has been on the rise thanks to new market structures such as innovative market mechanisms (FBMC), EU regulations forcing TSO to increase capacity, and undergoing infrastructure projects to expand intercountry electricity interconnectivity.

5.3 ETS and Market incentives

In this subchapter, the role of the ETS and overall market incentives in the electricity markets are being investigated.
When it comes to market incentives, most of them are meant to help in the energy transition toward RES.
The ETS as the world's first international emission trading scheme was established in 2005 to create a market for the reduction of harmful emissions. While not covering all aspects of emissions such as housing, the ETS explicitly covers manufacturing and the electricity sector (amounting to 40 % of greenhouse emissions within the EEA).
The ETS works on a "cap and trade" principle by setting the total amount of certain greenhouse gases that can be emitted by operators. The cap is reduced over time in order to decrease total emissions. Within the cap, operators are free to buy and receive emission allowances. After each year, operators must surrender enough allowance to cover their emissions or will otherwise be fined 100 € for each ton of CO2 not covered. In terms of implementation progress, the EU has over the last 10 years complemented Phase 2 (2008-2012) and Phase 3 (2013-2020). Since 2021, phase IV is ongoing. During the last decade, the ETS has moved away from the free allocation of certificates to the new norm of market-based auctions. Additionally, a single, EU-wide cap on CO2 emissions was established which replaced the previous system of national limits with an annual cap set in advance and reduced at a rate called linear reduction factor of 2.2 % (European Commission, 2023b; Quemin, 2022).

While criticized for the previously allocated overall dimensions of free certificates (and the ongoing practice at a reduced ratio) and a non-representative (low) price that does not reflect the true social cost of carbon, the ETS mechanism has made a significant contribution to reducing CO2 emission, estimated to be around 3.8 % of total emission in the time period between 2008 and 2016(Bayer & Aklin, 2020). Nonetheless, more robust, representative pricing has been shown to lead to the largest welfare gain and is the Pareto optimal solution for European states (Quemin, 2022).

In late 2022, some major reforms of the ETS were agreed to between the EC and the European Council. These include a reduction of 62 % in ETS emissions compared to 2005, a new annual reduction factor of 4.3% from 2023 on, the gradual inclusion of shipping emissions from 2024, the complete phasing out of free allowances by 2034, and the application of ETS on intra-European flights within 2026. Moreover, 24 % of all allowances will continue to be placed in a market stability reserve to address imbalances due to external shocks such as the Covid pandemic (Appunn & Wettengel, 2023).

While the EU has been developing its emission trading scheme over the last 10 years, it has remained up to each member state to introduce policies capable to fulfil their own climate objective. One of the most commonly used methods to encourage the consumption of renewable sources has been to give incentives to the holder of the energy plants via price incentives (tariffs). This method is called feed-in and can be of two types: feed-in premium and feed-in tariffs (the most used in European countries). In the former case, the incentives are summed to the value of the energy, which is evaluated at market price. Consequently, the measure is subject to market uncertainty. In the latter case, the incentive includes both the premium (the incentive) and the compensation for the energy produced, so that the market price of energy is taken as standard.

The second type of measure includes quantity-based policies that set goals for the integration of RES into the energy mix and rely on auctions or renewable portfolio schemes, which include flexibility mechanisms such as green certificates.

Additionally, tax measures serve to complement these two types of instruments (for instance exempting renewable energy from certain taxes or providing tax credits for investment in RES).

The role of the EC is to control and monitor the actions of countries and, when the national goals are not achieved, propose remedies (Bersalli et al., 2020; Fusco et al., 2022).

5.4 Decentralization and new forms of technological innovation/digitalization

Over the last decade, a trend towards decentralization as a more democratic and inclusive energy transition method has emerged. This shift stands in contrast to the previous (and to some degree, current) legal and governance system in which energy systems were predominantly centralized in a hierarchical way. It is being driven both by the need for a more decentralized nature of energy sourcing due to increased usage of RES and on the other hand a more inclusive way of changing the socio-economic relations embedded in the energy system through greater public participation and control (Heldeweg & Séverine Saintier, 2020).

With the widespread use of RES in private hands such as PVs or wind farms spread out across the country, we can observe a tendency to move away from a system with a clearly defined energy producer to an energy seller and finally to an energy consumer into the direction of a prosumer where energy is not only consumed but also produced and the excessive amount shared with the grid or other consumers. This process of energy sharing among prosumers, consumers, and grid/utilities involves two key elements: information and communication technologies and optimization techniques, often times managed by a local control centre connected to the smart grid (Zafar et al., 2018).

Driven by the need to address climate change and at the same time increase energy efficiency and security, decentralization means a shift from large, centralized power stations to small, local grids. Oftentimes, the ongoing process of decentralization is also depicted as the next step in the liberalization process where previously state-owned electricity monopolies are being broken up and new market actors are free to enter (Leal-Arcas et al., 2019). Additionally, new technologies and electricity management systems (EMS) are often described as necessary tools in the transition toward a carbon-neutral Europe (Maćkowiak-Pandera, 2018).

The introduction of the smart grid, an advance power mechanism that combines self-monitoring with integrated communication infrastructure to enable the bi-directional flow of energy and information can fulfil the requirements posed by the new electricity grid. It is forecast to contribute significantly toward reducing net annual emissions with 0.7 to 2.1 gigatons reduction of CO2 by 2050 (Leal-Arcas et al., 2019; Zafar et al., 2018).

Thanks to the internet, intelligent software, and responsive technologies it is possible to manage the electricity flow and adapt it to the actual circumstances such as charging plug-in electric cars at night when electricity demand is lowest. Smart grids cannot only respond to fluctuations in energy supply and demand but also keep track of energy flows as well as inform consumers and suppliers regarding real-time consumption.

While promising, smart grid and Prosumers based Energy Management and Sharing (PEMS) are faced with challenges such as a considerable amount of capital investment, the need to develop a common sharing vision within any community, the insufficient space for installation or concerns of data security and user privacy as well as an overall lack of regulation (Zafar et al., 2018).

The benefits of the smart grid are to allow for the proliferation of renewable energy generation, to incentivise the self-consumption of energy, to boost energy efficiency via demand response and can under the right also help to alleviate energy poverty (Leal-Arcas et al., 2019).

New energy management tools are being created to integrate with the smart grid.
Demand-side management (DSM), a novel development in smart grid technology, has been developed to reduce the cost of energy acquisition and the associated penalties by monitoring energy use and managing appliance schedules utilizing demand response, distributed energy resources, and energy efficiency tools. The aim is to reduce costs without the involvement of system operators through the implementation of a control system that selects the energy sources to power different loads according to the period of the energy demand required (Bakare et al., 2023).

6. The Development of the European Energy Market over the past 10 years

The following part of the paper deals with the development of the European Energy Market over the past 10 years. This timeframe was chosen so to exclude the distorting effects of the financial crisis but still give an overview of the long-term development of the European Energy Market. Due to a lack of data some of the graphs shown below do however show a shorter time period, while some go back way further.

The main focus of the upcoming part is the price development of gas and electricity prices. Nevertheless, the usage of different types of fuels will also be discussed.

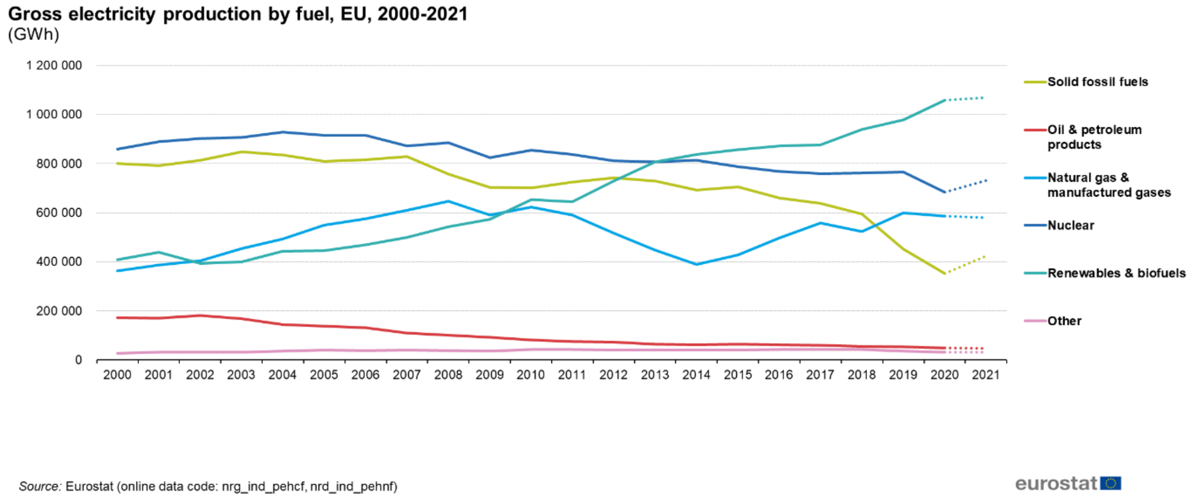

Figure 8: Gross electricity production by fuel type between 2000 – 2021 (Eurostat, n.d.)

The above-shown figure by (Eurostat, n.d.-b) shows the gross electricity production by fuel type in the European Union between 2000 and 2021. For a long period of time nuclear and solid fossil fuels were the main sources of electricity production. However, from 2010 on, renewables and biofuels started to drastically ramp up production and were the main sources of electricity production from 2013 on. From the year 2018 on, a rough decline of solid fossil fuels in electricity can be detected, while the electricity production of nuclear power plants stayed at an almost constant level. This effect was further bolstered by the Corona pandemic in 2020 which shut off many polluting industries.

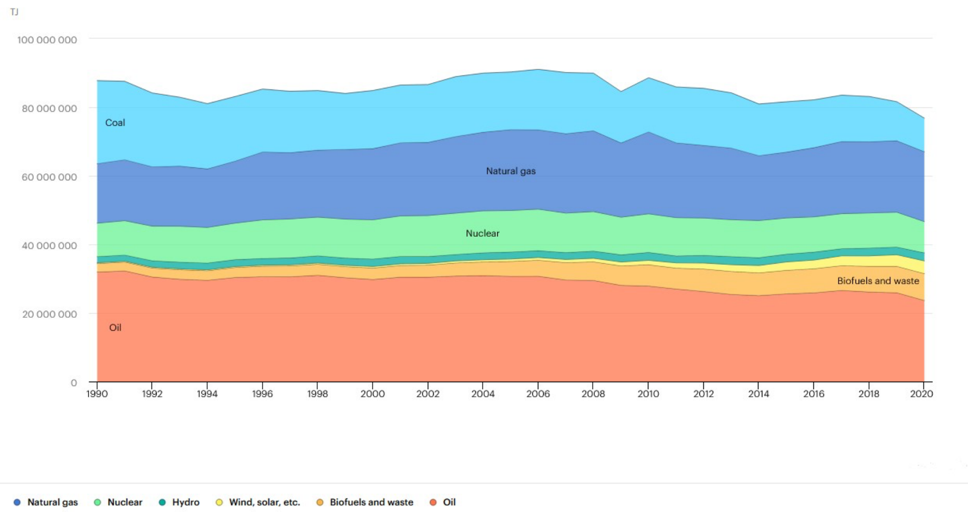

Figure 9: Total energy supply (TES) by source, Europe 1990-2020 (Europe – Countries & Regions, n.d.)

In Figure 9 by (*Europe – Countries & Regions*, n.d.) the total energy supply is mapped, dividing it further into the different sources. In this case, TES here excludes electricity and heat trade. Coal also includes peat and oil shale which were relevant. As the main focus of the paper is from roughly 2010 until now, only this part of the graph will be discussed. As can be seen, Natural Gas, Oil, and Coal have become less important over the past decade but are still a major source of energy. During the same timeframe, the nuclear energy supply remained almost the same. Biofuels and waste, on the other side, had a vast increase in the energy supply, as well as Hydro and wind, and solar. However, the percentages, of these energy sources are still diminishable in the grand picture.

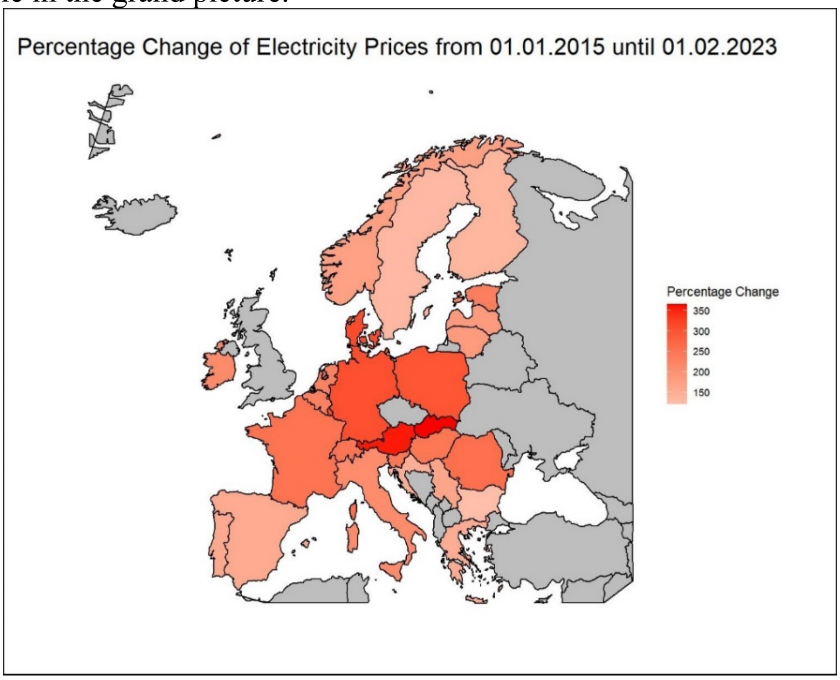

Figure 10: Percentage Change of Electricity Prices in Europe between 2015 and 2023 (Matt, 2022)

Figure 10 shows the percentage change in electricity prices between 2015 and 2023. The map is based on data from Matt (2022) and showcases the percentage change in most of Europe, with some exceptions such as the Czech Republic the United Kingdom, and Iceland, where no data was available. As can be seen, the electricity prices rose significantly in all of the shown countries. However, some countries experienced a more pronounced increase than others. The two countries where electricity prices rose the most are the two central European countries Austria and Slovakia. However, there are also countries like Norway, Sweden, and Finland where prices were rising less drastically than in many other countries. This trend can partly be explained by the high dependency on gas for electricity production in countries like Austria (31%), and the extremely low dependency on gas in countries like Norway, Sweden (1,2%), and Finland (11%) (European Council, 2023).

When it comes to gas prices, figure 11 depicts the price of TTF Gas futures from 2010 until March 2023 and was plotted using data from Barchart (n.d.). During a long period of time, namely between 2010 and mid/end of 2020 TTF gas futures prices stayed at a relatively stable level with only minor changes. However, from the beginning of 2021, a sharp increase in TTF gas future prices can be seen. In the summer of 2022 gas prices peaked at almost 250€ per MWh, whereas the TTF gas future price was below 50€ for the previous 10 years. Following this spike, gas prices started to drop again. Nonetheless, they still stayed at a relatively high level compared to the previous years.

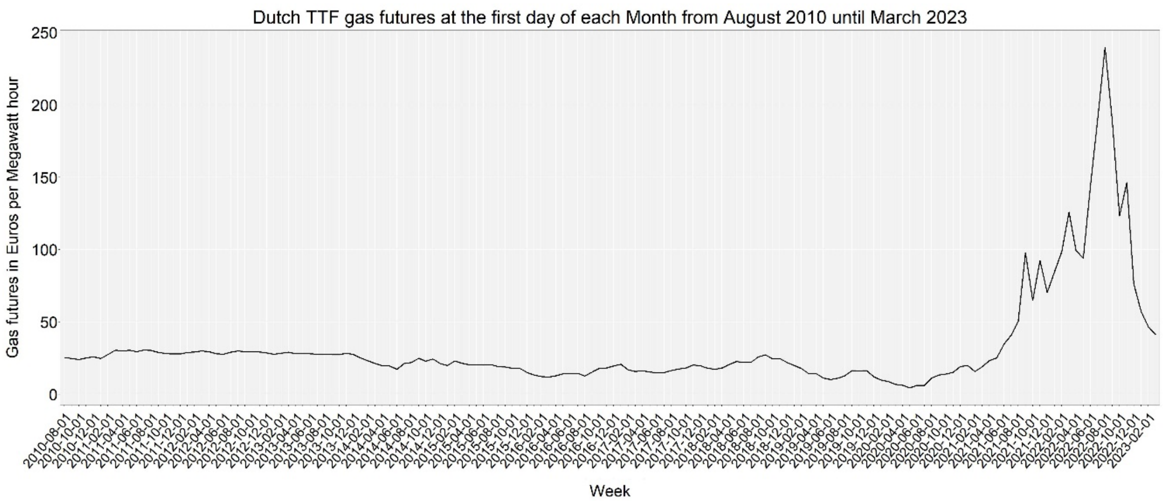

Figure 11: Dutch TTF Gas Futures at the first day of each month from August 2010 until March 2023 (Barchart, n.d.)

The same picture as in Figure 11 can be seen in Figure 12[2], also from Matt (2022)which shows the wholesale electricity prices in Euro over the last few years. The wholesale price of electricity is the price at which suppliers buy the electricity they supply to end users. Until around 2021, electricity prices remained at almost the same level, with only minor changes over the period. However, from 2021 onwards, prices started to increase dramatically and peaked in mid-2022 with a wholesale electricity price of more than €400 per MWh. Later on, electricity prices also start to fall but remain at a relatively high level compared to the years before 2021.

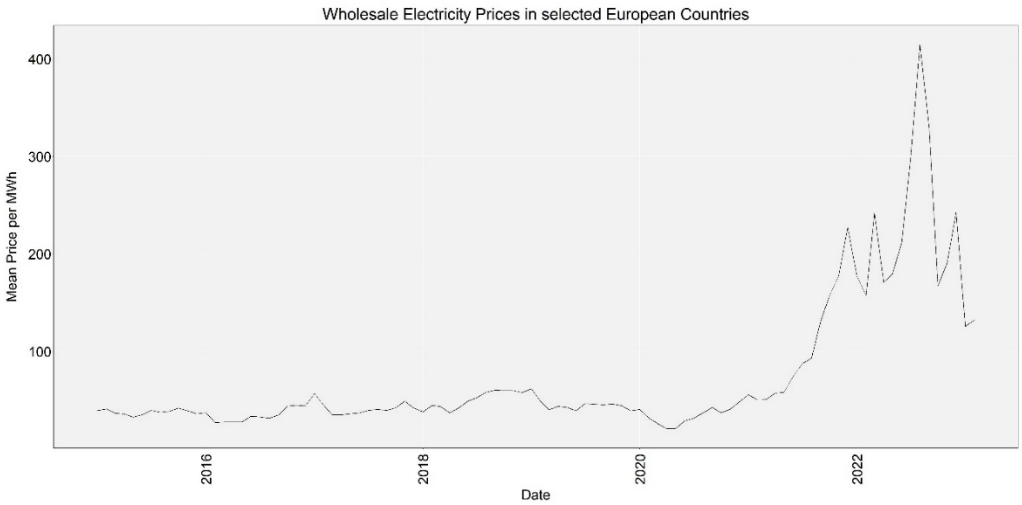

Figure 12: Wholesale Electricity Prices in selected European Countries (Matt, 2022)

[2] *Countries included: Austria, Belgium, Bulgaria, Switzerland, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Sweden*

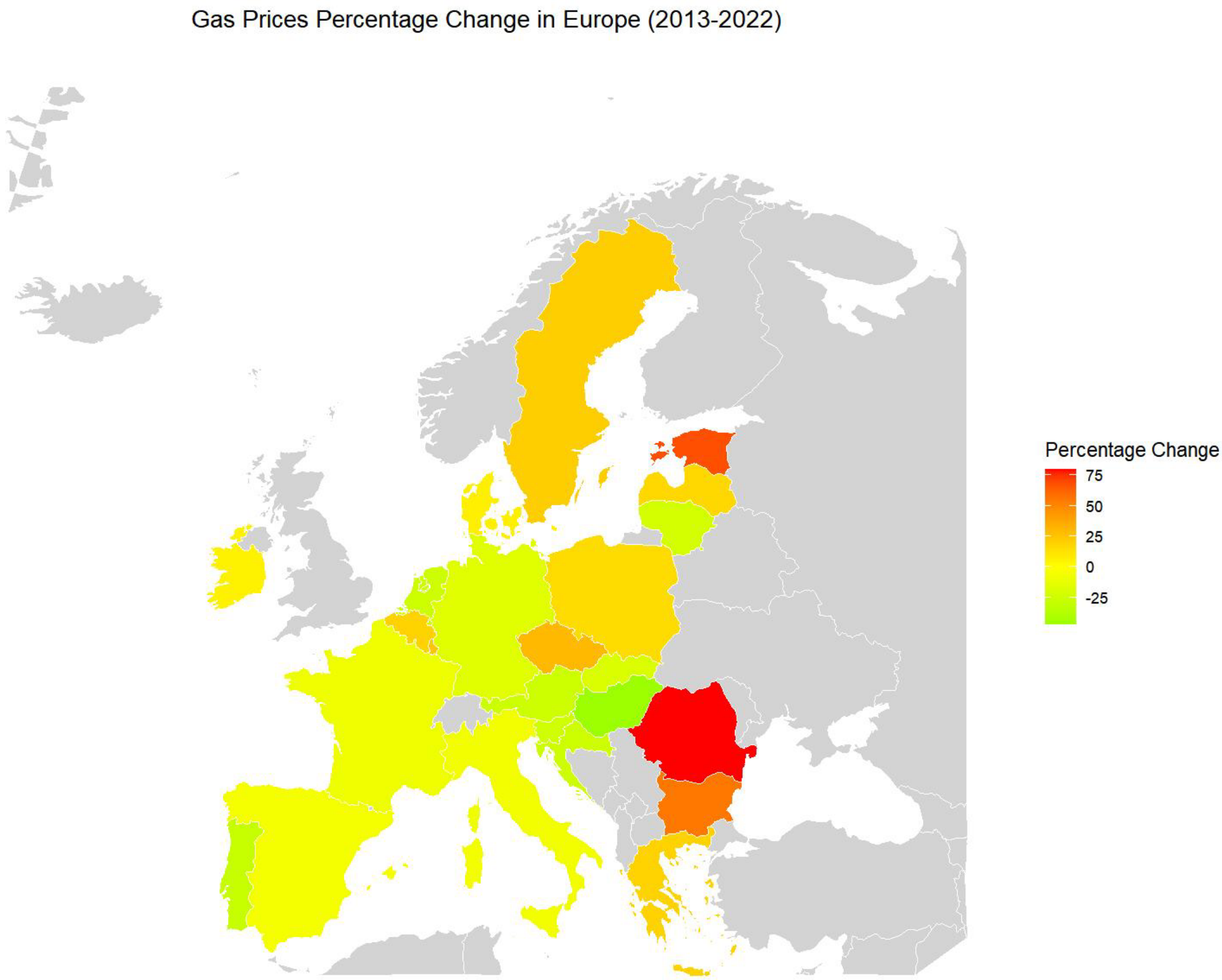

Figure 13: Percentage Change of Gas Prices in Europe (2013-2022) (Eurostat, n.d.-a)

To further showcase the increase of gas prices in literally all of Europe with only a few exceptions, Figure 13 with data by (Eurostat, n.d.-a) will be used. It can be seen that gas prices have developed differently throughout Europe. While some countries such as Hungary and Portugal saw a relatively sharp decrease in gas prices, some others like Estonia, Romania, and Bulgaria experienced high percental changes in gas prices. In the other European countries, the price development of gas prices was at a more moderate level and relatively homogenous throughout the whole continent.

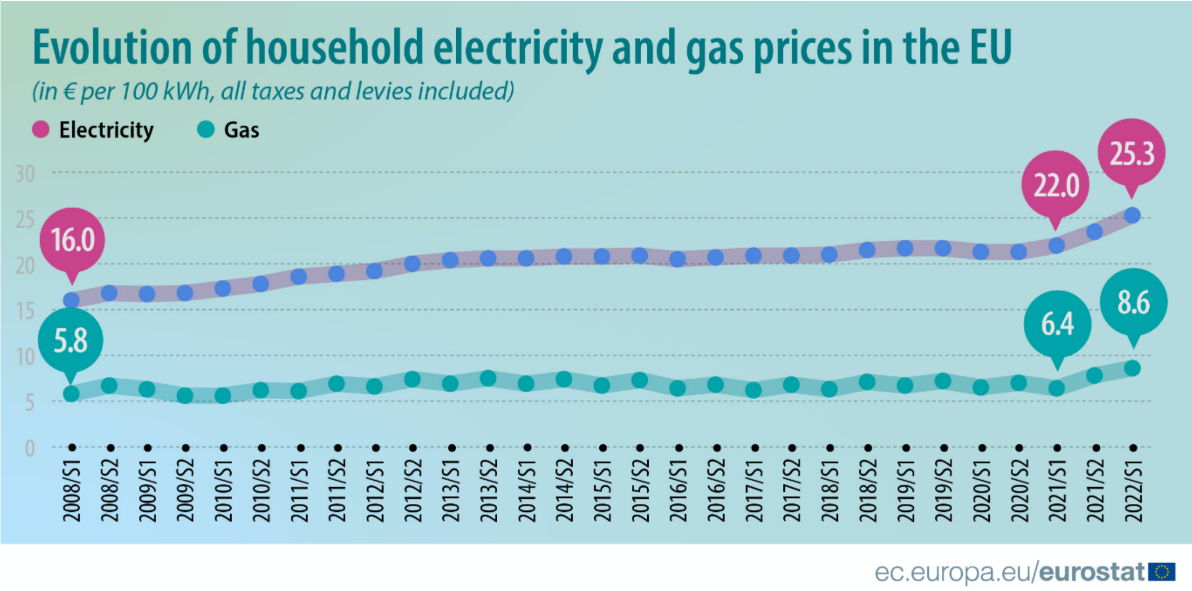

Figure 14: Evolution of Household Electricity and Gas Prices in the EU (Eurostat, 2022b)

So far mainly wholesale electricity prices and TTF gas future prices were used to show the rising level of energy and electricity prices in Europe. To also evidence the effects on the consumers, figure 14 by (Eurostat, 2022b) maps out the evolution of household electricity and gas prices in the European Union. As can be seen, the electricity price for household consumers has been almost constantly rising, but at a relatively moderate level. However, from the beginning of 2021, a relatively sharp increase in electricity prices can be seen. Almost the same is true for gas prices, which stayed at almost the same level over the past decade but have increased relatively sharply from the beginning of 2021 on.

The next chapter of the thesis deals with a more recent event, namely the Ukraine invasion, that has since then had a massive influence on the electricity market in Europe. To showcase the impact on the European energy market data from Russian exports and pipeline flows are used. Furthermore, the rise of electricity and gas prices for household consumers in the EU will be evidenced.

7. Current Effects of the Russian Invasion in Ukraine on the European Energy Markets

The Russian invasion of Ukraine began on the 24th of February 24, 2022. Since then, Russia has gained control of a sizable portion of Ukraine. However, in April 2022, Russia was forced to halt its advance on Kyiv, and Ukrainian troops were able to restore control of a significant portion of the country (Sadid et al., 2023; The Visual Journalism Team, 2022).

Western countries, particularly the US, EU, and UK, collectively backed and are still supporting Ukraine in the months that followed the invasion by delivering financial, humanitarian, and military aid. With a total contribution of close to 50 billion euros, the United States is clearly the country that supports Ukraine the most (Antezza et al., 2023).

The EU, NATO, and other Western nations are sanctioning all significant Russian businesses, including the financial and energy sectors, in addition to helping Ukraine. These penalties include the exclusion of significant Russian banks from the global financial messaging system SWIFT, the prohibition of all imports of Russian gas into the US, the EU's ban on refined oil products beginning in February 2023, and the EU's halt on imports of Russian coal (BBC, 2022)

Figure 15 by (OECD, n.d.) clearly illustrates that Russia's most important export goods are crude oil, petroleum gas, refined oil, and coal briquettes, which accounted for 133,6 billion USD in exports in 2020, or more than half of Russia's total 209 billion USD in exports during that year.

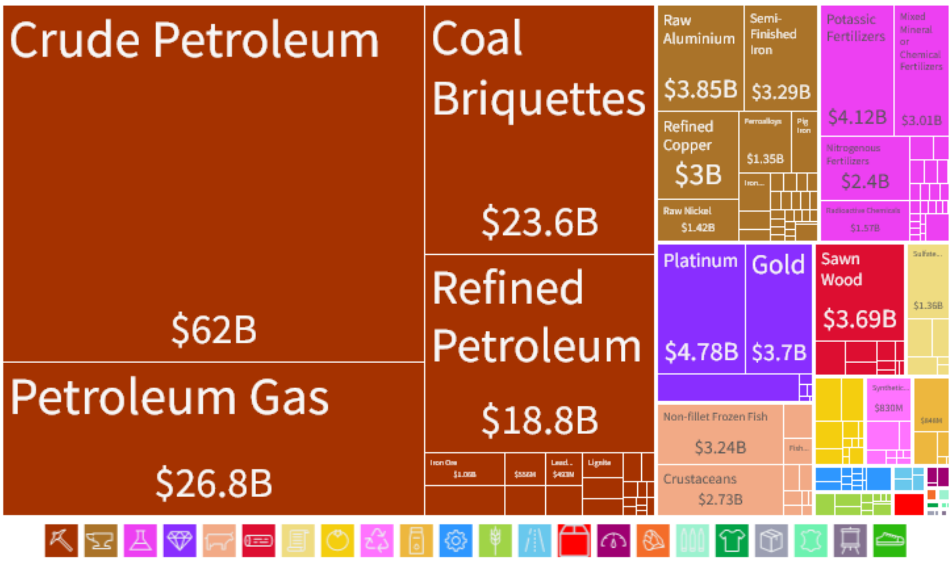

Figure 15: Russian exports in 2020 in USD (OEC, n.d.)

Sanctions have not yet been implemented due to the EU's heavy reliance on Russian gas, but as previously said the construction of the NordStream 2 gas pipeline between Germany and Russia has been put on hold (BBC, 2022). Overall speaking, dependence greatly varies across various EU member states. The three nations that import the most Russian gas are Latvia, Austria, and Bulgaria, while France, Belgium, and Estonia import the least.

Natural gas deliveries were gradually reduced following the imposition of EU sanctions on Russia, reaching zero or almost zero levels for several pipelines. The graph below shows how much natural gas was imported into European countries through the main pipelines between January 2021 and the beginning of January 2023. At the end of 2021, gas imports through the Ukraine Transit pipeline began to decrease. Russian gas imports via this channel began to rise again following the Russian invasion on February 24, 2022 (week 8), before falling to a constant level in week 20, 2022. Up until week 23, 2022, gas imports through the NordStream pipeline were quite consistent. After that, they began to drop sharply and have been fully stopped since week 36, 2022. As of week 20, 2022, imports through the Yamal pipeline have already been stopped. Only the imports made through TurkStream are essentially constant and at the same level as they were before the invasion of Ukraine.

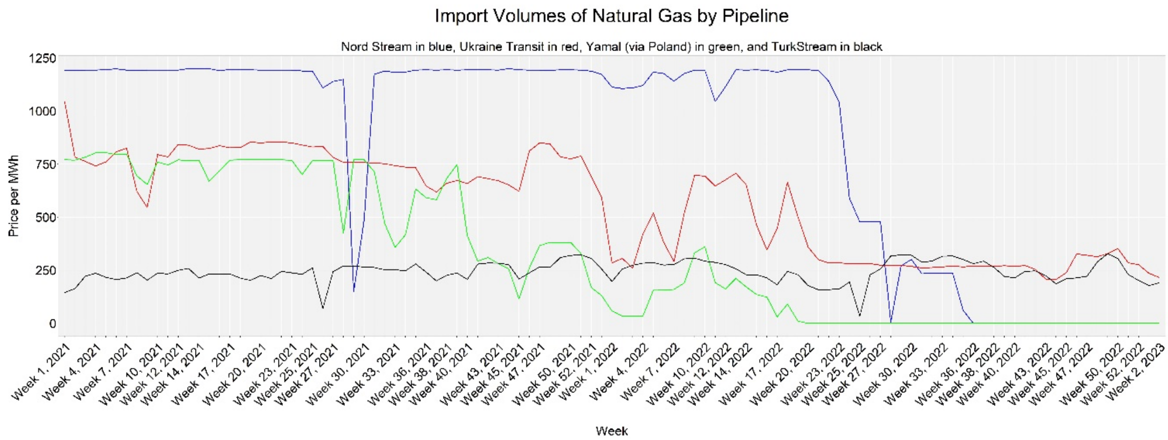

Figure 16: Import Volumes of Natural Gas from Russia by Pipeline (Statista, 2023)

Natural gas prices in Europe have risen to historically unheard-of levels as a result of the drop in Russian gas imports to the EU, notably through NordStream 1. Based on information from Statista (2023) figure 2 depicts the increase in gas costs from roughly 20€/MWh in pre-war times to more than 270€/MWh in August 2022. Gas prices began to decline once more in the following months and nearly returned to pre-war levels by the beginning of January 2023.

Costs for other major energy sources, such as coal and oil, have been greatly impacted by growing gas costs due to their substitutability. Furthermore, electricity costs were at an all-time high, owing mostly to European power market regulations based on the merit order concept. According to this premise, the market price of energy is established by the power plant that provides the last quantity of power required in the system. Prices tend to be cheaper when there is a lot of renewable capacity in the market; however, peak power plants, which are geared to meet peaks in demand, are frequently diesel or gasoline fuelled and have the greatest operational costs, and so determine the price for the whole market (Appunn & Wettengel, 2023; Next Kraftwerke, 2023).

As observed in previous statistics, gas prices began to rise before the commencement of the Russian invasion of Ukraine and peaked in August 2022. Figure 17 by Eurostat(2022b) will be used to further demonstrate the percental variations in gas prices in different European countries. It depicts the percentage change in natural gas prices for home users between the first half of 2022 and the first half of 2021. Gas costs were growing over practically all of Europe, but not uniformly. Estonia has had some of the biggest percentage changes, while

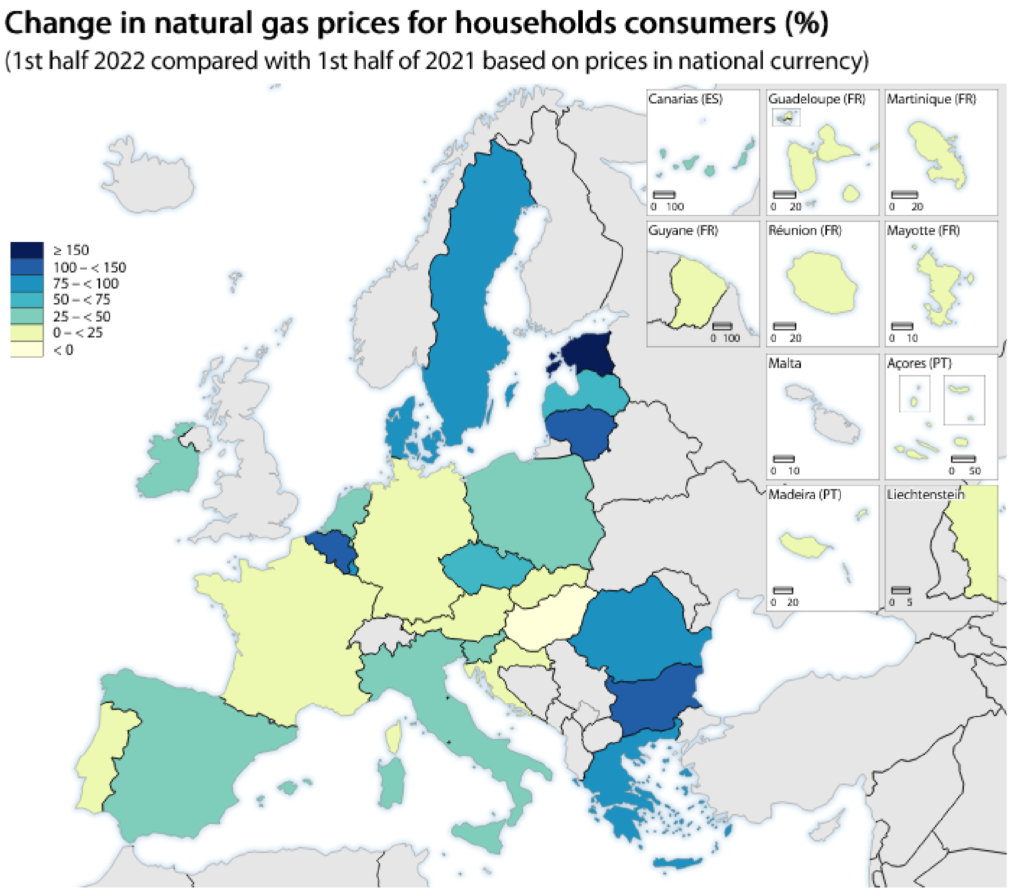

Figure 17: Change in natural gas prices for household consumers (Eurostat, 2022c)

Hungary has seen some of the lowest. This can be mainly explained by the previously mentioned merit order principle which the European market follows.

Figure 18 clearly demonstrates that electricity costs were growing dramatically in virtually all European nations, with a few outliers such as Portugal, the Netherlands, Poland, and Slovenia, where prices were even falling over the two-time frames examined. Contrarily, prices in Denmark, Estonia, and the Czech Republic were almost 55% higher than they had been.

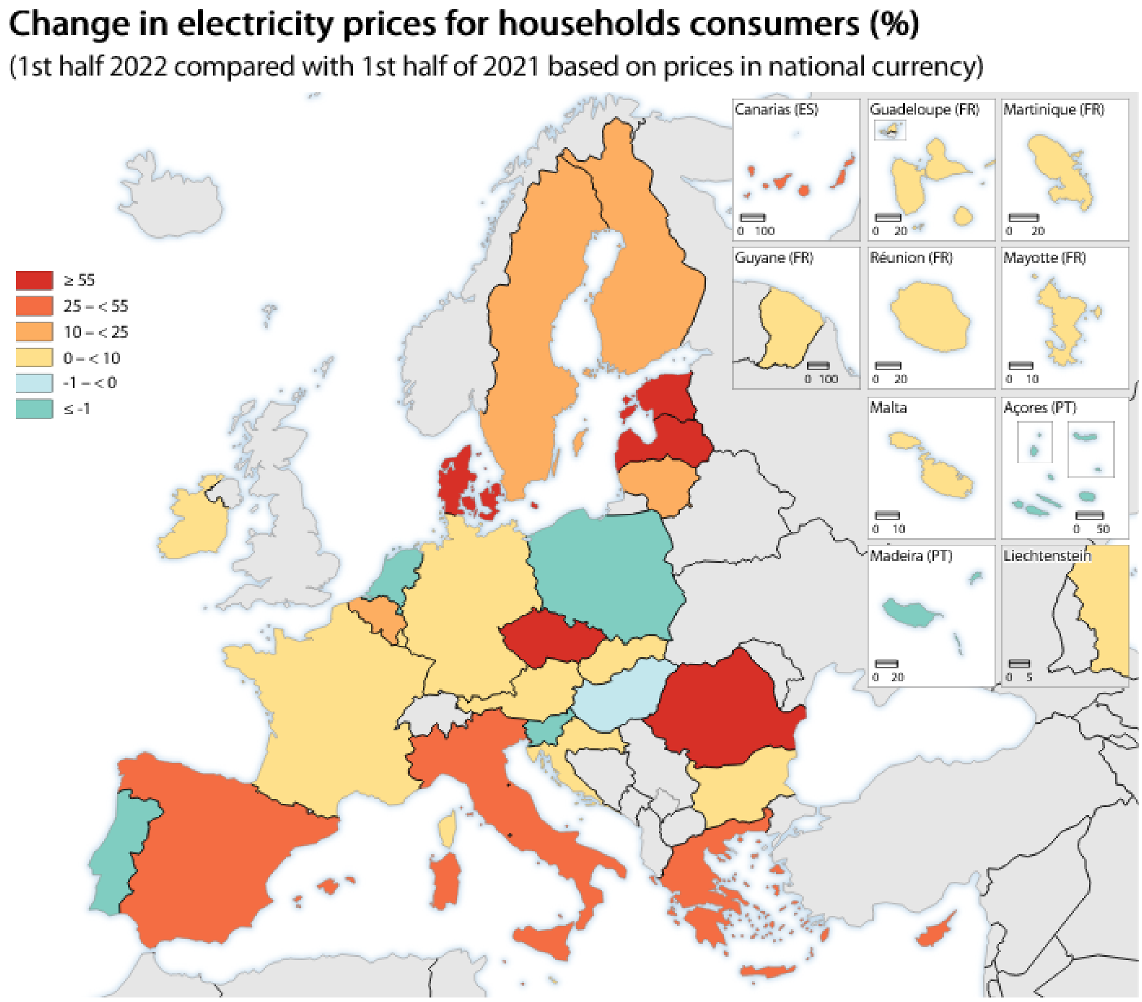

Figure 18: Change in electricity prices for household consumers (Eurostat, 2022c)

As can be seen in this analysis of the impact of the Russian invasion of Ukraine, the European energy and electricity markets are highly dependent on Russian gas deliveries through the various pipelines connecting the European grid, to Russian gas plants. Some short-term measures such as a Europe-wide 15 % gas saving measure over the winter of 2022-2023 or individual caps on electricity prices in Spain and Portugal were introduced. (Maaskant & Bogaert, 2023). Additionally, measures of accountability for wholesalers were introduced too after being accused of artificially inflating consumer prices and benefitting from the crisis. For this reason, the EU has introduced temporary windfall taxes, which impose a tax on income from the sale and supply of electricity above a certain threshold (Deloitte, 2023)

To reduce the impact of geopolitical events in the medium term, Europe is actively trying to get less dependent on external partners and produce more energy within its borders. The following part will highlight some avenues on how Europe can achieve higher independence from Russia and especially Russian gas in the upcoming years.

In order to facilitate the transition away from Russian gas, the EC launched the REPowerEU proposal in May 2022. The REPowerEU plan is divided into several parts, including both short-term and long-term initiatives such as energy conservation, diversifying energy suppliers, and hastening the adoption of renewable energy sources (European Commission, 2022b). In the following section four of the most important points will be highlighted to show how the EU Commission is planning on transitioning away from Russian gas.

Reducing fossil fuel consumption in industry and transport

The EC expects to reduce emissions and boost competitiveness by replacing renewable energy sources with fossil fuels in industrial operations. 35 billion cubic meters of natural gas shall be saved by 2030 through electrification, energy efficiency, and the increased use of both biogas and renewable hydrogen. The Commission will use the Innovation Fund and carbon contracts to fund green hydrogen and renewable energy. It will also establish an EU Solar Industry Alliance, give technical support, and increase efforts on critical raw materials. In the transportation sector, the Commission will present a Greening of Freight Package to increase efficiency, transition to zero-emission vehicles, and promote actions for local, regional, and national governments to replace fossil fuels (European Commission, 2022b).

Accelerating the implementation of renewable energy sources

The EC aims to enhance the 2030 renewables target to 45% under the Fit for 55 initiative. The plan for example includes a Solar Strategy to produce up to 600GW of solar power in the EU itself by 2030, a Solar Rooftop Initiative to install solar panels on new residential and public buildings, increased use of heat pumps, and the inclusion of geothermal and solar thermal energy into heating systems. Furthermore, a modification both to the Renewable Energy Directive itself and a proposal to change it are included. The policy seeks to import 10 million tonnes of renewable hydrogen and create 10 million tonnes of local renewable hydrogen by 2030. The (European Commission, 2022b) estimates that the biomethane action plan will increase output to 35 bcm by leveraging financial incentives and industrial cooperation.

Saving Energy

The "EU Save Energy Communication" that the EC proposes to create will outline urgent steps to reduce gas and oil consumption by 5% and enhance the "Fit for 55" program's energy efficiency target to 13%. Member nations are asked to implement financial plans and launch PR campaigns to promote energy conservation. Backup plans and customer priority standards are also in place in case of supply disruption (European Commission, 2022b).

Diversifying Energy Supplies

The EU has established an Energy Platform that pools demand and makes the most use of infrastructure in order to diversify energy sources. The Commission is considering creating a unified gas, LNG, and hydrogen procurement mechanism. Legislation to diversify the sources of gas is being studied. The EU External Energy Strategy prioritizes a green global energy transition while also advancing hydrogen and renewable energy sources. It also aims to boost energy efficiency and savings. Significant hydrogen shipping routes will be built in the North Sea and Mediterranean, and the EU will help Ukraine and other weaker nations (European Commission, 2022b).

As seen in the previous part, the Russian invasion of Ukraine had a huge impact on the overall energy and electricity sector in the EU. Prices were sharply rising, especially in the summer of 2022, and gas imports via the most important routes were cut dramatically. To tackle these price increases the EU has set up the REPowerEU plan which focuses on cutting prices both in the short, as well as the long term. Furthermore, this plan shall increase the electricity production within the EU itself and make it more resilient to geopolitical events arising in countries that play a vital role in supplying Europe with gas or other energy sources.

8. Discussion

The following discussion serves to critically evaluate the changes that occurred in the last 10 years and what they might entail in the future. The discussion will focus on the market trends and design that will play a major role in resolving the current crisis and preventing a new one in the future as well as on the geopolitical/economic implications of the Russian invasion for the European electricity markets.

The analysis of the development of the European Energy Market over the past 10 years reveals both positive and challenging trends. Shifting to renewables and biofuels as a main power production source is expected to vastly decrease the dependency on fossil fuels and is important for decreasing carbon emissions. However, the intermittent nature of renewable energy sources creates problems for grid stability and necessitates the development of effective energy storage devices (*Grid-Scale Storage – Analysis*, n.d.) in addition to increased network capabilities. Storage capabilities and infrastructure development are crucial for accommodating the intermittent nature of renewable energy sources and ensuring a reliable energy supply. Investments in energy storage technologies and the modernization of the grid infrastructure are essential to facilitate the integration of renewables and enhance energy security (European Commission, n.d.).

Declining amounts of solid fossil fuels in electricity production help to reduce greenhouse gas emissions. However, addressing environmental issues connected with these energy types, such as air pollution and public health risks, is crucial. Policies and incentives should be implemented to facilitate the phase-out of solid fossil fuels (Gerasimchuk et al., n.d.).

The efforts to diversify the European energy mix and reduce the overall fossil fuel dependency have decreased the importance of oil, coal, and natural gas. Nonetheless, the transition away from these fuels requires careful consideration of the associated challenges. Natural gas, for example, is sometimes regarded as a transitional fuel because of its reduced carbon emissions, although there are worries about extraction methods, such as fracking, and the overall environmental effect remains problematic (IEA, n.d.).

The European Energy Union idea aspires to promote a more integrated, secure, and sustainable energy market inside the European Union. Harmonization of energy policy, cross-border collaboration, and interconnection development all play important roles in developing a more robust and efficient energy system.

The increase in electricity and gas prices over the past years raises concerns about energy affordability and market dynamics. Geopolitical tensions, supply-demand dynamics, and policy changes contribute to this rise. European policymakers will have to address these challenges by establishing laws that help low-income families, promote energy efficiency, and ensure competitive pricing at the same time.

The overall design of the European energy market is critical to ensure fair competition, encourage investments in clean energy technologies, and facilitate the energy transition. Market regulations and mechanisms should be carefully crafted to balance the interests of stakeholders, promote renewable energy deployment, and enable a smooth transition toward a decarbonized energy system.

If the ETS is to incorporate the new climate ambitions such as the 2030 goals of reducing emissions by 55 %, an analysis has shown that allowance prices might increase to 45–94 €/tCO2 and thus reduce cumulative carbon emissions to 14.2–18.3 GtCO2 compared to 23.5–33.1 GtCO2 from the current trajectory. To back this up, ETS prices reached their all-time high in December 2021, above 86 €/tCO2 which might indicate that the stringency of the new 2030 targets is gradually internalized by the market (Bruninx & Ovaere, 2022).

Studies have also evidenced the need to substantially increase (up to ten-fold increase) the current growth rate of RES if climate neutrality is to be achieved until 2050, considering the maximum historical annual growth of 66 TWh/year (Pickering et al., 2022). The current crisis might thus have positive implications in this regard if investments are substantially increased.

Geopolitical Implications on the European energy market

The Ukrainian invasion by Russia is having major geoeconomic and geopolitical implications for the European electricity market, both short and long-term. The longstanding reliance and dependence on Russian gas has been an intensely discussed topic for many years, especially since the Russian annexation of Crimea in 2014 made it clear that Russia would not be playing by the rules of international law.

Despite this, major infrastructure projects like Nord Stream 2 (Nord Stream 1 was already connecting Russia and Germany via another pipeline since 2011) which was supposed to connect Russia and Germany via undersea pipelines continued without delays until the invasion in February 2022.

While the ongoing energy crisis is unlikely to have a major effect on the overall objective of the EU to create a carbonless European market, it will have implications on the way the EU will reach this goal both in terms of the overall energy mix and security/affordability issues. In the short term, the abrupt price hike has made the issue of energy affordability a central topic, surpassing all other policy considerations. Some coal-fired power plants in Germany eventually continued their operations despite being planned to phase out in 2022 due to environmental concerns, with similar things happening in Austria, the UK, and the Netherlands. While national governments were trying to reduce the negative effects on populations via subsidies, direct payments, capped prices, or other monetary benefits, the EU has endorsed measures such as a mandatory gas storage obligation, common gas purchases, and a (temporary) relaxation of rules on market intervention. The crisis also underscored that while committed to the energy transition, fossil fuels are still the backbone of European electricity usage.

In a long-term strategic sense, the Russian invasion has managed to make natural gas what RES used to be: both expansive and unreliable, and this might affect the policies of countries that have traditionally been more reluctant to commit to decarbonization such as Czechia or Poland (except Hungary which has acted opportunistically to lower EU sanctions and tried to remain in good relations with Russia). The strategic role of RES in these countries might be strengthened (Osička & Černoch, 2022).

Since there is little indication that the ongoing conflict is going to end anytime soon, Europe will very likely have to compensate for limited gas availability by on the one side investing in renewables, heat pumps, and biomass and on the other side delaying coal and lignite phaseouts to 2040 (thus, extending the end-date by a decade). If the 2 Celsius scenario of the Paris Agreement is to be respected, gas prices are projected to increase from 45 to 65 Euro/MWh by 2025 and remain at this level throughout the energy transition while having little overall impact on CO2 prices.

Countries with good wind resources, such as Denmark, Great Britain, and France are likely to increase investments in wind power to compensate for the missing gas availability. In Italy and the Balkans, a substantial increase in costs related to coal power will take place, indicating that gas is replaced by additional coal production. Norway for instance has announced to expand its number of windmills from the current two to 1500 by 2040 suggesting a major break in energy policy.

What is noteworthy to mention is that wind energy will have to be added to a larger extent than solar. This is due to the limited gas capacity that will require additional electricity in the winter period when heating demand is increased, and wind seasonality correlating with the increased demand. What has to be expanded universally Europe-wide is the investment in heat pumps to replace gas as a means to supply heat (Pedersen et al., 2022).

Additionally, new momentum for the development of hydrogen and nuclear power has increased with the UK and France announcing the creation of new reactors(Kuzemko et al., 2022).

Other authors have raised concerns that renewables and their difficult supply chains via rare earths or minerals used for production might lead to problems in the future and that a refocus on supply issues has in the past tended to coincide with a demotion of environmental goals such as the nuclear renaissance during the 1970s as a reaction to the oil crisis. The need for urgent measures brings about a tendency to rely on centralized, top-down responses from actors that can deliver solutions in a short time such as large-scale energy providers and these are usually not RES providers. Since in medium-term Europe will continue to rely on gas, they instead propose a diversification of energy sources which is also a strategic objective of the EU. Partners such as Qatar, Algeria, and Azerbaijan will play an increasingly important role in this regard, together with a strengthened partnership with the USA. New gas infrastructure will be needed such as pipelines and floating terminals which will cost billions to produce (Kuzemko et al., 2022).

All in all, the geopolitical implications of the war in Ukraine cannot be denied. Within little more than a year, the EU has basically supplanted Russian gas which amounted to almost 50 % of all gas imports before the war. The EU had done so by relying on other countries such as Norway, Algeria, and the USA while increasing renewable capacity (Euronews.green, 2023). Since there seems no possible end date for the ongoing conflict in Ukraine, it is likely that the EU will continue to move towards increased RES production and diversification of its supply via alternative countries and means such as wind and nuclear expansion.

New European initiatives like joint European gas purchases are being implemented, with the goal of securing better prices (Malingre, 2023).
By excluding Russian providers for years to come, these initiatives might suggest an even closer collaboration of European nations in the electricity market for years to come.

9. Conclusion

This chapter serves to conclude our findings and answers the two-folded research question posed.

The objective of the thesis was to analyse the European electricity market over the course of the last 10 years and based on these findings, give an outlook of what the market will look like in the future.

Throughout the last 10 years, we have identified 4 broad change issues: First, the European electricity market has substantially shifted toward renewable energy sources, even though at varying speeds nationally. On the one hand, most Western-European countries have recognized the strategic value of RES while Eastern Europeans have been more hesitant to accelerate the transition toward a carbon-neutral continent due to multiple reasons such as lower technology standards, infrastructure issues, or a population with fewer income to face the energy transition. This division of national interests has left the EU, more concretely the EC, as a central actor for common actions which has tried to steer EU countries in a more climate-friendly direction. Initiatives and directives such as the European Green Deal or the Clean Energy Packages have contributed toward creating enforceable and concrete goals on a supra-national level.

Additionally, new market models shave been developed, focussing on integrating existing markets by expanding and enhancing the use of market coupling mechanisms such as FBMC and PCR which allow for electricity to be traded between countries at an unprecedented range. At the same time, significant barriers to electricity trade persist with international trade of electricity accounting for little more than 15 % in 2022 and strategic bottlenecks in transmission capabilities.

New forms of information exchanges such as smart grid technologies coupled with a trend toward decentralization of energy sources through renewables have shaped a market in which consumers not only use up electricity but also play an active role in producing it. The integration of bi-directional information flows has contributed to the balance of the overall electricity markets which can leverage live information and thus optimize the flow of electricity in terms of price and time.

Lastly, the ETS market has moved away from the free allocation of CO_2 allowances toward a market-based auction approach which has increased its effectiveness. While the social cost of carbon is still not fully represented in the CO_2 price, actors in the electricity markets have begun to incorporate the cost of carbon in their operations.

In terms of prices, both electricity and gas prices have increased substantially over the last 8 years. This correlation can be attributed to the fact that in times of high gas prices, electricity prices tend to be higher as well due to the way electricity is priced according to the merit order principle. This rise can be explained by the ongoing energy transition with substantial investments in renewables whose costs are often passed on to consumers, an increased need to expand and secure infrastructure, an increased CO_2 price, (national) taxes and subsidies which can add to the overall prices as well as geopolitical international factors. Especially since the Russian invasion of Ukraine began, gas prices have been soaring due to lower Russian gas deliveries, especially via gas pipelines connecting Europe to Russia.

This has led to increased pressure to reform the European electricity and energy markets, for instance through the REPowerEU plan which includes several points. Some of the most important ones involve: reducing fossil fuel consumption in industry and transport, accelerating the implementation of RES, saving energy, and diversifying energy supplies.
While gas will continue to play an important role in the medium to long term of European energy production, it is expected that solar, wind, and nuclear will play an increasingly important part in securing supply.

10. References

ACER. (2023a). *ACER to consult on the methodology for electricity intraday flow-based capacity calculation in the Core region*. https://www.acer.europa.eu/news-and-events/news/acer-consult-methodology-electricity-intraday-flow-based-capacity-calculation-core-region

ACER. (2023b). *Cross-zonal capacity—70% target*. https://documents.acer.europa.eu/nl/Electricity/Market%20monitoring/Paginas/Cross-zonal-capacity-70-target.aspx

Antezza, A., Bushnell, K., Frank, A., Frank, P., Franz, L., Kharitonov, I., Kumar, B., Rebinskaya, E., Trebesch, C., & Schramm, S. (2023). *Ukraine Support Tracker Data*. https://www.ifw-kiel.de/publications/data-sets/ukraine-support-tracker-data-17410/

Appunn, K., & Wettengel, J. (2023). *Understanding the European Union's Emissions Trading Systems (EU ETS)*. Clean Energy Wire. https://www.cleanenergywire.org/factsheets/understanding-european-unions-emissions-trading-system

Bakare, M. S., Abdulkarim, A., Zeeshan, M., & Shuaibu, A. N. (2023). A comprehensive overview on demand side energy management towards smart grids: Challenges, solutions, and future direction. *Energy Informatics*, *6*(1), 4. https://doi.org/10.1186/s42162-023-00262-7

Baker, P., Hogan, M., & Kolokathis, C. (2018). Realising the benefits of European market integration. *Regulatory Assistance Project (RAP)*, 10.

Barchart. (n.d.). *Dutch TTF Gas Endex Apr '23 Futures Interactive Chart*. Barchart.Com. Retrieved 25 March 2023, from https://www.barchart.com/futures/quotes/TGJ23/interactive-chart

Bayer, P., & Aklin, M. (2020). The European Union Emissions Trading System reduced CO_2 emissions despite low prices. *Proceedings of the National Academy of Sciences*, *117*(16), 8804–8812. https://doi.org/10.1073/pnas.1918128117

BBC. (2022, January 27). What are the sanctions on Russia and are they hurting its economy? *BBC News*. https://www.bbc.com/news/world-europe-60125659

Bersalli, G., Menanteau, P., & El-Methni, J. (2020). Renewable energy policy effectiveness: A panel data analysis across Europe and Latin America. *Renewable and Sustainable Energy Reviews*, *133*, 110351. https://doi.org/10.1016/j.rser.2020.110351

Böckers, V., Haucap, J., & Heimeshoff, U. (2013). *Cost of non-Europe in the Single Market for energy: Benefits of an integrated European electricity market : the role of competition.* Publications Office. https://data.europa.eu/doi/10.2861/19914

Bórawski, P., Wyszomierski, R., Bełdycka-Bórawska, A., Mickiewicz, B., Kalinowska, B., Dunn, J. W., & Rokicki, T. (2022). Development of Renewable Energy Sources in the European Union in the Context of Sustainable Development Policy. *Energies*, *15*(4), 1545. https://doi.org/10.3390/en15041545

Brodny, J., & Tutak, M. (2020). Analyzing Similarities between the European Union Countries in Terms of the Structure and Volume of Energy Production from Renewable Energy Sources. *Energies*, *13*(4), 913. https://doi.org/10.3390/en13040913

Bruninx, K., & Ovaere, M. (2022). COVID-19, Green Deal and recovery plan permanently change emissions and prices in EU ETS Phase IV. *Nature Communications*, *13*(1), 1165. https://doi.org/10.1038/s41467-022-28398-2

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., & Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy*, *134*, 110960. https://doi.org/10.1016/j.enpol.2019.110960

Carfora, A., Pansini, R. V., & Scandurra, G. (2022). Energy dependence, renewable energy generation and import demand: Are EU countries resilient? *Renewable Energy*, *195*, 1262–1274. https://doi.org/10.1016/j.renene.2022.06.098

Chestney, N. (2022). Explainer: How natural gas is traded in Europe. *Reuters*. https://www.reuters.com/business/energy/how-natural-gas-is-traded-europe-2022-12-20/

Corona, L., Mochon, A., & Saez, Y. (2022). Electricity market integration and impact of renewable energy sources in the Central Western Europe region: Evolution since the implementation of the Flow-Based Market Coupling mechanism. *Energy Reports*, *8*, 1768–1788. https://doi.org/10.1016/j.egyr.2021.12.077

Cullinane, M., Judge, F., O'Shea, M., Thandayutham, K., & Murphy, J. (2022). Subsea superconductors: The future of offshore renewable energy transmission? *Renewable and Sustainable Energy Reviews*, *156*, 111943. https://doi.org/10.1016/j.rser.2021.111943

Deloitte. (2023). *Overview of windfall tax on electricity generators*. https://www.taxathand.com/article/29516/Belgium/2023/Overview-of-windfall-tax-on-electricity-generators

Dorsman, A., Westerman, W., Karan, M. B., & Arslan, Ö. (Eds.). (2011). *Financial Aspects in Energy*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-19709-3

Elavarasan, R. M. (2019). The Motivation for Renewable Energy and its Comparison with Other Energy Sources: A Review. *European Journal of Sustainable Development Research*, *3*(1). https://doi.org/10.20897/ejosdr/4005

Electricity Forum. (2023). *Types of Electricity—Modern Methods*. https://www.electricityforum.com/types-electricity

Ellerbeck, S. (2023). *Wind and solar power generated more electricity in the EU last year than gas did. Here's how* (Centre for Energy and Materials). World Economic Forum. https://www.weforum.org/agenda/2023/01/renewable-energy-electricity-record-europe/

ENTSO E. (2019). *Connecting Europe: Electricity*. file:///Users/leopoldreinisch/Desktop/Master%20Thesis/TYNDP2018_Executive%20Report.pdf

Etheredge, J. (2023). *How Do We Measure Electricity?* simplethread.

Euronews.green. (2023). *Europe's 'energy war' in data: How have EU imports changed since Russia's invasion of Ukraine?* https://www.euronews.com/green/2023/02/24/europes-energy-war-in-data-how-have-eu-imports-changed-since-russias-invasion-of-ukraine#:~:text=In%202021%2C%20the%20EU%20imported,12%20per%20cent%20in%20October.

Europe – Countries & Regions. (n.d.). IEA. Retrieved 30 May 2023, from https://www.iea.org/regions/europe

European Commission. (n.d.). *Energy storage*. European Commission. Retrieved 30 May 2023, from https://energy.ec.europa.eu/topics/research-and-technology/energy-storage_en

European Commission. (2015). *Towards a European Energy Union: A secure, sustainable, and competitive energy for every European* (p. 21). https://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF

European Commission. (2018). *Electricity interconnection targets*. https://energy.ec.europa.eu/topics/infrastructure/electricity-interconnection-targets_en#eu-electricity-interconnection-target

European Commission. (2019). *Clean energy for all Europeans package*. https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en

European Commission. (2020). *A European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2022a). *EU action to address the energy crisis*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/eu-action-address-energy-crisis_en

European Commission. (2023a). *Delivering the European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2023b). *Development of EU ETS (2005-2020)*. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en

European Commission. (2022b). *REPowerEU* [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131

European Commission. Directorate General for Energy. & Tractebel Impact. (2020). *Cross-border transmission capacity calculation: Analysis of the key parameters.* Publications Office. https://data.europa.eu/doi/10.2833/461068

European Council. (2023, May 10). *How is EU electricity produced and sold?* https://www.consilium.europa.eu/en/infographics/how-is-eu-electricity-produced-and-sold/

European Environment Agency. (2023). *Share of energy consumption from renewable sources in Europe (8th EAP)*. https://www.eea.europa.eu/ims/share-of-energy-consumption-from

European Parliament. (2022). *Europe's Energy Security. In Search of Supply Independence From Russia.* https://poland.representation.ec.europa.eu/system/files/2022-06/Europes_energy_security.pdf

Eurostat. (n.d.-a). *Database—Energy—Eurostat*. Retrieved 31 May 2023, from https://ec.europa.eu/eurostat/web/energy/database

Eurostat. (n.d.-b). *File:Gross electricity production by fuel, EU, 2000-2021 (GWh) v2.png*. Retrieved 25 March 2023, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Gross_electricity_production_by_fuel,_EU,_2000-2021_(GWh)_v2.png

Eurostat. (2022a). *From where do we import energy?* https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html#:~:text=It%20is%20measured%20by%20the,were%20met%20by%20net%20imports.

Eurostat. (2022b). *Electricity and gas prices in the first half of 2022*. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20221031-1

Florence School of Regulation. (2020). *Electricity markets in the EU*. https://fsr.eui.eu/electricity-markets-in-the-eu/

Fusco, E., Maggi, B., & Rizzuto, L. (2022). Alternative indicators for the evaluation of renewables in Europe: An efficiency approach. *Renewable Energy*, *190*, 48–65. https://doi.org/10.1016/j.renene.2022.03.007

Gerasimchuk, I., Merrill, L., Bridle, R., Gass, P., Sanchez, L., Kitson, L., & Wooders, P. (n.d.). *FOSSIL FUEL PHASE-OUT AND A JUST TRANSITION:*

Grid-Scale Storage – Analysis. (n.d.). IEA. Retrieved 30 May 2023, from https://www.iea.org/reports/grid-scale-storage

Gugler, K., Haxhimusa, A., & Liebensteiner, M. (2018). Integration of European Electricity Markets: Evidence from Spot Prices. *The Energy Journal*, *39*(01). https://doi.org/10.5547/01956574.39.SI2.kgug

Heldeweg, M. A. & Séverine Saintier. (2020). Renewable energy communities as 'socio-legal institutions': A normative frame for energy decentralization? *Renewable and Sustainable Energy Reviews*, *119*, 109518. https://doi.org/10.1016/j.rser.2019.109518

Hook, L., & Thomas, N. (2022). *Can Europe keep the lights on?* Financial Times. https://ig.ft.com/electricity-sharing/

Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., & Van Den Broek, M. (2018). Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. *Renewable and Sustainable Energy Reviews*, *81*, 2181–2195. https://doi.org/10.1016/j.rser.2017.06.028

IEA. (n.d.). *The Role of Gas in Today's Energy Transitions – Analysis*. IEA. Retrieved 30 May 2023, from https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions

IRENA. (2020). *CO-OPERATION BETWEEN TRANSMISSION AND DISTRIBUTION SYSTEM OPERATORS*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_TSO-DSO_co-operation_2020.pdf?la=en&hash=5D78444F4339DC130204A0F9A99A30753368AABC

Jegen, M. (2014). Energy policy in the European Union: The power and limits of discourse. *Energy Policy in the European Union*, *LES CAHIERS EUROPEENS DE SCIENCES PO.*(2).

Jones, D. (2023). *European Electricity Review 2023*. Ember. https://ember-climate.org/insights/research/european-electricity-review-2023/

Jotanovic, V., & D'Ecclesia, R. L. (2021). The European gas market: New evidences. *Annals of Operations Research*, *299*(1–2), 963–999. https://doi.org/10.1007/s10479-020-03714-5

Just Energy. (2023). *How Is Electricity Made?* https://justenergy.com/learning-center/electricity/

Kanellakis, M., Martinopoulos, G., & Zachariadis, T. (2013). European energy policy—A review. *Energy Policy*, *62*, 1020–1030. https://doi.org/10.1016/j.enpol.2013.08.008

Kuzemko, C., Blondeel, M., Dupont, C., & Brisbois, M. C. (2022). Russia's war on Ukraine, European energy policy responses & implications for sustainable transformations. *Energy Research & Social Science*, *93*, 102842. https://doi.org/10.1016/j.erss.2022.102842

Leal-Arcas, R., Akondo, N., & Rios, J. A. (2019). Energy Decentralization in the European Union. *Queen Mary University of London, School of Law*, *Legal Studies research paper No. 307*, 58.

Logan, J., Marcy, C., McCall, J., Flores-Espino, F., Bloom, A., Aabakken, J., Cole, W., Jenkin, T., Porro, G., Liu, C., Ganda, F., Boardman, R., Tarka, T., Brewer, J., & Schultz, T. (2017). *Electricity Generation Baseline Report* (NREL/TP--6A20-67645, 1342379; p. NREL/TP--6A20-67645, 1342379). http://www.osti.gov/servlets/purl/1342379/

Maaskant, K., & Bogaert, T. (2023). *Weathering the Storm: EU Responses to the 2022 Energy Crisis*. Teneo. https://www.teneo.com/weathering-the-storm-eu-responses-to-the-2022-energy-crisis/

Maćkowiak-Pandera, J. (2018). *Linking Sectors: Power, transport, heat united*. Heinrich Böll Stiftung. https://eu.boell.org/en/2018/04/24/linking-sectors-power-transport-heat-united

Malingre, V. (2023, May 11). EU launches historic joint gas purchase tender to increase energy security. *Le Monde*. https://www.lemonde.fr/en/european-union/article/2023/05/11/eu-launches-historic-joint-gas-purchase-tender-to-increase-energy-security_6026258_156.html#:~:text=On%20Wednesday%2C%20May%2010%2C%20the,Commission%20Vice%20President%20Maros%20Sefcovic.

Mata Pérez, M. D. L. E., Scholten, D., & Smith Stegen, K. (2019). The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security. *Energy Strategy Reviews*, *26*, 100415. https://doi.org/10.1016/j.esr.2019.100415

Matt, E. (2022, September 21). *European wholesale electricity price data*. Ember. https://ember-climate.org/data-catalogue/european-wholesale-electricity-price-data/

Meeus, L. (2020) *The Evolution of Electricity Markets in Europe*. Edward Elgar Publishing. https://doi.org/10.4337/9781789905472

Meeus, L., Purchala, K., & Belmans, R. (2005). Development of the Internal Electricity Market in Europe. *The Electricity Journal*, *18*(6), 25–35. https://doi.org/10.1016/j.tej.2005.06.008

Next Kraftwerke. (2023). *What is Market Coupling?* https://www.next-kraftwerke.com/knowledge/market-coupling#milestones-on-the-way-to-the-european-single-market

OECD. (n.d.). *Russia (RUS) Exports, Imports, and Trade Partners | OEC - The Observatory of Economic Complexity*. Retrieved 30 May 2023, from https://oec.world/en/profile/country/rus

Ofgem. (2014). *Bidding Zones Literature Review*. https://www.ofgem.gov.uk/sites/default/files/docs/2014/10/fta_bidding_zone_configuration_literature_review_1.pdf

Osička, J., & Černoch, F. (2022). European energy politics after Ukraine: The road ahead. *Energy Research & Social Science*, *91*, 102757. https://doi.org/10.1016/j.erss.2022.102757

Pedersen, T. T., Gøtske, E. K., Dvorak, A., Andresen, G. B., & Victoria, M. (2022). Long-term implications of reduced gas imports on the decarbonization of the European energy system. *Joule*, *6*(7), 1566–1580. https://doi.org/10.1016/j.joule.2022.06.023

Pellerin-Carlin, T., & Vinois, J.-A. (2018). 1. The governance of the Energy Union: A new relationship between European citizens and decision makers. *Notre Europe*.

Petcu, I. (2022). *How are EU electricity prices formed and why have they soared?* Union of the Electricity Industry - Eurelectric aisbl. https://www.eurelectric.org/in-detail/electricity_prices_explained/

Pickering, B., Lombardi, F., & Pfenninger, S. (2022). Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule*, *6*(6), 1253–1276. https://doi.org/10.1016/j.joule.2022.05.009

Pollitt, M. G. (2019). The European Single Market in Electricity: An Economic Assessment. *Review of Industrial Organization*, *55*(1), 63–87. https://doi.org/10.1007/s11151-019-09682-w

Poplavskaya, K., Totschnig, G., Leimgruber, F., Doorman, G., Etienne, G., & De Vries, L. (2020). Integration of day-ahead market and redispatch to increase cross-border exchanges in the European electricity market. *Applied Energy*, *278*, 115669. https://doi.org/10.1016/j.apenergy.2020.115669

Quemin, S. (2022). Raising climate ambition in emissions trading systems: The case of the EU ETS and the 2021 review. *Resource and Energy Economics*, *68*, 101300. https://doi.org/10.1016/j.reseneeco.2022.101300

Reuters. (2023). *EU extends gas price cap system to all EU hubs*. https://www.reuters.com/business/energy/eu-extends-gas-price-cap-system-all-eu-hubs-2023-03-31/

RITE Systems Analysis Group. (2023). *Various Methods of Electricity Generation*. https://www.rite.or.jp/system/en/learn-energy/energy-use/hatsuden/

Sadid, N., Gilbert, C., Clark, D., Foy, H., Kommenda, N., Stabe, M., Kao, J. S., Bernard, S., Chazan, G., Smith, A., Lewis, E., Campbell, C., Olearchyk, R., Rininsland, Æ., Learner, S., Reed, J., & Jones, C. (2023, May 26). Russia’s invasion of Ukraine in maps—Latest updates. *Financial Times*. https://www.ft.com/content/4351d5b0-0888-4b47-9368-6bc4dfbccbf5

Schinke, B., Klawitter, J., Döring, M., Komendantova, N., Irshaid, J., & Bayer, J. (2017). *Energy Planning for Sustainable Development in the MENA Region*. bicc- Bonn International Centre for Conflict Studies.

Shaw, S. (2022). *Why does the price of gas drive electricity prices, including renewables?* (Good Energy). Energy. https://www.goodenergy.co.uk/why-does-the-price-of-gas-drive-electricity-prices-including-renewables/

Statista. (2023). *EU & UK gas imports from Russia by route weekly 2023*. Statista. https://www.statista.com/statistics/1331770/eu-gas-imports-from-russia-by-route/

The Visual Journalism Team. (2022, February 24). Ukraine in maps: Tracking the war with Russia. *BBC News*. https://www.bbc.com/news/world-europe-60506682

United Nations Economic Commission For Europe. (2021). *Life Cycle Assessment of Electricity Generation Options*. United Nations.

https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options

United Nations Industrial Development Organization. (2009). *Energy efficiency technologies and benefits*. https://www.unido.org/sites/default/files/2009-02/Module12_0.pdf

Valarezo, O., Gómez, T., Chaves-Avila, J. P., Lind, L., Correa, M., Ulrich Ziegler, D., & Escobar, R. (2021). Analysis of New Flexibility Market Models in Europe. *Energies*, *14*(12), 3521. https://doi.org/10.3390/en14123521

Verzijlbergh, R. A., De Vries, L. J., Dijkema, G. P. J., & Herder, P. M. (2017). Institutional challenges caused by the integration of renewable energy sources in the European electricity sector. *Renewable and Sustainable Energy Reviews*, *75*, 660–667. https://doi.org/10.1016/j.rser.2016.11.039

Veum, K., & Bauknecht, D. (2019). How to reach the EU renewables target by 2030? An analysis of the governance framework. *Energy Policy*, *127*, 299–307. https://doi.org/10.1016/j.enpol.2018.12.013

World Nuclear Association. (2023). *Nuclear Power Reactors*. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

Zafar, R., Mahmood, A., Razzaq, S., Ali, W., Naeem, U., & Shehzad, K. (2018). Prosumer based energy management and sharing in smart grid. *Renewable and Sustainable Energy Reviews*, *82*, 1675–1684. https://doi.org/10.1016/j.rser.2017.07.018