



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF BUSINESS MANAGEMENT
DEPARTMENT OF BUSINESS TECHNOLOGIES AND ENTREPRENEURSHIP

Agnė Domarkienė

**TRANSFORMATION OF THE EUROPIEN ENERGY SECTOR IN THE
CONTEXT OF GREEN ECONOMY**

Master's degree Thesis

Business Management study programme, state code 6211LX058

International Business specialization

Business study field

Vilnius, 2025

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Annotation Main objective of the master thesis is to understand holistically the transformation process of the European energy sector towards climate neutral domain of the economy and designing a theoretical model of energy sector transformation. This includes an examination of the circumstances, headwinds and tailwinds, affecting the pace of change, and the analysis of the compatibility between economic growth and environmental objectives. The final master's thesis examines the process of European energy sector transformation towards the climate neutrality and sustainability goals. The composition and classification of the sector is assessed, its contribution to the economy, resources and the main factors influencing the green evolution are analysed. The indicators measuring the progress of the sector's transition have also been collected and systematized, and a statistical analysis of European energy indicators has been carried out. The examination of energy sector is concluded with the theoretical model that seeks to combine a wide 360-degree spectrum of elements operating in the energy transformation process. The final work includes regression analysis of the environmental and green energy transformation indicators with a purpose to uncover the impact of energy transformation on the environment. The compatibility of environmental and economic growth goals is assessed by exploring the hypothesis of the environmental Kuznets curve. Finally, the conclusions of the thesis are provided. The work consists of 6 parts: introduction, theoretical analysis, research methodology selection, practical part, conclusions and bibliography. The scope of work - 74 p. text without appendices, 21 illustrations, 11 tables, 1 appendix, 34 bibliographic sources.

Keywords: Energy sector, energy sector transformation, green energy, climate change, renewable energy, fossil fuel, sustainability, GHG emissions, electricity infrastructure, EU regulation.
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Anotacija

Pagrindinis šio magistrinio darbo tikslas yra visapusiškai ištirti bei atskleisti Europos energetikos sektoriaus transformacijos procesą į klimatui neutralią ekonomikos sritį bei nupiešti teorinį energetikos sektoriaus transformacijos modelį. Tyrimas apima išsamų iššūkių, galimybių bei aplinkybių, turinčių įtakos pokyčio tempui nagrinėjimą, taip pat ekonominio augimo ir aplinkosaugos tikslų suderinamumo analizę.

Baigiamajame magistro darbe nagrinėjamas Europos energetikos sektoriaus transformacijos procesas siekiant aplinkosauginių klimato kaitos tikslų. Įvertinama sektoriaus sudėtis ir klasifikacija, analizuojamas jo indėlis į ekonomiką, ištekliai ir pagrindiniai žaliąją evoliuciją įtakojantys veiksniai. Taip pat apžvelgti ir susisteminti sektoriaus transformacijos pažangą matuojantys rodikliai, atlikta Europos energetikos rodiklių statistinė analizė. Šį tyrimą apibendrina energetikos sektoriaus teorinis modelis, kuriuo siekiama apjungti platų 360 laipsnių spektrą elementų, veikiančių energijos transformacijos procese. Baigiamajame darbe atliekama aplinkos ir žaliosios energetikos transformacijos rodiklių regresinė analizė, siekiant atskleisti energijos transformacijos poveikį aplinkai. Aplinkosaugos ir ekonomikos augimo tikslų suderinamumas vertinamas tiriant aplinkos Kuzneco kreivės hipotezę. Galiausiai pateikiamos baigiamojo darbo išvados.

Darbą sudaro 6 dalys: įvadas, teorinė analizė, tyrimo metodologijos pasirinkimas, praktinė dalis, išvados ir literatūros sąrašas.

Darbo apimtis – 74 p. teksto be priedų, 21 iliustracija, 11 lentelių, 1 priedas, 34 bibliografiniai šaltiniai.

Prasminiai žodžiai: Energetikos sektorius, energetikos sektoriaus transformacija, žalioji energija, klimato kaita, atsinaujinanti energija, iškastinis kuras, tvarumas, šiltnamio efektą sukeliančios dujos, emisijos, energetikos infrastruktūra, ES reguliavimas.

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December 13, 2024

I declare that my Final Degree Paper entitled „Transformation of the European Energy Sector in the Context of Green Economy“ is entirely my own work. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers:
Doctor Giedrė Lapinskienė.

The academic supervisor of my Final Degree Paper is Doctor Giedrė Lapinskienė.

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INTRODUCTION

Relevance of the topic. To prevent the most severe impacts of the climate change and retain a livable planet, global temperature increase needs to be limited to well below 2°C above pre-industrial levels. Currently, mean earth temperature is already about 1.5°C warmer than it was in early 1900s, and emissions continue to rise. As outlined in Paris Agreement, to keep global warming well below 2°C, emissions need to be reduced by 45% by 2030 and reach net zero by 2050. The global challenge of fighting climate change has made the transition to a green economy an urgent priority internationally with European Union (EU) playing a critical role. The European Climate Law sets a legally binding target of net zero greenhouse gas (GHG) emissions by 2050. EU member states are required to take the necessary actions at regional and national level to meet the ambitious target. Achieving climate neutrality by 2050 means primarily cutting down the emissions in the energy sector and replacing fossil fuel energy sources that cause high emissions with renewable energy sources. EU is in a front line of this energy sector transformation, implementing ambitious policies and setting ambitious targets to reduce emissions and increase the share of renewable energy. (European Commission, 2022a)

Problem – EU plays a critical role in the decarbonization of the economy that is driven by the urgent need to prevent climate change and maintain a livable planet for future generations. At the core of this transition is energy sector that is responsible for 75% of greenhouse gas (GHG) emissions. To achieve climate neutrality, energy sector must transition from fossil fuel to renewable energy sources. This transformation is impacted by multiple factors: regulatory and policy initiatives, technological limitations, economic constraints, geopolitical challenges and social acceptance. This study focuses on the EU's efforts to transform energy sector in alignment with climate neutrality goals. It aims to analyze the factors influencing this transformation, key measurement indicators used to track the progress of the change and overall state of the European energy sector's transition towards climate neutrality.

Research object of the thesis oversees the entire energy sector within EU with a particular focus on regulation, policies, technological constraints and novelties, measurement indicators, composition and resources of energy sector. The research also includes the statistical analysis of the energy sector development as well an empirical analysis of the relationship between climate indicators, renewable energy development and economic growth.

Aim – to develop a theoretical model of energy sector transformation in the European Union framed with the key factors, measurement indicators and climate neutrality objectives.

Tasks:

1. Analyze the structure and dynamics of the energy sector – the composition, resources, processes, and the overall importance of the energy sector within the economy.
2. Develop a theoretical model for the energy sector.
3. Identify and analyze key factors driving energy sector transformation.
4. Describe the key indicators used to measure the performance of the energy sector within EU member states.
5. Conduct statistical analysis of energy sector trends in the EU.
6. Apply regression analysis to investigate the relationships between core indicators.
7. Present a theoretical model for energy sector transformation.

Research Methods. Methods leveraged in the thesis are the following: gathering and systemizing of theoretical material, statistical analysis of secondary data and regression analysis. Additionally, interpretation of the collected insights and hypothesis validation is performed.

1. THEORY ANALYSIS OF THE ENERGY SECTOR TRANSFORMATION IN THE CONTEXT OF THE GREEN ECONOMY

The energy sector stands at the center of global economic development, powering industries, households, and transportation systems. However, it is also the largest contributor to greenhouse gas (GHG) emissions, responsible for approximately 75% of the emissions globally. As the climate crisis accelerates, the need to transition from fossil fuels to renewable energy sources has become a critical priority, putting more pressure on governments and policy makers to accelerate the transformation. As laid out in European Green Deal, EU aims to be the world's first climate neutral continent by 2050 and has been steadily moving towards this target by replacing fossil fuel with renewable resources for energy generation. In the past decade this progress has increased the pace and started showing significant results, especially in the subsector of electricity generation. This chapter provides an in-depth analysis of the sector's structure, key resources, core processes and key factors influencing the transformation. As the outcome of this chapter, theoretical model of energy sector will be designed and provided by the author.

1.1. Energy Sector Insights: Classification, Primary Energy Sources and Contribution to EU Economy

Energy sector is considerably complex and broad in terms of its composition. The sector includes multiple interconnected companies, that are involved in the production, distribution, transmission, trade and management of different types of energy. Depending on the primary source used to produce energy, sector is also classified to renewable and non-renewable types of energy. Energy sector is essential to maintain and grow economy as well as to ensure a wellbeing of the population, energy infrastructure is considered critical on national and regional levels. Moreover, the sector represents a meaningful share of the Gross Domestic Product (GDP).

1.1.1. Classification of the Energy Sector and Performance of the Energy Sector Enterprises in EU Markets

According to Nomenclature of Economic Activities (Nace Rev. 2, 2008), energy sector is categorized in a division 35, section D for the Electricity, Gas, Steam and Air Conditioning

supply. The section includes generation of electric power, distribution and transmission of electricity, manufacture and distribution of natural gas, steam and air conditioning supply. All these energy services are classified in 3 groups according to NACE:

Group 35.1: Electric power generation, transmission and distribution. This group includes generation of electricity from various sources (e.g., thermal, nuclear, hydro, wind, solar), its transmission through high voltage grids and distribution to end users. It also includes electricity trade thru suppliers, balancing and demand response services.

Group 35.2: Manufacture of gas, distribution of gaseous fuels through mains. This group includes the manufacture of gas and the distribution of natural or synthetic gas to the consumer through the system of pipes (mains). This group also covers the trade of gas but excludes a wholesale of gaseous fuels, retail sale of bottled gas and direct selling of fuel.

Group 35.3: Steam and air conditioning supply. This group includes production, collection and distribution of steam and hot water for heating, power and other purposes. It also includes production and distribution of cooled air and chilled water for the purpose of cooling as well as production of ice for cooling purposes.

Table 1. NACE Energy sector classification

Division	Group	Class		ISIC Rev. 4
35	35.1		SECTION D — ELECTRICITY, GAS, STEAM AND AIR CONDITION- ING SUPPLY	
			Electricity, gas, steam and air conditioning supply	
			Electric power generation, transmission and distribution	
		35.11	Production of electricity	3510*
		35.12	Transmission of electricity	3510*
		35.13	Distribution of electricity	3510*
		35.14	Trade of electricity	3510*
		35.2	Manufacture of gas; distribution of gaseous fuels through mains	
			Manufacture of gas	3520*
			Distribution of gaseous fuels through mains	3520*
			Trade of gas through mains	3520*
	35.3	35.30	Steam and air conditioning supply	
			Steam and air conditioning supply	3530

Source: NACE Rev. 2 (2008)

Table 1 presents the full structure of the energy sector classified under NACE into groups and classes. According to Eurostat, there have been 172 800 companies registered in the division 35, section D of the Electricity, Gas, Steam and Air Conditioning supply in year 2021. These enterprises have employed 1.3 million people and generated 256.7 billion Eur of value added. In total, the energy sector has employed 0.9% of total EU population and accounted for three times more of the value added – a 2.7% share of GDP. These proportions indicate a very high labor productivity within the sector.

Energy sector was the third smallest among the NACE divisions in 2021 in terms of people employed, however it was also the second largest in terms of labor productivity, outperformed only by financial and insurance division. Labor productivity of energy sector was reported at 191 600 Eur per person employed, while the industry average was 60 200 Eur per person employed. Additionally, energy sector has been reported to have the highest wage-adjusted labor productivity ratio among NACE divisions accounting for 297.1% compared to the industry average of 154.4%.

The electricity power generation, transmission and distribution group (35.1) is by far the largest in terms of contribution to GDP, representing 84.5% from total energy sector value added in 2021. The group also dominates in number of enterprises (160 000) and turnover (1 600 000 Eur). Manufacture and distribution of gas group (35.2) and steam and air conditioning supply group (35.3) had similar shares in terms of number of enterprises (approx. 6000) and persons employed (about 130 000), but in terms of value-added manufacture and distribution of gas had a higher share (10.5 %) than steam and air conditioning supply (4.8 %). (Eurostat, 2023b)

Looking at a per country statistics, the share of network energy supply sector within the economy's value added was in the range of 0.9 % in Malta to 5.3 % in Poland, EU average was at 2.7 %. While in absolute numbers, Germany had the largest contribution of all member states and accounted for 29.3 % of total EU energy sector's value added, followed by France (14.5 %), Italy (10.5 %), the Netherlands (8.7 %) and Spain (7.2 %). The share in employment was lower, ranging from 0.3 % in Spain to 1.5 % in Bulgaria. (Eurostat, 2023b) As outlined, energy sector's contribution to value added and employment varies substantially across EU member states and these differences reflect the influence of resource availability, economic development, scale of industrialization shaping the energy sector's role in each country.

1.1.2. Energy Classification Based on Primary Energy Source

Companies within energy sector are participating in the processes of energy production, transmission, distribution and trade, from the primary source to the end customer consuming the energy. While energy is a rather broad definition, in the industry two main categories of energy are being widely used, these categories are based on the type of the primary energy that is being used to produce the secondary or final energy to be consumed. There are multiple sources of the primary energy that are being widely used such as nuclear, fossil fuels, wind, solar, geothermal, hydropower and others. These primary sources are converted to a secondary energy source, which is then being transmitted and distributed thru pipes and electricity grids

to homes and businesses. Most common secondary sources of energy are electricity, gas and petroleum, they are easy to store and transport to the end consumer.

Renewable energy is the energy that is produced from the earth's natural resources that are not limited or exhaustible, such as wind, tides and sun. Renewable energy is climate neutral, and it does not cause any greenhouse gas (GHG) emissions, therefore it is a good alternative to the traditional fossil fuel based energy. The types of renewable energy are the following:

- Hydropower
- Wind energy
- Solar energy
- Geothermal energy

Non-renewable energy comes from earth's sources that are limited and will eventually run out. The largest share of the non-renewable energy sources is produced from fossil fuels: coal, oil, and natural gas. All fossil fuels have formed in a similar way millions of years ago, when earth was covered with shallow seas and swampy forests. Plants and plankton grew in these ancient wetlands, these greens have absorbed sunlight and created energy through photosynthesis. When the organisms died, their remains sunk into the bottom of the sea, where the energy was stored and eventually turned into fossil fuels. Another broadly used type of the non-renewable energy is nuclear, it is sourced from radioactive chemical elements, such as Uranium or Plutonium. The following are the most common types of the non-renewable energy:

- Oil
- Natural gas
- Coal
- Nuclear

Currently the world's energy consumption is dominated by fossil fuels, representing over 80% of primary energy consumption. Renewable energy is making significant acceleration in the past decade, however it's share is still relevantly small compared to total consumption. To further analyze, both, renewable and non-renewable energy sources, have benefits and disadvantages. Fossil fuels have dominated the globe because they are quick and rather inexpensive to extract, easy to store or transport, most important the energy supply can be adjusted to demand, is stable and can serve as baseline. However, fossil fuels being burnt to produce energy are emitting CO₂ and is the reason behind the climate crisis. Using non-renewable fossil fuel based energy has negative impact to the environment and is not sustainable long term. Nuclear energy, differently from other non-renewable sources, is clean from GHG emissions and has no negative impact on the environment or contribution to global warming. Nuclear also has long lifecycle, high productivity, steady baseline supply that can be adjusted

based on demand. However, due to the high radioactivity and major accidents in the nuclear power plants that happened in the previous century, nuclear has very poor reputation and is rejected by society. Meanwhile, renewable energy sources are environmentally friendly, non-exhaustible, free to be used, but require a more significant initial investment. Furthermore, renewable energy production is not stable, it highly depends on the weather conditions and geographical location. Integrating renewable energy to the existing electricity grid also comes with challenges such as management of distributed variable generation and balancing of supply and demand. While both types of energy sources have benefits and disadvantages, transition from non-renewable energy sources to renewable energy sources and phasing out the fossil fuel is non-negotiable in order to mitigate climate change. (National Geographic, 2023).

Table 2. Advantages and disadvantages of the primary energy sources

Primary Energy source	Advantages	Disadvantages
Solar Energy	Non-polluting, abundant	High initial costs, weather dependence, large space requirements, and limited availability of materials
Wind Energy	Non-polluting, abundant, high output	High initial costs, weather dependence, large space requirements, some impact on ecosystem
Hydro Energy	Non-polluting, can be regulated to meet demand	Environmental impacts in dam areas, high construction costs, and vulnerability to drought
Biofuels	Abundant, fewer emissions than traditional fossil fuels	Contributes to air pollution
Nuclear Energy	Non-polluting, stable, can be regulated based on demand	Very high initial cost, long-term radioactive waste storage, safety concerns, uranium material is needed
Coal	Widely available, inexpensive, reliable for large-scale power generation, can be regulated to meet demand.	Very high GHG emissions, causes acid rain, poses health risks to miners
Natural gas	Widely available, cleanest-burning fossil fuel, versatile, can be regulated to meet demand	High transportation/ initial infrastructure costs, emits GHG, risk due to geopolitical situation, used by Russia to finance the war
Oil (petroleum)	Efficient fuel for transportation, easy to transport	Emits GHG, expensive, limited reserves

Source: Author based on IEA

To recap, the energy sector is classified under NACE and is composed of three major subsectors: electric power generation, transmission and distribution (1), manufacture and distribution of gas (2), steam and air conditioning supply (30). The electric power generation, transmission and distribution subsector dominates based on employment and value-add with 1.3 million people employed and 84.5 % of sectoral value added. Energy sector is also classified based on the primary sources used to generate energy into renewable and non-renewable resources. Transition of the primary sources from fossil fuel to renewable is the cornerstone of energy sector transformation. The following chapter explores key indicators of energy sector

transformation as well as climate indicators that are used to monitor developments of the climate change and its consequences across ecosystem.

1.2. Overview of the key performance indicators of the Energy Sector

To understand the dynamics and progress of the energy sector transformation as well as the impacts it has on environment, comprehensive list of measurements and performance indicators are needed. Key performance indicators provide a structured approach for quantification and analysis of the environmental, economic, technological, and social dimensions of the transformation process. Levering these data points not only helps monitor the progress, but also provides valuable insights for policy makers that are critical for assessment of the regulatory impacts and setting up the future goals. This chapter focuses on the main indicators and metrics used for monitoring of energy sector transformation progress and dynamics of climate change.

Climate Indicators. U.S. Environmental Protection Agency (EPA) offers fifty-four indicators that illustrate the causes and effects of warming climate. Core metrics include GHG emissions, global temperature anomalies, sea level rise, biodiversity loss, glacier mass reduction. These indicators offer a comprehensive view of the environmental impacts.(EPA Climate Change Indicators, 2024). In the 2024 report produced by World Meteorological Organization (WMO), following climate indicators are analyzed:

- GHG concentrations in the atmosphere, measured in parts per million.
- Global mean Earth's surface air temperature relative to pre-industrial levels (1850–1900), measured in degrees Celsius (°C).
- Sea ice extent (both Antarctic and Arctic): an area of ocean covered by sea ice, measured in square kilometers (km²).
- Glacial mass balance: net gain or loss of ice mass from glaciers, measured in millimeters of water equivalent.
- Ocean heat content: amount of heat stored in the upper layers of the ocean, measured in joules.
- Sea level: an increase in the average global sea level due to melting ice, measured in millimeters (mm) per year.
- Precipitation patterns: reported increases in the frequency and intensity of weather extremes such as heatwaves, floods or storms.

There are multiple ground stations, satellites and floating buoys in the ocean that measure and collect data on developments of climate warming. Accuracy and consistency are

critical, as these data points are leveraged by scientists and reported to policy makers for further decision making and action plan development. Climate indicators are being measured by multiple agencies and institutions worldwide among which the most influential are:

- European Environment Agency (EEA)
- Eurostat
- Copernicus Climate Change Service (C3S)
- European Commission Directorate General for Climate Action (DG CLIMA)
- Joint Research Centre (JRC)
- European Space Agency (ESA)
- European Network of Transmission System Operators for Electricity (ENTSO-E)
- Climate ADAPT Platform (EEA & European Commission)

These institutions collectively contribute to better awareness and understanding of environmental developments and are providing data that is critical for governments and policy makers.

Energy Transformation Indicators. These indicators are employed to track and evaluate the progress of the energy sector transition from fossil fuel to renewable energy sources. Main focus is directed towards integration of renewable energy sources into electricity grid, consumption of energy by primary source and industry, installed renewable capacity, storage capacity, energy efficiency metrics and GHG associated with energy sector. According to International Energy Agency (IEA), energy sector is shaped by its regulation and policies that are formed based on the data points collected and reported. Hence, it is fair to conclude that energy transformation indicators are helping to develop energy policies and guide governments and institutions in making informed decisions to accelerate transition towards clean energy (International Energy Agency, 2021). The metrics reported by IEA are the following:

- GHG emissions: total CO₂ emissions by sector measured in tonnes.
- Energy intensity: energy consumption per unit of GDP.
- Share of renewables in energy supply: percentage of electricity generation from renewable sources.
- Energy consumption by sector measured in TWh.
- Total installed renewable energy capacity: total capacity of renewable energy systems (solar, wind, hydro) installed measured in MW.
- Carbon intensity of energy production: GHG emissions per unit of energy generated measured in tonnes per MWh.
- Electricity access: percentage of the population with access to electricity.
- Energy prices.

- Energy storage capacity: installed capacity of battery and other energy storage technologies measured in MW.

Same as climate indicators, energy transformation indicators are critical in understanding whether implemented regulations, policies and technological solutions are driving the intended change. The indicators can also be used for comparison of market developments and benchmarking, for identification of the best practices that could further be scaled to other economies. Energy transformation indicators are also great tool for EU institutions and policy makers that could be used to put pressure on lagging markets. A combination of the energy sector transformation indicators and climate indicators reflect a complex and highly interconnected process of energy transition. Main indicators are summarized in the Table 3 below that include definitions as well as list of institutions that are measuring, collecting or reporting on these metrics.

Table 3. Key climate indicators and energy sector transformation indicators

Indicator	Type	Description	Reported by
Greenhouse Gas Emissions (GHG)	Energy transformation Climate	Total emissions of CO ₂ , CH ₄ , N ₂ O measured in CO ₂ equivalents	UNFCCC, EEA, IEA, Eurostat
Carbon Intensity of Energy	Energy transformation	Emissions per unit of energy produced, reflecting decarbonization	IEA, Eurostat
Renewable Energy Share	Energy transformation	Percentage of total energy consumption from renewable sources	IEA, EEA, IRENA, Eurostat
Energy Intensity	Energy transformation	Energy consumption per unit of GDP, indicating efficiency	IEA, Eurostat, World Bank
Installed Renewable Energy Capacity	Energy transformation	Total capacity of solar, wind, hydro, and other renewable systems	IRENA, EEA, IEA, Eurostat
Electricity Access	Energy transformation	Percentage of population with access to electricity	World Bank, IEA, UNDP
Energy Storage Capacity	Energy transformation	Capacity of batteries, pumped hydro, and other storage solutions	IEA, ENTSO-E, Eurostat
Energy Consumption	Energy transformation	Total consumption of energy by primary energy source (renewable and non-renewable)	IRENA, IEA, Eurostat
Energy Supply	Energy transformation	Total supply of energy by primary energy source (renewable and non-renewable)	IRENA, IEA, Eurostat
Sea Level Rise	Climate	Annual increase in global sea levels due to climate change	WMO, EEA
Global Surface Temperature	Climate	Global average temperature changes relative to pre-industrial levels	WMO, NASA, Copernicus (C3S)

Deforestation Rates	Climate	Annual loss of forest cover, impacting carbon sequestration	FAO, EEA
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Source: Author based on data from EPA, WMO, IEA

To summarize, in the context of energy sector transformation towards climate neutral resources, two sets of performance indicators have been analyzed. Energy sector transformation is driven by the climate warming challenges; hence, climate and energy transformation indicators are being used as the key metrics reflecting the progress of the transition as well as the impact on the environmental outcomes. Key metrics reflecting the climate change are average surface temperature, sea level rise, GHG emissions, glacier mass and severe weather events. While energy transformation indicators are primarily focused on renewable energy consumption, installed capacity, energy efficiency, carbon intensity and others. The next chapter transitions to an exploration of the key factors influencing energy sector transformation that not only shape the development of the energy sector but also define its resilience and ability to adapt in an increasingly complex landscape.

1.3. Analysis of the key factors impacting the Transformation of the Energy Sector: Regulatory, Technological, Geopolitical and Socio – Economic

The energy sector transformation primarily focuses on the transition away from energy production mainly from fossil fuels towards a system in which renewable energy sources are dominant. However, various factors need to be considered as well as many complex questions to be resolved for successful transition. Several critical factors influence the transformation of the energy sector. Among these are regulatory frameworks, technological constraints and advances, geopolitical dynamics, and socio-economic conditions.

Regulatory factors. These include governmental policies and legislation that either promote or delay a shift to renewable energy resources. The regulatory factor is probably the most fundamental of the drivers for the transition to renewable energy use today. In contrast, past energy transitions have been driven by economic benefit and competition. The present energy transition is motivated differently, to avoid or reduce global climate change that is happening because of energy sector emissions, global leaders and governments have developed a solid regulatory framework that guide and accelerate energy transformation in EU. Climate crisis is in a way the main factor behind energy transformation, that is forcing the governments to promote transition to renewables, despite it is more costly than existing fossil fuel energy options at least in the near-term.

Technological factors. Technological constraints such as the integration of intermittent renewable sources into the existing grid, or aging infrastructure contributes to significant risks in succeeding with climate neutrality targets if not addressed in time. Energy system is no longer one way since more and more distributed generation and prosumers are being integrated. Moreover, renewable generation is highly volatile - solar and wind power highly depends on the weather. That requires integration of storage systems and back up or baseline generation to balance supply and demand. The existing infrastructure of grid was designed especially for centralized, predictable source. To adapt it to be able to handle decentralized variable renewable energy sources requires change. Smart grid technologies could help achieve this task at least partially but they require significant investments.

Geopolitical factors. Geopolitical dynamics and risks significantly impact the developments of the energy sector transformation. Distribution of the primary energy resources, energy trade agreements and political stability have major influence on energy prices, availability, regional and local policies. One of the potential risks rising from the political tensions, is that the focus of policy makers and global leaders might drift away from the climate neutrality goals, as the question of energy availability and resilience of the energy infrastructure becomes immediate. Another major risk for Europe is the dependency on energy imports, especially natural gas and oil that historically were primarily imported from Russia. The outcomes of the war in Ukraine have showcased the vulnerabilities associated with this dependency, it caused both – energy shortage and energy price spikes. As a reaction, Europe has mobilized and focused on the search of the alternative markets to serve the energy needs of EU as well as accelerated the transition away from the fossil fuel towards renewable energy sources.

Socio-economic factors. Cost and access to the energy as well as public awareness are two important socio-economic factors influencing energy sector. The transition to the renewable energy needs to be inclusive and ensure that all society benefits from the clean energy and that no one stays behind. If the renewable energy will only be the privilege of wealthy, this will not only increase the gap between social strata of society but will also cause major public resilience and slow down the transformation. Another aspect impacting the shift is the significant financing that is needed for the energy transformation. Switching to renewables requires new infrastructure as well as restructuring of the existing energy sector to integrate the variable distributed sources of energy. Consumers may also require financial incentives to switch away from the fossil fuels, as they would incur costs when switching to renewables, for example replacing gas boiler to the electric heat pump. Although the question of climate change is important to a growing share of society, when consumers are asked to make

changes in their lifestyle, the question of cost, economic benefit and convenience is asked. There are uncertainties around consumer willingness to change the behavior and potentially pay more in the short-term for a long-term wellbeing.

However, this question is only relevant to those, who already have secure access to energy. A big concern is the communities that experience poverty and have no or limited access to energy. Providing cheap energy for those in poverty is a priority for governments, therefore in some countries it comes of a bigger importance than switching to a more expensive carbon-neutral sources of energy. Ultimately, governments can force through change but may be reluctant to do this in EU countries where political power is determined by voters. (Wyllie, 2021).

To better understand how these factors influence the transformation of the energy sector in Europe, which accelerate the change and are the tailwinds of the transformation, which are on the opposite, the barriers slowing it down and need to be overcome. A comprehensive in-depth analysis of the factors influencing the energy sector transition will be carried out in this chapter to answer these questions and gain further knowledge of the forces shaping the present and future model of energy sector.

1.3.1. EU Economy Decarbonization Policies that are Impacting the Development and Priorities of the Energy Market Players

The European Union (EU) has established a comprehensive regulatory framework to guide the transformation of the energy sector. This framework is designed to ensure a secure, sustainable, and competitive energy supply for all member states. Its objectives include designing a well-functioning energy market with secure energy supply, reducing waste, promoting energy efficiency, and finally, the transition from fossil fuel to renewable energy sources is at the core of the regulatory framework of EU. The European Commission in 2015 has launched a new strategy for a resilient Energy Union with a forward-looking climate change policy. The goal of the Energy Union is to give EU consumers secure, sustainable, competitive and affordable energy. According to the Energy Union, the five main aims of the EU's energy policy are to:

- Diversify Europe's sources of energy, ensuring energy security through solidarity and cooperation between EU countries.
- Ensure the functioning of a fully integrated internal energy market, enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers.

- Improve energy efficiency and reduce dependence on energy imports, cut emissions, and drive jobs and growth.
- Decarbonize the economy and move towards a low-carbon economy in line with the Paris Agreement.
- Promote research in low-carbon and clean energy technologies and prioritize research and innovation to drive the energy transition and improve competitiveness. (European parliament, 2024).

Earth's surface temperatures continue to rise and are inconsistent with limiting the rise in global temperature to well below 2°C and avoiding severe consequences of the climate change. Reversing these trends and reaching climate neutrality by mid-century, in line with the 2015 Paris Agreement's goal, demands deep transformations not only of the energy sector but also of economies and societies. Overcoming the challenges of the century requires the development and implementation of long term, region and country-specific decarbonization strategies going beyond environmental goals. In the Fig. 1 provided below, European energy sector regulatory framework is presented, outlining key policies, regulation as well as directives that drive EU members towards climate neutrality goals.

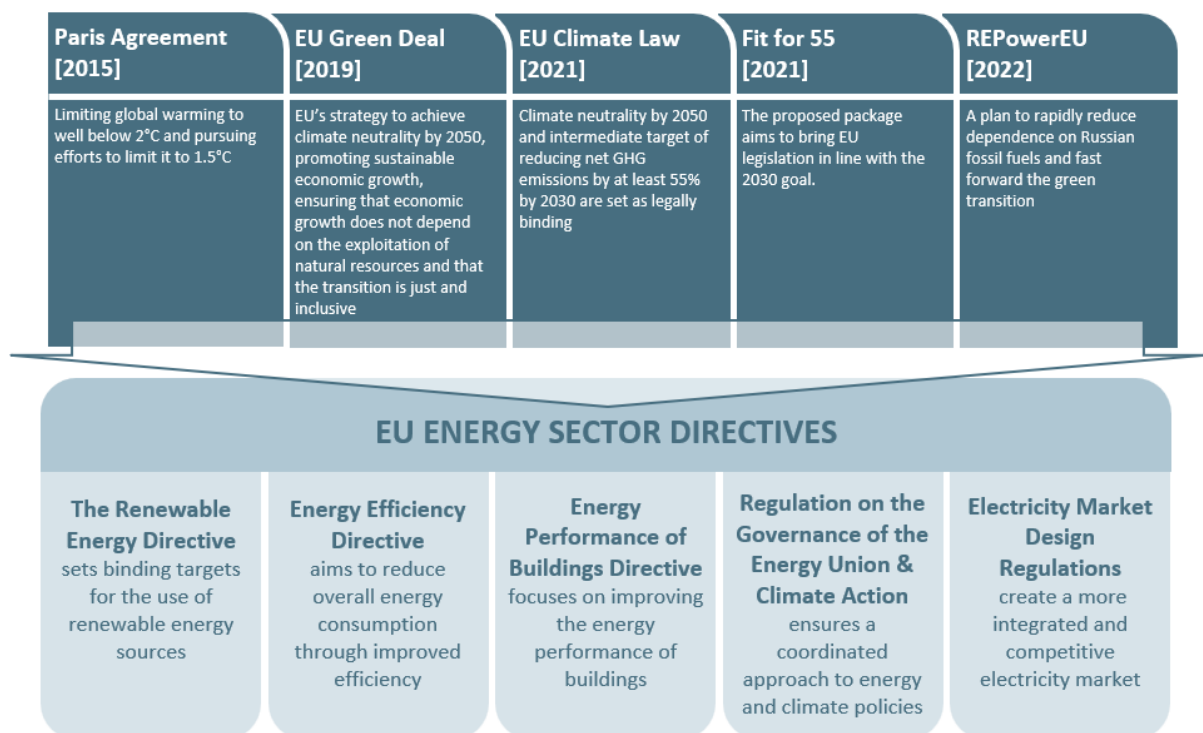


Fig. 1. EU Energy Sector Regulatory framework

Source: Author

The energy sector's regulatory framework provided in Fig. 1 offers a good high-level overview of how various legal instruments interact and align to achieve their respective goals

and objectives. However, to gain a deeper understanding of the energy sector's development in Europe and the critical objectives it aims to achieve, it is essential to examine each policy and directive in greater detail.

The Paris agreement. It is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016. Its overarching goal is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations together to combat climate change and adapt to its effects (United Nations, 2015).

However, in recent years, world leaders have stressed the need to limit global warming to 1.5°C by the end of this century. That's because the UN's Intergovernmental Panel on Climate Change indicates that crossing the 1.5°C threshold risks unleashing far more severe climate change impacts, including more frequent and severe droughts, heatwaves and rainfall. To limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030.

Implementation of the Paris Agreement requires economic and social transformation, based on the best available science. The Paris Agreement works on a five-year cycle of increasingly ambitious climate action carried out by countries. Since 2020, countries have been submitting their **national climate action plans, known as nationally determined contributions (NDCs)**. Each successive NDC is meant to reflect an increasingly higher degree of ambition compared to the previous version.

With the Paris Agreement, countries established an enhanced **transparency framework (ETF)**. Under ETF, starting in 2024, countries will report transparently on actions taken and progress in climate change mitigation, adaptation measures and support provided or received. It also provides for international procedures for the review of the submitted reports. The information gathered through the ETFs will feed into the Global stocktake which will assess the collective progress towards the long-term climate goals. This will lead to recommendations for countries to set more ambitious plans in the next round.

The EU and all its member states have signed and ratified the Paris Agreement and are strongly committed to its implementation. In line with this commitment, EU countries have agreed to set the EU on course to becoming the first climate-neutral economy and society by 2050. As required by the agreement, the EU submitted its long-term emission reduction strategy and its updated climate plans (nationally determined contribution, NDC) before the end of 2020,

pledging to reduce EU emissions by at least 55% by 2030, compared to 1990 levels. The EU and member states updated the EU's energy transformation targets in 2023. The EU is in the frontline of the transformation towards green energy system, with ambitious targets and consistent policy implementations, it sets standards worldwide. (Renewable Energy Agency, 2020)

Paris agreement has set the fundamentals for the green economy policies and regulation, with a clear urgency to action and immediate need to transition to decarbonization. Energy sector with electricity subsector at its core are in the focus of policy makers and governments, as energy sector represents around 75% of total GHG emissions globally. (Baron, 2016)

The European Green Deal. If Paris Agreement sets the global framework for climate action, then the EU Green Deal is a plan of action for EU member states, that needs to be followed to meet the aggressive goals and objectives. The Green Deal could be viewed as an operational plan developed for EU to achieve the goals of the Paris Agreement.

The main goal of European Green Deal is achieving climate neutrality by 2050, and it contains a package of policy initiatives developed to help transition towards this goal. The document underscores the need for a holistic and cross-sectoral approach, that encourages all institutions and business to collaborate and contribute to the ultimate climate neutrality goal. The package includes initiatives covering energy, transport, manufacturing, agriculture and finance. The initiatives in the package are strongly interlinked. (European Council, 2024)

The European Green Deal was initiated in December 2019 by the EU Commission and as of then serves as EU's strategy plan to making the EU's economy sustainable. Key objectives of the EU Green Deal include:

- Climate neutrality: achieving net-zero greenhouse gas emissions by 2050.
- Circular economy: promoting sustainable resource use and reducing waste.
- Biodiversity: protecting and restoring ecosystems and biodiversity.
- Ensuring sustainable food systems from production to consumption.

The European Climate Law. It writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate neutral by 2050. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. This target is legally binding and based on an impact assessment carried out by the Commission. The European Climate Law is a cornerstone of the EU's climate policy, enshrining the goals of the European Green Deal into legally binding commitments.

The law aims to ensure that all EU policies contribute to this goal and that all sectors of the economy and society play their part. On 12 December 2019, European Council in its conclusions has agreed on the objective of achieving a climate neutral Europe by 2050. It is in

line with the objectives of the Paris Agreement, while also recognizing that it is necessary to put in place an enabling framework that benefits all member states and encompasses adequate instruments, incentives, support and investments to ensure a cost-efficient, just, as well as socially balanced and fair transition, considering different national circumstances in terms of starting points.

On 4 March 2020, the European Commission adopted its proposal for a European climate law, as an important part of the European Green Deal. On 17 September 2020, the Commission adopted a proposal amending its initial proposal to include a revised EU emissions reduction target of at least 55% by 2030. The Commission also published a communication on the 2030 climate target plan, accompanied by a comprehensive impact assessment.

On 10-11 December 2020 the European Council in its conclusions, endorsed a binding EU target of a GHG emissions reduction by at least 55% by 2030 compared to 1990. The Council adopted a general approach on 17 December 2020, after which the Council and the Parliament launched a series of trilogue meetings with the aim of securing an agreement on the final text.(European Council, 2021). The main objectives of the EU Climate law are:

- Set the long-term direction and action plan for meeting the 2050 climate neutrality objective through all policies, in a socially fair and cost-efficient manner.
- Set a more ambitious EU 2030 target, to set Europe on a responsible path to becoming climate-neutral by 2050.
- Create a system for monitoring progress and take further actions if needed.
- Provide predictability for investors and other economic actors.
- Ensure that the transition to climate neutrality is irreversible.

In 2023, for the first time, the Commission assessed progress towards the climate neutrality and its objectives, as required under the European Climate Law. The findings were published as part of the 2023 Climate Action Progress Report. Although greenhouse gas emissions continue to fall and there are encouraging signs of action on the ground, the Commission's assessment is that current progress towards the EU's climate neutrality objective appears to be insufficient. Action is most needed in areas which still require significant reductions in emissions (e.g. buildings, transport).

The assessment of progress on adaptation at the national level shows that member states need to take significantly more action to adapt to climate change – for instance, on governance, funding, risk assessments, nature-based solutions, as well as monitoring, reporting and evaluation to reduce their social and economic vulnerabilities to the intensifying climate-related risks. (European Commission, 2023)

Fit for 55. This package aims to translate the climate ambitions of the EU's Green Deal into law. The package is a set of proposals to revise climate, energy and transport related legislation and put in place new legislative initiatives to align EU laws with the EU's climate goals. Fit for 55 refers to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. (European Council, 2023). The proposed package aims to bring EU legislation in line with the 2030 goal. The Fit for 55 package is a comprehensive set of proposals by the European Union for reaching the EU's climate objectives, package consists of following components:

- The EU emissions trading system (EU ETS), a carbon market based on a system of cap-and-trade of emission allowances for energy-intensive industries and the power generation sector. It is the EU's main tool in addressing emissions reductions.
- The social climate fund, this proposal aims to address the social and distributional impact of the new emissions trading system for buildings and road transport. Based on social climate plans to be developed by the member states, the fund aims to provide support measures and investments for the benefit of vulnerable: households, micro-enterprises, transport users.
- The carbon border adjustment mechanism (CBAM) aims to ensure – in full compliance with international trade rules – that the emissions reduction efforts of the EU are not offset by increasing emissions outside its borders through the relocation of production to non-EU countries (where policies applied to fight climate change are less ambitious than those of the EU) or through increased imports of carbon-intensive products. CBAM targets imports of products in carbon-intensive industries. It is designed to function in parallel with the EU's emissions trading system (EU ETS) as well as to mirror and complement its functioning on imported goods.
- Member states' emissions reduction targets. The effort sharing regulation, last amended in 2018, sets binding annual greenhouse gas emissions targets for member states in sectors that are not covered by the EU emissions trading system (EU ETS) or the regulation on land use, land use change and forestry (LULUCF). These sectors include road and domestic maritime transport, buildings, agriculture, waste, small industries.
- Emissions and removals from land use, land use change and forestry. The land use, land-use change and forestry (LULUCF) regulation set a binding commitment for the EU to reduce emissions and increase removals in the land use and forestry sectors. The new rules set an increased EU level target of at least 310 million tonnes of CO₂ equivalent net removals of greenhouse gases for 2030. Binding national targets are defined for each member state.

- CO2 emission standards for cars and vans. Cars and vans account for 15% of the total EU emissions of carbon dioxide. The regulation introduces progressive EU wide emissions reduction targets for cars and vans for 2030 and beyond, including a 100% reduction target for 2035 for new cars and vans.
- Reducing methane emissions in the energy sector. The proposal aims to track and reduce methane emissions in the energy sector. The text is the first of its kind and is a crucial contribution to climate action, as methane is the second most important greenhouse gas after carbon dioxide. The proposal follows from the strategic vision set out in the EU Methane Strategy in 2020. At the COP26 UN Climate Conference in 2021, the EU launched the Global Methane Pledge in partnership with the United States, whereby over 100 countries committed to reducing their methane emissions by 30% by 2030 compared to 2020 levels.
- Sustainable aviation fuels (advanced biofuels and electro fuels) have the potential to significantly reduce aircraft emissions. However, this potential is largely untapped as such fuels represent only 0.05% of total fuel consumption in the aviation sector. The ReFuelEU Aviation proposal aims to reduce the aviation sector's environmental footprint and enable it to help the EU achieve its climate targets.
- Decarbonized fuels in shipping. Despite progress in recent years, the maritime sector still relies almost entirely on fossil fuels and constitutes a significant source of greenhouse gases and other harmful pollutant emissions. The goal of the FuelEU maritime initiative is to reduce the greenhouse gas intensity of the energy used on board of ships by up to 80% by 2050. The new rules promote the use of renewable and low-carbon fuels in shipping.
- Alternative fuels infrastructure. The main objective of the regulation on alternative fuels infrastructure (AFIR) is to ensure that citizens and businesses have access to a sufficient infrastructure network for recharging or refueling road vehicles and ships with alternative fuels. The new rules will enable the transport sector to significantly reduce its carbon footprint. They set a number of targets for 2025 or 2030 including recharging stations for cars and vans to be installed every 60 km, hydrogen refueling stations to be deployed from 2030 onwards, users of electric or hydrogen-fueled vehicles to be able to pay easily at recharging or refueling points.
- Renewable energy. The proposal is to increase the current EU target of at least 32% of renewable energy sources in the overall energy mix to at least 40% by 2030. It also proposes the introduction or enhancement of sectorial sub-targets and measures across

sectors, with a special focus on sectors where progress with integrating renewables has been slower to date, in particular in the fields of transport, buildings and industry.

- Energy efficiency. The revised EU energy efficiency directive is aiming to reduce final energy consumption at EU level by 11.7% in 2030, compared to projections made in 2020. The new rules will accelerate energy efficiency efforts by member states by increasing annual energy savings obligations and decreasing the energy consumption of public sector buildings.
- Energy performance of buildings. Buildings account for 40% of energy consumed and 36% of energy-related direct and indirect greenhouse gas emissions in the EU. The energy performance of buildings directive, revised in 2024, aims to make buildings in the EU more energy efficient by 2030 and beyond. The main goals of the directive are for all new buildings to be zero-emission by 2030 and for existing buildings to be transformed into zero-emission buildings by 2050.
- The hydrogen and decarbonized gas market package proposes revised and new rules to lower the carbon footprint of the gas market. The goal is to shift from natural gas to renewable and low-carbon gases and boost their uptake in the EU by 2030 and beyond. The package aims at creating a regulatory framework for dedicated hydrogen infrastructure, markets and integrated network.
- Energy taxation. The proposal for a revision of the European Council directive on the taxation of energy products and electricity aims to align the taxation of energy products, improve the EU internal market by updating the scope of energy products.

REPowerEU. Russia's unprovoked and unjustified military aggression against Ukraine, has massively disrupted the world's energy system. It has caused high energy prices and it has heightened energy security concerns, bringing into the attention the EU's over-dependence on gas, oil and coal imports from Russia. High amounts paid for Russia's fossil fuels were helping Russia sustain its war against Ukraine.

In March 2022, EU leaders agreed in the European Council to phase out Europe's dependency on Russian energy imports as soon as possible. Drawing on the Commission's communication, they invited the Commission to swiftly put forward a detailed REPowerEU plan. REPowerEU is about rapidly reducing EU dependence on Russian fossil fuels by fast forwarding the clean transition and joining forces to achieve a more resilient energy system and a true Energy Union.

Building on the Fitfor55 package of legislations and completing the actions on energy security of supply and storage, this REPowerEU plan puts forward an additional set of actions to (1) save energy, as savings are the quickest and cheapest way to address the current energy

crisis. Reducing energy consumption cuts households' and companies' high energy bills in the short and long term and decreases imports of Russian fossil fuels. Reducing energy consumption through higher efficiency is a vital component of the clean energy transition which increases the resilience of the EU economy and shields its competitiveness against high fossil fuel prices. Additionally, EU has been working intensively with international partners to (2) diversify supplies and control the rise in energy prices. Following the mandate by the European Council, the Commission and Member States have set up an EU Energy Platform for the voluntary common purchase of energy. Furthermore, actions are focused to (3) quickly substitute fossil fuels by accelerating Europe's clean energy transition and (4) smartly combine investments and reforms. (European Union, 2022)

Thanks to the measures taken because of REPowerEU, the EU has overachieved its voluntary target of a 15% gas demand reduction; the reported gas demand fell by 18% from August 2022 to March 2024. Another goal coming from the REPowerEU is directed towards avoiding blackouts and energy shortages, to achieve that EU has developed a system and agreement to fill up fully gas storage ahead of every winter. EU members agreed to fill underground gas storage to 80% of capacity by 1 November 2022. Through collaboration, EU countries exceeded this, instead achieving 95% of gas storage capacity. The annual target has since been raised, with countries now expected to achieve 90% of capacity by 1 November, which again was achieved as expected way earlier by mid-August. At the end of the winter heating season on 1st of April 2024, the volume of gas in storage was remaining at the solid capacity of 59% of the total. That is a record at the close of the winter season and a good starting point for refilling for next year.

Energy prices in Europe have also decreased substantially from their peaks in 2022, partially due to the coordinated European response to the threats of Russia and consistent investment to green energy production. Additionally, common procurement has been implemented to get equal access to affordable energy for all member states, this allowed EU to start buying a share of gas collectively and not compete for limited supplies. (European Commission, 2022b)

Two years into the war with policies being in place, the EU has successfully achieved most of the ambitious targets set out in the REPowerEU plan and is now on good track to get completely rid of Russian fossil fuels while continuing to pursue the green transition and supporting Ukraine. The REPowerEU remains focused on further reducing imports of Russian gas, boosting industrial decarbonization, faster roll-out of renewables, investing in energy infrastructure and its resilience, improving energy efficiency.

The EU legislation alongside Paris agreement forms the basis of the ambitious decarbonization goals of energy sector and builds pathway for a transition to a sustainable, competitive, and secure energy system. With policies developed through the European Green Deal, EU Climate law, Fitfor55 and REPowerEU the EU is focused on implementing climate neutrality goals at every level of energy market. These policies address combination of environmental challenges, geopolitical threats, technological constraints and socioeconomic priorities such as energy accessibility and affordability. The regulations also emphasize the need of member states collaboration, acceleration of renewable energy adoption, energy sector resilience, and reducing dependence on fossil fuels imports. While the regulation of energy sector is the primary factor driving the transformation, other factors also play meaningful role and should not be disregarded. Consequentially, in the following chapters, technological, geopolitical, and socio-economic factors will be analyzed, and their impacts will be evaluated.

1.3.2. Technological and Infrastructure Barriers in the Energy Sector Transformation

At the center of the energy sector transformation is full decarbonization of electricity production and electrification of other subsectors, such as transportation or heating and cooling. As a result of that, according to International Energy Agency global electricity demand will increase by 40% within next few years by 2030 and will more than double by 2050 compared to consumption levels of 2021. Author highlights that mentioned electricity consumption growth trends have been projected yet not considering the expansion of the AI use that has accelerated in the past year and requires huge computing power and enormous amounts of energy. Meanwhile, the share of renewable energy in the global electricity generation should reach 60% by 2030 and 90% by 2050. This rapid expansion of electricity consumption together with challenges posed by need to integrate renewable energy sources to the legacy electricity grid is raising technological challenges that need to be addressed and will require both, the investment and change in operational management of electricity systems.

The electric power systems are complex and consist of multiple elements, such as power lines, transmission lines, transformers and meters. The electricity grid was designed to deliver electrons one way from a centralized generation source, such as power plant, to distributed consumers of the electricity. However, with the renewable generation being integrated, the grids now need to transform and accommodate the requirement of delivering energy across the system from multiple distributed small energy sources to the households and business that have demand at the time. Moreover, the supply is no longer stable and cannot be turned on or off based on the demand, as renewable generation is dependent on the weather conditions and electricity is generated when wind is blowing, or sun is shining. Balancing the demand and

supply is one of the major challenges posed on the electricity systems. The electrification of energy sector together with the technical challenges of integrating growing amount of distributed renewable energy sources indicate that as energy sector transforms, the infrastructure needs to transform accordingly or else it can become a barrier to achieving net zero goals. Further in this chapter technological challenges that electricity infrastructure is and will be facing on the way towards fully green and sustainable energy system are reviewed.

Variability and adequacy of the renewable generation. Renewable energy is being generated thru distributed variable sources, such as wind parks, hydropower stations or solar panels. Energy generation from these sources is unpredictable and is not constant as it depends on weather conditions, time of a day and geographical location. According to International Energy Agency, by 2030 around 90% of electricity generation will need to come from variable renewable energy sources (VRE), to achieve net zero target.

Electricity generation from many distributed energy sources presents significant challenges to the electricity grid. For decades electricity grids have been transporting energy from several big power stations that were producing constant base line generation, that could be adjusted based on the demand or seasonality. Meanwhile VREs are producing electricity when sun is shining and wind is blowing, and as a rule these conditions for same geographical location are similar. Meaning, that on a good day all VREs are producing electricity and supply exceeds demand, while during the night when there is no sunshine and no wind, there would be zero electricity generated, so there is no supply, while demand continues to exist.

For electricity transmission and distribution operators integrating VRE sources at a greater scale, these characteristics lead to significant challenges. Ensuring the reliable operation of an electricity system requires addressing four critical aspects: (1) resource adequacy, which means matching supply with demand, that involves maintaining a sufficient amount of baseline energy generation to meet demand; (2) network adequacy, ensuring the grid has the capacity to transport electricity from generation points to consumption points; (3) frequency stability, which requires system operators to balance supply and demand instantly to maintain the system's frequency; and (4) voltage stability, which involves maintaining consistent voltage and phase angles across the system, particularly in regions with high renewable energy penetration, where generation is often distant from consumption centers and transmission lines may be overloaded. (Philip Hirschhorn & Tom Brijs, 2021)

Aging infrastructure. About a third of Europe's low voltage grid is over 40 years old, by 2030 this will be up to 55%. In Central and Eastern European countries, there are sections of the network that have been in service for over 50 years. This demonstrates that much of the EU network needs to be upgraded or replaced even without growth in renewable generation.

(Brown et al., 2024) Meanwhile, following EU regulation and FitFor55 package, it is expected that these aging electricity grids will integrate approximately 800 GW of solar and wind capacity by 2030, this is more than three times of the 2020 installed capacity size. Grids consist of interconnectors, transmission grids and distribution networks. Adequate grid infrastructure will be crucial to ensure growing amounts of wind and solar power generation can be integrated into the electricity system and transported to where demand exists. Reforms to grid planning will be needed to ensure sufficient infrastructure investment. The European Commission estimates that a 584 billion Eur investment in grids is required by 2030. Industry estimates that 375-425 billion Eur of this needs to be in the distribution network. Investments in cross-border interconnectors and storage need to be 6 billion Eur per year.

Extreme weather events. Grids are like bloodstream systems of electricity circulation, built out of power stations, substations, transformers, transmission and distribution lines, the grid connects electricity supply to demand. It is a complex and intricate network, exposed to many natural and man-made external risks. According to Swiss Re Institute analysis, more than 1 in 3 of power outages in US during 2012-2023 time period were associated with severe weather related events. As temperatures rise, precipitation patterns – observed increases in the frequency and intensity of weather extremes such as heatwaves, tropical cyclones, and floods, quantified by event statistics, become more often. Climate change also causes heatwaves, droughts, cold waves, heavy snow, wildfires, all these external threats have significant impact on electricity grid:

- Extreme temperatures, in particular heatwaves can cause thermal damage of underground cables, reduced generator and transformer efficiency, reduced efficiency of solar panels and negative effects on wind turbine operation. Meanwhile cold waves can damage power lines due to ice and heavy snow; low temperatures can affect operation of turbines and increase pressure on dams and reservoir structures. (E.DSO, 2022)
- Extreme precipitation causes flooding of substations, damage to transformers, switchgears and control equipment, while droughts result in degradation of underground cables.
- Stronger and longer lasting winds result in damage of overhead cables and poles, especially in the areas with vegetation, where falling trees brake poles and damage electricity cables. Wind turbines shut down to prevent wear and tear during heavy wind and storms. (Mitali Chatterjee, 2024)

In the context of climate change, increasing resilience of electricity grid becomes critical. For example, new substations should have permanent flood protection structures or

built on higher ground within flood prone areas. Protection zones should be cleaned from trees of the overhead power lines to reduce damage from falling trees during the storms. Heat resistant coating should be used on cables and poles to reduce the probability of catching fire in the areas with high risk of wildfires. Building underground substations could be a good option to improve resilience to protect from both extreme weather events and other external risks.

Cyber-security is in an increasingly complex task that needs to be managed carefully across all the industries. As with most sectors, energy sector progressively uses digital technologies to better manage plants, grids, and operations to improve quality of supply, provide better services to customers, and enable clean energy transitions through the integration of distributed energy resources. However, this digital progress is creating risks. Digital systems, telecommunication equipment, smart meters, remote management of the grid multiply the exposure and risk of the cyberattack.

There is limited reporting available on the number of cyberattacks on the energy infrastructure due to the sensitivity of the topic and underreporting. However, number of cyberattacks in general is increasingly growing and energy sector is not an exception. According to IEA reports, number of attacks on utilities has doubled from 2020 to 2022. Following Russian invasion to Ukraine physical and cyberattacks have been reported on the energy infrastructure in Ukraine and Europe, those include disabling of remote controls, interrupting meter systems as well as breaching access to consumer sensitive data. (Marc Casanovas & Aloys Nghiem, 2023)

The article published in Applied Energy journal by Sanjana Vijayshankar and associates explores the risks and the possible outcomes of the cyberattacks on the energy systems, it analyses three use cases of the recent cyberattacks as well as the literature available on the topic to better understand the particularities of the cybersecurity challenges. (Sanjana Vijayshankar et al., 2023). As electricity sector becomes highly digitized and managed remotely thru control centers, the threat and possible outcomes of cyberattacks become severe and more probable. As explored in the article, Ukraine's energy system was attacked in 2015 thru phishing emails that delivered malware to control system SCADA. Once access has been gained, the hackers have caused power outage for 225 000 customers by remotely manipulating the system's settings. This use case puts light on how vulnerable energy systems are and how significant the outcomes of the cyberattacks could be on the power system. It also highlights the urgency to invest into cybersecurity systems and importance of the infrastructure resilience.

Electricity management systems are increasingly integrated thru number of communication systems (cellular, IoTs) that allow remote data streams, control over the operations, thus, the need for cybersecurity continues to grow. Moreover, utilities gain access

to enormous amount of sensitive consumer data, that could be a target by hackers and is another headache for cybersecurity teams. These threats require major care from energy companies as well as governments and policy makers, especially in the light of the geopolitical instability in the region.

Technological challenges and risks are standing on the way as obstacles that need to be overcome on the way to fully green electricity systems. Resolving these challenges is a critical task for electricity system transmission and distribution operators as well as regulators and policymakers. Rapid acceleration of the electricity consumption, urgency to integrate massive amounts of distributed VREs into electricity grid, frequent and severe extreme weather events as well as growing cyberattack risk due to sector digitalization put great pressure with limited time to act. Significant investments are needed to make sure that electricity infrastructure is capable to enable the transition to net zero emissions energy system. Furthermore, as economies and society become more dependent on undisrupted energy supply, addressing physical and cyber risks become an existential task.

1.3.3. Geopolitical Challenges and Significance of the Energy Network Resilience in the context of Russia-Ukraine conflicts

The energy sector is critical for global economic stability, yet it remains highly fragile to geopolitical challenges. The Ukraine war has developed beyond conventional warfare and has significant economic effect across Europe, disturbing regional energy stability, exposing the EU's dependency on imported energy. War on the Ukraine soil also highlighted the urgent need to enhance energy infrastructure security, especially in the Baltic states. Further analysis will be conducted by author to better understand the challenges caused and focus on their implications on energy sector in Europe.

EU's dependency on energy imports. Before the invasion to Ukraine, the European Union was Russia's largest gas market, approximately 40% of Russian natural gas imports have been directed to EU. This became a huge dependency and made the EU exposed to possible power outages. Energy import was also used as a geopolitical tool by Russia, with deliberate disruptions in natural gas supplies causing energy shortages in EU. The present conflict, along with associated sanctions on Russia, has influenced energy trade dynamics.

As a response REPowerEU plan has been initiated by EU to reduce reliance on Russian gas by diversifying gas suppliers and accelerating the renewable energy transition. The Baltic states have taken bold moves to reduce their dependency on Russian energy, mainly on the natural gas and oil sectors. Lithuania stopped importing natural gas from Russia in early April 2022 and became the first European Union member state to do so. This decision was part of

Lithuania's broader strategy to achieve energy independence. The move was facilitated by the Klaipėda LNG terminal Independence, a so-called Floating Storage Regasification Unit, operational since 2014. (Charlie Duxbury, 2022)

Following Lithuania's example, several other EU countries – Poland, Bulgaria, Finland, Estonia, Latvia – have entirely stopped their imports of natural gas from Russia. While majority of EU countries have made moves in eliminating Russian gas imports, many of them have reduced but not entirely stopped their imports from Russia. The European Union has set a goal to end all Russian gas imports by 2027. In the meantime, countries are working towards increasing the number of possible alternative energy suppliers from other continents and improving the security of the energy sector infrastructure.

Gas revenues and their role in war financing. The relationship between revenues from natural gas, coal and oil exports and the financing of the war in Ukraine is a major concern that has been repeatedly escalated by Ukrainians. Export of natural gas has historically been a meaningful component of the Russia's economy. For 2021 revenues from oil and natural gas made up approximately 45% of Russia's budget, however a more precise split between gas and oil is not available. Once the war started and sanctions have been put in place, and EU significantly reduced its energy imports from Russia, however, oil and gas sector combined still accounted for 16.7% of Russia's GDP in 2024. (Statista Research Department, 2024)

Russian economy is progressively becoming militarized and supported by high revenues from energy exports. The structure of the economy has changed as more and more resources have been poured into the war machine that is literally being fuel by gas and oil money. In last two years, Russian economy has gone thru significant militarization, and it is believed that financing for the military actions came from energy sector revenues. Production in the war-related industries improved by approximately 60% compared 2024 with 2022. Meanwhile, production in other manufacturing sectors has remained stable or even declined. Russia's federal government deficits have remained relatively small, at approximately 2% of GDP in 2022 and 2023 primarily because of the revenues from oil and gas. (Yuriy Gorodnichenko et al., 2024)

Impact on energy supply and prices. The war has significantly disturbed the EU energy trade, it has caused rise in energy prices, that had a positive outcome too – an acceleration towards renewable resources. After Ukraine invasion in 2022, Russia cut 80 billion cubic meters of pipeline gas supplies to Europe, sending the region into an energy crisis. While the European Union committed to phase out Russian fossil fuel imports as soon as possible, EU faced an immediate energy deficit it needed to fill. There have been slowdowns in gas deliveries from Russia's Gazprom even before the war, also there was little of output of hydropower and

nuclear energy remaining in EU, therefore Russia has been able to push EU to a 160 billion cubic meters of gas deficit in 2022.

This has caused and unprecedented volatility in energy prices across Europe, natural gas prices surged to record highs in 2022, with the Dutch gas price reaching 339.20 Eur/MWh, compared to pre-crisis levels well below 50 Eur/MWh. Although ever since the prices of energy have reduced and are no longer at their peak, they remain higher compared to pre-war levels. In Germany, Europe's largest economy and top manufacturer, wholesale electricity prices average 138 Eur/MWh for the last few years according to the data from Ember, this is approximately 280% increase since the start of the war. Meanwhile, France, Italy and Netherlands are also experiencing over 200% jumps in average electricity costs over the same time frame. Poland's electricity costs have increased by 180%, and Spain's by 103%. Such a dramatic swell in energy bills has impacted every energy consumer in Europe and forced all energy intensive businesses to turn to energy efficiency search. (Gavin Maguire, 2024)

Vulnerabilities of energy infrastructure. As reported, energy infrastructure is being severely damaged during the war in Ukraine, this showcases gaps in protection of the critical infrastructure, lack of reserve of spare components that are needed to quickly repair the damaged pieces of the grid. Bombardments of the power plants, transformers and other elements of the electricity grid has caused black outs, energy shortages and other challenges for communities as well the government. Moreover, physical attacks on energy infrastructure went beyond borders of Ukraine, examples of the Nord Stream pipeline damage and recent damage of the telecommunication lines stress the need for the protection of the energy and utility infrastructure.

Since the outbreak of hostile war actions in Ukraine, the Russian forces have pursued a deliberate campaign of targeting the energy infrastructure, which included power plants, substations, and transmission lines. In middle of 2024, roughly 80% of the country's energy infrastructure was damaged or destroyed, causing blackouts and disrupting operation of the electricity and heating systems. The destruction of energy infrastructure has distressing impact on civilians, especially during the bitter winter months. The United Nations warned that further attacks may trigger more mass displacement, while millions of Ukrainians will have to survive without regular electricity and heating. Claims of corruption and mismanagement hindered efforts to rebuild and protect the energy grid. The contractors faced obstacles such as lack of financing and unnecessary bureaucratic hurdles that delayed the restoration of essential services for people.

In response to these challenges, Ukraine is moving toward decentralized renewable sources of energy. Solar and wind power plants are more difficult to target and much faster to

repair, most importantly they are widely scattered and too many to target compared to nuclear power plant for example. Some solar farms have been damaged in attacks but have been repaired and functioning within seven days. This goes to the very important reason the EU has identified to physically safeguard its energy infrastructure from the threat of sabotage, terrorist attacks, and hybrid war methods, something it knows firsthand from the war in Ukraine. The Baltic and Nordic regions are enhancing energy infrastructure security through joint initiatives, recognizing the interconnected nature of their energy systems and the shared risks they face. (Pillai, 2023)

War in Ukraine and its consequences on Ukrainian and European energy sector has highlighted the vulnerability of the energy infrastructure, volatility of energy prices and high dependency on energy imports. Europe found itself at the mercy of Russia, who was conveniently using energy as a geopolitical tool. The EU has responded with an action plan outlined in REPowerEU that focused on strengthening critical infrastructure and diversifying energy supply as well as accelerating renewable energy adoption.

1.3.4. Socio – Economic Factors, Including Public Resistance, Political Motivation and Cost of Switching to the Renewable Energy Sources

The transition to renewable energy sources is not only a technical challenge but also a socio-economic effort shaped by public sentiment, political will, and investments required. Public resistance to renewable energy projects often comes from a lack of awareness, concerns over environmental impacts, or skepticism about climate change mitigation as a reason for energy sector transformation by itself. Political motivation plays a dual role, as governments must balance the urgency of climate goals with the demands of their voters and stakeholders, including businesses and communities. Additionally, the cost of switching to renewable energy is also a barrier, specifically in poorer communities. Addressing these socio-economic factors is critical to ensuring a just and inclusive energy transition that helps achieve decarbonization goals.

NIMBYism (not in my backyard) is very common reaction that generally is expressed by communities when an infrastructure project, such as wind farm, solar park, hydrogen storage or even transmission lines are planned to be built near people's homes or in their neighborhoods. In general, societies are positive about the expansion of the renewable energy, but the fear of the negative impact on the aesthetics of the view thru the window, potential impact on local environment and negative effect on their property prices create major opposition and sometimes even protests by local communities. This factor needs to be managed softly thru extensive

communication, awareness building and involvement of local governments, businesses and communities at very early stages of the project.

Financial barriers. As any new technology, renewable energy infrastructure has higher initial cost compared to fossil fuel energy alternative in the early stage of its developments. While the cost of the components needed for the renewable system are declining, there is still a gap that is considered to be a substantial obstacle, especially for parts of community that experience energy poverty. Additionally, as discussed in 1.3.2. chapter integrating variable distributed sources of energy and accommodate surge in electricity consumption will require huge investments to the energy infrastructure.

According to the International Renewable Energy Agency (IRENA), achieving net zero emissions by 2050 would require global energy investment to exceed 4.4 trillion USD annually. It is said that for every euro invested in renewable energy system, another euro needs to be invested to the reconstruction of the grid.

Another critical aspect is achieving a just transition, ensuring that workers, communities, and industries affected by the shift from fossil fuels are not left behind. For regions heavily reliant on coal mining or other carbon-intensive industries, such as Silesia in Poland, the switch to renewables poses a threat to lose daily incomes for big share of population.

Political will and governance. The transition to renewable energy requires strong political will when navigating competing interests between ambitious climate policies and immediate expectations of the voters. Governments must balance their commitment to decarbonization with the need to address the concerns of communities. Political will is often tested when implementing EU policies in local law. The recent resistance from farmers in the EU regarding higher taxation for oil prices illustrates how public opinions can influence decisions of governmental institutions.

As we explore the stoppers of the energy transformation, it is important to pay attention that there are also positive socio-economic trends that help facilitate sustainable energy solutions:

- Growing awareness and concern about environmental issues and climate pollution.
- Younger generations are advocating for protection of the planet and reducing waste.
- Digitalization has a positive impact on the operational management of energy systems.
- Declining cost to become a prosumer and economic benefit to do so.
- Greater focus on Corporate Social Responsibility (CSR).

To summarize, energy sector is primarily impacted by four major external factors that either accelerate or set back the transformation towards carbon free energy system. Regulatory factors play a critical role and are primer drivers towards renewable energy resources. Thru

regulatory policies and directives adoption of renewable energy is accelerated within EU member states as they have a legal obligation to achieve sustainability goals. While technological improvement and innovation are major drivers of green energy, technological challenges pose significant risks. With infrastructure limitations in integrating renewable energy resources, aging infrastructure and severe weather impacts, technological challenges remain one of the major obstacles to be resolved to transition to fully renewable energy system. Geopolitical challenges are primarily focused around the EU dependency on the energy imports, that coincidentally are sources primarily from Russia. With the Ukraine – Russia war in the context, the need to address this dependency has become critical. Additionally, learnings from the ongoing war developments highlight the need of the energy sector infrastructure resilience and physical protection. Finally, the socio-economic factors present a dual impact. On one hand side, the society, especially younger generations, demonstrate higher concern regarding climate change and are more willing to change their behaviors to address the issue, however, access to affordable energy as well as lack of public education on environmental problems and limited understanding is a barrier to transition towards sustainable, but short term more expensive energy system.

1.4. Academic Perspectives on Green Energy Transformation

Energy sector and climate crisis are at the center of attention of scientists and governments for over a decade. This has led to multiple researches and articles being available and exploring the topic and there is an extensive list of literature examining the impacts of non-renewable energy consumption (NREC), renewable energy consumption (REC) and income per capita on reduction of CO₂ emissions. There are also multiple studies carried out by institutions and governments that offer valuable insights into the key factors, challenges, and impacts of this transformation across different regions. Table 4 provides a summary of some of the studies in this area and their key findings.

Table 4. Literature review summary

Study	Scope	Methodology	Conclusion
Mapping Europe renewable energy landscape: insights into solar, wind, hydro, and green hydrogen production (Qusay Hassan et al., 2024)	27 EU countries and UK between 2001-2021	Comparative analysis, correlation analysis	This correlation implies that countries with higher energy consumption are also the ones investing more in renewable energy infrastructure and thus have higher renewable energy potential.
Renewable energy and CO ₂ emissions: New evidence with the panel threshold model (Chen et al., 2022)	97 countries between 1995-2015	Dynamic panel threshold regression model (DPTRM)	The linear model findings suggest growth in non-renewable energy consumption is positively and significantly associated with the growth of CO ₂ emissions per capita. Also, the growth in trade openness leads to increased CO ₂ emissions per capita growth.

			Renewable energy consumption growth and CO2 emissions per capita growth is only significant and negative if countries consume higher levels of renewable energy.
A spatial analysis of the renewable energy transition determinants in Europe in light of the Russia-Ukraine war (Andrea Gatto et al., 2024)	27 EU countries and UK	Spatially clustered regression (SCR)	Results of the spatially clustered regression highlight that, that the reduction of energy imports from outside the EU is perceived negatively, the protection of critical energy infrastructure has positive association.
Accelerating renewables: Unveiling the role of green energy markets (Amar Rao et al., 2024)	12 countries from 2003 to 2021	Correlation analysis, quantile regression	GDP per capita, exhibit mixed relationships with clean energy consumption across different quantiles, suggesting that the economic impact on renewable energy consumption is complex and dependent on various factors.
The impacts of renewable energy, financial inclusivity, globalization, economic growth, and urbanization on carbon productivity (Muntasir Murshed et al., 2022)	7 countries between 2007-2018	Regression	The findings support that enhancing the level of energy use efficiency by 1% helps to improve carbon productivity by around 0.3% in the long run.
How economic growth, renewable electricity and natural resources contribute to CO2 emissions? (Daniel Balsalobre-Lorente et al., 2018)	5 EU markets between 1985-2016	Panel least squares, correlation analysis	The results confirm the negative effect of renewable electricity consumption on CO2 emissions.

Source: Author

One of the most influential papers according to the author is the research conducted by Chaoyi Chen, Mehmet Pinar and Thanasis Stengos (Chen et al., 2022) that aims to investigate the relationship between renewable energy consumption and CO₂ emissions, focusing on the varying levels of renewable energy adoption across 97 countries from 1995 to 2015. This study follows the dynamic panel threshold regression model (DPTRM) to investigate the role of GDP per capita and energy consumption per capita on CO₂ emissions per capita. The findings reveal that renewable energy consumption significantly reduces CO₂ emissions per capita, but only significant and negative if countries consume higher levels of renewable energy. In countries below this threshold, the environmental benefits of renewable energy adoption remain limited. This emphasizes the importance of scaling up renewable energy investments to achieve meaningful reductions in emissions. On the same direction, the study finds that non-renewable energy consumption is positively and significantly associated with increased CO₂ emissions, highlighting its negative environmental impact.

The article by Qusay Hassan (Qusay Hassan et al., 2024) studies renewable energy capacities and potential outputs across 27 European Union countries and the United Kingdom for the time period of 2001 to 2021. The primary aim of the article is to evaluate the production potential of four key renewable energy technologies – solar, wind, hydro and hydrogen – to identify regional options for future energy strategies. The study is extensive and focusing on several objectives:

- Examination of the potential and actual production of renewable energy types across regions.
- Assessment of the current state of renewable energy infrastructure, production levels, and future potential.
- Insights into the performance of individual countries, identifying leaders in renewable energy production.
- Evaluation of the green hydrogen production capacities and advancements.
- The relationship between electricity consumption patterns and the potential for renewable energy production.
- Identification of the areas with high renewable energy potential.
- Progress and future outlook of the overall EU progress in transitioning towards renewable energy.

Correlation analysis is performed to explore the relationships between energy consumption, investments in renewable energy infrastructure, renewable energy potential and outputs. The analysis indicates that the capacity for renewable energy production is proportional to the electricity consumption, which underscores the relevance and potential of renewable energy sources in meeting the future energy demand in the EU and the UK. This correlation implies that countries with higher energy consumption are also the ones investing more in renewable energy infrastructure and thus have higher renewable energy potential. The analysis shows that green hydrogen production is an essential and growing part of the renewable energy landscape in Europe, providing an alternative and sustainable fuel source for various applications, including transportation, heating, and industrial processes. Onshore and offshore wind regions, particularly those in the northern and coastal areas, benefit from higher wind speeds, which can be harnessed for energy-intensive hydrogen production. The outcomes underscore the importance of integration and cooperation between regions. Regions with high green electricity potential should collaborate with those with deficits, developing energy transfer networks such as smart grids that can distribute excess renewable energy where it is needed most.

A different perspective has been provided in the research by Andrea Gatto, Raffaele Mattera and Demetrio Panarello following the war actions in Ukraine (Andrea Gatto et al., 2024). This article brings together a group of scholars to analyze rapidly emerging energy policy responses in Europe to the latest external crisis. This study analyses responses at national and European Union levels, it is observing refocus in policies regarding geopolitical energy security as well as analyzing potential implications on the ongoing sustainable transitions in EU. This study leverages a spatially clustered regression (SCR) methodology to explore

regional dynamics and patterns that impact renewable energy adoption, particularly in the context of higher physical risks that is forced on the energy infrastructure by war events. The article assesses energy infrastructure security concerns and how they shape renewable energy policies. Leveraging surveys authors conclude that reducing energy imports from non-EU countries is perceived negatively, indicating that such efforts may face resistance from the society and businesses. On the other hand, the protection of critical energy infrastructure demonstrates a positive reaction by the target audience and confirms the importance of a resilient energy system. It is highlighted by authors that a refocus on energy supply security can contribute towards deprioritisation of the decarbonization targets and countries might turn back to more emission heavy energy resources such as coal. Authors summarize, that if EU's Fitfor55 represented a shift towards greater consideration of environmental sustainability, equity and social justice in energy policy, the REPowerEU responses to the current crisis represent a relative shift of political focus back to geopolitical supply security. As part of this refocus, clean energy supply has emerged as the best solution to European energy security long-term. However, there are obvious risks that short-term energy supply security may further extend coal and gas use and contribute to growing international tensions around sustainable transitions to net zero goal. (Andrea Gatto et al., 2024)

An article by Amar Rao, Satish Kumar, and Sitara Karim investigates the factors influencing clean energy consumption across 12 countries from 2003 to 2021 (Amar Rao et al., 2024). Using correlation analysis and quantile regression, the research aims to understand the relationships between key economic indicators, such as GDP per capita, and clean energy adoption. The findings reveal that the relationship between economic growth and renewable energy consumption is non-linear and varies across different countries. In some cases, higher GDP per capita is associated with increased renewable energy consumption, while in others economic growth is not directly linked to higher renewable energy adoption rates, suggesting that factors such as policy adoption and social acceptance also play significant roles.

The article by Muntasir Murshed investigates the interactions between key factors influencing carbon productivity across seven countries from 2007 to 2018 (Muntasir Murshed et al., 2022). The author leverages regression analysis to explore the impact of renewable energy, economic growth, urbanization, financial inclusivity, and globalization on carbon productivity. The key objective is to assess how renewable energy adoption contributes to improving carbon productivity. The findings of research confirm that renewable energy consumption has a positive effect on carbon productivity.

The research carried out by Daniel Balsalobre-Lorente, Muhammad Shahbaz, David Roubaud and Sahbi Farhani analyses the effects of economic growth, renewable energy

consumption, and availability of natural resources on CO₂ emissions in five EU countries (France, Germany, Italy, Spain, and the UK) from 1985 to 2016 (Daniel Balsalobre-Lorente et al., 2018). The authors are leveraging panel least squares and correlation analysis to estimate how renewable energy consumption impacts CO₂ emissions and whether natural resource availability contributes to reduction of GHG emissions. The findings confirm that renewable energy consumption has a significant negative effect on CO₂ emissions in line with other articles analyzed. Conversely, economic growth is positively associated with CO₂ emissions, suggesting that increased economic activity leads to higher energy consumption and emissions. This leaves author questioning if there are other indicators or criteria worth analyzing to better understand the relationship between economic growth and environmental decline.

Overall, investigated articles come to unanimous conclusion that increase in the share of renewable energy consumption is limiting CO₂ emissions and therefore help achieve global sustainability goals. While the first finding is dominant in all articles, there are still many questions unanswered regarding relationship between economic growth and GHG emissions. Findings in multiple studies vary suggesting that GDP growth has inconsistent impact on CO₂ emissions and additional criteria need to be considered.

1.5. Theoretical Model of Energy Sector

As explored earlier, energy sector, is complex and highly interconnected. Understanding energy sector requires evaluation of its resources, composition, key influencing factors, and performance indicators. Together, these elements create a theoretical model that reflects sector's structure as presented in Fig. 2.

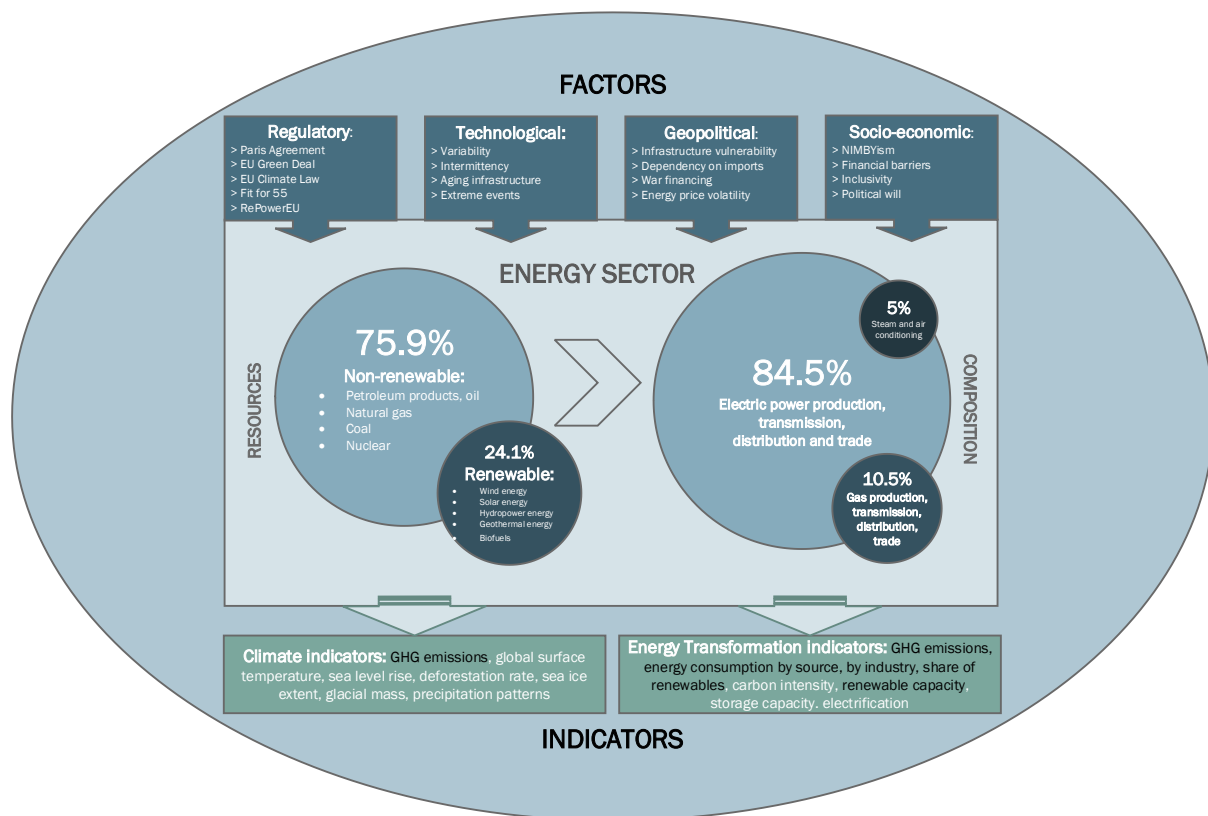


Fig. 2. Theoretical Energy Sector Model

Source: Author, based on Eurostat and NACE data

Resources. Energy sector is structured on the resources needed to deliver the power to the end consumer. The resources for energy are classified into non-renewable and renewable based on their nature. Non-renewable resources, such as petroleum, natural gas, coal, and nuclear energy, continue to dominate the global energy consumption with 75.9% of the European Union’s energy market share in 2023, according to the European Commission. However, renewable energy sources, including wind, solar, hydropower, geothermal, and biofuels, are accelerating in past decade. The transition to renewables is central to achieving net-zero goals and fighting climate change. In this context, regulation plays a critical role, serving as a primary driving factor behind the growth of renewable energy adoption.

Energy sector composition. The energy sector is composed by three subsectors as defined by NACE:

- Electricity production, transmission, distribution and trade, contributing 84.5 % of sectoral value added in 2021.
- Gas Manufacturing, transmission, distribution and trade, contributing 10.5 % of sectoral value added, focused on natural gas production, purification, and distribution to the final consumer.

- Steam and air conditioning subsector includes the production and distribution of steam, hot water, chilled water, and cooled air for heating and cooling. This subsector represents 5% of the energy sector's value added.

This composition highlights the dominant role of the electricity generation, transmission, distribution and trade subsector.

Factors influencing energy sector. Energy sector is primarily impacted by four major external factors that either accelerate or set back the transformation towards carbon free energy system:

- Regulatory factors play a critical role and are main drivers towards renewable energy resources. Thru regulatory policies and directives adoption of renewable energy is accelerated within EU member states as they have a legal obligation to achieve sustainability goals.
- Technological factors. While technological improvement and innovation are major drivers of green energy, technological challenges pose significant risks. With electricity grid limitations in integrating renewable energy resources, aging infrastructure and severe weather impacts, technological challenges remain one of the major obstacles to be resolved to transition to fully renewable energy system.
- Geopolitical factors are primarily focused on the EU dependency on the energy imports. With the Ukraine – Russia war in the context the need to address this dependency has become critical. Additionally, learnings from the ongoing war developments highlight the need of the energy sector infrastructure resilience and physical protection.
- Socio-economic factors present a dual impact. On one hand side, the society, especially younger generations, demonstrate a higher concern regarding climate change and are more willing to change their behaviors to address the issue, however, access to affordable energy as well as lack of public education on environmental problems and limited understanding is a barrier to transition towards sustainable, but short term more expensive energy system.

Key performance indicators. In the context of energy sector transformation towards climate neutral resources, two sets of performance indicators have been analyzed. Energy sector transformation is driven by the climate neutrality goals; thus, climate and energy transformation indicators are key metrics reflecting the progress of the transition as well as the impact on the environmental outcomes. Key metrics reflecting the climate change are average surface temperature, sea level rise, GHG emissions, glacier mass and severe weather events. Energy

transformation indicators are primarily focused on the renewable energy consumption, installed capacity, energy efficiency, GHG emissions.

The theoretical model of energy sector combines various internal and external elements that are defining the sector as presented in Fig. 2. The central part of the model is the composition of the sector based on the NACE nomenclature, and the resources used for energy generation. Both components are impacted by the external factors: regulatory, technological, geopolitical and socio-economic. These factors serve as a key driver impacting the developments within both – the composition of the sector as well as the resources used. The ongoing change of the sector is measured thru a set of climate and energy transformation indicators and outline the progress in the transition.

The first chapter of the thesis provides a theoretical overview of the energy sector in the EU and gives great emphasis to its transformation and transition into renewable sources. It identifies and systemizes key indicators used for monitoring transformation progress, together with metrics leveraged for tracking the dynamics of climate warming and its associated impacts. Key factors that influence the transformation of the energy sector are explored, including regulatory, technological, geopolitical, and socio-economic. The author goes on to develop a regulatory framework for the EU energy sector, giving an overview of the key regulatory instruments for climate mitigation, from the Paris Agreement to the EU Energy Directives, and how these are interconnected. Analysis of the scientific literature is conducted and key findings summarized. Concluding this chapter is a theoretical model for the energy sector that integrates these various elements into a holistic framework reflecting the complexity and dynamics of the sector.

2. DATA AND METHODS USED FOR THE ANALYSIS OF ENERGY SECTOR TRANSFORMATION

In the previous chapter various factors influencing the development of renewable energy have been examined, identifying those that either accelerate or hinder its growth. This chapter shifts focus to an in-depth statistical analysis of the EU energy sector's performance and assessment of how acceleration of the renewable energy impacts CO₂ emissions, a primary indicator of greenhouse gases (GHG). Additionally, this empirical study explores the relationship between GDP and CO₂ emissions, providing insights into how economic growth affects GHG emissions and, consequently, climate change. Together, these analyses aim to deepen an understanding of the interplay between renewable energy, economic development, and environmental sustainability.

2.1. Statistical analysis of Energy Sector trends in the EU

As part of commitment to the European Green Deal and the legally binding target of achieving climate neutrality by 2050, the EU is actively working to transform its energy sector. This transformation focuses on increasing the share of renewable energy, enhancing energy efficiency, and reducing dependency on fossil fuels. Such a shift is critical for mitigating climate change and ensuring a sustainable future. A range of authoritative sources will be utilized for this analysis, including Eurostat, Ember, Eurelectric, ACER, and others, which provide comprehensive data on the sector's evolution. The chapter will assess the pace of the EU's energy transition and evaluate how effectively the sector is progressing toward its ambitious sustainability goals.

Climate Indicators. As defined in Chapter 1.2. these indicators are used to assess the global and regional trends of a changing climate. As outlined by the WMO in a State of the Global Climate report, 2023 and 2024 will be the two warmest years on record, with the latter being on track to be the warmest, making the past 10 years, 2015 to 2024, the warmest ten years in the 175-year observational record. While the long-term warming, measured over decades, remains below 1.5°C, boosted by the El Niño, January - September 2024 global mean surface air temperature was $1.54 \pm 0.13^\circ\text{C}$ above the pre-industrial average, surpassing the ambition outlined in the Paris agreement to keep it to 1.5°C, as outlined in Fig. 3.

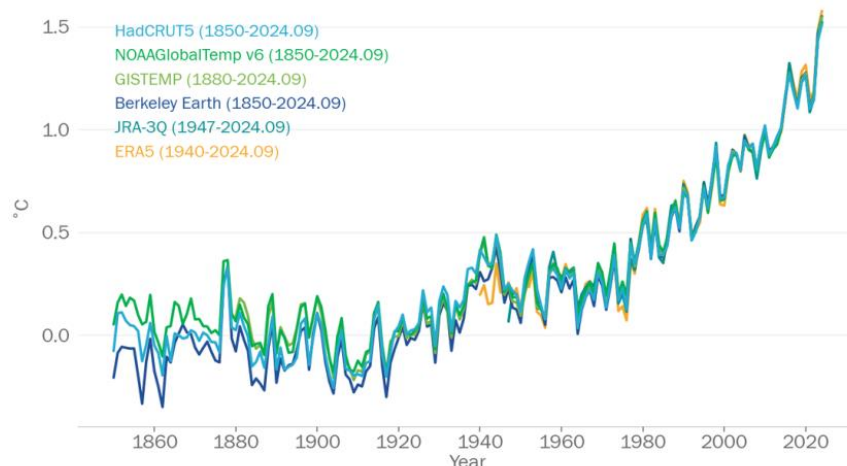


Fig. 3. Annual global mean temperature anomalies (relative to 1850–1900) from 1850 to 2024 from six datasets. The 2024 average is based on data from January–September.

Source: WMO, State of the Climate 2024 Update for COP29

Antarctic and Arctic Sea ice extent in 2024 have both been well below average. In 2023, globally, glaciers lost an estimated water equivalent to about 5 times the amount water in the Dead Sea. Antarctic sea-ice extent was reached around 19 September, with an extent of 17.2 million km. In 2023, glaciers lost an observed record 1.2 meter water equivalent of ice. In Switzerland, glaciers have lost about 10% of their remaining volume in 2021/2022 and 2022/2023.

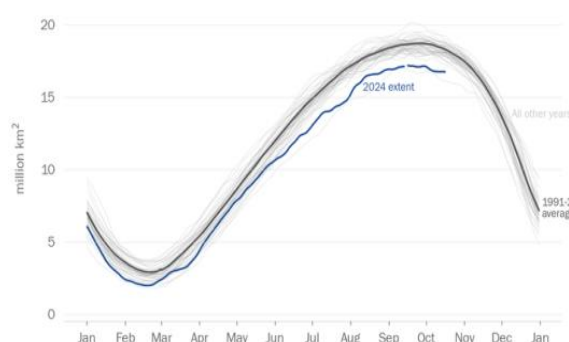


Fig. 4. Daily Antarctic and Arctic sea ice extents in 2024 compared to the average and historical records since 1978.

Source: WMO, State of the Climate 2024
Update for COP29

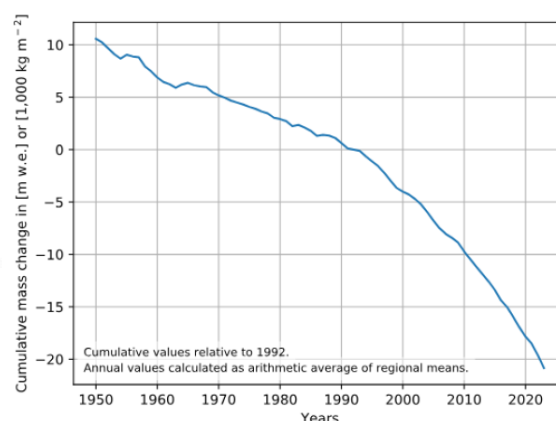


Fig. 5. Global cumulative mass change of reference glaciers since 1950. 0 = 1992. Shown in meter water equivalent.

Source: WMO, State of the Climate 2024
Update for COP29

As water warms, it expands. This thermal expansion, combined with the melting of glaciers and ice sheets, contribute to sea level rise. The long-term rate of sea-level rise has more

than doubled, increasing from 2.13 mm a year between 1993 and 2002 to 4.77 mm a year between 2014 and 2023.

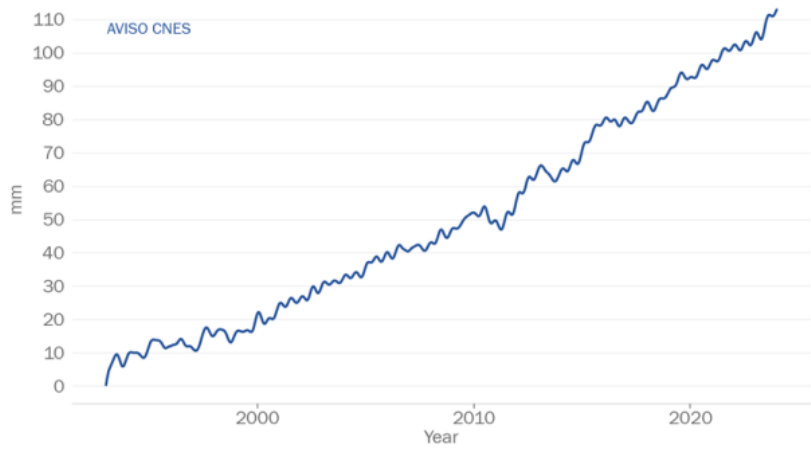


Fig. 6. Global mean sea level from 1993-2023.

Source: WMO, State of the Climate 2024 Update for COP29

A key outcome of the COP28 report highlights a pressing concern: the energy transition is progressing too slowly, and the ambitious targets must be reassessed and accelerated. Understanding climate variability and change is essential for optimizing renewable energy generation, ensuring the resilience of energy systems, driving energy efficiencies, and reevaluating action plans and sustainability targets. Looking specifically at the energy sector, key indicator that is used to identify the progress towards climate neutrality targets is GHG emissions. For this purpose, GHG emissions reported for the energy sector have been analyzed for the period of 2013 – 2022 in Europe. As presented in Fig. 7 in the past 10 years GHG emissions in the energy sector have decreased from 3000 million tonnes to 2600 million tonnes by approx. 15% in total.

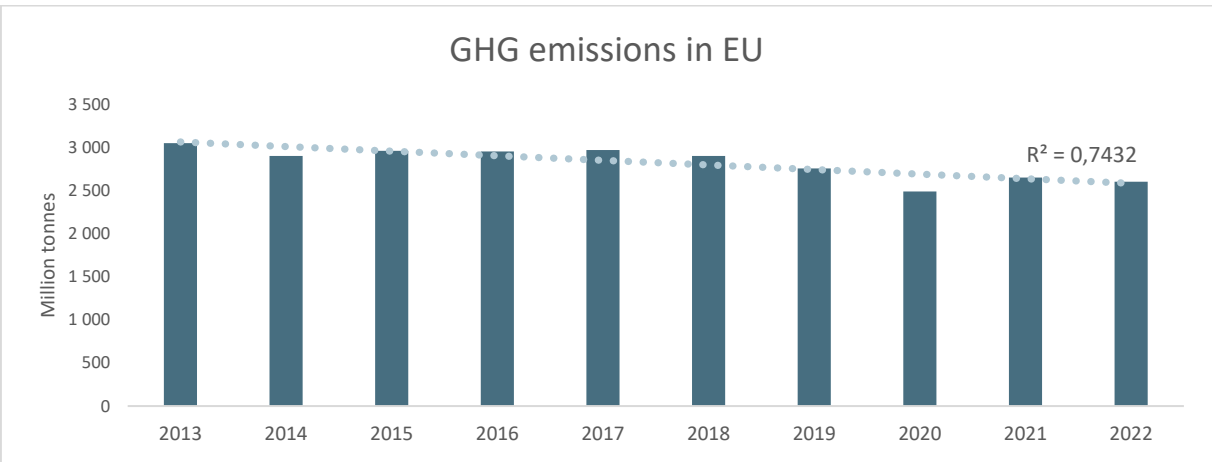


Fig. 7. GHG emissions 2013-2022.

Source: Prepared by author based on Eurostat data

As presented in Fig. 7 in the past 10 years GHG emissions in the energy sector have decreased 3000 million tonnes to 2600 million tonnes by approx. 15% in total. The results confirm the positive impact of the energy sector decarbonization efforts.

Table 5. GHG emissions by EU country 2013-2022

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Austria	9,7	9,2	9,4	9,4	9,6	9,2	9,3	8,4	8,8	8,3
Belgium	11,2	10,6	11	10,8	10,7	10,8	10,6	9,6	9,9	9,3
Czechia	12,5	12,3	12,4	12,5	12,6	12,4	11,8	10,7	11,4	11,1
Denmark	10,5	9,8	9,2	9,5	9,1	9	8,3	7,5	7,7	7,5
Estonia	16,7	16,1	13,7	15	15,9	15,3	11,1	8,6	9,5	10,5
Finland	11,9	11,1	10,4	10,9	10,4	10,6	10	8,8	8,7	8,5
France	7,6	7	7,1	7,1	7,1	6,8	6,7	5,9	6,2	6
Germany	11,9	11,3	11,3	11,2	11	10,6	10	9	9,4	9,3
Iceland	15,9	16	16,4	16,7	17,3	17,4	15,7	13	13,5	14,1
Ireland	13,6	13,1	13,6	13,9	13,7	13,6	12,9	11,9	12,3	12,2
Latvia	5,6	5,6	5,6	5,7	5,8	6,1	6,1	5,6	5,8	5,6
Lithuania	6,8	6,8	7	7,1	7,2	7,2	7,3	7,2	7,3	6,8
Netherlands	12,3	11,7	12,1	12,1	11,9	11,6	11,1	9,8	9,9	9,2
Norway	10,8	10,8	10,8	10,5	10,3	10,3	9,9	9,3	9,2	9,2
Sweden	5,8	5,8	5,7	5,6	5,5	5,3	5,1	4,5	4,7	4,5

Source: Prepared by author based on Eurostat data

To better understand market level contributions to GHG emissions, 2013-2022 GHG tones per capita data was analyzed for 15 EU markets. As provided in the Table 5, Sweden, Latvia, Lithuania and France have the least GHG emissions per capita compared across EU region. While on the other side we have Iceland and Ireland having the most GHG emissions per capita. However, compared over time the biggest progress of reducing GHG emissions is reported in Estonia with 37% drop, Finland and Denmark with 29% and Netherlands with 25% drop in GHG emissions per capita over 10 years.

Energy Indicators. Before diving into the dynamics of the energy indicators in EU, it is worthwhile looking at a projected scenarios developed by the International Energy Agency. A Pre-Paris agreement trajectory outlines the CO₂ emissions rise to more than 50 Gt by 2050 and rise of a median global average surface temperature of around 3.5 °C by 2100 in a do-nothing scenario, labeled as Pre-Paris baseline. STEPS (Sustainable Development Scenario) represent a pathway that aligns with achieving the sustainable development goals, particularly those related to energy access, air quality, and climate action. However, it does not fully align with the more ambitious targets of the Paris Agreement, especially regarding global temperature limits. APS (Announced Pledges Scenario) assumes that countries will implement the climate pledges and commitments they have publicly announced, including those made under national

climate plans, international agreements. This includes national pledges for carbon reduction, renewable energy deployments and other climate actions. Meanwhile, NZE (Net Zero Emissions Scenario) is a scenario that envisions global net-zero emissions by 2050. Corresponding to these scenarios, APS and NZE should be sufficient to limit global temperatures rise below 2°C compared to preindustrial levels as outlined by IEA in the Fig. 8.

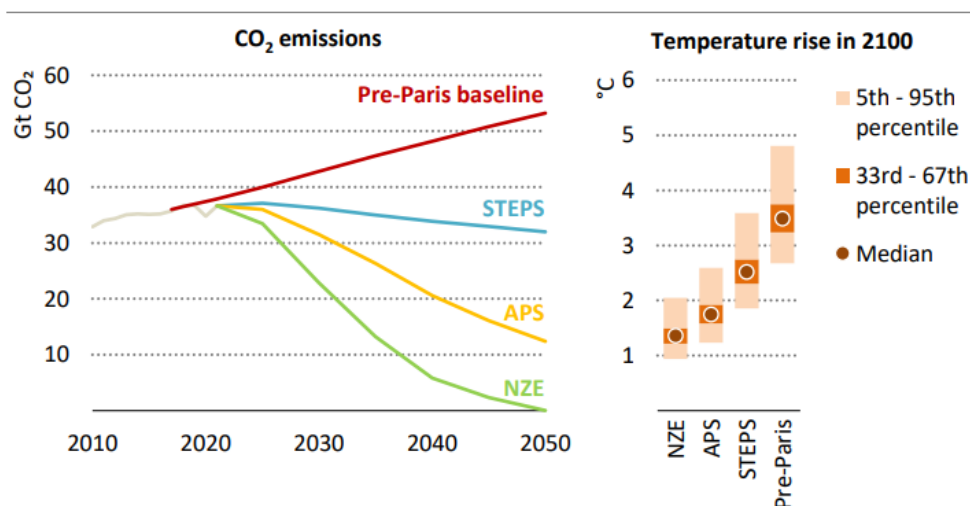


Fig. 8. Energy-related CO₂ emissions, 2010-2050 and temperature rise in 2100 by scenario.

Source: Net zero by 2050, A roadmap for the global energy sector 2022, International Energy Agency

Achieving the APS and NZE scenarios will require significant transition in the energy sector. To better understand how EU is doing in terms of migrating towards renewable energy sources, Eurostat data for 2022 has been analyzed. In 2022, EU reached a 23% share of its gross final energy consumption from renewable sources as presented in Fig. 9, it is 1.1 percentage points (pp) higher than in 2021. Sweden, Norway and Iceland lead among EU countries, with two-thirds of their gross final energy consumption in 2022 derived from renewable sources. The lowest proportions of renewables were recorded in Ireland (13.1%), Malta (13.4%), Belgium (13.8%) and Luxembourg (14.4%).

As presented in Fig. 10, of all the branches in the energy sector, electricity has achieved the highest share of renewable sources that made up 41.2% of gross electricity consumption in the EU, 3.4 percentage points (pp) more than in 2021 (37.8%). Sweden, Denmark and Austria had most of their electricity produced from renewable sources, whereas Norway and Iceland report all their electricity production to come from renewable sources. At the other end of the scale, the lowest shares of electricity from renewable sources were reported in Malta (10.1%), Hungary (15.3%), Czechia (15.5%) and Luxembourg (15.9%).

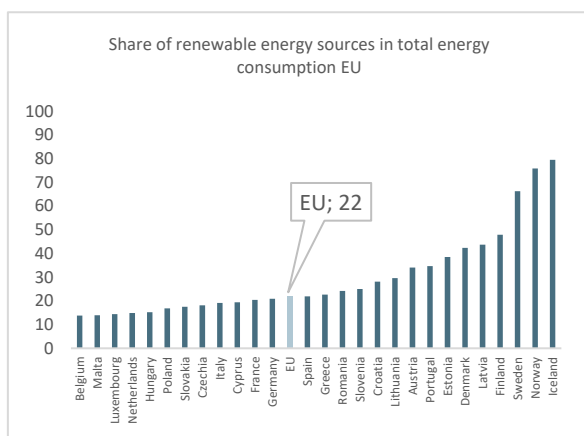


Fig. 9. Share of renewable energy sources in total energy consumption EU, 2022

Source: Prepared by author based on Eurostat data

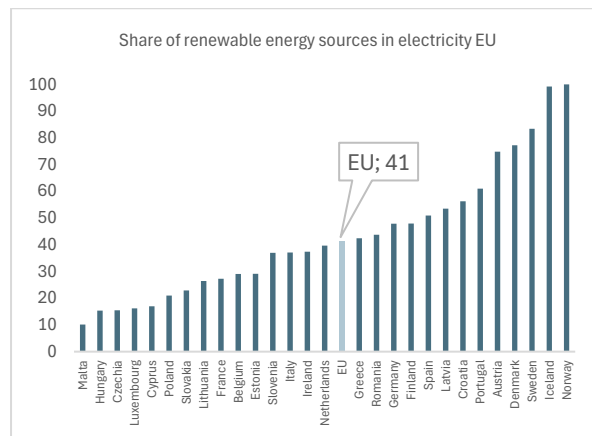


Fig. 10. Share of renewable energy sources in electricity EU, 2022

Source: Prepared by author based on Eurostat data

Looking into the heating and cooling branch of energy sector in 2022, renewable energy accounted for 24.8 % of total energy use, increasing from 11.7% in 2004. Developments in the industrial sector, services and households contributed to this growth. Ambient energy captured by heat pumps for heating and renewable cooling are also considered. The share of energy from renewable sources in heating and cooling is presented in Fig. 12. Among the EU countries the share of energy from renewable sources in heating and cooling was more than half in Sweden (69.4%), Estonia (65.4%), Latvia (61.0%), Finland (58.5%), Lithuania (51.5%) and Denmark (50.1%). At the other side of the scale, with a share of energy from renewable sources in heating and cooling of less than 10% were Ireland (6.3%) and the Netherlands (8.6%).

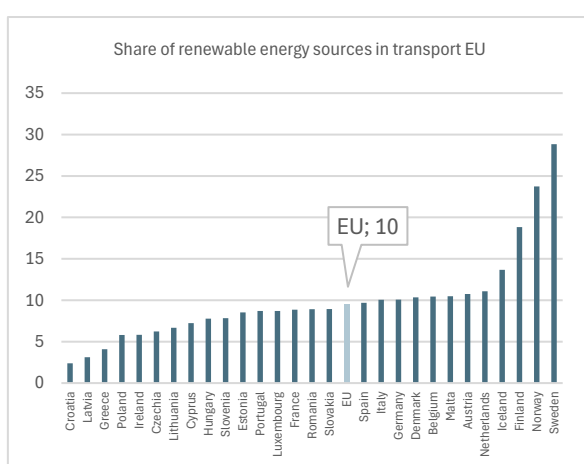


Fig. 11. Share of renewable energy sources in transport EU, 2022

Source: Prepared by author based on Eurostat data

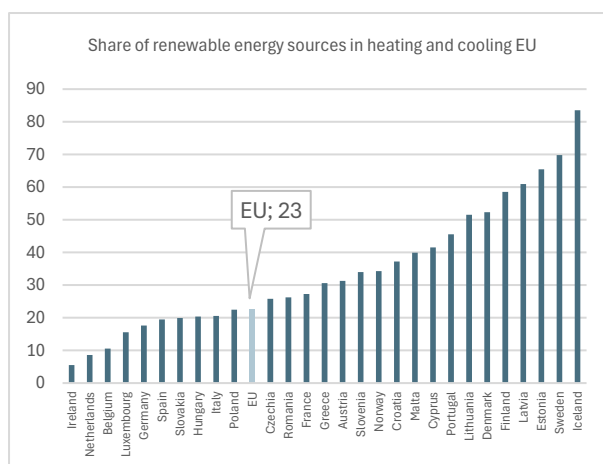


Fig. 12. Share of renewable energy sources in heating and cooling EU, 2022

Source: Prepared by author based on Eurostat data

The most challenging situation is with transport sector, where only 10% of renewable energy is used in transport activities in 2022 as presented in Fig. 11. The common target for the share of renewable energy used in transport by 2030 is 29%, therefore immediate actions need to be taken to achieve this goal. Highest adoption of renewable energy sources in transport was reported in Sweden with 29.2% in Sweden, Norway with 23.7% and Finland with 18.8%. Slowest adoption remains in Croatia (2.4%), Latvia (3.1%) and Greece (4.1%).

As reported by International Energy Agency, electricity consumption will at least triple compared to 2020. At the point of the report was prepared in 2021 the growth of energy demand due to AI acceleration was not evaluated. In the 2023 publication by International Energy Agency, it is projected for global electricity demand to rise at a faster rate over the next three years, growing by an average of 3.4% annually through 2026. Additionally, it is projected that electricity generation will be dominated by renewable sources as soon as 2030 as outlined in a Figure 13.

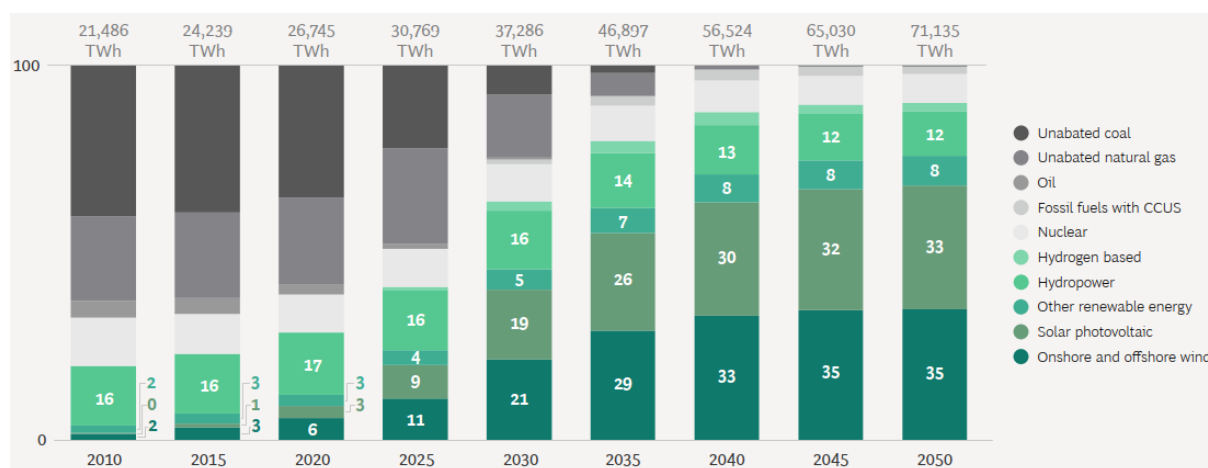


Fig. 13. Share of total global electricity generation.

Source: Net zero by 2050, A roadmap for the global energy sector 2021, International Energy Agency

While looking at ambitious targets for energy sector it is critical to understand that the progress of the past 10 years has been dramatical, completely reshaping the balance between fossil and renewable sources used in the electricity generation as presented in the Fig. 14 sourced from EMBER. The EU accelerated its shift away from fossil fuels in 2023, with record falls in coal, gas and GHG emissions. Fossil fuels dropped by a record 19% to their lowest ever level at less than one third of the EU's electricity generation.

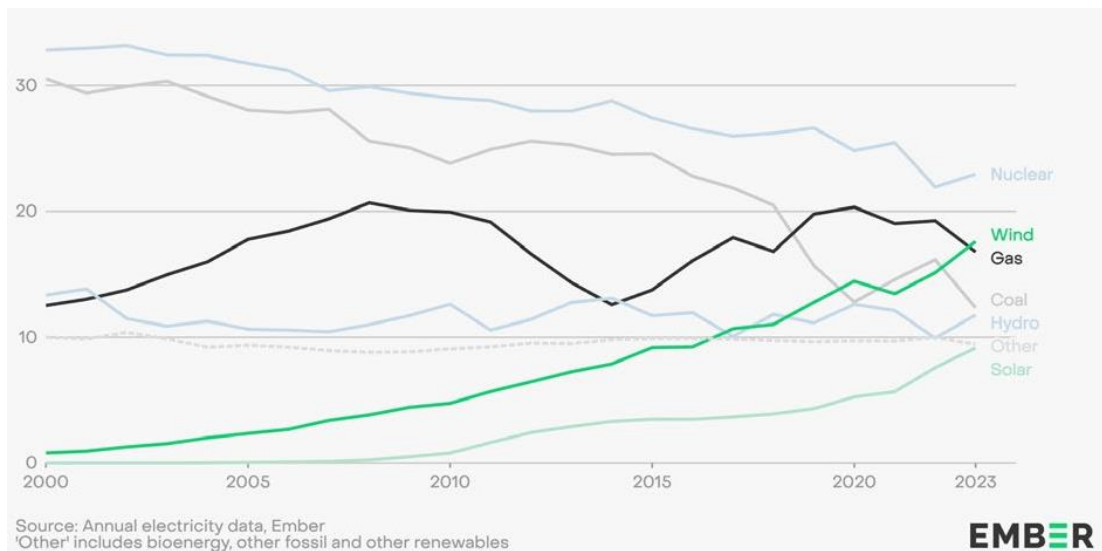


Fig. 14. Share of EU electricity generation by source.

Source: EMBER

Renewables rose to a record 44% share, surpassing 40% for the first time, as presented in the Fig. 15. Wind and solar continued to be the drivers of this renewable's growth, producing a record 27% of EU electricity in 2023 and achieving their largest ever annual capacity additions. Furthermore, wind generation reached a major milestone, surpassing gas for the first time. Coal was already in long-term decline, and that trend resumed in 2023. The temporary slowdown in coal plant closures during the energy crisis did not prevent a huge fall in coal generation this year, with a wave of plant closures imminent in 2024. Gas generation fell for the fourth consecutive year, and as coal nears phase-out in many countries, gas will be next to enter terminal decline.

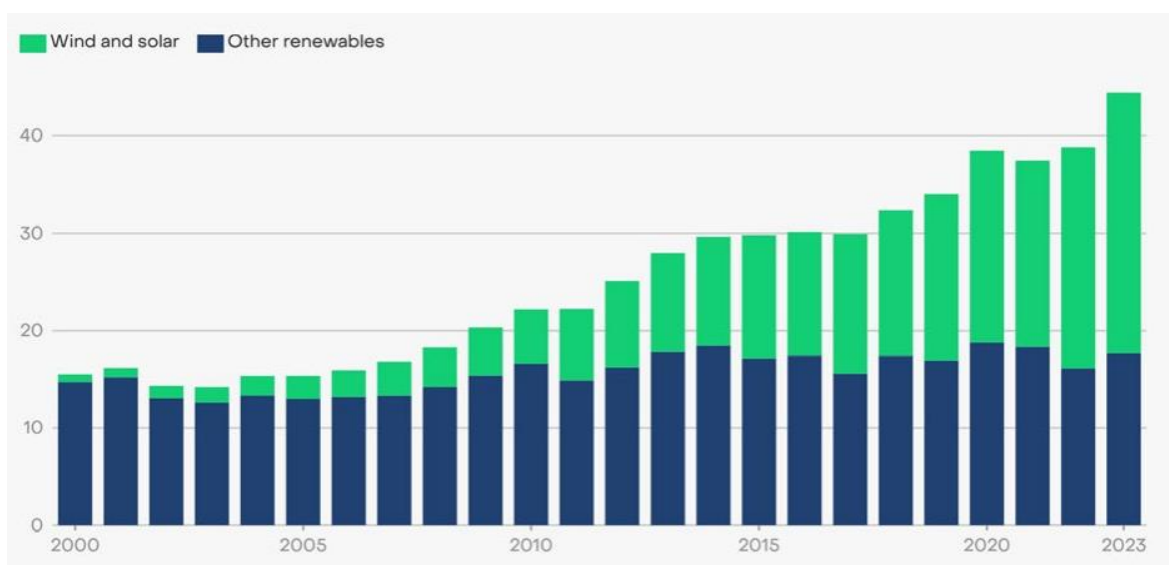


Fig. 15. Electricity generation share from renewable sources in EU.

Source: EMBER

Both coal and gas generation had a record percentage fall in 2023, leading to a record drop in power sector CO₂ emissions as pointed out in Fig. 16. Fossil generation fell to less than a third of the EU's electricity generation (33%) for the first time ever. Coal generation fell by 26% (-116 TWh) to 333 TWh, the largest annual percentage reduction since at least 1990. As a result, coal dropped to the lowest level ever and made up just 12% of the EU's electricity in 2023. Gas generation fell by 15% to 452 TWh. This is the biggest annual reduction and the fourth year in a row that it has declined. In 2023, gas generation was 20% below the pre-Covid level in 2019 (569 TWh), but it was still above the lowest year on record. At 17% of the EU's electricity mix, gas generated more power than coal (12%) in 2023.

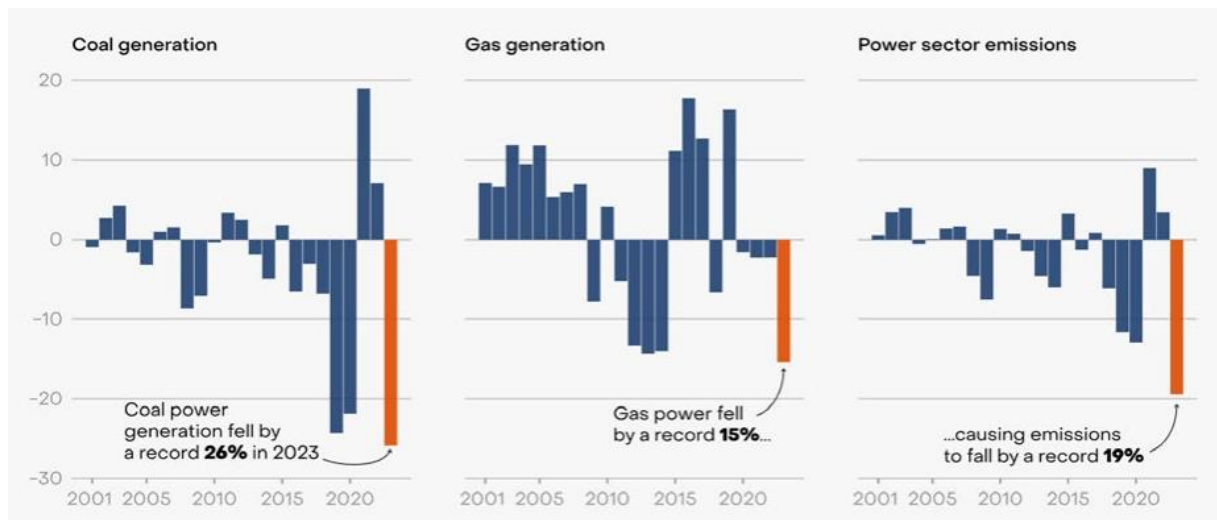


Fig. 16. Annual change in electricity generation emissions (%) in EU.

Source: EMBER

One of the major drivers of gas, oil and coal decline, was Russia – Ukraine war, in terms of volumes (Fig. 17), by end of December 2022 gas and oil imports were less than 1/3 of pre-invasion levels, while imports of coal stopped altogether since the entry into force of related sanctions on Russia. It is anticipated that the complete closure of gas and oil imports to the EU will be achieved by 2027.

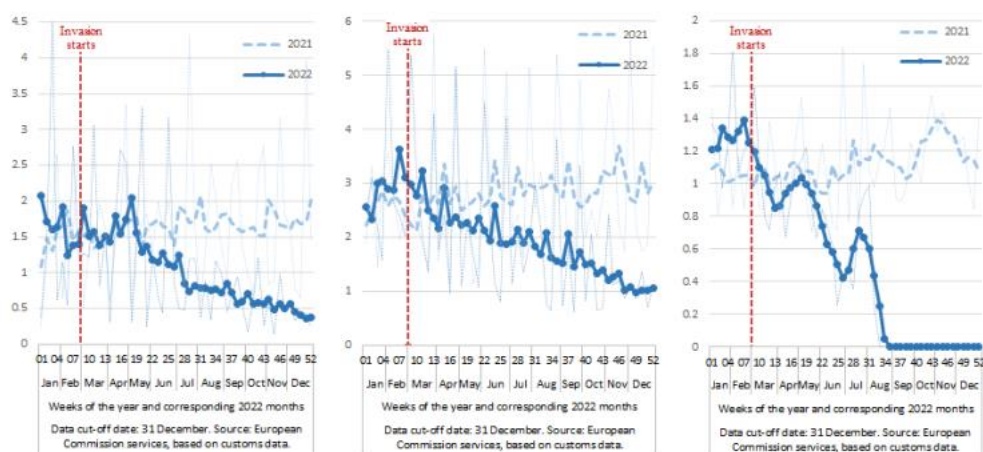


Fig. 17. Weekly EU imports fossil fuels (gas, oil, coal) from Russia, volumes.

Source: Publications office of the European Union

The statistical analysis completed as part of this thesis highlights the significant progress and the challenges of the EU's energy sector. While electricity generation is rapidly transitioning towards renewable resources and is reported to have 44% of the electricity generation to be coming from renewable sources in 2023, the sectors of transportation as well as heating and cooling are lagging. Driven by geopolitical dynamics and challenges, EU has significantly reduced its coal and gas usage for electricity generation by 26% and 15% accordingly in the last year. However, the statistical analysis also outlines that climate indicators further demonstrate dramatical shift towards ecological crisis and therefore calls out for a need to accelerate and increase in ambition for energy related sustainability goals.

2.2. Indicators Used and Methodology Chosen for the Empirical Analysis

For this empirical study, panel data was gathered from Eurostat to analyze the relationship between CO₂ emissions, renewable energy growth, and economic growth. To examine these dynamics, following key indicators have been selected for the analysis:

- CO₂ (carbon dioxide) emissions as an equivalent of the GHG emissions, measured in tonnes per capita.
- GDP (Gross Domestic Product) per capita, a measure of the economic performance of a country that represents the total monetary value of all goods and services produced within a country over a given year, divided by the population of the indicated country. This metric is chosen as a proxy for the economic growth.
- Renewable Energy Consumption (REC) and Non-Renewable Energy Consumption (NREC) indicators were chosen as parameters conveying the development of the green

energy in the given market. REC is energy consumption from renewable sources including hydro, geothermal, wind, solar, biomass and waste measured in tonnes of oil equivalent per capita. NREC is energy consumption from non-renewable sources including coal, oil, nuclear and natural gas measured in tonnes of oil equivalent per capita.

- Renewable Energy Installed Capacity (RECAP) is total installed capacity of the renewable sources (solar, hydro and wind) measured in kW per capita. It indicates total potential of the given market to produce renewable energy domestically and is also chosen an indicator of the renewable energy development.
- Number of registered electro vehicles (EV) per capita in the given market as an indicator suggesting electrification and therefore decarbonization of the given country.

For consistency, datasets were selected from Eurostat based on standardized and highly comparable methodologies (Eurostat, 2023a). To accurately analyze the relationships in the data, all indicators have been converted to per capita metrics, ensuring that they are on a consistent scale. Using mixed levels – such as per capita for one indicator and total values for another – would distort comparisons and lead to misleading results in the regression analysis.

The example of the panel data set used for the analysis is provided in the Table 6, where key indicators over a given period of time and selected markets are listed.

Table 6. The example structure of the analysed data

Country	Year	CO2	GDP	REC	NREC	RECAP	EV
Austria	2013						
Austria	2014						
Austria	...						
Austria	...						
Austria	2022						
Belgium	2013						
...	...						

Source: Author

A quantitative analysis approach is employed to examine the relationship between greenhouse gas emissions (CO₂), renewable energy growth, and economic growth (GDP). In the Fig. 18 the steps of the analysis, the econometric estimation, and the process of evaluation and adjustment of the statistical model are presented.

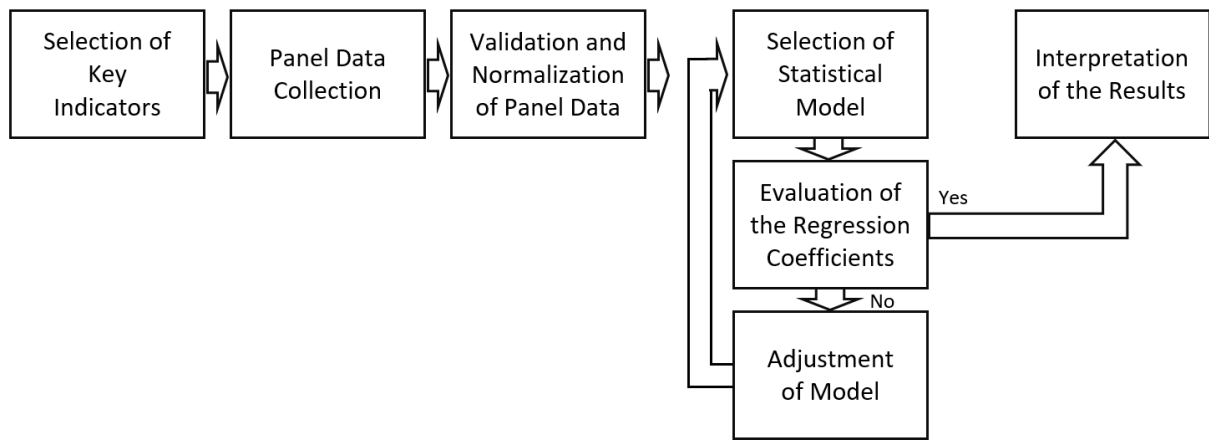


Fig. 18. Approach of the Econometric Estimation

Source: Author

The empirical study is based on the panel data and the research covers the following econometric concepts:

- panel data;
- data normalisation;
- multicollinearity test;
- multiple linear regression;
- hypothesis testing.

As outlined in the Fig. 18 as a first step panel data was collected from Eurostat. The time-series for the panel data observations used in the analysis is from year 2013 to 2022. Initial set of 27 EU markets has been narrowed down to 15 markets based on their competitiveness scores in the World Competitiveness Ranking (International Institute for Management Development, 2024). Switzerland was excluded due to insufficient data across several variables essential to the analysis. The datasets were thoroughly reviewed to ensure data completeness, leading to the exclusion of any markets with missing information. The EU countries used in the study are Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Lithuania, Luxembourg, Netherlands, Norway, Sweden.

For consistency and statistically comparable analysis data was normalized by adjusting raw data to fit within a specific range and scale. All the indicators gathered have been adjusted to per capita metrics for selected markets. The following steps included multicollinearity testing, regression analysis and hypothesis testing, these steps are further detailed in the chapter 3.1 of the thesis.

3. ASSESSMENT OF THE MAIN INDICATORS OF ENERGY SECTOR TRANSFORMATION IN EU: A REGRESSION ANALYSIS APPROACH

In this chapter, an empirical analysis is conducted to investigate the relationship between CO₂ emissions and key economic and energy indicators for chosen EU countries. The analysis uses a Multiple Linear Regression model to assess the effects of economic growth, renewable and non-renewable energy consumption, installed renewable energy capacity, and the adoption of electric vehicles on CO₂ emissions per capita. Data for this study includes 15 EU countries and covers the period from 2013 to 2022. All data are sourced from the Eurostat database.

3.1. Leveraging Linear Regression analysis to examine the relationship of renewable energy development and CO₂ emissions

Multiple Linear Regression model is leveraged to examine the relationship between CO₂ emissions per capita and energy consumption per capita (renewable and non-renewable energy consumption per capita), renewable energy installed capacity per capita and GDP per capita. Linear regression is a statistical method that models the relationship between one or more independent variables (also called predictors or explanatory variables) and a dependent variable (also called response or outcome variable). The goal of linear regression is to find the best-fitting line or equation that describes how the dependent variable changes as a function of the independent variables. The equation of the line can be used to make predictions, test hypotheses, or understand how different factors influence the outcome of interest.

Linear regression assumes that the relationship between the independent and dependent variables is linear, meaning that it can be expressed by a straight line. The equation of the line has the form:

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + b_nx_n + e \quad (1)$$

where:

y is the dependent variable.

$x_1, x_2, \dots, x_n$ are the independent variables.

b_0 is the intercept (the value of y when all x 's are zero).

$b_1, b_2, \dots, b_n$ are the coefficients (the slopes of the line for each x).

e is the error term (the difference between the observed and predicted values of y).

To examine the relationship between CO₂ emissions per capita and energy consumption per capita (renewable and non-renewable energy consumption per capita), renewable energy installed capacity per capita and GDP per capita the following formula will be used:

$$CO2_{it}=b0+b1GDP_{it}+b2GDP2_{it}+b3REC_{it}+b4NREC_{it}+b5RECAP_{it}+b6EV_{it}+e_{it} \quad (2)$$

where:

i, t denotes the independent variable in country i and year t .

$b1, b2, b3, b4, b5, b6$ are the coefficient estimates on the relevant variables.

$CO2_{it}$ – is carbon dioxide emissions in metric tons per capita as a proxy for environmental pollution in country i and year t .

GDP_{it} – is the value of real gross domestic product in Eur per capita in country i , year t .

REC_{it} – is electricity consumption from renewable sources including hydro, geothermal, wind, solar, biomass and waste measured in tonnes of oil equivalent per capita.

$NREC_{it}$ – electricity production from non-renewable sources including coal, oil and natural gas measured in tonnes of oil equivalent per capita.

$RECAP_{it}$ – is total installed capacity of the renewable sources (solar, hydro and wind) measured in kW per capita.

EV_{it} – is number of registered electro vehicles per capita in the given market.

e_{it} – denotes normally distributed error term.

Prior to running linear regression analysis, multicollinearity test was performed to identify if there is correlation between dependent and independent variables, as well as to check whether there is any cross-sectional dependence of the variables used. One of the assumptions of linear regression is that the independent variables are not correlated with each other. This is called the assumption of no multicollinearity. Multicollinearity occurs when two or more independent variables are so highly correlated that they can essentially explain each other. The Table 7 provides a correlation matrix among 6 variables. CO₂ emissions have strong positive correlation with non-renewable energy consumption, moderate positive correlation with GDP per capita and weak correlation with renewable installed capacity. CO₂ emissions also show negative moderate correlation with renewable energy consumption and EVs registered per capita.

Table 7. Correlation matrix

	CO2	REC	NREC	RECAP	GDP	EVs
CO2	1					
REC	-0,28322	1				
NREC	0,650404	0,03416	1			
RECAP	0,103425	0,134707	0,555523	1		
GDP	0,38395	-0,05521	0,42422	0,581951	1	
EVs	-0,21656	0,099475	0,106215	0,625208	0,275483	1

Source: Author

For five dependent variables evaluated, correlation table also shows strong positive correlation between renewable installed capacity and energy consumption (both renewable and non-renewable), GDP and electro vehicles registered. Multicollinearity can cause problems for the estimation and interpretation of the regression coefficients, such as the coefficients may have large standard errors and low t-values, making them insignificant and unreliable. For this purpose, renewable installed capacity (kW per capita) will be further removed from the regression analysis.

To confirm the appropriateness of the regression equation, significance P-value needs to be evaluated. The Table 8 presents the ANOVA (Analysis of Variance) of the regression and helps in understanding the overall fit of the regression model and whether the predictors collectively have a significant effect on the dependent variable. P-value (Significance F) helps determine whether the F-statistic is significant.

Table 8. Multiple Linear Regression Statistics

<i>Regression Statistics</i>	
Multiple R	0,78276072
R Square	0,612714344
Adjusted R Square	0,602030602
Standard Error	2,326115343
Observations	150

Source: Author

The results obtained in Table 8 show that the model is significant with P-value < 0.01 (6,15945E-29) and therefore null hypothesis can be rejected. R square of 0,612714344 indicate that the analysis explain 61,27% of cases, which is considered high.

Table 9. Multiple Linear Regression ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	4	1241,243908	310,310977	57,3501617	6,15945E-29
Residual	145	784,5678255	5,41081259		
Total	149	2025,811733			

Source: Author

Once the model's significance was confirmed and null hypothesis rejected, the coefficients of the linear regression will be analyzed to determine the relationship between dependent variable, which is CO₂, and independent variables: consumption of renewable and non-renewable energy, GDP and electro-vehicles registered per capita.

Table 10. Multiple Linear Regression Coefficients

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	7,615165889	0,547348635	13,9128252	1,7366E-28	6,533353445	8,696978334
REC	-3,647400126	0,726171974	-5,022777326	1,47525E-06	-5,082649668	-2,212150584
NREC	1,324774205	0,124440593	10,64583648	6,48265E-20	1,078822405	1,570726005
GDP	3,83277E-05	1,15903E-05	3,306887439	0,001189427	1,542E-05	6,12355E-05
EVs	-29,62878486	5,189541623	-5,70932599	6,18814E-08	-39,88570403	-19,3718657

Source: Author

The model shows significant relationship between all four independent variables and CO₂ with the P-value <0.01 for all except GDP, that has a P-value of <0.05. Renewable energy consumption and EVs registered has a strong negative relationship with CO₂ emissions, meanwhile use of non-renewable energy as well as GDP shows positive relationship with CO₂.

This proves the hypothesis that by decreasing the consumption of the non-renewable energy that comes from fossil fuels and increasing the consumption of the renewable energy, including the replacement of the internal combustion engine automobiles with electro-vehicles will result in reduction of the CO₂ emissions. However, further analysis is required to better understand the relationship between GDP and the GHG emissions.

3.2. Exploring the hypothesis of the environmental Kuznets Curve (EKC)

To further understand the relationship between GDP and CO₂ emissions, the observations of the GDP and CO₂ on a country level have been plotted and presented in a Figure 19. All scattered plot graphs with exception of Estonia, Lithuania and Latvia show nice trendline as when GDP improves, CO₂ emissions decline. Meanwhile, for Estonia values are

very scattered and trendline is rather flat, on the other hand, for Lithuania and Latvia there is an opposite correlation – when GDP improves, CO2 emissions grow.



Fig. 19. CO2 and GDP scattered plot analysis

Source: Author

Markets have further been grouped and analyzed following the hypothesis of the environmental Kuznets Curve (EKC) which argues that “economic growth initially brings environmental degradation that is followed by a phase of environmental improvement”. (David I. Stern, 2004)

Table 11. EU markets grouped by phase of development according to EKC

Phase	Phase description	Countries	Country characteristics
GDP ↑ GHG ↑ Initial Phase (Rising)	Economic growth brings environmental degradation	Latvia, Lithuania	GDP relatively low with steady growth starting from approx. 4000Eur to 14000Eur per capita followed by GHG growth.
GDP ↑ GHG → Turning Point	Economic growth brings no effect on environment	Estonia	GDP relatively low growing from 6000Eur to 16000Eur per capita, GHG emissions close to flat.
GDP ↑ GHG ↓ Later Phase (Declining)	Economic growth brings environmental improvement	Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Ireland, Luxembourg, Netherlands, Norway, Sweden	GDP high, starting from approx. 30000Eur per capita and further growing, followed by GHG decline.

Source: Author

As it is observed in the Table 11, markets with low GDP demonstrate appreciation of CO₂ emissions as GDP improves, while for more developed markets with higher GDP, CO₂ declines as GDP improves. This observation is in line with the hypothesis of the environmental Kuznets Curve (EKC). In early stages of economic development, industrialization and urbanization lead to increased resource use and therefore increase in pollution. All three markets – Latvia, Lithuania, Estonia – that demonstrate distinct patterns in GDP and GHG relationship compared to majority of the markets in the model also differ in their economic developments. GDP of these three markets starts as low as 4000 Eur per capita which in some cases is 10+ times higher than GDP in a more developed markets that are part of this analysis. Following hypothesis of the EKC, mentioned markets need to achieve certain maturity of the economic growth before they will start demonstrating decline in the CO₂ emissions.

To further explore possibility of discovering EKC within this study, the developments of the GDP and CO₂ emissions over time in the markets with lower GDP have been depicted in the Figure 20. In all the three markets it is visible that YoY as GDP improves, CO₂ emissions are also growing, however once GDP of approx. 12000-14000 Eur per capita is achieved, CO₂ emissions start declining while GDP continues growing on annual basis. Following hypothesis

of EKC, after a certain income threshold, societies have the means to invest in cleaner technologies, enforce environmental regulations, and shift to green economic targets and sustainable practices.

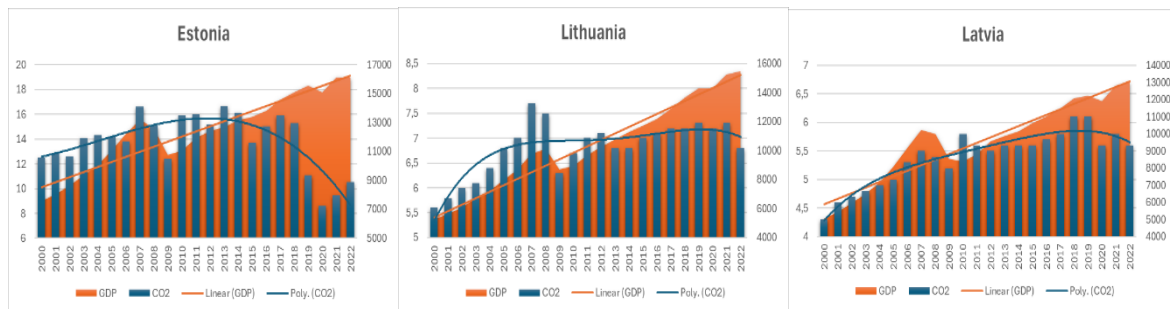


Fig. 20. CO₂ and GDP developments over time (2000-2022)

Source: Author

Diagrams outlined in Fig. 20 confirm previous evaluation and grouping of markets, it is abundantly clear that Estonia with GDP closing 16000 Eur per capita is already demonstrating GHG curving down in the past few years, while it was growing steadily as GDP improved in previous years. Breaking point for Estonia was around 13000 Eur per capita. Lithuania and Latvia both demonstrate stabilization and slight decline in GHG as they are approaching 11000-12000 Eur per capita economic growth.

The analysis confirms the relevance of the Environmental Kuznets Curve (EKC) hypothesis in explaining the relationship between GDP and CO₂ emissions. In countries with lower GDP levels (Latvia and Lithuania), economic growth corresponds with increased CO₂ emissions. However, as GDP reaches a certain threshold (approximately 12,000-13,000 Eur per capita), a stabilization or decline in emissions is observed (Estonia). Meanwhile, for developed markets with higher GDP levels (above 30,000 Eur per capita), GDP growth result in CO₂ emissions decline.

3.3. Concluding Insights of the Empirical Analysis

Industry transformation is the process of change triggered by internal or external events, that modify the composition, dynamics, processes and competition within industry. As a result of transformation of the certain market, new business models may appear, start ups and new players might emerge and completely change the landscape of the business. This definition well explains the transformation of the energy sector that is happening in that decade and the stages yet to come. The shift overall is driven by external need to reduce the emissions and stop climate warming, it is further escalated thru policies and regulations, shaped by technological

boundaries, geopolitical struggles and socio-economic factors. Forced by these drivers energy sector is changing its composition as more power is being produced by renewable sources on annual basis. The composition of the sector is also not static as the innovation and need to resolve technological puzzles invite new players to the market, such as solar and wind parks, storage and balancing service providers, demands side flexibility, CO₂ capturing service providers and many others. Moreover, customers are also invited to be active members of the energy market by producing the electricity and trading in the market. Industry wise the lines also become blurry as transport becomes highly reliant on the electricity grid due to the expansion of the EVs.

Earlier chapters laid a basis by analyzing the energy sector holistically, starting from its composition, resources, processes, and the factors influencing the transformation. Furthermore, indicators used to measure and monitor the progress were investigated and further supported by statistical analyses that reveals the current state of the sector's evolution. Regression analysis has been performed to understand the relationships between core indicators – GHG emissions, GDP, renewable and non-renewable energy consumption as well as electro vehicles registered. The results of the regression showed that renewable energy consumption and EVs registered have a strong negative relationship with CO₂ emissions, meanwhile use of non-renewable energy as well as GDP shows positive relationship with CO₂. Further analysis has been conducted to understand the relationship between GHG emissions and GDP, which has confirmed the hypothesis of environmental Kuznets Curve (EKC).

Author has combined the results of the analysis completed and the insights gathered to build a theoretical model of the energy sector transformation that aims to capture the complexity and connections existing between all distinct elements within the structure of the model. Energy sources, processes, final energy products, technological losses, and waste management are all part of this framework and deliver their role as the energy moves from one stage to other. Regulatory, technological, geopolitical and socio-economic factors fuel and shape the cycle, while outcomes are measured through a set of key performance indicators. This model draws the flow of energy from its primary sources to final consumption, addressing the losses, emissions, and byproducts generated along the way. By focusing on renewable energy and carbon management, the model highlights the need for an integrated approach to achieve climate goals, especially in this interim phase while around three quarters of EU's energy are still produced from fossil fuel. Ultimately, this model is meant to serve an overarching framework that can explain how the whole industry is transformed to execute on a goal of limiting temperature increases to well below 2°C by 2050.

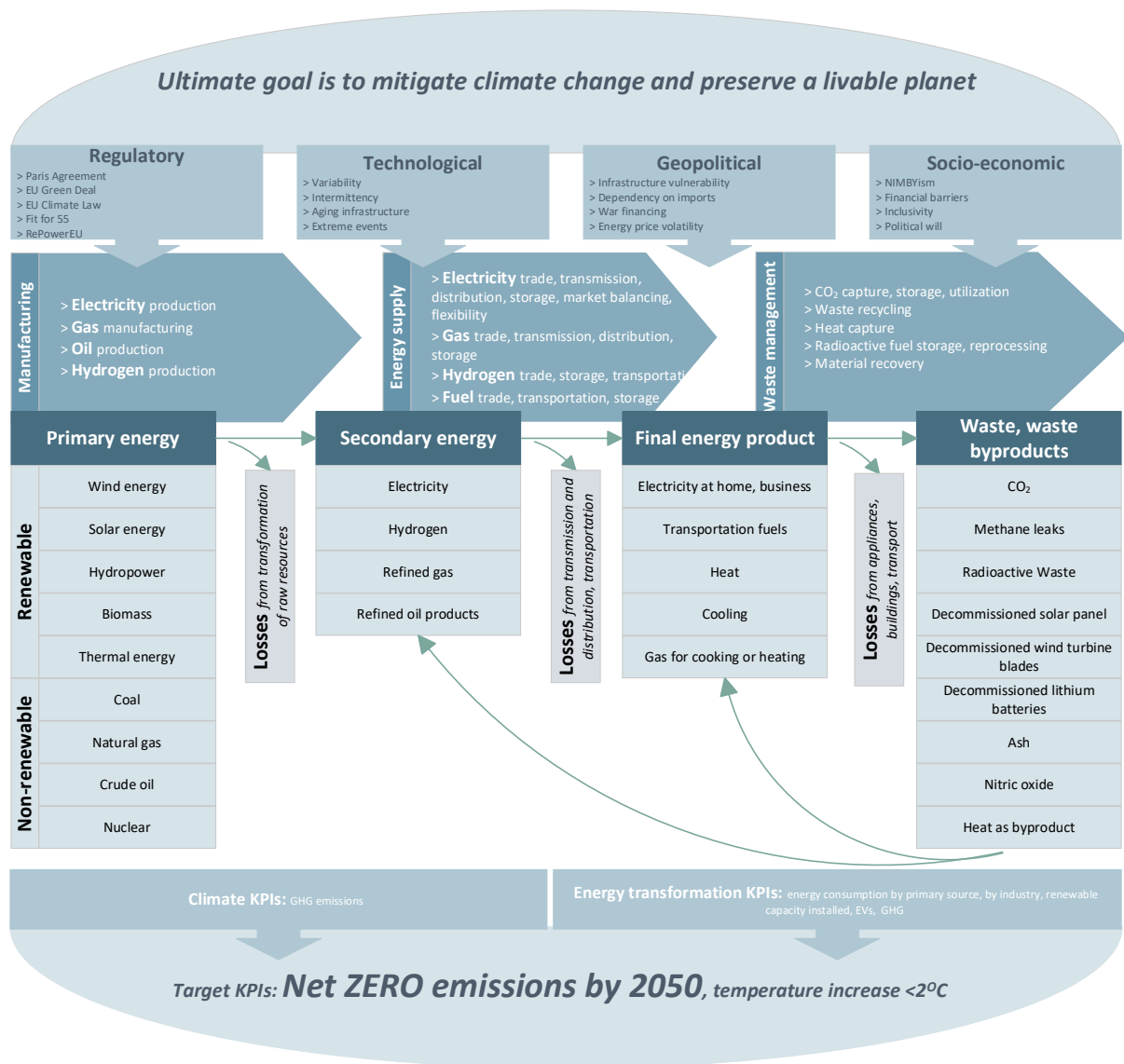


Fig. 21. Theoretical model of the energy sector transformation

Source: Author

To finalize, the energy transformation model presented is a comprehensive theoretical model of the energy sector transformation that aims to cover a 360-degree understanding of the sector composition, resources, processes, external factors, measurement indicators and interconnecting forces that shape the transition towards full decarbonization. This model showcases the flow of energy from its primary sources to final consumption, addressing the losses, waste, byproducts generated along the way and the processes employed down the way. This circulation is driven by regulation, technological challenges, geopolitical complexities and socio-economic movers, the result of which is measured and monitored thru a comprehensive list of standardized performance indicators. This holistic view is employed to present a framework of energy sector transformation, that improves the understanding of the sector developments and the key drivers towards the climate neutrality goals.

CONCLUSIONS

1. The energy sector is classified under NACE and is composed by three major subsectors: electric power generation, transmission and distribution (1), manufacture and distribution of gas (2), steam and air conditioning supply (3). The electric power generation, transmission and distribution subsector dominates based on employment and value-add with 1.3 million people employed and 84.5 % of sectoral value added. Energy sector is also classified based on the primary sources used to generate energy into renewable and non-renewable resources. Transition of the primary sources from fossil fuel to renewable is the cornerstone of energy sector transformation.
2. The theoretical model of energy sector combines various elements that are shaping the framework and structure of the sector. The central part of the model is the composition of the sector, and the resources used for energy generation. Both components are impacted by the external regulatory, technological, geopolitical and socio-economic factors that drive the developments within both – the composition of the sector as well as the resources used. These developments are measured thru a set of climate and energy transformation indicators and outline the progress in the transition towards decarbonization of the energy sector.
3. Energy sector is primarily impacted by four major external factors that either accelerate or set back the transformation towards carbon free energy system. Regulatory factors play a critical role and are primer drivers towards renewable energy resources. Thru regulatory policies and directives adoption of renewable energy is accelerated within EU member states as they have a legal obligation to achieve sustainability goals. While technological improvement and innovation are major drivers of green energy, technological challenges pose significant risks. With infrastructure limitations in integrating renewable energy resources, aging infrastructure and severe weather impacts, technological challenges remain one of the major obstacles to be resolved to transition to fully renewable energy system. Geopolitical challenges are primarily focused around the EU dependency on the energy imports, that coincidentally are sources primarily from Russia. With the Ukraine – Russia war in the context the need to address this dependency has become critical. Additionally, learnings from the ongoing war developments highlight the need of the energy sector infrastructure resilience and physical protection. Finally, the socio-economic factors present a dual impact. On one hand side, the society, especially younger generations, demonstrate a higher concern regarding climate change and are more willing to change their behaviors to address the issue, however, access to affordable energy as well as lack of public education

on environmental problems and limited understanding is a barrier to transition towards sustainable, but short term more expensive energy system.

4. In the context of energy sector transformation towards climate neutral resources, two sets of performance indicators have been analyzed. Energy sector transformation is driven by the challenges posed by climate warming; thus, climate and energy transformation indicators are the key metrics reflecting the progress of the transition as well as the impact on the environmental outcomes. Key metrics reflecting the climate change are average surface temperature, sea level rise, GHG emissions, glacier mass and severe weather events. While energy transformation indicators are primarily focused on renewable energy consumption, installed capacity, energy efficiency, carbon intensity and others.
5. The statistical analysis completed as part of this thesis highlights the significant progress and the challenges of the EU's energy sector. While electricity generation is rapidly transitioning towards renewable resources and is reported to have 44% of the electricity generation to be coming from renewable sources in 2023, the sectors of transportation as well as heating and cooling are lagging. Driven by geopolitical dynamics and challenges, EU has significantly reduced its coal and gas usage for electricity generation by 26% and 15% accordingly in the last year. However, the statistical analysis also outlines that climate indicators further demonstrate dramatical shift towards ecological crisis and therefore call out for a need to accelerate and increase in ambition for energy related sustainability goals.
6. Regression analysis has been performed to understand the relationships between core indicators – GHG emissions, GDP, renewable and non-renewable energy consumption as well as electro vehicles registered. All indicators have been normalized to per capita basis for 15 EU markets in a period of 2013 to 2022. The results of the regression show that renewable energy consumption and EVs registered have a strong negative relationship with CO₂ emissions, meanwhile, use of non-renewable energy as well as GDP shows positive relationship with CO₂. Further analysis has been conducted to understand the relationship between GHG emissions and GDP, which has confirmed the hypothesis of environmental Kuznets Curve (EKC). The economic development initially brings environmental degradation that is followed by environmental improvement once certain economic maturity is achieved.
7. The final outcome of the thesis is a comprehensive theoretical model of the energy sector transformation that aims to cover a 360-degree understanding of the sector composition, resources, processes, external factors, measurement indicators and interconnecting forces that shape the transition towards full decarbonization. This model showcases the flow of energy from its primary sources to final consumption, addressing the losses, waste,

byproducts generated along the way and the processes employed down the way. This circulation is driven by regulation, technological challenges, geopolitical complexities and socio-economic movers, the result of which is measured and monitored thru a comprehensive list of standardized performance indicators. This holistic view is employed to present a framework of energy sector transformation, that improves the understanding of the sector developments and the key drivers towards the climate neutrality goals.

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Appendix 1. Certificate regarding participation in the conference “Science – future of Lithuania. Economics and management”



CERTIFICATE

This is to certify that

Agnė Domarkienė

participated in the 27th Conference for Young Researchers

**„SCIENCE – FUTURE OF LITHUANIA.
ECONOMICS AND MANAGEMENT“**

that took place on October 22, 2024, at Vilnius Gediminas Technical
University at the Faculty of Business Management

and delivered a presentation

TRANSFORMATION OF THE EUROPIEN ENERGY SECTOR IN THE
CONTEXT OF GREEN ECONOMY

Vice-Dean for Research of the Faculty of Business Management

Prof Dr Viktorija Skvarciany