KTH Industrial Engineering
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Onshore Wind Energy Market Analysis

of Sweden, Poland, and Romania

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Master of Science Thesis
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Abstract

The shift towards sustainability is a key point in many countries’ energy programs. Among renewable energy technologies, wind power offers high productivity and reliability. However, its profitability is strongly dependent on the support of favorable political environment, national and/or European incentives, and market opportunities. With this regard, this study presents a methodology to highlight how different scenarios impact on the remuneration from similar featured wind farms. Indeed, a wind farm pre-feasibility study is performed in three different locations in Sweden, Poland, and Romania respectively. Both technical and economic results are compared, and conclusions are carried out. First, a study defining detailed country profiles is performed by focusing on wind energy current scenario and development of future scenarios. Key investment actors and business models are analyzed in order to define market opportunities and criticalities. This research is crucial and preliminary to choose proper features and realistic assumptions for the pre-feasibility wind projects. Therefore, the first results come from these market analyses which outline various bottlenecks in the countries energy systems. Specifically, the Swedish permitting phase is affected by the local “municipal veto” which sets limits on the wind turbines height. The biggest barrier in Poland is the “10H rule” imposing strict distances between wind farms and houses. Lastly, the most relevant Romanian issue is the grid capability which needs to be expanded in order to accommodate the desired renewable energy capacities. The first assumptions of the wind farm designs aim at overcoming these criticalities, by choosing a wind turbine model with acceptable height and rotor diameter and assuming approved permits. Finally, the research continues with the design of three 100 MW wind farms located in sites with similar annual average wind speeds. Thus, techno-optimizations lead to the final layout orientations by minimizing wake effects. Hence, the economic analysis shows that the wind farm located in Romania has higher productivity and profitability, followed by the Swedish and the Polonian wind farms. However, the comparison study exposes another relevant difference. The Swedish and Polonian assumptions on the permitting phase are related to political rules already planned to be modified or removed uniquely, such as the municipal veto and 10H rule. On the contrary, the Romanian barrier regards a grid expansion involving huge investments along with political decisions. In conclusion, given that the three pre-feasibility projects are already cost-effective, the profitability of the projects raises along with decreasing of investment costs from the technical side, and implementation of necessary amendments from the political one.

Sammanfattning

Förändringen mot hållbarhet är en nyckelpunkt i många lands energiprogram. Bland teknik för förnybar energi erbjuder vindkraft hög produktivitet och tillförlitlighet. Lönsamheten är dock starkt beroende av stödet av gynnsam politisk miljö, nationella och / eller europeiska incitament och marknadsmöjligheter. I detta avseende presenterar denna studie en metodik för att belysa hur olika scenarier påverkar ersättningen från liknande vindkraftsparker. I själva verket genomförs en genomförbarhetsstudie på vindkraftsparker på tre olika platser i Sverige, Polen respektive Rumänien. Både tekniska och ekonomiska resultat jämförs och slutsatser genomförs. Först utförs en studie som definierar detaljerade landsprofiler genom att fokusera på vindkraftsströmsscenario och utveckling av framtida scenarier. Viktiga investeringsaktörer och affärsmodeller analyseras för att definiera marknadsmöjligheter och kritik. Denna forskning är avgörande och preliminär för att välja lämpliga funktioner och realistiska antaganden för förberedande vindprojekt. Därför kommer de första resultaten från dessa marknadsanalyser som beskriver olika flaskhalsar i ländernas energisystem. Specifikt påverkas den svenska tillåtningsfasen av det lokala "kommunala vetot" som sätter gränser för vindkraftverkets höjd. Den största barriären i Polen är ”10H-regeln” som innebär strikta avstånd mellan vindkraftsparker och hus. Slutligen är den mest relevanta rumänska frågan nätkapaciteten som måste utökas för att tillgodose önskad kapacitet för förnybar energi. De första antagandena om vindparkens utformningar syftar till att övervinna dessa kriterier genom att välja en vindkraftverksmodell med acceptabel höjd och rotordiameter och antaga godkända tillstånd. Slutligen fortsätter forskningen med utformningen av tre vindkraftsparker på 100 MW belägna på platser med liknande årliga genomsnittliga vindhastigheter. Således leder teknooptimeringar till den slutliga layoutorienteringen genom att minimera väckningseffekter. Följaktligen visar den ekonomiska analysen att vindkraftsparken i Rumänien har högre produktivitet och lönsamhet, följt av svenska och polska vindkraftparker. Jämförelsesstudien visar dock en annan relevant skillnad. De svenska och polska antagandena om tillståndsfasen är relaterade till politiska regler som redan planeras att ändras eller tas bort unikt, till exempel kommunvetoret och 10H-regeln. Tvärtom gäller den rumänska barriären en nätutvidgning med stora investeringar tillsammans med politiska beslut. Sammanfattningsvis, med tanke på att de tre projekten för genomförbarhet redan är kostnadseffektiva, ökar lönsamheten för projekten tillsammans med minskade investeringskostnader från den tekniska sidan och genomförande av nödvändiga ändringar från den politiska.

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I have always been tempted by new experiences, countries, and environments because they are challenges inspiring me to do better. Therefore, it was not a surprise when I figured out that also my master thesis research would have led to a change in my life. During the last year of my Master Program's at KTH, I have come into contact with Enel Green Power for the opportunity to get an internship. I got passionate about this company's world, activities, and the huge market it is part of. As for me, developing a master thesis with Enel meant also coming back to Italy after three years abroad. Leaving Stockholm, my friends, and my Swedish life was the first challenge I faced. Second, being part of an industrial reality for the first time was strongly inspiring and stimulating. Now, with this experience behind me, I feel lucky because it was the best way to close the wonderful cycle of my Master's.

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Marta

Rome, September 2020

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Abbreviations

AC: Alternate current
AEP: Annual energy production
ANAR: National Administration Apele Romane
ANRE: National Regulatory Authority in Energy
BRP: Balance responsible party
CAB: County of administration board
CAGR: Compound annual growth rate
CEER: Council of European energy regulators
CfD: Contract for difference
CFIM: Commodity forward instruments market
CGNEE: China General Nuclear Europe Energy
CHP: Combined heat and power
CMBC: Centralized market for bilateral electricity contracts
CSEIP: Credit Suisse Energy Infrastructure Partners
DC: Direct current
DSO: Distribution system operators
EEZ: Exclusive economic zone
EIA: Environmental impact assessment
EPP: Energy Policy for Poland
ERO: Energy Regulatory Office
ETS: Emissions trading scheme
EU: European Union
EUR: Euro
FIP: Feed-in premium
FIT: Feed-in tariff
GC: Green certificate
GDP: Gross domestic product
GE: General Electric
GHG: Greenhouse gas
H&C: Heating and cooling
IEA: International Energy Agency
IRENA: International Renewable Energy Agency
IRR: Internal rate of return
LCOE: Levelized cost of electricity
LEA: Overhead electricity lines
M&A: Mergers and acquisitions
Mtoe: Million tons of oil equivalent
NECP: National Energy and Climate Plan
NES: National Energy System
NIMBY: Not in my back yard
NPV : Net present value
NREAP: National Renewable Energy Action Plan
O&M: Operational and maintenance
OECD: Organization for Economic Co-operation and Develo
PGE: Polska Grupa Energetyczna
PPA: Power purchase agreement
PSE: Polskie Sieci Elektroenergetyczne S.A.
PV: Photovoltaic
PWEA: Poland Wind Energy Association
REC: Renewable electricity certificate
RES: Renewable energy sources
RWEA: Romanian Wind Energy Association
SEA: Strategic environmental assessment
SEA: Swedish Energy Agency
SEE: Southeast Europe
SME: Small and medium-sized enterprises
SWEA: Swedish Wind Energy Association
TFC: Total final consumption
TGE: Towarowa Gielda Energii
TPES: Total primary energy supply
TSO: Transmission system operator
UK: United Kingdom
US: United States
VRE: Variable renewable energy
YoY: Year over year

About the Report

This report focuses on the analysis of onshore wind energy market in Sweden, Poland, and Romania. Sweden is a global leader in terms of low-carbon economy, and it is well-integrated with its climate objectives. On the contrary, Poland's energy system is relevantly dominated by coal and its shift towards renewables is slow and currently limited by strict national rules. Finally, Romania has a great potential for renewables even if its aged infrastructures need expansion and upgrade to enable the desired energy transition. Therefore, these three countries' research covers a large range of energy environments which gives a wide knowledge of different schemes and scenarios.

The report observes the following structure:

- Chapter 1, *Introduction*: Report's objectives, delimitations, and structure.
- Chapter 2, *Theoretical background*: Analysis of today's world and European wind energy numbers as well as future projections. Overview of the wind farms assets and wind turbines components with current status of the technology, key technical challenges, and possible solutions. Then, market analysis, criticalities, and drivers.
- Chapters 3, 4, 5, *Sweden, Poland, Romania*: Detailed country profiles, onshore wind energy markets, financing supports, and challenges for future developments.
- Chapter 6, *Pre-feasibility study*: Selection phase based on current most common and strategic decisions taking into consideration countries limitations and criticalities. Technical phase with optimal wind farm layout design and annual energy production estimation. Economic phase analyzing the profitability of the project by observing wind energy costs and possible revenues in each country. Comparison phase with both technical and economic results confront.
- Chapter 7, *Conclusions*: Summary of findings of the research work, comparison of the three countries opportunities, openness to wind energy investments.

1. Introduction

1.1 Background

Living in an interconnected world, sharing its potential and criticalities, and competing for higher knowledge as key source for economic improvements and quality of life is a daily engineering challenge. Technological barriers set current market limits and define investments directions. Thus, the link between technology and markets outlines innovations drivers and plans changes aiming at higher wellness and developed economies.

In the electricity production, the ongoing objective is switching from centralized fossil-fuel generation to distributed renewable energy units. This shift is supported by both technological development and financing mechanisms creating an attractive businesses environment. Investors, therefore, look for the combination of innovative renewable energy technologies and positive environments where innovations can efficiently take place.

Worldwide, Europe is engaged positively in the energy transition and supported by EU Commission and its political units as well as national governments. Indeed, renewable and sustainable energy sources offer significant opportunity to proceed towards the carbon-free energy systems' objective. This process needs continuous improvements of multiple technologies as well as countries' grid expansion and infrastructures. Among the renewable technologies, moreover, wind energy industry offers huge potential due to fast development and improvement during the last years.

Among the European utilities generating electricity from renewables, Enel SpA ranks among the 25 top companies per capitalization [1]. In detail, Enel Green Power is an Italian multinational renewable energy corporation grouping Enel's global renewable energy interests. The company operates over 30 countries across the five continents. Its 1198 power plants account for 46 GW of installed capacity and produce electricity by hydropower, wind, solar, geothermal, and biomass technologies [2]. This Master thesis has been performed in the form of internship at Enel Green Power to study the development of wind energy business and potential entry strategies in Sweden, Poland, and Romania.

1.2 Delimitations

The target of renewable business development analysis is looking for potentialities of specific renewable energy technologies in various sites. Thus, the research aims to identify bottlenecks and potential solutions which may open opportunities to business. Therefore, the preliminary delimitations consist of the type of renewable energy technology as well as the countries which new installed capacities are supposed to be placed on.

Wind resource is abundant all over the world. Specifically, Europe's high ranking in terms of installed capacity competes with giants such as the United States and China. As a result, wind power technology has been selected as object of this research. Regarding the locations, northern and eastern European countries have beneficial locations in terms of wind intensity, usable lands, and markets which are already inclined to prompt transition towards renewables. Particularly, the three selected countries are Sweden, Poland, and Romania. In Europe, these nations boast high installed wind energy capacity; Sweden ranks the sixth position. Moreover, these three countries have large exploitable market due to both favorable terrain and market conditions. As a consequence, the interest in a deep analysis is high.

1.3 Purpose and Method

The aim of the research is to identify emerging trends, potential opportunities, major bottlenecks, and strategic solutions of the onshore wind energy market in Sweden, Poland, and Romania. The methodology follows a specific structure which firstly aims at gaining the proper knowledge of current technical and market situations. Secondly, the implemented methods lead to gather the interesting current data to outline future scenarios. Thirdly, the study develops the pre-feasibility wind farm projects with similar features located in the selected three countries. This last phase is particularly interesting because it allows to observe how different country overviews, limitations, incentives, and grid properties impact the profitability of wind farms. Therefore, the comparison of different areas and environments in which similar wind farms are placed, gives the opportunity to figure out the three countries' overall wind energy profitability.

At the beginning, detailed country profiles present energy overviews, renewables status, national objectives, support schemes, and business models opportunities. Then, the research focuses on wind energy current scenario and data. The ongoing picture sets the basis for the development of future scenarios, showing how the technology suits each country terrains and business environments differently. Moreover, key actors and new investments models, technologies, and projects decisions are analyzed to understand the market directions. The pre-feasibility wind projects are designed by assuming common size and wind turbines characteristics in each location. In conclusion, both technical and economic results are compared. The variations of wind energy costs, market and contracts, and electricity costs in the three countries bring out differences on the final results and sensitivity analysis.

2. Technical Background

2.1 Wind Energy Overview

2.1.1 Wind Energy in the World

In 2017, global renewable energy consumption increased 5% year over year (YoY) and reached 10.4% of the total final energy consumption. Moreover, the share of renewables is expected to increase two percentage points to 12.4% in 2023. Bioenergy remains the largest renewable energy source in 2023 because of its considerable use in heat and transport, wind registers the second-largest growth, followed by solar photovoltaic (PV) and hydropower. The electricity sector demonstrates the most rapid renewable energy share growth, from a 25% share in 2017 to 30% in 2023. In detail, wind generation is estimated to increase two-thirds over the forecast period, with its share in global electricity generation growing from 4% in 2017 to almost 7% in 2023 [3].

The year 2019 saw global new wind power installations surpassing 60 GW, a 19% growth compared to 2018, and bringing the cumulative installed capacity to 651 GW. The mature onshore wind market reached 54.2 GW, representing 17% YoY growth, and taking cumulative onshore wind beyond the 600 GW milestone, while the offshore wind market passed 6 GW and has been named as the new challenge in the energy transition. During the initial years of wind power deployment, Europe was the key region for global wind installations, and it accounted for 47% of the global installation in 2010. Subsequently, other regions experienced rapid wind deployment and, by 2018, the largest onshore wind market was in China with nearly one-third of the global installed capacity. However, the European Union (EU) has a record year in 2018 in terms of financing new wind capacity with almost 27.2 billion euros (EUR) invested in 16.7 GW of new wind farms at an average of 1.42 EUR/MW for onshore wind and 2.38 EUR/MW for offshore wind. In conclusion, the world's top five markets in 2019 for new installations were China, the United States (US), the United Kingdom (UK), India, and Spain, making up 70% of the global installation last year. In terms of cumulative installations, in 2019, the top five markets were China, the US, Germany, India and Spain, which together accounted for 72% of the world's total wind power installation [4].

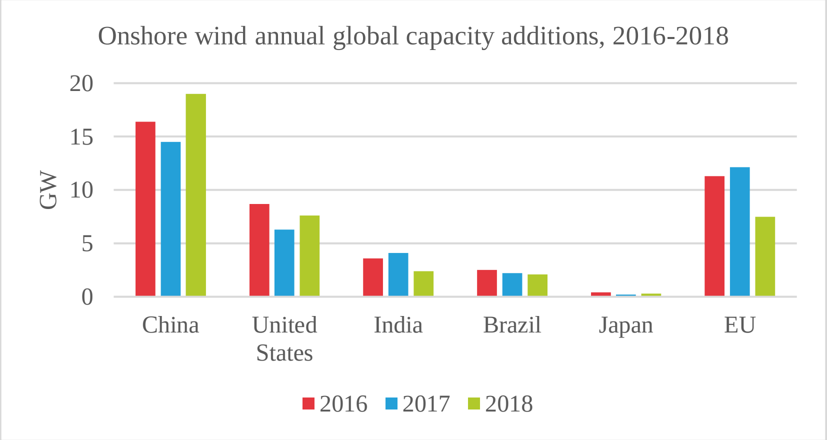


Figure 1: Onshore wind energy installed capacity additions per year and regions [5]

Considering the wind resource availability, large market potential, and cost competitiveness, onshore wind is expected to drive overall renewables growth over the next decade in a significant part of the world. According to the International Renewable Energy Agency (IRENA) [5], for the next three decades, with continuous technology advancements, cost reductions, right policies and supportive measures, onshore wind power installations would have a compound annual growth rate (CAGR) of more than 7% YoY. Indeed, by 2030 the total installed capacity of onshore wind would grow more than three-fold reaching 1,787 GW, and nearly ten-fold by 2050 nearing 5,044 GW, compared to 542 GW in

2018. However, a global onshore wind installed capacity of 5,044 GW by 2050 represents only 5.3% of the global wind resource potential of at least 95 TW as estimated by World Wind Energy Association (WWEA). Along with the growth in net wind capacity additions, another key issue is the replacement of wind turbines that are ending their technical lifetimes and the repowering of existing projects to extend their operating lifetimes. To summarize, accounting for new capacity as well as replacements, the total annual additions would stabilize at an annual average of 200 GW in the last decade to 2050 [6].

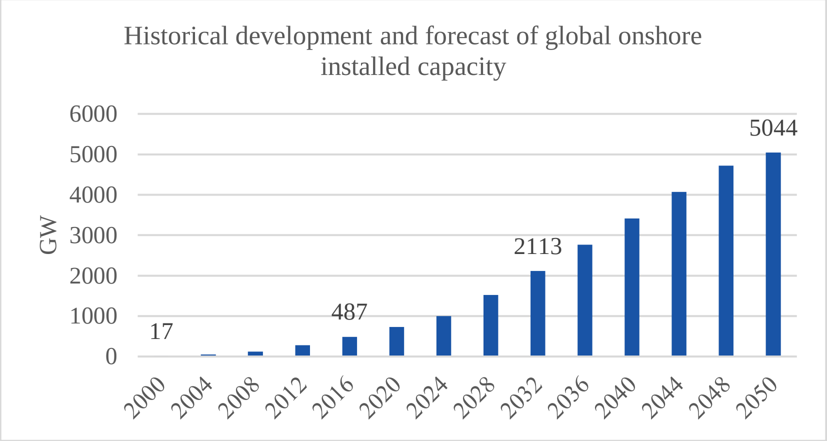


Figure 2: Historical development and forecast of cumulative onshore wind global installed capacity [6]

2.1.2 Wind Energy in Europe

Europe’s renewable capacity is forecast to grow by one-quarter (144 GW) over 2018-23 due to apposite support schemes, and continued cost reductions mainly for solar PV and wind technologies. Wind is an industrial success for Europe and, therefore, accounts for almost half of the estimated renewable capacity expansion (68 GW), followed by solar PV (59 GW) [7].

In 2019, 15.4 GW of wind power capacity were installed which is 27% more than 2018 but 10% less than the record year of 2017. The cumulative wind power installations capacity in Europe reached 205 GW in 2019, of which 89% onshore and 11% offshore. Germany remains the country with the largest capacity and together with Spain, the UK, France, and Italy has 67% of the wind power in Europe. Moreover, five other countries such as Sweden Turkey, Denmark, Poland, and Portugal had more than 5 GW installed power plants [8].

Today onshore wind energy is the cheapest source of new power capacity in many countries in Europe and offshore auction prices have reached significant reduction targets. Thus, as it is estimated to have this tendency also in the future years, wind energy represents a leading source for the power system transition and acceleration of electrification [9].

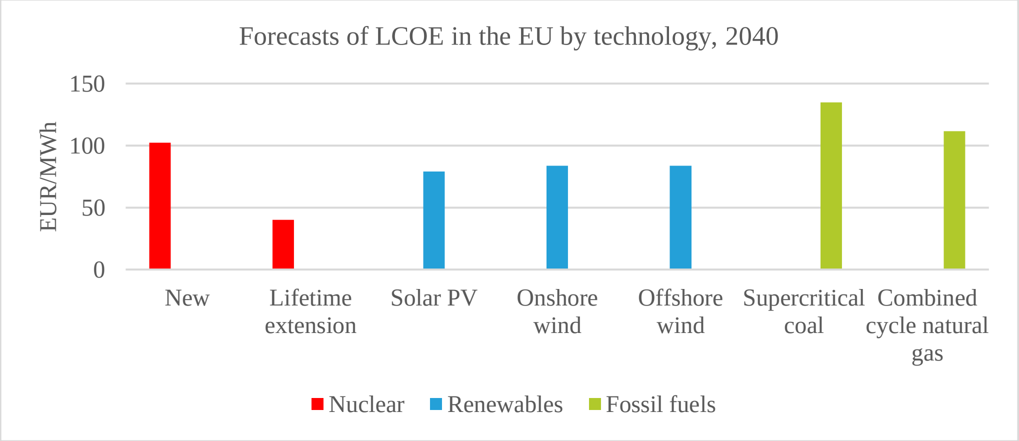


Figure 3: 2040 forecasted different technologies’ Levelized Cost of Electricity (LCOE) in the EU [9]

Europe’s leadership in wind energy is the result of a structured regulatory framework, which was introduced in the early 2000s and contained the 2020 goals. However, not all the states have policies in place for the deployment of renewable energy post-2020. The first source of uncertainty for wind energy installation in the decade after 2020 is the overcapacity of inflexible and carbon intensive assets which put pressure on the wholesale power prices. Other sources are the opening of auctions to projects in neighboring countries, the varying legislation on spatial planning and the interpretation that the countries give to the EU environmental guidelines about licensing areas for renewable energy projects. Moreover, the amount of repowering and lifetime in mature wind energy markets play a key role, as well as the reinforcement of electrical grids which host an increasing wind energy capacity [10].

Based on these promising but also varying aspects, WindEurope and the National Wind Energy Associations update the capacity scenarios every two years to reflect the latest market and policy developments in the EU. In 2017, WindEurope described three possible scenarios for wind energy capacity installations in 2030. In the Low Scenario, no binding templates are agreed for *National Energy and Climate Plans* and the EU-wide 27% renewable energy target fails. In the Central Scenario, the Renewable Energy Directive is implemented as proposed by the European commission and the EU-wide RES is achieved. Lastly, in the High Scenario, this target for 2030 is increased to 35% and the wind industry has a higher deployment rate. According to these studies, EU onshore wind power cumulative capacity in 2030 could be in a range between 207 GW and 299 GW, while the offshore one between 49 GW and 99 GW. To summarize, the EU electricity demand met by wind energy in 2030 is estimated to be 21.6% in the Low Scenario, 29.6% in the Central Scenario, and 37.6% in the more optimistic High Scenario [10].

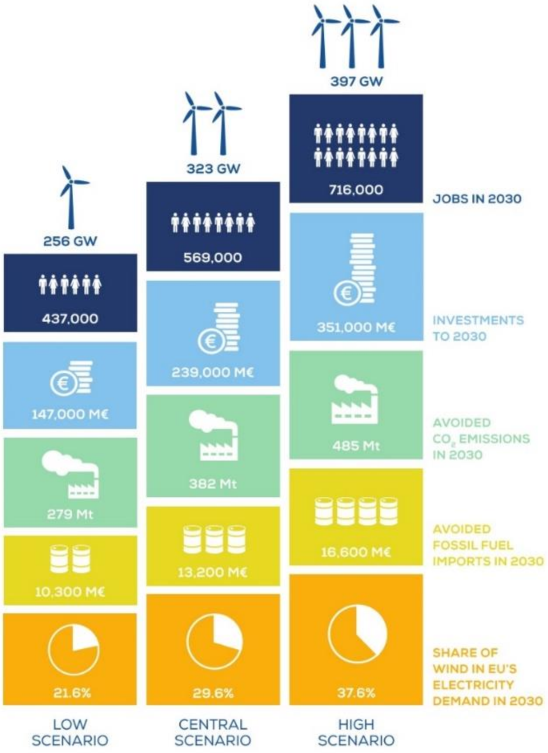


Figure 4: Three different scenarios for wind energy in Europe, 2030 [10]

2.2 Technical Aspects

Wind turbines operate as power-producing and consuming systems for large electrical networks or as stand-alone power for a specific load. Wind turbines may be installed as single units or in large arrays called “wind farms” or “wind parks”. Before wind turbines can be installed and connected to an electrical system, the exact location needs to be determined with the aim of maximizing energy capture, but at the same time respecting numerous constraints. Some barriers for wind farms' installations, for instance, are public acceptance, minimum distance rules to residential buildings, visual and naturalistic constrains, accessibility, connection to electrical grids, and so on [11].

2.2.1 Wind Farms Asset

The wind farm siting and permitting is the first phase of the project and it aims at choosing a location that maximizes the net revenue while minimizes noise, environmental and visual impacts, and overall cost of energy. The permitting process, then, includes also acquiring land rights and applying for permits. Permitting varies relevantly country by country, state by state, and sometimes even town by town. Generally, permits that must be obtained are related to building construction, noise emission, land use, grid connection, and environmental issues.

The second phase is dedicated to engineering. The wind resource at potential site needs to be estimated so that the procedure can follow with micro siting, choice of the type of wind turbine and its exact position, and evaluation of the economics of the project [12].

Third, the financing process aims at obtaining power purchase agreements or using national supports. Subsequently, after permits, procurement, and financing are gained, the wind farm construction starts. The site needs to be prepared for hosting the complex infrastructure of a wind farm including not only individual wind turbines, but also the turbine-grid connection, roads, and data collection systems. The grid connection consists of electrical conductors, transformers, and switchgears enabling connection and disconnection. The objective is to minimize voltage drops between the turbine and the point of connection (POC) to the electrical grid. Many modern wind turbines are equipped with a transformer in the tower base, or sometimes groups of wind turbines share one transformer, in order to control the voltage levels. In fact, generators in large power plants produce power at high voltage which is firstly fed into high-voltage transmission system, then transferred to the local distribution system operating at lower voltage, and lastly distributed to neighborhoods. The integration of wind power into electrical grids show typical interconnection problems such as steady state voltage levels, flicker, harmonics, and grid capacity limits. Research is focusing on advances in wind farm control capabilities, wind forecasts, large balancing areas, and use of energy storage as methods to limit these negative effects. To summarize, high levels of energy penetration can be achieved if wind power plants are integrated with control areas, usage of excess energy, or grid-scale energy storage. Moreover, access roads enabling transport of long elements (blades and tower) and on-site maintenance represent a significant cost and issue.

The last phase consists of the wind farm operation. Modern wind farms include systems for controlling individual turbines and displaying operating information called "supervisory control and data acquisition" (SCADA). The information usually includes operating state, energy production, wind speed and direction, power curves that allow system operators to shut down some turbines, maintenance, and repair messages, and sometimes also rotor speed, pitch angle, and so on [11].

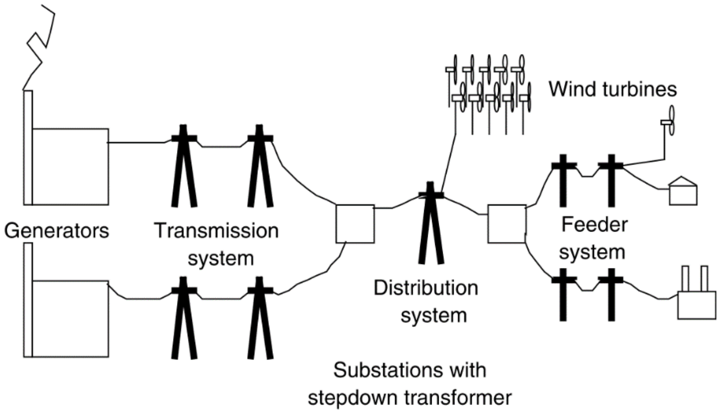


Figure 5: Electrical grid system schematic [11]

Once siting issues, permitting process, and infrastructure configuration have been treated, numerous technical wind farms issues arise. Spacing between multiple wind turbines is a crucial one given the fact that wind resource may vary across a wind farm due to terrain effects. As a result, the extraction of energy by upwind turbines results in lower wind speeds at the downwind turbines and, therefore, increase of wake effects, turbulence, wake-induced fatigue in turbines, and decrease of overall energy production. Thus, the wind turbines located in a wind farm will not produce 100% of the energy that similar isolated turbines would produce because of array losses which can be reduced by optimizing the geometry of the wind farm, the distribution of turbine sizes, and their spacing [11].

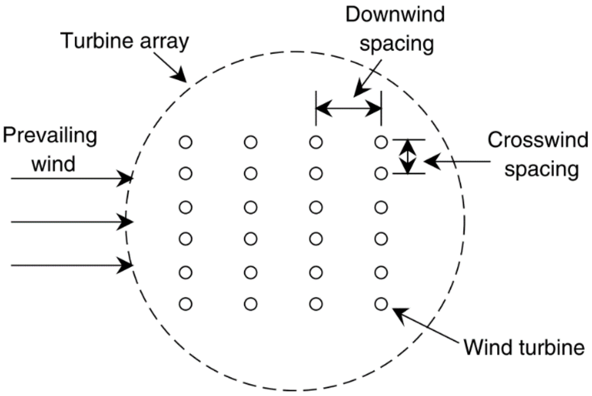


Figure 6: Wind farm array schematic [11]

2.2.2 Wind Turbines Components

A wind turbine is a machine that converts the fluctuating power stored in the wind into useful electrical power. The first design objective is using assemblages of mechanical and electrical components to gather electricity and, at the same time, respecting constraints such as the economical one whereby the plant should produce energy at a lower cost compared to fossil fuels and other renewables one. The cost of energy from a wind turbine is a function of many factors, but the most relevant ones are wind turbines cost, their installation, operation, and maintenance costs, and annual energy production. These factors are influenced by turbine’s characteristics as well as wind site resource. The fundamental concern of a turbine design, therefore, must be the balance between the initial costs and the long fatigue-resistant life, which means minimizing components costs while maximizing the endurance and the productivity. Usually components’ weight and size are sought to be as low as possible, turbines should be guaranteed to survive to high stresses in extreme events and should be able to operate with a minimum of repairs over a long period of time. Thus, application will be a major force in choosing turbine size, generators types, and method of control. For example turbines for utility power have power ratings in the range of 500 kW to 3 MW with rotor diameters in the range of 39-90 m, while turbines for use of utility customers or in remote communities are typically in the 10 to 500 kW range [11].

A wind turbine consists of several subsystems:

- rotor (blades, hub, aerodynamic control surfaces),
- drive train (shafts, couplings, gearbox, mechanical brakes, generator),
- nacelle and frame,
- yaw control,
- tower (foundation and erection).

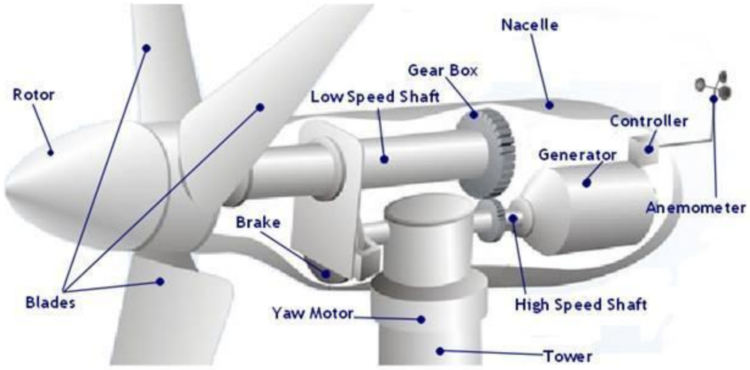


Figure 7: Wind turbine components [13]

- Rotor subsystem

Rotor subsystem is composed by a hub and blades which capture the wind's energy, convert it into rotational shaft energy and pass it on to the drivetrain. Blades are the only element which is really impacted by wind. Most modern wind turbines have three blades, some have two or even one. Three blades guarantee a smooth operation because of the constant polar moment of inertia. However, a key consideration is that the stress in the blades increase with the number of blades for a turbine of a given solidity (area of the blades relative to the swept area of the rotor). Moreover, increasing the design "tip speed ratio" (ratio between tangential speed of the tip and actual speed of the wind which gives an indication of the turbine efficiency) implies decreasing the number of blades. Furthermore, axis orientation, position, power control, and speed of the rotor hub are crucial decisions in the design process. Rotor can have horizontal or vertical axis, however, in most modern wind turbines, the rotor axis is parallel to the ground which means horizontal because of numerous advantages such as lower costs of energy due to lower rotor solidity, and higher productivity due to higher average height of the rotor swept. In a horizontal axis turbine, rotor may be either upwind or downwind of the tower. Upwind machines have the rotor facing the wind, while the most common downwind machines have the rotor placed on the lee side of the tower. Moreover, there are various options for controlling power aerodynamically such as stall, pitch, or aerodynamic surfaces control. First, stall control reduces aerodynamic lift at high angles of attack to reduce torque at high wind speeds. Consequently, the rotor speed must be separately controlled by an induction generator. Second, variable-pitch machines permit blades to rotate around their long axis, change their angle called "pitch angle" and, therefore, also the angle of attack of the relative wind and the amount of torque produced. Third, some wind turbines utilize aerodynamic surfaces on the blades to control or modify power. In most cases they are used for breaking the turbine, while in some cases they may provide a fine-tuning effect. To conclude, constant or variable speed is another important characteristic of the rotor. Historically, most rotors have operated at constant rotational speed, however today, variable-speed rotors are more used because they can be operated differently at the optimum tip speed ratio to maximize power conversion in case of low winds and at lower tip speed ratios to reduce loads in the drive train in case of high winds [13].

- Drive train subsystem

The drive train system is the electro-mechanical subsystem comprising shafts, bearings, gearbox, brakes, generator, and other functional components. The key objective is to transfer mechanical power from the rotor hub to the electric power generator. The generators use the difference created by the shaft movement in electrical charge to produce a change in voltage which is actually electrical pressure that moves an electrical alternating current through power lines for distribution. The choices between generators types (DC generator, AC synchronous generator, or AC asynchronous generator) and their speeds have a significant effect on design and weight of other components such as gearbox and power electronics. In fact, if rotor speed and generator speed are the same (synchronous speed), no gearbox is needed. On the other hand, if rotor speed and generator speed vary, a torque converter such as gearbox is needed in the drive train. Typical squirrel cage induction and synchronous generators have one synchronous speed [13].

- Nacelle and frame subsystem

Nacelle is the part of the turbine that houses all components that transform wind’s kinetic energy into mechanical energy to turn a generator that produces electricity. Nacelle is installed on top of tower and contains more than 1,500 small and large components. Then, the frame is made of two main parts. The main frame is generally made of cast steel and holds yaw system, gearbox, and main shaft. In addition, generator, transformer, and electrical cabinets are secured to a rear frame constructed of steel. Once yaw system and its motors are installed and pass their functional tests, the two halves of the frame are joined [14].

- Yaw control subsystem

All horizontal axis wind turbines are furnished of a yaw system which orients the machine as the wind direction changes. In downwind machines, blades are typically coned a few degrees in the downwind direction so that yaw motion can be free. However, the most common upwind turbines are supplied with a active yaw control system including yaw motor, gears, and a brake to keep the turbine stationary in yaw when it is properly aligned. In case of extremely high wind speed, yawing is also used as control system so that rotor is turned away from the wind, reducing power [13].

- Tower subsystem

The foundation is the link between the tower, which is the largest and heaviest part of the wind turbine, and the subsoil. The tower, thus, elevates the rotor nacelle assembly at the desired height which is chosen based on an economic compromise between energy capture and costs. Indeed, the higher the tower, the higher the wind speeds and the lower loads due to turbulence. Therefore, the research and new construction is moving towards ever-increasing hub heights with which higher yields can be achieved [13].

2.2.3 Current Status of the Technology

The breakthrough in renewable capacity additions over the past years has been achieved due to significant projects cost reductions driven by technology improvements, specialization and standardization, broader supply chains, economies of scale, competitive procurement, and a large number of experienced active project developers. Currently, onshore wind is one of the most competitive source of new power generation capacity. The total installed costs of onshore wind fell by an average of 22% between 2010 and 2018 and are expected to drop further in the next three decades, reaching an average range of 600-900 EUR/kW compared to current levels of 1,390 EUR/kW in 2018. With this regard, China and India deployments have contributed relevantly given their relatively low-cost structures [8].

A combination of improved wind turbine technologies, higher hub heights, longer blades, project siting and operational efficiencies has led to increased capacity factors. The global weighted average capacity factor for new projects increased from an average of 27% in 2010 to 34% in 2018. However, ongoing improvements in the world’s wind markets would further improve the average capacity factor to reach 55% by 2030 and 58% by 2050 [8].

The global weighted average LCOE of onshore wind projects commissioned in 2018, at 0.052 EUR/kWh, was 13% lower than in 2017 and 35% lower than in 2010. Overall, costs of electricity from onshore wind are now at the lower end of the fossil fuel cost range. Looking towards 2030, the cost of onshore wind power would be fully competitive, well below the lower fossil fuel range [15].

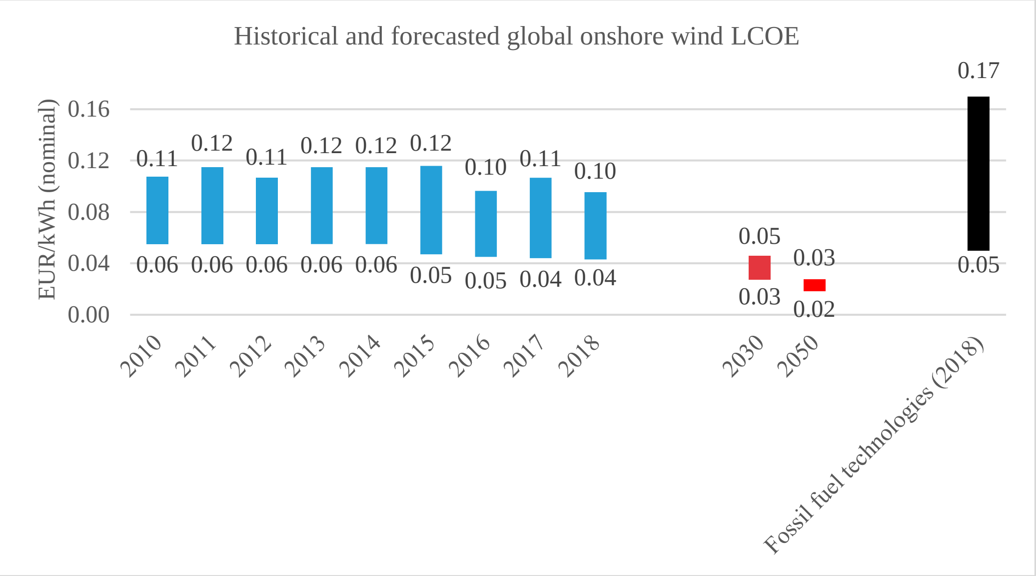


Figure 8: Historical global onshore wind LCOE and projections [5]

The key parameters that denote advancements in the technology are rotor diameter and hub height. The world's largest onshore wind turbine was produced in 2019 by Vestas and it is called EnVentus V150-V162 [16]. Furthermore, a new bigger prototype is expected for the second half of 2020 by Siemens Gamesa of up to 6.6 MW installed capacity and up to 170 meters rotor diameter (SG 5.8) [17].

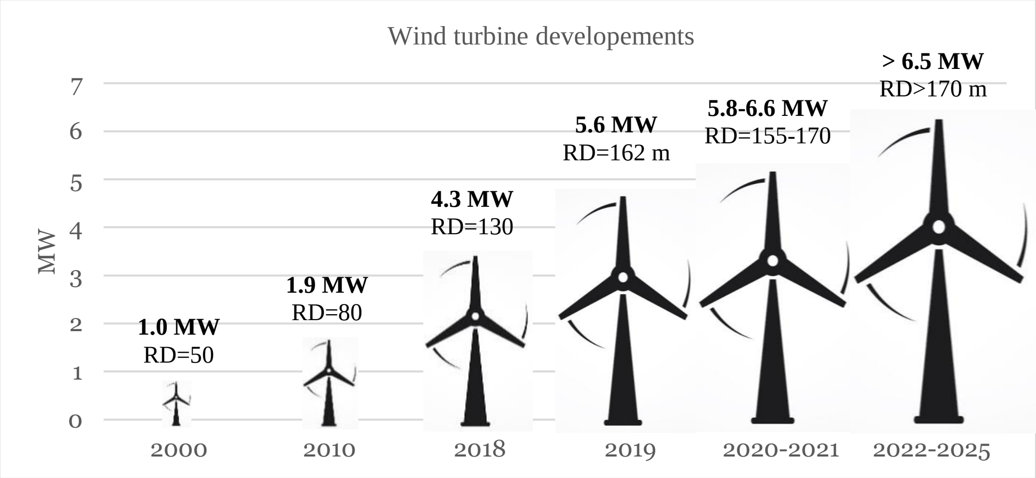


Figure 9: Wind turbine developments with focus on rotor diameter and hub height [5]

Globally, the European producers occupy a major share of the wind turbine technologies supply side which is composed for nearly a quarter of the market by wind turbines, a share of 15% by rotor blades, 7% gear boxes and generators covering the rest. Denmark's Vestas remains the world's largest wind turbine supplier with 20% of the global wind installations in 2018, meaning more than 60,000 turbines installed and a total joint capacity of over 100 GW sold in 36 countries. The German/Spanish company Siemens Gamesa held more than 12% of the overall market share in 2018, while other German suppliers like Enercon and Senvion moved down the ranking due to the decline in installations in Germany. However, Chinese producers such as Goldwind and Envision are progressively gaining importance even though it is still more limited to the Chinese domestic market than the international one. GE Renewable Energy remained the fourth largest supplier due to numerous plants in the US market [18].

Regarding wind turbine technologies, Vestas and Goldwind were the top suppliers in geared drive and direct turbine systems which continue to be the favorite turbine technology in the 2018 market. Specifically, the high-speed geared systems occupied 69.7% of the market, the market share of direct drive turbine technologies was 26.6%, and 3.7%

hybrid drive systems. Moreover, the size and type of wind turbines vary significantly between countries and regions, mostly resulting from regulatory restrictions on height, age or projects and wind speeds. The general trend continued towards larger machines, including longer blades, larger rotor size and higher hub heights. In Europe, for instance, the weighted average power rating of onshore turbines was 3.1 MW in 2019 with a rotor diameter of around 120 meters, while the average of rated capacity of newly installed offshore turbines was 7.2 MW with a rotor diameter of around 155 meters. By country, the largest averages were seen in the United Kingdom (nearly 4 MW onshore), Germany and Denmark (nearly 3.8 MW onshore) and Canada (3.3 MW onshore) [18].

Other manufacturers, including General Electric Renewable Energy (GE) and Siemens Gamesa, are focused increasingly on the repowering market in order to extend turbine lifetime while increasing a wind farm's performance. For instance, Siemens Gamesa makes blade tip extensions to improve the output of existing turbines and has developed upgrades to make the company's turbines more aerodynamic. By 2019, 460 MW of Europe's capacity was repowered, mostly in Germany, Austria, France, Portugal, and Spain enabling to extend turbine lifetime, increase output and reduce operational and maintenance costs (O&M) [18].

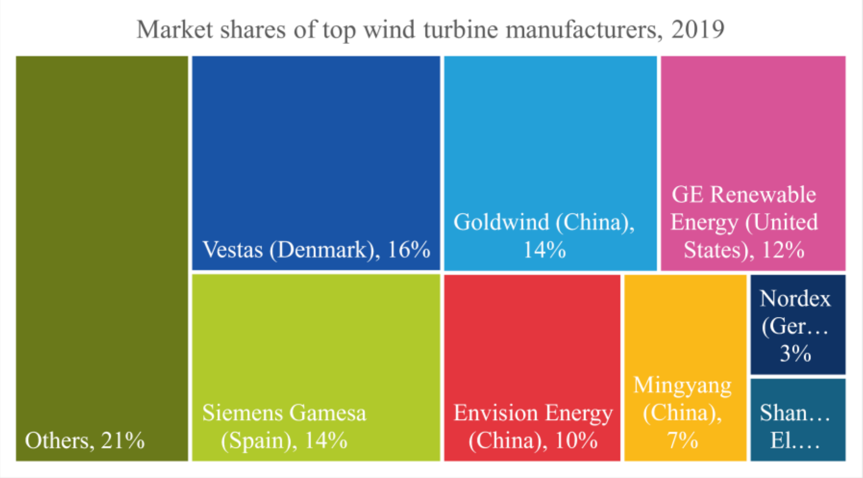


Figure 10: Market shares of top wind turbine manufacturers in 2019 [15]

In 2019, investments on onshore wind energy amounted to nearly 53 billion EUR, relevantly higher than 50 billion EUR invested in 2013. However, deploying a total installed onshore wind capacity of more than 5000 GW by 2050 would require an average annual investment of 135 billion EUR over the period to 2030 and 196 billion EUR over the remaining decades to 2050 going mainly to the installation of new onshore wind power capacities and a very small share for replacement of retired installed capacities. However, from 2040, more than one-third of the total average annual investment will be needed to replace existing plants with advanced technologies. According to IRENA [5], the wind industry suppliers would have to plan and invest adequately to expand their supply needs with facilities in emerging wind markets in order to prepare the future wind capacity additions of more than 200 GW per year and cut down the complications involved with transportation. In fact, at a regional level, Asia would account for more than half of the global average annual investments, followed by North America [8].

2.2.4 Technical Challenges and Innovations

Wind energy is one of the key renewable technologies needed to point at global energy transformation in line with the Paris climate goals. Despite the technology is available at a large scale and it is cost-competitive, wind power projects still face serious constraints both from a technology and market side. Mitigating these barriers, through a range of implementation measures, is crucial to boost future deployment.

- The largest technical challenge is related to grid connection, integration, and lack of infrastructure supporting variable renewable energy (VRE). Indeed, the increasing share of VRE brings significant changes in how the power system needs to operate due to the variable nature of wind and solar resources. Therefore, the success of the energy transition will be supported by the implementation of strategies and adequate measures deployed to maintain grid stability and reliability despite sources variations. At present, the share of VRE in electricity generation in Group of Twenty (G20) countries is about 10%, however it is estimated to increase to 34% by 2030 and 60% by 2050. This growth in VRE power requires innovative technical solutions for both supply and demand sides, system flexibility measures, and reinforcement of power grids. IRENA estimates that the investments in grids, generation adequacy and flexibility measures, such as battery storage, pumped hydropower, electric vehicle battery capacity, and hydrogen integration, would total around 12 trillion EUR for the period 2016-2050 to integrate 60% VRE by 2050 [5].

- Concerns about technology maturity and performance drove several research projects to explore innovations in design, materials requirement, and manufacturing techniques. For instance, innovative materials and aerodynamic profiles of the blades are critical to improve performances, maximize energy production, and reduce operation and maintenance costs. Wind turbine blades are mostly made of a composite material that enables lighter and longer blades and, thus, higher performance. Recycling the nearly 2.5 million tons of composite materials in use in the wind energy sector, through either mechanical or thermal processes, would mean reducing the total use of raw materials. Moreover, for the newer turbine blades, different sustainable materials and cost-effective recycling processes are being considered [5].
- Another technical challenge is optimizing the power inverters reliability and dimensions in order to reduce turbine installation and operation costs. Some research aims at limiting the number of active elements in power modules and thereby defects, adding humidity protections, introducing advanced predictive algorithms that improve maintenance activities, and making the power electronics operational even in humid conditions. Furthermore, the digital revolution is also affecting wind energy with new technologies for turbine monitoring and control. Using big data and artificial intelligence could help in predicting with a high degree of accuracy when the turbine would need maintenance, while automatic regulations, such as pitch and yaw control, are able to maximize the overall energy output. With the help of artificial intelligence, GE in Japan reduced maintenance costs by 20% and increased power output by 5%. In addition, McKinsey’s Utilityx saved 10-25% of maintenance and replacement cost through predictive maintenance [5].

These innovations offer a portfolio of solutions that can be combined in order to reduce costs and maximize system benefits. In addition, energy policies and support schemes, such as auctions, are increasingly aiming at supporting the integration of VRE, especially in countries with large potential of wind and solar energy.

2.3 Market Analysis

2.3.1 Key Mechanisms in National Renewable Energy Support Policies

Worldwide, governments have focused their energy policy attention primarily on promoting the development of renewable power generation technologies. The choice of the instrument depends on the market technology, scale, timeframe, and location since it determines the price exposure that renewables producers face. This range of market price risk affects the expected rate of return, which is function of the project risk and capital costs. The quantity-based support schemes are renewable energy sources (RES) quota obligations with tradable certificates and tendering procedures or auctions. Furthermore, the price-based support schemes are feed-in tariffs and premiums, investment subsidies, fiscal incentives, or fossil fuel taxes [19].

- Electricity quota obligations

Renewable energy electricity targets can be cascaded down to electricity suppliers, generators or consumers through electricity quota obligations which vary in their design according to the quota type, time frame, technology, obligated entities, and compliance rules. In most countries, renewable obligations or quotas are supported by tradable renewable electricity certificates (RECs). A REC is typically awarded to a generator for each MWh of renewable energy produced. Market clients participate in receiving or buying a certain number of certificates to meet the mandatory quotas established for the year. The effectiveness of quota obligations is highly dependent on the national and subnational targets and supported by adequate compliance and enforcement. Furthermore, a dynamic and efficient market for trading certificates enables positive outcomes, and the presence of penalties for entities that fall short of the legally required number of certificates guarantees that certificates have high value on the market.

- Auctions

The state or the regulatory authority organizes competitive tender procedures for the supply of renewable electricity, which is then supplied on a contract basis at the price resulting from the winners of the tender. Renewable power auctions were held in at least 48 countries worldwide in 2018, up from 29 countries in 2017. Policy makers have used the flexibility of auction mechanisms to design tenders to meet various national goals beyond awarding contracts at minimum prices. Auctions also can be designed to overcome unintended consequences that have been overlooked previously in power sector development such as the exclusion of local communities and small actors or the concentration of projects in specific areas.

- Feed-in pricing policies

Feed-in tariff (FITs) instrument promotes an administratively-set price, typically higher than the wholesale electricity price, at which the renewable electricity is sold to the network operator for a predefined period (usually 10-15 years). Moreover, the feed-in premium (FIPs) set an extra price component in addition to the electricity price that can obtain in the market. Despite the shift to auctions in many countries, FIT policies continue to play a role in national and sub-national policy schemes and were in place in 111 countries by the end of 2018. However, FIT support for utility-scale renewable projects is often now limited to countries with emergent renewable energy markets. Moreover, this instrument is also used to support less-established technologies or technologies with relatively high project development costs that often are not included in auctions.

- Other subsidies

Mechanisms such as capital grants, third-party financing, consumers grant, and rebates are investment subsidies provided to investors developing renewable capacity. Moreover, tax credits, excise and property tax exemptions are other fiscal incentives as well as carbon taxes or taxes on other pollutants, such as SO_x and NO_x, which are imposed on the use of fossil fuels. The latter can indirectly benefit renewable electricity producers by reducing their relative process in comparison with those of electricity produced from fossil fuels.

According to the 2011 Council of European Energy Regulators (CEER) RES Status, 10 years ago and especially in the period 2014-2015, FIT schemes were the most prevalent form of RES support throughout Europe (21 out of 28 member countries). In 2017, many CEER member countries supported two or more different schemes, often combining FIT schemes with more market oriented support elements such as investments grants (Austria, Malta), FIP (Czech Republic, Germany, Italy, UK) or green certificates (UK, Italy). However, in the latest CEER RES Status, providing an overview of the support schemes by technology in 2017, a steady move toward market-oriented support schemes was observed. Specifically, by the end of 2017, 18 out of 29 countries had either introduced tendering schemes or were about to do so. These procedures tend to be of lower cost than administratively set support levels, especially given the adaptability of this instrument to technological innovation and reduced unit costs in solar and wind. However, since most RES support schemes were introduced in the early 2000s and support times often last for 20 years, an increasing number of supported RES installations will reach the end of their support time from 2020 onwards and onshore wind is planned to own the largest share of RES capacities running without support. In fact, according to CEER Report of 2018, the proportion of gross electricity produced receiving RES support already differed widely from one country to another, ranging from 3% in Norway to 63% in Denmark, with an average of approximately 17% across CEER Member countries [20] [21] [22].

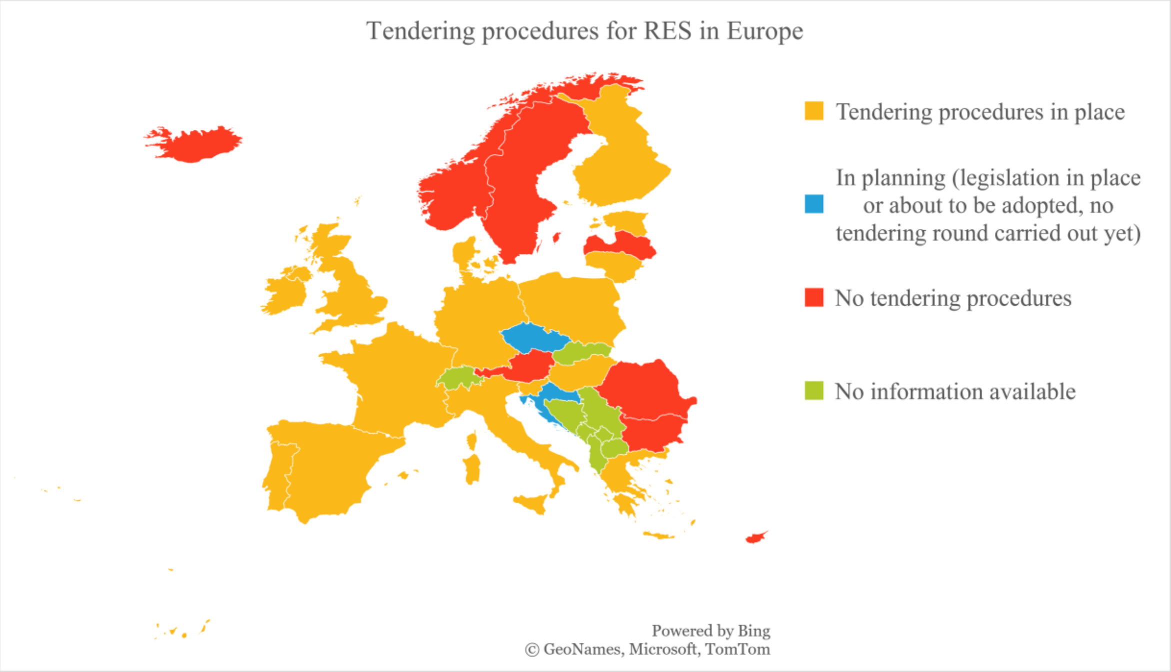


Figure 11: Overview of implementation status of RES tendering procedures in Europe [21]

2.3.2 Power Purchase Agreements (PPAs) Business Model

Wind power, among the energy sector, dominates the market for mergers and acquisitions (M&A) by accounting for about half of all transactions reported in the last years. They are transactions in which the ownership of companies, business organizations, or their operating units are transferred or consolidated with other entities. In fact, the growth of renewable energy capacity has contributed to lower technology and installation costs, and better integration with existing transmission networks [23]. In addition, the cost of renewable electricity generation has reduced to a level that in many countries is competitive with conventional electricity sources. Therefore, this has led to the phasing out of many subsidy systems and encouraged the greater use renewable electricity business models, including PPAs, corporate PPAs, utility PPAs, or electricity trading [24] [25].

In fact, the most common technique to reduce potential loss for many market participants is using long-term PPAs which are contracts between the buyer (off-taker) and the power producer or investor to purchase electricity at a pre-agreed price for a pre-agreed period of time. The electricity sold can come from existing renewable energy supply or a new project for which usually long term PPAs, at least a duration that covers the dept term of the project finance, are signed. Moreover, the pricing structure can be based on either a fixed price or a discount from the wholesale market price with a fixed floor. Renewable corporate PPAs success comes from several benefits both for buyers and developers. On the one hand, corporate buyers use this business model to increase cost visibility over future electricity costs by locking in a fixed price and avoiding capital requirement dependency, reduce electricity costs, and meet “green” goals as part of their sustainability strategy. On the other hand, developers aim at risk mitigation, stable and long-term income for easier bankability, and expansion into new markets by increasing the pool of potential customers [26].

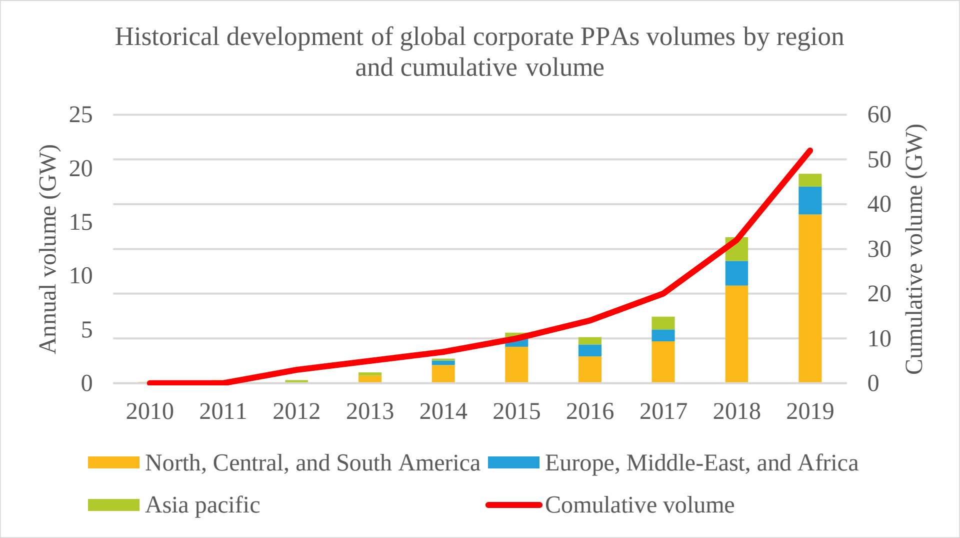


Figure 12: Historical development of corporate PPAs volumes by region and cumulative volume [27]

2.3.3 General Market Criticalities and Drivers

- Permitting phase is one of the key steps in the wind project development process as well as a relevant critical issue in the wind market progress. Development of a wind farm is a complex process involving developers, landowners, utilities, the public, and local and state agencies and requiring from one to two years and more from initial planning to project operation. Moreover, the permitting phase is one of the steps that usually points out uncertainties that contribute to lengthy analyses and processes. The most relevant barriers in the project approval are impacts on species, visual impact, flicker, radar interference, noise, land area usage, and not in my back yard (NIMBY). Public opposition is, therefore, one of main existing issue blocking many projects' permissions and affecting the deployment rate. In order to regulate this, many legislations provide requirements regarding the minimum distance to dwellings and noise limits which main cause is the aerodynamic noise from the blades and subsequently wind speed and wind turbines' size. The minimum distance law differs country by country and significantly impact the wind farms productivity and their chances to be approved. Apart from complying with the setback distances, supportive measures to local communities, engagement from the early stages, and equitable distribution of the economic benefits and costs are relevant to limit public opposition. On social and environmental protection side, wind industry is currently working on implementing social protection measures, reduce harm to biodiversity through careful selection of wind farm sites, handle and manage local impacts in appropriate ways that are acceptable to most stakeholders [28].
- Other market key barriers are high initial cost of capital and long payback periods, limited financing channels, evolving policies with impact on remuneration, and not priced or fully priced carbon emissions and local air pollutants. Wind energy has been supported by a range of policy instruments which need to be chosen properly to provide long term stability, adaptation to different market conditions, streamlined permitting processes, possibilities for corporate sourcing, and so on. From a regulatory and policy point of view, complex frameworks, insufficient financial policy support, and lack of quality control measures, skilled professionals, and long-term policy targets and well-coordinated policy mix represent large barriers. With this regard, deploying sustainable finance initiatives and mobilize revenue streams for instance through carbon pricing and other measures is crucial to enlarge the fiscal scale and foster sector diversification to finance the energy transition process. Moreover, the revision of business models is a key driver for capturing new opportunities. Specifically, the combination of falling prices and competitive pressure results in decreasing revenues and seeking growth outside traditional business models. For instance, the model of signing corporate PPAs has been taking place especially in North America and Northern Europe with large companies involved. However,

there are two key areas required for the model to become stronger an even stronger and more stable growth driver:

    - Establishing corporate sourcing in developing markets, where there is lack of experience of investors and banks and evaluation of the risk, but big opportunity to unlock additional volume besides government targets and activate further investments in grid and infrastructure.
    - Allowing smaller and local corporates to enter corporate sourcing for instance through aggregation of a customer base [4].

- Lastly, most energy markets have crucial challenges in terms of cost efficiency, renewable integration, and security/timing of supply. New solutions, therefore, have the potential to unlock more volume or renovate the way of doing business in the wind industry. First, co-location or hybrid solutions are efficient integration systems in which wind energy and another energy source and/or storage solution are combined in the same project. Second, complementary solutions or virtual power plants are wind energy projects in different locations which are virtually managed. Third, wind energy projects can be part of financial solutions which can exclude actual physical delivery of electricity and, therefore, they can cover corporate PPAs and risk management tools. Fourth, onsite provision or off grid solutions are projects in which wind energy takes part of a micro-grid or decentralized energy system.

3. Sweden

3.1 Country Profile

3.1.1 Energy Insights

3.1.1.1 Country Overview

Sweden is located in the north of Europe and borders Norway, Finland, and the Baltic Sea. Its area of 450,000 square kilometres is covered for two-thirds by forests. In 2019, the country accounted for 10.12 million inhabitans, however most Swedes live in the south and specifically one-third in the areas of Stockholm, Gotherburg, and Malmo [29].

Sweden is a constitutional monarchy in which the king plays a representative role only, while the single-chamber parliament is elected by proportional representation. The government is supported by the 21 administrative counties in the development of energy policy. Even if Sweden has joined the EU in 1995, it decided to maintain its own currency, the Swedish krona, instead of Euro. However, the EU sets legal requirements for the Swedish energy policy regarding electricity and gas markets, energy efficiency, renewable energy goals, energy taxation, greenhouse gas (GHG) emissions.

The country's prosperity and stability built up an open-market economy and a welfare state in which, in 2018, the gross domestic product (GDP) was around 478.1 billion EUR and the GDP per capita was around 45.74 thousand EUR, which means 15% higher than the Organization for Economic Co-operation and Development (OECD) average. Furthermore, unemployment counted 6.6% in 2019, and the GDP growth rate 0.8% YoY [29].

As in most of the developed countries, the largest sector is service, while the country's industry is led by exports and focused on local forest and mineral resources processing. The major exports are vehicles, machinery, pulp and paper, pharmaceuticals, and oil products. Last, the primary sector accounts for 1% of the GDP.

Population (million)	10.04
GDP (billion USD)	478.1
GDP growth rate	2.2%
Electricity demand (TWh)	133.5
Electricity demand pro-capita (MWh)	13.1

Table 1: Sweden key data (2018) [26]

3.1.1.2 Primary Energy and Electricity Supply

Hydropower takes a central role in the energy supply and it is followed by nuclear power and bioenergy coming mainly from domestic forest resources. In 2017, these three sources accounted for 73% of the total primary energy supply (TPES). Despite a small usage of peat, the country had no domestic fossil fuel production, however oil accounted for 84% of the total energy imports in 2017. In fact, since the introduction of nuclear between 1973 and 1986, the TPES has remained at around 50 million tons of oil equivalent (Mtoe). However, the energy mix has shifted from oil to biofuels and renewables [29].

Electricity generation is nearly emissions free due to high hydropower and nuclear power production which each of them accounts for 40% of the domestic production. The remaining electricity comes from wind, bioenergy, and waste. Most relevantly, financial subsidies have made wind power grow rapidly in recent years, and therefore Sweden has become a net exporter of electricity coming from wind power plants [29].

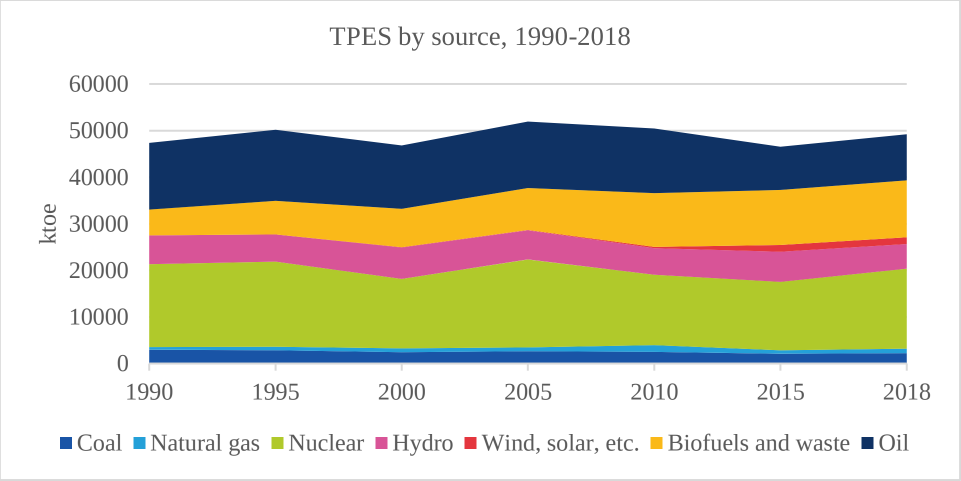


Figure 13: Historical development of TPES by source in Sweden [30]

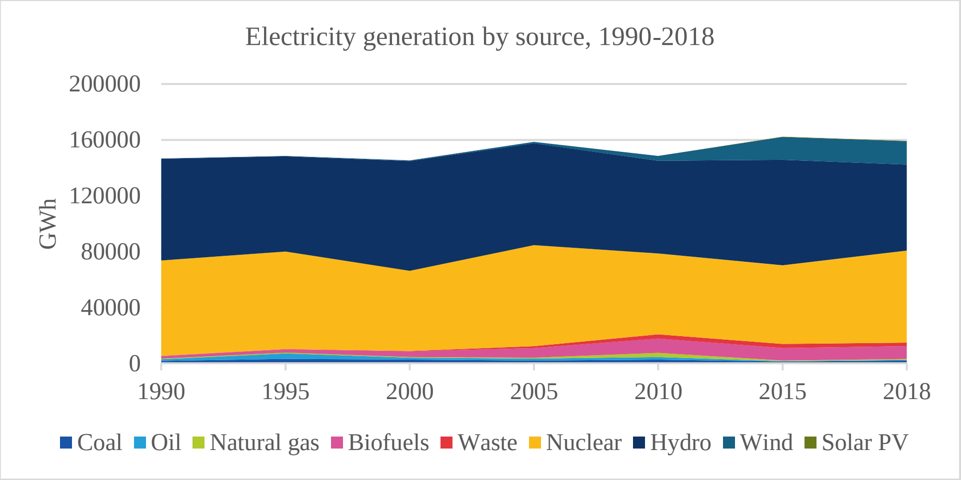


Figure 14: Historical development of electricity generation by source in Sweden [30]

3.1.1.3 Energy Consumption

So far, the energy demand has been quite stable unless for some variabilities such as the financial crisis of 2008 and the cold winter of 2010. Electricity is the largest source of total final consumption (TFC) followed by oil, biomass-based fuels and waste, and district heating (DH) and industry which consumes 40% of TFC. In residential and commercial sectors, electricity accounts for more than half of the total consumption because of the use of heat pumps and electric heating in buildings. The total electricity demand in Sweden was 141.5 TWh in 2017, while the electricity consumption per capita was 14.3 MWh. This indicator, furthermore, is estimated to grow with a rate of 0.4% per year between 2017 and 2030. In contrast with this electronification process, the transport sector, still depends on oil even though Sweden has the highest share of renewable transport fuels of the International Energy Agency (IEA) members [29].

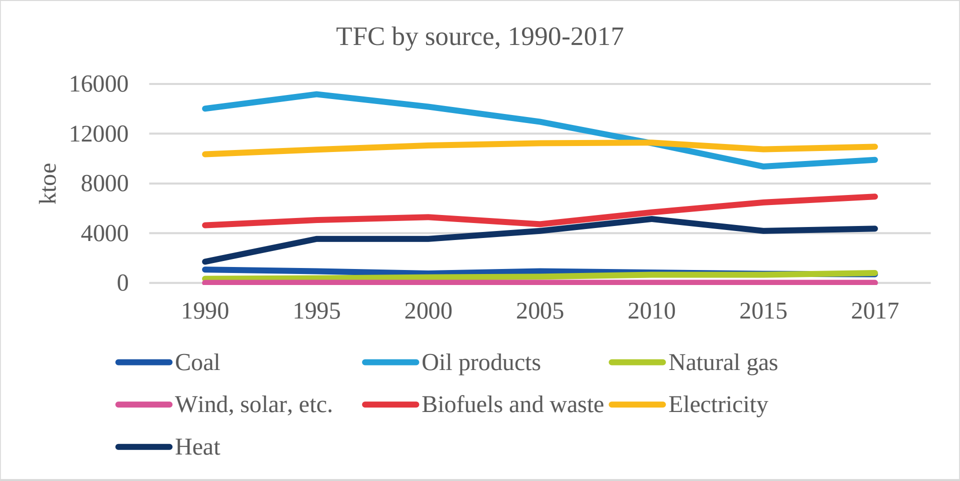


Figure 15: Historical development of TFC by source in Sweden [30]

3.1.1.4 Renewable Energy Sources Evolution

Sweden has the second-lowest share of fossil fuels in electricity generation among all IEA member countries, after Switzerland. The electricity market, therefore, is dominated by RES. Specifically, in 2017, nuclear energy covered 40% of the electricity supply, hydropower another 40%, wind 11%, biofuels and waste 8%, and others, including solar energy, 1%. In 2017, the country accounted for 95.1 TWh of renewable electricity out of a total production of 164.2 TWh, and 32.4 GW installed renewable capacity out of 39.8 GW total. Furthermore, the electricity generation and trade are increasing since the introduction of the electricity certificate system in 2003 which invests on new renewable power capacity [29].

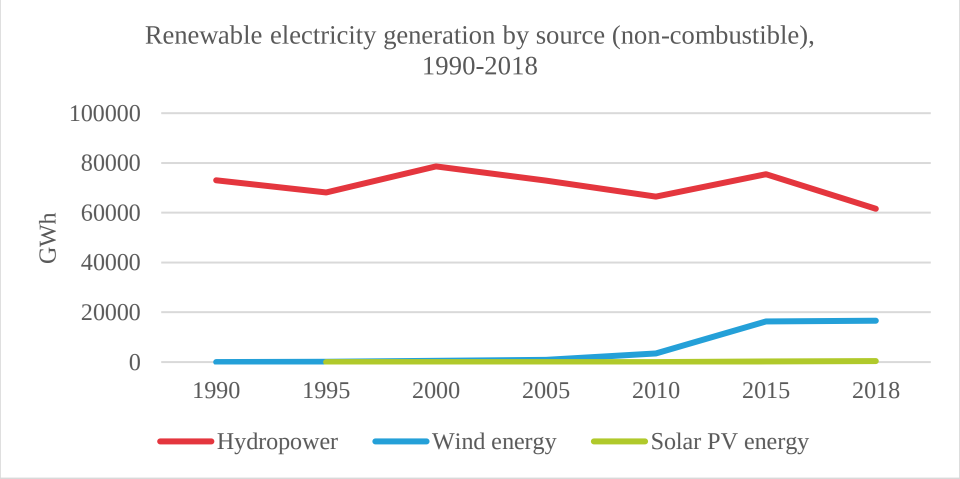


Figure 16: Historical development of renewable electricity generation by source in Sweden [30]

Excluding large hydro, the energy sources in which the top renewable asset owners are investing the most are wind, biomass and waste, small hydro, and solar in order of importance. The largest owned-state Swedish energy company is Vattenfall which is a producer of electrical energy, district heating supplier and electricity grid. In 2017, it owned renewable energy power plants for a total of 0.6 GW installed capacity, of which 0.4 GW was installed wind power. Secondly, the private German energy group E.ON owned 0.5 GW renewable installed capacity. Then, Statkraft, leading international hydropower company, Europe's largest supplier of renewable energy and Sweden's fourth largest electricity producer owned 0.4 GW of only wind installed capacity. Furthermore, Fortum, Allianz, Green Investment Bank, GE, Eolus, Enercon, Apg are some of the actors in the country’s RES market. To summarize, the companies which are keen on committing to the wind energy market are fund investment companies, which are a corporation or trust engaged in the business of investing the pooled capital of investors in financial securities [31].

3.1.2 Electricity Market

3.1.2.1 Electricity Network Structure

The Nordic market area including Norway, Sweden, Denmark, Finland, Estonia, Lithuania, and Latvia, since 2011, has been divided into price or bidding areas. In Sweden, for instance, four areas have been defined: Luleå (SE1), Sundsvall (SE2), Stockholm (SE3), and Malmö (SE4). The northern areas, SE1 and SE2, have a generation surplus, while in the south, SE3 and SE4 have a generation shortage. In 2017, for instance, Sweden was a uniform price region 59.7% of the time, for 30.7% of the time there were two regions and for 9.6% of the time the country was divided in three. Most of the price differences occur between north and south during periods of transmission restrictions or production losses. Therefore, the price differences encourage increasing generating and transmission capacity which will lead to price convergence among the areas [29].

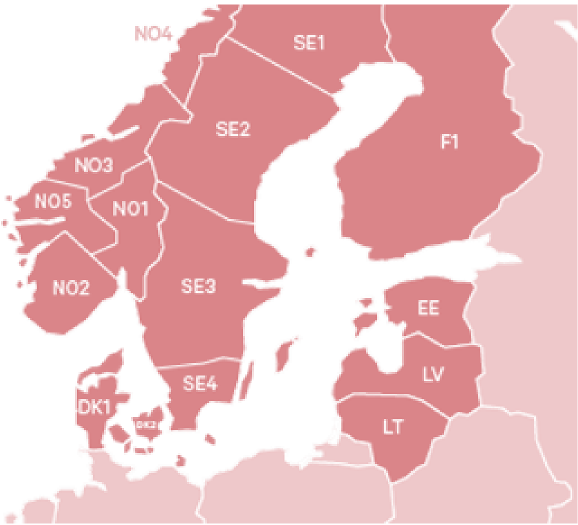


Figure 17: Electricity areas in the Nordic countries [32]

Phisically, the electricity passes through various grid levels as it is transported from the power stations to the consumer. First, Swedish electricity generation is dominated by the state-owned Vattenfall for over 40% of the total, Fortum (50.8% owned by the Finnish state), and Uniper (47% owned by Fortum). These three major generators also own the nuclear power capacity in the country. When generators plan to connect their projects to the electricity grid in areas with not enough capacity to accommodate the new project, the generator connecting the first project is forced to pay the upgrading grid’s capacity sometimes bigger than the needed one, while the subsequent generators could take advantages and avoid this cost. In order to reduce this so-called “threshold effect” for new renewable electricity generator, from 2015, the government decide that the distribution system operators (DSOs) must recoup the entire investment for upgrading the grid, while generators only pay for additional share of grid cost due to their connection to the grid [29].

After being generated, the electricity is transported through the Swedish electricity network consisting of 564,000 kilometers of power cables, of which around 382,000 km are underground and 182,000 km overhead lines. The transmission system operator (TSO) is the 100% state-owned Svenska Kraftnät. Transmission runs from the north, where most hydropower and wind power are generated, to the south, where the consumption is mainly located. The increasing wind power generation in the north of Sweden and in neighboring countries, and the bottlenecks in the Swedish grid are the main reasons of a need to increase both the national and the cross-border capacity. Sweden is well connected to its neighborhood Finland, Norway and Denmark, but also has direct links to Germany, Lithuania, and Poland. The total export capacity is 10,575 MW, which is around 1,000 MW higher than the import one. In addition, two additional interconnector projects are at advanced stages. The high-voltage direct current (HVDC) line Hansa Power Bridge, supposedly in operation in 2025/26, will connect SE4 with Germany with a planned capacity of 700 MW. Moreover, the 3AC is a line that by connecting SE1 and Finland with a planned capacity of 800 MW, will increase trading capacity as well as power adequacy in 2025. Moreover, the 1.2 GW Sydvastlanken (South-West link) transmission project is commissioned in 2019 and is expected to make the price differences between areas 3 and 4 fall considerably [29].

After the transmission, electricity is delivered to around 5.4 mission customers through around 170 distribution network companies. The largest network companies are the state-owned Vattenfall Eldistribution AB, Ellevio AB and E.ON Energidistribution AB. Commonly, production, distribution and trade are carried out within the same group but have different legal units, except if the distribution network company has more than 100,000 customers.

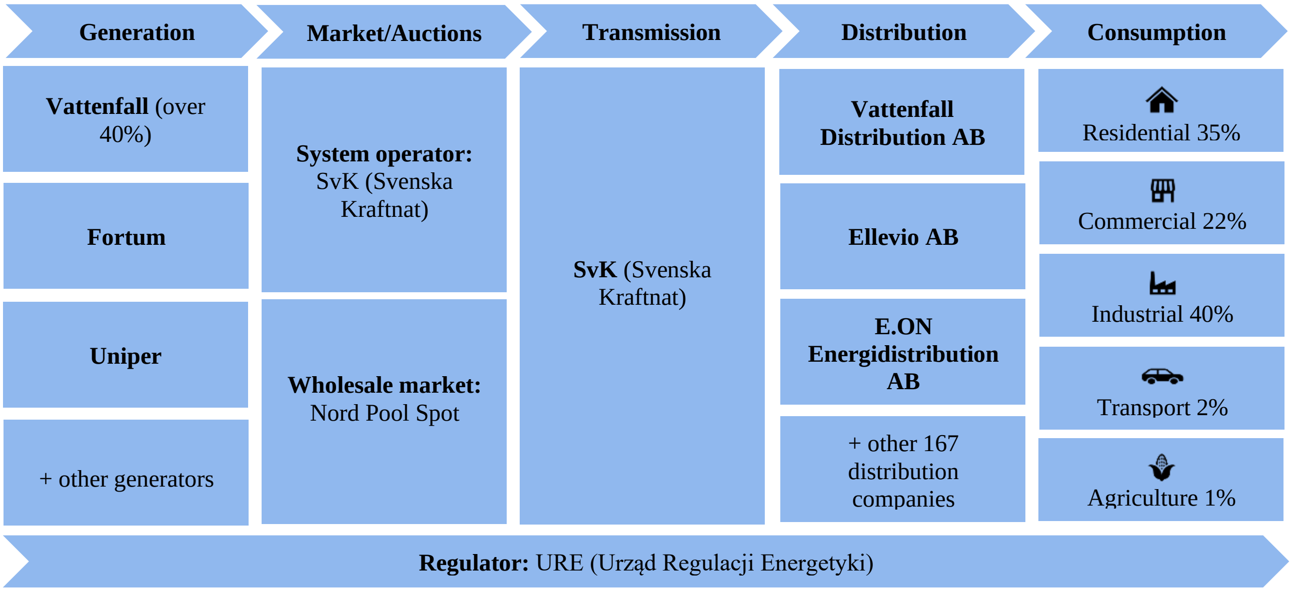


Figure 18: Power market players in Sweden [31]

3.1.2.2 Wholesale Market

On the commercial side, producers sell electricity, either directly or via the power exchange, to electricity traders, which in turn sell it to the consumers. Therefore, the consumers pay for two separate services, the production of electricity on the commercial side and the physical transport over the grid. The players in the electricity market, therefore, need to cooperate closely in order to deliver a reliable supply and maintain a free market with fair competition. Suppliers, however, are free to decide to offer variable price contracts, fixed price, or mixed ones. The majority of low consumption customers sign for a single tariff in which they pay the same price per kWh regardless of the time of usage. All the metering data for the electricity market are hold by the Swedish TSO Svenska Kraftnat and the regulator Swedish Energy Markets Inspectorate (SEMI) by operating the so-called “data hub” [33].

The Nordic power exchange (NordPool) has a spot market (physical trading) where electricity is traded on an hourly basis up to the day before delivery. Around 95% of the physical power trade in Sweden takes place at the Nord Pool with two physical power markets: the bigger day-ahead market (Elspot) and the smaller continuous intraday market (Elbas). Nord Pool is responsible for the market up to the point of gate closure which is defined as one hour before real time. After the gate closure, the various national TSOs take the power systems responsibility.

In addition to the physical NordPool markets, the National Association of Securities Dealers Automated Quotations Nasdaq OMX, or Nasdaq Nordic, offers a futures market (financial trading) concerning longer-term transactions.

Wholesale electricity prices in the Nordic region have been declined since 2011 due to demand growth and supply increase. Therefore, the Nord Pool Elspot price has varied between 20 and 40 EUR/MWh in contrast with 90 EUR/MWh of 2010/11. Since the LCOE for nuclear, hydropower and biomass co-generation were around 34 EUR/MWh, for wind power around 70 EUR/MWh, and for waste co-generation around 28 EUR/MWh, the market-driven investment in new capacity has been low. Price variation is very dependent on the availability of hydropower which is the biggest source for Nord Pool generation [29].

In 2017, electricity price for industry was 55.38 EUR/MWh, which is the second lowest among the IEA countries because of both low wholesale prices and the applicable level of taxation for the industry manufacturing process. In fact, industry taxes account for 1% of the electricity price, while households' average price is 157.98 EUR/MWh, of which 38% were taxes.

Electricity supply needs to be secure and the growing share of wind power and the changing consumptions need to be balanced. The Nordic TSOs therefore agreed in 2018 to develop a Nordic balancing markets aiming at automatic and manual frequency restoration reserves [29].

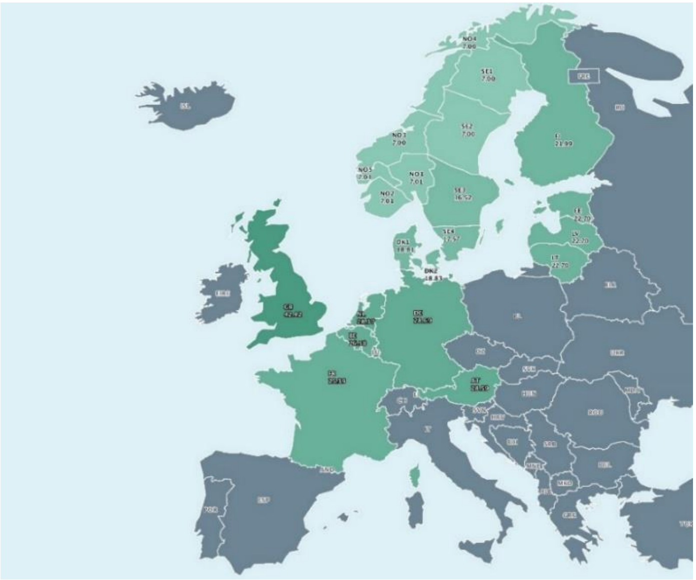


Figure 19: Day-ahead NordPool prices (EUR), 19 March 2020 [32]

3.1.3 Country's Policy Objectives

Sweden's energy policies have aimed at high share of RES for long. The carbon dioxide (CO_2) taxation was introduced in 1991, as one of the first countries in Europe, to promote efficient energy demand and non-fossil fuel energy supply. In 2003, a great support came from the implementation of the Green Certificate System. Moreover, since 2015, a Parliamentary Committee called "Energy Policy Commission" has been created to deal with energy policy with a focus on electricity supply. The *2016 Energy Agreement*, approved by parliament in 2018, set long-term targets such as 100% renewable electricity generation by 2040 and 50% decrease in energy intensity (primary energy supply per GDP) from 2005 to 2030. Furthermore, Sweden also aims to reduce transportation GHG emissions by at least 70% between 2010 and 2030 as part of a climate policy framework. So far, Sweden has been able to increase the use of RES covering more than half of final energy consumption due to taxation on CO_2 emissions and electricity certificate system. As a result, the 2016 Energy Agreement sets to prolong the electricity certificate system until 2030 and expands it to deliver an additional 18 TWh of renewable electricity between 2020 and 2030. However, to achieve 100% renewable electricity by 2040, additional 60 TWh green electricity is needed to maintain today's level of electricity generation. Therefore, Sweden should also assess the system electricity system adequacy based only on RES, of which wind and hydropower play a key role [29].

3.2 Onshore Wind Energy

3.2.1 Wind Plant Current Installations

At the end of 2019, Sweden had 4,099 wind turbines, of which 79 offshore, with a total installed capacity of 8.98 GW which is 21.5% more than the previous year installed capacity. Indeed, in 2019 wind power had an actual electricity production of 19.5 TWh. In addition, 971 wind turbines, accounting for 4.27 GW of installed capacity, were under construction by December 2019, 8.18 GW permitted and 7.71 GW in permission process [34].

Since 2017, the number of wind turbines has increased, but less than how much the installed capacity rose, which means that larger machines were chosen. Moreover, since the production had also increased more than the installed capacity, higher production per installed MW can be noticed and this means that the technological development brought to larger wind turbines both in terms of installed power, rotor diameter, hub height, and therefore higher efficiency. In 2017, Sweden was close to cross the threshold of 3 MW turbines on average and the average rotor diameters exceeded 110 m compared to the range of 77-96 m in which most of the countries' wind turbines heights were the previous year. In 2018, the average height of wind turbines under construction was 193 meters and the most common wind turbines technical features forecasted for 2020-2021 are 150 meters of rotor diameter, 4.2 MW of installed capacity, and 16 GWh of annual production. Regarding wind turbine suppliers in Sweden, Vestas owns 46% of the total capacity under construction, Nordex is a relevant runner-up, and GE is the third largest supplier [35] [36].

Furthermore, in accordance with the global tendency, the weighted-average LCOE of Swedish onshore wind projects is planned to lower supporting, therefore, the development of the technology also from the economic side.

	By the end of 2018	By the end of 2019	By the end of 2020 (forecast)
Number of turbines	3,652	4,099	4,549
Wind installed capacity (MW)	7,395	8,984	10,883
Wind electricity production (TWh)	16.4	19.5	26.7
Wind estimated annual production (TWh)	19.5	24.7	30.9

Table 2: Wind power numbers in Sweden [30]

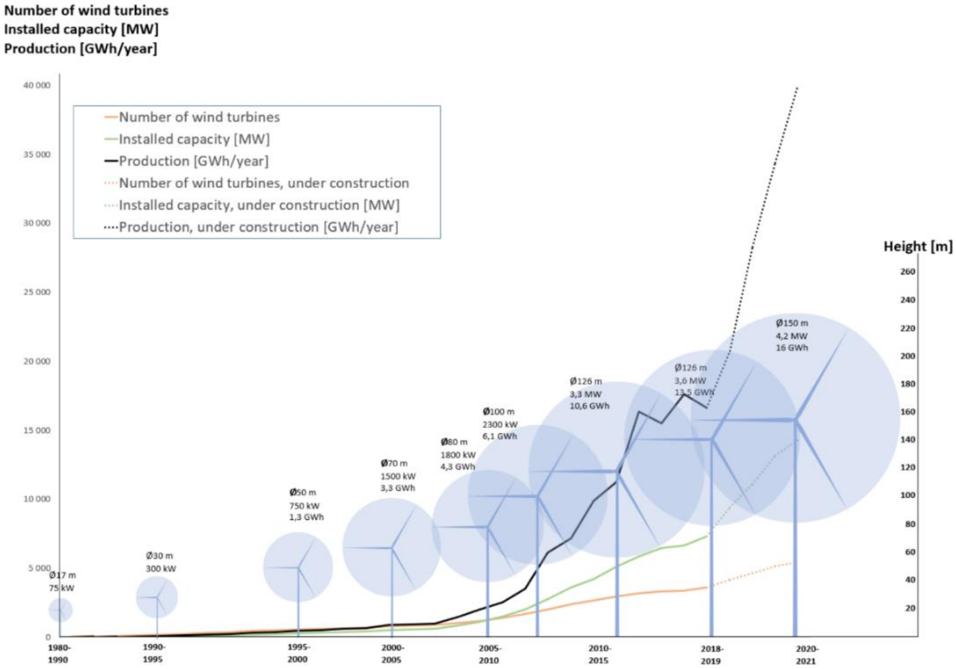


Figure 20: Historical and forecasted development of wind turbines in Sweden [35]

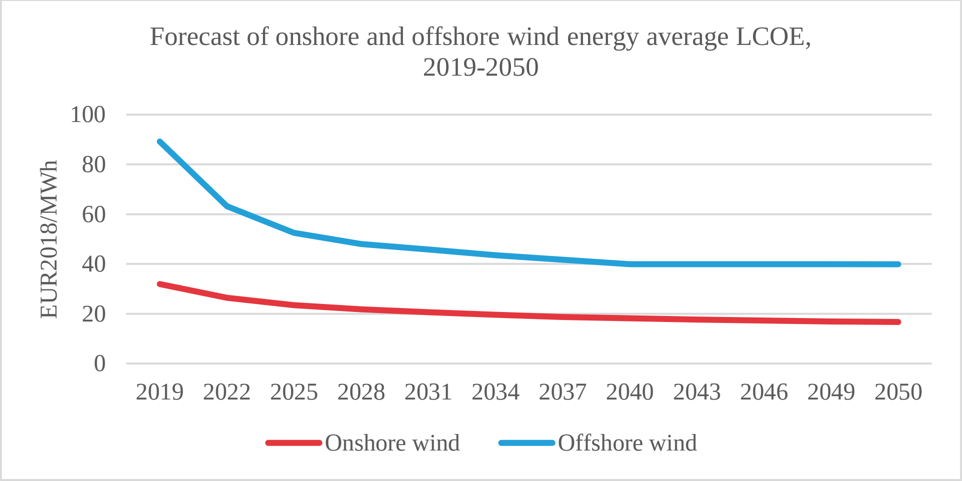


Figure 21: Forecasted onshore and offshore wind energy average LCOE in Sweden [37]

3.2.2 Wind Energy Scenarios

The strong expansion of wind power in Sweden continues despite the low support from electricity certificates during the last years, even if these price levels have recovered slightly in 2018 due to prolongation and extension of the electricity certificate market with 18 TWh until 2030 as well as potential entry of new rules such as the so-called “stop-mechanism” investigated by the Swedish Energy Agency (SEA) (see 3.3.1.1 section) [35].

According to the Swedish Wind Energy Association (SWEA) statistics [38], the number of turbines should pass from 4,099 to 4,549 between the end of 2019 and the end of 2020. As a result, the added capacity should be 1,898.9 MW in 2020, higher than 1,588.4 MW which was the added capacity of last year, and the estimated annual production should pass from 24.7 TWh to 30.9 TWh in 2020. If we focus on the statistics of geographical spread, SE2 is the bidding area in which more turbines will be installed. In fact, the under-construction projects located in this area are considerable higher than the other electricity area’s ones.

Moreover, in accordance with SWEA forecast, three future scenarios can be outlines based on assumptions regarding which projects will be realized considering actual and future market situation. In the Low Case, only projects where turbine contracts have been already signed, will be realized and no further investments are made. The Central Case is considered the most realistic scenario meaning that projects with signed turbine contracts, 30% of permitted projects and 15% of under permission projects will be realized. Lastly, in the High Case scenario, signed turbine contracts projects, around 60% of the permitted projects, and 30% of the under-permission ones are taken into consideration. According to the Base Case, between 2019 and 2023 the annual production will increase more significantly compared to how much the number of cumulative installed wind turbines and capacity will increase. This means that the efficiency, size, and production of the turbines will also increase a lot [38].

To conclude, the production in 2018 was 16.4 TWh, while in 2023 is planned to be 42 TWh corresponding to 5,500 wind turbines, according to the Svensk Vindenergi’s Central Scenario. Furthermore, the estimated production for 2040 is 90 TWh with 5,000 turbines given that most of today’s turbines will be replaced in 2030-2040 [34].

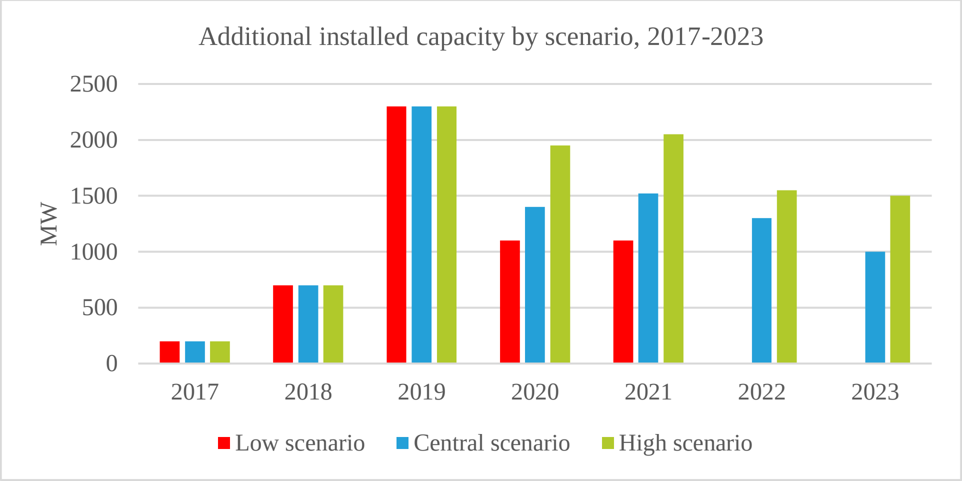


Figure 22: Historical and forecasted development of additional installed capacity by scenario in Sweden [38]

For what concerns the wind plants' location, as part of the effort to increase the share of renewable energy and meet the country's goals, some areas of national interest for wind power production have been identified by SEA and raised the profile of wind power in relation to other interests. In fact, there is a considerable difference between the number of permits given to wind power plants which are planned to be located in the north of Sweden compared to the south and central Sweden. In SE1 and SE2 (north), there are 1,409 planned wind turbines installations, while 949 are the wind turbines planned in SE3 and SE4 (south). As a result, if all the planned wind farms will be constructed, Norrbotten and Sunsvall, in the north, will surely become have the biggest amount of installed wind power in Sweden [39].

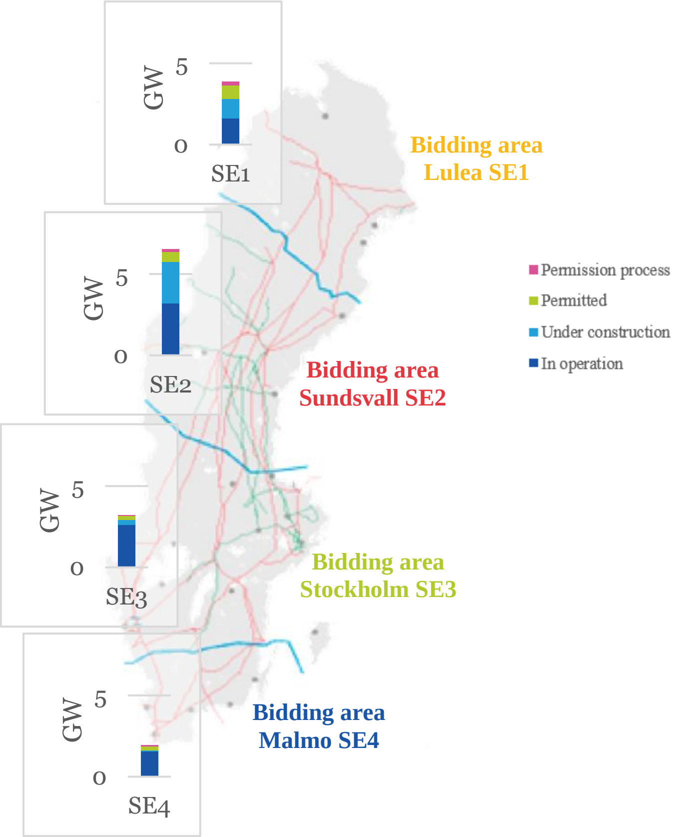


Figure 23: New investments in Sweden by bidding area and project phase, 2017-2022 [39]

3.2.3 Wind Power Permitting Process

The process towards the permitting and construction of wind power plans has several steps and timings which vary depending on different factors such as number of turbines, height, rotor diameter, distance from the shore, and so on. In Sweden, lead times for permit applications and grid connections are excessively long, sometimes exceeding 10 years. A new wind power project must go through two separate permitting processes: one for building the wind farm, called "environmental permit", and another for connecting it to the grid, called "concession". The process from initial consultation to environmental permit acquisition normally takes 6–7 years for a large wind farm, including the appeal period. Then, the permit is valid for 5 years and, during that time, the developer must apply for the permit to connect the project to the grid. Sometimes, the environmental permit runs out before the connection to the grid is completed and an extension is often difficult to obtain. When both permits are in place, a final investment decision (FID) can be completed [40].

The main laws regulating wind power plants permitting process are "The Environmental Code" and "The Planning and Building Act". In addition to the two laws, several more laws may be relevant depending on the location and size of the wind power plant as the law about electricity, utility easements act, cultural act, reindeer husbandry act, forestry act, law on the protection of landscape-details, the electronic communications act, law on electromagnetic compatibility and transport agency's regulations. According to the codes, the mini and small wind power plants are defined as one turbine with a total height of 20 to 50 meters or a rotor diameter exceeding 3 meters and require information to neighbors and a building permit from the municipality. Medium-sized wind power plants include one turbine with rotor diameter exceeding 50 meters or two or more turbines placed together in a group. These plants require a notification according to the Environmental Code and a building permit according to the Planning and Building Act. Both of them are considered by the municipality which must also consider if a permit from the county of administration board (CAB) is needed. Last, large wind power plants consist of two or more turbines placed together in a group with rotor diameter higher than 150 meters or seven or more turbines placed in a group were one or more are higher than 120 meters. These cases can be handled by the CAB according to the Environmental Code and approval from the municipality. In fact, since 2009, municipalities have the authority to veto planned wind power plants within their areas without any motivation for their decision. This means that the authority responsible for giving permission may only give it for the wind power plant if the municipality has given its approval. As a result, the municipal veto appears as an instrument increasing uncertainty and making it harder to foresee the outcome and timing of the permitting processes. During the application, the environmental impact assessment (EIA) should be issued and typically includes:

- description of the project,
- description of measures to avoid or reduce adverse effects on the environment,
- information required to identify and assess effects on human health,
- environment and management of land, water, and other resources,
- presentation of alternative sites, designs,
- non-technical summary of the details referred to in the listed points above [41].

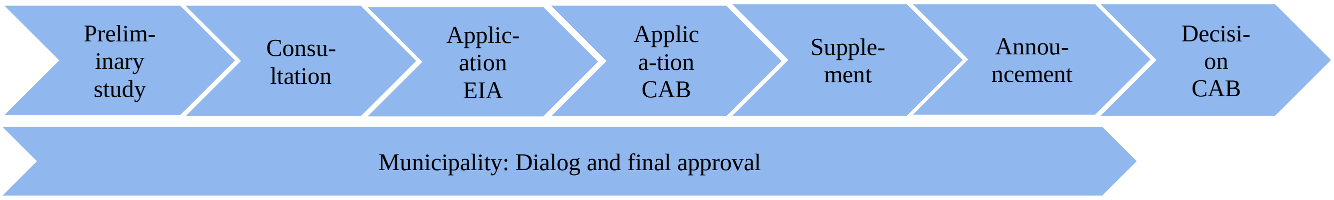


Figure 24: Approval process for permit of large-scale wind turbine projects in Sweden [41]

This permitting process, however, is open to some refusals that can occur due to deficiencies in the application, excess of the maximum total wind turbines' height defined by each municipality (country's average 194 m, while maximum value 240 m), insufficiently examination on impacted species and, so on. Indeed, between 2014 and 2018, 59 permit applications out of 187 were rejected, representing 32% of the total number of proposed projects. In detail, the first reason of rejection was municipal denial (25%), the second one was related to special protection issues, followed by armed forces, flaws in the applications, and reindeer husbandry. In addition, there are many obtained permits which are not used and, therefore, the construction had not started yet. With this regard, in December 2018, SEA conducted a survey to investigate the causes of this step back or uncertainty. The most common reason was that the municipality had expired the approval, or the project has been rejected in a higher court. The second cause was that the municipality had inserted limitations in the technology to be used and, therefore, these restrictions made the wind farm construction not or less profitable. In fact, even if wind turbines with larger rotors, heights, and producibility have been developed recently, the majority of the municipalities keeps strict height limitations. Therefore, sometimes a special request for changing the technical limitations of the municipality is submitted instead of deciding not to build the plant definitely. However, the report covering the approved wind power in Sweden released in fall 2018 by the CAB of Halland showed that all projects had been approved except the ones that were reviewed at the time of its release [36] [35].

To conclude, statistics show that, for what concerns onshore wind plants, the number of consultations per year have been decreased, nearly halved between 2014 and 2015, and kept falling for the three following years.

3.3 Supports and Challenges for Future Development

3.3.1 Financing Mechanisms and Instruments at National Level

3.3.1.1 Legal Framework

In 2003, Sweden introduced the green certificate (GC) system in order to meet the goals of 60% of electricity TFC from renewables by 2010 and 50% clean energy in the gross of energy by 2020 according to the EU directives. In 2012, Norway joined the system and the target became to increase electricity production from RES by 28.4 TWh within 2020. From 2012 to 2018, the Swedish-Norwegian electricity certificate system contributed to an expected 26.8 TWh of new renewable annual production, of which 19.1 TWh was mainly wind energy in Sweden and 7.7 TWh was mainly hydropower in Norway. In 2017, therefore, the Swedish Parliament decided to extend the certificate system with a new renewable energy target of additional 18 TWh by 2030 in order to reach the 100% electricity renewable target by 2040. However, the expansion of wind power develops much faster than expected and the aim of having an annual production of 18 TWh by 2030 is believed to be reached already by 2021 [29]. One explanation to the accelerated expansion is that the Swedish Energy Agency was commissioned to carry out the *Control station 2019* with three objectives, including investigate a so-called “stop-mechanism” and alternatives such as a volume-related stop-mechanism. According to the agreement with Norway, this mechanism will be introduced in Sweden before the 31st of December 2020 aiming to define a deadline on when facilities must be operational in order to be approved for the award of electricity certificates. Another investigation conducted by SEA is whether a requirement should be made that a certain period of time after the award of electricity certificates has ceased before a new allocation period may start after extensive reconstruction. Lastly, in accordance with the bill *New target for renewable electricity and control station for the electricity certificate system 2017*, the State Energy Authority shall monitor if there has been an allocation of electricity certificates when the variable electricity price in Sweden is zero or lower and shall analyze any effects on the electricity market in such an event [35] [42].

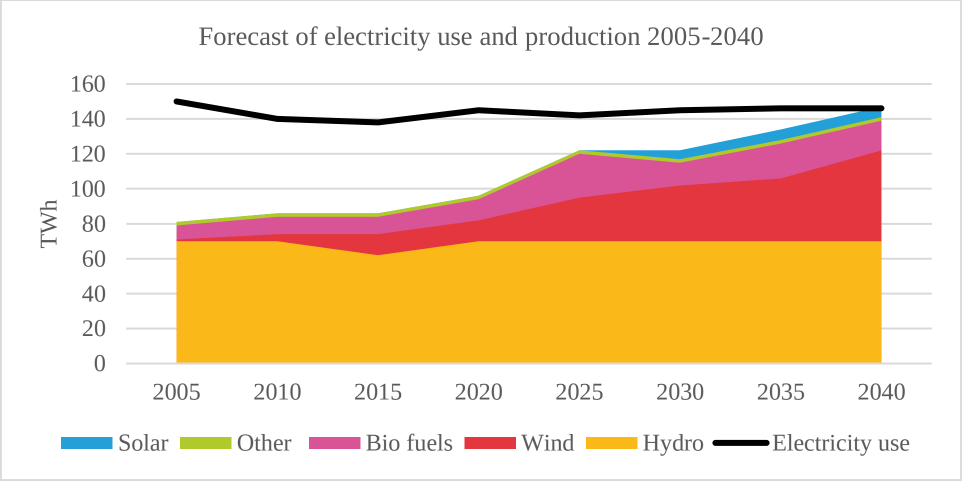


Figure 25: Historical development and forecasted electricity use and production in Sweden [42]

The electricity certificate system aims at promoting the development of renewable electricity production and, as it is technology neutral, supports the most cost-effective production. In detail, the system has a target that defines how much new renewable electricity production must be developed by a certain year. This target is then broken down to the annual growth rate necessary to reach the objective. The demand for electricity certificates is created by the fact that non-renewable electricity suppliers and large electricity customers are obliged to buy certificates to meet a certain share, called “quota obligation”, of their calculation-relevant electricity supply (or consumption for the large customers). To summarize, a quota obligation is an annual obligation on the part of non-renewable electricity suppliers to hold electricity certificates corresponding to their sale and use of electricity during the previous calendar year. Producers of RES electricity receive one certificate for each MWh of electricity produced. In this market, certificates prices are determined by supply and demand and generators receive this as extra income in addition to the electricity price. This makes investments in new RES production more profitable. Every year, the market participants with quota obligation must purchase electricity certificates to fulfil their obligation. Quota obligation is being transferred from electricity users to suppliers, except for older production plants which are phased out of the system depending on the type of plant and when it was built. Moreover, the system is not applied in the case of electricity users who use electricity produced by themselves, imported or purchased on the Nordic Power Exchange, and users in electricity-intensive companies [29].

Anyways, in 2017, 24.1 million certificates had been emitted in Sweden of which 71% regarded wind power, 22% biofuels, 6.7% hydropower, 0.6% peat and solar.

The remuneration scheme, therefore, comprises of power revenues which are estimated to rise mainly due to increase of CO_2 prices and dry weather in north Europe, electricity certificate revenues which are experiencing a dramatic decrease in the last 2-3 years and they are estimated to be negligible from 2023 onwards, and guarantees of origin revenues (around 1-1.5 EUR/MWh). In detail, on the one hand, the power price was between 22 and 55 EUR/MWh in the period 2005-2018 and it is estimated to increase in the next years. On the other hand, the GCs price was between 29 and 14 EUR/MWh between 2005 and 2016, while in 2017-2018 it went down to 6 EUR/MWh and this downward trend is estimated to continue [43].

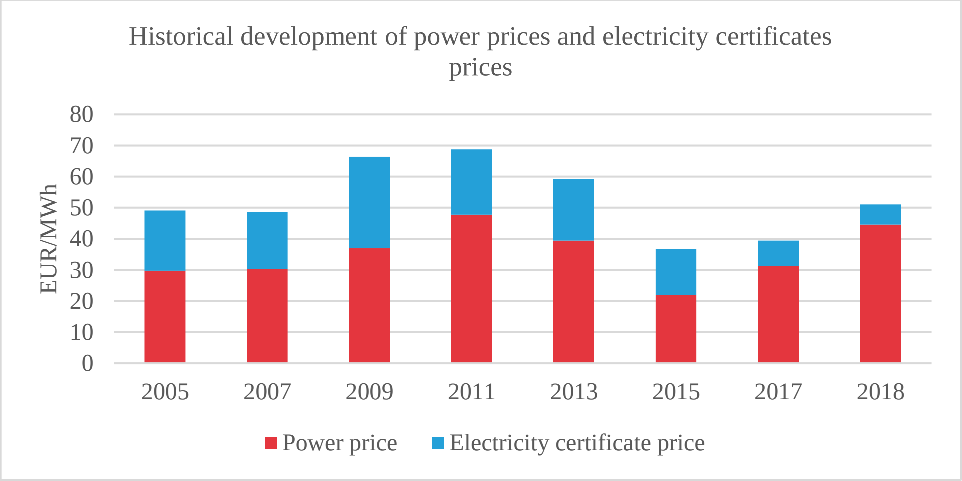


Figure 26: Historical development of power prices and electricity certificates prices [31] [44]

3.3.1.2 Other Business Models

- Merchant market risk vs corporate PPAs

Sweden and Norway use a certificate market-based support scheme. However, the importance of the certificate market income stream is declining and, as most likely it will remain at a competitive price level with other electricity sources, the power market exposure will represent a major risk factor for investors.

First, hydrology represents a first point of uncertainty because it determines wet or dry years and, therefore, high or low hydropower production. As a result, annual average prices fluctuations significantly impact the entire Nordic market. Furthermore, for the future, large volumes of wind are expected to enter the market due to favorable conditions and need to replace old nuclear power plants. However, despite high degree of hydro, fuel prices are of high importance for price level. An additional uncertainty factor is the area price risk. In fact, bidding zones are an important instrument for handling internal bottlenecks. However, both number of price zones and price zone definitions can change and have a big impact on the market for investors [45].

These uncertainty factors have contributed surely to the success of more secure contracts such as PPAs. In fact, in 2017 1.4 GW renewable capacity, of which 80% wind power projects, were signed in Europe by using these contracts, compared to 500 MW in 2014. The Nordic countries, moreover, have taken a key role in this market as, in 2018, Norway owned 36% of the total PPAs European wind capacity, while Sweden 29%. There are two main types of PPAs in Sweden:

- Baseload, when the consumer buys a fixed volume for a fixed price regardless of the actual production (e.g. 60-70% of the anticipated production of the specific wind park)
- As produced, when the consumer buys either the entire or parts of the production of the facility for a fixed price which is often lower than a baseload agreement but in addition the consumer and a balance responsible party (BRP) must agree upon the terms for when external electricity might be needed, and this is a service that the BRP charges a fee for. The producer delivers the electricity to the BRP who delivers the electricity to the final consumer while balancing the power either by buying external electricity or selling the surplus, depending on the production of the wind park and the consumer’s electricity consumption at that specific moment.

Wind energy developers are now often investment funds, European utilities with RES investment mandates, and traditional Nordic utilities that invest often team up with international investor. On the demand side, however, new players such Google and Facebook wish to realize new projects through PPAs often useful for supplying data centers

[24]. Furthermore, other common off takers are traditional power intensive industry, mainly aluminum smelters, which wish to connect PPAs to specific wind projects or change from price based PPAs pricing to cost based schemes.

Concerning ongoing agreements, Google is the major player in the PPAs Swedish market, and it has signed several agreements during the past 7 years. Specifically, in 2013, the company signed its first 10-years corporate PPA in Europe with OX2's including all output from the 72 MW Maevaara wind farm. Then, in 2014, Google signed another 10-year agreement with Eolus for 100% production of a group of wind plants with 59 MW installed capacity as well as a 12-year deal with BlackRock's project in Norway. Moreover, one of the largest aluminum companies worldwide Norsk Hydro is now dealing with a 19-year PPA for 20 years of 60% production of a Vattenfall wind farm project with 84 turbines which will be commissioned in 2021/2022 (Blakliden/Fabodberget). In addition, Facebook has signed a 15-year PPA agreement with Luxcara to purchase 100% of the electricity production from three Bjerkeim projects, located in Norway, to power their data centres in Odense and Lulea (Sweden) [35].

Producers and Investors	**Off-takers**
Investment funds: BLACKROCK Luxcara ARDIAN CREDIT SUISSE HgCapital Aquila Capital	New players with RES focus and data centers interest: Google f
European utilities with RES investment mandates: SWM Stadtwerke München ewz BKW	Traditional power intensive industry: Alcoa HYDRO
Traditional Nordic utilities teaming up with International or European investors: Eidsiva Statkraft TrønderEnergi	

Figure 27: PPA market actors in Sweden [45]

- PPAs success in the Nordic Countries

The Swedish goal of 100% renewable electricity generation by 2040 makes the country very attractive to investors that are interested to long-term investments such as electricity distribution or district heating companies. Moreover, a large share of existing production will reach its technical lifespan within 20-30 years and, therefore, a total of 105 TWh of accumulated annual production will need to be replaced. This change forward renewables means also that the power system needs to be prepared for higher variable production, flexibility, and transmission capacity. Furthermore, the decline of government-set FITs in favor of REC system means that corporate PPAs are becoming more important as a way for investors to take projects to financial close.

The first reason for these Nordic PPAs is the development of data centers which represent a power-hungry sector that could re-shape the electricity sector. In fact, the growth forecasts for internet traffic going via data centers are promising, especially in the Nordic area due to cool weather, which helps the centers to run smoothly and the predictability of the wind speed which guarantee a certain stable production. Therefore, giants like Amazon, Apple, eBay, Facebook, Google, or manufacturers such as Abheuser-Busch, General Motors, and Kimberly-Clark may own, or lease data centers powered by renewable energy as part of their green goals [46].

Second, the low power prices have encouraged developers to enable corporates to secure long-term low prices. This has been caused by a fossil fuels price fall followed by a growing renewable supply where developers have been forced to look at long-term PPAs to get certainty. For instance, Eurostat has reported that electricity prices for non-household consumers in the second half of 2017 were 0.15 EUR/kWh in Germany and Italy, compared to 0.06-0.07 EUR/kWh in Sweden, Finland, and Norway [32].

Third, the stability which these companies are looking for is also given by the predictable and reliable regulations framework which make the power market transparent. The governments in Norway and Sweden have cut energy taxes and backed the rollout of new even huge renewables projects. The Swedish regulatory certainty is evident, for instance, in the closure of Vattenfall's Ringhals 1 and 2 nuclear plants due to happen in 2020 and 2019 respectively [46].

Lastly, to encourage renewable projects, governments establish support regimes that can have a significant impact on the PPAs development. For instance, where such schemes provide electricity fixed price (such as under a FIT or Contract for Difference CfD model), developers are less incentivized to sign PPAs. On the other hand, electricity certificate or quota systems increase uptake of corporate PPAs through mandating utilities or corporate buyers, while subsidies such as Tax Credits increase PPAs through facilitating lower priced power. In Sweden, the support regime defines quotas placed on utilities to source a certain amount of electricity from renewable sources without government mandated controls to ensure that the certificates price is driven by market forces. When these quotas are applied to large consumers, they lead to a higher uptake of PPAs. The first years of the joint electricity certificate market between Sweden and Norway, from 2013 to 2015, were characterized by rising surpluses and falling prices due to rapid technological development coupled with a new type of investor with lower yield requirements. In the next phase, 2016-2017, 18 million electricity certificates were in excess, meaning a surplus fall but still also prices fall, therefore the link between balance and price was broken. From 2018, however, prices have increased and the Swedish landscape for corporate PPAs has become attractive for buyers looking towards long term sustainability [26].

To conclude, these reasons match in the Scandinavian countries the combination of certainty, cost, and buyer demand that put solid basement for secure PPAs.

3.3.2 Financing Mechanisms and Instruments at EU Level

All EU supports in Sweden are intended to help achieving:

- Smart growth: develop an economy based on knowledge and innovation
- Sustainable growth: promote a more resource-efficient, greener, and more competitive economy
- Inclusive growth (growth for all): stimulate an economy with a high level of employment and social and territorial cohesion.

Horizon 2020 program allocated 1.97 billion EUR to Sweden in 2018, aiming at the creation and improvement of clean energy technologies such as smart energy networks, tidal power, and energy storage. Specifically, Innovation and Networks Executive Agency (INEA) is running parts of *Horizon 2020* in the areas of transport and energy production, while the *Executive Agency for Small and Medium-sized Enterprises (SMEs) Program* is supporting innovation of energy efficient technologies and solutions for buildings, heating and cooling, and more [47].

EU helps also nuclear research and training activities by financing Sweden through *Euratom Research and Training Program*. In 2018, 123.6 million EUR were assigned for improving nuclear safety, security and radiation protection, notably to contribute to the long-term decarbonization of the energy system in a safe and efficient way.

Moreover, EU supports also SMEs to access finance in all phases of their lifecycle. *Competitiveness of Enterprises and SMEs Program* favors businesses have easier access to guarantees, loans, and equity capital [48].

3.3.3 New Investments and Key Actors

Foreign direct investments (FDIs) dominate new wind power projects in Sweden and only a few projects are financed by Swedish companies. One reason is that wind power investments yield a quite high rate of return even with current low revenue levels due to minimized economic risks secured by PPAs and long-term agreements. This lowers the uncertainties related to operating costs and future income and leaves the uncertainty only to electricity certificate system revenues. Another trend is that wind turbine suppliers such as Vestas, GE, and Enercon, also become investment partners in wind power projects [35].

The current investments list, which projects' commission date is in the period between 2017 and 2022 , shows that the number of wind turbines planned during this period is 2,018, which accounts for 8,193 MW and around 793 million EUR, considering only the published investments' data. Around 49% of the total country estimated annual electricity production comes from new wind power plants which will be built in the electricity area SE2. Then, the northeast electricity area SE1 will host 37% of the country annual electricity production, followed by SE3 with 11% and SE4 with 3% [39].

Concerning who is active in the wind energy market, the first name in the list is the world's fourth-largest wind turbine manufacturer Enercon which is involved in a total of 1.2 GW planned wind farms in Sweden, meaning around 19% of the country's new wind energy market. The German company has production facilities in Germany, Sweden, Brazil, India, Canada, Turkey and Portugal and, as of 2017, had installed more than 26,300 wind turbines all over the world, with a power generating capacity exceeding 43 GW. Enercon wind turbines have some special technical features which are generalized with the term gearless propulsion concept. In these gearless turbines, the hub with the rotor blades connects directly to the rotor of the ring generator (direct drive). The rotor unit rotates on a front and rear main bearing about a fixed axis. The speed of the rotor is transmitted directly to the high-pole synchronous generator, where the rotor rotates in the stator, differently. Rotation speed and the mechanical load changes over the service life are lower than geared systems. Thus, the large Enercon generators lead to high tower head masses, and construction and logistical challenges. Specifically, in Sweden, Enercon is involved in the big project Maximus (Markbygden Etapp 2) in the north area Norrbotten. This project aims at the construction of 201 turbines, with commission date 2021, the installed capacity 844 MW and estimated annual production 2.79 TWh. Moreover, Stor-Skalsjon is a 260 MW wind power plant commissioned for 2020 and located in the electricity area SE2. Lastly, Enercon is also involved in Erstrask plant which is part of the Markbygden project as Maximus. However, the German manufacturer company owns this wind farm by 25% with the investment company Renewable Infrastructure Group Limited, also known as TRIG [49] [50].

Secondly, CGN Europe Energy (CGNEE) is one of the subsidiaries of China General Nuclear Power Group involved in investments, development, construction, operation and management of project assets, but aiming also at becoming a major player in the renewable energy sector in Europe and Africa. CGNEE is investing in the construction of six wind farms located in electricity areas SE1 and SE2, with a total of 1.1 GW installed capacity which means 19% of the country's investments in wind industry commissioned between 2017 and 2022. Markbygden ETT, estimated to produce 2 TWh annually and part of the largest Swedish wind project Markbygden located in SE1, is owned by CGNEE by 75% and GE Wind by 25%. Moreover, five other wind farms in SE1 and SE2 were commissioned between 2018 and 2020 in collaboration with the French fashion company Hermes, amounting to about 801 MW installed capacity and 2.6 TWh estimated annual electricity production [51].

Another large investor in the current Swedish wind market is Luxcara, independent asset manager who provides institutional investors with access to equity and debt opportunities in the international renewable energy market. Luxcara owns only one but large project in Sweden which is part of the Markbygden farm, and it is called Onusberget (Markbygden etapp 3). This 142-turbines wind farm is one of the two sub-projects of the third and final stage of Markbygden, which is potentially the largest stage of the project and is located between the villages of Koler and Långträsk in the western parts of the wind park area [52].

Credit Suisse Energy Infrastructure Partners (CSEIP) is a relevant actor in the Swedish wind energy market as well. In Sweden, Credit Suisse acquired an 80% share in the Nysater project built at a site close to Sundsvall, central Sweden, and supposed to be completed by the end of 2021. Thus, the German utility E.ON holds the remaining 20% stake. Furthermore, in the same area, Credit Suisse owns also 80% of the Solberg wind farm through a power purchase agreement with the Swedish company Fortum. To summarize, CSEIP is involved in around 477 MW of wind installed capacity which is 8% of the new wind energy investment of the country [53].

Lastly, many other investors take smaller but still significant shares of the total new investments in the Swedish wind energy market. Companies of particular importance are the Dutch pension fund APG, the private investment house

Ardian, Green Investment Group, Prime Capital, Foresight Group, Stena Renewable, the independent investment and asset manager KGAL, BlackRock, Holmen Energy, and the 100% Swedish state-owned energy company Vattenfall.

3.3.4 Main Barriers

The development of the projects can be impacted by several problems impacting the permitting process.

- Opposition by residents to a proposed wind power plant in their local area (NIMBY). Northern part of Sweden, Norrland, is the least densely populated area and, therefore, the least problematic one. In general, an important factor for the population's positive attitude to wind turbines may be the opportunity for new jobs. Moreover, early involvement of the local community, early information, and openness to the views of the people who have to live with the wind power plants seems to be common success factors for local acceptance.
- The Swedish Armed Forces, in some cases, has objections due to disturb of their electronic equipment, danger caused by rotating blades near airports and artillery range, and disorder wireless communication in the air.
- The lead times for getting approval are 2-3 years, from submission of the application to final approval.
- Municipal Veto represents a key issue and, therefore, has been questioned due to difficult prediction for a project developer and impossibility to appeal against it as it is a political decision.
- Any citizen and several recognized non-governmental organization (NGOs) can appeal against the decision at a higher instance within three weeks of the announced decision. Even if in over 90% of the cases the appeals are rejected, this prolongs the time for the approval process.
- Reindeer herding, especially in the northern part of Sweden, is an issue for local acceptance.
- In Sweden there is no national standard for a bird- and species inventories. This makes it difficult for both the applicant and the CAB to draw the limit and level of details in the inventory [28].

According to SWEA, a roadmap should be followed in order not to break the political promises of reaching 100% renewable electricity by 2040. This roadmap includes:

- shorten and simplify permit process for new wind farms by involving local community, dealing with municipal limitations and veto power, and keeping required distance from armed forces
- introducing a «stop rule» within the GC system that limits volume and date so that when certain volume is met investor get a pre-specified time to complete investments,
- modernize grid and electricity system by eliminating bottlenecks in the north-south corridor
- abolish grid connection costs for offshore wind power projects [38].

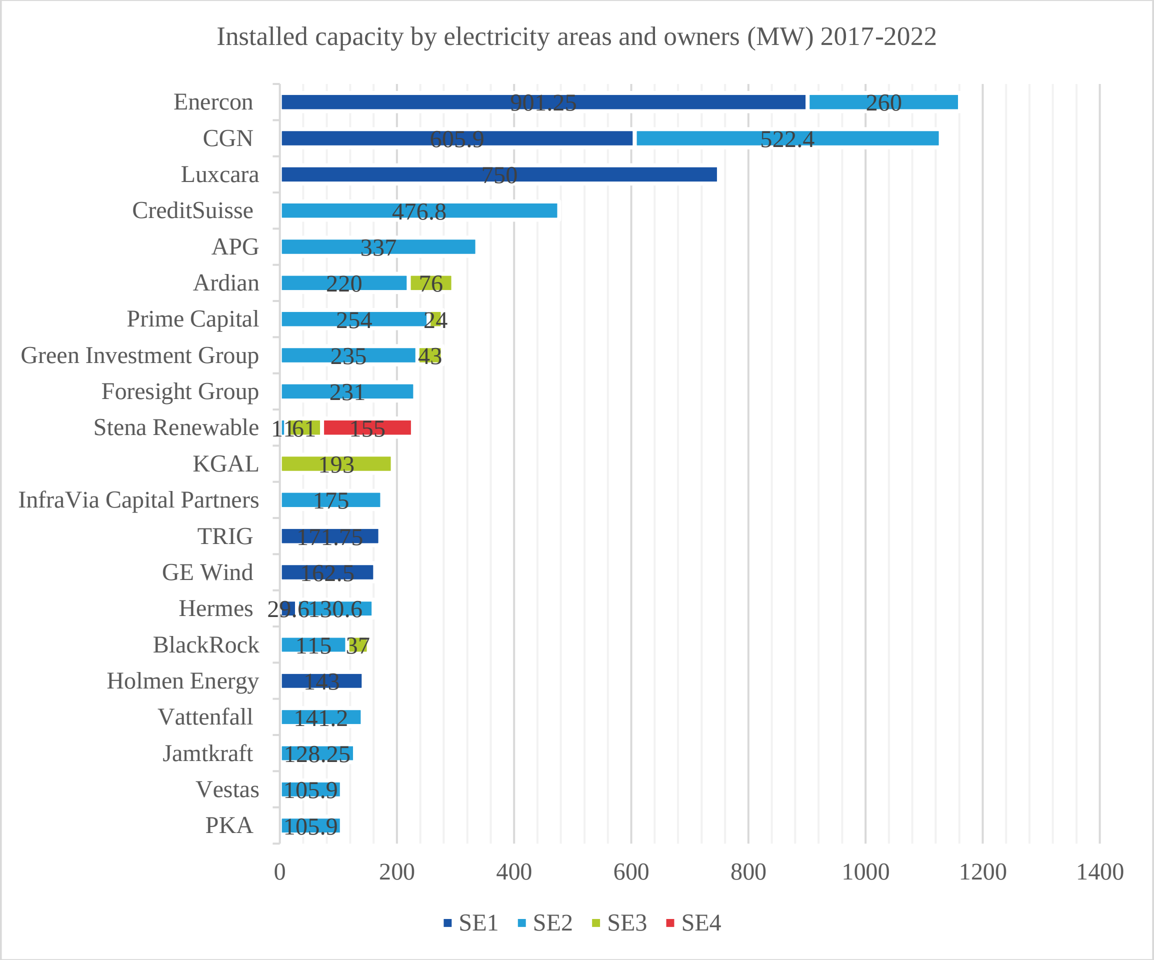


Figure 28: Key actors in wind energy market in Sweden and new investments installed capacity by bidding areas [39]

4. Poland

4.1 Country Overview

4.1.1 Energy Insights

4.1.1.1 Country Overview

Poland is a Central European country neighboring with Germany, the Czech and Slovak republics, Ukraine, Belarus, Lithuania, the Russian Kaliningrad Oblast exclave, and the Baltic Sea. Its total area of 312,679 square kilometers and its population of 38.36 million inhabitants (2019) make Poland the ninth-largest country in Europe and the sixth most populous member state of the European Union [54].

Poland is a democracy with a president, a Council of Ministers representing the government, and a prime minister. Administratively, the country is divided into 16 provinces called “voivodeships”, which are subdivided into counties called “powiats”, and these are further divided into municipalities called “gminas”.

The country’s economy has shown its strength by being resilient to the 2009 world economic and financial crisis and experiencing a relevant upswing in 2010-2011. Moreover, since 2014 the Polish economic activities accelerated as private consumption and investment replaced external trade as the main growth engine. In 2018, the real GDP was around 503.6 billion EUR, while the GDP growth was 4.10% YoY and the unemployment rate 2.9% [54].

The internal national investment has been low compared to similar per capita income countries, while, due to public investment supported by EU funds, Poland has significantly upgraded its infrastructure networks over the last decade. However, the main environmental problem is poor air quality which is related to old and inefficient household heating infrastructure based on coal, and heavy reliance on aged car fleet.

Population (million)	37.98
GDP (billion EUR)	503.6
GDP growth rate	5.15%
Electricity demand (TWh)	165.6
Electricity demand pro-capita (MWh)	4.3

Table 3: Poland key data (2018) [51]

4.1.1.2 Primary Energy and Electricity Supply

Poland has the largest share of coal in TPES among the IEA countries and the sixth-largest share of fossil fuels. Moreover, it is the largest coal producer and consumer in the EU. In fact, in 2018, 133 TWh out of 169 TWh of electricity production was produced by coal, meaning that coal covered 79% of energy production and 51% of TPES. Therefore, the share of installed capacity in lignite and hard coal is still high, even if it decreased slightly from 72% in 2017 to 70% at the end of 2018. More than 70% of the coal is used for heat and power generation, and specifically coal provides 81% of the electricity and 86% of the heat produced in the country. In 2018, oil was the second-largest energy source with 24% of the TPES, mostly imported. Then, natural gas’s TPES share was 15% of which one-third was produced domestically and the remaining part was imported [55].

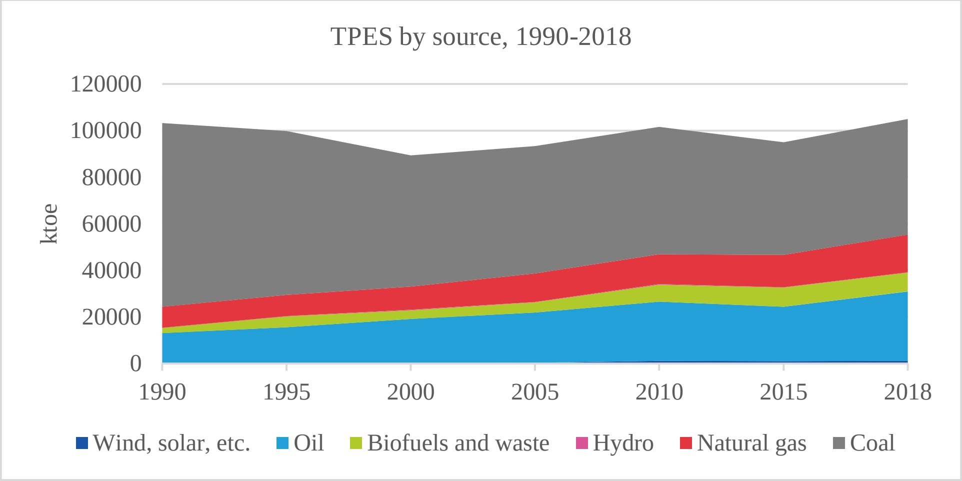


Figure 29: Historical development of TPES by source in Poland [56]

Even if renewable capacities such as biomass, waste, and wind power have been increasing among the last years, electricity generation is still relevantly dominated by coal. In 2018, renewable energy sources provided 10% of both TPES and electricity generation. The country has started a slow transition from coal towards more oil, gas and renewable. In fact, coal production has more than halved its peak of 128 Mtoe, reached in 1978, to 48 Mtoe of 2018. The biggest electricity production changes experienced in 2018 as compared to 2017 were the lignite production decrease due to the shutdown of the Adamów power plant, the onshore power plants production decrease related to unfavorable legal regulations, and the increase of coal and gas power plants after the completion of the Kozienice plant and the Plock combined heat and power (CHP) plant. Even if Poland has no nuclear power plants, two reactors, with total installed capacity of 6 GW, were planned to be built. To conclude, in 2018, electricity production remained at the 2017 level and the growing demand was covered by imports which volume increased two-and-half-fold [54].

To summarize, a coal phase-out announcement is unlikely in the short term, as 90% of the country's coal-fired capacity is held by state-controlled interests, compared to just 10% of the country's wind assets.

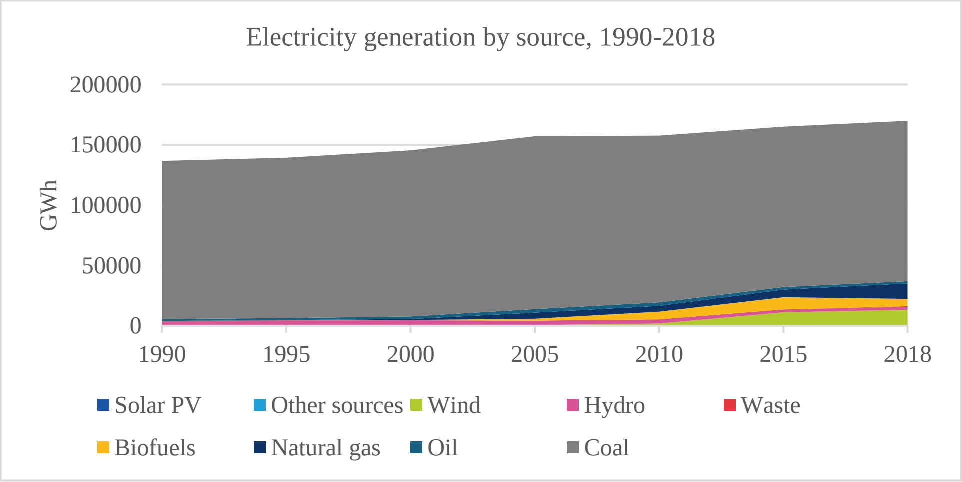


Figure 30: Historical development of electricity generation by source in Poland [56]

4.1.1.3 Energy Consumption

Among sectors, transport has experienced a large increase in its consumption recently. In 2018, transportation accounted for 29% of TFC, which key source is oil. Secondly, the residential sector accounted for 27% of TFC in 2018 and its main source was coal, which was followed by heat. In fact, Poland has one of the largest district-heating markets in Europe, providing one-fifth of TFC in households. Then, industry has decreased its share of TFC among the last years, reaching 21%. The following sectors in terms of TFC share are the commercial sector, non-energy use, and agriculture and forestry [54].

The electricity final consumption has increased by 32.44%, from 1990 to 2018, reaching 165.55 TWh. The main consumption has always come from industry sector which is followed by commercial and public services, residential sector, agriculture, and transport.

In the period between 2009 and 2018, a demand growth of 1.6% was experienced. However, GDP is growing faster than electricity demand. The annual maximum peak power demand in the Polish system is also growing and, in 2018, it reached a new record level of 26.45 GW. In fact, the problem of rapidly growing peak power demand in summer is worsening [55].

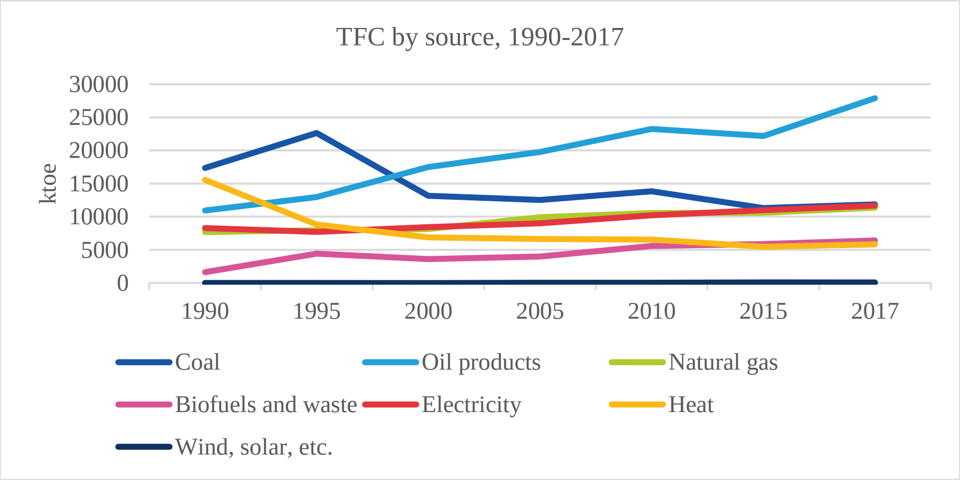


Figure 31: Historical development of TFC by source in Poland [56]

4.1.1.4 Renewable Energy Sources Evolution

Poland has achieved significant progress in the deployment of renewable energy sources in recent years. Nonetheless, Poland has a lower than average share of renewables in TPES (compared to 14% in IEA countries). Indeed, even if the share of RES in TPES doubled from 5% in 2005 to 10% in 2015, a down trend showing the lowest production and share of RES in the mix after 2014 was noted in 2018. Specifically, the share of RES in electricity production decreased from 11% in 2017 to 10% in 2018, of which 12.8 TWh (7.6%) was produced by onshore wind, 3.8 TWh (2.3%) was produced by using biomass, and the remaining 3% was produced by hydro, biomass cofiring, biogas, and photovoltaics [54].

Until 2007, the main renewable energy source was hydro power. Subsequently, biofuels and waste grew and became the largest renewable source in terms of TPES and TFC, with 8.2 Mtoe of TPES in 2018 which corresponds to 85% increase since 2005. In recent years, there has been another shift in renewable power production, as a result of the rapid expansion of wind energy. In fact, the largest share in terms of electricity production has newly become wind power. It increased by 550% from 2010 to 2015, reaching 12.8 TWh in 2018, corresponding to 7.6% of total generation. However, in 2018 onshore wind energy decreased its development trend in the country due to strict legal regulations. Then, hydro power became the third-largest renewable with a production stable around 2.39 TWh in 2018. Lastly, solar energy’s generation was around 0.301 TWh in 2018 which, even if it is growing over the recent years, remains a small share. To summarize, among RES, 5 GW of onshore wind has been installed between 2010 and 2018, while solar capacity and especially PV has tripled to 560 MW in 2016-2018 [57] [55].

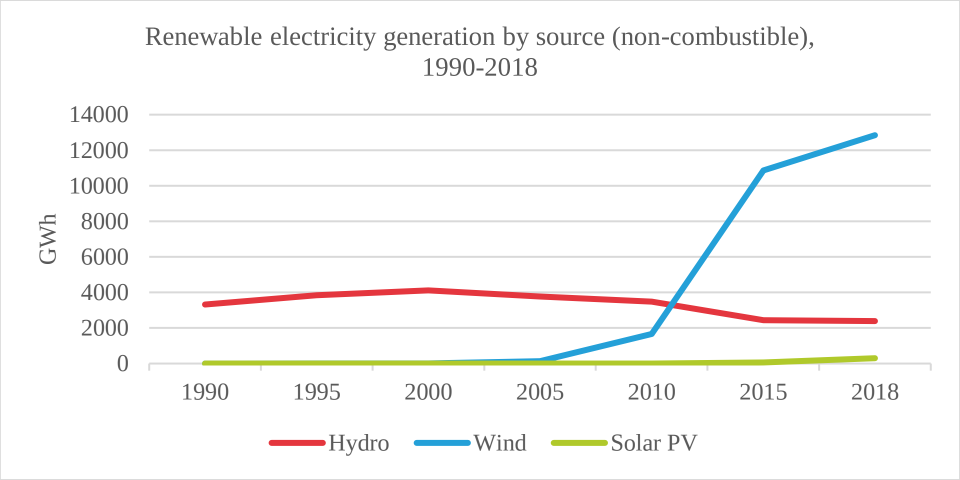


Figure 32: Historical development of renewable electricity generation by source in Poland [56]

According to the country's energy policy called *Poland National Energy Climate Plan (NECP)* and revised in November 2019, Polish renewable expansion will be mostly based on PV solar and offshore wind technologies. In 2030 wind technology is expected to dominate the RES growth, but significant contribution would arrive from solar energy as well. In detail, PV solar capacity is expected to massively increase reaching 5 GW by 2025 and 16 GW in 2040, while offshore wind is expected to begin playing a role in the power mix from 2026, accounting for 6 GW by 2030 and 8 GW by 2040.

According to *IRENA Remap 2030* estimation [58], the deployment of solar PV could follow the trend in Germany but with some delay due to limited solar potential and economic incentives. Assuming an annual installation rate of 1% of the total peak demand for solar PV, a total capacity of 5 GW could be installed by 2030. The solar plants could be evenly distributed throughout the country since average solar irradiation is almost uniform, apart for the Northern Poland which could require more renewable electricity generation due to lack of coal power plants. Moreover, the new *Renewable Energy Act* in Poland supports smaller solar PV installations associated with distributed rooftop installations as well as auction system gives financial helps for the construction of larger installations.

Furthermore, since domestic production of fossil fuels is insufficient to satisfy energy demand of Polish citizens, big electricity production from easily accessible, inexhaustible, and secure sources, such as offshore wind, is of key importance in order to limit the imports of fuels from abroad. In a vision of an energy transition, offshore wind enjoys the highest public acceptance among all electricity production technologies, and moreover as turbine's efficiency increases, wind farms become increasingly less expensive and therefore competitive. Moreover, Poland holds full jurisdiction over the territorial sea and partial jurisdiction over the Exclusive Economic Zone (EEZ) which is divided with Sweden, Russia, Denmark, and Germany. From the spatial development plan for maritime areas, the PWEA estimated that the potential of the Polish EEZ, counting approximately 2.5 thousand square kilometers, reaches at least 10-12 GW, meaning around 50 TWh per year which is one third of today's annual electricity consumption of the country. Overall, offshore wind energy could bring innovation for the entire Polish economy. In fact, 6 GW of capacity, which are supposed to be almost reached in 2030, would support 77 thousand jobs, 60 billion PLN of added GDP, and 15 billion PLN of budget revenues from taxes and fees. To conclude, in order to move the entire offshore wind farm construction program forward, the offshore wind farm locations in the spatial development plan for the Baltic Sea must be guaranteed and an appropriate support scheme with a defined time horizon is needed. In the recent January 2020, indeed, the Polish Government has presented a draft law on offshore wind to provide a framework for the development of 4.6 GW, proposing a detailed remuneration scheme. Moreover, the country's largest generator Polska Grupa Energetyczna (PGE) has secured environmental permits for almost two offshore wind projects in the Baltic Sea accounting for a total capacity of 2.5 MW [59].

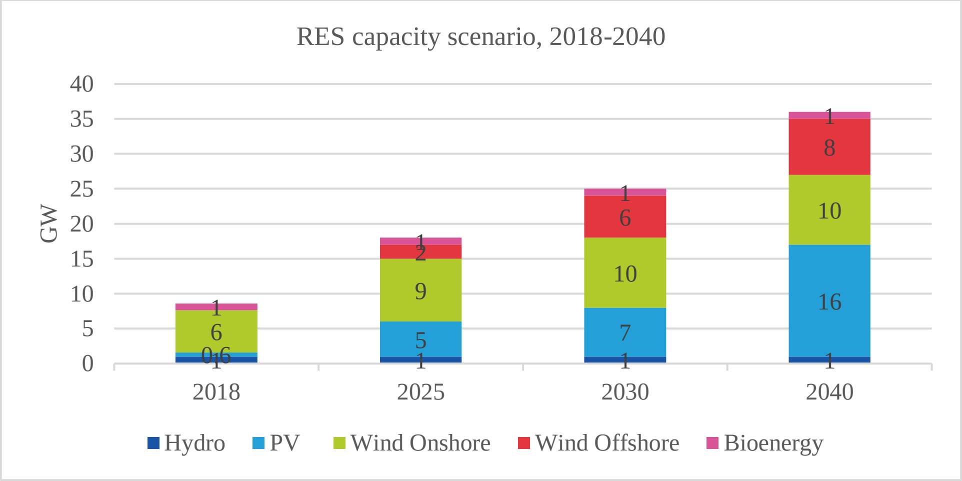


Figure 33: Forecast of RES capacity in Poland by technology [60]

4.1.2 Electricity Market

4.1.2.1 Electricity Network

Since 1997, the Polish electricity generation and retail has been acted by state-owned large companies. In 2018, the three largest generators held in total almost 2/3 of installed capacities and were responsible for almost 70% of domestic electricity production:

- PGE is the largest player in the Polish electricity market, selling 66.05 TWh of electricity in 2018. The State Treasury owns 57.39% of the company while the remaining shares are traded on the Warsaw Stock Exchange.
- Enea Group expanded its production in 2018, reaching 26.11 TWh of electricity generation due to the acquisition of Engie's 1.9 GW Polianec coal-fired power plant and the commissioning of the 1,075 MW Kozienice coal-fired plant in late 2017. Enea is owned by the State Treasury for 51.51%.
- TAURON Group, created after the merger of the generator PAK with the Stalowa Wola power plant, Enion, and Energia-Pro distributors, supplied over 15 TWh of electricity in 2018. The company is owned by 30.06% by the State Treasury and controls most of the Polish hard coal resources.

To summarize, in 2018, 69.7% of production belonged to these three companies. In detail, 43% of the generation market was held by PGE, 10% by TAURON Group, 17% by Enea, 4% by PAK, 4% by ORLEN, and 3% by PGNiG [61].

After generation, the country disposes of a transmission network which is linked with the neighboring countries enabling a synchronous operation with the interconnected countries such as Sweden, Germany, the Czech Republic, Slovakia, Lithuania, Ukraine, and Belarus since 2015. Poland has one TSO which is the fully state-owned Polskie Sieci Elektroenergetyczne S.A. (PSE). PSE manages a transmission network of 14,195 km and is responsible for approving access to the transmission system and use of system tariffs. Also, the ancillary services are part of the TSO's functions aiming at guaranteeing system security.

Then, electricity distribution is performed by 176 DSOs supplying electricity to around 16.8 million customers. These include five entities directly connected to the transmission grid who legally unbundled from former distribution companies and 171 DSOs which are not obliged to be legally separated. Tariffs are set by the DSOs and approved by the Energy Regulatory Office (ERO). No cross-subsidies of distribution costs are applied, and tariffs are composed of a fixed and a variable cost element [54].

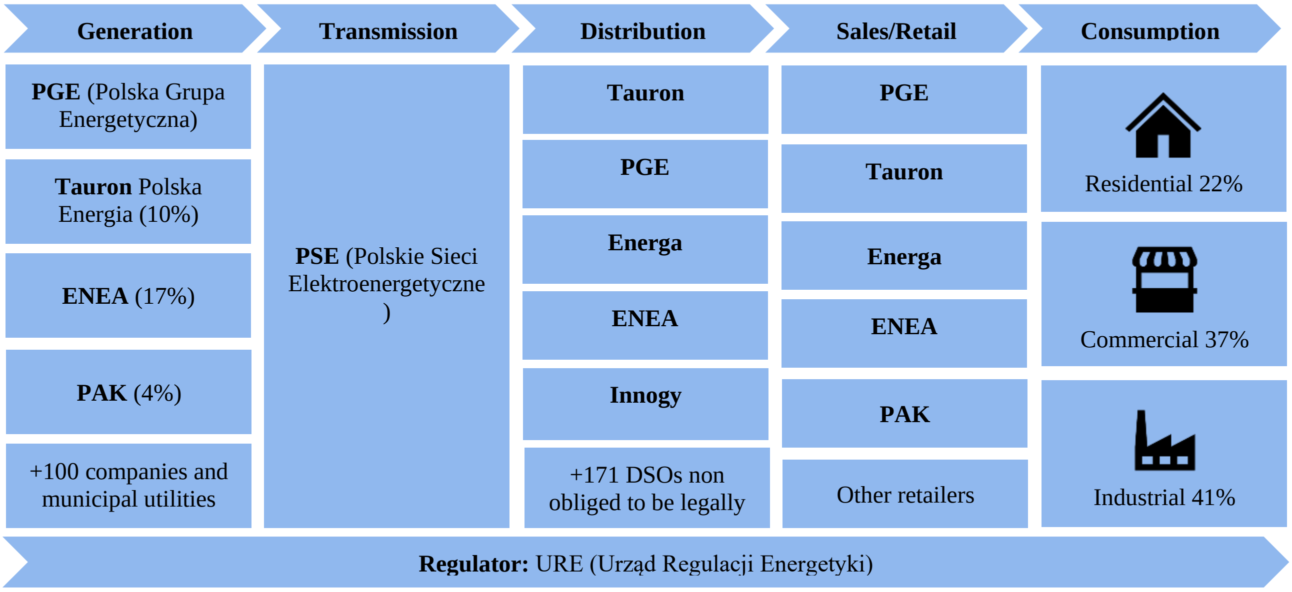


Figure 34: Power market players in Poland [62]

Poland is generally a net exporter. Since 2000, exports, mainly to Czech Republic and Slovakia, have ranged between 8-16 TWh. On the other hands, since 2000, imports had ranged 3-14 TWh of which 55% came from Germany, 24% by Sweden, and 12% by Lithuania.

The Baltic region holds big wind energy potential and, therefore, wind capacity could grow by 30-45 GW by 2030. High penetrations of wind power require the TSO to balance VRE especially at night when load on the system is low by using demand response, interconnections, and peaking technologies. In fact, more wind into the system makes net demand drop to low levels which could not be covered easily by inflexible coal-fired capacity given that a substantial portion of coal capacity cannot be shut off at night as it would not be able to ramp up to meet the next day's demands.

Although improvements have been made to modernize Polish energy infrastructure, some other big investments are necessary to ensure a sustainable supply of energy, reduce carbon-powered plants, and increase use of RES. At present, Poland is one of the least connected EU member states in terms of electricity infrastructure, therefore it needs to extend the electricity transmission grid and strengthen electricity security. Indeed, operators of distribution systems plan investments especially in northern Poland aiming at amplifying connection to the grid, improving grid access to renewable sources, and increasing supply reliability including interconnections with neighboring countries. These will allow exchange of at least 25% of electricity used in Poland by 2030. An interesting project is the Baltic Ring which means establishing a large synchronized energy system connecting Norway, Sweden, Finland, Denmark, Germany, Poland, Lithuania, Latvia, and Estonia. Then, the European Supergrid is another large-scale project that may facilitate the deployment of fluctuating renewable power sources by balancing in national grid. In conclusion, the transition of national power markets to international tendency, due to improved cross-border interconnections and initiates like the Baltic Ring or the Supergrid may have economic consequences for renewable energy prospects in Poland [58].

Figure 35: Cross-border interconnections in the Polish energy system [58]

4.1.2.2 Wholesale market

The power exchange managed by Towarowa Gielda Energii (TGE) S.A., the Polish Power Exchange (POLPX), is responsible for the sales and purchases of electricity, which are conducted also in the auction system. The markets offered by TGE are intraday market, day-ahead market and commodity forward instruments market with physical delivery (CFIM). The CFIM owns the largest volume of trade. Electricity trading on the TGE market has been steadily growing since 2010. In 2011, the EU Regulation on wholesale energy market integrity and transparency entered into force and, therefore, new obligations were imposed on national regulatory authorities regarding wholesale energy market monitoring and market manipulation. In 2015, the Financial Supervision Authority granted TGE a license to operate a financial market allowing TGE to offer new products for hedging risk in the electricity market [54].

Wholesale power prices in Poland are relatively high and reached the highest point in 2018 with an average price of 49.4 EUR/MWh, in contrast to the EU average which has been steadily decreasing since 2012 with the addition of zero-marginal cost renewables. Poland became a net electricity importer in 2016, as the country's aging coal fleet is inefficient, and the cost of coal generation increases due to higher carbon prices. Onshore wind technology remains expensive in Poland in the range between 64 and 50 EUR/MWh, the second highest in Europe [62].

4.1.3 Country's Policy Objectives

The Polish energy policies are driven significantly by EU directives and requirements. Indeed, in 2009, since the European Parliament imposed mandatory 2020 targets for Poland called EU 20/20/20 goals, the first *National Renewable Energy Action Plan (NREAP)* for Poland was submitted aiming at:

- limit GHG emissions in the sectors not covered by the *EU Emissions Trading Scheme (EU ETS)* to 14% above 2005 levels,
- reduce energy consumption by 20% of the projected 2020 levels,
- increase the share of RES to 15% of the gross final energy consumption including an increase in the use of renewables in transport to 10%.

Moreover, another Poland's policy objective was energy security. The country aimed at reducing the dependence on imports from Russia, given that historically most of the oil and natural gas imports came from Russia. The diversification of energy sources, both in terms of fuel and technology, and the use of existing domestic energy resources were considered of first interest. Coal was expected to remain the main fuel in the medium term; however, the support went mainly to the development of cleaner technologies and the internal production of liquid and gaseous fuels from coal [54].

However, since Poland is not expected to reach its 2020 RES Target, the targets have been revised in November 2019 and the *Energy Policy of Poland for 2040 (EPP2040)* draft energy policy has been created. Specifically, Poland updated its energy policy targets to:

- Reduction of coal's share in its generation mix from 80% to 60% in 2030
- Raise of the share of renewables to 21% in gross final energy consumption in 2030
- Introduction of the country's first nuclear capacity by 2033
- Improvement in energy-efficiency by 23% by 2030 (in relation to 2007 levels)
- Reduction of CO_2 emissions by 30% by 2030 (in relation to 1990 levels)

Overall, the draft of the *Energy Policy of Poland for 2040 (EPP2040)* sets strategic directions subdivided into actions regarding optimal use of energy resources, development of power capacity and transmission infrastructure, supply diversification, development of energy markets, launch of nuclear energy, development of renewable energy sources, heating and cogeneration, and energy efficiency improving [60].

The biggest change to the revised draft is the decision to withdraw from a phase out of onshore wind capacity. The previous draft policy had installed onshore wind capacity falling from a high of 7 GW in 2025 to just 0.8 GW in 2040. The revised draft, on the contrary, forecasts capacity reaching a high of 9.497 GW in 2020 and increasing slightly to 9.761 GW in 2040. The RES growth is to be achieved through the rapidly developing PV market and the construction of the first offshore wind farms in the Polish part of the Baltic Sea. However, both capacity estimates for 2040 have been revised downwards, PV from 20 GW to 16 GW and offshore from 10 GW to 8 GW. Relevant further development in order to meet the new goals will be energy storage and more gas-fired plant [63].

4.2 Onshore Wind Energy

4.2.1 Wind Plant Current Installations

Even though, the Polish energy sector is traditionally based on coal, wind energy is leader among the country's renewable energy sources and experienced the most dynamic development among them since 2005. Specifically, in 2019 wind power plants installed capacity was 5.92 GW, while electricity produced by wind was 12.8 TWh in 2018, amounting to 84.3% of the RES production, but only 7.7% of the total country's production. Currently, the Zachodniopomorskie province (West Pomeranian) benefits from Baltic Sea winds and, therefore leads the country in terms of wind farm capacity with almost 1.5 GW. Then, Wielkopolskie (Greater Poland) accounts for 687 MW and Pomorskie (Pomeranian) for 685 MW [64].

	2015	**2016**	**2017**	**2018**
Wind installed capacity (GW)	4.58	5.81	5.85	5.88
Wind electricity production (TWh)	10.86	12.59	14.91	12.84

Table 4: Wind power numbers in Poland [61] [60]

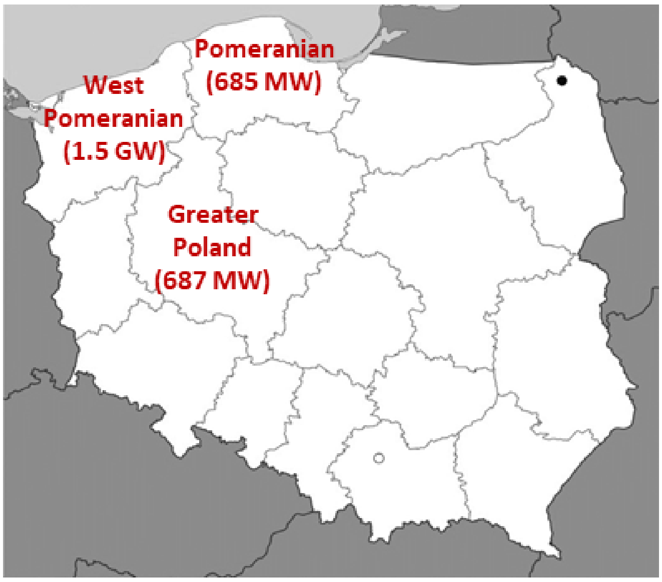


Figure 36: Provinces benefitting from Baltic Sea winds and wind installed capacity [64]

The current picture of the wind sector has been impacted by a phase of stagnation in which projects ready to be built were waiting for the possibility to be completed. In fact, the year 2016 was undoubtedly the worst time for wind power in all its history in Poland. One of the main reasons for halting the development of this industry was the entry into force of the Wind Farm Act, which introduced the 10H rule and banned the erection of modern wind turbines in over 99% of the country's area. Subsequently, the fall of green certificates prices and lack of auctions for wind farms with a capacity above 1 MW in 2016 were other factors impacting strongly the wind industry development [65].

However, onshore wind power had a relevant number of auctions taking place in December 2019. Poland held the largest European dedicated onshore wind farm auctions ever with a total volume of 2.2 GW. In fact, the energy transition towards renewable, especially wind energy, is supported by the fact that the current onshore wind LCOE is lower than the current coal LCOE, meaning that the weighted average bidden price is below the market price [8].

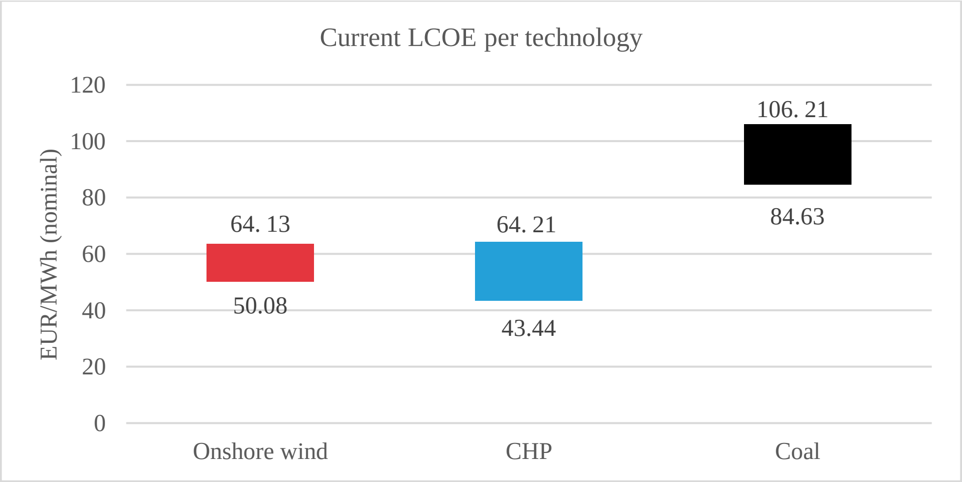


Figure 37: Current LCOE in Poland by technology [37]

4.2.2 “The Wind Farm Act”

In 2016, a new bill entered into force introducing changes to the *Act on Renewable Energy Sources (Amending Act)* and an *Act on Investments in Wind Power Plants (Wind Farm Act)*. Since its introduction, the *Wind Farm Act* has provided significant restrictions in terms of location, development and operation of wind farm projects on the territory of Poland.

First, the Act introduced a minimum distance requirement between the wind power plant and residential buildings, or nature protected areas (natural parks, nature reserves, landscape parks, Natura 2000 parks) and Forest Promotional Complexes (LKP). This distance was defined as 10 times the height of the wind power plant, calculated from ground level to tip height, which is the highest point of the wind turbines including the rotor. With respect to existing wind farms, no modernizations, including increasing their operating parameters, are to be allowed and, in addition, the distance requirement does not apply to the projects under development with building permits already secured. This 10H rule, which imposes a minimum distance of approximately 1.5-2 km, makes the Polish setbacks limits the strictest in Europe.

Second, under the Wind Farm Act, the new wind farms may only be located on the basis of local master plans, which are adopted in the form of resolution of the local authorities, rather than on the basis of zoning permits.

Third, the real estate tax (RET) regulations, which is a local tax payable by an owner of a land or a structure to the municipality in which the land or structure is located, was decided to be determined by the council of each municipality independently, but without exceeding the maximum values set out in the Act on Local Taxes and Fees [64].

4.2.3 Wind Energy Scenarios

Wind power in Poland has an enormous potential both onshore and offshore. On the one hand, a growing capacity of onshore projects is ready to take part in auctions and existing onshore wind farms are planned to be comprehensively repowered. On the other hand, approximately 6 GW of offshore wind power plants are estimated to be built by 2030 in the Polish Baltic Sea. Nonetheless, the development of wind energy technologies still depends on decisions made at national level such as a stable regulatory framework and the removal of administrative barriers to new investments. The EPP 2040, presented in 2018, provides legislative solutions limiting further onshore wind development.

Two wind energy development scenarios, differing in onshore investments in the 2040 perspective, can be outlined, according to the Polish Wind Energy Association (PWEA).

- The first scenario is called “Stagnation scenario”. It is based on *EPP 2040* assumptions and governmental declarations which assume no increase in installed capacity after 2025. This scenario assumes only replacement investments when 10 GW of onshore wind is reached.
- Second, the “Growth scenario” was outlined coherently with the European Union climate policies which assume deep emission reductions or climate neutrality of the entire economy by mid-21st century. It considers capacity increase after 2025 and substantial growth in the 2030s.

In the 2020-2025 period, both analyzed scenarios estimate equal onshore installed capacity growth from 6.3 GW to 10 GW. Subsequently, from 2026, in the stagnation scenario capacity remains unchanged at 10 GW, whereas in the growth scenario it increases to 12.5 GW in 2030, 17.5 GW in 2035, and 24 GW in 2040 [65].

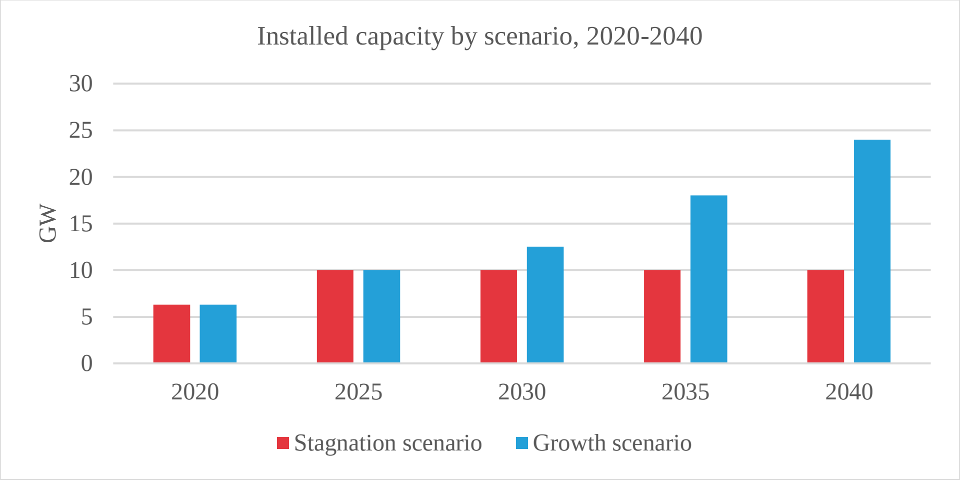


Figure 38: Forecasted installed capacity in Poland by scenario [65]

Subsequently, with reference to the updated *EPP 2040* consistent with the *2030 National Energy and Climate Plan (NECP)* required by the European Commission, some remarks concerning the wind energy sector development have been highlighted. Considering, the total economic potential of onshore wind investments adjusted for soil valuation class as 38 GW, thus the 2030 market potential has been calculated with regard to the possible exploitation of the economic potential given existing and expected market determinants. In the short term, wind projects are expected to be implemented under the auction scheme, and therefore approximately 3.5 GW. Assuming that restrictive regulations limiting available sites, such as the 10H rule, will be modified, in 2030 the minimum market potential scenario accounts for 11 GW, while in the maximum scenario 22 GW may be reached. In accordance with WiseEurope forecasts [65], it is estimated that wind energy development may bring up to 42,000 new jobs in 2040. In addition to the number of onshore wind dependent jobs, local content in the supply chain and consolidation of the position of Polish plants on the international market needs to be considered.

To conclude, according to PWEA [66], the share of RES could increase to the 25% in final energy consumption in 2030, safe operation of the power system could be enabled, and opportunity for the Polish power system could be created based on cost-effective, environmentally-friendly, and innovative solutions. The substantial estimated decrease of electricity prices, in 2040, to 79.4 EUR/MWh as well as the reduction of CO_2 emissions to 282 kg/MWh suggest that access to inexpensive and price-stable electricity from RES is crucial for further growth of the Polish economy and sustainability.

4.2.4 Wind Power Permitting and Grid Connection

Before building a wind farm, the project developer needs to obtain permits from the local authorities and, subsequently, grid connection authorization.

Firstly, for what concerns permitting phase, procedures to follow to obtain all the necessary permits in Poland are unclear. The investor, in fact, is obliged to contact individually a large number of authorities, such as bodies responsible for grid connection, spatial planning, and environmental concerns. Their lack of coordination and cooperation result in confusion for the investor and, therefore, delays.

Second, when applying for grid connection, the Polish distribution companies do not provide the developer with a specific deadline by which they will be granted grid access. This makes it uncertain as to when the wind plant will be operational. Moreover, the national grid has a limited capacity and, since developers do not receive information in terms of grid capacity available and are unsure of their interconnection acquisition, many apply in advance for more capacity than actually needed in order to anticipate potential land gains for the project. This leads to the so-called “queue for the connection point", in which DSOs treat all applications in the same way without verifying the feasibility of capacity applied [67].

4.3 Supports and Challenges for Future Development

4.3.1 Financing Mechanisms and Instruments at National Level

4.3.1.1 Legal Framework

- Contracts for Difference (CfD)

Since 2005, the Polish parliament enacted the *Act on Renewable Energy Source (RES Act)* in which mandatory quotas for utilities and green certificates issued by the ERO have been used to encourage the production and use of RES. Moreover, on 1 July 2016, the *New Act on Renewable Energy Sources (New RES Act)* entered into force. For existing renewable energy installations, the green certificate system was maintained together with the opportunity to change to the auction-based mechanism through specific tenders. Thus, for new installations that started generating electricity on or after 1 July 2016, the *RES Act* introduced a new auction-based subsidy instrument:

- a guaranteed price of electricity in the form of either auction or FIT for small-scale installations
- auction FIP for larger RES installations replacing the quota system, called CfD, where both FIT and FIP would be awarded in auctions.

There were also separate types of support for renewable energy prosumers as well as so-called "energy clusters" or "energy co-operatives" using renewable energy sources.

In this system, for each auction the government orders a certain amount of renewable energy per basket, which are groups in which technologies and installations sizes are divided. When the auction is organized, project developers submit a bid with a price per unit of electricity at which they are able to sell the electricity. This price has to be lower than a maximum bid price set and published previously by the Minister of Energy, which is called "reference price". Subsequently, the government evaluates the offers in terms of the price and other criteria such as grid connection conditions, building permit, timetable, and signs a power purchasing agreement with the bidder who offers the lowest price to produce the ordered energy quantity. Once the auction session closes, the ERO President immediately informs the public about the auction results, the minimum and maximum price in PLN/MWh for which the electricity from RES has been sold by auction, and the total amount in MWh and value in PLN of the electricity from RES sold by auction, broken down by consecutive calendar years [68].

Basket	Technology	Size	
I	Power plants using non-agricultural biogas, biomass, biofuels, waste	≤1MW	>1MW
II	Hydropower, geothermal energy, offshore wind energy	≤1MW	>1MW
III	Agricultural biogas installations	≤1MW	>1MW
IV	Onshore wind and solar PV installations	≤1MW	>1MW
V	RES hybrid installations	≤1MW	>1MW

Table 5: Polish auctions' baskets

Thus, the mechanism of support is created by the fact that once producers have constructed their project and start to generate electricity, they are paid, by the state-owned corporation Zarządca Rozliczeń S.A., the difference between the "bidden price", determined in the auction, and the market price per unit of green electricity sold. Precisely, the compensation is settled in a monthly basis calculated as product of the electricity generated and sold within each day of given month and daily difference between the price agreed in the auction and the daily arithmetic average of all weighted average hourly electricity prices quoted at the commodity exchange in the next day and two days after the transaction date exchange session. However, there is no compensation if the average market price quoted on the day-ahead market is negative for at least six subsequent hours, and if in the case the market price is higher that the strike price in a given month, this should be settled with future negative balance. As a rule, the support period for a given RES installation is 15 years with a long stop date for the support scheme set by the *RES Act* which is currently the 30 June 2039. However, before the auction is held, the Minister of Energy may reduce the maximum period for FIT or FIP support in such a year's auctions and the reduced support periods is applied only to those installations that win auctions in the year for which the reduced period was set [68].

The increasing interest on auction schemes is driven by their ability to be flexible in their design, transparent in showing the real price of the product being auctioned, secure in prices and quantities as they are determined before the construction of new projects, and liable to investors since it minimizes the likelihood that its remuneration will be challenged in the future as the market and policy landscapes change. Despite its strengths, this system could be a barrier for small players whose transaction costs are high in comparison to the total anticipated profits and, moreover, early implementations of auctions might bring the risk of underbidding and delays in the construction of new capacity [69].

To summarize, in Poland projects that started producing electricity after January 2016 were no longer be eligible for green certificates, and depending on their size, may have applied for a premium by means of an auction mechanism. The ERO is responsible for the supervision of the auctions and the winners are chosen based on the outcome of a prequalification procedure and then an auction procedure.

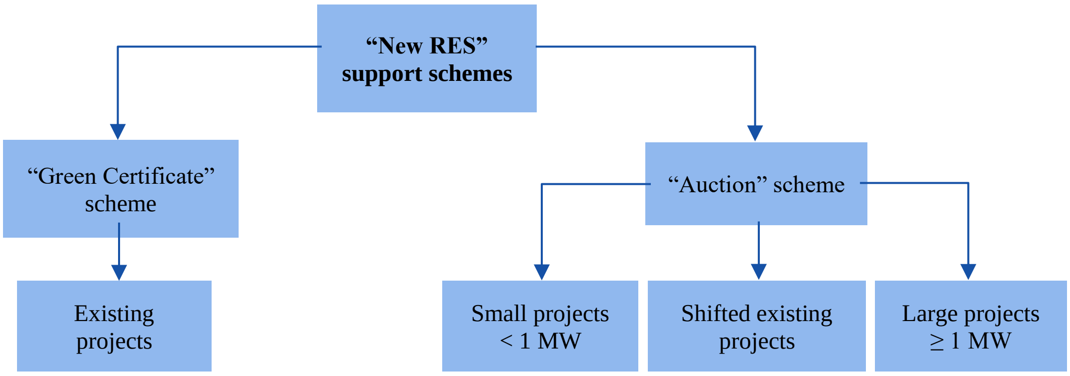


Figure 39: Current support schemes in Poland

- Auction System in Poland

Since 2016, when the *Amending Act on Renewable Energy Sources* became effective, significant modifications occurred in the support system. Auctions were divided into baskets based on technologies, efficiency of the installation (capacity factor below and above 4,000 MWh/MW/year) and capacities of installations (below and above 1 MW). Furthermore, the producers who made a shift from the certificates of origin scheme to the new one will take part in separately organized auctions. The volume and value of electricity that is contracted each year by the Polish government is of key importance.

As wind power is coupled with solar in one technological basket, the competition in the auction in the Polish climatic conditions is high. In 2019, the Polish auction results for projects of onshore wind above 1 MW installed capacity represented the biggest win in Europe, the Middle East, and Africa (EMEA) since 2017. In detail, the government held a 2.5 GW auction for above 1 MW projects, awarding over 2.2 GW of new onshore wind capacity and 0.3 GW to solar PV. Only half of the funds originally allocated was used and the average price fell to 49.2 EUR/MWh which was below the wholesale electricity price of 52 EUR/MWh. The previous tender was held in November 2018 with 1.162 GW awarded by wind projects out of 1.2 GW. In that case, the average weighted price was 45.3 EUR/MWh and it was so low that the Polish government spent only 52% of the budget allocated to the auction [70].

	November 2018	**December 2019**

Volume awarded (TWh) and share	42 (93.32%)	113.97 (68%)
Value or assigned budget (billion EUR) and share	1.929 (52.27%)	7.18 (54%)
Number of winning offers	31 (all wind)	101
New capacity installed: onshore wind + solar (MW)	1.2 (1.162 + 0.038)	2.5 (2.2 + 0.3)
Average price (EUR/MWh)	45.93	49.20

Table 6: Auctions results for new onshore wind and PV plants (Basket No.4) with installed capacity > 1 MW [67] [68]

Besides PV and onshore wind, biomass, biogas, bioliquids, offshore wind, geothermal and hydro compete in six different auction baskets and, moreover, each basket is separated by size above and below 1 MW capacity. The results for these baskets in 2018 showed that the auctioned amount was less than 30% percent of the total offered volume in all cases, the number of bids was below five except for the agricultural biogas installations below 1 MW, and the average prices were around 100 EUR/MWh. This analysis indicates an insufficient level of competition and likely poor cost efficiency, resulting in very small number of bids [70].

- 2020 Auctions

In conclusion, for what concerns tenders for 2020, the government announced on January 22, 2020 its intention to organize two rounds of auctions. Regarding industrial-size PV and wind installations, the maximum volume was set at 46.29 TWh of the value of 3.162 billion EUR. Support for big installations is estimated to cover approximately 800 MW of industrial-size onshore wind projects and 700 MW of PV projects (1,500 MW together in the auction basket). Moreover, Deputy Energy minister told the Polish Lower House about the government’s plans to soften distance rules for onshore wind turbines in “municipalities where there is social acceptance”. In fact, since the Polish 2040 Energy plan calls for a generation mix having solar as predominant technology reaching 16GW until 2024, onshore wind 10GW and off-shore 8GW, it is estimated that without liberalization of the “10H rule”, PV technology could benefit from the fact that it is grouped in the same basket as onshore wind and, therefore, it might consume most of the contracted volume. As a result, the average auctions’ bidden price could increase generally due to higher average LCOE produced by solar plants (51 USD/MWh in 2019) compared to wind plants (47 USD/MWh in 2019) [71].

Due to the global outbreak of COVID-19, Polish government adopted a set of legislation aimed at limiting the economic crisis such as the *Act of 31 March 2020*, or Anti-Crisis Shield 1.0, on the amendment of the Act on specific measures to combat COVID19. This Act enabled RES energy producers benefiting from the auction support system in the event of specific circumstances caused by the state of epidemic (or the state of epidemic hazard) to apply to the President of the ERO for an extension (by a maximum of 12 months) of the deadline for the first sale of electricity generated in the RES installation and for an extension of the permissible “age” of equipment included in the RES installations [72].

4.3.1.2 Other Business Models

- Corporate PPAs

Even if in Poland tenders are the most common business model in stipulating agreements for sale of renewable electricity, the interest in corporate PPAs is constantly growing. The main reasons for the rise in popularity of PPAs include decreasing costs of renewable energy, increasing costs of energy produced by conventional sources which translate into higher market electricity prices, consumers’ growing environmental awareness, and opportunity for a long-term supply agreement at a previously agreed price.

Polish lawmakers recognize a few types of PPAs:

- On-site, with the producer’s RES plant immediately next to the customer’s plant

- Near site direct wire, with the RES plant located nearby the customer and a dedicated direct line transmitting power
- Classic off-site, where the energy produced in a RES plant is transmitted to the customer over grid operator's transmission and distribution lines. Off-site PPAs can be multi-seller (several RES producers sell power to one customer) or multi-buyer (one producer sells power to several customers)

Moreover, there are virtual or synthetic PPAs which are not contracts for supply to end consumers but contracts for difference signed between the producer and the end consumer in which a fixed and stable power price is guaranteed in a long-term perspective. The Polish laws allow construction of a direct line between producer and customer (near site direct wire), which means transmitting electricity without using the public grid and, therefore, without payment of the transmission fees from both parties. However, since the construction of this direct line has to be approved by the President of the ERO, so far, the authority has not been enthusiastic about the construction wherever and whenever the connection to the grid was possible. On the contrary, off-site PPAs involving the use of operator's grid are more common [73].

Depending on the support system, quota system or auctions, producers need to respect some limitations.

- Operators of RES power plants can sell electricity to business partners through PPAs without losing the right to receive green certificates. Therefore, for instance, some part of the electricity produced by a RES plant can be sold to an "obliged seller" under the quota scheme, and the other part can be directly connected to an end customer under a PPA. Moreover, since renewable energy generators are not covered by the so-called "power exchange obligation", PPAs can be signed also for existing plants that still obtain green certificates.
- As EU funding programs and state resources often support the construction of RES power plants, the Polish RES Act applies provisions to situations where the auction system support is combined with other forms of state and, therefore, over-funding may occur. It is thus admissible to sell electricity under a PPA in the case of power plants whose construction benefitted from public aid [73].

As mentioned before, PPAs are particularly suitable for existing large renewable power plants which receive green certificates and can sell electricity in any way of their choice. However, the current drastic increase of coal and electricity prices in Poland reveal the advantages of signing PPAs also for new renewable energy projects. In fact, according to the forecast of the Institute for Renewable Energy (IEO), the average electricity price in Poland will reach around 75 EUR/MWh in 2030, which is significantly higher than the average auction price for large onshore wind and solar projects in 2019 being 49.2 EUR/MWh. In conclusion, both the PPAs price level below the wholesale market price and the danger of failing global sustainable targets due to high share of CO_2 emission outline that PPAs in Poland are an attractive opportunity for renewable energy developers.

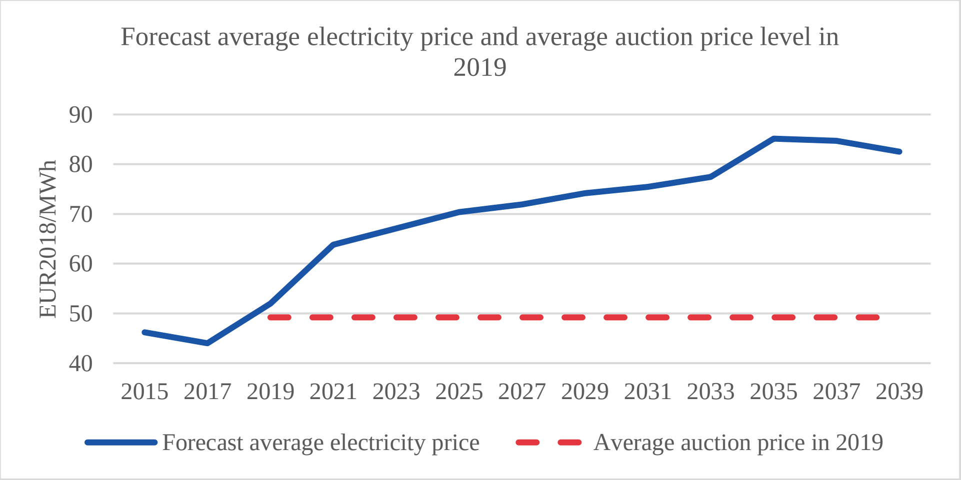


Figure 40: Forecasted average electricity price in Poland compared to average auction price in 2019 [66]

4.3.2 Financing Mechanisms and Instruments at EU Level

In March 2020, the European Commission presented the *European Climate Law* that proposes a legally binding target of net zero greenhouse gas emissions by 2050 in accordance with the *European Green Deal (EGD)*. Therefore, the EU Institutions and the Member States are bound to take the necessary measures and middle targets such as, for instance, reaching 50-55% GHG emissions reduction by 2030 compared to 1990.

Even if Poland is already a large recipient of EU development funds, the country requires adequate framework and funding to enable a smooth transition to decarbonization. Therefore, Poland stands at a crossroads between continuing pouring taxpayer dollars into an unprofitable polluting industry, shifting to imported natural gas or embracing clean technology proposed by EU.

The *European Green Deal Investment Plan (EGDIP)*, also referred to as *Sustainable Europe Investment Plan (SEIP)*, is the investment pillar of the Green Deal and it will mobilize at least 1 trillion EUR in sustainable investments over the next decade. Furthermore, the "Just Transition Mechanism" is one part of the plan that will mobilize at least 100 billion EUR in investments over the period 2021-2027 to support workers and citizens of the regions most impacted by the transition [74]. This mechanism is structured on three pillars of financing:

- Just Transition Fund, consisting in 7.5 billion EUR provided from the future long-term EU budget to regions where many people currently work in coal, lignite, oil shale and peat production or regions that host greenhouse gas-intensive industries. This fund aims at giving workers the opportunity to develop skills and competences for the job market of the future and more generally support investments in clean energy transition such as energy efficiency.
- Dedicated just transition scheme under the *InvestEU Programme*, which is part of the EU budget, to mobilize up to 45 billion EUR of investments helping those regions' economies in finding new sources of growth such as projects for decarbonization, economic diversification of the regions, energy, transport, and social infrastructure.
- Public sector loan facility with the European Investment Bank backed by the EU budget to mobilize between 25 and 30 billion EUR to be used for concessional loans to the public sector such as investments in energy and transport infrastructure, district heating networks, and buildings' renovation or insulation [74].

Even if the Just Transition Fund will provide support to all EU Member States, the allocation method considers the scale of the transition challenge, the social challenges in job losses and need for subsequent reskilling of workers for employment, and the Member States' level of economic development and related investment capacity. Member States will prepare one or more *Territorial Just Transition Plans* providing an outline of the transition process until 2030 and identifying the most impacted territories that need support. For each of these territories, the plans will set out the social, economic, and environmental challenges and give details on measures for economic diversification, reskilling, and environmental rehabilitation as appropriate. The approval of the plans by the Commission will give access to dedicated financing from the Just Transition Fund (pillar 1), as well as from the InvestEU (pillar 2), and the public sector loan facility by the EIB (pillar 3).

Moreover, the Innovation and Modernization funds, which are not part of the EU budget but are financed by revenues from the auctioning of carbon allowances under the *EU Emissions Trading System*, will provide some 25 billion EUR for the EU transition to climate neutrality. First, the Modernization Fund is a dedicated funding program to support 10 lower-income EU Member States in their transition to climate neutrality. In detail, Poland was supported with 50 million EUR to power sector from earmarked auctions started in 2019. Second, the Innovation Fund supports investments in energy efficiency, RES, and other low-carbon innovation in energy intensive industry [74].

4.3.3 New Investments and Key Actors

In 2019, the Polish landscape was dominated by 10 players totalizing 3 GW of cumulative RES capacity which could be translated into over 40% of total RES capacity of the country. The first top player in terms of renewable installed capacity is PGE Capital Group, the Poland's largest energy sector company with respect to sales revenues and net profit with its own fuel resources, power generation, and distribution networks. In 2019, PGE's renewable power plants accounted for 571 MW cumulative installed capacity of wind power plants, in the major part, but also biomass ones. Secondly, Enea, a power industry company based in Poznań and the fourth largest energy group in Poland, totalized 406 MW mainly installed in biomass plants. Then, the Portuguese renewable energy company Energias de Portugal (EDP) put its focus entirely on wind energy and, in 2019, accounted for 372 MW installed capacity. The interest on wind energy was put also by the investment company Kulczyk, which owned 270 MW installed capacity entirely on wind plants. Lastly, Tauron, RWE, Energa, Invenergy, Vortex Energy, and IKEA follow in the list by accounting for installed capacity mainly in wind power plants and then in biomass ones. Moreover, more than 8 MW are now commissioned, respecting the proportions shown in 2019 cumulative installed capacity between the top 10 players and their wind or biomass major interest [62].

For what concerns the investments, Poland attracted around $4.5 billion in new investment in clean energy over 2013-18, of which 68% went to onshore wind. The punitive wind act saw investment in that sector collapse after 2015, with minimal investment levels in 2017, and a slow recovery in 2018 and 2019 thanks to auctioned projects moving forward. Most of the capacity proposed in 2018 was installed by EDP with 0.4 GW of wind capacity. Secondly, the German RWE AG and E.ON accounted for 0.2 GW each of wind power plants capacity. Third, the multinational electric utility company Engie and EDF had installed each 0.1 GW of wind capacity in Poland. Last, 0.08 GW have been registered for the Italian energy company ERG.

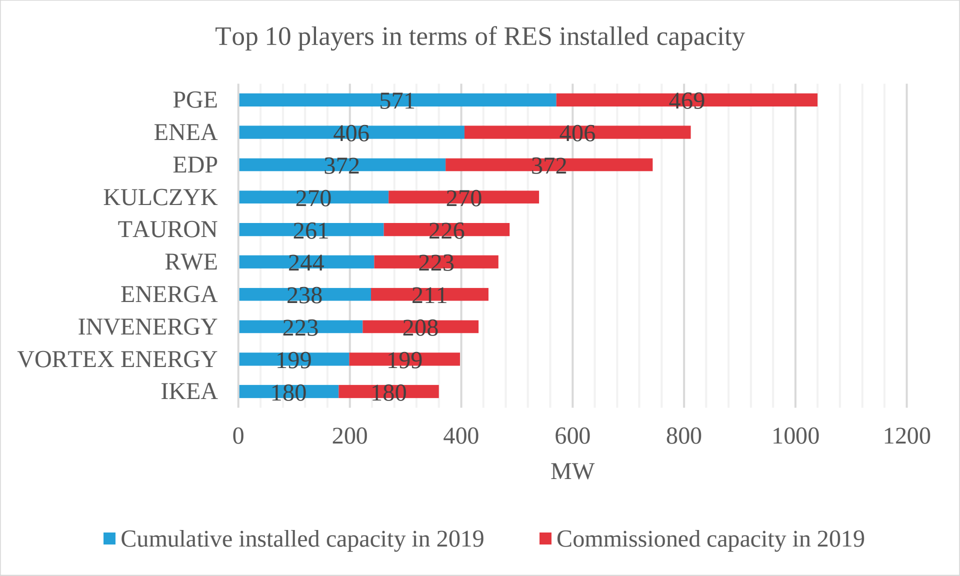


Figure 41: Top 10 players in Polish RES market [62]

To conclude, rising electricity prices and lack of green supply options available on the Polish market have increased interest in renewable PPAs from both local energy intensive companies and international players. Therefore, in 2019 a platform for clean energy buyers and suppliers called "RE-Source Poland Hub" was established by PWEA as a foundation aiming to facilitate the energy transition in Poland via corporate renewable energy sourcing. This is a multi-stakeholder forum bringing together the interests of both buyers and sellers to unlock the potential for corporate renewable energy sourcing [62].

4.3.4 Main Barriers

4.3.4.1 Market and Legal Framework Barriers

Some big criticalities are related to public opposition resulting in punitive acts limiting areas and profitability of several projects.

- Political risk. The 2015 parliamentary elections brought significant changes in the directions of economic and energy policy of the Polish government. It affected the RES sector by blocking virtually further development of onshore wind power in favor of biomass, biogas, PV or geothermal sources. Emblematic legal effects of the change of thinking about wind power are the adoption of the Wind Farm Act and the multiple increase of the taxable base for property tax which significantly reduce the profitability of new and existing wind farms. Moreover, wind farms are facing the problem of permanent drop in revenue from sales due to the collapse of the green certificate market price.
- Property tax. The increase in property tax is a significant new financial burden for wind energy projects. The *Wind Farm Act* defines the entire wind turbine with all its technical elements as a building structure. Therefore, there are strong arguments to calculate property tax in 2017 on the value of entire wind turbine with technical elements, whereas until the end of 2016 the taxable base included only the value of foundation and tower. It is estimated that due to this tax increase, the LCOE for wind farms will increase by more than 4.40 EUR/MWh.
- Prohibitive minimum distance requirement. International practice regarding minimum distances is a topic that raises debates. Globally setback and location guidelines vary to a large extent, even on a regional level. Therefore, the limitations introduced by the *Wind Farm Act* in Poland appear overly restrictive compared to European practice. For instance, the minimum distance requirement in Poland also applies to projects where a building permit was obtained before the entry into force of the new regulations if there is a need for re-permitting after 2016. Practice shows that there is significant probability of wind farms' layout changes due to different geological obstacles encountered at the earthworks stage.
- Difficulties with funding. Due to decrease in wind projects profitability and increase in risk, acquiring funding is extremely difficult so that the level of own contribution required by the banks has risen to above 50% in many cases. The costs of loan financing are also higher and often exceed the return on investment in current conditions. Therefore, the approach of the banks has also hanged as they are really cautious about their participation in wind power projects, and many of them have decided to completely give up funding of wind projects [65].

4.3.4.2 Permitting Phase Barriers

According to PWEA, the main administrative barriers impacting the RES generation market are:

- lack of transparency in the decision-making process for authorizing grid connection
- badly defined requirements for environmental impact assessment process, spatial planning permission and grid connection process which vary throughout the country
- slow Natura 2000 certification process for the authorization of wind farm projects due to unexpected changes in the protected locations list

To summarize, as the application process is structured heterogeneously and varies from project to project, inaccurate estimation of both timeframe and costs is common in the building permit application process. Poland's power sector is dominated by four major utilities all controlled by the state. They can be called on to prioritize national interests even in cases where the economics may suggest another direction. Indeed, several utilities broke off long-term contracts with renewables producers when REC prices plunged, arguing about higher tariffs that did not follow the downward trajectory of certificate prices. Moreover, concerning wind farms, the procedures to be followed to obtain all the necessary permits in Poland are highly unclear since the investor is obliged to contact individually the body responsible for grid connection and the one responsible for spatial planning and environmental given that they do not cooperate effectively with each other. Nevertheless, the lead time for the authorization procedure is around two years, which is relatively short in comparison to the other countries [62] [67].

4.3.4.3 Grid Connection Barriers

Four crucial barriers for obtaining grid connection of wind energy projects in Poland have been identified by PWEA:

- reserving of connection capacity or queue for the connection point
- lack of transparency and published data in the process, such as availability of grid capacity
- wind production curtailment and ungiven grid access priority to RES due to threat to the grid security
- limited validity of offers, which often expire in the period between their being made and the start of the wind farm’s construction.

The Polish grid has limited capacity and, therefore, since information about availability of grid capacity are not published, many developers apply for more capacity than the actual need leading to long time delays due to the so called “queue for the connection point”. Moreover, transmission and distribution operators can curtail production from wind, arguing that wind generation poses a threat to the security of the smooth functioning of the grid. In fact, it is confirmed that in Poland more than 50% of the planned projects encounter serious problems due to the constraints of the existing grid capacity. Likewise, according to PWEA, despite the Polish law granting priority grid access to renewable energy, neither TSO nor DSOs commit to this piece of legislation since the legislation is not well-defined [67].

5. Romania

5.1 Country Profile

5.1.1 Energy Insights

5.1.1.1 Country Overview

Romania is a European Union member state of Southeast Europe (EU SEE) together with Bulgaria, Croatia, and Slovenia. In 1859, Modern Romania was formed through a union of the Danubian Principalities of Moldavia and Wallachia and, now, it is governed on the basis of a multi-party democratic system with separation of powers between the legislative, executive and judicial branches [75].

Romania is the largest of the Balkan countries with an area of 238,391 square kilometers and, in 2019, its population accounted for 19.3 million inhabitants. It ranks 52nd in the human development index (HDI) and is a developing country with a GDP of 214.2 billion EUR and a strong annual economic growth rate of 4.1% in 2019, mainly driven by private consumption and an investment rebound. According to the Romania Country Economic Memorandum (2020) [76], Romania's income per capita increased from 26% of the EU-28 average in 2000 to 63% in 2017.

The region has a large variety of natural resources (forests, natural gas, fertile agricultural lands, brown coal and lignite, crude oil, mineral, hydrological networks, etc.) and a great potential of renewable energy. The intensive development of Romanian industries was based on natural resources exploitation without mitigating negative effects on the environment. However, after joining EU in 2007 and approving the *National Renewable Energy Action Plan* and the *Energy Strategy*, strategies regarding RES were considered [77].

Population (million)	19.3
GDP (billion EUR)	214.2
GDP growth rate	4.1%
Electricity demand (TWh)	49.64
Electricity demand pro-capita (MWh)	2.55

Table 7: Romania key data (2019) [76] [77]

5.1.1.2 Primary Energy and Electricity Supply

Unlike most of SEE region's countries which are importers of natural gas and oil, Romania holds over 60% of the region's oil reserves and 80% of its gas. However, Romanian gas reserves have strongly decreased from 713 billion cubic metres (bcm) in 1980 to less than 100 bcm in 2017 due to rapid depletion and re-evaluation. Moreover, in 2017, the country accounted for 82 Mt of crude oil reserves, 11 Mt of hard coal reserves, and 280 Mt of lignite ones.

Over the past two decades, the deep recession of the early 1990s and the financial crisis in 2008 with implementation of energy efficiency measures have caused a considerable decline in TPES. Nevertheless, the energy mix of the TPES has not changes visibly. Now, half of Romania's installed generating capacity is coal, gas, and nuclear and, therefore, these three technologies account for approximately two-thirds of the annual electricity generation. Specifically, in 2017, natural gas and oil represented the largest shares in TPES with around 28% each. Lignite and solid fossil fuels followed them with 16%, biofuels with 12% and nuclear with around 9%. In renewables, hydropower dominates, followed by wind, solar and biomass energy, which collectively generate a third of the country's electricity. More than 3% of the TPES is covered by hydropower and wind and solar energy took around 2.5%. The Romanian cumulative installed capacity in 2018 was around 23.6 GW which is the largest of the entire SEE region. Hydropower plants took the first place with 6.7 GW installed capacity, solid fossil fuels accounted for 5.8 GW, natural gas 5.1 GW, wind 3 GW and solar PV 1.4 GW. Lastly, nuclear power plants capacity was around 1.3 GW. However, despite climate and environmental challenges, investment of new coal power plants and replacement plants is currently under consideration [78].

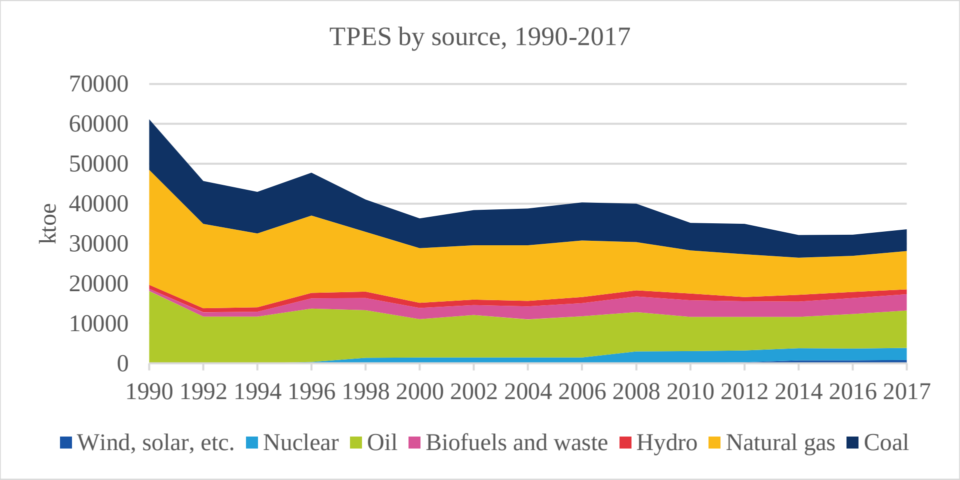


Figure 42: Historical development of TPES by source in Romania [79]

The most relevant sources for power generation in 2017 were coal with 26% of the Romanian electricity generation, hydropower with 23%, nuclear with 18%, and natural gas with around 17%. Indeed, among SEE, Romania and Bulgaria have plans for additional nuclear generation capacity which will contribute to enforce the role of important electricity exporter in the region. Furthermore, one of the main reasons for strong yearly variations in the electricity trade is the high share taken by hydropower which implies a dependency on precipitation levels. To conclude, wind power produced 11.5% of the total country’s electricity, solar power around 3%, and biofuels less than 1% [79].

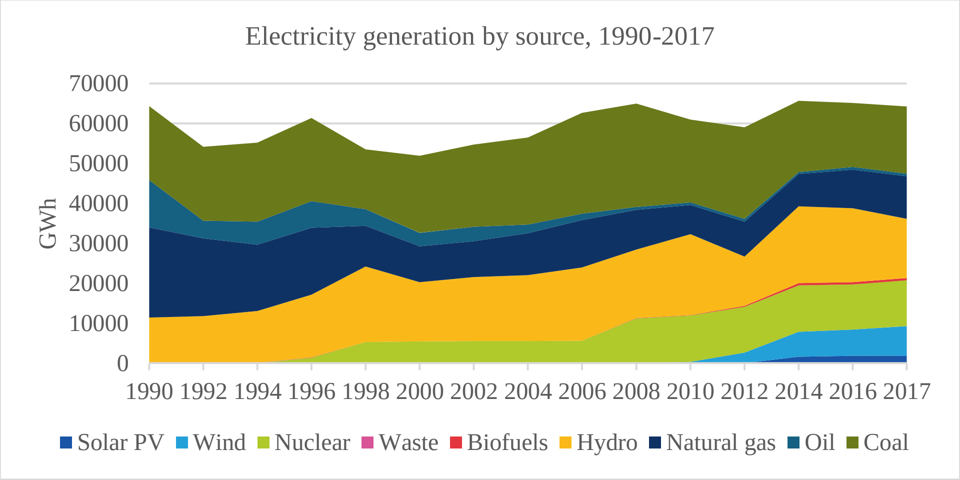


Figure 43: Historical development of electricity generation by source in Romania [79]

5.1.1.3 Energy Consumption

Among the sectors, residential occupied 32% of the Romanian TFC in 2017, transport and industry shares were 26% each, electricity 16%, commercial and public services 8%, and the remaining is divided into non-energy use, agriculture, and forestry. The TFC main sources are oil products for transportation increasing recently and overcoming the use of natural gas which, on the contrary, has experienced a decline since around 1990. Also, electricity and biofuels represent important sources, while heat, coal, renewables, and crude oil have a minor share.

The electricity final consumption has significantly decreased in the years before 2000, while since that point, it has experienced stable growth rates in the entire SEE region mainly because of electrification of industrial sector, increasing demand of residential one and slightly of commercial one. Currently, final energy consumption per capita is around 70 GJ which is almost half of the EU-28 average (around 130 GJ) [78].

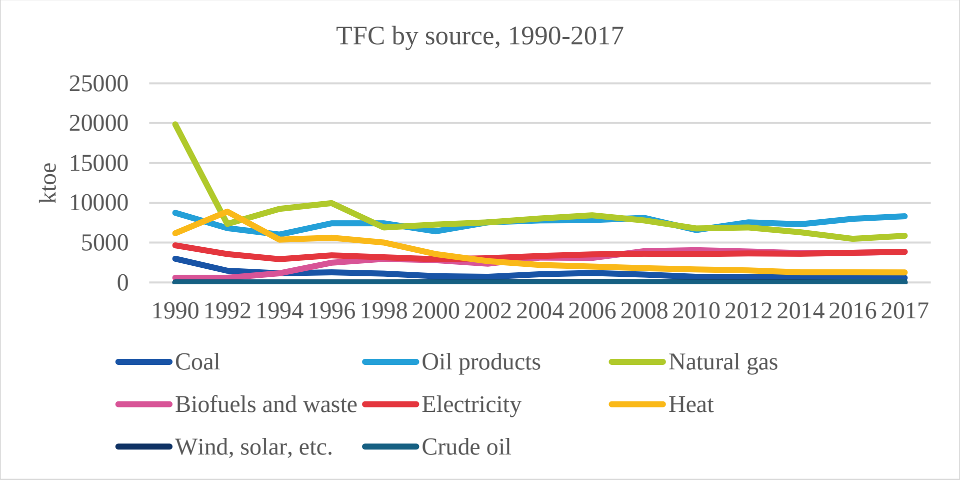


Figure 44: Historical development of TFC by source in Romania [79]

5.1.1.4 Renewable Energy Sources Evolution

All the economies in the SEE region have adopted renewable energy targets at international level, including *EU's RED* requiring at least 20% renewable TFC by 2020, the *EnC Treaty*, and the *Paris Agreement*. Moreover, Romania submitted its *National Energy and Climate Change Plan for 2021-2030 (NECP)* specifying 2030 target of 27.9% share of RES energy in final consumption, country's types of energy resources, and potentials of renewable energy by source. However, technological barriers, implications of economic efficiency and environmental limitations reduce this potential significantly [78].

Historically, SEE region has been significantly shaped by large hydropower plants producing 23% of the national power generation, while heating needs have mainly been covered by biomass sources. Overall, Romania had a lower share of RES in the TFEC (17%) in 2017 compared to the *NREAP* target, largely used in the residential sector, more than in transportation and industry. Nonetheless, estimates unexploited potential for renewable energy is still substantial.

Since hydropower owns one of the major technical potential in the power sector (38 TWh), in 2016 the EU commissioned a study on hydropower for the Western Balkans aiming at developing its possibility in a way that balances energy generation, flood protection, and environmental concerns. The study concluded that immediate priority for investment should be the rehabilitation and increase efficiency of existing hydropower plants as well as ecological restoration measures. Another great potential belongs to biomass, which electricity production was 525 GWh in 2017, mainly in CHP plants. Moreover, Romania has the benefit of enjoying the best wind resources of the SEE region with average wind speeds of 6-7 m/s and an onshore wind utility-scale potential of around 154 GWh. The solar potential is also relevant, if though so far solar PV has contributed only to 2.8% of domestic power generation with its 1.4 GW of installed capacity and currently it is facing stagnation in deployment. To conclude, investments in renewable energy and promotion of proper legal frameworks are crucial for achieving strategic objectives in the energy sector. In fact, in Romania the green certificates incentive scheme attracted international investors and the installed capacity in the country increased from 5 MW in 2008 to 3244 MW in 2014, when the support scheme was phased out and new investments significantly decreased [80].

In 2015, however, the government announced a new energy strategy, calling for 1 trillion EUR of investment to make Romania an eastern European energy crossroads and enhance the national transmission network through 2016-25. The strategy calls for major investment in two new nuclear reactors in collaboration with China, interconnectors and developing new gas finds in the Black Sea. These may leave little room for expansion of renewables in the country, though the country's aging thermal fleet will likely create a capacity gap from mid-2020s [81].

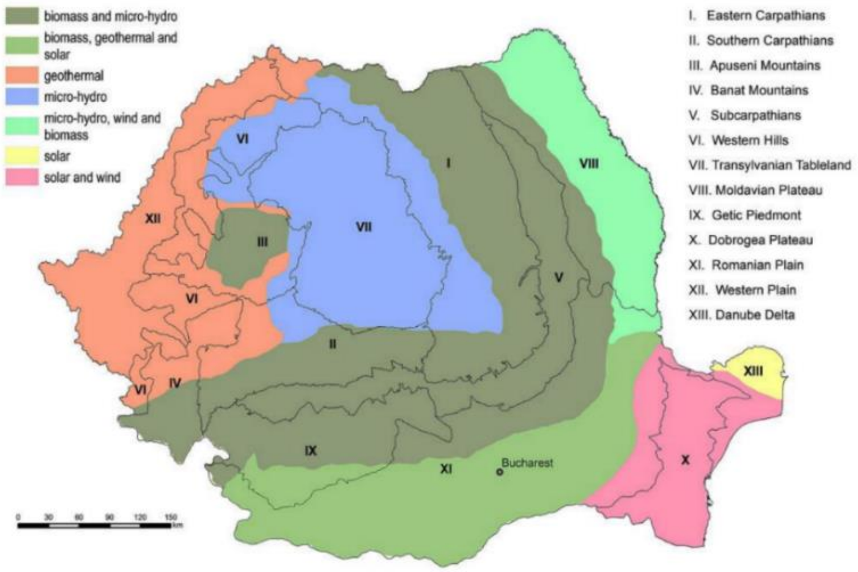


Figure 45: Spatial distribution of RES types and potential on main relief units of Romania [80]

According to Deloitte [82], three different scenarios for renewable energy in Romania in 2030 can be assumed and involve overall investments in the Romanian energy system between 18 and 25.3 billion EUR. Apart from extension of existing nuclear units' lifetime, commission of two additional nuclear reactors, and elimination of most of the national coal units, the proposed scenarios are mainly based on further deployment of wind and solar potential. Between 2020 and 2030, the reference scenario estimates to double both the net wind and solar installed capacity respectively from 3 GW to 6 GW, and from 1.5 GW to 3 GW, totalizing therefore 65% of net installed capacity coming from RES and 40% increase of this value compared to 2020. Potential scenario A compensates the lack of two additional nuclear reactors planned for the reference scenario with approximately 1 GW of extra wind energy and 1.25 GW of extra solar energy compared to the previous scenario. Therefore, RES net installed capacity could reach 70% share, with an increase of 60% compared to 2020. Lastly, potential scenario B estimates 7 GW of installed wind energy and 4.7 GW of solar one, accounting for 71% RES installed capacity and 64% increase compared to 2020. Therefore, between 2020 and 2030, the share of renewable energy could increase from 26.8% to 32.4%, 35%, or 35.5% respectively in the three different scenarios. Furthermore, 51% of the electricity will be generated from RES in the reference scenario, and 57% and 58% in potential scenario A and B. However, the evolution of the shares may be influenced by the likelihood of the implementation of certain projects and environmental regulations. Some assumptions, on which the modelling of the scenarios have been based such as the consumption increase, have led to estimations of average LCOE for solar and wind energy lower than average electricity price in all three scenarios due to technology development.

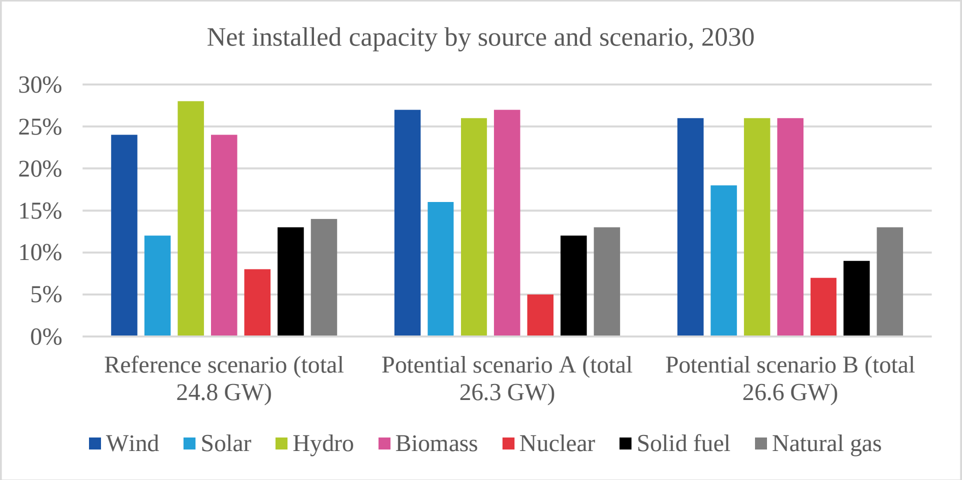


Figure 46: Forecast of 2030 net installed capacity in Romania by source and scenario [82]

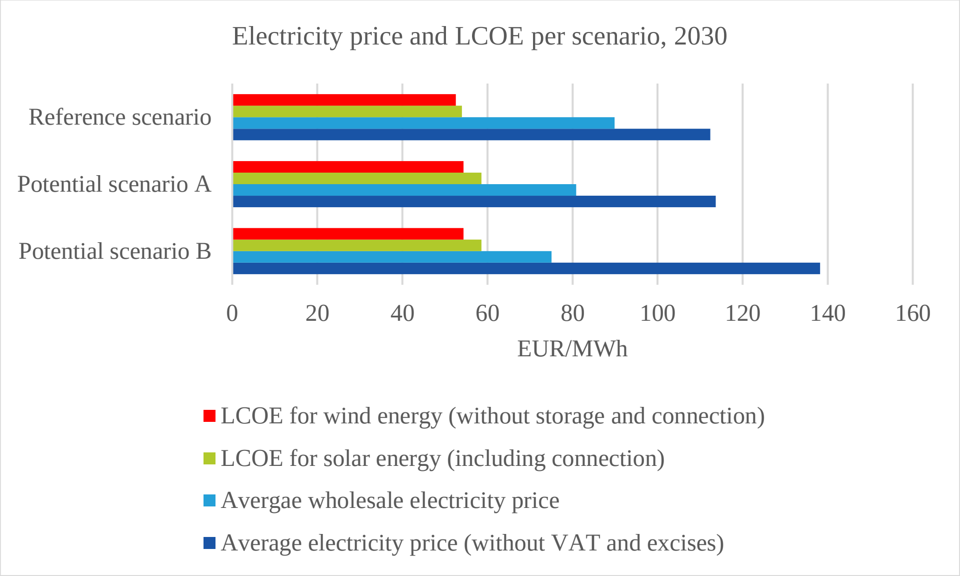


Figure 47: Average electricity price and LCOE in Romania 2030 by scenario [82]

5.1.2 Electricity Market

5.1.2.1 Electricity Network

Romania has gradually shifted toward a liberalized energy sector. Indeed, since 2007 consumers have been eligible to switch electricity supplier, in 2014 the price liberalization was finalized for non-household consumers, and in 2018 for household consumers. Generators sell power to retail market through bilateral contracts or auctions, and to consumers through bilateral contracts. The largest amount of electricity generated belongs to CE Oltenia for 24% (mainly focused on coal energy), Hidroelectrica for 23% (hydro energy), Nuclearelectrica for 19% owning 2 reactors, OMV Petrom for 6% (mainly focused on gas), and Electrocentrate Bucuresti for 5%. OMV Petrol is one of the largest corporations in Romania and the largest oil and gas producer in SEE. In late 2004, however, the company was privatized by the Romanian state and sold to Austrian oil company OMV. On the contrary, all the other big generators are majority state owned [81].

For what concerns electricity transmission, Transelectrica acts as a wholly unbundled and independent Transmission System operator (TSO) and it is publicly traded company with 58.7% of the shares being held by the Ministry of Economy and Commerce, 13.5% by a joint-stock company established by the Romanian state that is called Fondul Proprietatea, and 27.8% being floated on the Bucharest Stock Exchange [83] [84]. The electricity transmission grid is composed by overhead electricity lines (LEA) and power substations, which represent a total length of the electricity transmission grid of 8,834.4 km. In the total LEA length, 83.6% were put into operation during the period 1960-1979, 14.07% from 1980 and 1999, and approximately 2.3% after 2000. Moreover, the high-voltage electricity transmission lines and electricity distribution lines put into operation after 2000 have a small share, therefore most of the installations that are currently in operation have a long operation time, mainly over 35 years.

With this regard, there are several licensed DSOs active in Romania. In detail, the consumers' market is split into eight areas with four distribution companies: Electrica 42%, Enel 26%, E.ON 17%, and CEZ 16%. The distribution and retail divisions have transitioned to being predominantly privately owned. Key asset owners include Enel 21%, Electrica 19%, E.ON 11%, CEZ 7%, OMV 5%, and others 37%. Moreover, suppliers can also sell to each other via bilateral contracts or auctions.

In conclusion, the Romanian consumption can be divided into industrial sector for 48%, residential sector 28%, and commercial sector 24%. Residential customers can qualify for regulated tariffs from a supplier of last resort [81].

The share of total net imports on gross inland consumption is 22% mainly referred to oil, then coal and gas, and lastly biomass. Moreover, after a long period as electricity exporter, in 2019, electricity export halved while import rose by 78.5%. This import reliance was due to a slump in power output associated with a slight decline in consumption [85].

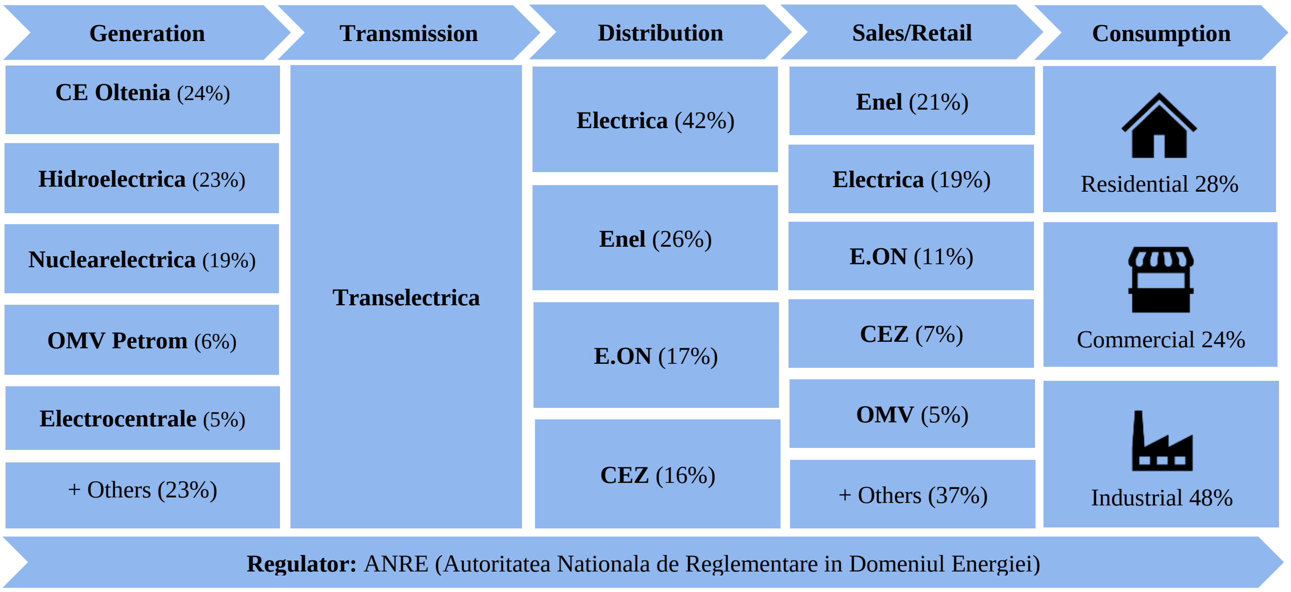


Figure 48: Power market players in Romania [81]

5.1.2.2 Wholesale market

Romania's power prices have historically been lower than Hungarian and Bulgarian ones, though they have been rising steadily due to higher carbon prices and an aging coal and nuclear fleet. Moreover, in 2020 the privatization of state-owned hydro assets is expected as well as the sale of some assets. This could put significant pressure on wholesale prices. Recently, retail power prices in Romania have soared, and in 2019 electricity consumption dropped because of higher electricity prices [78].

The market structure follows the principles of vertical unbundling that has been adopted throughout the EU. OPCOM is the unique power market operator and it is against fully liberalization. It operates the Day Ahead and Intraday market and it also provides facilities for trading of GCs and forward energy products. However, there are aspects of the Romanian electricity market that differ from most western European countries such as the prohibition of bilateral forward contracting outside the central platform. Therefore, all forward contracting has to be conducted in one of the markets organized by OPCOM, except RES producers up to 3 MW who can contract only with the so-called “Last Resort Suppliers”. Furthermore, an intraday market is in place, but despite growing in the past months, there are still little volumes traded compared with the rest of the national energy markets and with the European average. Balancing Market is operated by the TSO and is mandatory for all market participants. At this moment, there is a price cap represented by a maximum of 93 EUR/MWh spread between Day Ahead Market Closing Price and the balancing market upward (deficit) prices for each hour interval [81].

5.1.3 Country’s Policy Objectives

The daily fight against climate change carried on by the EU through the Paris Agreement and the Energy Union Strategy is crucial also in Romania’s national plans. In fact, after joining the EU in 2007, Romania faced big changes in the alignment energy policy and legislation and promotion of renewable energy, but also the country became attractive for investments. On the 31st of December 2019, the final *National Energy and Climate Change Plan 2021-2030 (NECP)* [86] was submitted to the European Commission including a summary of the points of views from the public. The key objectives are:

- ETS emissions reduction of 43.9% compared to 2005,
- non-ETS emissions reduction of 2% compared to 2005,
- energy efficiency increase of 37.5% compared to PRIMES 2007 projection for 2030,
- total share of renewable energy in final gross energy consumption of 27.9% with specific shares of 39.6% in RES-E, 17.6% RES-T, and 31.3% RES-H&C.

A set of policies and measures have been developed to achieve the overall GHG reduction target and national GHG absorption that are in line with the objectives of the *Energy Strategy of Romania*, the *National Strategy for Climate Change and Economic Growth*, the *National Action Plan* for the implementation of the national strategy for climate change and economic growth, and other strategies and documents.

5.2 Onshore Wind Energy

5.2.1 Wind Plant Current Installations

The wind resources abundance in the region has enabled onshore wind to become a cost competitive source of new power generation. The weighted-average capacity factor has shown a slight upward trend in line with the values achieved in other European countries, while the weighted-average onshore wind LCOE commissioned in SEE during 2018 was 0.063 EUR/kWh, 4% lower than the ones for projects in other European countries [78].

The first wind turbine installed in Romania was placed in Tulcea County in 2006. Since that time, things have constantly been changing and Romania's wind energy sector has started to play an increasingly important role. At the end of 2011, Romania's wind power station capacity amounted to 982 MW, a more than two-fold increase since the end of 2010 and a 70-fold increase compared to the end of 2009. According the national TSO Transelectrica, in 2012 Romania's installed capacity of wind power experienced a boom reaching around 1822 MW due to a high investment in the sector accounting for 1.28 billion EUR. Indeed, during the period 2010-2014, investments program such as the GCs incentive scheme made wind industry attracting for many international investors and the installed capacity increased from 5 MW to 3244 MW. However, between 2015 and 2017, the phasing out of incentives resulted in a gradual collapse of new investments [80].

Currently, approximately 3 GW of wind energy is installed, meaning 13% of the total Romanian net installed capacity (22.4 GW). Moreover, around 10% of the total country's net electricity production (67.58 TWh) comes from wind energy. The largest contributor of the country's wind electricity is Fontanele-Cogealac wind farm (600 MW) located in Constanța County (south-east) and owned by CEZ Group. The second and third biggest wind farms are located in Constanța County and owned by Energias de Portugal, while other large wind farms are located in Tulcea County (south-east) and owned by Enel Green Power. To summarize, Constanța and Tulcea counties represent the most interesting areas of the country for what concerns wind energy installations and, indeed, the two counties together host almost 87% of the country's wind energy capacity (installed, under construction, approved, and proposed) [80].

	2012	**2014**	**2016**	**2018**
Wind installed capacity (GW)	1.84	2.89	3.01	3.01
Wind electricity production (TWh)	2.64	6.20	6.59	6.32
Share of total electricity generation	4.47%	9.45%	10.14%	9.36%

Table 8: Wind power numbers in Romania [81]

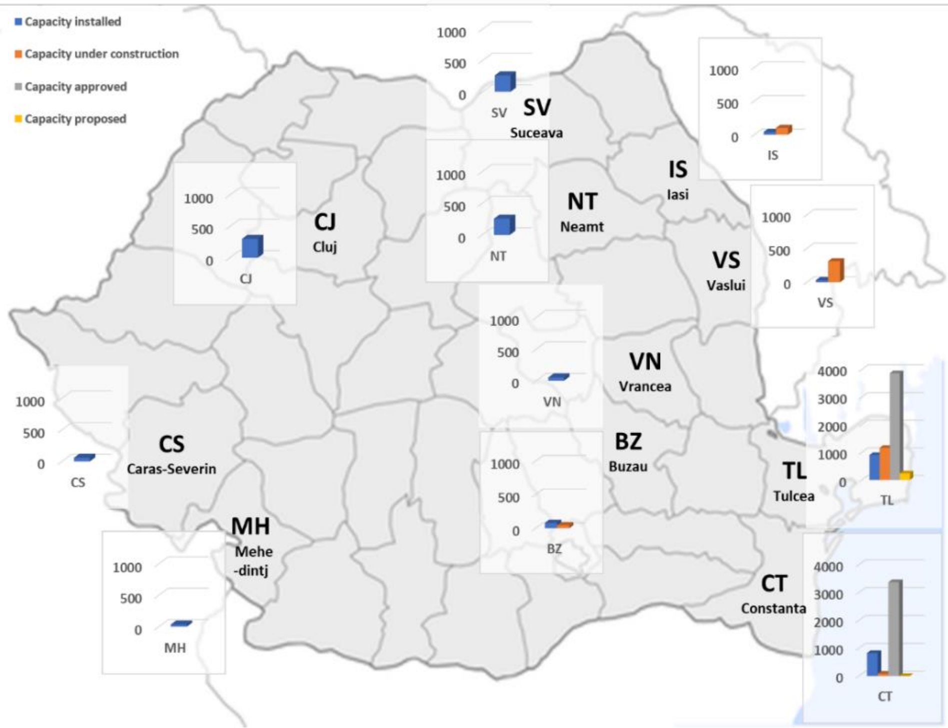


Figure 49: Wind farms' capacity by Romanian county (MW) [87]

5.2.2 Wind Energy Scenarios

According to Deloitte [82] and in line with the Romania's *National Climate Change Strategy 2013-2020*, three different scenarios capture the most likely situations that could affect the Romanian energy sector in the next decade.

- Reference Scenario assumes extension of existing nuclear units' lifetime and commission of two additional nuclear reactors in 2030-2031. Moreover, it includes gradual elimination of all coal units by 2035, decrease of load factor for power plants operating on natural gas, and installation of additional RES energy capacities.
- Potential Scenario A forecasts the same assumptions as the reference scenario unless the construction of two additional nuclear reactors which will be avoided in favor of additional 1 GW from wind sources and 1.25 GW from PV sources.
- Potential Scenario B characteristics are extension of existing nuclear units' lifetime, commission of two additional nuclear reactors in 2030-2031, disposal of three coal units, and replacement of reduced coal capacity with RES totalizing around 7 GW of wind energy and 4.7 GW of solar energy.

The share of wind energy in the net installed capacity in 2030 can vary between 24% and 27%, while the share of wind energy in the net electricity production in 2030 can vary between 20% and 23% according to the three different scenarios. As regards all sectors which influence the global weight of RES (heating and cooling, electricity, and transport), renewables contribute in majority in the electricity sector reaching 68.4% of the total production in the Potential scenario B 2030, secondly heating and cooling sector is provided by maximum 33.9% by RES, and transport by 23% [82].

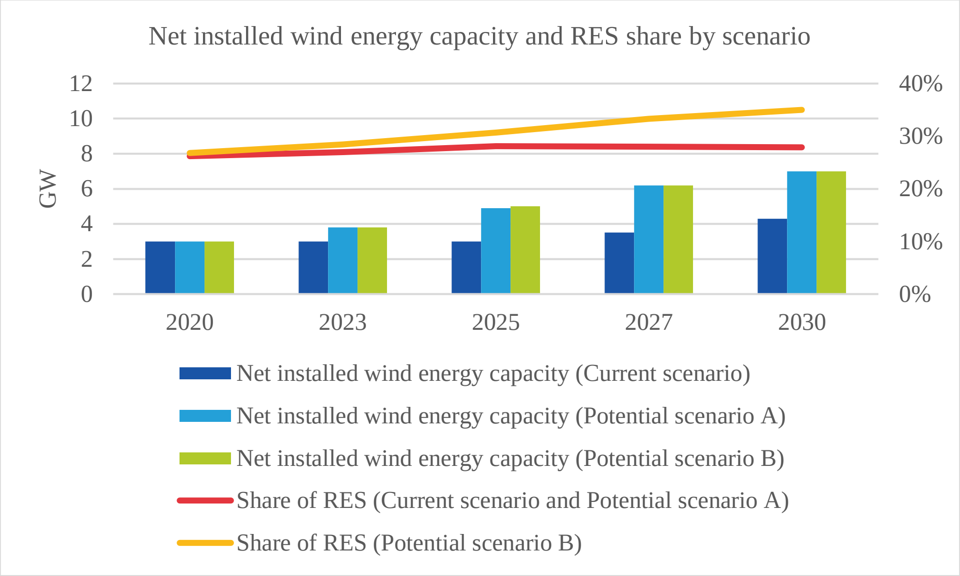


Figure 50: Forecasted net installed wind energy capacity and share of RES in Romania by scenario [82]

Moreover, one of the assumptions on which scenarios modelling has been based is the increase in the electricity consumption which will have to be supported by investments in new plants and grids with the related expenditure reflecting in electricity price. LCOE for wind energy is forecast to be significantly lower than average wholesale electricity price for the three different scenarios as well as LCOE for coal plants.

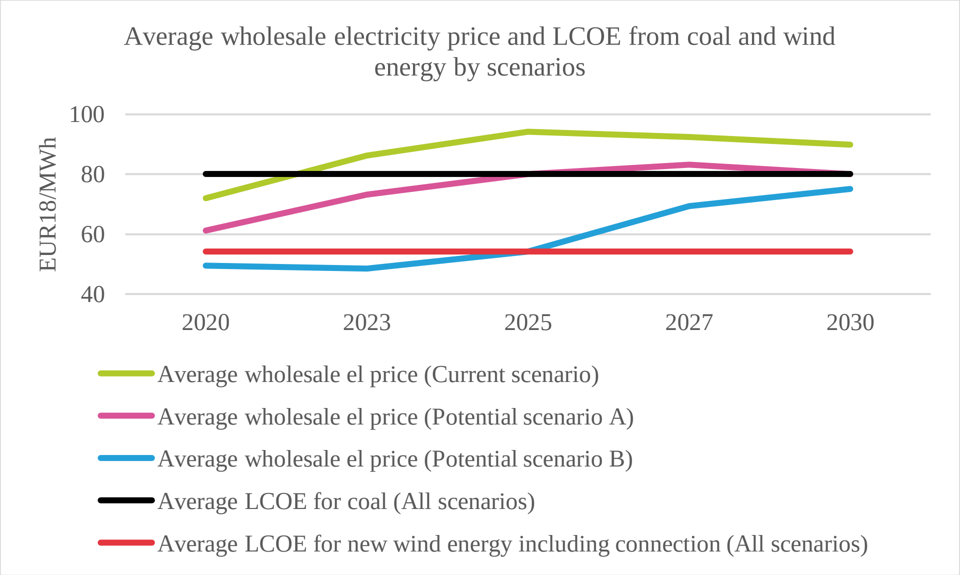


Figure 51: Forecasted average wholesale electricity price and Levelized Cost of Electricity (LCOE) from coal and wind energy in Romania by scenario [82]

5.2.3 Wind Power Planning and Permitting

The usual procedure required for construction and operation of a wind project include obtaining permits, authorizations, and licenses during both the building and operation phases.

The key regulatory documents to be obtain during the building phase are:

- Urban Planning Certificate, prior to obtain the building permit. Due to legislative landscape evolution in the last ten years resulting in less bureaucratic administrative environment, now this certificate is issued in electronic form. It indicates the network operators which will issue the relevant endorsements and its issuance term is maximum 15 working days as of the submission of the request.

- Prior permits listed in the Urban Planning Certificate, which depend on the specificity of the project and the area where it is located. It can be issued by different authorities such as operators managing water, electricity, gas, oil networks, etc.
- Zonal Urban Plan (PUZ), issued by the relevant local council where the land plot is located and with a validity of maximum 5 years as of the date of approval.
- Screening decision in the Strategic Environmental Assessment (SEA) procedure or Environmental Permit for PUZ. The Regional Environmental Protection Agencies, as competent authorities, assess if the wind project will be subject to a shorter SEA procedure ending with the screening decision or the full SEA procedure ending with the Environmental Permit. The permit is issued within 25 days as of submitting the full documentation for the screening decision.
- Power Location Endorsement issued by the distribution/transmission network operator with issuance timeline of 15 days with a special term of 5 days in case the document is conditioned on performing deviation works and/or other network works.
- Documents relating to the access roads (prior approval, establishment and/or access authorization, and agreement for using and accessing the road area). The road manager, which varies depending on the road (Transport Ministry for national roads, County Council for county roads, or Local Counties for local roads), issues the permit which is valid throughout the duration of the works performed.
- Technical Interconnection Endorsement issued by the distribution/transmission network operator to which the installation will be connected. The current regulatory framework ensures 30 days from submission of full documentation instead of 90 days as in the previous framework.
- Establishment Authorization. National Regulatory Authority in Energy (ANRE) issues this permit which is valid for minimum 1 year and has a special issuance term for green energy generation facilities of 30 days as opposed to 60 days as in the previous legislation.
- Interconnection Agreement concluded with the relevant local network operator.
- Interconnection Certificate issued by the distribution/transmission network within 10 calendar days as of the submission of the full documentation required.
- Screening decision in EIA procedure or Environmental Approval. The county Environmental Protection Agency/Delta Dunarii Biosphere Reservation assesses if the wind project will be subject to a shorter EIA procedure ending with the screening decision or the full EIA procedure ending with the Environmental Approval. The full EIA procedure may apply, for example, if the project is located in or in the vicinity of natural protected areas and may impact such areas.
- Water management approval issued by Territorial Water Management Authorities or National Administration Apele Romane (ANAR) depending on complexity of the project.
- Natura 2000 Approval issued only if projects are in or in the vicinity of natural protected areas and may impact such areas. If a project is subjected to the SEA procedure or EIA procedure, the impact on natural protected areas should be assessed in said procedure and no stand-alone Natura 2000 Approval is required.
- Building Permit (BP), issued by President of the county council, General Mayor of Bucharest Municipality, Mayors of Districts of Bucharest, Municiaplity Nayors of administrative units, Institutions of the defense system, public order or national security, depending on the construction works intended to be performed.

Moreover, during the operation phase the key regulatory documents to be obtained are:

- License for the commercial exploitation of the electricity and thermal production facilities in cogeneration, issued by ANRE in Energy within 30 days from the date the full documentation is submitted and with a validity of 25 years.

- Environmental authorization, issued by the county Environmental Protection Agency or in exceptional cases, depending on project type or location, by the National Environmental Agency or Delta Dunarii Biosphere.
- Water Management Authorization issued by Territorial Water Management Authorities or ANAR, depending on complexity of the project [88].

5.3 Supports and Challenges for Future Development

5.3.1 Financing Mechanisms and Instruments at National Level

5.3.1.1 Legal Framework

Since 2008, Romania has promoted investments in renewable energy sector, to achieve its 2020 target of 35% renewable electricity consumption, through a GCs trading mechanism combined with a mandatory GCs acquisition fixed quota established by the regulatory authority ANRE. According to this support scheme, renewable energy producers have the right to receive GCs and sell these to the suppliers of electricity to end consumers. The GCs market is separated from the electricity one and the price fluctuates between a minimum and a maximum value which is yearly regulated [89].

This scheme applies for 15 years from the commissioning date of the power plant and benefits only to renewable power plants commissioned before the end of 2016. Therefore, until 2032, the GCs support scheme will be in place for capacities put in operation until end of December 2016 which count for approximately 3000 MW in wind power capacities and 1300 MW in solar PV plants. Subsequently, poor design and an unexpected drop in power demand caused the scheme to overheat, leading the government to impose quota reductions to limit pressure on retail electricity prices. As of 1 January 2017, no new beneficiaries could enter the scheme [90].

Anyways, the most recent changes applied by the Romanian Government in the national legislation have been collected in the *Government Emergency Ordinance no.24 of 30 March 2017*, called “the Ordinance”, aiming at striking a balance between producers and consumers interests.

- Introduction of a new way for calculating the green certificate quota that must be purchased by suppliers for every MWh of consumed electricity. This includes the total quantity of GCs estimated to be issued between 2017 and 2031 (including the GCs temporary suspended from trading during 2013 and 2014) divided by the number of years left until the end of the support scheme. This annual static quota will be calculated every two years by ANRE. For instance, for 2017-2018, the Ordinance provides for a static annual quantity of GC of 14,910,140 GCs.
- Extension of GCs validity issued after 1 January 2017, and that of those postponed from 1 July 2013, until the end of 2031. This measure minimizes the risk that GCs expire, given their previous validity of 12 months.
- From September 2017, introduction of dedicated centralized market operated by OPCOM (Romanian gas and electricity market operator) for GCs trading in order to ensure the anonymity of parties involved. Therefore, bilateral sale-purchase agreements market will be forbidden unless for existing agreements.
- Prohibition of repeated transactions of GC as a measure against market speculation.
- Setting new minimum and maximum trading values to 29.4 and 35 EUR/GC respectively (unchanged for 2017 and 2018). Also, the penalty for electricity suppliers not acquiring the compulsory number of GCs will be lowered from 110 to 70 EUR/GC.
- Introduction of provisions limiting the medium impact on end-consumer invoices to 11.1 EUR/MWh.

To counter oversupply, ANRE announced that it will increase the annual quota of certificates suppliers must procure. For 2018, it will be 0.346 per MWh and, moreover, from 2019 the number of certificates available will be linked to demand. However, since as it is now Romania is no more an attractive market to invest in renewable energy, the investors expect that grid parity will be achieved, a new support mechanism will be implemented, or that at least long-term bilateral negotiated PPAs will be allowed [91].

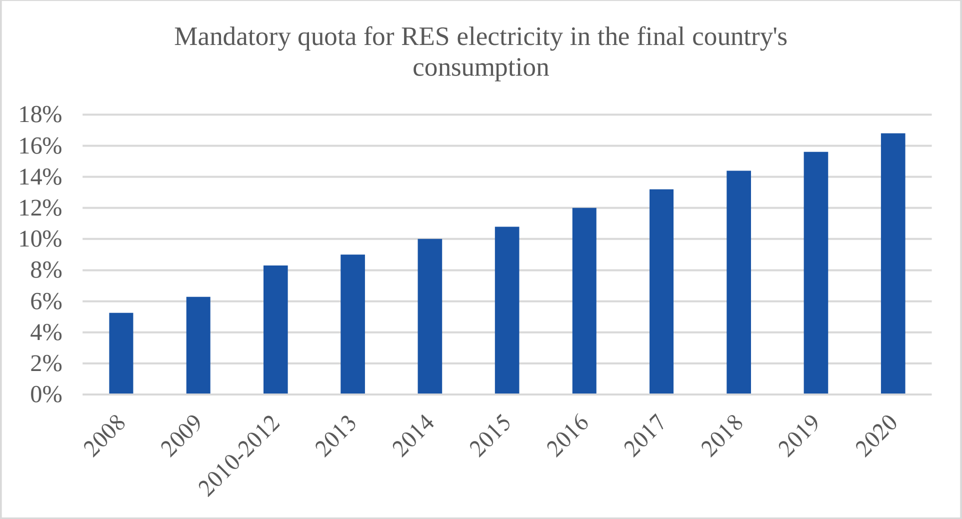


Figure 52: Historical development of mandatory quota for electricity produced by RES in the final total Romanian consumption [81]

5.3.1.2 Other Business Models

- Contracts for Difference

The GCs system has undergone numerous changes that reduced substantially the original support and lead to a steep decline in investor confidence. Therefore, on March 2019, the Romanian Ministry of Energy and ANRE have proposed to replace the quota regime with a new premium system inspired by the British CfD system, to start from 2021, that does not impact the final price of electricity paid by consumers and targets both the renewables and nuclear sector [92] [93].

The scheme helps producers using low-carbon technologies as eligible producers get access to the support generally through auctions, while base-load technologies such as nuclear may be subject to an individually negotiated CfD. They sign a private law contract, valid until the investment is recovered, with OPCOM S.S., the Romanian power and gas market operator and agree on a "strike price" which producers will sell electricity at. If the market price, referred as reference price and set annually as the average price on the day-ahead market, falls below the strike price, the counterparty will reimburse producers the difference. Likewise, if the market price exceeds the strike price, the producers will reimburse the difference to the counterparty [78].

Unlike the current renewable energy support scheme, a CfD-type mechanism can provide additional benefits and create an attractive and predictable environment for investors such as:

- Eliminating exposure to volatile wholesale prices and, therefore, improving revenue safety and stability
- Avoiding overcompensation of producers when the electricity price increases above the exercise price
- Protecting producers from price fluctuations on the market and consumers from support payment when the market price of electricity increases
- Guaranteeing a contractual agreement under the law over a predetermined period which provides flexibility for project developers and protection against unanticipated changes
- Addressing the risks related to long-term investments by creating a clear and transparent framework
- Targeting the lowest price offered by an investor/developer by benefitting from the CfD mechanism based on auctions
- Leading to a more efficient allocation of capital expenditures in the context of constructing RES power plants [86]

The downward trend of technology costs as well as the national RES potential may support Romania to ensure a favorable regulatory framework that allows the development of adequate financing mechanism/instruments both for investors and consumers. Within LCOE, the financing cost accounts for a significant share beside initial capital cost, operating and maintenance cost, and capacity factor. Moreover, while technological development leads to the decrease in the costs of required initial capital, the decrease in O&M expenditure and the increase of the capacity factor, financing costs must be minimized through financing mechanisms and instruments [82].

- PPAs

Romania is looking into adopting regulations to allow corporate PPAs to boost the stagnant renewables sector. According to NECP 2021-2030, legislation will be amended to offer possibility to the final costumers and projects developers to conclude, on centralized markets, a long-term contract which can attract private funding. However, legislative adjustments mitigating contractual risks, are needed to allow all participants to the electricity market to sign PPAs and, therefore, stimulate investment in RES, lower the cost of their integration, and increase the bankability of investment. In addition, restricting the centralized energy market in Romania often puts electricity producers in a situation of losing financial value through the impossibility of direct bilateral contracts with external buyers [94].

According to Deloitte studies, the quantity of RES electricity purchased/produced at global level amounted to 465 TWh in 2017 and PPAs become preferred instruments to secure electricity particularly by large companies. Furthermore, 66% of the 100 largest companies in the world set targets regarding the consumed energy produced by using RES and many of them joined RE100, a group of 140 companies (2018) undertaking to purchase 100% of consumption from renewable sources.

In 2018, ANRE launched an initiative which seemed to be a step forward in the attempt to create favorable conditions for investors in new production units. A process of public consultations was released regarding a Regulation on the organized trading framework on the centralized market for the award of power supply contracts for very long periods (which are very similar to PPAs). Indeed, this regulation gives the possibility to operators, which have concluded a connection contract with a grid operator concerning the connection of a power plant or combined heat and power plant, to trade the produced electricity based on the concluded contract on the long-term centralized market. Therefore, this contract can be used as a security instrument for cash flows before a bank or financing institution and, moreover, the contracted price can be adjusted upon delivery by reference to the date of conclusion of the contract through the use of specific indicators published by the electricity wholesale market operator for the centralized electricity markets. However, the trading framework provides that the bid must include well-defined characteristics regarding the quantity of electricity offered for purchase/sale, the time slots for supply, the contractual term, the requested/offered price and the supply terms, the payment and security, firmly established upon their placing on the market [82].

Under these circumstances, however, this trading instrument' attractiveness for market participants appears to have limitations:

- Impossibility of implementing all versions of PPAs, such as “on-site” or “near site” contracts which limit certain grid-related costs
- Profiling productions eliminated renewable energy producers
- The limit of at least 3 participants to submit bids
- Participation fees must allow the unprohibited access to the market
- Total transparency of the contract is unacceptable
- The signing of a contract without knowing the partner may be incompatible for companies listed on the stock exchange and not only for them
- The duration of a PPA implementation process is not determined
- Certain parties usually involved in new projects, for instance financing institution and law firm, are excluded from this process
- There can be no aggregators
- The fixed contractual term, a certain contract validity terms is required [82].

- CMBC

NECP draft regulation considered creation of a new type of trading of the centralized market for bilateral electricity contracts (CMBC) called “CMBC-flex” according to which contracts are awarded through extended auctions with the use of products to ensure flexibility of long-term trading. In the CMBC-flex trading model, the daily delivery profile may have an hourly power variation of up to +/-25%, subject to mutual notification of the amount of electricity in the contract, and the time interval of the delivery profile may vary by +/-1 hour, provided that the number of hours in the range is constant. However, it remains to be seen if the CMBC-flex trading will pass the market test and will be assimilated to PPAs [94].

- Green Bonds

Since 2014, “Green Bonds” have started to be issued by organizations, financial institutions, and other enterprises as means of promoting projects involving energy from renewable sources. Then, since 2015, all over the world and especially in the United States, the green bond market has seen a significant growth. However, the market is still young, and investors continue to allocate a small part of their capital for RES investments. In Central and Eastern Europe, five countries have already entered the green bonds market with a subscription volume worth 2.3 billion EUR. Therefore, also the regional market is experiencing an upward trend and it defines three main types of green bonds: those issued by the Government, those issued by the public sector/State companies, and those issued by the corporate environment. Furthermore, the market growth potential is determined both by a regulatory framework favorable to RES development and by the investors’ awareness of sustainable development options’ support.

In Romania, the potential for the green bonds market’ development is coupled with the appearance of preferential factors such as initiatives by the Government, stable legislative framework, and adjustment of the investors’ preferences which would result in a favorable investment environment. Moreover, the EU legislation will encourage national initiatives in order to meet the RES targets and stimulate activities of investment in RES, among which the issuance of green bonds [82].

5.3.2 Financing Mechanisms and Instruments at EU Level

During the period 2001-2018, the entire SEE region benefitted from 17.8 billion EUR in renewable energy investment, excluding the ones from large hydropower projects. An estimated 94% of the investments went to power-sector projects, while about 5% to transport sector and 1% to heat sector.

In terms of technology, wind was clearly dominating with 60% of the total cumulative of clean energy investment, followed by solar with 23%, small hydropower with 9%, bioenergy with 8% and geothermal with less than 1%. However, in the past two years, solar PV has been benefitted by new investments, and wind has been preferred compared to small hydropower and bioenergy [78].

In detail, for the period 2014-2020, European Structural and Investment Funds (ESIF) have set the goal of investing in energy efficiency and renewable energy sources. Therefore, between 2021 and 2030, the EU will supply instruments to allow the continuity of ESIF through programs such as InvestEU which will unite the multiple support mechanisms of the EU offered to Member States in the period 2021-2027. Furthermore, the legislative *Clean Energy Package* proposes cooperation mechanisms aiming at encouraging cross-border cooperation between EU countries. These mechanisms are:

- NER 300, which finances demonstration projects related to innovative technologies in the field of RES. It is a funding instrument based in the revenues available further to the auctioning of 300 million of carbon emission allowances, and therefore it is not part of the general budget of the EU.
- Modernization Fund, which gives incentives to the 10 low income Member States including Romania as regards the modernization and decarbonation of their energy systems. Romania will receive 12% of the Modernization Fund (at least 27 million allowances), therefore if the price of a tone of carbon dioxide were 25

EUR, the country would have at its disposal an amount equivalent to over 900 million EUR, which would have to be directed to projects considered priorities and which may benefit from 100% funding.

- Projects of common interest (PCI), which will contribute to the achievement of the final goals of the Energy Union: ensuring accessible, secure, and sustainable energy for all Europeans. In Romania, five projects have been included on this list as part of *Priority Corridor No.3* on electricity, called “North-South Electricity Interconnections in Central Europe and South Eastern Europe”. According to Transelectrica, their implementation, together with the projects included in the *Plan for the Development of the Electricity Transmission Grid 2018-2027*, will lead to the achievement of the interconnection target of 15% for 2030 [82].

5.3.3 New Investments and Key Actors

Romania was one of Europe's most attractive countries for clean energy investment thanks to its GC scheme and robust economic growth. Investment in renewables projects grew from 588 million EUR in 2010 to 1.8 billion EUR in 2012, and GC prices traded at the ceiling price (60 EUR per certificate) until 2013. During this boom, the major investors in Romania's energy market were the European Investment Bank, EBRD as well as BNP Paribas, UniCredit, and Citigroup. However, government quota reductions in 2013 made investment activities decrease until falling to just 35 million EUR in 2015. In 2014, with quotas cut and mounting GC oversupply, prices crashed to the official floor of 30 EUR/MWh in 2014. Producers struggled to find off takers for their GCs, causing market distress to the point of developers disassembling operational wind farms. Fortunately, in the last years the country has started to invest again in clean energy focusing mostly in energy smart technologies and, in lower share, biofuels, solar, and wind [80].

The top renewable energy project owners are CEZ Group with 609 MW of renewable installed capacity, EDP – Energias de Portugal SA with 600 MW, and Enel SpA with 505 MW. Then also Verbung AG and Monsoon Alma Srl have respectively 199 MW and 195 MW of renewable installed capacity. Moreover, the top Romanian project lenders are mainly banking companies and in detail the largest shares are covered by European Investment Bank with 535.88 million USD, BNP Paribas with 367.30 million USD, and Unicredit with 201.13 million USD [81].

For what concerns wind energy, the players currently owning the largest shares of the national wind energy installed capacity are in order CEZ Group, Enel Green Power, and EDP. CEZ Group (Czech Republic) operates a 600 MW wind park at Fantanele/Cogealac, which involved an investment of 1.1 billion EUR. Fantanele wind farm (347.5 MW) is operational since 2011 and Cogealac wind farm (252.5 MW) is operational since November 2012. CEZ continues its investment policy in Romania with 400 million EUR targeting development through acquisitions in renewable energy. Then, ENEL Green Power (Italy) has an installed capacity of around 500 MW in Dobrogea region, and it has connected, in late 2012, three new wind farms to the grid of 206 MW (Elcomex EOL, Targusor and Gebelesis) which involved an investment of 340 million EUR. Lastly, Energias de Portugal (Portugal) has an installed capacity of 285 MW both in Dobrogea and Moldova counties which involved an investment of nearly 430 million EUR.

However, there are other players such as Tomis Team and Verbund which own significant amount of under construction capacity. Specifically, Tomis Team is the owner of Tomis Team Dobrogea, a 600 MW under construction wind power plant located in Tulcea/Constanta region which will equal in capacity the current largest wind power plant in the country, called Fontanele-Cogealac and owned by CEZ Group. In addition, Verbund (Austria) is developing a 225 MW wind farm project in Casimcea in two phases, which involves 300 million EUR [80].

Nonetheless, since the total approved capacity in the country is relevantly higher than the commissioned and under construction one, the wind energy market is planned to change its balance. In particular, the largest change will be related to Eolica Dobrogea with its 1666 MW approved installed capacity in Tulcea and Constanta counties. The company is based in Switzerland but develops and implements wind energy projects in Romania. Moreover, also Sinus Holding and Green Energy are players which already enter the market with respectively 700 MW and 200 MW approved installed capacity.

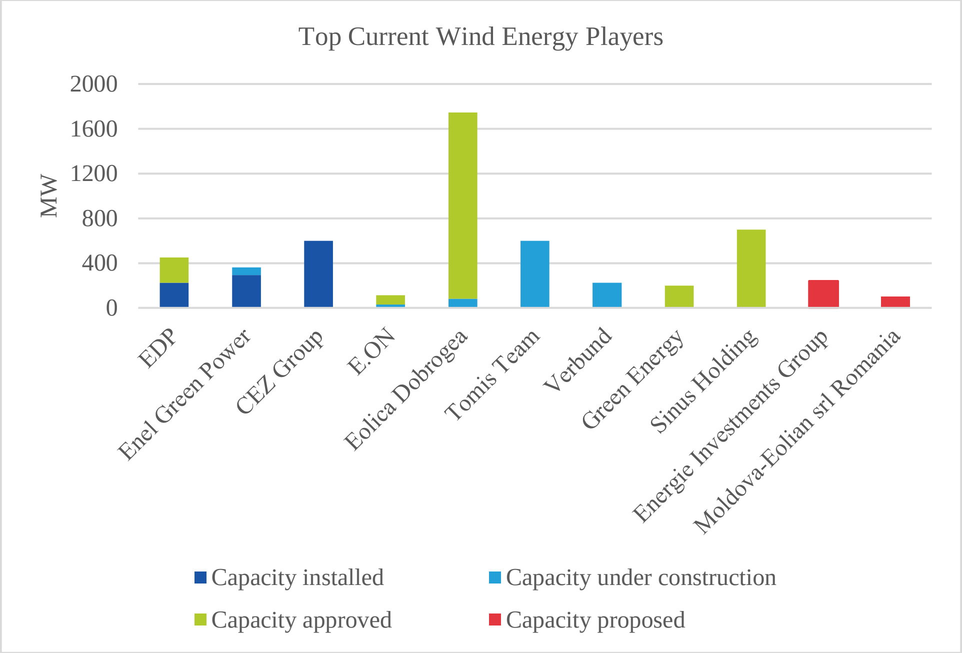


Figure 53: Top players in the current Romanian onshore wind market [87]

5.3.4 Main Barriers

Renewable project delivery has historically been slowed by limited grid capacity exacerbating, therefore, the country's green certificate oversupply by not allowing for exports to neighboring countries. In addition, another key barrier for renewable developers was related to land and planning due to lack of transparency, uncertainty over ownership and red tape. More generally, Romania scored in the bottom of the *Bloomberg Country Risk Assessment July 2018* and it has been seen particularly weak for its financial and political strength [81].

- Characteristics of current electricity trading framework

One of the most relevant criticalities to the development of renewable energy sources is the available trading framework in Romania. In line with OPCOM rules, a producer of electricity from RES, with units with installed capacity higher than 3 MW, should contract on the wholesale market a quantity of electricity with a pre-established time. Therefore, the impossibility of supplying the contracted energy due to the variable nature of RES production because of unperfect weather forecast, is severely penalized on the balancing market. On the other hand, other producers operating on the retail market in Romania, conclude supply contracts with customers based on variable profiling depending on the consumption of these customers whose can terminate unilaterally the contract without any penalties applied, subject to a 21-day prior notice. On the wholesale market, even if the notice period were similar, the option of the unilateral termination of contract implies the payment of penalties which significantly increase the trading costs of the market participants. Moreover, the sale/purchase of electricity on markets operated by OPCOM is accompanied by the obligation of submitting security instruments which increase the trading costs. Moreover, the inadequacy of the trading framework is also the result of the size of the balancing market. In fact, a balancing market on which the traded quantities are high is the proof of its non-adjustment to the needs of the market participants which generates additional costs [82].

- Limited access to the grid

Limited grid capacity has historically slowed renewables project delivery. For safe operation of the National Energy System (NES), Transelectrica uses a calculation methodology for the power received from wind and PV power plants based on availability of the fast tertiary reserve both for increase and decrease. Moreover, using the same calculation criteria, procedure aims at evaluating the influence of installed wind and solar capacity on the required reserves in NES in the following year, but also at indicating the power produced by wind and PV power plants. Thus, the current regulatory framework allows the installation of new wind and PV power plants depending on the availability of sun and wind as well as hydropower and natural gas in the capacity of suppliers of the fast tertiary reserve. Even in the case of unlimited integration of RES in the grid in terms of safe operation, the transmission and distribution infrastructures' conditions are not optimal because of shortcomings and challenges from a technological point of view requiring significant investments for upgrading, digitalization, reinforcement, extension and increase in the interconnection of the grid [82].

- Costs for connection to the grid

According to the Romanian Wind Energy Association (RWEA), the total costs for connection and reinforcement of the transmission grid in case of a large wind farm may reach 120,000 EUR/MWh, meaning 10% in addition to the initial costs (equipment, materials, etc). In fact, Romania is classified as deep transmission tariffs country, which means that the new electricity production units have to fully cover the costs for the extension of the grid, including the distribution grid [82].

- Unpredictable fiscal framework

Recent examples of this unpredictability are the proposal for amendment of the Fiscal Code to include the towers supporting wind turbines in the category of building for which local public administration authorities may change local taxes and duties and the *Government Emergency* which provides for the obligation of producers to pay a contribution of 2% of the turnover for supplies of electricity [82].

- Geographical expansion of the resource

One of the particularities of NES is that almost the entire production of energy from RES is located in Dobrogea. One of the many effects of this concentration is that wind production varies often across a wide power interval, from zero to almost close to the installed capacity and therefore this transmission operator is subject to dangerous technical stress. For instance, during the periods of strong wind in Dobrogea, Transelectrica must evacuate to the west/north-west part of the country approximately the entire wind and nuclear energy produced, while when wind intensity decreases, the National Energy Dispatcher must order rapid increase of power which negatively effects the lifecycle of those energy units. In order to maintain the decrease in GHG emissions occurring due to the transformation of the industrial sector, RES investments will be necessary but possible only with a stable and adequate framework reflecting in a minimum cost of capital for investors and, implicitly, in a sustainable contribution of the energy sector to the national decarbonation targets [82].

- Slow progress of digitalization

The digitalization rate in the Romanian energy system is slow because of the regulatory authority reluctance to assess the benefits of the process after dealing with initial high costs. Therefore, the implementation of a basic component of digitalization such as smart metering has been postponed being completed by 2028 [82].

6. Pre-feasibility Study

6.1 Methodology

Wind energy is attracting a lot of investments in recent decades and, as the market is increasingly competitive, minimizing costs and increasing production is crucial for the design of new wind farms. From a wind energy production perspective, the screening of an upwind turbine on the downwind turbine is a big loss called “wake effect”. The optimization of a wind farm layout, therefore, aims at minimizing this effect in order to increase the electricity production and, therefore, revenues. Furthermore, from an economic point of view, policy framework, electricity price, PPA bids’ level, and technology limitations imposed by the government have a strong impact on the project profitability.

After a deep understanding of the energy markets in Sweden, Poland, and Romania, with focus on wind energy, a pre-feasibility study of wind energy projects in the three countries has been developed. As these three countries are featured by very different energy mix and market and have been following distinct energy policy paths during last decades, this comparative analysis results interesting and worthwhile.

For all countries, four phases have been followed in order to obtain results enabling the desired comparisons:

1. Selection phase. In the first part of the project, a market research was carried out to decide a proper wind farm size and wind turbines type based on the recent investments’ most common selections. Moreover, the site was selected, and wind speeds and directions data were gathered.
2. Technical phase. The optimal turbines positioning derives from a wake losses calculation. Once the final topological layout was obtained, the analysis followed with capacity factor and annual energy production calculations.
3. Economic phase. After studying the national framework evolution and the PPA market potential, the wind farm profitability was calculated by using some economic indicators such as LCOE, NPV, IRR. Moreover, through some sensitivity analysis, the most impactful parameters can be observed.
4. Comparison phase. Lastly, the three countries’ results were compared, and the national markets potentials were sized.

6.2 Selection Phase

6.2.1 Wind Farms and Wind Turbines Data

The wind farm installed capacity as well as the wind turbines' type and capacity were assumed to be equal in all projects located in Sweden, Poland, and Romania. This choice gives the opportunity to better compare the influence of the market prices, progression, and frameworks on the wind farm profitability without need to consider big differences in the electricity production.

The average capacity in the current investment in Sweden (2017-2022), 110 MW, was used as a guide for sizing reasonably the wind farm [39]. The total installed capacity, therefore, was fixed at 100 MW, while the selected wind turbines capacity at 4.2 MW, meaning 24 turbines per wind farm. Regarding the wind turbines type, Vestas was chosen as the most common wind turbine manufacturer in Sweden and globally. The most suitable model according to the selected sites' average wind speed was Vestas V150, with rotor diameter of 150m and hub height of 123m. This model allows reaching high heights, leading capacity factor in low wind conditions, significant increase in annual energy production, and low sound power level to reduce the impact on surroundings [95]. Since, the three selected countries are featured by These features have been carefully matched with the assumed countries' limitations of 200m maximum tip height and 150m maximum rotor diameter.

	Data	**Comments**
Wind farm size (MW)	100	Average capacity current investment 2017/2022: 110 MW [39]
Wind turbines capacity (MW)	4.2	Predicted installed capacity per turbine 2020-2021: 4-4.2 MW [35]
Number of wind turbines	24	

Table 9: Wind farm data

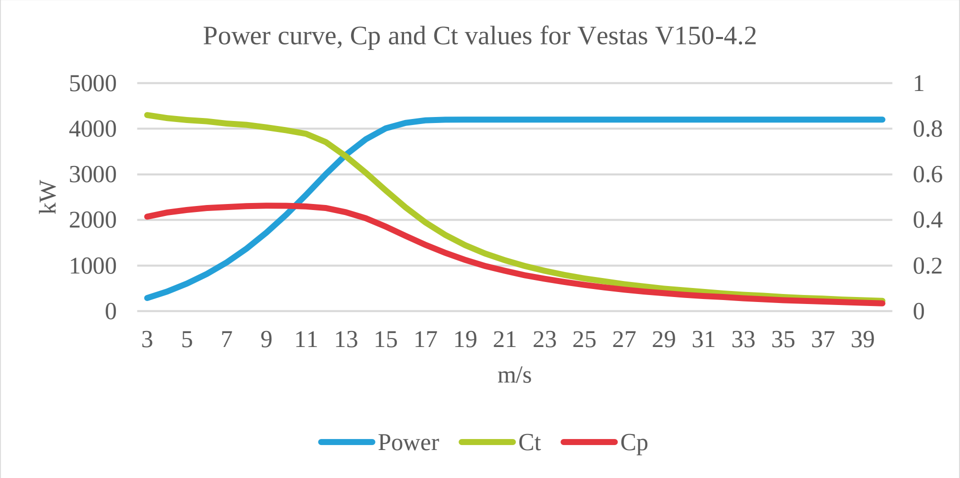


Figure 54: Vestas V150-4.2 power curve and power and thrust coefficient curves [95]

6.2.2 Wind Farms Sites

For what concerns the wind farm location, numerous factors need to be taken into consideration such as wind data, terrain characteristics, existing grid connection points, availability of incentives or favorable markets for signing Power Purchase Agreements. In Sweden, Västerbotten, which is located in electricity bidding area two, was selected as strategic position. Indeed, the higher number of current investments is in SE2, given lower electricity price, land availability, and PPAs opportunities. Specifically, the wind farm was assumed to be in a less densely populated area, with a terrain mainly dominated by forests but, however, easy access to roads enabling fast and uncomplicated transportation. Another advantage of the selected location is the close distance to a 380 kV transmission line (25 km) and a substation called Grundfors (41 km) [96]. The site is featured by third wind class, which fits the chosen wind turbines' type, and wind speed average at hub height of around 6.5 m/s.

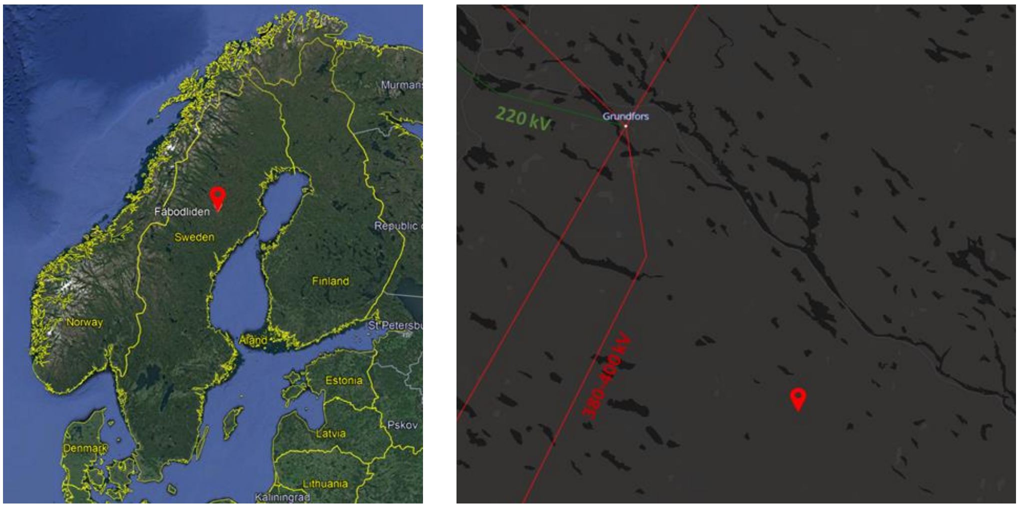


Figure 55: Wind farm location in Sweden (lat. 64.603° and long. 17.984°) and map of the closest transmission lines and substation [96]

Similarly, in Poland and Romania, the same wind farm size and wind turbines' type were considered, while the locations were selected according to similar wind speed average at hub height as the Swedish case and paying attention on the mostly chosen areas for wind energy projects due to good wind conditions, favorable government limitations, and high profitability. Poland's northern regions profit particularly from the Baltic Sea winds and, therefore, Pomeranian is a profitable area for wind farms. Furthermore, as Tulcea and Costanta regions in Romania account for the major share of wind projects, a specific location in Tulcea with average wind speed of around 7 m/s was selected for the wind farm pre-feasibility study.

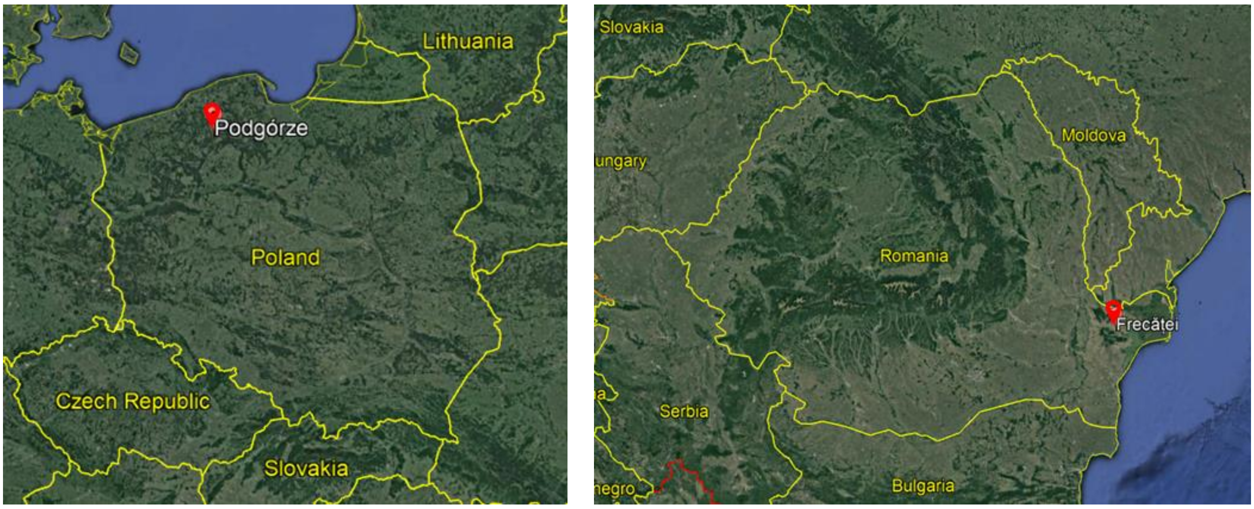


Figure 56: Wind farm location in Poland (lat. 54.123° and long. 17.208°) and Romania (lat. 45.129° and long. 28.685°)

6.3 Technical Phase

The technical phase objectives are the estimations of annual energy production (AEP) and capacity factor. First, in the micro siting, turbines were positioned and spaced 7 times the rotor diameter length between rows and 4 times the rotor diameter length between columns, meaning 1050 and 600 meters, respectively. The triangle shifted disposition was chosen in order to reduce the impact of the first-row turbines on the wind facing the second-row ones [11].

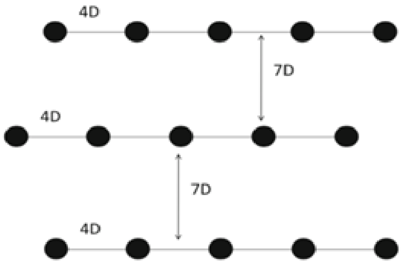


Figure 57: Turbines distances and distribution [11]

Wind turbine wakes are one of the most important aspects in wind power meteorology because they decrease electricity production and increase the loading of downstream wind turbines. A key aspect of a wind farm design is using a proper wake model to predict performances and plan wind power plant control strategies. The Jensen wake model is the wake modelling method used in this design and one of the most popular models among engineering applications due to its simplicity, practicality, and robustness. Using a specific control volume and assuming a top-hat inflow profile and a linearly expanded wake function of the downstream distance x at a rate $a = \frac{u_0 - u_r}{u_0}$, the normalized velocity can be found as $\frac{u_w}{u_0} = 1 - \frac{2a}{(1+2ax/D_r)^2}$ with u_0 undisturbed wind speed, u_r wind speed at the rotor level, D_r rotor diameter, and u_w wind speed after passing the wind turbine [97].

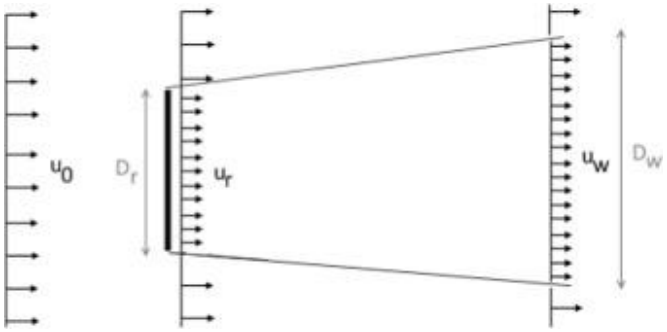


Figure 58: Control volume of the Jensen wake model [97]

Using the layout with turbines positioned with reasonable distances and the wind rose at hub height obtained due to annual data collection of wind speed intensities and directions [98] [99], the Jensen single wake model was applied to every angle in the range 0°-180° in order to get the optimal layout orientation that reduces as much as possible wake losses and maximize, therefore, energy generated.

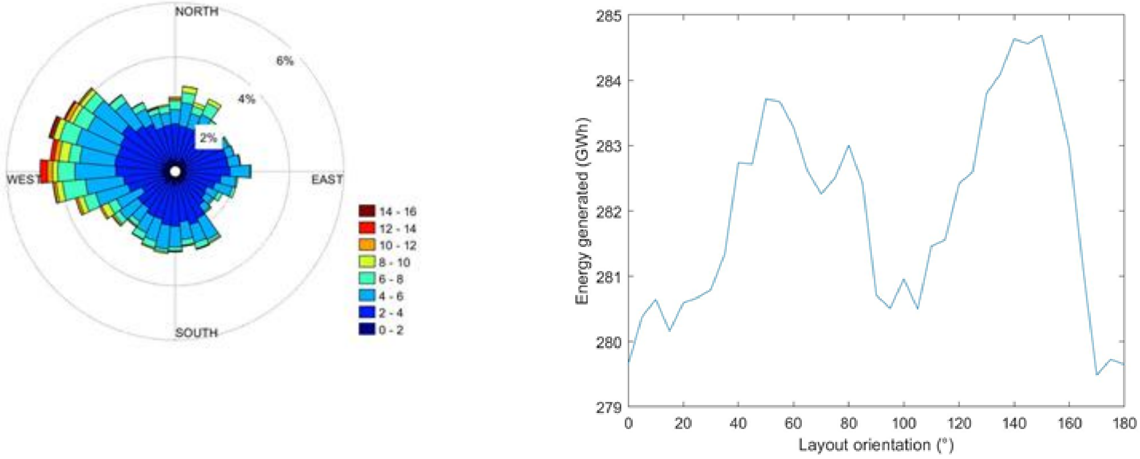


Figure 59: Wind rose in selected location in Sweden and energy generated by varying the layout orientation

This analysis was carried out for the three locations (see Annex). Even if the average wind speed at hub height was carefully chosen to be similar in the three designs, the wind speed intensities and directions in a year were very different. Therefore, given distinct wind roses, the layouts have different optimal orientations, precisely 150° in the Swedish case, 70° in the Polish case, and 10° in the Romanian case.

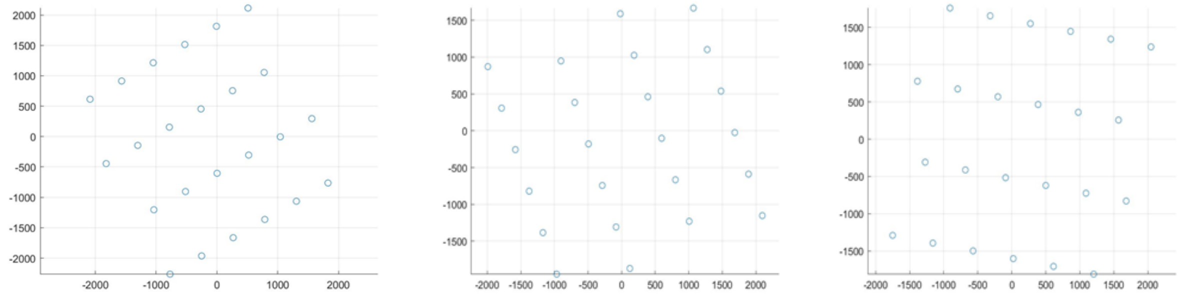


Figure 60: Final layout in Sweden, Poland, and Romania (in order)

The reduced wind speeds, output of the Jensen model, were used to calculated to annual energy productions including the wake effect. However, some other losses were assumed in the final calculations such as electrical losses, electrical grid availability, wind turbine availability, balance of plant availability, degradation surface of blades, and others. Finally, an estimation of the wind farms productivity and capacity factor were obtained.

		Sweden	**Poland**	**Romania**
Assumptions	Electrical losses	2.5%		
	Electrical grid availability losses	0.2%		
	Wind turbine availability losses	2.5%		
	B.O.P. availability losses	0.5%		
	Degradation surface of blades	0.5%		
	Other losses	0.5%		
Calculations	Capacity Factor	35.5%	38.1%	41.6%
	AEP considering only wake losses (GWh)	313.74	336.00	367.23
	AEP considering every losses (GWh)	300.56	321.89	351.81

Table 10: Estimation of AEP and capacity factor in the three wind farms

6.4 Economic Phase

6.4.1 Economic Assumptions

Estimating a wind farm’s feasibility and profitability are the principal concerns of any investor. As these examinations depend on the location’ market, electricity price, technology and grid connection costs, assuming reasonable numbers is crucial to guarantee accuracy of the results. The economic phase aims at estimating the wind farms profitability through economic indicators, based on costs and revenues, which are useful to compare different projects quickly.

First, the wind farms’ features are assumed to perfectly fit the various national limitations, so that all projects have been permitted already. The most limiting factor in Sweden is the maximum tip-height law which gives municipalities reasons to ban many wind farms proposals. Hence, the tip-height limit in this wind farm’s location, Västerbotten, is assumed to be 200 m, while the selected wind turbines measure hub height of 123 m with rotor diameter 150 m and, therefore, tip height of 198 m. Furthermore, the Polish most problematic limit is the 10H rule which imposes to build wind farms at least 10 times the wind turbine’s tip-height away from any property. In this case, as the government’ plans appear to be moving in this rule removal direction, the 10H rule is assumed to be already softened or repressed. Lastly, Romanian limitations are given in terms of wind turbines’ size, which is strongly linked to the rotor diameter. In such a case, the rotor diameter limit in Tulcea, the designed wind farm’s site, is assumed to be 150 m so that the selected Vestas V150 wind turbines fit the municipality’s threshold.

As permits are gained, the construction time is assumed to be 1.5 years and, thus, the wind farms are assumed to be operational from the beginning of 2022. From that time, the project lifetime is assumed to be 20 years. Regarding wind turbines, furthermore, their lifetime is assumed to be 25 years with a depreciation rate of 4%.

All costs are considered with an inflation rate of 2%, in common to Sweden, Poland, and Romania. Recent years’ national electricity costs’ trends were the basis of the assumed forecasted cost of electricity which vary during the project lifetime from 38 to 75 EUR/MWh in Sweden [32], from 55 to 62 EUR/MWh in Poland [100], and from 50 to 60 EUR/MWh in Romania [101]. The O&M costs and the total installed costs, including turbines costs, grid connection costs, and construction costs, have been assumed differently in the three countries according to the current price levels [37]. The difference in the total costs among the three countries can be explained by analyzing the wind energy installations. The Polish wind energy market is not traditionally accustomed to big wind turbines because of the current 10H rule, therefore the initial costs are high due to lack of market. The Romanian wind energy market is also lacking of samples because of problems in the grid. On the contrary, the Swedish costs are lower because Sweden is leader in Europe for the most advanced wind energy technologies.

Regarding revenues, 60% of the produced electricity is supposed to be sold through a PPA contract for 10 years at PPA bid prices, which are consistent with the average current bids in the three countries. Thus, the rest of the production is dependent on the electricity market price forecasts as it is sold to the national grid.

		SWEDEN	POLAND	ROMANIA	Comments
Assumptions	Permitting phase	Tip-height limit in Västerbotten assumed to be 200m	10H limit has been softened or removed	Rotor diameter limit in Tulcea assumed to be 150m	Projects have been permitted
	Timeframe	1.5 years of construction from now			Operational from 2022
	Project lifetime	20 years			
	Turbines lifetime	25 years			Salvage value considered
	Inflation rate	2%			
	Depreciation	4%			
Costs	Forecasted cost of electricity (EUR/MWh)	from 38 to 75	from 55 to 62	from 50 to 60	Following the recent years national trends
	Total cost (EUR/MW)	1,020,000	1,520,000	1,578,000	BNEF 2019 for Sweden and Poland [37] + European average total installed cost for onshore wind projects in 2019 [102]
	O&M costs (EUR/MW)	18,090	24,570	14,320	O&M costs in 2019 [37]
Benefits	Annual energy production (MWh)	300,560	321,890	351,810	
	PPA	60% of the production for 10 years			

Table 11: Pre-feasibility projects assumptions

6.4.2 Economic Results

These assumptions lay the foundations for estimations of economic indicators such as Levelized Cost of Electricity (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR).

The LCOE is a measure of the average net present cost of electricity generation for the power plant over its lifetime. Therefore, it represents the average revenue per unit of electricity produced that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle. Specifically, this indicator is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered [103].

$$LCOE = \frac{\sum_{i=0}^{N} \frac{C_i}{(1+r)^i}}{\sum_{i=0}^{N} \frac{B_i}{(1+r)^i}}$$

with N= project lifetime, C_i= project costs, B_i= project benefits or revenues, and r= discount rate.

The NPV is use in investment planning to analyze the profitability of a projected investment. It is calculated as the difference between the present value of cash inflows and the present value of cash outflows over a period of time. Thus, a positive net present value indicates that the projected earnings generated by an investment exceeds the anticipated costs and the project will be profitable, while an investment with a negative NPV will result in a net loss [104].

$$NPV = \sum_{i=0}^{N} \frac{(B_i - C_i)}{(1+r)^i} + \frac{S}{(1+r)^N}$$

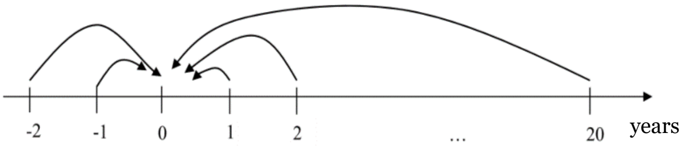
with N= project lifetime, B_i= project benefits or revenues, C_i= project costs, S= salvage based on depreciation, r= discount rate.

In addition, the Internal Rate of Return (IRR) is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. IRR calculations rely on the same formula as NPV does [105].

$$IRR = r, \ \ when\ NPV = 0$$

As the cash flows show, the investment is supposed to be entirely dove in the first year, 2020, while from 2021 the only components are O&M costs and revenues both from PPA and electricity grid sale. However, since a discounted cash flow is made of present value of future cash flows, a discount rate needs to be used. Therefore, the actualization was performed through the Weighted Average Cost of Capital (WACC) method. Many companies, indeed, calculate their cost of capital, meaning the required return necessary to make a project worthwhile, and use it as their discount rate when budgeting for a new project [106]. This value depends on market value of company's equity and market value of company's debt, cost of equity, and cost of debt.

$$WACC = \frac{E}{V} * R_e + \frac{D}{V} * R_d * (1 - T_c)$$



with E= market value of the company's equity, D= market value of the company's debt, $V = E + D$ = total market value of the company's financing, R_e= cost of equity, R_d= cost of debt, and T_c= corporate tax rate.

The WACC was calculated by using the current estimations of cost of equity and cost of debt for onshore wind energy in the three countries and by assuming a hypothetical but realistic debt to equity ratio [37] [107].

	SWEDEN	**POLAND**	**ROMANIA**
Cost of equity	6.0%	7.0%	6.7%
Cost of debt	3.5%	4.0%	3.3%
Debt to equity ratio	0.5		
Discount rate (WACC assumption)	4.8%	5.5%	5.0%

Table 12: WACC estimations

In conclusion, using PPAs bids consistent with the current average levels, meaning 29 EUR/MWh in Sweden, 47 EUR/MWh in Poland, 43 EUR/MWh in Romania, the project cash flows as well as the selected economic indicators were estimated (see Annex).

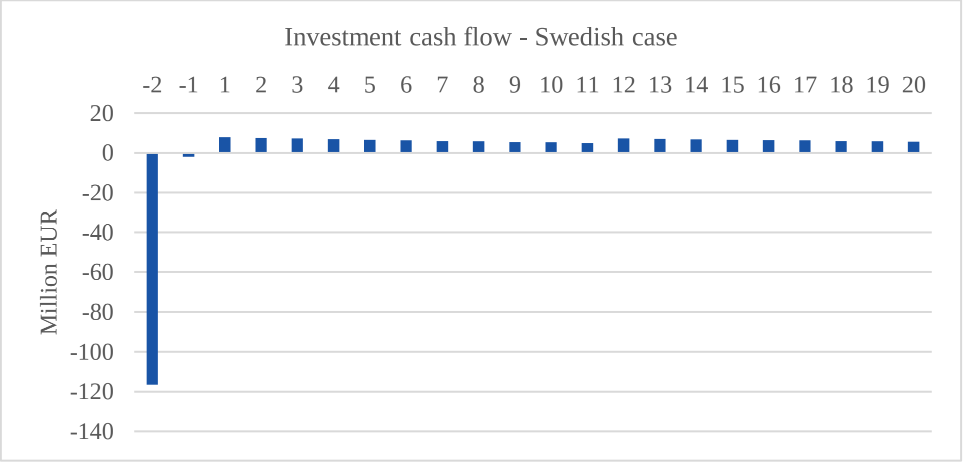


Figure 61: Project cash flow of the wind farm located in Sweden

	SWEDEN	**POLAND**	**ROMANIA**
PPA bid (EUR/MWh)	29	47	43
LCOE (EUR/MWh)	36.17	45.65	38.16
NPV (million EUR)	10.90	4.12	22.57
IRR	5.6%	5.7%	6.4%

Table 13: Economic results

6.4.3 Sensitivity Analysis

The sensitivity analysis, also referred to as what-if analysis, is a financial model that determines how variables, such as the estimated economic indicators, are affected based on changes in other known variables [108]. Considering the fact that making predictions about the future electricity wholesale prices as well as investment and O&M costs is challenging, a sensitivity analysis making the known variables varying from -60% to +60% was performed to better define how the investment profitability could change.

The factors impacting a wind farm profitability are multiple, however, in these pre-feasibility studies, the most interesting analysis can be done on investment cost, O&M costs, electricity price, and PPA bid variations.

Results show the same trends for all three countries (see Annex). First, as expected, the LCOE is not affected by the revenues from the sale of electricity, while the NPV depends both on costs and revenues. In accordance with the sensitivity analysis results, the investment cost is the most sensitive parameter for both calculation of NPV and LCOE values. Indeed, even if the positive NPVs in the design configurations mean profitability opportunity for the projects, a future increase of 40% of the investment costs makes NPVs turn into negative in all three countries. Moreover, another essential parameter is the electricity price. While, as mentioned before, LCOE is not affected by revenues, NPV is significantly impacted by nominal electricity spot price variation. Indeed, if the wholesale price decreases of about 40%, the NPV values turn into negative and the projects' profitability fails. The PPA bid variation, on the contrary, has a smaller effect on the projects' returns.

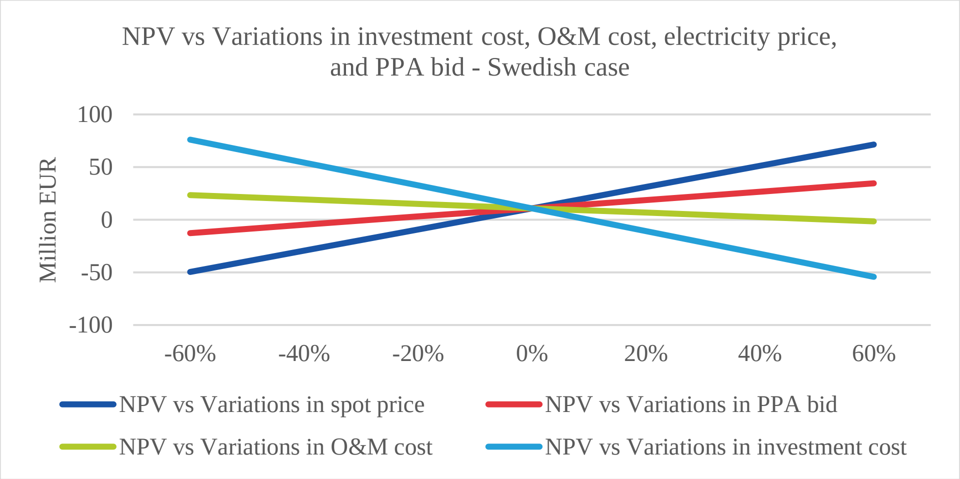


Figure 62: Sensitivity analysis on NPV by varying investment cost, O&M cost, electricity price, and PPA bid in Sweden

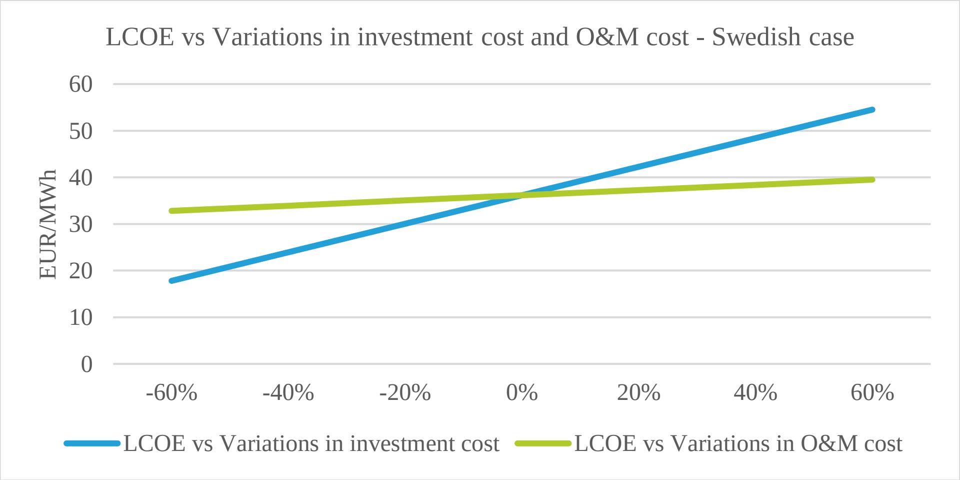


Figure 63: Sensitivity analysis on LCOE by varying investment cost and O&M cost in Sweden

6.5 Comparison Phase

From an economic point of view, the wind farms projects result feasible in all three selected countries. Indeed, the pre-feasibility studies show positive NPVs, IRRs higher than the discounted rates, and reasonable LCOEs. However, since the assumptions have a key role in the projects, it is interesting to analyze how much reasonable they are. Indeed, the profitability analysis do not bring to the same numbers and extents in Sweden, Poland, and Romania.

First, the average annual wind speed in the selected Swedish site differs of about 0.5 m/s and 0.8 m/s with the Polish location and the Romanian one respectively. This little difference, however, generates a gap in the electricity production which is automatically linked with a gap in the NPVs. Specifically, one can observe that a decrease of 1 m/s in the annual average wind speed corresponds to a reduction of 67 GWh in the AEP on average. As a consequence, this decrease in the production is linked with a difference in the NPV estimations. Therefore, as this aspect regards the specific selected sites exclusively, the overall production and profitability difference between Sweden, Poland, and Romania is considered minimized slightly.

In addition, the economic analysis is of key importance to get information on the profitability of the wind farm which can be built, however, only if permits are obtained. Therefore, the assumptions regarding the already obtained permits is at the basis of every analysis coming after. As mentioned, the limiting factors in the permitting phase of the three countries are different in terms of costs and complexity. The Swedish government has control on the maximum wind turbine tip-height, the Polish one sets the minimum distance between wind farms and houses through the 10H rule, and the Romanian limit is the grid capability. Thus, the assumptions, on which the projects are based, are not all reasonable in equal measure. Currently, the Swedish wind market is limited by the possibility of veto which gives municipalities the opportunity to set strict rules on the wind farm technological features. However, upgrades on this rule are already planned to be applied in the future. Furthermore, the Polish 10H rule is also in the process of change since the desired energy system transition needs rules promoting renewables. However, the main barrier in Romania is the grid capability because of aged infrastructures and wind farms location. In fact, the Romanian wind energy region is concentrated only in two counties due to favorable conditions. Therefore, the difference between the Swedish and Polish assumption with the Romanian one is the involvement of not only political implications and decisions, but also massive investments and expansion works.

7. Conclusions

This research focuses on onshore wind energy market in Sweden, Poland, and Romania. The initial part of the study was dedicated to the market analysis of the countries above. The first phase aiming at developing detailed current scenario was followed by the construction of future scenarios and the analysis of the potentialities as well as criticalities of the market. As a result, the markets' analysis highlighted the difficulties that the selected countries are facing at present to improve their energy systems and reach lower-carbon economy assets. The shift to renewables is a complex challenge including technological improvements, civil works, market adjustments, large initial investments, political amendments, and community's acceptance. This transition needs years and requires engagement on the part of the government as well as the citizens.

Sweden's energy policies have aimed at high share of RES since 1991 with the CO_2 taxation. Lastly, in the Energy Agreement 2016, the government drew up the new target of 100% RES electricity generation by 2040, the reduction of energy intensity and transport emissions, and the extension of the GC system until 2030. According to this research's market analysis, the Swedish key challenge is to shorten and simplify the permitting process by dealing with the municipal limitations and the veto power. Moreover, new proposals such as the "stop-mechanism" may enforce the current legal framework.

In the Polish energy system, the implementation of the Wind Farm Act in 2016 marked the beginning of a stagnation period for wind power. In fact, according to this study, the most important barriers to wind energy development are related to the 10H rule, property tax, and difficulties in funding, due to wind projects profitability decrease and risk increase. The permitting procedure is limited by inaccurate estimation of timeframes and costs as the application varies from project to project. From a grid connection point of view, the unpublished data on available grid capacity emphasizes the "queue for the connection point" phenomenon. Lastly, wind energy is impacted by production curtailment and ungiven grid access priority due to threat to the grid security.

Romania's NECP 2021-2030 aims at emissions reduction, energy efficiency increase, and renewable energy increase. However, the entire production of renewable energy is located in the south-eastern area of the country. As a result, the main country's challenges are related to technical stress in the transmission operator. The infrastructures' conditions are not optimal because of shortcomings and technical problems which require significant investments. Moreover, Romania is a "deep transmission tariffs" country, meaning that new electricity production units have to fully cover the costs for the extension of the grid, including the distribution grid.

Additional interesting results have been obtained by the pre-feasibility study of the wind farms located in the three countries. The aim of the projects was to understand how different policies and markets have impact on wind farms profitability. Therefore, keeping the same wind farm size and wind turbines model but choosing three different locations in three different country brought to relevant conclusions. The comparison among the economic results show that the most profitable project is the wind farm placed in Tulcea, Romania. However, this site has a slightly higher annual average wind speed compared to the Swedish and Polish ones. A subsequent analysis outlined that a decrease of 1 m/s in the annual average wind speed results in a decrease in the AEP and NPV. Therefore, the location selection is an impactful parameter. In addition, other sensitive indicators are related to the country market status and renewable costs. PPAs average bids, investment and O&M costs as well as electricity prices have played an essential role in the economic analysis. Essentially, the basic premises of the pre-feasibility study consist of obtaining permits and building rights and in my study, these are considered already obtained. However, the countries' permitting process bottlenecks cannot be superseded in equal measure. The political issues, for instance, can be solved by amending laws quickly and simply while technical objects requiring huge investments, such as the national grid extension, imply more difficulties and long time to be finalized.

As a result, this research has outlined a deep understanding of the three countries' profiles and the main challenges to increase the feasibility and profitability of wind farm projects. From an investor point of view, the first choice would be Sweden because of good profitability and the most advanced technology market which implies lower costs. Then, the choice would fall on Romania due to high profitability but no current opportunities to expand the wind energy market. Last, Poland would be the last investor's choice because of lower profitability and high uncertainty in the investments.

Future works might include more accuracy in the choice of the wind farm sites. It would increase the feasibility of the projects and eliminate differences in the AEP, due to various annual average wind speed. Furthermore, the economic analysis precision could raise by considering additional factors such as national corporate taxes, keen estimations of costs and future electricity prices. Lastly, the actualization of the cashflows through the WACC method would result in a precise calculation if the real company's equity and debt values were used.

Annex

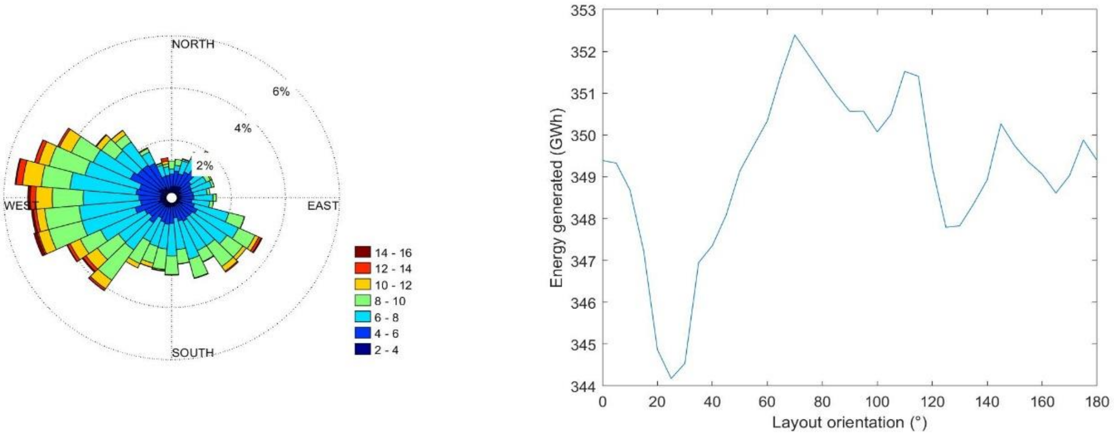


Figure 64: Wind rose in selected location in Poland and energy generated by varying the layout orientation

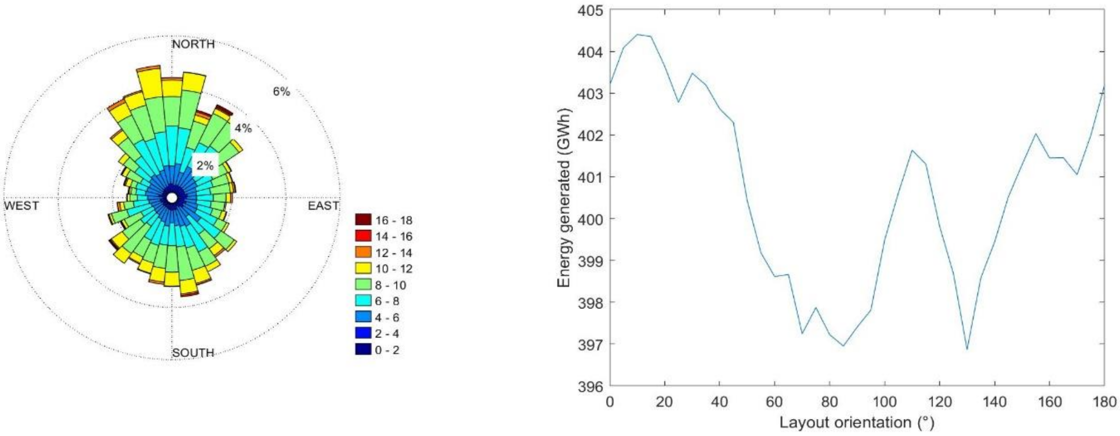


Figure 65: Wind rose in selected location in Romania and energy generated by varying the layout orientation

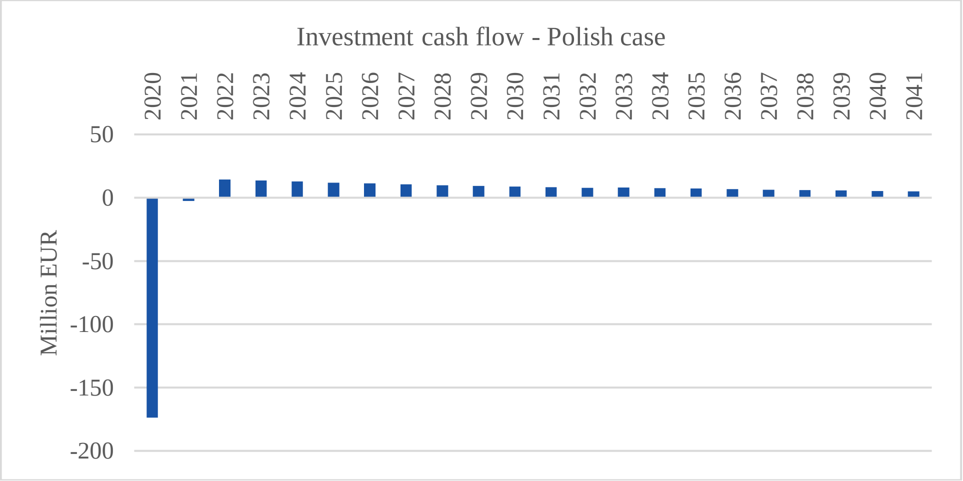


Figure 66: Project cash flow of the wind farm located in Poland

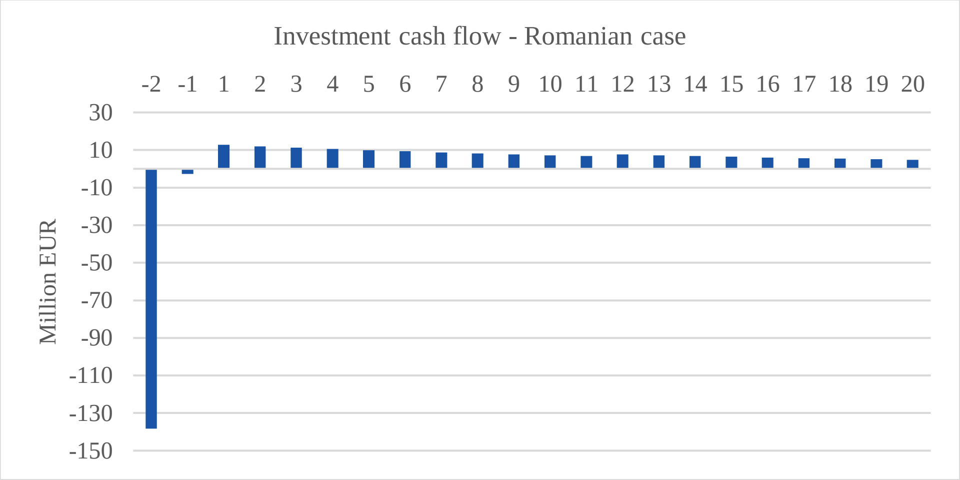


Figure 67: Project cash flow of the wind farm located in Romania

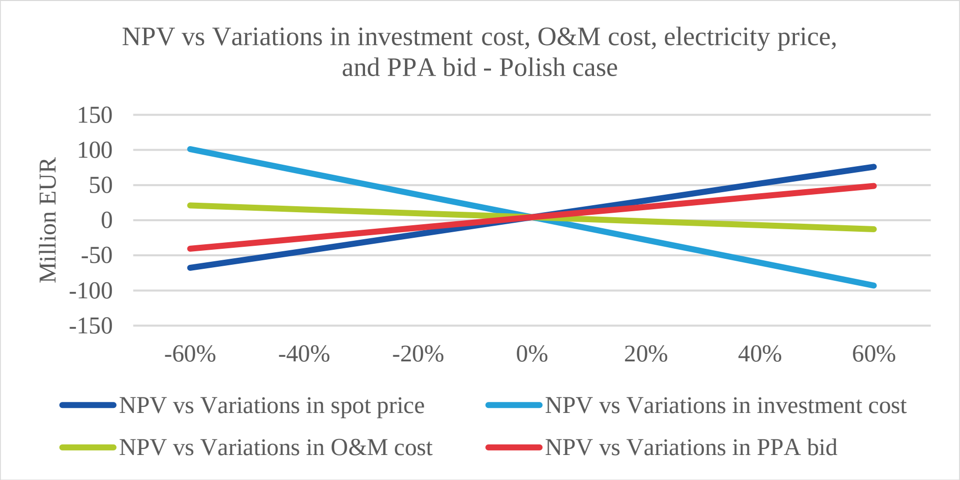


Figure 68: Sensitivity analysis on NPV by varying investment cost, O&M cost, electricity price, and PPA bid in Poland

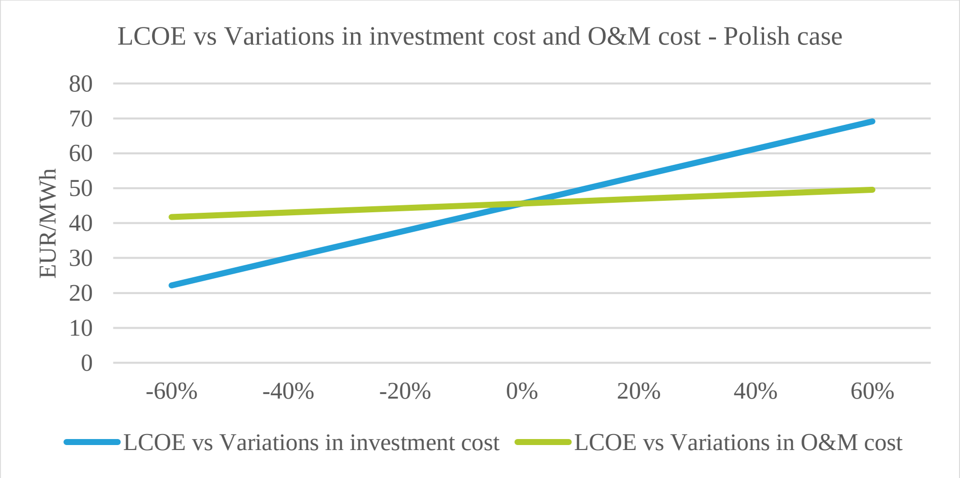


Figure 69: Sensitivity analysis on LCOE by varying investment cost and O&M cost in Poland

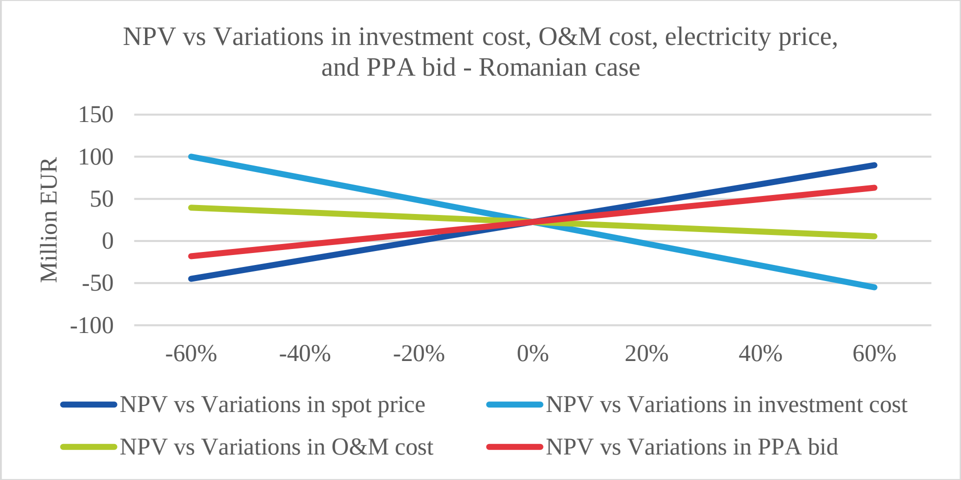


Figure 70: Sensitivity analysis on NPV by varying investment cost, O&M cost, electricity price, and PPA bid in Romania

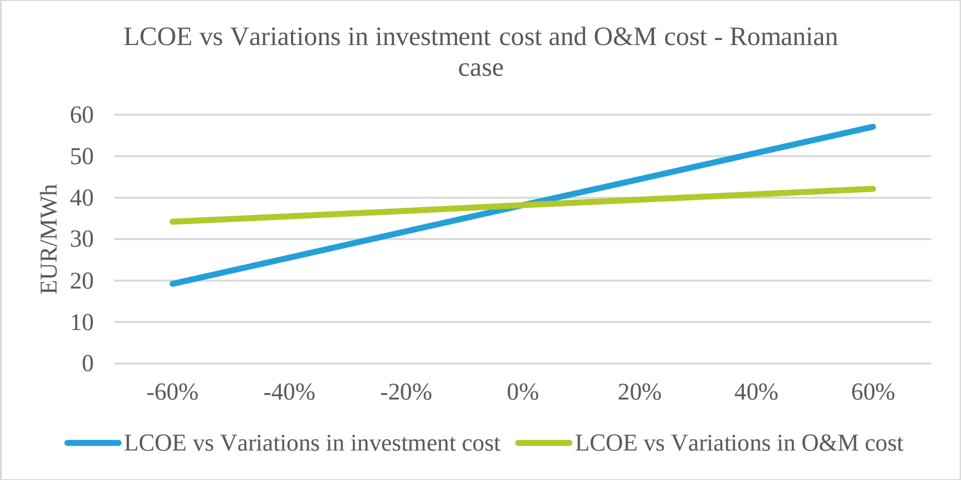


Figure 71: Sensitivity analysis on LCOE by varying investment cost and O&M cost in Romania

Matlab Codes

```
clear all
close all
clc

%% WIND TURBINES TECHNICAL SHEET AND WIND SITE DATA
technical_data = load('Technical sheet V150-4.2_just columns.csv'); % four columns:
windspeeds, power, ct, cp
wind_site_data = load('wind_data_site_justcolumns_R.csv'); % two columns: direction,
intensity
P = 4.2; %[MW]
wind_speeds = technical_data(:,1);
power = technical_data(:,2);
Ct = technical_data(:,3);
Cp = technical_data(:,4);
% coefficients curves plots
figure
plot(wind_speeds ,Cp);
hold on
plot(wind_speeds ,Ct);
title ("Coefficients curves")
legend ("Power coefficient", "Thrust coefficient");
xlabel ("Wind speed [m/s]");
xlim([3 22.5])
% power curve plot
figure
plot(wind_speeds,power);
title ("Power curve")
xlabel ("Wind speed [m/s]");
ylabel("Power [kW]");
xlim([3 22.5])

%% LAYOUT PARAMETERS
column = 6;
col_dist = 600; %[m]
row = 4;
row_dist = 1050; %[m]
num = column*row;

%% OPTIMAL ANGLE TEST
index = 1;
for angle = 0:5:180
%figure
[xy] = grid_layout_triangle(row , column , angle , row_dist , col_dist);
grid_col = xy(:,1);
grid_row = xy(:,2);
%plot(grid_col,grid_row, 'o')
% reduced wind speeds
D = 150; %[m]
k = 0.075;
Ct_values = [0 0 Ct' 0 0]';
Cp_values = [0 0 Cp' 0 0]';
wind_dir = wind_site_data(:,1);
wind_int = wind_site_data(:,2);
Ct_u = [0 2.99 wind_speeds' 22.51 100]';
[u2] = reduced_wind_speeds(xy,D,k,wind_int,wind_dir,Ct_values,Ct_u);
%reduced energy generated
Cp_u = [0 2.99 wind_speeds' 22.51 100]';
[E_sum] = energy_generated(num , D, Cp_values , Cp_u , u2, 1) * 10^-9;
energy_values.value(index) =  E_sum;
energy_values.angle(index) =  angle;
index = index+1;
end
% Reduced energy generated vs layout orientation
figure
title ("Energy generated for different layout orientations");
```

```
xlabel ("Layout orientation [°]");
ylabel("Energy generated [GWh]");
plot(energy_values.angle,energy_values.value)
% Max reduced energy generated and corresponding layout angle
[E_max_value, E_max_index] = max(energy_values.value);
angle_E_max = energy_values.angle(E_max_index);

%% GRID LAYOUT WITH OPTIMAL ORIENTATION
figure
[xy] = grid_layout_triangle(row , column , angle_E_max , row_dist , col_dist);
grid_col = xy(:,1);
grid_row = xy(:,2);
title ("Final layout")
plot(grid_col,grid_row, 'o')
scatter(xy(:,1),xy(:,2))
grid on
hold on
axis on
axis equal

%% REDUCED ENERGY GENERATED IN OPTIMAL ORIENTATION
% reduced wind speeds in optimal orientation
D = 150; %[m]
k = 0.075;
Ct_values = [0 0 Ct' 0 0]';
Cp_values = [0 0 Cp' 0 0]';
wind_dir = wind_site_data(:,1);
wind_int = wind_site_data(:,2);
Ct_u = [0 2.99 wind_speeds' 22.51 100]';
[u2] = reduced_wind_speeds(xy,D,k,wind_int,wind_dir,Ct_values,Ct_u);
% reduced energy generated in optimal orientation
Cp_u = [0 2.99 wind_speeds' 22.51 100]';
[E_sum] = energy_generated(num , D, Cp_values , Cp_u , u2, 1); %[Wh]

%% CAPACITY FACTOR
hours = 8760;
capacity_factor = E_sum /(P*10^6* num*hours);



function [u2] = reduced_wind_speeds(xy,D,k,u,dir,Ct,Ct_u) [109]
%CALCULATE AEP Calculate wind speeds reduced by wakes.
% xy: num * 2 matrix of E/W and N/S WT coordinates (meter system)
% D: Rotor diameter
% k: wake decay constant (e.g. 0.075 onshore and 0.04 offshore)
% u: wind speed time series
% dir: wind direction time series (time_steps * 1, 0 is N, 90 is E)
% Ct and Ct_u: Ct and corresponding wind speeds (x * 1)
Ct = fit(Ct_u,Ct,'linearinterp');
num = size(xy,1); % Number of WTs
d = pdist2(xy,xy); % distance between WTs
dir = round(dir);
dir(dir==0) = 360;
if size(u,2) == 1
    u = repmat(u,1,num); % same raw wind speed for all WTs
end
pin = zeros(num,360,num)>0; % initialize
for n = 1:num
    pin = in_wake(xy,n,k,D,pin); % within wake for angles 1-360
end
catic = zeros(num,size(u,1),num,'single');
for n = 1:num
    for m = 1:num
        if n~=m
            temp = ismember(dir,find(pin(m,:,n)));
            catic(m,temp,n) = (1-sqrt(1-Ct(u(temp,n)))./(1+2*k*d(n,m)/D)^2;
        end
    end
end
```

```
for n = 1:num
    vu = 1-sqrt(sum(catic(n,:,:).^2,3));
    u2(:,n) = real(u(:,n).*vu');
end
end
```

```
function [E_sum] = energy_generated(num , D, Cp , Cp_u , u, t) [109]
%Calculate the total generation of a wind farm.
% D: Rotor diameter
% u: wind speed matrix , output of function " reduced_wind_speeds.m"
% Cp and Cp_u: Cp and corresponding wind speeds (x * 1)
% t: Time step between wind measurements
Cp = fit(Cp_u ,Cp ,'linearinterp');
num_t = size(u,2); % wind turbines
num_u = size(u,1); % wind measurements
if size(u,2) == 1
    u = repmat(u,1,num); % same raw wind speed for all wind turbines
end
for i = 1:num
    Cp_t(:,i) = Cp(u(:,i));
end
rho =1.225; %[kg/m3]
P_av = 0.5* rho*u.^3*D^2/4*pi; %[W]
E_t = Cp_t.*P_av.*t; %[Wh]
E_sum = sum(E_t(:)); %[Wh] annual
```

```
function [xy,M] = grid_layout_triangle(row , column , angle , row_dist , col_dist) [109]
%Generate the xy coordinates of the wind farm layout
% row: y cooidinates
% columns: x coordinates
% angle: angle wind farm in degrees
angle_rad = angle /180*pi;
t_num = row*column;
t_id = 0;
for i = 1:row
    for j = 1: column
        t_id = t_id + 1;
if t_id <= column
    x(t_id) = (t_id - 1)*col_dist;
    y(t_id) = 0;
end
if t_id > column
    x(t_id) = x(t_id -column);
    y(t_id) = y(t_id -column) + row_dist;
end
M(i,j).s = [x(t_id)-((col_dist*(column-1))/2) y(t_id)-((row_dist*(row-1))/2)];
    end
end
t_id = 0;
for i = 1:row
    for j = 1: column
        t_id = t_id+1;
        if rem(i,2)==0
          x_p = M(i,j).s(1)*cos(angle_rad)+(col_dist/2)*cos(angle_rad) +
M(i,j).s(2)*sin(angle_rad);
          y_p = M(i,j).s(2)*cos(angle_rad)-(col_dist/2)*sin(angle_rad) -
M(i,j).s(1)*sin(angle_rad);
        else
            x_p = M(i,j).s(1)*cos(angle_rad)+ M(i,j).s(2)*sin(angle_rad);
            y_p = M(i,j).s(2)*cos(angle_rad)- M(i,j).s(1)*sin(angle_rad);
        end
         x(t_id) = x_p;
         y(t_id) = y_p;
    end
end
```

```
x = x';
y = y';
xy = [x y];
```

```
function varargout = wind_rose(D,F,varargin)  [110][111]
%WIND_ROSE   Wind rose of direction and intensity
%   Syntax:
%      [HANDLES,DATA] = WIND_ROSE(D,I,VARARGIN)
%   Inputs:
%      D   Directions
%      I   Intensities
%      VARARGIN:
%       -dtype, type of input directions D, standard or meteo,
%            if meteo, the conversion dnew=mod(-90-D,360) is done;
%            if not meteo, standard is used (default)
%       -n, number of D subdivisons
%       -di, intensities subdivisons, default is automatic
%       -ci, percentage circles to draw, default is automatic
%       -labtitle, main title
%       -lablegend, legend title
%       -cmap, colormap [jet]
%       -colors, to use instead of colormap, for each di
%       -quad, Quadrant to show percentages [1]
%       -ri, empty internal radius, relative to size of higher
%            percentage [1/30]
%       -legtype, legend type: 1, continuous, 2, separated boxes [2]
%       -bcolor, full rectangle border color ['none']
%       -lcolor, line colors for axes and circles ['k']
%       -percbg, percentage labels bg ['w']
%       -ax, to place wind rose on pervious axes, the input for ax
%            must be [theax x y width], where theax is the previous
%            axes, x and y are the location and width is the wind
%            rose width relative to theax width (default=1/5)
%       -parent, by default a new axes is created unless parent is
%                given, ex, parent may be a subplot
%       -iflip, flip the intensities as they go outward radially, ie,
%                highest values are placed nearest the origin [{0} 1]
%       -inorm, normalize intensities, means all angles will have 100%
%       -incout, if 0, data outside di limits will not be used [0 {1}]
%   Output:
%      HANDLES   Handles of all lines, fills, texts
%      DATA   Wind rose occurences per direction and intensity
%   Examle:
%      d=0:10:350;
%      D=[];
%      V=[];
%      for i=1:length(d)
%        n=d(i)/10;
%        D=[D ones(1,n)*d(i)];
%        V=[V 1:n];
%      end
%      figure
%      wind_rose(D,V)
%      figure
%      wind_rose(D,V,'iflip',1)
%      figure
%      wind_rose(D,V,'ci',[1 2 7],'dtype','meteo')
%      % place it on a previous axes;
%      ax=axes;
%      plot(lon,lat)
%      wind_rose(D,V,'ax',[ax x y 1/3])
%   MMA 26-11-2007, mma@odyle.net
%   IEO, Instituto Español de Oceanografía
%   La Coruña, España
%   10-12-2007 - Added varargin ci and n (nAngles removed as input)
%   17-12-2007 - Added varargin ax, colors
%   22-02-2008 - Added varargin dtype
```

```
%   08-05-2008 - Bug fix (bar at dir=0 could be incorrect in some cases)
%   14-05-2008 - Added varargin iflip
%   16-06-2008 - Added varargin parent
%   10-06-2009 - Added varargin incout
%   27-04-2010 - Added output DATA
%   17-06-2010 - Bug fix (E(i,end)=length(find(b>=Ag(end-1))),
%   previously was ...b>Ag...). So, the percentages where wrong only when using
intensities equal to the lower value of the highest intensity subdivision, basically an
academic case.
handles=[];
% varargin options:
dtype='standard';
nAngles=36;
ri=1/30;
quad=1;
legType=2;
percBg='w';
titStr='';
legStr='';
cmap=jet;
colors=[];
Ag=[]; % intensity subdivs.
ci=[]; % percentage circles
lineColors='k';
borderColor='none';
onAxes=false;
iflip=0;
inorm=0;
parent=0;
IncHiLow=1; % include values higher and lower that the limits of Ag.
vin=varargin;
for i=1:length(vin)
  if isequal(vin{i},'dtype')
    dtype=vin{i+1};
  elseif isequal(vin{i},'n')
    nAngles=vin{i+1};
  elseif isequal(vin{i},'ri')
    ri=vin{i+1};
  elseif isequal(vin{i},'quad')
    quad=vin{i+1};
  elseif isequal(vin{i},'legtype')
    legType=vin{i+1};
  elseif isequal(vin{i},'percbg')
    percBg=vin{i+1};
  elseif isequal(vin{i},'labtitle')
    titStr=vin{i+1};
  elseif isequal(vin{i},'lablegend')
    legStr=vin{i+1};
  elseif isequal(vin{i},'cmap')
    cmap=vin{i+1};
  elseif isequal(vin{i},'colors')
    colors=vin{i+1};
  elseif isequal(vin{i},'di')
    Ag=vin{i+1};
  elseif isequal(vin{i},'ci')
    ci=vin{i+1};
  elseif isequal(vin{i},'lcolor')
    lineColors=vin{i+1};
  elseif isequal(vin{i},'bcolor')
    borderColor=vin{i+1};
  elseif isequal(vin{i},'ax')
    ax=vin{i+1};
    try
      onAxes=ax(1);
      onAxesX=ax(2);
      onAxesY=ax(3);
      onAxesR=ax(4);
    catch
      disp(':: cannot place wind rose on axes, bad argument for ax')
```

```
      return
    end
  elseif isequal(vin{i},'iflip')
    iflip=vin{i+1};
  elseif isequal(vin{i},'inorm')
    inorm=vin{i+1};
  elseif isequal(vin{i},'parent')
    parent=vin{i+1};
  elseif isequal(vin{i},'incout')
    IncHiLow=vin{i+1};
  end
end
% other options:
% size of the full rectangle:
rs=1.2;
rl=1.7;
% directions conversion:
if isequal(dtype,'meteo')
  D=mod(-90-D,360);
end
% angles subdivisons:
D=mod(D,360);
Ay=linspace(0,360,nAngles+1)-0.5*360/nAngles;
% calc instensity subdivisions:
if isempty(Ag)
  % gen Ag:
  f=figure('visible','off');
  plot(F); axis tight;
  yl=get(gca,'ytick');
  close(f)
  dyl=diff(yl); dyl=dyl(1);
  if min(F)<yl(1),   yl=[yl(1)-dyl yl];   end
  if max(F)>yl(end), yl=[yl yl(end)+dyl]; end
  Ag=yl;
end
for i=1:length(Ay)-1
  if i==1
     I=find( (D>=Ay(i) & D<Ay(i+1)) | D>=Ay(end));
  else
    I=find(D>=Ay(i) & D<Ay(i+1));
  end
  b=F(I);
  for j=1:length(Ag)-1
    if j==length(Ag)-1
      J=find(b>=Ag(j) & b<=Ag(j+1)); % include data with last Agg
    else
      J=find(b>=Ag(j) & b<Ag(j+1));
    end
    E(i,j)=length(J);
  end
  if IncHiLow
    E(i,1)=length(find(b<Ag(2)));
    E(i,end)=length(find(b>=Ag(end-1)));
  end
end
b=sum(E,2)/length(D)*100;
% normalize data:
if inorm
  n=sum(E,2);
  for i=1:length(n)
    E(i,:)=E(i,:)/n(i);
  end
  b=100*ones(size(b));
end
% check if has values higher or lower than the Ag limits
hasH=length(find(F>Ag(end)));
hasL=length(find(F<Ag(1)));
% calc number of percentage circles to draw:
if isempty(ci)
```

```
  if inorm
    ci=[25 50 75];
    g=120;
    ncircles=3;
  else
    dcircles=[1 2 5 10 15 20 25 30 50];
    ncircles=3;
    d=abs(1./(dcircles/max(b))-ncircles);
    i=find(d==min(d));
    d=dcircles(i(1));
    if d*ncircles<max(b)
      ncircles=ncircles+1;
    end
    ci=[1:ncircles]*d;
    g=ncircles*d;
  end
else
  ncircles=length(ci);
  g=max(max(ci),max(b));
end
% plot axes, percentage circles and percent. data:
if parent
  wrAx=parent;
  set(wrAx,'units','normalized');
else
  wrAx=axes('units','normalized');
end
ri=g*ri;
handles(end+1)=fill([-rs*g rl*g rl*g -rs*g],[-rs*g -rs*g rs*g rs*g],'w',...
                     'EdgeColor',borderColor);
if onAxes
  set(handles(end),'facecolor','none')
end
hold on
handles(end+1)=plot([-g-ri -ri nan ri g+ri nan 0 0 nan 0 0],...
                    [0 0 nan 0 0 nan -g-ri -ri nan ri g+ri],':','color',lineColors);
t0=[0:360]*pi/180;
labs=[];
Ang=[1/4 3/4 5/4 7/4]*pi;
Valign={'top' 'top' 'bottom' 'bottom'};
Halign={'right' 'left' 'left' 'right'};
for i=1:ncircles
  x=(ci(i)+ri)*cos(t0);
  y=(ci(i)+ri)*sin(t0);
  circles(i)=plot(x,y,':','color',lineColors);
  handles(end+1)=circles(i);
labs(i)=text((ci(i)+ri)*cos(Ang(quad)),(ci(i)+ri)*sin(Ang(quad)),[num2str(ci(i)),'%'],...
      'VerticalAlignment',Valign{quad},'HorizontalAlignment',Halign{quad},...
      'BackgroundColor',percBg,'FontSize',8);
end
handles=[handles labs];
% calc colors:
if isempty(colors)
  cor={};
  for j=1:length(Ag)-1
    cor{j}=caxcolor(Ag(j),[Ag(1) Ag(end-1)],cmap);
  end
else
  cor=colors;
end
% fill data:
n=sum(E,2);
if iflip, E=fliplr(E); end
for i=1:length(Ay)-1
  if n(i)
    t=linspace(Ay(i),Ay(i+1),20)*pi/180;
    r1=ri;
    for j=1:length(Ag)-1
      r2=E(i,j)/n(i) *b(i) +r1;
```

```
      x=[r1*cos(t(1)) r2*cos(t) r1*cos(fliplr(t))];
      y=[r1*sin(t(1)) r2*sin(t) r1*sin(fliplr(t))];
      if iflip, jcor=length(Ag)-1-j+1;
      else, jcor=j;
      end

      if E(i,j)>0, handles(end+1)=fill(x,y,cor{jcor}); end
      r1=r2;
    end
  end
end
axis equal
axis off
% uistack has problems in some matlab versions, so:
%uistack(labs,'top')
%uistack(circles,'top')
ch=get(wrAx,'children');
if inorm
  % only bring circles up in inorm case.
  for i=1:length(circles)
    ch(ch==circles(i))=[]; ch=[circles(i); ch];
  end
end
for i=1:length(labs)
  ch(ch==labs(i))=[]; ch=[labs(i); ch];
end
set(wrAx,'children',ch);
% N S E W labels:
bg='none';
args={'BackgroundColor',bg,'FontSize',8};
h(1)=text(-g-ri, 0,'WEST', 'VerticalAlignment','top',   'HorizontalAlignment','left',
args{:});
h(2)=text( g+ri, 0,'EAST', 'VerticalAlignment','top',
'HorizontalAlignment','right',args{:});
h(3)=text( 0,-g-ri,'SOUTH','VerticalAlignment','bottom','HorizontalAlignment','left',
args{:});
h(4)=text( 0, g+ri,'NORTH','VerticalAlignment','top',   'HorizontalAlignment','left',
args{:});
handles=[handles h];
% scale legend:
L=(g*rl-g-ri)/7;
h=(g+ri)/10;
dy=h/3;
x0=g+ri+(g*rl-g-ri)/7;
x1=x0+L;
y0=-g-ri;
if legType==1 % contimuous.
  for j=1:length(Ag)-1
    lab=num2str(Ag(j));
    if j==1 & hasL & IncHiLow
      lab='';
    end
    y1=y0+h;
    handles(end+1)=fill([x0 x1 x1 x0],[y0 y0 y1 y1],cor{j});
    handles(end+1)=text(x1+L/4,y0,lab,'VerticalAlignment','middle','fontsize',8);
    y0=y1;
  end
  if ~ (hasH & IncHiLow)
handles(end+1)=text(x1+L/4,y0,num2str(Ag(end)),'VerticalAlignment','middle','fontsize',8)
;
  end
elseif legType==2 % separated boxes.
  for j=1:length(Ag)-1
    lab=[num2str(Ag(j)) ' - ' num2str(Ag(j+1))];
    if j==1 & hasL & IncHiLow
      lab=['<',num2str(Ag(2))];
    end
    if j==length(Ag)-1 & hasH & IncHiLow
      lab=['>=',num2str(Ag(j))];
```

```
    end
    y1=y0+h;
    handles(end+1)=fill([x0 x1 x1 x0],[y0+dy y0+dy y1 y1],cor{j});
  handles(end+1)=text(x1+L/4,(y0+dy+y1)/2,lab,'VerticalAlignment','middle','fontsize',8);
    y0=y1;
  end
end
% title and legend label:
x=mean([-g*rs,g*rl]);
y=mean([g+ri,g*rs]);
handles(end+1)=text(x,y,titStr,'HorizontalAlignment','center');
x=x0;
y=y1+dy;
handles(end+1)=text(x,y,legStr,'HorizontalAlignment','left','VerticalAlignment','bottom')
;
if onAxes
  place_wr(onAxes,wrAx,onAxesX,onAxesY,onAxesR);
end
if nargout>=1
  varargout{1}=handles;
end
if nargout>=2
  varargout{2}=E;
end
function place_wr(ax,ax2,x,y,width)
if nargin < 5
  width=1/5;
end
uax=get(ax,'units');
pax=get(ax,'position');
set(ax,'units',uax)
axXlim=get(ax,'xlim');
axYlim=get(ax,'ylim');
x_ax2=pax(1)+pax(3)*(x-axXlim(1))/diff(axXlim);
y_ax2=pax(2)+pax(4)*(y-axYlim(1))/diff(axYlim);
pax2=get(ax2,'position');
width=pax(3)*width;
height=pax2(4)*width/pax2(3);
pax2=[x_ax2 y_ax2 width height];
if 1
  % place at centre of the wr, not the bottom left corner:
  ax2Xlim=get(ax2,'xlim');
  ax2Ylim=get(ax2,'ylim');
  dx=(0-ax2Xlim(1))/diff(ax2Xlim)*pax2(3);
  dy=(0-ax2Ylim(1))/diff(ax2Ylim)*pax2(4);
  x_ax2=x_ax2-dx;
  y_ax2=y_ax2-dy;
  pax2=[x_ax2 y_ax2 width height];
end
set(ax2,'position',pax2)
function cor = caxcolor(val,cax,cmap)
%CAXCOLOR   Caxis color for value
%   Find the color for a given value in a colormap.
%   Syntax:
%     COLOR = CAXCOLOR(VALUE,CAXIS,COLORMAP)
%   Inputs:
%      VALUE
%      CAXIS   Default is current caxis
%      COLORMAP   Default is current colormap
%   Output:
%      COLOR   RGB color vector
%   Example:
%      figure
%      pcolor(peaks)
%      color=caxcolor(0);
%      set(gcf,'color',color)
%   MMA 28-5-2007, martinho@fis.ua.pt
% Department of Physics
% University of Aveiro, Portugal
```

```
if nargin < 3
  cmap = get(gcf,'colormap');
end
if nargin < 2
  cax = caxis;
end
n=size(cmap,1);
i= (val-cax(1))/diff(cax) * (n-1) +1;
a=i-floor(i);
i=floor(i);
i=min(i,n);
i=max(i,1);
if i==n
  cor=cmap(n,:);
elseif i==1
  cor=cmap(1,:);
else
  cor=cmap(i,:)*(1-a) + cmap(i+1,:)*a;
end
```

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