DEPARTMENT OF ELECTROTECNHICAL AND COMPUTER ENGINEERING (DEEC)

DIOGO CHAVES LOPES DE FREITAS

Bachelor degree in Environmental Engineering

# European Potential of Wind Technologies for Electricity Generation under Project Drawdown Framework

NOVA UIVERSITY OF LISBON

November, 2021

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MASTER IN RENEWABLE ENERGY ENGINEERING

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# Abstract

The global climate and environmental emergency demand global, swift and immediate action. The decarbonization of all greenhouse gas emitting sectors, from transport and electricity generation to the residential sector, must be prioritized.

Electricity production is one of the critical points for this transition, much due to the amount of GHG (Greenhouse Gases) emitted by several conventional fossil fuel power plants and the expected growth of renewable energy technologies that can significantly shift the existing electricity production mix. Nevertheless, technological challenges will mark this energy transition. While some technologies are already market-ready, competitive with fossil fuel powerplants, others still need to develop and are expected to have significant price reductions. This way, it will still be possible to combine the security of energy supply, environmental protection and an attractive economic performance for investors and consumers through significant integration of renewable energy.

As part of the regionalization activities of Project Drawdown in Europe, this work main objective is to obtain, through analysis and interpretation of various studies and articles, the future range of potential of wind energy technologies in a European and European Union context between the years 2020 and 2050, modelling the decrease of $CO_{2e}$ emissions and financial needs of their increased adoption in the electricity generation mix.

The second objective is to identify and characterize the three main wind technologies with technical and economic parameters - Onshore, Offshore and Small. The last objective is to identify and develop an analysis of each wind technology's future potential electricity generation using a vast set of energy scenarios with different assumptions, models, and timeframes.

Regarding the total values collected for the European Union, electricity generation for 2050 is expected to range between 1 116 – 5 256 TWh/y, with 812 - 2 591 TWh/y corresponding to Onshore generation, 304 - 2 556 TWh/y to Offshore generation and 0.6 - 109 TWh/y to generation through Small Wind systems. In total, wind power systems make up between 6.7 - 23.3 % of the European Union's energy mix. Over the next 30 years, these technologies are expected to reduce between 6.71 – 32.21 Gt $CO_{2e}$ with increased lifetime operating costs of around 310 – 2 700 billion €.

Keywords: Climate Change, Energy Transition, Onshore Wind, Offshore Wind, Small Wind Turbines, Decarbonization, Project Drawdown

# Resumo

A emergência climática exige uma ação global rápida e imediata. A descarbonização de todos os sectores emissores, desde o transporte e produção de eletricidade até ao sector residencial, deve ser uma prioridade.

A produção de eletricidade é um dos pontos críticos para esta transição, muito devido à quantidade de GEE (Gases com Efeito de Estufa) emitida por várias centrais elétricas convencionais alimentadas a combustíveis fósseis e ao crescimento esperado das tecnologias de energias renováveis que podem alterar significativamente o mix de produção de eletricidade existente. No entanto, os desafios tecnológicos marcarão a tão esperada transição energética. Enquanto algumas tecnologias já estão prontas para o mercado, competitivas com as centrais elétricas a combustíveis fósseis, outras ainda precisam de se desenvolver e estão previstas reduções de preços significativas. Desta forma, ainda será possível combinar a segurança do aprovisionamento energético, a proteção ambiental e um desempenho económico atrativo para investidores e consumidores através de uma integração significativa de energias renováveis.

Como parte das atividades de regionalização do Projeto Drawdown na Europa, este trabalho tem como principal objetivo obter, através da análise e interpretação de vários estudos e artigos, a gama futura do potencial das tecnologias de energia eólica num contexto Europeu e da União Europeia entre os anos 2020 e 2050, modelando a diminuição das emissões de $CO_{2e}$ e as necessidades financeiras da sua crescente adoção no mix da produção de eletricidade.

O segundo objetivo é identificar e caracterizar as três principais tecnologias de energia eólica através de parâmetros técnicos e económicos - Onshore, Offshore e Small. Finalmente, o último objetivo consiste na identificação e desenvolvimento de uma análise da futura geração de eletricidade potencial para cada tecnologia eólica, utilizando um vasto conjunto de cenários energéticos com diferentes pressupostos, modelos e prazos temporais.

Relativamente aos valores totais recolhidos para a União Europeia, espera-se que a geração de eletricidade para 2050 varie entre 1 116 - 5 256 TWh/ano, com 812 - 2 591 TWh/ano correspondentes à produção Onshore, 304 - 2 556 TWh/ano à produção Offshore e 0,6 - 109 TWh/ano à produção através de sistemas de aproveitamento do vento de pequena escala. No total, os sistemas eólicos constituem entre 6,7 - 23,3 % do mix energético da União Europeia. Nos próximos 30 anos, espera-se que estas tecnologias reduzam entre 6.71 – 32.21 Gt $CO_{2e}$ com um aumento dos custos operacionais ao longo da vida útil de cerca de 310 – 2 700 mil milhões de euros.

Palavras-chave: Alterações Climáticas, Transição Energética, Energia Eólica Onshore, Energia Eólica Offshore, Pequenas Turbinas Eólicas, Descarbonização, Projeto Drawdown

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# List of Acronyms

**AAU -** Average Annual Use

**APEC** – Asia-Pacific Economic Cooperation

**ASSET** – Advanced System Studies for Energy Transition

**CCUS** – Carbon Capture Usage and Storage

**DERA** – Drawdown Europe Research Association

**ECF** – European Climate Foundation

**EDP** – Energias de Portugal

**ESS** – Energy Storage Systems

**ETP** – Energy Technologies Perspectives

**EU** – European Union

**EUREF** – European Union Reference Scenario

**EWG** – Energy Watch Group

**FOM** – Fixed Operating and Maintenance Costs

**GHG** – Greenhouse Gas

**GP** – Greenpeace

**GRO** – Global Renewables Outlook

**IEA** – International Energy Agency

**IEEJ** – The Institute of Energy Economics, Japan

**IRENA** -– International Renewable Energy Agency

**JRC** – European Commission Joint Research Centre

**LUT** – Polytechnic University of Lappeenranta

**NDC** - Nationally Determined Contributions

**NIMB** – Not In My Backyard

**OECD** – Organization for Economic Cooperation and Development

**RES** – Renewable Energy Sources

**RRS** – Reduction Replacement Solutions

**SDG** – Sustainable Development Goals

**SDS** – Sustainable Development Scenario

**SPE** – Solar Power Europe

**STEPS** – Stated Policies Scenario

**TAM** – Total Addressable Market

**UNEP** – United Nations Environmental Program

**UNFCCC** - United Nations Framework Convention on Climate Change

**VMA** -– Variable Meta-Analysis

**VOM** – Variable Operating and Maintenance Costs

**VRE** – Variable Renewable Energy

**WEC** – World Energy Council

**WEO** – World Energy Outlook

**WWEA** – World Wind Energy Association

# Glossary

**Adoption (ADPT)**: This acronym is sometimes used throughout this work in reference to the projections about the adoption of wind technologies for electricity generation, expressed in TWh.

**Total Addressable Market (TAM):** in the context of this work refers to the total amount of electricity generated during a given year, also expressed in TWh.

**Variable Meta-Analysis (VMA):** refers to a statistical analysis of a set of technical end economic features that characterize technological solutions. Some of them are First Cost (or Installation Cost), Lifetime Capacity, O&M Costs and Emission Factors.

**Implementation Unit:** This is the unit in which one can express the acquisition, installation, or implementation of the given solution. Since solutions in this work relate to electricity generation, the Functional Unit is TW, referring to the installed capacity.

**Functional Unit:** Is the unit in which one can express the intended outcome produced by the solution or the function of the solution. These two units are closely related; it is only through the implementation of the solution that it can be delivered its function. Since solutions in this work relate to electricity generation technologies, the Functional Unit is TWh, referring to the amount of electricity generated.

# 1 Introduction

One of the most critical issues worldwide today is climate change. In the search to combat this problem and find a way not to leave irreversible damage on the planet, several efforts have been made globally through Agreements and Protocols to set long-term emissions reduction objectives (as the Paris Agreement).

Under the current climate and environmental emergency, Project Drawdown, a non-profit organization whose main aim is to help the world achieve its carbon neutrality by achieving Drawdown, was created. “Our mission is to help the world achieve “Drawdown” - the point in the future when levels of greenhouse gases in the atmosphere stop rising and begin to steadily decrease, thus halting catastrophic climate change - as quickly, safely and equitably as possible” (Project Drawdown, 2021). This organization aims to help achieve this by preventing potential catastrophes by presenting numerous solutions for various sectors to start making changes now. Each solution reduces greenhouse gases by avoiding emissions and/or sequestering carbon dioxide already in the atmosphere (Project Drawdown, 2021).

One of the most impactful and globally adopted Agreement is the Paris Agreement. This agreement which “aims to achieve the decarbonization of the world’s economies and sets as one of its long-term objectives to limit the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C, recognizing that this will significantly reduce the risks and impacts of climate change.” (APA, 2016). This protocol has been neglected since, “... some 75% of the 184 national pledges that make up the Paris Agreement were found to be insufficient to slow climate change. To make matters worse, some of these pledges are still not even being implemented” (Made for minds, 2019), the article further points out that, “If implemented as per the agreement, current targets will achieve near 3ºC warming by the end of this century.” (Canadell, 2019).

One of the key solutions to meet GHG reduction targets is the development and scaling of renewable energy technologies and the decrease in the use of conventional fuel ones. A renewable resource is defined as a natural resource whose rate of exploitation is lower than its natural replacement rate. That is, resources such as sun, water, wind, biomass, among others, are considered renewable resources. In contrast, fossil fuels such as coal, oil, and natural gas take millions of years to form. Since the exploitation rate to which they are subject is much higher than their replacement rate, they are considered non-renewable resources.

The depletion of the world non-renewable reserves, in addition to the environmental impacts and its increased awareness, have been key factors for the promotion of a profound energy transition coupled with the development of new technologies. These have appeared and have been improving over the last 40 years for taking advantage of renewable resources.

There are several negative impacts of conventional fossil fuel-based technologies. In the case of coal, its exploration destroys entire landscapes, requires a large amount of manpower and energy, countless machines in operation and movement, and the combustion of petroleum derivatives for this machine’s movement. This constant movement and soil removal lead to a degradation of air quality in the region since the dust that is lifted and small particles of the exploited resource can be carried by the wind and subsequently contaminate adjacent resources and habitats (Wang Yun-jia, 2019). Regarding the case of oil, there are several stages of dealing with this resource that have severe consequences. Starting with the exploration, the possible spills inherent to drilling, going to the transportation where the sinking of oil tankers is not such an uncommon theme, having the capacity to ruin vast habitats as well as to turn the area into a dead zone, lifeless and polluted place for many years, leads to an additional concern and an increased need to avoid such events (National Oceanic and Atmospheric Administration, 2020). On the other hand, the exploitation of solar energy, geothermal, wind and others, and not so abrasive for the various habitats on our planet.

For solar energy, more specifically in the planning of the solar plant project, permanent damage to the habitat is considered, since it will be necessary to remove the fauna and flora present there, as well as, in some instances, to proceed to a general alignment of the land in question so that the panels present, at the end of the installation, the desired slope (U.S. Energy Information Administration, 2020). In this case, it should be noted that the impact of this technology is much lower than the impact of coal plants since it is emission-free production, and its presence in the landscape is much more tenuous than that of a coal mine. Its implementation does not destroy the soil on the site, so the fauna and flora can return after the end of the project's life. The case of wind and geothermal energy are two renewable energy technologies with fewer problems.

For geothermal energy, a strategically located plant can perform the necessary work being this technology adopted in particular locations. Nevertheless, many geothermal sites are located in remote and sensitive ecological areas, so project developers must consider this in their planning processes (Union Of Concern Scientists, 2013). In the case of wind energy, its most significant impact is the noise derived from the movement of its blades itself. These are distributed punctually, occupying little space on the ground, where the ground fauna and flora can continue to live. However, there is still a need for further studies regarding the impact of wind turbines on the death of birds. Regarding landscape issues, due to their height and the existence of wind farms, it can be argued that their impact might be relevant, noting the presence, at a distance, of something that is not natural to the landscape (Office of Energy Efficiency & Renewable Energy, n.d).

There are some rare cases where countries, without access to or the ability to exploit these non-renewable resources (whether due to non-existence in their territory, social reasons, or even technological incapacity for their identification and exploitation), cannot use them as a primary mean of electricity production, due to the high cost and, therefore, must swap as quickly as possible to renewable energy. "These sources avoid importing fossil fuels such as coal and natural gas to generate electricity, avoid the emission of greenhouse gases and reduce the price of electricity in the electricity market, contributing to greater economic and environmental sustainability of the country." (APREN, 2021).

Although a large pool of renewable technologies already exists, with a significant increase in efficiency and electricity production, wind energy is one of the most mature renewable energy technologies. In the most recent years, wind technologies have presented exponential growth and are currently one of the key technologies in the power market with one of the highest installed capacity worldwide and with huge potential on both onshore and offshore settings.

Currently, in the European electricity generation mix, the weight of Onshore and Offshore and Micro wind represents only about 11.6% of the Total Electricity Production (IEA, 2021). However, a lot has been and is going to be done on this topic. Therefore, "European

Commission estimates between 240 and 450 GW of offshore wind power is needed by 2050 to keep temperature rises below 1.5°C. Wind electricity generation will represent at least 50% of the total energy mix in 2050, and 30% of the future electricity demand will be supplied by offshore wind" (European Commission, 2020). Another article also stated that "the most recent study from industry body Eurelectric refers that Europe's power sector could be fully decarbonized by 2045. In this scenario, wind energy would provide 50% of Europe's power" (Wind Europe, 2018). As quoted before, many efforts are being made to bring wind power as one of the leading technologies on the energy mix and, the most impressive parameter is the weight that Offshore wind will have in the years to come.

Over the years, the cost reduction of these technologies has been significant; besides decreasing by large margins, this value, in a gap of roughly 30 years, had been reduced by about 3 – 4 times. It should be noted that there are numerous projections for various years and from multiple entities, and it is difficult to reach a range of values on which everyone agrees. According to the Lawrence Berkeley National Laboratory (2016), "more efficient turbines combined with lower capital and operating costs could see reductions of between 17 and 35 per cent by 2035." In "Cost development of low carbon energy technologies" by JRC (2018), the scenarios point out an expected reduction in investment costs between 5%-38% for onshore wind and 16%-61% for offshore wind. There are many other entities and respective studies with predictions referring to LCOE data, installation costs, prices, and many other technical variables development.

## 1.1 Motivation

The energy market is currently one of the most important in the world. Renewable energy has been gradually increasing its importance and, in some locations, replacing traditional sources of electricity generation. In recent years there has been growing concerns about climate change, and this has become an issue of high importance and discussion worldwide. However, there is still much to achieve to meet the global goals and carbon neutrality.

For 2016, energy (electricity, heating and transportation) accounted for about 73.2% of global GHG emissions (Our World In Data, 2020). Decreasing this amount requires replacing traditional sources of electricity production with renewable energy and increasing energy efficiency. Apart from the non-depletion of the world's reserves of coal, oil and gas, these resources, since they are renewable, will never run out. Due to worldwide bets and of several companies in these three wind electricity generation technologies, it was observed a drastic decrease in its price in the last two decades, thanks to the maturation of technologies and increased investment in the area. This way, renewable technologies have become a competitive market having, in some countries, the lowest price per MWh.

This is where wind technologies come into play. Besides the general knowledge of wind electricity generation, associated costs, impacts and many more, a key factor to understand such importance is the impact associated with the $CO_2$ emissions reduction until the year 2050. In Project Drawdown, wind technologies, such as Onshore, Offshore and Small wind, were rated according to the degree of impact, out of 76 solutions identified. After the analysis conducted, for scenario 2, where Drawdown would be reached in the mid-2040s, Onshore wind came out as the most impactful solution, Offshore wind as the thirty-third and Small wind as the less promising, occupying the seventy-sixth place. This way, for project Drawdown, Onshore wind would generate more electricity and, as such, would be able to avoid more $CO_{2e}$ emissions.

This way, it came as relevant to do this same analysis for the European region, trying to understand the growth potential of these technologies, their role in the future energy mix, that will undoubtedly be dominated by renewable energy. Besides the global evaluation of wind technologies, it was thought to go even deeper and do this same analysis for Onshore, Offshore and Small wind technologies. Therefore, the importance of the work further developed, where a study and evaluation of several scenarios was conducted to understand future wind potential adoption, emissions reduction impact, associated costs, and many more parameters. It is essential to mention that the respective work is based on the methodology of Project Drawdown, in this case, it consists of a partnership with DERA (Drawdown Europe Research Association). This partnership is crucial to determinate differences in potential between certain technologies in different parts of the world, enabling a general analysis and contextualization of which technology has the most significant potential in a given location as well as the main challenges associated with this installation.

Since it is not expected that only one renewable technology will dominate the market, there will always be an opportunity in the market for different types of renewable technology. Wind energy is one of those renewable resources that are key to support the much-needed energy systems transition. Besides the expected growth in electricity production associated with wind technologies, it would also be important and exciting to understand the role that such technologies will have in a newer future where renewable energy sources will dominate the European Union electricity generation mix. There is where the importance of future scenarios evaluation, understanding their emissions reduction potential, associated costs, and the upsides and downsides come into play.

These future scenarios analysis and interpretation will also enable the exploration and contextualization between technologies, focusing on the three wind technologies. This comparison will also inform us of the role of wind technologies in the European electricity generation mix integrated with solar, hydro, geothermal, and others.

## 1.2 Objectives

As part of the regionalization activities of Project Drawdown in Europe, this work main objective is to obtain, through analysis and interpretation of various studies and articles, the future range of potential of wind energy technologies in a European and European Union context between the years 2020 and 2050, evaluating the decrease of $CO_{2e}$ emissions and financial needs of their increased adoption.

The second goal of this work was to identify and characterize the three different wind technologies regarding their technical and economic parameters to determine their long-term impact on the European and European Union energy systems.

Finally, the last objective, in a nutshell, was to identify and develop an analysis of the future potential electricity generation of each wind technology - Onshore, Offshore and Small according to a different set of energy scenarios with different assumptions, models and timeframes.

Additionally, there was added a new technology comparation parameter, new to Drawdown's studies, based on both jobs created per TWh and materials needed by TWh.

Therefore, this parameter enabled us to understand the job creation potential of each technology as well as the difference between materials consumptions.

### 1.3 Dissertation Structure

The dissertation is structured in 10 parts. The following part of this thesis will start by presenting Project Drawdown, the organization, the goals and the works already published. Next, a summary is presented about wind resource, where such resource is explained.

Afterwards, on chapter four and five is presented the European Union and Global Electricity Generation mix, differentiating the weight and impact of each source, either renewable or non-renewable, followed by the literature review where it will be highlighted the most important and impactful reports and studies on long term energy and emissions projections.

The following section includes the details related to data collection and subsequent use, more specifically, the methodology chapter, where a detailed description of what was conducted throughout all stages and an overview of the Project Drawdown RRS model used.

Chapter seven presents the results for the three wind technologies for multiple scenarios, followed by a sensitivity analysis of key parameters. This section also includes relevant discussion points of the work developed and the results obtained. Finally, chapters eight presents the discussion made and chapter nine the conclusions taken throughout the course of this work.

# 2 Project Drawdown

The work developed herein builds upon on Project Drawdown Framework and modelling tool, this chapter will put it in perspective and set the scene for the work developed in this dissertation. Thus, this chapter presents Project Drawdown, its goals, interests and solutions, followed by a general presentation about wind and the three most essential wind solutions. Afterwards, the current status and trends of wind technologies, as well as a focus on long term energy and climate studies that set the literature review.

## 2.1 Project Drawdown

Project Drawdown (www.drawdown.org) is a non-profit organization whose primary goal is to help the world reach its carbon neutrality by achieving Drawdown. This organization aims to help achieve this and thus preventing potential catastrophes by presenting numerous solutions for various sectors to start making changes now. “Our mission is to help the world reach “Drawdown”— the point in the future when levels of greenhouse gases in the atmosphere stop climbing and start to decline, thereby stopping catastrophic climate change steadily — as quickly, safely, and equitably as possible” (Project Drawdown, 2021) “Each solution reduces greenhouse gases by avoiding emissions and/or by sequestering carbon dioxide already in the atmosphere” (Project Drawdown, 2021).

In 2017, “Drawdown, The most comprehensive plan ever proposed to reverse global warming” came out and quickly became a New York Times bestseller and top-ranked on several Amazon topics. This book consists of a high-level summary of the work done by an international team of experts (policy, research, action-oriented) to model and summarize the 100 most impactive solutions to tackle climate change. This way, it was given a plan and a direction to address some of the problems we want to fight daily.

More recently, Project Drawdown developed the “Drawdown’s “System of Solutions” Helps to Achieve the SDGs” that describes the connection between “Drawdown solutions” and the targets and goals set out by the United Nations Sustainable Development Goals (SDGs) (Frischmann et al., 2020). This paper stands that with the solutions previously defended, more significant gains can be achieved with the implementations of parallel action, leading to achieving Sustainable Development Goals by 2030. In 2020, Project Drawdown also presented “The Drawdown Review” 2020, where the project updates the solutions presented, 76 for this study, and the respective classification according to the scenarios analyzed. As usual, Project Drawdown developed an optimistically plausible scenario - scenario 1 that was unable to reach Drawdown within the period of study (2020–2050), only in 2060 could this scenario reach the Drawdown, and scenario 2, with faster and more pervasive adoption of climate solutions, reaching the point of Drawdown in the mid-2040s. This same paper reveals the Global impact of wind technologies, assigning, for scenario 1, the classifications of sixth, twenty-sixth and Seventy-sixth for Onshore, Offshore and Small wind respectively and, for scenario 2, the classifications of first, thirty-third and Seventy-fifth in the ranking of the most relevant measures to reduce GHG emissions.

The sectors addressed by the project range are split into emission sources from electricity, buildings, industry, transport, or emission sinks, such as land sinks and coastal and ocean sinks, the last of which focuses on the potential for carbon sequestration. Together, they make up the Drawdown Framework for climate solutions, published in 2017 as the project's inaugural work in print publication. Within each sector, measures to reduce GHG in the atmosphere are presented, and the potential to reduce emissions between the years of 2020 and 2050 using these same alternatives. This way, these subcategories of the respective sectors are based on existing technologies and practices, which, when improved and scaled, will reduce the overall GHG emissions. Figure 1 presents, according to the Project Drawdown, the weight of each sector in the total reduction or sequestration of $CO_2$ emissions up to 2050.

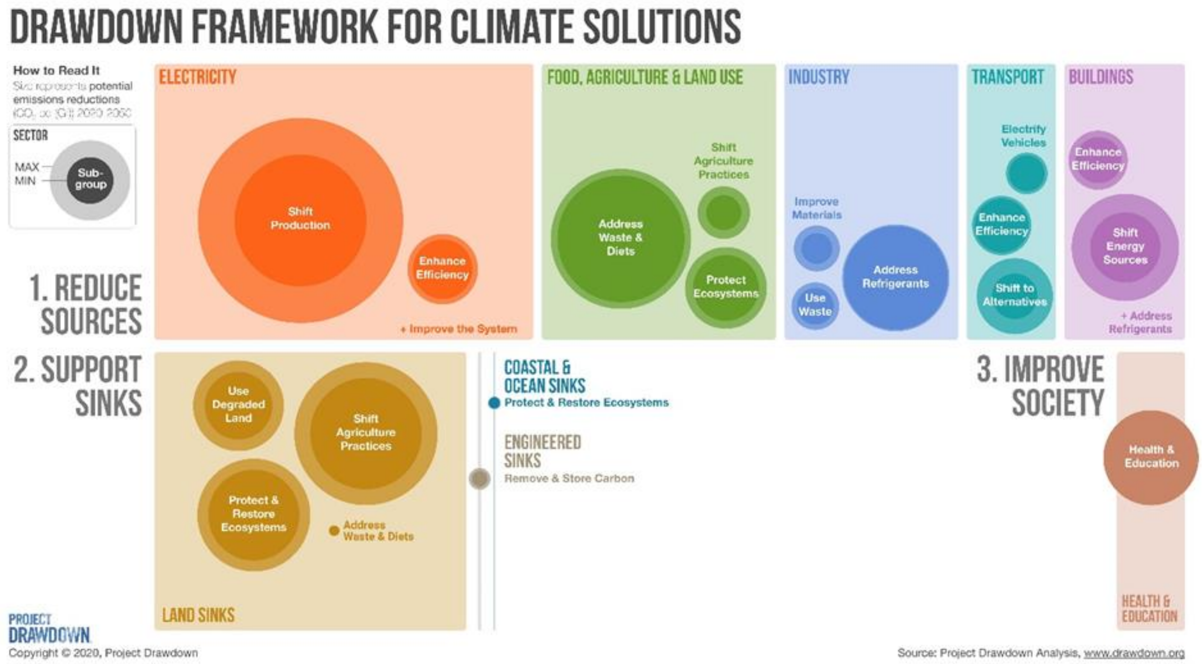


Figure 1. Drawdown framework for climate solutions (Drawdown, 2021)

According to figure 1, the solutions with the most significant impact, in the case of the "reduce sources" cluster, are primarily concentrated around electricity, with more emphasis on changing the way electricity is produced and in the area of food, agriculture and land use, with more importance in addressing waste and diets. Regarding the "support sinks" cluster of solutions, land sinks are undoubtedly the environment with the greatest capacity to sequester carbon, mainly by shifting agriculture practices, protecting and restoring ecosystems.

Regarding the energy sector, most relevant for the work in question, for Project Drawdown, the three main criteria that must be improved and enhanced over the next 30 years are based on energy efficiency, mainly in industry and households, a change in the production of electricity shifting from fossil fuels to renewables, and finally improve the system, through flexible grids for transmission and effective energy storage making possible to better balance electricity supply with demand. Figure 2 presents the potential for carbon reduction or sequestration by technology between 2020 and 2050.

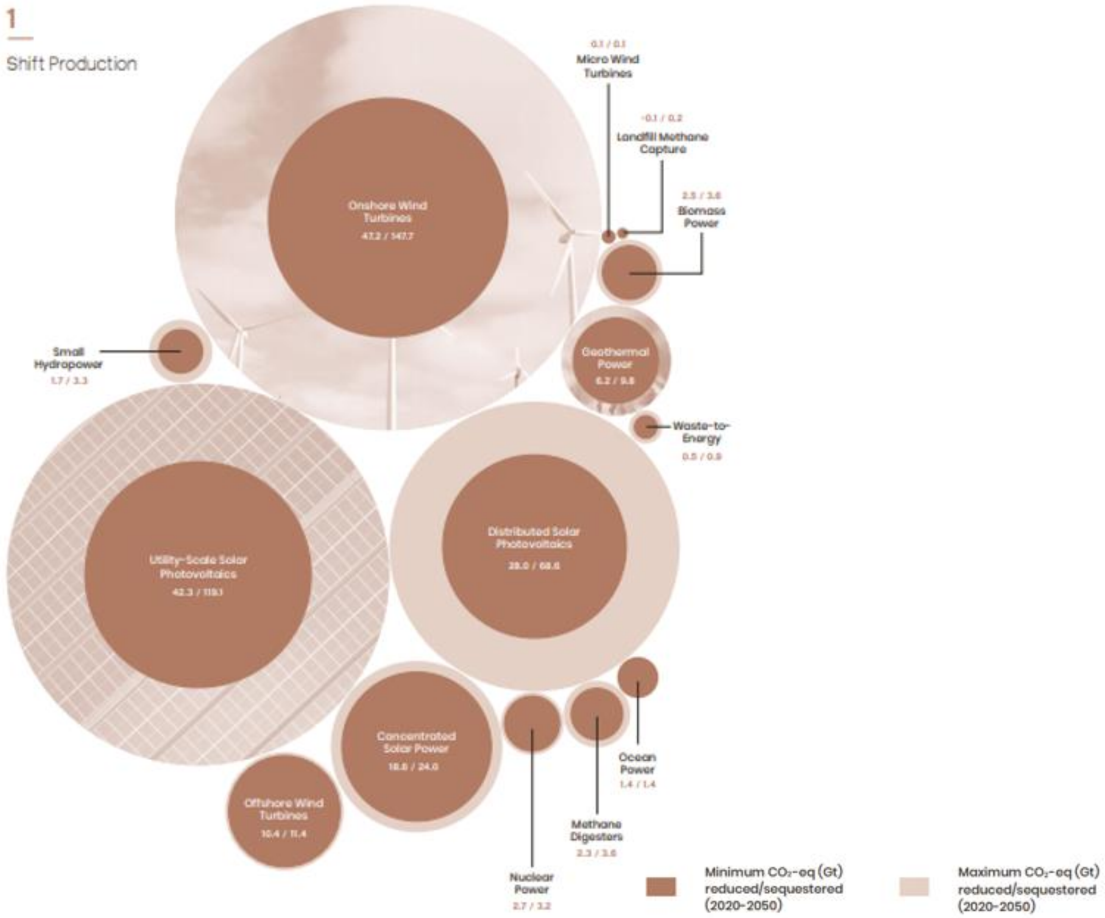


Figure 2. Reduction of $CO_2$ emissions by technology between 2020 and 2050 for the Electricity Sector (Drawdown, 2020)

A simple interpretation of figure 2 reveals, unequivocally, which are, for Project Drawdown, the leading technologies that have the greatest potential for $CO_2$ reduction and sequestration at a global scale. Solar energy, namely utility-scale solar photovoltaics, distributed solar photovoltaics, and concentrated solar power, the latter with the greatest weight, corresponds to the largest slice of the possible $CO_2$ reductions. Wind energy comes in second place where an abrupt discrepancy is shown between Onshore and Offshore technologies. In this case, Onshore comes as the leading technology in the wind department. Concerning this figure, it is also interesting to discuss that, although Project Drawdown considers the accumulated impact of Offshore wind to be much lower in 2050 than the weight of Onshore wind, according to numerous studies, by 2050, the production of electricity by Offshore wind turbines will be higher than the electricity produced by Onshore wind turbines (European Commission, 2020). Therefore, the cumulated impacts in $CO_2$ emissions reduced according to the same time frame can tremendously change.

As Project Drawdown began to be developed in a global context, it was set as relevant to contextualize solutions assessing them in different world regions, exploring a diversity of datasets, supporting policy assessments and detailing future solutions potential. Under this view, Drawdown Europe Research Association (DERA) was created in 2019 to promote this research component, applying the methodology previously used to a European context. Silveira (2020) explored the potential of Solar Technologies for Electricity Generation for the European scale, the first work done for this European regionalization process.

It is in this context that the work performed herein is framed, focusing on three solutions for the wind electricity sector, namely Onshore and Offshore wind energy, as well as energy from decentralized wind electricity production, the so-called Small wind technologies.

# 3 Wind Energy

The wind, consequence of pressure variations in the Earth's atmosphere, pressures resulting from differences between the temperature and humidity of a given location, moves from areas where its value is higher to areas where its pressure is lower, constantly trying to equalize these pressures. However, it should be noted that the wind is not the same or does not have equal ranges everywhere. There are several wind systems scattered around the planet, and these are due to the forces created by the Earth's rotation and the respective gravity generated, as well as the morphology of the surface of the planet, the solar exposure to which that area is subject and, finally, the Coriolis effect (National Geographic, nd).

The operation of the turbines explained in a nutshell, happens when the "wind turns the blades, which spin a shaft connected to a generator or the generator's rotor, which makes electricity." (WIND Exchange, 2018).

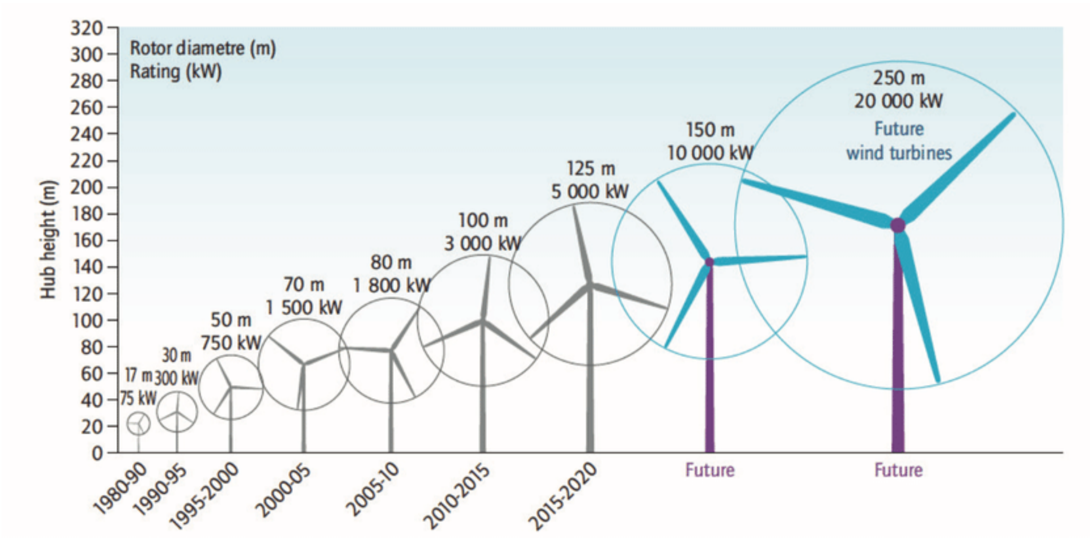


Figure 3. Wind turbine size evolution and future prospects (Deskos, 2019)

At first, the rudimentary technology present in wind turbines allowed wind energy to be harnessed at the height of 17 meters; however, this rose to 50 meters in around 20 years. The evolution of wind turbines is one of the most discussed topics in this area and, since the beginning of the new millennium, this value has doubled. It is also expected that, in the near future, this value will almost quadruple. This race for height is not in vain.

The energy use of wind is defined, in a nutshell, by the kinetic energy of air masses, that is, the power available in the wind. Thus, knowing that:

1º $P = \frac{\Delta \mathrm{E}}{\Delta \mathrm{t}}$ and that

2º $Ec = \frac{1}{2} \times m \times v^2$ it is possible to determine the power available

3º $P_{disp.} = \frac{1}{2} \times A \times \rho \times v^3$, considering that

4º m = $A \times \rho \times v$.

Proceeding to calculate the Mechanical Power, 5º $P.mec = \frac{1}{2} \times Cp \times A \times \rho \times V^3$

A = Area swept by blades in rotation = $\pi \times \text{Blade length}$

$\rho$ = Air Density (T=20ºC) = 1,2 $kgm^{-3}$

Cp = Power Coefficient

v = Wind speed

ΔE = Energy variation

Δt = Time Variation

m = mass flow

In conclusion, since $P_{elet} = \eta_{elet} \times P_{mec}$, the Electric Power that can be extracted by wind energy depends mostly on wind speed; in other words, to produce more energy, it is necessary to install the turbine in places where the wind is stronger. However, it should be noted that turbines do not operate at speeds of around 90 – 100 km/h, due to the capacity of the materials, to avoid damage to the structure and equipment. On the other hand, with wind speeds below 12 km/h, wind does not have enough energy to create rotation in the turbine rotor. (UNC TV Science, nd).

The figures presented, both 4 and 5, taken from the Global Wind Atlas (2020), are inserted here in order to understand the potential of this energy source in question, as well as its distribution in global terms, the respective differences in terms of Onshore and Offshore wind energy, and, finally, the difference in height versus wind speed. To not make their interpretation tiresome and monotonous, it was decided to make only one comparison. There is the possibility of making comparisons between the World and Europe, as well as for altitudes of 50, 100, 150 and 200 meters; it was preferred only to make the comparison between European countries between the heights of 50 and 200 meters, thus being more perceptible the difference in wind speed with increasing height for the geographical area that is being analyzed.

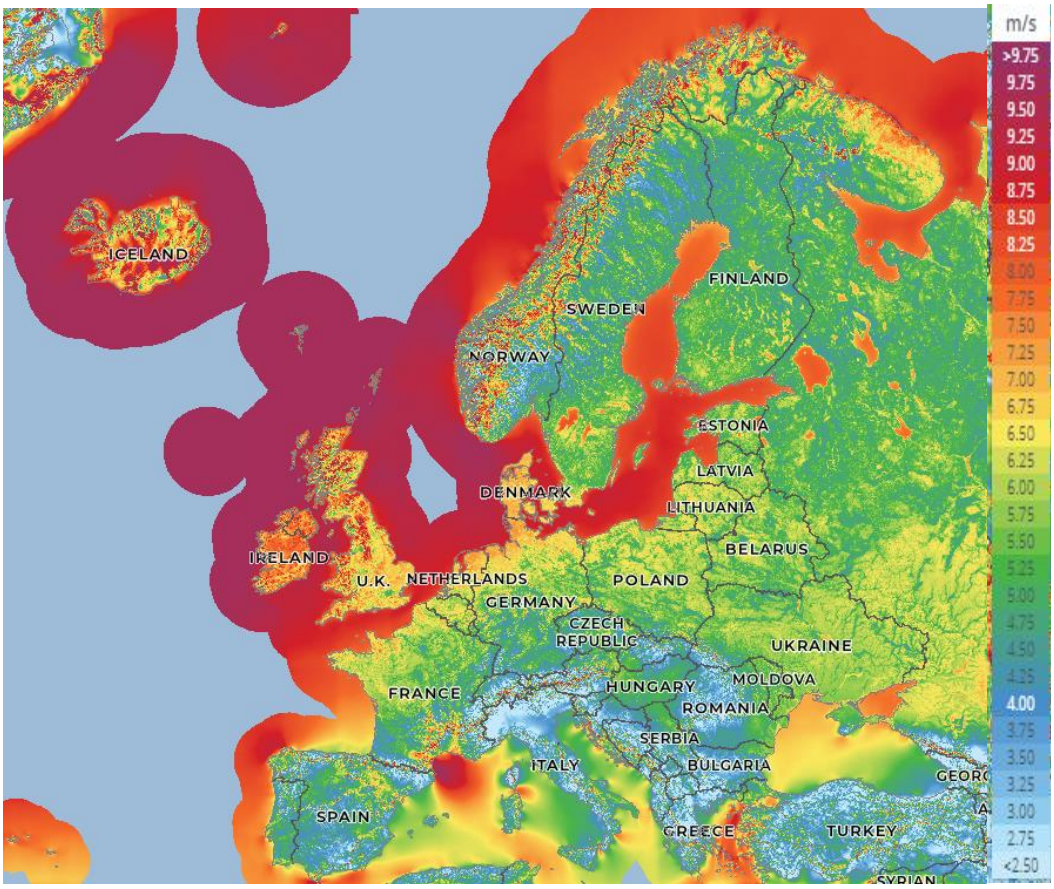


Figure 4. Wind speed 50 meters, Europe (Global Wind Atlas, 2020)

At 50 meters high, the wind speed has a very uneven distribution, and in coastal areas, the wind speed is much higher compared to more inland areas. This fact is mainly explained by the irregularities present on the Earth’s surface since the wind, when colliding with buildings, trees, mountains and different morphologies of the terrain, loses strength and thus loses speed. Consequently, there will be a decrease in energy in that same mass of air.

Regarding Europe, the wind speed in the Nordic countries is much higher in coastal areas, and there are several points on land where the wind speed is also relatively high, much due to their altitude and the presence of mountains where, at its peak, the wind speed is usually higher. However, it is worth noting the huge difference between the coastal and maritime areas with the more central and inland zones.

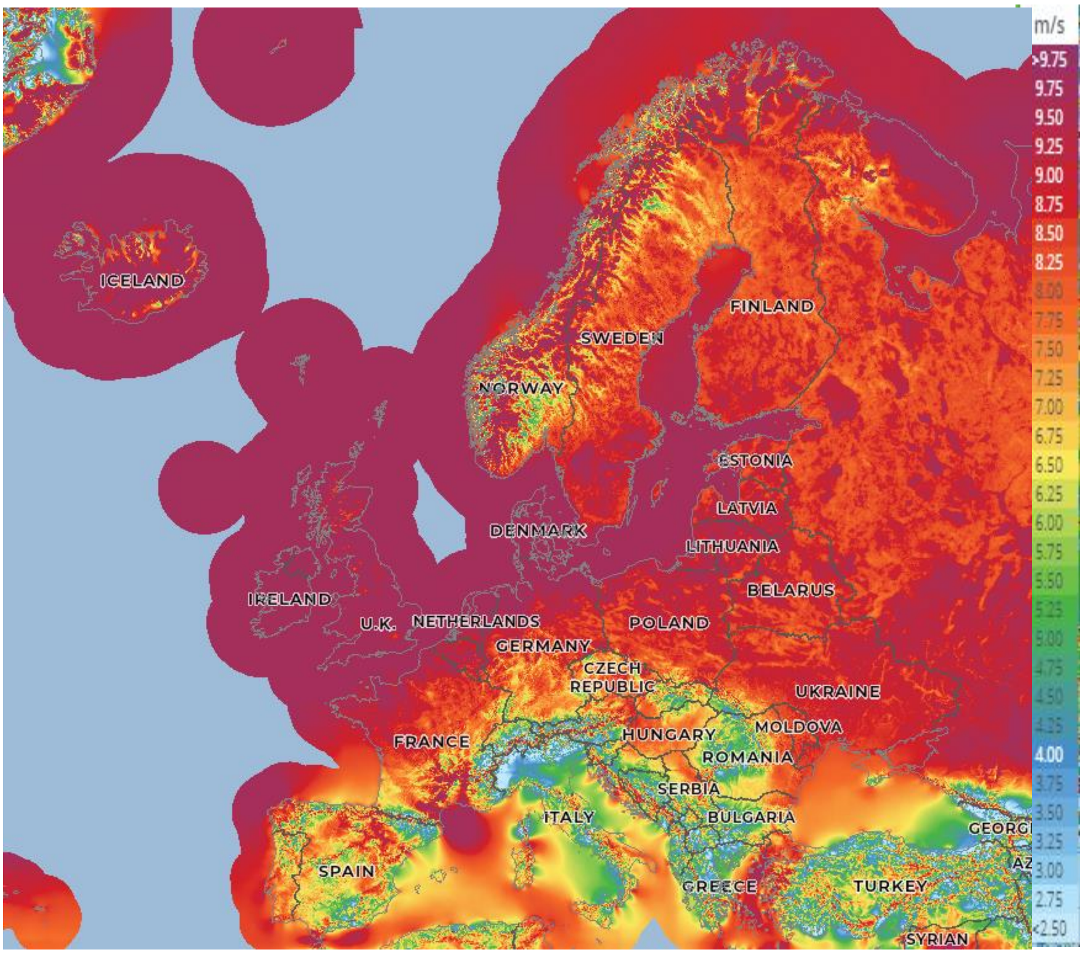


Figure 5. Wind speed at 200 meters, Europe (Global Wind Atlas, 2020)

For the height of 200 meters, the wind speed in the Nordic countries continues to be much higher, starting to exist a greater homogeneity of wind speed in these coastal areas. This same speed tends to be much lower in southern Europe, specifically in the Mediterranean Sea areas. Relatively to 50 meters, there is a good increase in wind speed in countries like France, Germany, Poland, among others, realizing this variation in wind speed concerning the height at which it is measured. A quick swoop around immediately reveals the overall color change in Europe, mainly in the northern countries, like France, Germany, Netherlands, Sweden, among a few others.

In the European paradigm, it is worth noting a significant potential of onshore wind farms in Nordic countries, whether these are Denmark, Norway, Sweden, Finland, or even in the United Kingdom, Ireland and Iceland, but also the vast potential of offshore wind farms, namely on the Portuguese coast and in the North or Baltic Sea as well. By lumping the two figures together, one can see why much of the existing offshore projects in Europe focus mainly on the coastal areas adjacent to the UK.

In summary, after analyzing the figures above, it becomes understandable the modern race is towards heights. Since wind speed tends to increase with height, the desire to produce more energy has become a technological challenge. As such, to maximize production and efficiency, larger wind turbines with blades whose rotor diameter can reach 222 meters (Siemens Gamesa, 2020) have begun to be produced. This desire for heights is further supported by the possible reduction of the required deployment area; they can run at higher speeds because the hub is higher, a smaller number of turbines can lead to a reduction in costs and, therefore, a decrease in the price per MWh, however, in the event of a technical failure or equipment failure, replacement costs may be higher.

### 3.1 Onshore Wind Turbines

Onshore wind is a very well-established technology with a vast potential market and space to grow and develop. This technology is distinguished for its onshore deployment and construction, in which the base is set a few meters into the surface using a circular concrete foundation, making it impossible to tip the wind turbine over due to the force of the wind. These turbines are most likely to be horizontal axis since this technology can produce more electricity from a given amount of wind. Horizontal axis means the rotating axis of the wind turbine is horizontal, or parallel with the ground. (Wind Power, 2009).

“Onshore wind has shown cost reductions for more than three decades”, “the capacity factor has also increased significantly, going hand in hand with higher hub heights and larger rotor diameters.”. “The overall learning rate for LCOE for data between 1990 and 2017 is 11.4%. Combining this learning rate with anticipated growth in global onshore wind deployment yields a projected LCOE of 3.7$ cents/kWh by 2030, a reduction of approximately 25% from 2018 levels, making it highly competitive with expected prices of new coal and natural gas generation” (Junginger et al., 2020).

Vertical axis turbines are usually installed in extensive plains or in more mountainous areas, namely, on their summits. In the case of plains, these are clean areas free of obstacles. These obstacles would remove speed and energy from the wind, thus reducing the electricity production of a given wind turbine. In the case of ridges, the air masses tend to go up the slope due to the respective heating from the insolation.

Onshore wind can be distributed in different ways. They can appear sporadically along a ridge or, in the case of higher production and greater energy needs of a particular location, on wind farms. Wind farms are usually implemented in areas known to be especially windy regularly and are characterized by occupying large land areas, as shown in figure 6, with a large number of turbines able to harvest as much energy as possible. Therefore, they can maximize production without having to worry about the wind velocity fluctuations throughout the years.

Figure 6. Example of a Wind Farm (Balkan Green Energy News, 2020)

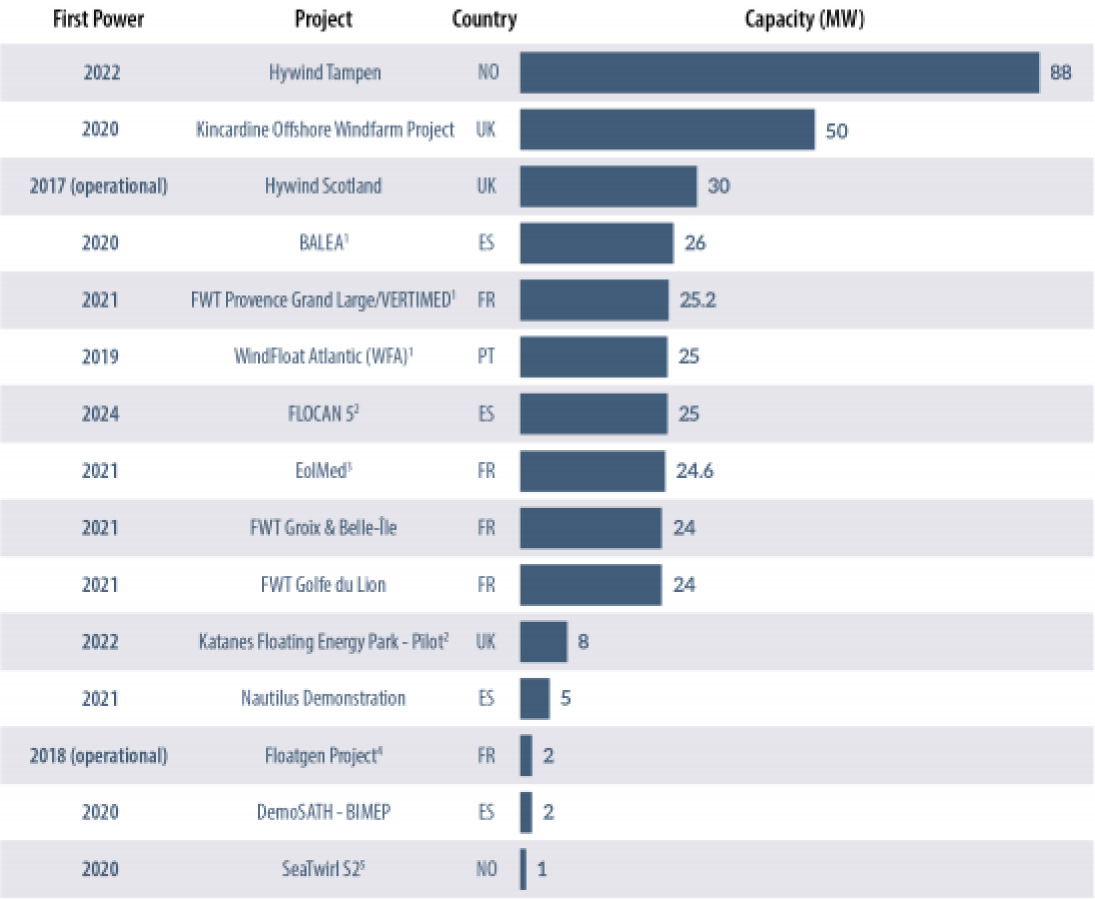
### 3.2 Offshore Wind Turbines

Offshore wind is a less mature technology with less time on the market, however, despite its development limitations, namely its attachment to the seabed or floating platforms, it is one of the technologies with the most significant potential and room to grow. This technology still presents several areas to be explored, and more and more projects for floating offshore wind farms are being submitted.

“Offshore wind is a highly promising renewable energy source (RES) that could make a major contribution to global and European efforts to decarbonize the economy by 2050 and keep global warming to around 1.5°C above pre-industrial levels” (European Commission, 2020).

The deployment area of fixed offshore turbines is globally smaller than the deployment area of onshore wind turbines since to operate they had to be fixed to the seabed. As such, they could only be placed in places where the continental shelf extends for a few kilometers, with low depth, leaving other areas of great potential unutilized. According to Akar Offshore Wind, about 80% of the world’s offshore wind resources are present in waters deeper then 60 meters, the max the maximum depth for the installation of fixed platforms (Akar Offshore Wind, 2021). However, the development of floating platforms, based on offshore oil and gas exploration technology, allows the turbines to be fixed not to the rocky substratum but a floating platform. This way, they are freed from one of their most significant limitations, the depth of the continental shelf. “At water depths greater than 35 to 40 meters, the bottom-fixed wind turbine is no longer economically competitive. In contrast, floating wind turbines, conceivable even from depths of 30 meters thanks to the Ideal foundation, have no limits.” (BWIdeal, ND)

One of the critical points of this technology is the absence of natural obstacles such as mountains, vegetation, and houses, since the sea surface, despite the waves, is flat, allowing a constant obtaining of energy due to little variable wind patterns in these same places. Furthermore, as seen before, the offshore wind speed can be much higher compared to some onshore locations. This way, figure 7 presents the nearest Floating Offshore Wind projects expected to be deployed up to 2022. According to figure 8, there are three ways to attach offshore wind farms to the seabed, and according to figure 9, there are five main types of floating platform technologies.



| First Power | Project | Country | Capacity (MW) |
|---|---|---|---|
| 2022 | Hywind Tampen | NO | 88 |
| 2020 | Kincardine Offshore Windfarm Project | UK | 50 |
| 2017 (operational) | Hywind Scotland | UK | 30 |
| 2020 | BALEA[1] | ES | 26 |
| 2021 | FWT Provence Grand Large/VERTIMED[1] | FR | 25.2 |
| 2019 | WindFloat Atlantic (WFA)[1] | PT | 25 |
| 2024 | FLOCAN 5[2] | ES | 25 |
| 2021 | EolMed[3] | FR | 24.6 |
| 2021 | FWT Groix & Belle-Île | FR | 24 |
| 2021 | FWT Golfe du Lion | FR | 24 |
| 2022 | Katanes Floating Energy Park - Pilot[2] | UK | 8 |
| 2021 | Nautilus Demonstration | ES | 5 |
| 2018 (operational) | Floatgen Project[4] | FR | 2 |
| 2020 | DemoSATH - BIMEP | ES | 2 |
| 2020 | SeaTwirl S2[5] | NO | 1 |

Figure 7. Offshore Wind floating projects (European Commission, 2018)

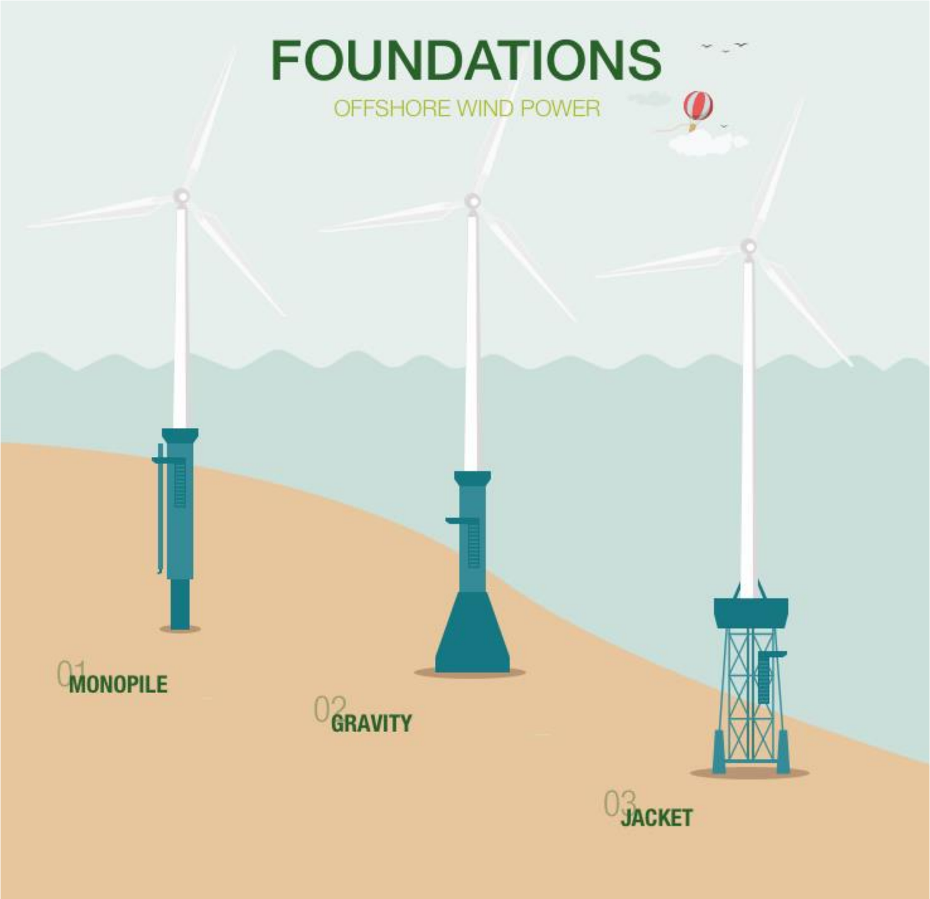


Figure 8. Common fixed Offshore Wind turbines (Iberdrola, ND)

Figure 9. Most used floating platforms (Wind Power, 2019)

According to the literature, there are more than 30 concepts being developed worldwide; however, the ones above illustrated are the most mature and most used globally. The table 1 below shows the average depths at which each technology is installed and its stability systems.

Table 1. Offshore Platforms and key differences (Floating Production Systems, N,D)

| *Offshore Platforms* | *Depth (meters)* | *Stability Systems* |
|---|---|---|
| *Barge* | ➢ *80* | *Rely on Boyancy* |
| *Semi-Submersible* | ➢ *120* | *Rely on Boyancy* |
| *Articulated Multi-Spar* | | *Rely on Boyancy* |
| *Spar* | ➢ *120* | *Relys on the gravity* |
| *Tenson-Leg Platform* | *50 – 60* | *Tension in the moring system* |
| *Monopile* | *0 - 15* | *Fixed to the seabed* |
| *Gravity* | *0 - 30* | *Fixed to the seabed* |
| *Jack-et/Tripod* | *25 - 50* | *Fixed to the seabed* |

The literature varies a lot regarding the depth to which each type of platform can operate; however, one of the main factors in the choice depends on the rock substrate, sea depth, and platform fixations to the same seabed. Regarding environmental impact, it is also essential to distinguish the difference between floating wind platforms and fixed offshore wind turbines since the last one is much more evasive to the seabed activity throughout the installation and operation.

### 3.3 Small Wind

Small wind turbines are a decentralized technology that relies on the production of energy through wind. This technology is usually adopted only in windy locations or locations with constant wind patterns over the years. It can reduce electricity bill costs by 50% - 90% and expenses associated with extending utility power lines to remote locations (Small Wind Electric Systems, n.d). These types of wind turbines are also commonly used in water pumping systems on farms and ranches and are quite common on larger sailboats. “In lower-income countries, micro wind turbines can help expand access to electricity, giving people a way to light their homes or cook their evening meals, avoiding emissions from dirty diesel generators or kerosene lamps. Microturbines can also be placed on large structures, such as skyscrapers, to take advantage of stronger, steadier breezes.” (Project Drawdown, 2021)

There are two types of Small wind turbines, horizontal axis and vertical axis. Currently, the most used turbine in today’s market is the horizontal-axis wind turbine, usually with 2 to 3 blades. Horizontal axis means the rotating axis of the wind turbine is horizontal or parallel with the ground. Vertical-axis wind turbines consist of two types: Savonius and Darrieus. (Nayar, et.al, 2011). Due to its small size and its individual use and in places with plenty of space, this technology presents a very low value compared to other technologies in the global mix of electricity generation. Figure 10 presents an example for horizontal and vertical wind turbines, whereas figure 11 presents both Savonius and Darrieus wind turbines.

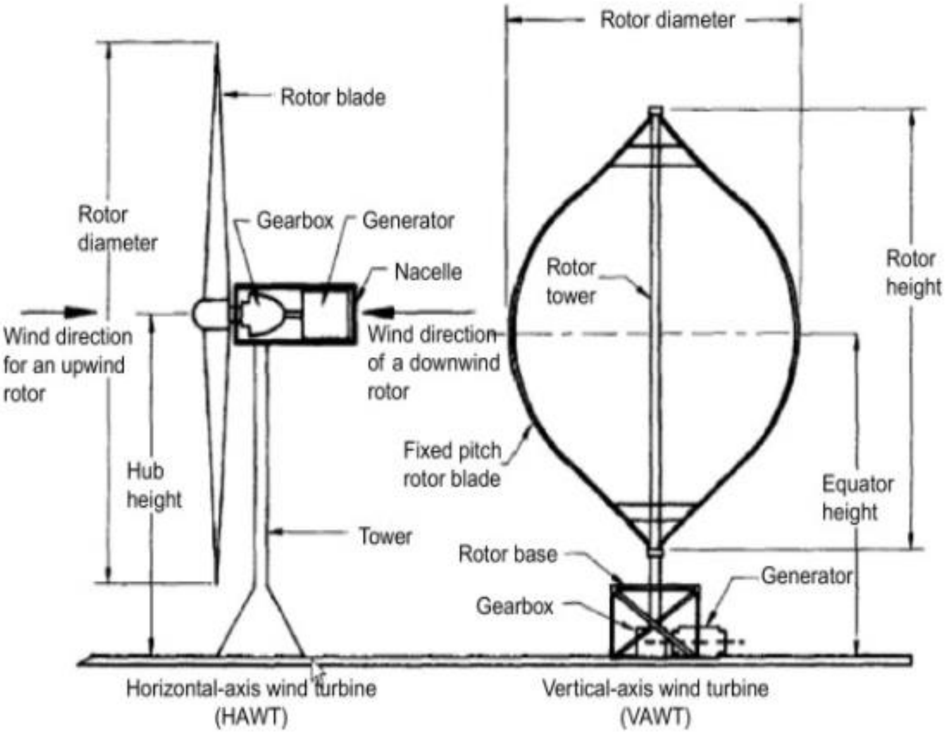


Figure 10. Examples of a Horizontal-axis wind turbine and a Vertical-axis wind turbine. (Islam et al., 2018)

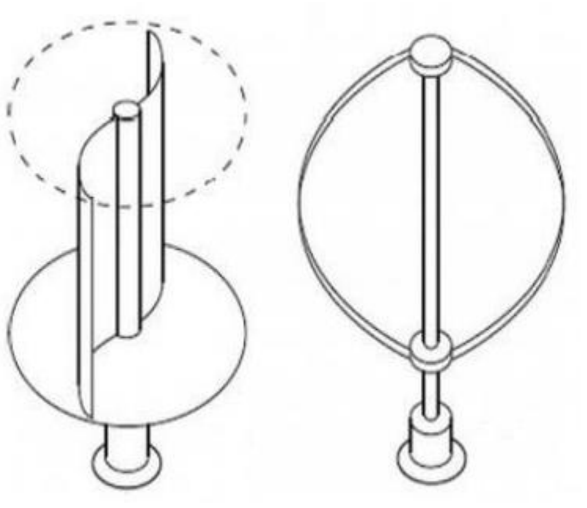


Figure 11. Savonius and Darrieus wind turbine. (Castellani, 2019)

# 4 Current Status and trends of Wind Technology

One, if not the earliest use of wind energy, consisted of the art of navigation, “People used wind energy to propel boats along the Nile River as early as 5 000 BC. By 200 BC, simple wind-powered water pumps were used in China, and windmills with woven-reed blades were grinding grain in Persia and the Middle East.” (U.S. Energy Information Administration, 2021)

Besides the scientific improvement throughout the years and the switch of the main goal, instead of navigation and crushing seeds, electricity production, wind energy started to grow and develop as one of the most important technologies. With the public interest, political support came as well, boosting even more global wind technologies impact. Since then, wind technologies for electricity generation have evolved and improved immensely. With the adoption of the previously presented technologies, the creation of new wind farms, and the global introduction of new turbines and mechanisms, a constant decline in price has been observed throughout the years and a steady increase in performance.

Nevertheless, only a small percentage of both European and global electricity generation mix is produced based on wind technologies. For the first case, in 2018, Onshore wind represents about 9.81% and Offshore Wind 1.79%, summing a total of 11.6% (IRENA, 2021). In the Global electricity generation mix, for the same year, Onshore represents about 4.48% and Offshore 0.26%, having wind a total share of around 4.7% (IRENA, 2021). It is essential to highlight that generation through small wind technologies is included in the Onshore technologies since it is based on onshore deployment. With this quick data reveal, it is easy to understand the low weight of wind technologies in the global electricity generation mix, being more relevant in the European Union context. Figures 12 and 13 sums up the data retrieved.

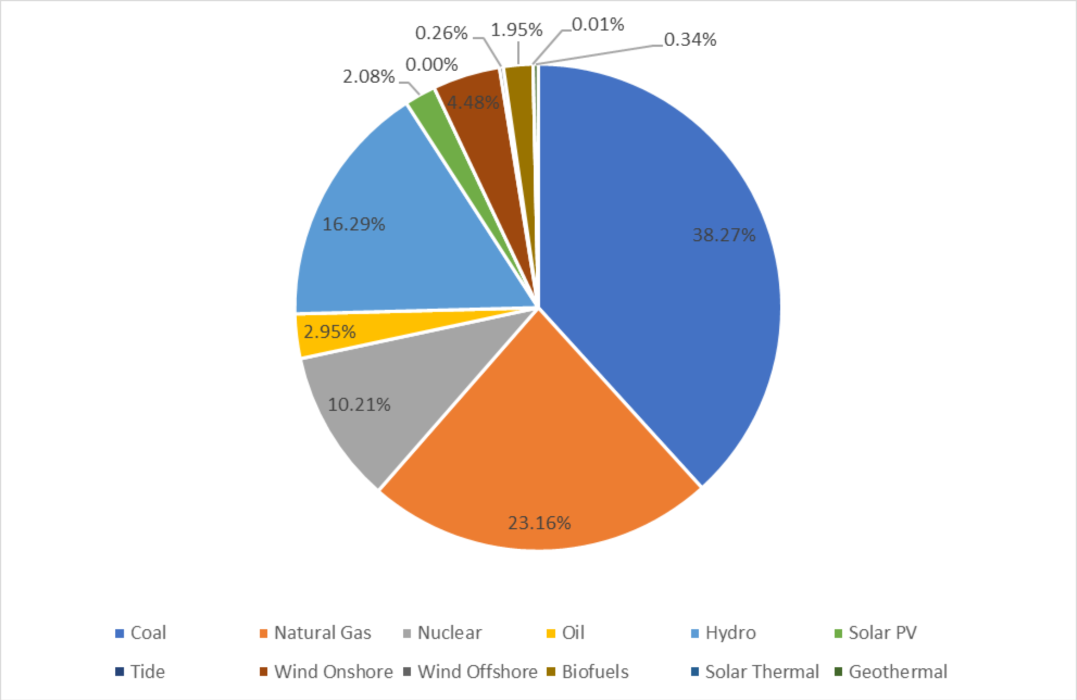


Figure 12. World Electricity Generation Mix (2018) (Data from IEA and IRENA, 2021)

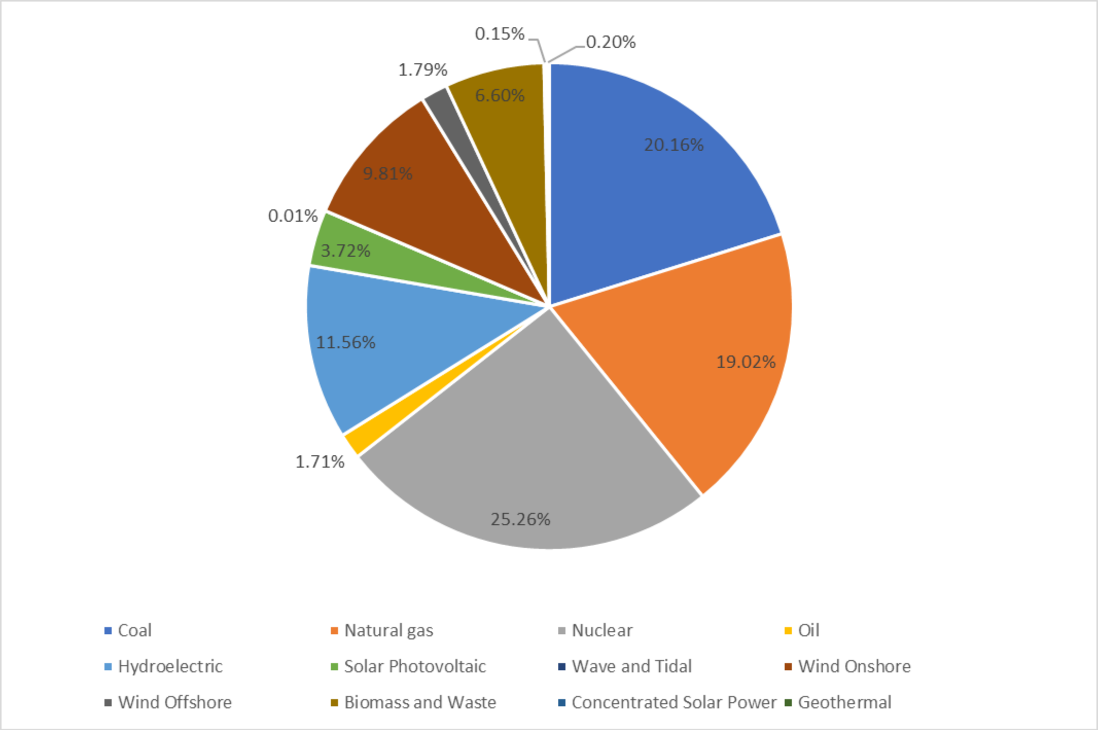


Figure 13. European Union Electricity Generation Mix (2018) (Data from IEA and IRENA, 2021)

According to IEA (2021), in 2018, 74% of the Global electricity generation came from nonrenewable sources, contrasting with the 66% used in the European Union region. Also, besides comparing the use of renewable and nonrenewable sources, coal use comparison must be made. Being the more pollutive and impactful source of energy, coal continues to be primarily used in countries like Poland, China, and the United States. However, besides the general global use of this energy source, the European Union comes relatively well with roughly 20% of electricity generation from coal, compared with the 38% used globally. The tables further presented, Tables 2 and 3 represent the historical electricity generation values for the two leading wind technologies and the respective percentage

Table 2. Electricity Generation of wind technologies - historical values (European Union, TWh) (Adapted from IRENA, 2021)

| Technology (TWh) | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Onshore | 70 | 82 | 104 | 118 | 130 | 144 | 172 | 195 | 221 | 233 | 271 | 268 | 316 | 325 |
| Offshore | 2 | 2 | 2 | 3 | 5 | 7 | 11 | 14 | 19 | 25 | 37 | 40 | 51 | 59 |

Table 3. Percentage of electricity generated by wind onshore and offshore (%) - historical values (European Union) (Adapted from IRENA, 2021)

| Technology (%) | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Onshore | 98.0 | 98.0 | 97.9 | 97.2 | 96.2 | 95.3 | 94.0 | 93.4 | 92.0 | 90.3 | 88.1 | 87.0 | 86.1 | 84.7 |
| Offshore | 2.0 | 2.0 | 2.1 | 2.8 | 3.8 | 4.8 | 6.0 | 6.6 | 8.0 | 9.7 | 11.6 | 13.0 | 13.9 | 15.3 |

Regarding the technology adoptions presented above, it is worth noting the considerable increase in electricity production, having grown, since 2005, 533%, with annual increases reaching 41%. However, there were years where the amount of electricity produced is only marginally higher than the previous year, a factor that can be explained by the lower movement of air masses in some regions of the European Union, or some cases, due to the end of life of specific wind farms. In addition to the increase in electricity produced by Onshore wind farms, the importance and growth that Offshore wind farms are starting to show in the global mix should also be highlighted. One of the main setbacks for implementing this technology is the depth of the near shore continental coast of certain countries that do not have sufficient distance or depth to install wind farms there. However, with the development of offshore technologies, offshore wind farms no longer need to be fixed to the seabed and floating platforms, thus allowing a dramatic increase in the possible sites for offshore wind farms.

The existing difference between the electricity production of these two technologies is quite large, in 2005, 98% of the production came from onshore wind while a mere 2% came from offshore. Nevertheless, by 2018 this figure had decreased to 85% for Onshore technology and increased to 15% for Offshore. According to the literature, as the technology matures, Offshore could be expected to pass the output generated by Onshore due to higher capacity factors.

# 5 Long term energy and climate studies

This section sets the scene for long term energy scenarios, with primary considerations, thoughts, and choices of different publications and reports. This way, an insight of different publications will be presented, splitting them according to their different models, time frames, scenarios evaluated, and other key aspects.

Several international projects/reports from diverse entities address long-term projections of energy systems, greenhouse gas-related emissions, and technological roadmaps. Due to their different objectives, regional aggregations, timeframes, and scopes, their results, tools, and methodologies are diverse. Models used by different sources have different behaviors and can significantly impact climate change mitigation costs projections and other policy-relevant information. Models usually differ in how various detailed aspects of the system are represented and how the components interact; these differences in the models are due to the different choices on how to best approach the analysis for GHG mitigation pathway.

The literature presents a consensus on the technical challenges, such as generation, demand base, transmission infrastructures, that the energy transition may face when heading towards the decarbonization of the power sector. On the other hand, the costs and the criticality of such requirements are still very much in debate. These are due to the diverse aspects of technologies, can rapidly change, and can help in the policy-making process.

Throughout the papers and studies reviewed, much differentiation is conducted within the entities and studies. Nevertheless, all these documents focus on the long-term perspective revealing the urge and importance to address future electricity production topics, much due to the climate crisis, the need for an energy transition, and understanding the associated costs. With the scenarios presented within the studies, there is still the possibility of understanding if global and national goals are also being achieved.

The main differences presented throughout the literature review are focused on the studies timeline, the region where the study is focused, if the entities are public or private and the different types of models used. A few selected examples to showcase the wider variety of studies available is disclosed below.

Regarding the timeline frame of each study, Shell, a public company that presents a timeline of study that goes until 2100, Greenpeace, a non-governmental organization, presents studies with a timeline that goes until 2050 and, to understand the variety of timeframes, Wind Europe, with over 400 members, published the “Wind energy in Europe, Scenarios for 2030” that addresses electricity generation values that go as far as 2030.

Besides the timeline frame, the regionalization of studies also varies and impacts the data that needs to be collected. For example, Wind Europe study “Wind energy in Europe, Scenarios for 2030”, 2017, presents several types of values for the European context, “World Energy Outlook 2019”, from IEA (2019) has a global approach, nevertheless also has a more continent detail information and, reports such as “Global Offshore Wind: Annual Market Report 2020”, from Norwegian Energy Partners (2020) only addresses national values.

Some studies use different models with different structures and levels of detail; and explore different scenarios seeking to make a comparison between them. Some examples are “Benchmarking Scenario Comparisons: Key indicators for the clean energy transition, from

IRENA (2020), where a detailed comparison between scenarios is made as well as JRC (2020) report, “Towards net-zero emissions in the EU energy system by 2050”, where the same analysis is conducted for several specific scenarios. Regarding the model’s comparison, “Assessing the Total Addressable Market and major assumptions” from Project Drawdown (2017) is a very well and extensive study where three models are presented and subsequently dissected. Due to the high number of studies reviewed, Table 4 shows only a few entities, studies, and scenarios used in this work as data sources.

Table 4. Selected examples of long term energy projections studies.

| Source Document Name | Organization | Scenario | Reference |
|---|---|---|---|
| **Decarbonisation Pathways** | Eureletric | Scenario 1<br>Scenario 2<br>Scenario 3 | Eureletric, 2018 |
| **Gas for Climate** | Navigant | Navigant min gas<br>Navigant OTP gas | Navigant, 2019 |
| **Wind Energy in Europe: Scenarios for 2030** | Wind Europe | Central Scenario<br>High Scenario<br>Low Scenario | Wind Europe, 2017 |
| **The Vision Scenario for the European Union** | Oko-Institut e.V | Reference Scenario<br>Vision Scenario | Oko-Institut e.V, 2018 |
| **Energy Technology Perspectives 2017** | IEA | IEA Stated Policies Scenario<br>IEA Current Policies Scenario<br>IEA Sustainable Development Scenario | IEA, 2017 |
| **Energy [r]evolution** | Greenpeace | Reference<br>[r]evolution<br>Advanced energy [r]evolution | Greenpeace, 2015 |
| **100% Renewable Europe 2020** | Solar Power Europe | Laggard<br>Moderate<br>Leadership | Solar Power Europe, 2020 |
| **Deployment Scenarios for Low Carbon Technologies** | EU Joint Research Centre | Baseline<br>Div 1<br>Res 1<br>Res_Near_Zero | EU Joint Research Centre, 2018 |
| **Achieving the Paris Climate Agreement Goals** | IFS | IFS 5C<br>IFS 2C<br>IFS 1,5C | IFS, 2019 |
| **Offshore Wind Outlook** | IEA | Stated Policies Scenario<br>Sustainable Policies Scenario | IEA, 2019 |
| **Net Zero by 2050: From Whether to How** | Climact | EFC Technology<br>EFC Shared Effort<br>EFC Demand-Focus | Climact, 2018 |

## 5.1 International Energy Agency World Energy Outlook (IEA, 2019)

Published since 1977 and annually updated since 1998, IEA’s World Energy Outlook (WEO) might be one of the most complete and authoritative publications in the energy sector. Like many other publications in the energy sector, World Energy Outlook 2019 provides a group of scenarios that are further discussed and explain. These developed scenarios are based on technical developments, political, economic, and environmental trends, therefore, the scenarios developed are not future predictions but portray several possibilities. Additionally, the World Energy Outlooks have been paying even more attention to subjects such as sustainability and energy access for all, referring that almost one billion people still do not have electricity as a regular part of their life and the fast renewable-driven energy transition.

This study for 2019 presented three different scenarios based on different climate and policy ambitions that will serve as the spine for the report's results and further discussion. These scenarios are entitled as Current Policies Scenario (CPS), Stated Policies Scenario (SPS), and the Sustainable Development Scenario (SDS). The first one, Current Policies Scenario (CPS), is the most conservative one, defined as what would happen if the world continued with the trends displayed without any additional policy changes.

Secondly, the intermediate scenario comes Stated Policies Scenario (SPS), the previously called New Policies Scenarios in the previous WEO, whose primary goal is to portray the possible outcome of announced policies and other governmental plans and goals that are still not operational. Anticipating a potential lack in announcements of futures plans, this scenario can be considered conservative since it considers an increase in energy demand by 1% per year until 2040.

The most ambitious scenario on the 2019 WEO is the Sustainable Development Scenario (SDS) that, in a nutshell, “maps out a way to meet sustainable energy goals in full, requiring rapid and widespread changes across all parts of the energy system.” (IEA, WEO, 2019). This scenario is in line with the Paris Agreement, now known to be insufficient to maintain the global temperature below 1.5ºC, and it was inspired by United Nations Sustainable Development Goals.

### 5.2 The Vision Scenario for the European Union, Oko-Institut, 2018

Published in February of 2018, it has, as a primary goal, to try and provide a global framework and a $CO_2$ emission budget for the European Union. Having as a principle the current oscillations in fossil fuel prices and, therefore, the variation in fossil fuel energy. The Vision Scenario for the European Union believes that this oscillation will lead to new and better energy and climate policies for the next decades.

Having this bared in mind, two different scenarios were developed: the Reference Scenario, less ambitious, and the Vision Scenario, more ambitious.

The Reference Scenario was developed based on the ambitions displayed at the time for the energy and climate policies reflected in the European Commission’s Baseline Scenario from 2016. This study presented values for emissions reduction, 42% in 2050 and, the share of power generation from renewable sources was expected to reach 53% in 2050. One of the key criteria also presented in this study was the slight decline in nuclear power production throughout the following decades.

The Vision Scenario, a more ambitious one, is based on the GHG reduction goal not to overpass the increase of 2ºC of the global temperature. One of the differentiating aspects is considering land use and the plantation and increase of global forest that could enable a 95% emission reduction. For comparison, in this scenario, for 2050, renewable energy would represent 97% of the total primary energy supply, net power generation would go as high as 100% for renewable energy, and nuclear energy would no longer exist in 2045.

### 5.3 Wind energy in Europe in 2018, Wind Europe

Also published in 2018, the Wind Europe report is less detailed and specific for global information. Although in some cases, a more global information was needed and happily embraced, reports focus on the geographical area studied are even more welcome. Starting by referring to the total installed capacity in the European Union and referring to it as the second-largest form of power generation, wind is pointing out to take the first place in the year after the study publication, 2019.

While, in some studies, data for Onshore, Offshore, and Small wind technologies were hard to find, sometimes all gathered up in the wind category, in this report, a detailed installed capacity per country for the EU-28 is conducted for Onshore and Offshore. Nevertheless, results for Europe are also present, differentiating the countries added to this geographical area.

Besides supplying electricity and power generation, this report comes out as one of the most detailed, providing numerous information for the VMA (Variable Menta Analysis) data. In other words, this appears to be one of the most complete reports for the technology in the study providing information regarding the wind turbines size, wind power generation in % for each country, decommissioning and repowering of wind installations, investments needed, and many more key details.

### 5.4 Decarbonisation pathways, Eurelectric, 2018

Providing the most usable number of scenarios for the current work, Decarbonization pathways is, undoubtedly, one of the most important reports. With the main goals of increasing EU-28 contribution in the Paris Agreement and to help decarbonize Europe, believing that such a process would remain competitive in the global market and lead this transition, Eurelectric has created three different scenarios. Afterward, this report also presents a detailed analysis of the power sector decarbonization pathways, particularly the associated costs.

Referring to the scenarios created by this entity, starting with the less ambitious, Scenario 1, followed by scenario and 2 and, the more ambitious, Scenario 3. Stating with Scenario 1, entitled this way due to the lack of name presented by the report, Scenario 1 shows global decarbonization of EU’s economy of 80%, whereas Scenario 2 and 3 present 90% and 95% respectively. Nevertheless, they are all based on different assumptions. For the first case, this scenario is based on accelerating current technological trends, policies, and customer uptake. In contrast, Scenario 2 is based on a significant policy shift to remove barriers and promote decarbonization and electrification. Finally, the last scenario is based on an early technological breakthrough and deployment at scale through global coordination.

Besides presenting data for the power sector, this reports also presents data for transport, building, and industries electrification throughout the years and scenarios. Additionally, in the transport industry, electrification rates are also present for several means of traveling, starting in the passenger’s car and ending in rail transport. The same detailed analysis is also conducted for residential sectors, cooking, space heating, etc., and the iron and steel industries, chemical industries, and others.

### 5.5 Other Publications

As expected, many other publications have contributed to the work developed herein, whether by providing technical details, more inside information about diverse technologies, scenario retrieval, and even deepening knowledge in the energy sector. Without the possibility of mentioning them all and giving more details of each of their main characteristics, Table 4 previously shown enhances the more important works for this thesis and the most important to discuss.

# 6 METHODOLOGY

The following chapter is divided into two sections. Firstly, there will be a brief presentation about the Project Drawdown model where each of the three solutions was described, and a range of scenarios was modeled. This excel model was the backbone for the development of the analysis and the results obtained on $CO_{2e}$ emissions reduction, electricity generation (TWh), associated investments and savings, and other key indicators. Secondly, a detailed description of each methodological step is depicted. The analysis conducted had in mind both a Europe and European Union scope of analysis. As such, four models were created, three for the European Union scope and, due to the lack of information, one for Europe.

## 6.1 Project Drawdown RRS Model

To develop the analysis of the long-term impact of the three wind solutions (onshore, offshore, small wind) studied herein up to 2050, the bottom-up solutions-oriented excel based model from Project Drawdown - RRS model, where RRS stands for Reduction and Replacement Solutions model was used. This excel model is designed to accommodate a large pool of data, from technical, financial, and environmental data characterizing each solution introduced, supplying the expected results and calculations in the same file.

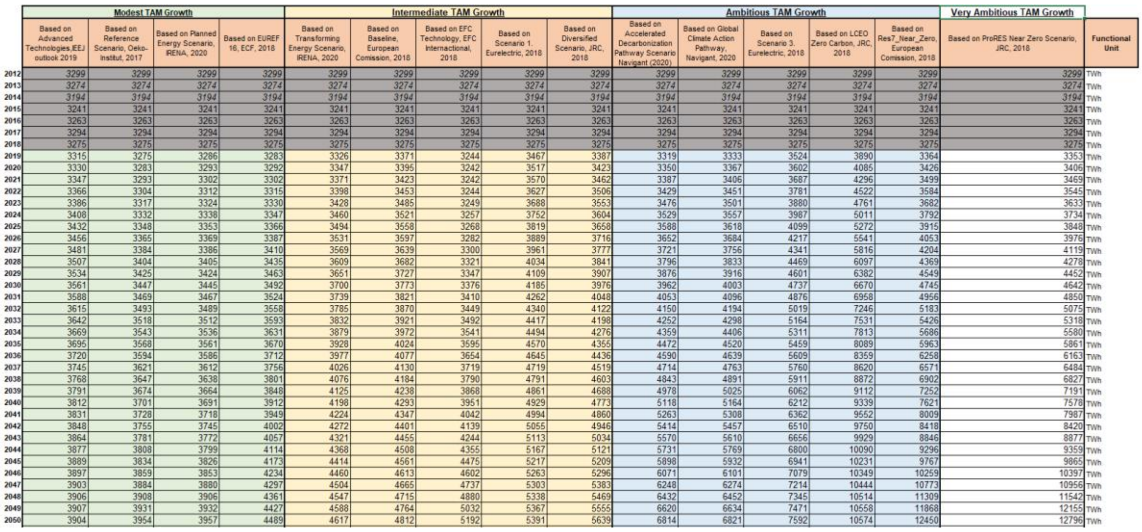
“The RRS core model is an Excel workbook that contains all of the data necessary to calculate the greenhouse-gas reductions and financial implications associated with a solution and allows users to change important inputs and see how the results are impacted. The RRS core template model is a pre-designed framework to calculate results.” (Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide)

This model has three main inputs, TAM (Totable Addressable Market) and Adoptions projections, and all the VMA data collected, later explained in section 6.2.5. This model is based on roughly 24 sheets, all used for different purposes and linked for the reacquisition results are also specific sheets to accommodate the scenarios retrieval, for the subsequent interpolation process to have annual data, as well as sheets to accommodate and treat all the VMA data and all his parameters. These interconnected sheets are divided between Basic and Advanced, combining information such as First Costs, Operating Costs, Adoption Data, Carbon Price Analysis and many more.

Besides the database formed on this excel model and sequent ability to retrieve results from it, the main goal for the use of this model was to develop the final values that will be later on analyzed, values like Lifetime Operating Savings, Emissions Reduction, Margin First Cost, between others.

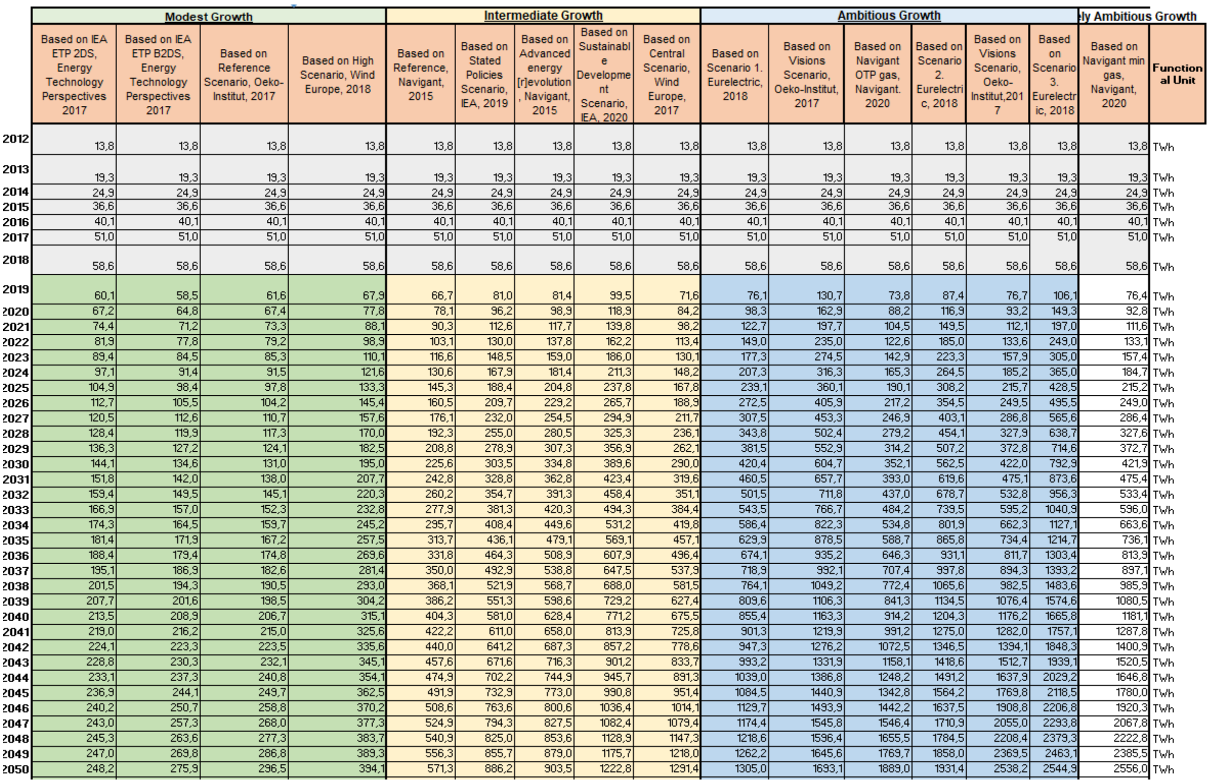
It is in the Drawdown RRS model that all the data was entered. This excel model is the brain that enables the retrieval of all the parameters that are latter going to be used, such as Implementation Unit Adoption Increase in 2050, Functional Unit Adoption Increase in 2050, Marginal First Cost 2015-2050, Net Operating Savings 2020-2050, Lifetime Operating Savings 2020-2050, Total Emissions Reduction; among many other but with lower level of importance.

All the data collected and afterwards analyzed was entered in this excel, starting by the TAM for the European Union or Europe, figure 14, the Adoptions used for this study, figure 15 and all the VMA data gathered in figure 16.



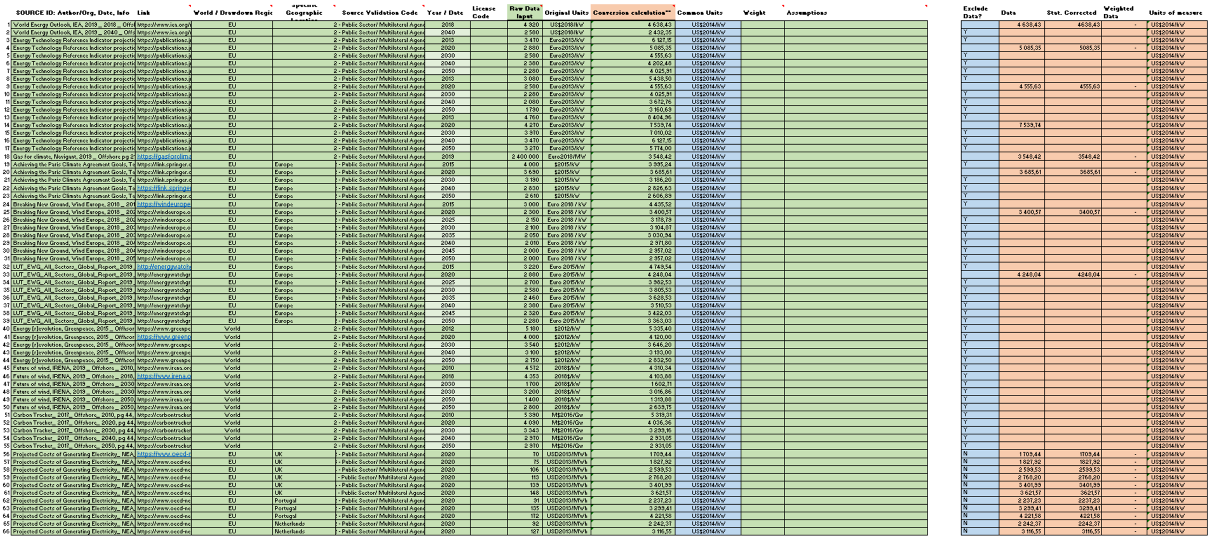
| | Modest TAM Growth | | | | Intermediate TAM Growth | | | | | Ambitious TAM Growth | | | | | Very Ambitious TAM Growth | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Based on Advanced Technologies,IEEJ outlook 2019 | Based on Reference Scenario, Oeko-Institut, 2017 | Based on Planned Energy Scenario, IRENA, 2020 | Based on EUREF 16, ECF, 2018 | Based on Transforming Energy Scenario, IRENA, 2020 | Based on Baseline, European Comission, 2018 | Based on EFC Technology, EFC Internactional, 2018 | Based on Scenario 1. Eurelectric, 2018 | Based on Diversified Scenario, JRC, 2018 | Based on Accelerated Decarbonization Pathway Scenario Navigant (2020) | Based on Global Climate Action Pathway, Navigant, 2020 | Based on Scenario 3. Eurelectric, 2018 | Based on LCEO Zero Carbon, JRC, 2018 | Based on Res7_Near_Zero, European Comission, 2018 | Based on ProRES Near Zero Scenario, JRC, 2018 | Functional Unit |
| 2012 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | 3299 | TWh |
| 2013 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | 3274 | TWh |
| 2014 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | 3194 | TWh |
| 2015 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | 3241 | TWh |
| 2016 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | 3263 | TWh |
| 2017 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | 3294 | TWh |
| 2018 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | 3275 | TWh |
| 2019 | 3315 | 3275 | 3286 | 3283 | 3326 | 3371 | 3244 | 3467 | 3387 | 3319 | 3333 | 3524 | 3890 | 3364 | 3353 | TWh |
| 2020 | 3330 | 3283 | 3293 | 3292 | 3347 | 3395 | 3242 | 3517 | 3423 | 3350 | 3367 | 3602 | 4085 | 3426 | 3406 | TWh |
| 2021 | 3347 | 3293 | 3302 | 3302 | 3371 | 3423 | 3242 | 3570 | 3462 | 3387 | 3406 | 3687 | 4296 | 3499 | 3469 | TWh |
| 2022 | 3366 | 3304 | 3312 | 3315 | 3398 | 3453 | 3244 | 3627 | 3506 | 3429 | 3451 | 3781 | 4522 | 3584 | 3545 | TWh |
| 2023 | 3386 | 3317 | 3324 | 3330 | 3428 | 3485 | 3249 | 3688 | 3553 | 3476 | 3501 | 3880 | 4761 | 3682 | 3633 | TWh |
| 2024 | 3408 | 3332 | 3338 | 3347 | 3460 | 3521 | 3257 | 3752 | 3604 | 3529 | 3557 | 3987 | 5011 | 3792 | 3734 | TWh |
| 2025 | 3432 | 3348 | 3353 | 3366 | 3494 | 3558 | 3268 | 3819 | 3658 | 3588 | 3618 | 4099 | 5272 | 3915 | 3848 | TWh |
| 2026 | 3456 | 3365 | 3369 | 3387 | 3531 | 3597 | 3282 | 3889 | 3716 | 3652 | 3684 | 4217 | 5541 | 4053 | 3976 | TWh |
| 2027 | 3481 | 3384 | 3386 | 3410 | 3569 | 3639 | 3300 | 3961 | 3777 | 3721 | 3756 | 4341 | 5816 | 4204 | 4119 | TWh |
| 2028 | 3507 | 3404 | 3405 | 3435 | 3609 | 3682 | 3321 | 4034 | 3841 | 3796 | 3833 | 4469 | 6097 | 4369 | 4278 | TWh |
| 2029 | 3534 | 3425 | 3424 | 3463 | 3651 | 3727 | 3347 | 4109 | 3907 | 3876 | 3916 | 4601 | 6382 | 4549 | 4452 | TWh |
| 2030 | 3561 | 3447 | 3445 | 3492 | 3700 | 3773 | 3376 | 4185 | 3976 | 3962 | 4003 | 4737 | 6670 | 4745 | 4642 | TWh |
| 2031 | 3588 | 3469 | 3467 | 3524 | 3739 | 3821 | 3410 | 4262 | 4048 | 4053 | 4096 | 4876 | 6958 | 4956 | 4850 | TWh |
| 2032 | 3615 | 3493 | 3489 | 3558 | 3785 | 3870 | 3449 | 4340 | 4122 | 4150 | 4194 | 5019 | 7246 | 5183 | 5075 | TWh |
| 2033 | 3642 | 3518 | 3512 | 3593 | 3832 | 3921 | 3492 | 4417 | 4198 | 4252 | 4298 | 5164 | 7531 | 5426 | 5318 | TWh |
| 2034 | 3669 | 3543 | 3536 | 3631 | 3879 | 3972 | 3541 | 4494 | 4276 | 4359 | 4406 | 5311 | 7813 | 5686 | 5580 | TWh |
| 2035 | 3695 | 3568 | 3561 | 3670 | 3928 | 4024 | 3595 | 4570 | 4355 | 4472 | 4520 | 5459 | 8089 | 5963 | 5861 | TWh |
| 2036 | 3720 | 3594 | 3586 | 3712 | 3977 | 4077 | 3654 | 4645 | 4436 | 4590 | 4639 | 5609 | 8359 | 6258 | 6163 | TWh |
| 2037 | 3745 | 3621 | 3612 | 3756 | 4026 | 4130 | 3719 | 4719 | 4519 | 4714 | 4763 | 5760 | 8620 | 6571 | 6484 | TWh |
| 2038 | 3768 | 3647 | 3638 | 3801 | 4076 | 4184 | 3790 | 4791 | 4603 | 4843 | 4891 | 5911 | 8872 | 6902 | 6827 | TWh |
| 2039 | 3791 | 3674 | 3664 | 3848 | 4125 | 4238 | 3868 | 4861 | 4688 | 4978 | 5025 | 6062 | 9112 | 7252 | 7191 | TWh |
| 2040 | 3812 | 3701 | 3691 | 3912 | 4198 | 4293 | 3951 | 4929 | 4773 | 5118 | 5164 | 6212 | 9339 | 7621 | 7578 | TWh |
| 2041 | 3831 | 3728 | 3718 | 3949 | 4224 | 4347 | 4042 | 4994 | 4860 | 5263 | 5308 | 6362 | 9552 | 8009 | 7987 | TWh |
| 2042 | 3848 | 3755 | 3745 | 4002 | 4272 | 4401 | 4139 | 5055 | 4946 | 5414 | 5457 | 6510 | 9750 | 8418 | 8420 | TWh |
| 2043 | 3864 | 3781 | 3772 | 4057 | 4321 | 4455 | 4244 | 5113 | 5034 | 5570 | 5610 | 6656 | 9929 | 8846 | 8877 | TWh |
| 2044 | 3877 | 3808 | 3799 | 4114 | 4368 | 4508 | 4355 | 5167 | 5121 | 5731 | 5769 | 6800 | 10090 | 9296 | 9359 | TWh |
| 2045 | 3889 | 3834 | 3826 | 4173 | 4414 | 4561 | 4475 | 5217 | 5209 | 5898 | 5932 | 6941 | 10231 | 9767 | 9865 | TWh |
| 2046 | 3897 | 3859 | 3853 | 4234 | 4460 | 4613 | 4602 | 5263 | 5296 | 6071 | 6101 | 7079 | 10349 | 10259 | 10397 | TWh |
| 2047 | 3903 | 3884 | 3880 | 4297 | 4504 | 4665 | 4737 | 5303 | 5383 | 6248 | 6274 | 7214 | 10444 | 10773 | 10956 | TWh |
| 2048 | 3906 | 3908 | 3906 | 4361 | 4547 | 4715 | 4880 | 5338 | 5469 | 6432 | 6452 | 7345 | 10514 | 11309 | 11542 | TWh |
| 2049 | 3907 | 3931 | 3932 | 4427 | 4588 | 4764 | 5032 | 5367 | 5555 | 6620 | 6634 | 7471 | 10558 | 11868 | 12155 | TWh |
| 2050 | 3904 | 3954 | 3957 | 4489 | 4617 | 4812 | 5192 | 5391 | 5639 | 6814 | 6821 | 7592 | 10574 | 12450 | 12796 | TWh |

Figure 14. TAM data split by Modest, Intermediate, Ambitious and Very Ambitous growth scenarios for the European Union



| | Modest Growth | | | | Intermediate Growth | | | | | Ambitious Growth | | | | | | ly Ambitious Growth | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Based on IEA ETP 2DS, Energy Technology Perspectives 2017 | Based on IEA ETP B2DS, Energy Technology Perspectives 2017 | Based on Reference Scenario, Oeko-Institut, 2017 | Based on High Scenario, Wind Europe, 2018 | Based on Reference, Navigant, 2015 | Based on Stated Policies Scenario, IEA, 2019 | Based on Advanced energy [r]evolution, Navigant, 2015 | Based on Sustainable Development Scenario, IEA, 2020 | Based on Central Scenario, Wind Europe, 2017 | Based on Scenario 1. Eurelectric, 2018 | Based on Visions Scenario, Oeko-Institut, 2017 | Based on Navigant OTP gas, Navigant. 2020 | Based on Scenario 2. Eurelectric, 2018 | Based on Visions Scenario, Oeko-Institut,2017 | Based on Scenario 3. Eurelectric, 2018 | Based on Navigant min gas, Navigant, 2020 | Functional Unit |
| 2012 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | 13,8 | TWh |
| 2013 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | 19,3 | TWh |
| 2014 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | 24,9 | TWh |
| 2015 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | 36,6 | TWh |
| 2016 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | 40,1 | TWh |
| 2017 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | 51,0 | TWh |
| 2018 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | 58,6 | TWh |
| 2019 | 60,1 | 58,5 | 61,6 | 67,9 | 66,7 | 81,0 | 81,4 | 99,5 | 71,6 | 76,1 | 130,7 | 73,8 | 87,4 | 76,7 | 106,1 | 76,4 | TWh |
| 2020 | 67,2 | 64,8 | 67,4 | 77,8 | 78,1 | 96,2 | 98,9 | 118,9 | 84,2 | 98,3 | 162,9 | 88,2 | 116,9 | 93,2 | 149,3 | 92,8 | TWh |
| 2021 | 74,4 | 71,2 | 73,3 | 88,1 | 90,3 | 112,6 | 117,7 | 139,8 | 98,2 | 122,7 | 197,7 | 104,5 | 149,5 | 112,1 | 197,0 | 111,6 | TWh |
| 2022 | 81,9 | 77,8 | 79,2 | 98,9 | 103,1 | 130,0 | 137,8 | 162,2 | 113,4 | 149,0 | 235,0 | 122,6 | 185,0 | 133,6 | 249,0 | 133,1 | TWh |
| 2023 | 89,4 | 84,5 | 85,3 | 110,1 | 116,6 | 148,5 | 159,0 | 186,0 | 130,1 | 177,3 | 274,5 | 142,9 | 223,3 | 157,9 | 305,0 | 157,4 | TWh |
| 2024 | 97,1 | 91,4 | 91,5 | 121,6 | 130,6 | 167,9 | 181,4 | 211,3 | 148,2 | 207,3 | 316,3 | 165,3 | 264,5 | 185,2 | 365,0 | 184,7 | TWh |
| 2025 | 104,9 | 98,4 | 97,8 | 133,3 | 145,3 | 188,4 | 204,8 | 237,8 | 167,8 | 239,1 | 360,1 | 190,1 | 308,2 | 215,7 | 428,5 | 215,2 | TWh |
| 2026 | 112,7 | 105,5 | 104,2 | 145,4 | 160,5 | 209,7 | 229,2 | 265,7 | 188,9 | 272,5 | 405,9 | 217,2 | 354,5 | 249,5 | 495,5 | 249,0 | TWh |
| 2027 | 120,5 | 112,6 | 110,7 | 157,6 | 176,1 | 232,0 | 254,5 | 294,9 | 211,7 | 307,5 | 453,3 | 246,9 | 403,1 | 286,8 | 565,6 | 286,4 | TWh |
| 2028 | 128,4 | 119,9 | 117,3 | 170,0 | 192,3 | 255,0 | 280,5 | 325,3 | 236,1 | 343,8 | 502,4 | 279,2 | 454,1 | 327,9 | 638,7 | 327,6 | TWh |
| 2029 | 136,3 | 127,2 | 124,1 | 182,5 | 208,8 | 278,9 | 307,3 | 356,9 | 262,1 | 381,5 | 552,9 | 314,2 | 507,2 | 372,8 | 714,6 | 372,7 | TWh |
| 2030 | 144,1 | 134,6 | 131,0 | 195,0 | 225,6 | 303,5 | 334,8 | 389,6 | 290,0 | 420,4 | 604,7 | 352,1 | 562,5 | 422,0 | 792,9 | 421,9 | TWh |
| 2031 | 151,8 | 142,0 | 138,0 | 207,7 | 242,8 | 328,8 | 362,8 | 423,4 | 319,6 | 460,5 | 657,7 | 393,0 | 619,6 | 475,1 | 873,6 | 475,4 | TWh |
| 2032 | 159,4 | 149,5 | 145,1 | 220,3 | 260,2 | 354,7 | 391,3 | 458,4 | 351,1 | 501,5 | 711,8 | 437,0 | 678,7 | 532,8 | 956,3 | 533,4 | TWh |
| 2033 | 166,9 | 157,0 | 152,3 | 232,8 | 277,9 | 381,3 | 420,3 | 494,3 | 384,4 | 543,5 | 766,7 | 484,2 | 739,5 | 595,2 | 1040,9 | 596,0 | TWh |
| 2034 | 174,3 | 164,5 | 159,7 | 245,2 | 295,7 | 408,4 | 449,6 | 531,2 | 419,8 | 586,4 | 822,3 | 534,8 | 801,9 | 662,3 | 1127,1 | 663,6 | TWh |
| 2035 | 181,4 | 171,9 | 167,2 | 257,5 | 313,7 | 436,1 | 479,1 | 569,1 | 457,1 | 629,9 | 878,5 | 588,7 | 865,8 | 734,4 | 1214,7 | 736,1 | TWh |
| 2036 | 188,4 | 179,4 | 174,8 | 269,6 | 331,8 | 464,3 | 508,9 | 607,9 | 496,4 | 674,1 | 935,2 | 646,3 | 931,1 | 811,7 | 1303,4 | 813,9 | TWh |
| 2037 | 195,1 | 186,9 | 182,6 | 281,4 | 350,0 | 492,9 | 538,8 | 647,5 | 537,9 | 718,9 | 992,1 | 707,4 | 997,8 | 894,3 | 1393,2 | 897,1 | TWh |
| 2038 | 201,5 | 194,3 | 190,5 | 293,0 | 368,1 | 521,9 | 568,7 | 688,0 | 581,5 | 764,1 | 1049,2 | 772,4 | 1065,6 | 982,5 | 1483,6 | 985,9 | TWh |
| 2039 | 207,7 | 201,6 | 198,5 | 304,2 | 386,2 | 551,3 | 598,6 | 729,2 | 627,4 | 809,6 | 1106,3 | 841,3 | 1134,5 | 1076,4 | 1574,6 | 1080,5 | TWh |
| 2040 | 213,5 | 208,9 | 206,7 | 315,1 | 404,3 | 581,0 | 628,4 | 771,2 | 675,5 | 855,4 | 1163,3 | 914,2 | 1204,3 | 1176,2 | 1665,8 | 1181,1 | TWh |
| 2041 | 219,0 | 216,2 | 215,0 | 325,6 | 422,2 | 611,0 | 658,0 | 813,9 | 725,8 | 901,3 | 1219,9 | 991,2 | 1275,0 | 1282,0 | 1757,1 | 1287,8 | TWh |
| 2042 | 224,1 | 223,3 | 223,5 | 335,6 | 440,0 | 641,2 | 687,3 | 857,2 | 778,6 | 947,3 | 1276,2 | 1072,5 | 1346,5 | 1394,1 | 1848,3 | 1400,9 | TWh |
| 2043 | 228,8 | 230,3 | 232,1 | 345,1 | 457,6 | 671,6 | 716,3 | 901,2 | 833,7 | 993,2 | 1331,9 | 1158,1 | 1418,6 | 1512,7 | 1939,1 | 1520,5 | TWh |
| 2044 | 233,1 | 237,3 | 240,8 | 354,1 | 474,9 | 702,2 | 744,9 | 945,7 | 891,3 | 1039,0 | 1386,8 | 1248,2 | 1491,2 | 1637,9 | 2029,2 | 1646,8 | TWh |
| 2045 | 236,9 | 244,1 | 249,7 | 362,5 | 491,9 | 732,9 | 773,0 | 990,8 | 951,4 | 1084,5 | 1440,9 | 1342,8 | 1564,2 | 1769,8 | 2118,5 | 1780,0 | TWh |
| 2046 | 240,2 | 250,7 | 258,8 | 370,2 | 508,6 | 763,6 | 800,6 | 1036,4 | 1014,1 | 1129,7 | 1493,9 | 1442,2 | 1637,5 | 1908,8 | 2206,8 | 1920,3 | TWh |
| 2047 | 243,0 | 257,3 | 268,0 | 377,3 | 524,9 | 794,3 | 827,5 | 1082,4 | 1079,4 | 1174,4 | 1545,8 | 1546,4 | 1710,9 | 2055,0 | 2293,8 | 2067,8 | TWh |
| 2048 | 245,3 | 263,6 | 277,3 | 383,7 | 540,9 | 825,0 | 853,6 | 1128,9 | 1147,3 | 1218,6 | 1596,4 | 1655,5 | 1784,5 | 2208,4 | 2379,3 | 2222,8 | TWh |
| 2049 | 247,0 | 269,8 | 286,8 | 389,3 | 556,3 | 855,7 | 879,0 | 1175,7 | 1218,0 | 1262,2 | 1645,6 | 1769,7 | 1858,0 | 2369,5 | 2463,1 | 2385,5 | TWh |
| 2050 | 248,2 | 275,9 | 296,5 | 394,1 | 571,3 | 886,2 | 903,5 | 1222,8 | 1291,4 | 1305,0 | 1693,1 | 1889,0 | 1931,4 | 2538,2 | 2544,9 | 2556,0 | TWh |

Figure 15. Adoption data split by Modest, Intermediate, Ambitious and Very Ambitous growth scenarios for the European Union



| | SOURCE ID: Author/Org, Date, Info | Link | World / Drawdown Regic | Specific Geographic | Source Validation Code | Year / Date | License Code | Raw Data Input | Original Units | Conversion calculation** | Common Units | Weight | Assumptions | Exclude Data? | Data | Stat. Corrected | Weighted Data | Units of measure |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | World Energy Outlook, IEA, 2019 _ 2018 _ Offs | https://www.iea.org/ | EU | | 2 - Public Sector/ Multilateral Agenc | 2018 | | 4 920 | US$2018/kW | 4 638,43 | US$2014/kW | | | | 4 638,43 | 4638,43 | - | US$2014/kW |
| 2 | World Energy Outlook, IEA, 2019 _ 2040 _ Offs | https://www.iea.org/ | EU | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 2 580 | US$2018/kW | 2 432,35 | US$2014/kW | | | Y | | | | US$2014/kW |
| 3 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2013 | | 3 470 | Euro2013/kW | 6 127,15 | US$2014/kW | | | Y | | | | US$2014/kW |
| 4 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2020 | | 2 880 | Euro2013/kW | 5 085,35 | US$2014/kW | | | | 5 085,35 | 5085,35 | - | US$2014/kW |
| 5 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 2 580 | Euro2013/kW | 4 555,63 | US$2014/kW | | | Y | | | | US$2014/kW |
| 6 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 2 380 | Euro2013/kW | 4 202,48 | US$2014/kW | | | Y | | | | US$2014/kW |
| 7 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 2 280 | Euro2013/kW | 4 025,91 | US$2014/kW | | | Y | | | | US$2014/kW |
| 8 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2013 | | 3 080 | Euro2013/kW | 5 438,50 | US$2014/kW | | | Y | | | | US$2014/kW |
| 9 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2020 | | 2 580 | Euro2013/kW | 4 555,63 | US$2014/kW | | | | 4 555,63 | 4555,63 | - | US$2014/kW |
| 10 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 2 280 | Euro2013/kW | 4 025,91 | US$2014/kW | | | Y | | | | US$2014/kW |
| 11 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 2 080 | Euro2013/kW | 3 672,76 | US$2014/kW | | | Y | | | | US$2014/kW |
| 12 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 1 790 | Euro2013/kW | 3 160,69 | US$2014/kW | | | Y | | | | US$2014/kW |
| 13 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2013 | | 4 760 | Euro2013/kW | 8 404,96 | US$2014/kW | | | Y | | | | US$2014/kW |
| 14 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2020 | | 4 270 | Euro2013/kW | 7 539,74 | US$2014/kW | | | | 7 539,74 | | | US$2014/kW |
| 15 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 3 970 | Euro2013/kW | 7 010,02 | US$2014/kW | | | Y | | | | US$2014/kW |
| 16 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 3 470 | Euro2013/kW | 6 127,15 | US$2014/kW | | | Y | | | | US$2014/kW |
| 17 | Energy Technology Reference Indicator projecti | https://publications.j | EU | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 3 270 | Euro2013/kW | 5 774,00 | US$2014/kW | | | Y | | | | US$2014/kW |
| 18 | Gas for climate, Navigant, 2019 _ Offshore pg 2 | https://gasforclima | EU | | 2 - Public Sector/ Multilateral Agenc | 2019 | | 2 400 000 | Euro2018/MW | 3 548,42 | US$2014/kW | | | | 3 548,42 | 3548,42 | - | US$2014/kW |
| 19 | Achieving the Paris Climate Agreement Goals, T | https://link.springer.c | EU | Europe | - Public Sector/ Multilateral Agenc | 2015 | | 4 000 | $2015/kW | 3 995,24 | US$2014/kW | | | Y | | | | US$2014/kW |
| 20 | Achieving the Paris Climate Agreement Goals, T | https://link.springer.c | EU | Europe | - Public Sector/ Multilateral Agenc | 2020 | | 3 690 | $2015/kW | 3 685,61 | US$2014/kW | | | | 3 685,61 | 3685,61 | - | US$2014/kW |
| 21 | Achieving the Paris Climate Agreement Goals, T | https://link.springer.c | EU | Europe | - Public Sector/ Multilateral Agenc | 2030 | | 3 190 | $2015/kW | 3 186,20 | US$2014/kW | | | Y | | | | US$2014/kW |
| 22 | Achieving the Paris Climate Agreement Goals, T | https://link.springe | EU | Europe | - Public Sector/ Multilateral Agenc | 2040 | | 2 830 | $2015/kW | 2 826,63 | US$2014/kW | | | Y | | | | US$2014/kW |
| 23 | Achieving the Paris Climate Agreement Goals, T | https://link.springer.c | EU | Europe | - Public Sector/ Multilateral Agenc | 2050 | | 2 610 | $2015/kW | 2 606,89 | US$2014/kW | | | Y | | | | US$2014/kW |
| 24 | Breaking New Ground, Wind Europe, 2018 _ 201 | https://windeurope | EU | Europe | - Public Sector/ Multilateral Agenc | 2015 | | 3 000 | Euro 2018 / kW | 4 435,52 | US$2014/kW | | | Y | | | | US$2014/kW |
| 25 | Breaking New Ground, Wind Europe, 2018 _ 202 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2020 | | 2 300 | Euro 2018 / kW | 3 400,57 | US$2014/kW | | | | 3 400,57 | 3400,57 | - | US$2014/kW |
| 26 | Breaking New Ground, Wind Europe, 2018 _ 202 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2025 | | 2 150 | Euro 2018 / kW | 3 178,79 | US$2014/kW | | | Y | | | | US$2014/kW |
| 27 | Breaking New Ground, Wind Europe, 2018 _ 203 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2030 | | 2 100 | Euro 2018 / kW | 3 104,87 | US$2014/kW | | | Y | | | | US$2014/kW |
| 28 | Breaking New Ground, Wind Europe, 2018 _ 203 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2035 | | 2 050 | Euro 2018 / kW | 3 030,94 | US$2014/kW | | | Y | | | | US$2014/kW |
| 29 | Breaking New Ground, Wind Europe, 2018 _ 204 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2040 | | 2 010 | Euro 2018 / kW | 2 971,80 | US$2014/kW | | | Y | | | | US$2014/kW |
| 30 | Breaking New Ground, Wind Europe, 2018 _ 204 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2045 | | 2 000 | Euro 2018 / kW | 2 957,02 | US$2014/kW | | | Y | | | | US$2014/kW |
| 31 | Breaking New Ground, Wind Europe, 2018 _ 205 | https://windeurope.o | EU | Europe | - Public Sector/ Multilateral Agenc | 2050 | | 2 000 | Euro 2018 / kW | 2 957,02 | US$2014/kW | | | Y | | | | US$2014/kW |
| 32 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatch | EU | Europe | - Public Sector/ Multilateral Agenc | 2015 | | 3 220 | Euro 2015/kW | 4 749,54 | US$2014/kW | | | Y | | | | US$2014/kW |
| 33 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2020 | | 2 880 | Euro 2015/kW | 4 248,04 | US$2014/kW | | | | 4 248,04 | 4248,04 | - | US$2014/kW |
| 34 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2025 | | 2 700 | Euro 2015/kW | 3 982,53 | US$2014/kW | | | Y | | | | US$2014/kW |
| 35 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2030 | | 2 580 | Euro 2015/kW | 3 805,53 | US$2014/kW | | | Y | | | | US$2014/kW |
| 36 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2035 | | 2 460 | Euro 2015/kW | 3 628,53 | US$2014/kW | | | Y | | | | US$2014/kW |
| 37 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2040 | | 2 380 | Euro 2015/kW | 3 510,53 | US$2014/kW | | | Y | | | | US$2014/kW |
| 38 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2045 | | 2 320 | Euro 2015/kW | 3 422,03 | US$2014/kW | | | Y | | | | US$2014/kW |
| 39 | LUT_EWG_All_Sectors_Global_Report_2019_ | http://energywatchgr | EU | Europe | - Public Sector/ Multilateral Agenc | 2050 | | 2 280 | Euro 2015/kW | 3 363,03 | US$2014/kW | | | Y | | | | US$2014/kW |
| 40 | Energy [r]evolution, Greenpeace, 2015 _ Offsho | https://www.greenpe | World | | 2 - Public Sector/ Multilateral Agenc | 2012 | | 5 180 | $2012/kW | 5 335,40 | US$2014/kW | | | Y | | | | US$2014/kW |
| 41 | Energy [r]evolution, Greenpeace, 2015 _ Offsho | https://www.greenp | World | | 2 - Public Sector/ Multilateral Agenc | 2020 | | 4 000 | $2012/kW | 4 120,00 | US$2014/kW | | | Y | | | | US$2014/kW |
| 42 | Energy [r]evolution, Greenpeace, 2015 _ Offsho | https://www.greenpe | World | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 3 540 | $2012/kW | 3 646,20 | US$2014/kW | | | Y | | | | US$2014/kW |
| 43 | Energy [r]evolution, Greenpeace, 2015 _ Offsho | https://www.greenpe | World | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 3 100 | $2012/kW | 3 193,00 | US$2014/kW | | | Y | | | | US$2014/kW |
| 44 | Energy [r]evolution, Greenpeace, 2015 _ Offsho | https://www.greenpe | World | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 2 750 | $2012/kW | 2 832,50 | US$2014/kW | | | Y | | | | US$2014/kW |
| 45 | Future of wind, IRENA, 2019 _ Offshore _ 2010, | https://www.irena.or | World | | 2 - Public Sector/ Multilateral Agenc | 2010 | | 4 572 | 2018$/kW | 4 310,34 | US$2014/kW | | | Y | | | | US$2014/kW |
| 46 | Future of wind, IRENA, 2019 _ Offshore _ 2018, | https://www.irena.o | World | | 2 - Public Sector/ Multilateral Agenc | 2018 | | 4 353 | 2018$/kW | 4 103,88 | US$2014/kW | | | Y | | | | US$2014/kW |
| 47 | Future of wind, IRENA, 2019 _ Offshore _ 2030 | https://www.irena.or | World | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 1 700 | 2018$/kW | 1 602,71 | US$2014/kW | | | Y | | | | US$2014/kW |
| 48 | Future of wind, IRENA, 2019 _ Offshore _ 2030 | https://www.irena.or | World | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 3 200 | 2018$/kW | 3 016,86 | US$2014/kW | | | Y | | | | US$2014/kW |
| 49 | Future of wind, IRENA, 2019 _ Offshore _ 2050, | https://www.irena.or | World | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 1 400 | 2018$/kW | 1 319,88 | US$2014/kW | | | Y | | | | US$2014/kW |
| 50 | Future of wind, IRENA, 2019 _ Offshore _ 2050, | https://www.irena.or | World | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 2 800 | 2018$/kW | 2 639,75 | US$2014/kW | | | Y | | | | US$2014/kW |
| 51 | Carbon Tracker_ 2017_ Offshore_ 2010, pg 44, | https://carbontracker | World | | 2 - Public Sector/ Multilateral Agenc | 2010 | | 5 390 | M$2016/Gw | 5 319,31 | US$2014/kW | | | Y | | | | US$2014/kW |
| 52 | Carbon Tracker_ 2017_ Offshore_ 2020, pg 44, | https://carbontracker | World | | 2 - Public Sector/ Multilateral Agenc | 2020 | | 4 090 | M$2016/Gw | 4 036,36 | US$2014/kW | | | Y | | | | US$2014/kW |
| 53 | Carbon Tracker_ 2017_ Offshore_ 2030, pg 44, | https://carbontracker | World | | 2 - Public Sector/ Multilateral Agenc | 2030 | | 3 343 | M$2016/Gw | 3 299,16 | US$2014/kW | | | Y | | | | US$2014/kW |
| 54 | Carbon Tracker_ 2017_ Offshore_ 2040, pg 44, | https://carbontracker | World | | 2 - Public Sector/ Multilateral Agenc | 2040 | | 2 970 | M$2016/Gw | 2 931,05 | US$2014/kW | | | Y | | | | US$2014/kW |
| 55 | Carbon Tracker_ 2017_ Offshore_ 2050, pg 44, | https://carbontracker | World | | 2 - Public Sector/ Multilateral Agenc | 2050 | | 2 970 | M$2016/Gw | 2 931,05 | US$2014/kW | | | Y | | | | US$2014/kW |
| 56 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-n | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 70 | USD2013/MWh | 1 709,44 | US$2014/kW | | | N | 1 709,44 | 1709,44 | - | US$2014/kW |
| 57 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 75 | USD2013/MWh | 1 827,92 | US$2014/kW | | | N | 1 827,92 | 1827,92 | - | US$2014/kW |
| 58 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 106 | USD2013/MWh | 2 599,53 | US$2014/kW | | | N | 2 599,53 | 2599,53 | - | US$2014/kW |
| 59 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 113 | USD2013/MWh | 2 768,20 | US$2014/kW | | | N | 2 768,20 | 2768,20 | - | US$2014/kW |
| 60 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 139 | USD2013/MWh | 3 401,99 | US$2014/kW | | | N | 3 401,99 | 3401,99 | - | US$2014/kW |
| 61 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | UK | - Public Sector/ Multilateral Agenc | 2020 | | 148 | USD2013/MWh | 3 621,57 | US$2014/kW | | | N | 3 621,57 | 3621,57 | - | US$2014/kW |
| 62 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | Portugal | - Public Sector/ Multilateral Agenc | 2020 | | 91 | USD2013/MWh | 2 237,23 | US$2014/kW | | | N | 2 237,23 | 2237,23 | - | US$2014/kW |
| 63 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | Portugal | - Public Sector/ Multilateral Agenc | 2020 | | 135 | USD2013/MWh | 3 299,41 | US$2014/kW | | | N | 3 299,41 | 3299,41 | - | US$2014/kW |
| 64 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | Portugal | - Public Sector/ Multilateral Agenc | 2020 | | 172 | USD2013/MWh | 4 221,58 | US$2014/kW | | | N | 4 221,58 | 4221,58 | - | US$2014/kW |
| 65 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | Netherlands | - Public Sector/ Multilateral Agenc | 2020 | | 92 | USD2013/MWh | 2 242,37 | US$2014/kW | | | N | 2 242,37 | 2242,37 | - | US$2014/kW |
| 66 | Projected Costs of Generating Electricity_ NEA_ | https://www.oecd-ne | EU | Netherlands | - Public Sector/ Multilateral Agenc | 2020 | | 127 | USD2013/MWh | 3 116,55 | US$2014/kW | | | N | 3 116,55 | 3116,55 | - | US$2014/kW |

Figure 16. Example of VMA table data gathering (i.e. investment costs)

## 6.2 Research Procedure in Detail

Firstly, it is essential to remind the reader of the main objectives of this thesis. The main goal of this work is based on obtaining, through analysis and interpretation of various studies and articles, the possible future electricity generation in Europe, from 2020 until 2050, along with the estimated potential adoption of three wind generation solutions - Onshore wind, Offshore wind and Small wind to size their individual and combined contributions relative to GHG abatement and its associated investment, lifetime, capacity factor, fixed and variable costs, among other relevant parameters for the price variations of the technologies. Briefly, the methodology was based on the following steps:

1. Literature Review and Data Collection
2. Compilation of Historical EU and European Energy Mix evolution and current adoption
3. Gathering and treating data about Total Addressable Market (TAM) projections
4. Gathering and treating data about Adoption (ADPT) of Wind Technology projections
5. Scenario's definition
6. Gathering and treating data for Variable Meta-Analysis (VMA) inputs
7. Feeding data and Running scenarios in Drawdown RRS model
8. Perform Sensitivity analysis

### 6.2.1 Compilation of Historical EU and European Energy Mix evolution and current adoption

Before collecting information regarding future projections, it is necessary to establish a database with historical values regarding the various technologies analyzed. When collecting information on electricity production in the European Union as for Europe, two international entities were used. The IEA was consulted first and then IRENA. However, it should be noted that the historical values presented by both entities slightly differed. This difference can be explained by the different methods used to calculate the electricity generated. It should be noted that all values gathered for the European Union account for data for the United Kingdom, as most of the studies reviewed present data for EU-28. At this phase, the goal was to create a historic time-series for conventional technologies and renewable technologies from 2005 until the last year of record data, 2018.

Since the information provided by the IEA did not differentiate between the various technologies belonging to solar, hydro, and wind energy, the IRENA RE electricity Statistics was consulted (IRENA, 2021). This way, the history acquired was based on values between the two entities. Conventional technologies, as well as hydro and geothermal, were recollected from the IEA (2021), while the remaining renewable technologies, namely Onshore wind and Offshore wind, were taken from IRENA (2021).

Due to the reduced weight of Small wind, none of the entities in question presented any type of data for this technology. Therefore, data was collected from WWEA (2017), namely from several reports provided by the entity. It should be noted that the values presented in the studies in question were taken from Total Cumulative Installed Capacity, collecting values for the countries of the European Union. These values were subsequently converted into Electricity Generation, using the expression $365(days) \times 24\, h/day \times Installed\, Capacity \times Capacity\, Factor$, capacity factor which assumed a value of 17% (average value for this technology) (U.S. Department of Energy, 2018). All this data was later filled into the Drawdown RRS model that will be explained a few steps ahead.

### **6.2.2 Gathering and treating data about Total Addressable Market (TAM) projections**

For the various reports to be used in this part of the methodology, they need to present projections for Total Addressable Market (TAM) values for Europe or the European Union until, preferably, the year 2050. After analyzing and collecting data from more than 30 reports published between 2015 and 2021, totaling 71 scenarios for TAM, it is easy to state that this is one of the parameters with the highest availability of data and the greatest input for the model. Table 5 presents Electricity Generation by source for the EU-28, from 2005 to 2018, with Table 6 presenting the percentage of electricity produced by each of these sources.

According to both Table 5 and 6, it should be noted a gradual decrease in the use of fossil fuels, which is more evident in the last two years, except for natural gas. On the other hand, renewable sources are starting to grow gradually, with the most significant being solar and wind.

Table 5. Historical Electricity Generation by source (European Union, TWh) (Adapted from IEA and IRENA, 2021)

| Technology (TWh) | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 996 | 1 018 | 1 023 | 935 | 848 | 864 | 887 | 935 | 909 | 843 | 828 | 738 | 710 | 660 |
| Oil | 143 | 136 | 115 | 108 | 99 | 87 | 78 | 75 | 65 | 62 | 65 | 64 | 60 | 56 |
| Natural Gas | 668 | 684 | 740 | 790 | 732 | 765 | 705 | 584 | 511 | 458 | 498 | 611 | 664 | 623 |
| Biofuels | 59 | 66 | 73 | 82 | 93 | 107 | 114 | 129 | 138 | 147 | 159 | 161 | 164 | 168 |
| Waste | 26 | 28 | 31 | 32 | 33 | 36 | 38 | 39 | 39 | 41 | 44 | 47 | 47 | 50 |
| Nuclear | 998 | 990 | 935 | 937 | 894 | 917 | 907 | 882 | 877 | 876 | 857 | 840 | 830 | 827 |
| Hydro | 348 | 351 | 348 | 364 | 367 | 408 | 341 | 368 | 404 | 407 | 372 | 381 | 331 | 379 |
| Geothermal | 5 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 7 |
| Solar PV | 1 | 3 | 4 | 7 | 140 | 23 | 46 | 68 | 81 | 93 | 103 | 106 | 114 | 123 |
| Wind | 71 | 83 | 105 | 120 | 134 | 150 | 181 | 207 | 238 | 254 | 303 | 304 | 362 | 377 |
| Other Sources | 10 | 6 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Total | 3 326 | 3 372 | 3 385 | 3 388 | 3 349 | 3 366 | 3 308 | 3 299 | 3 274 | 3 194 | 3 241 | 3 263 | 3 294 | 3 275 |

Table 6. Electricity generation by source (%) - historical values (European Union) (Adapted from IEA and IRENA, 2021)

| Technology Adoption | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 29.9 | 30.2 | 30.2 | 27.6 | 25.3 | 25.7 | 26.8 | 28.3 | 27.8 | 26.4 | 25.6 | 22.6 | 21.6 | 20.2 |
| Oil | 4.3 | 4.0 | 3.4 | 3.2 | 3.0 | 2.6 | 2.3 | 2.3 | 2.0 | 2.0 | 2.0 | 2.0 | 1.8 | 1.7 |
| Natural Gas | 20.1 | 20.3 | 21.8 | 23.3 | 21.9 | 22.7 | 21.3 | 17.7 | 15.6 | 14.3 | 15.4 | 18.7 | 20.1 | 19.0 |
| Biofuels | 1.8 | 2.0 | 2.2 | 2.4 | 2.8 | 3.2 | 3.5 | 3.9 | 4.2 | 4.6 | 4.9 | 4.9 | 5.0 | 5.1 |
| Waste | 0.8 | 0.8 | 0.9 | 0.9 | 1.0 | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 |
| Nuclear | 30.0 | 29.4 | 27.6 | 27.7 | 26.7 | 27.2 | 27.4 | 26.7 | 26.8 | 27.4 | 26.4 | 25.7 | 25.2 | 25.3 |
| Hydro | 10.5 | 10.4 | 10.3 | 10.7 | 10.9 | 12.1 | 10.3 | 11.1 | 12.3 | 12.8 | 11.5 | 11.7 | 10.1 | 11.6 |
| Geothermal | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Solar PV | 0.0 | 0.1 | 0.1 | 0.2 | 4.2 | 0.7 | 1.4 | 2.1 | 2.5 | 2.9 | 3.2 | 3.2 | 3.4 | 3.8 |
| Wind | 2.1 | 2.5 | 3.1 | 3.6 | 4.0 | 4.5 | 5.5 | 6.3 | 7.3 | 8.0 | 9.4 | 9.3 | 11.0 | 11.5 |
| Other Sources | 0.3 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Nevertheless, although this parameter is usually found in the studies analyzed, the collection of information can be quite different from one to another. At all stages of the data collection process, whether for TAM, Adoptions, and even data for VMA, there was always a small inherent error due to the way the data was presented. In studies where the data was displayed in tables or excel, the data collection was done straightforwardly; however, in studies where this same data was provided in graphs, to draw out these same values, there can be small interpretation errors. A few examples of this difficulty are presented in the figures below (Figures 17 and 18).

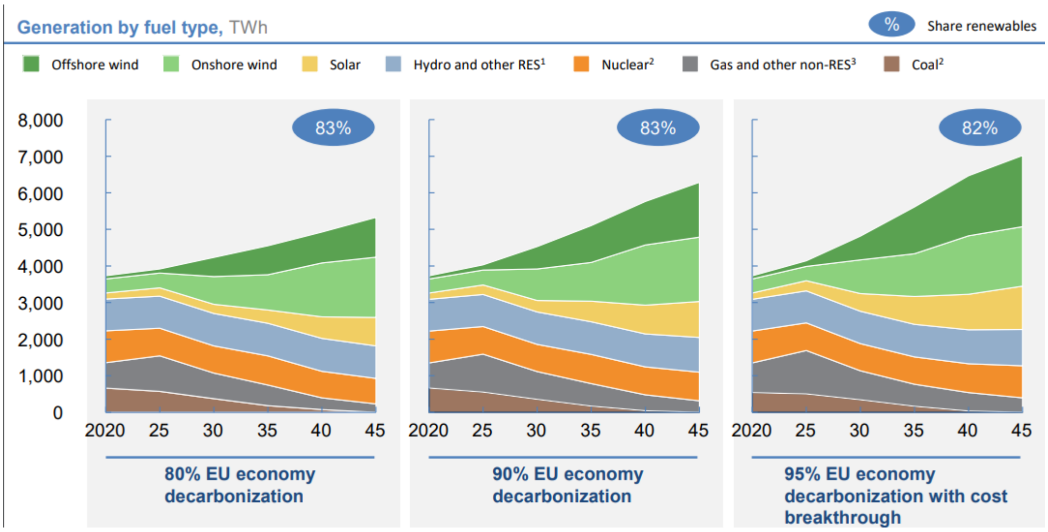
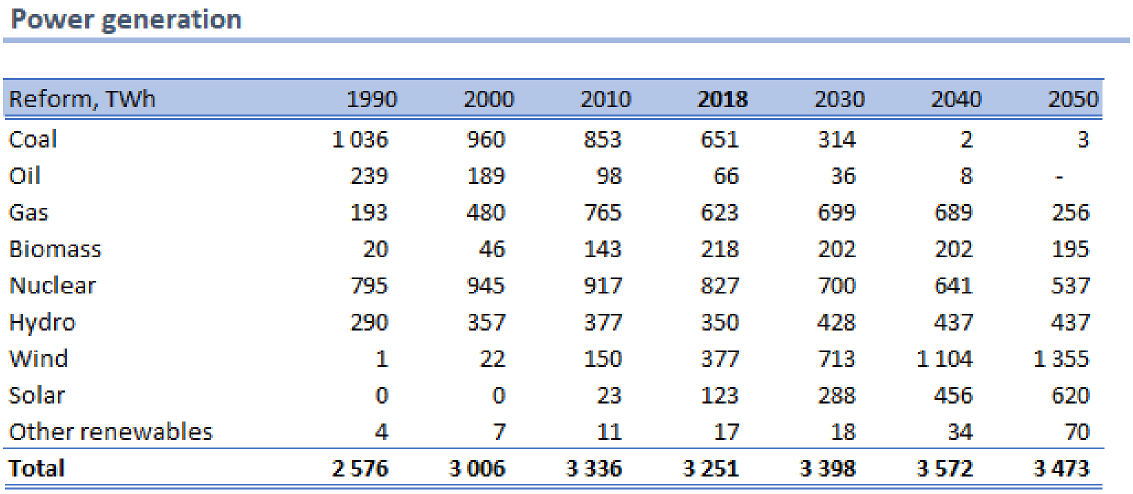


Figure 17. Values for TAM (TWh), Eureletric Decarbonisation pathways (Eureletric**,** 2018)



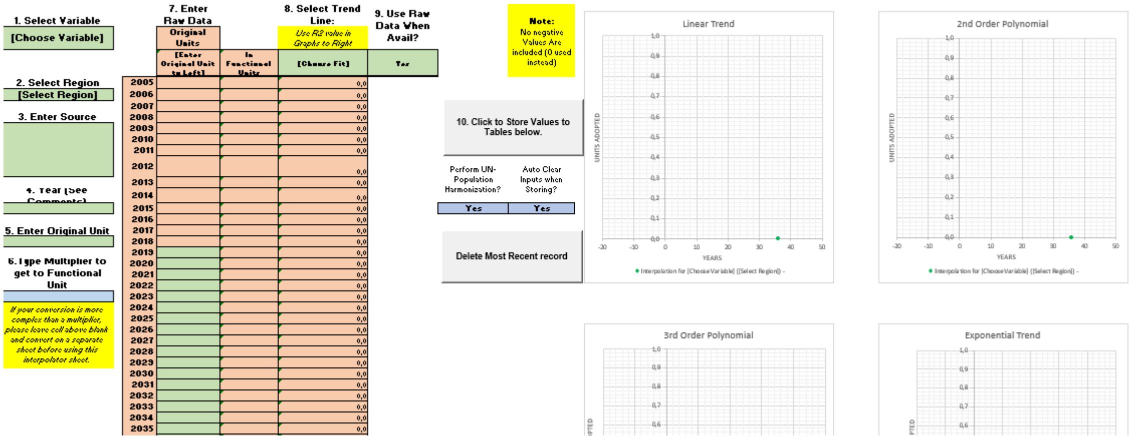
**Power generation**

| Reform, TWh | 1990 | 2000 | 2010 | **2018** | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Coal | 1 036 | 960 | 853 | 651 | 314 | 2 | 3 |
| Oil | 239 | 189 | 98 | 66 | 36 | 8 | - |
| Gas | 193 | 480 | 765 | 623 | 699 | 689 | 256 |
| Biomass | 20 | 46 | 143 | 218 | 202 | 202 | 195 |
| Nuclear | 795 | 945 | 917 | 827 | 700 | 641 | 537 |
| Hydro | 290 | 357 | 377 | 350 | 428 | 437 | 437 |
| Wind | 1 | 22 | 150 | 377 | 713 | 1 104 | 1 355 |
| Solar | 0 | 0 | 23 | 123 | 288 | 456 | 620 |
| Other renewables | 4 | 7 | 11 | 17 | 18 | 34 | 70 |
| **Total** | **2 576** | **3 006** | **3 336** | **3 251** | **3 398** | **3 572** | **3 473** |

Figure 18. Values for TAM (TWh), Energy Technologies Perspectives 2020 (IEA, 2020)

The various studies also show significant variations between the time frame of values that are given. Using figure 17, we found variations every five years, starting in 2020 and ending in 2045, and, in the case of figure 18, only three data points were collected, beginning in 2030 and jumping every 10 years up to 2050. Most studies provide data from time frames between five and 10 years, however, some studies presented values only for 2030 or 2050.

Thus, to be used in the Drawdown RRS model, that needs annual values; these various scenarios underwent the best fit interpolation, which in most cases was either 2nd or 3rd polynomial interpolation (interpolation tool built in the Drawdown excel-based model). The polynomial used was always the best fit to the raw data previously collected. This way, the values collected were interpolated, making it possible to have annual values built upon the trends and figures of the external sources.



1. Select Variable
[Choose Variable]

2. Select Region
[Select Region]

3. Enter Source

4. Year (See Comments)

5. Enter Original Unit

6. Type Multiplier to get to Functional Unit

*If your conversion is more complex than a multiplier, please leave cell above blank and convert on a separate sheet before using this interpolator sheet.*

| | 7. Enter Raw Data Original Units [Enter Original Unit to Left] | In Functional Units | 8. Select Trend Line: *Use R2 value in Graphs to Right* [Choose Fit] | 9. Use Raw Data When Avail? Yes |
|---|---|---|---|---|
| 2005 | | | 0,0 | |
| 2006 | | | 0,0 | |
| 2007 | | | 0,0 | |
| 2008 | | | 0,0 | |
| 2009 | | | 0,0 | |
| 2010 | | | 0,0 | |
| 2011 | | | 0,0 | |
| 2012 | | | 0,0 | |
| 2013 | | | 0,0 | |
| 2014 | | | 0,0 | |
| 2015 | | | 0,0 | |
| 2016 | | | 0,0 | |
| 2017 | | | 0,0 | |
| 2018 | | | 0,0 | |
| 2019 | | | 0,0 | |
| 2020 | | | 0,0 | |
| 2021 | | | 0,0 | |
| 2022 | | | 0,0 | |
| 2023 | | | 0,0 | |
| 2024 | | | 0,0 | |
| 2025 | | | 0,0 | |
| 2026 | | | 0,0 | |
| 2027 | | | 0,0 | |
| 2028 | | | 0,0 | |
| 2029 | | | 0,0 | |
| 2030 | | | 0,0 | |
| 2031 | | | 0,0 | |
| 2032 | | | 0,0 | |
| 2033 | | | 0,0 | |
| 2034 | | | 0,0 | |
| 2035 | | | 0,0 | |

**Note:** No negative Values Are included (0 used instead)

Perform UN-Population Harmonization? Yes

Auto Clear Inputs when Storing? Yes

Figure 19. Excel structure used for the interpolations

The mechanism used in figure 19, since it is already optimized, is very easy to use. First, the variable to be analyzed is introduced, in this case, the TAM, using, in the case of adoption, the variable “Adoption”. Afterwards, region selection, EU-28 or Europe, and, finally, the name of the study and scenario, the year it was published, and the units in which this value was collected. In the left column is placed the historical value as well as the collected values for the years found. The column on the right, Raw Data, allows you to use the raw data collected or adapt to the values entered to best fin the trendline. This option is present here since, sometimes, when using raw data, there are abstract variations that are inconsistent with possible future reality, as shown in figure 20.

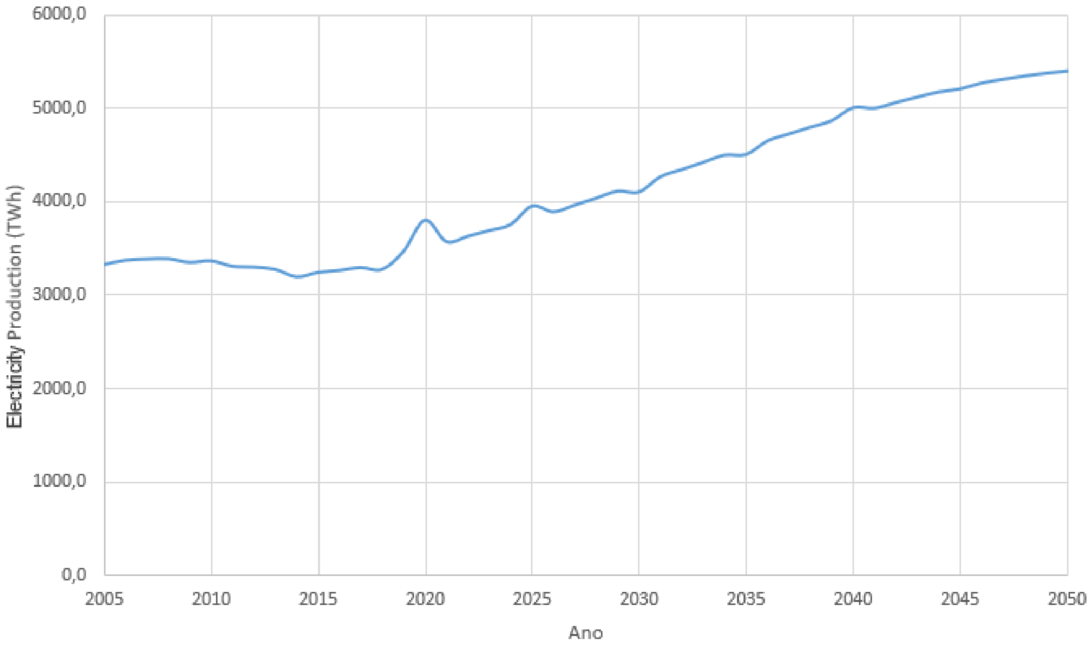


Figure 20. Interpolation rresult example using Raw Data from external source

After obtaining the interpolation values, the respective analysis was carried out, eliminating cases in which the values collected from the study were lower than the historical values for 2018, which means that the projections of electricity production for the study in question were lower than the historical values obtained for 2018. This step happens very much due to the publication date of the studies; older studies do not present such ambitious projections for the years 2018 to 2020 and, as such, the expected value for the year 2018 presented used to be lower than the historical value for the same year. Studies whose interpolation presented an initial decrease after 2018 and, after a few years, the value increased again were also removed. It was concluded that this type of data is not plausible since a prolonged decrease followed by an increase does not correspond to reality. On the other hand, studies where electricity production is constantly increasing and situations where electricity production is constantly decreasing, a situation explained by a significant increase in energy efficiency and the corresponding decrease in electricity production, are included in the type of data and expected growth.

### 6.2.3 Gathering and treating data about Adoption (ADPT) of Wind Technology projections

The collection of existing information for the wind technologies faced the same process and difficulties inherent to the collection of TAM values, going through tables where the collection of information was difficult, to studies that did not present the various existing wind technologies, or encompassing the three technologies studied together as “Wind”. While for TAM values, 71 scenarios were collected with relative ease, in the case of Wind Solutions Adoptions, this collection was more complex and with far fewer scenarios collected.

The methodology subsequently used, namely for the interpolation of sporadic values, was, in all aspects, the same as the methodology used for the TAM, except that the interpolation variable was now “Adoption”. The pool of scenarios collected was much smaller than the TAM scenarios, largely due to the lack of specificity of certain studies. As such, 15 scenarios were collected for Onshore wind, two of them corresponding to Europe and the remaining 13 to the European Union. For Offshore wind, 18 scenarios were gathered belonging these same 18 scenarios to the European Union. No studies with explicit data for Europe were found for this technology. During the collection and processing of data, it was immediately noticeable the emphasis that is made for the European Union compared with Europe.

For small wind, the approach was different due to inexistence of data from the global/regional long term projection studies assessed. With the existing collection and projections in the “Small Wind World Report” of the World Wind Energy Association (WWEA), 5 assumptions were made. Firstly, the latest historical value, for the year 2016, unfolded that the countries of the European Union represented 30% of the total energy generation through this technology. Therefore, if there were electricity production forecasts for the next 4 years, it was considered that of that 100%, 30% would be produced in the European Union. Due to the rarity of projections of this technology, three gross projections were carried out.

In the first one, it was considered that electricity production in the following year would increase 15% relative to the previous year. That is, energy produced in 2021 would be 15% higher than in 2020, energy produced in 2022 would be 15% higher than in 2021 and so on. Such value was considered due to the current trends in Onshore wind deployment and projects growth. A gross assumption since it would be very hard for Small wind to follow Onshore wind deployment and growth. Other two scenarios tested assume a decrease of the initial growth (15%) by half, while for the other assumption, the annual growth would be double compared to the initial one. Finally, the last assumptions can also be considered rough assumptions based on the electricity produced by wind Onshore overall. By comparing the historical 2018 value for Onshore wind with the 2018 value for small wind, a ratio of around 0.23% was obtained- In 2018, roughly 0.23% of Onshore wind electricity production was from Small wind. Due to the reduced presence of scenarios for this technology, 13 scenarios were then carried out based on the Onshore scenarios. To do so, the percentage of annual growth was calculated for each of the Onshore scenarios, and this same growth, different from scenario to scenario, was used to create the scenarios for Small wind. However, it should be noted that the growth of small wind is not expected to coincide with the expected growth of Onshore technology. Figures 21 and 22 present the Electricity Generation by adoption as well as the respective percentage.

Figure 21. Electricity Generation by Adoption, historical values (European Union, TWh) (Adapted from IRENA, 2021)

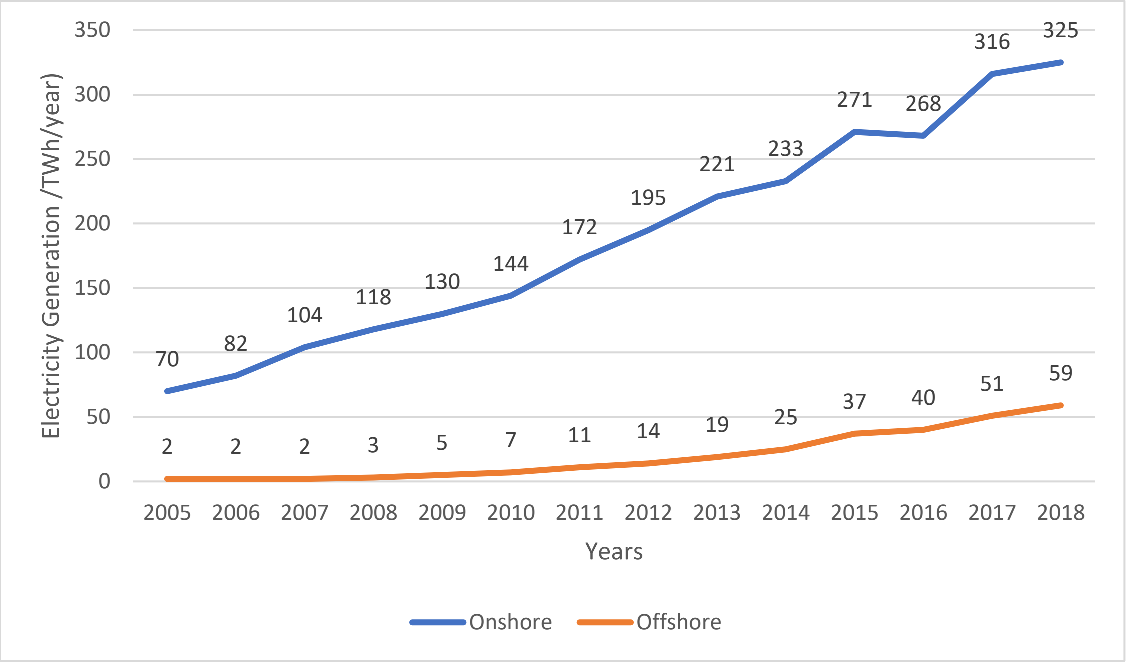
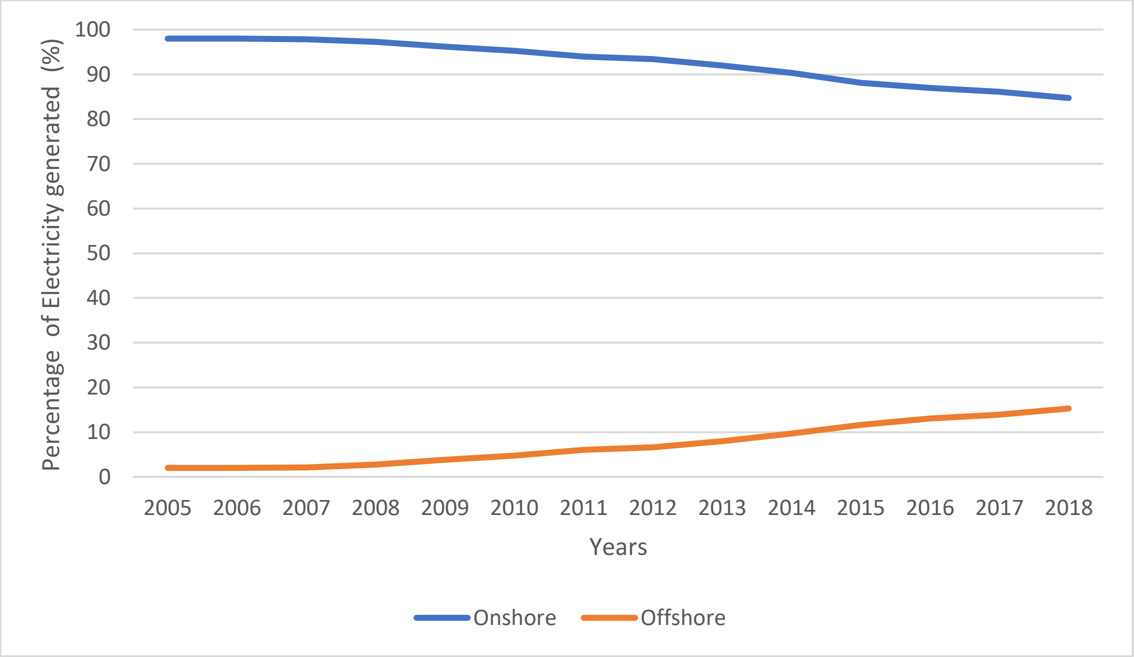


Figure 22. Percentage of Electricity Generated by source (%) (Adapted from IRENA, 2021)



### 6.2.4 Scenario's definition

As previously mentioned, due to restrictions present in the Drawdown excel model structure, analysis is limited to a maximum of 16 scenarios for Adoption and 15 for TAM; therefore, scenarios selection was conducted to narrow the sample used. The exclusion criteria used for this selection were the following, ordered by degree of significance:

1. Studies where the estimated values for 2018 were lower than the historical values collected;
2. Decline in the values of electricity generated and the subsequent increase;
3. Studies where it was necessary to remove certain data points so that growth trends would be continuous;
4. Variability of studies (studies by different entities);
5. Number of data points published for the projections;
6. Year of study publication (Priority to more recent studies);
7. Whether the data is presented in tables or graphs (the latter presents a greater error in data collection);
8. $R^2$ value of the interpolation, more aligned with the raw data used from external sources;

For a more detailed analysis, the European Union and Europe scenarios were also differentiated, whether for the TAM value or the value for future adoption. However, it should be noted that there is a greater quantity and diversity of studies for the former than for the latter; that is, there are many more studies focusing on the European Union than for Europe.

Subsequently, the studies were ranked according to the expected electricity value for the year 2050. This way, it became clear which studies had the most ambitious scenarios and which had the least ambitious ones until that same year.

From the original, diverse pool, this final selection considered choosing scenarios of studies with different background assumptions, models used, technologies availabilities, and restrictions. After choosing the scenarios, a differentiation was carried out among them according to the electricity generation values for the year 2050, divided among Modest Growth, Intermediate Growth, Ambitious Growth, and Extreme Growth for each wind power solution. The last portion was made considering only the scenario with the highest electricity generation level for 2050.

### 6.2.5 Variable Meta-Analysis

Subsequently, data was collected to develop a VMA (Variable Meta-Analysis). Data such as Implementation Cost, Fixed Operating Costs, Technology Lifetime, Capacity Factor, Indirect Emissions, among others. This way, it will be possible to obtain a large pool of data evaluating the maximum, minimum and average of each of the parameters in question. This last stage, resulted from consulting numerous studies, the 30 previously analyzed, plus about 20 scientific studies and reports. The data collection and subsequent VMA, was roughly based on 6 main steps.

***1.*** *Data collection for various financial and technological parameters for the three existing wind technologies*

For the first stage, in addition to the review of the studies previously analyzed, it consisted mainly of consulting various scientific studies and reports in order to retrieve such specific data. The information found is referred to parameters such as First Cost, Lifetime, Annual Capacity, Variable Operating and Maintenance Costs (VOM), Fixed Operating and Maintenance Costs (FOM), $CO_2$ Indirect Emissions, Learning Rates, Jobs created throughout all the different phases as well as the materials needed per TW. These parameters sum up to a total of 9.

It is important to also state that the data retrieved was not only for the Solutions analyzed but also for conventional technologies which the solutions replace (herein Coal, Oil and natural gas technologies for electricity generation). In order to have a larger pool of data for the for future selection, all kind of values were collected. Besides data for the European Union as well as for Europe, data for world and other countries or group of countries were also taken in consideration as well as the time frame from 2005 to 2050.

After the data retrieval it is easy to say that there is much more information for some of these parameters, like First Costs as well as Average annual use (AAU), contrary to data for Variable Operating and Maintenance Costs. It is also important to state the difference in data present for the different types of technologies. There are a lot of scientific studies and reports for Onshore wind with a lower number for Offshore wind. However, for Small wind Technologies only a few studies were helpful resulting in much less data points. Finally, the data collected and later presented has some difference on the number of data points for each technology and for each parameter.

### ***2.*** *Data selection according to geography and time-space for TAM and Adoption*

Since the work under development aims to present scenarios of electricity generated up to the year 2050 for two distinct geographical locations, European Union and Europe, it was necessary to carry out an evaluation of existing data points distribution. The aim of this selection consisted of two parts. Firstly, to understand how many data points would belong to the zones of analysis and, secondly, to what year these values corresponded. To this end, table 7, presented below, was divided into four parts to assess trends and significant regional variations showing the importance of updated data sources and targeted data points for the regions in study.

Table 7. Data points for each technology and cut off data assumptions

| **Offshore** | **World before 2015** | **World after 2015** | **EU before 2015** | **EU after 2015** |
|---|---|---|---|---|
| First Cost (US$2014/kW) | 5045 | 4085 | 5113 | 3328 |
| First Cost # Datapoints | 51 | 84 | 45 | 35 |
| VOM (US$2014/kWh) | 0.03 | 0.01 | 0.04 | 0.02 |
| VOM # Datapoints | 9 | 3 | 2 | 1 |
| FOM (US$2014/kW) | 182.7 | 133.4 | 185.9 | 181.5 |
| FOM # Datapoint | 41 | 64 | 38 | 36 |
| AAU (TWh/TW/year) | 3609.1 | 4106.0 | 3814.58 | 3895.89 |
| AAU # Datapoint | 40 | 51 | 22 | 19 |
| **Onshore** | **World before 2015** | **World after 2015** | **EU before 2015** | **EU after 2015** |
| First Cost | 2070 | 2131 | 1878 | 2583 |
| First Cost # Datapoints | 189 | 112 | 150 | 61 |
| VOM | 0.02 | 0.02 | 0.03 | 0.03 |
| VOM # Datapoints | 31 | 24 | 22 | 19 |
| FOM Cost | 71.1 | 64.0 | 72.3 | 75.4 |
| FOM # Datapoints | 45 | 56 | 43 | 39 |

| | | | | |
|---|---|---|---|---|
| AAU | 2727.0 | 2990.4 | 2569.7 | 2777.8 |
| AAU # Datapoints | 63 | 55 | 44 | 38 |
| **Small** | **World before 2015** | **World after 2015** | **EU before 2015** | **EU after 2015** |
| First Cost | 5763.70 | 5756.82 | 8049.62 | 6036.05 |
| First Cost # Datapoints | 27 | 13 | 8 | 4 |
| VOM | | 0.03 | | |
| VOM # Datapoints | | 2 | | |
| FOM Cost | 50.90 | | 65.21 | |
| FOM # Datapoints | 6 | | 2 | |
| AAU | 1248.79 | 1230.78 | 1102.41 | 946.08 |
| AAU # Datapoints | 18 | 12 | 13 | 7 |

Table 7 shows the difference in data points between the two zones and the respective time period cut off (2015). Besides the data points, it is also possible to make a preliminary comparison between the values for the world and the values for the geographical area that is going to be later analyzed. The price increase in several financial factors is highlighted, more expressive in Offshore technology.

Since the analysis is intended for the European Union and Europe, the main objective would be to use data for that same geographical area. The other parameter that would also be of great interest to be analyzed would be the time frame of the data in question, with more recent data being of greater interest, rejecting forecasts due to their inherent uncertainties. Thus, due to the high existence of data for the European Union and Europe between 2015 and 2021, we proceeded to the analysis considering only these data points, excluding all others. In the case of Small wind, due to the low existence of data, an analysis was carried out for all regions, however, only between 2015 - 2020.

Variables like indirect $CO_2$ emissions and materials consumption were not included in this analysis since those values do not present significant variation according to different zones of the globe, following a global supply chain. Values for conventional technologies included all geographical areas, since their costs doesn't depend so much on were they are used at, but considering the same time frame.

### ***3.*** *Exclusion of projections data*

In order to obtain a more conservative and more realistic analysis for the present time, the spectrum of years between 2015 and 2020 was considered. Due to the evolution of technology, values prior to 2015 were not as significant or as representative of current reality (i.e. lifetime, costs, among others). It was preferred not to include future projections of these variables, which are highly dependent on various assumptions and can be changed due to a greater or lesser maturity of the respective technologies considered. To this end, an average learning rate was considered relative to the collected bibliography, a value that differs between the three technologies analyzed.

### ***4.*** *Conversion to Reference Unit*

Due to the different units in which the collected information was presented, it was necessary to establish a standard unit for each parameter. Table 8 presents the units used for each parameter of the VMA in the RRS model.

Table 8. Reference Unit for each Parameter

| Parameter | Reference Unit |
|---|---|
| First Costs | US$2014/kW |
| Lifetime | TWh/TW |
| Average Annual Use | TWh/TW/year |
| Variable Operating Costs | US$2014/kWh |
| Fixed Operating Costs | US$2014/kW |
| Indirect $CO_2$ Emissions | t $CO_2$-eq/ TWh |
| Learning Rates | % |
| Jobs | Job / TW |
| Materials | t / TW |

After setting the reference unit it was necessary to convert all the collected values to that same unit. Regarding the economic parameters, since the RRS Drawdown model bases all its financial calculations on US$2014, this same conversion was necessary. For the analyses developed later in the thesis, the values will be converted to Euro€2021, making this parameter more current and more contextualized.

### 5. *Materials and Jobs Impact Assessment*

In order to bring more novelty to the study in question, two new parameters previously mentioned were added, jobs and materials that have not been explored in previous analysis for Project drawdown at global scale (Project Drawdown, 2020) or regional scales (Silveira, 2020).

Within the new materials category it is stressed that the “majority of wind turbine installations (76.8%) do not utilize components containing rare earth elements, with the most common technology, doubly fed induction generators accounting for 57.5% of the market” (Serrano-González and Lacal-Arántegui, 2016). “On the other hand, the market share of wind turbines that uses permanent magnets (contain rare earth elements) was 23.2% in 2013. The portion of wind turbines that uses permanent magnet generators can be further broken down into geared and direct drive wind turbines, which represent 6.9% and 16.3% of the global wind turbine market, respectively” (Serrano-González and Lacal-Arántegui, 2016). “70.3% of wind turbines containing permanent magnets are directly driven”. As such, it will be possible to carry out an extra analysis of the impacts associated with the use of resources and, mainly, metals and rare metals by the different technologies as well as the impact that the growth of technologies will have on the labor market in Europe and the European Union.

For both jobs and material, given per TW and TWh, another step was required. For the values presented in TWh, these were multiplied by the value of electricity generated for the year 2050, both for the Modest Growth scenario and the Ambitious growth scenario. A similar procedure was used for the TW case. However, these ones were independent from the electricity generation values.

### 6.2.6 Sensitivity Analysis

In order to be assess the impact that each one of the VMA parameters has on the results, a, sensitivity analysis regarding the collected values for main variables was performed. In this way, it becomes possible to understand the variation adjacent to the alteration of each input. It should be noted that each parameter previously analyzed and selected, in VMA, was altered *ceterus paribus,* choosing maximum and minimum values. The sensitivity analysis did not consider variations in the values for TAM and Adoption since these correspond to the main determinants for the core scenarios chosen.

Considering that the intent is to explore the boundaries of each result, maximum and minimum values for each parameter, it was also needed to set a base line, a point of reference for this comparison. Therefore, both Modest growth, the lowest ambitious scenario, and Ambitious growth, the second more ambitious scenarios were used.

After changing the average value to the maximum and minimum, one parameter at a time, for each scenario aggregate, Modest and Ambitious Growth, a pool with 24 takes for each technology was retrieved, totaling 76 rounds.

Given that, for conventional technologies, the values for fixed costs, variable costs and others are already well defined, the technologies are mature and with a low difference between maximum and minimum, it was only decided to perform a sensitivity analysis on one parameter of this category of technologies. Fuel prices present monthly variations, sometimes derived from times of instability in their places of extraction, high demand and respective lack of supply, natural phenomenon’s which make their transport or exploitation impossible, among others. As such, it was also decided to analyze this parameter and its implications on the impact of increased wind renewable technologies adoption.

# 7 Results

The various stages of this work allowed for different types of results. Some outputs are the result of data collection and organization from the different sources consulted, whether from the data points collected in the different phases of the VMA or in the collection of electricity generated for both TAM and Adoptions. Other values occur from the operation of the Project Drawdown's RRS model with the two scenarios that were used for the results, Modest and Ambitious Growth scenarios. Regardless of the type of data and its final results, all are portrayed in this section.

## 7.1 Total Addressable Market

One of the main goals of the work developed is to obtain and analyze the future potential European/European Union Total Addressable Market projections for 2050, in this case, electricity generation scenarios (in TWh) where the solutions studied are framed. After all the data collection process, a total of 71 different TAM projections was retrieved.

Due to the lack of detail of some electricity and energy studies, that do not refer or reveal values for wind, solar and hydro specific technologies adoptions, namely, Onshore wind, Offshore wind, Small wind, Utility scale solar photovoltaics, among many other, scenarios for the adoptions analyzed were hard to find. However, this studies usually have something in common. Almost all of them have values for both Europe and European Union Total Addressable Market projections up to 2050.

There is a significant difference between TAM projections in the same study as well as compared to different ones. This is mainly due to the different scenarios and assumptions used in the development of each one as well as the modeling used. Some studies, like “energy [r]evolution” by Greenpeace, from 2015, have 3 different scenarios. The reference scenario, which includes the current pathway taken, the [r]evolution as well as the Advanced energy [r]evolution, the most ambitious scenarios. The main difference between the scenarios in this type of studies for the TAM values, are mainly the adoption of renewable energy technologies as well as the increase in energy efficiency. Figure 23 below summarizes the values of electricity generated for the year 2050 according to each scenario of each study analyzed.

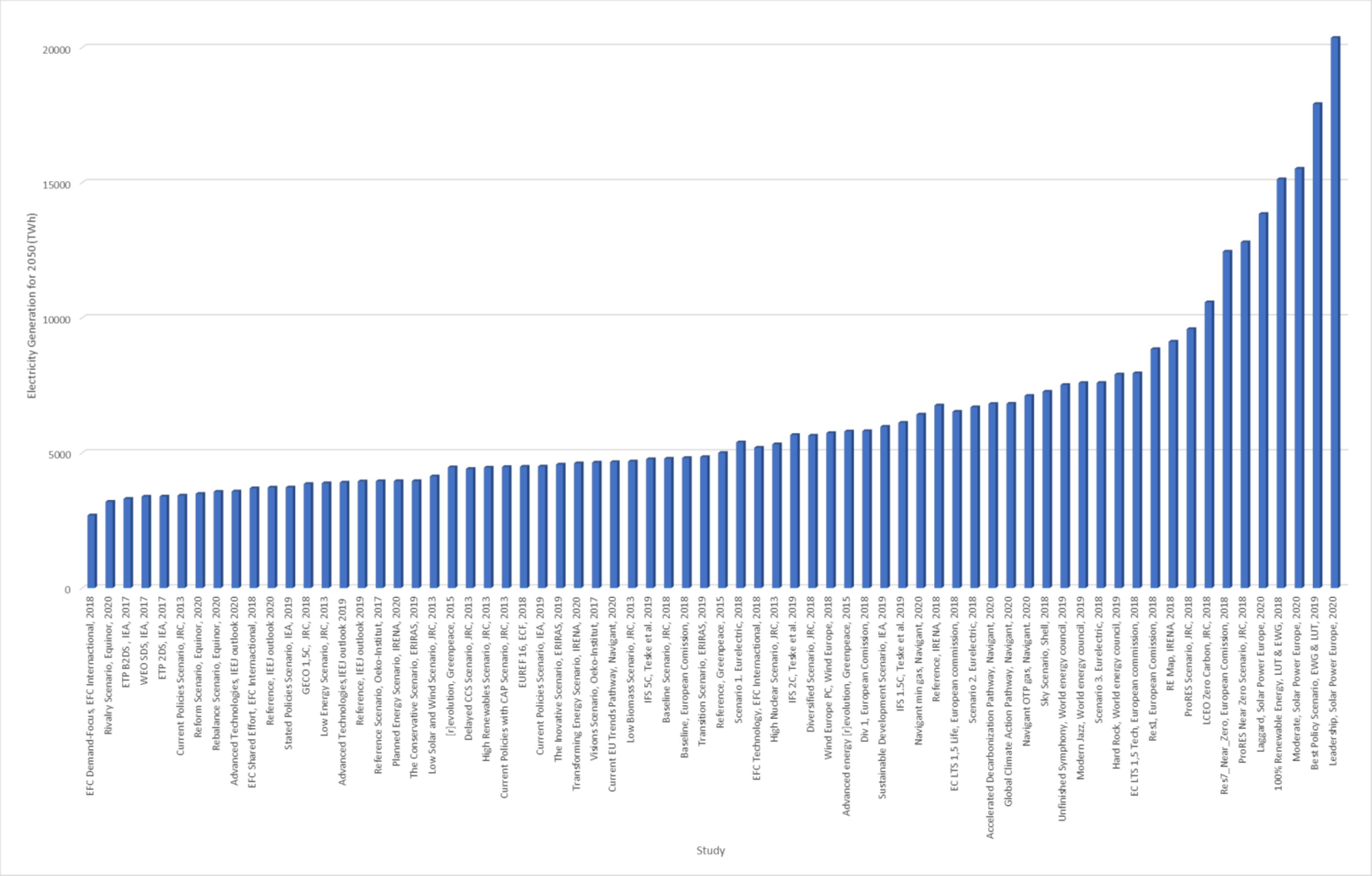


Figure 23. Electricity Generation in 2050 for each TAM's scenario (EU-28 and Europe)

According to the previous figure, it exists a large variation between many of the studied scenarios. One could argue that this high difference between scenarios could be due to the year of publications. However, this was not the case. Certain studies, like “Energy Perspectives, 2020”, from Equinor, have the one of the lowest TAM projections for the three scenarios developed. This variation can occur due to the type of energy system model used for the studies, the respective climate mitigation efforts, other main energy supply/demand drivers (GDP, population) used or technological detail of the databases used, between other. Different scenarios from different entities with different assumptions could only lead to wider range of values for the data collected. Nevertheless, 90% of the studies here present were published after 2017. This way, the idea of the influence of the year of publication against the TAM value is immediately excluded.

In view of the variation of values in the figure shown above and diversity of studies, and as abovementioned, that the RRS model could all assess a reduced sample, below in figures 24 and 25 are depicted the selected scenarios.

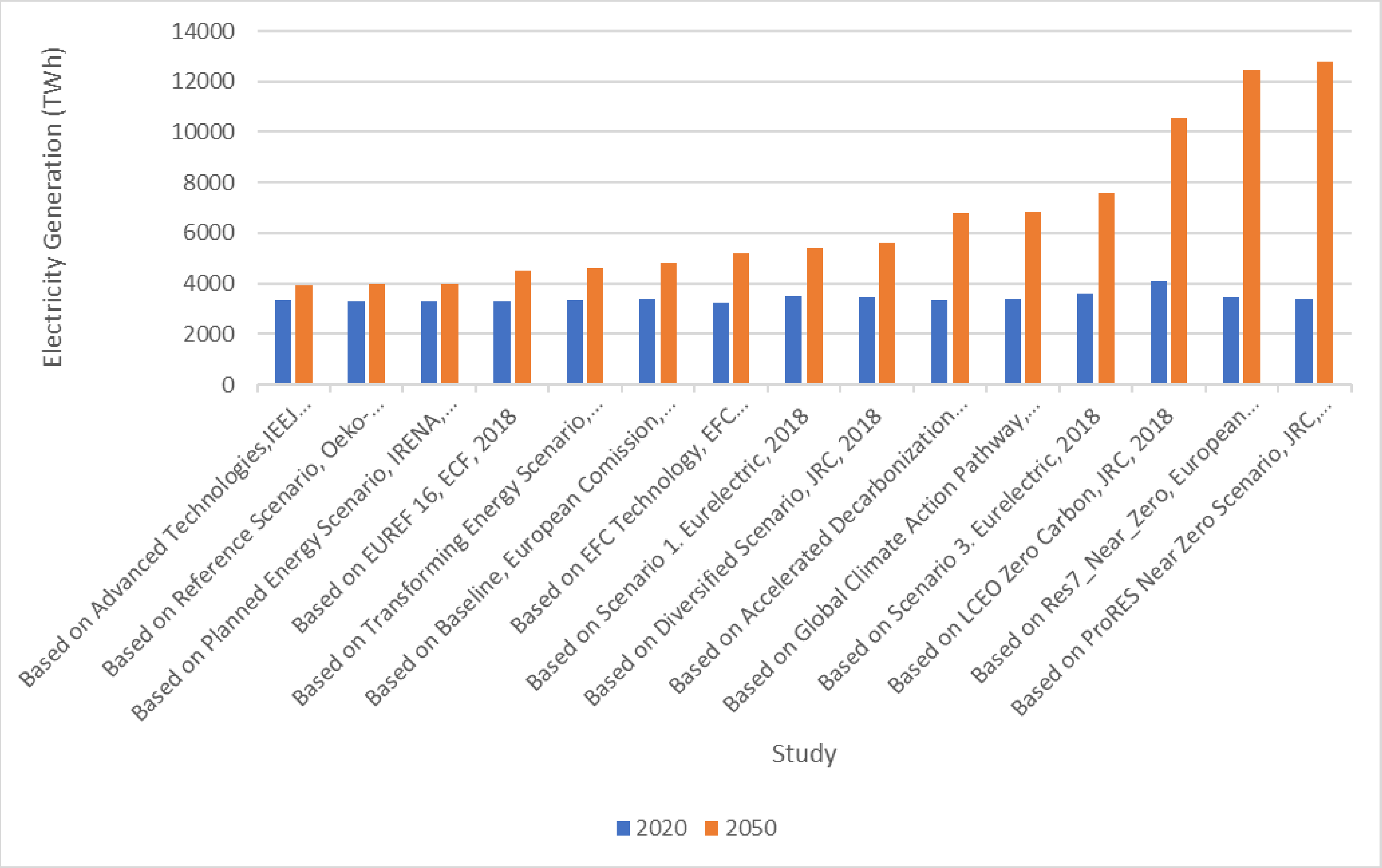


Figure 24. Electricity Generation comparison for 2020 and projections for 2050 for the European Union

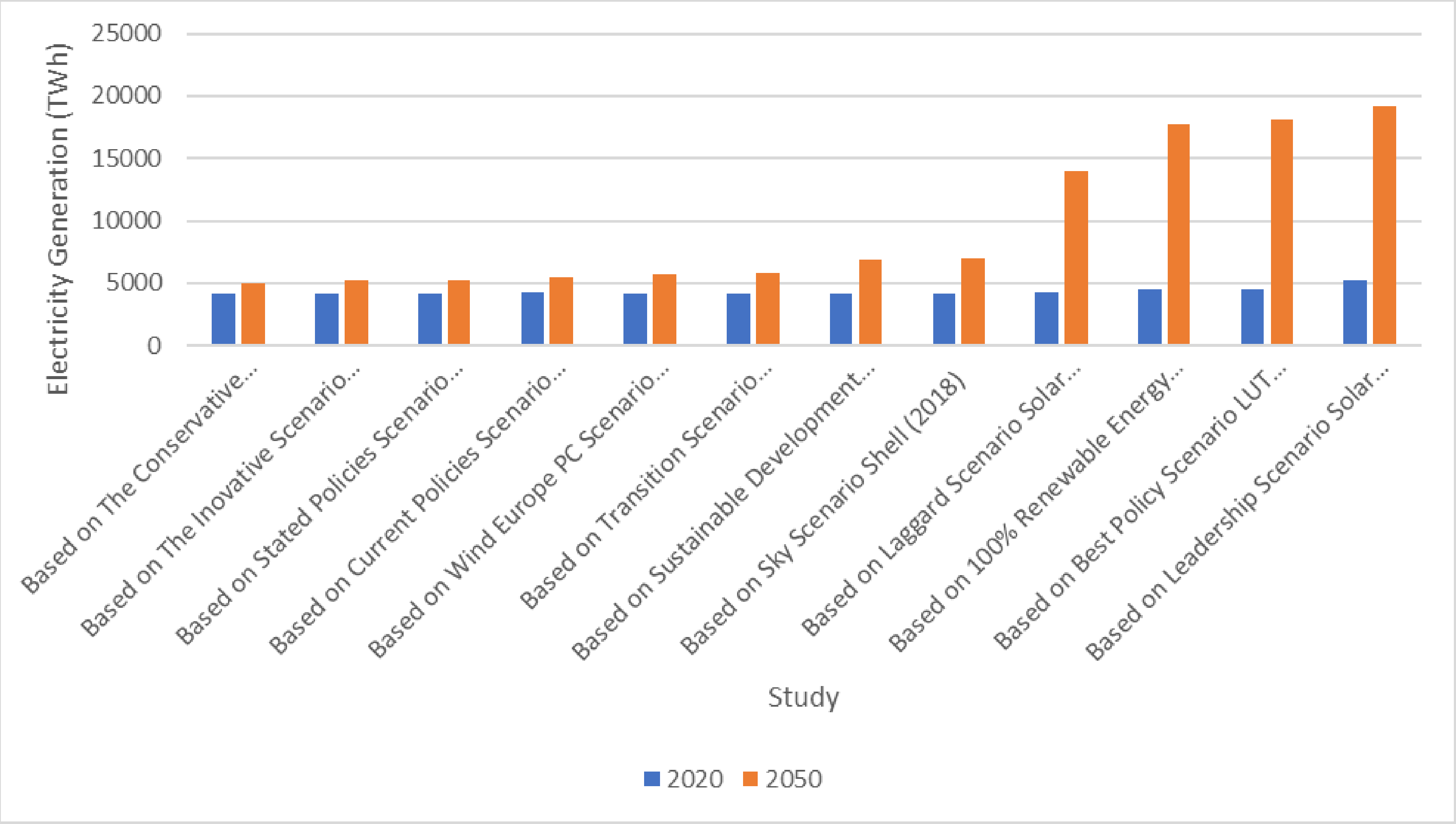


Figure 25. Electricity Generation comparison for 2020 and projections for 2050 for Europe

Making a comparison between the TAM values for 2020 and 2050 for the two analyzed geographical areas, European Union (figure 24) and Europe (figure 25), it is easily noticeable the variation between this time frame. Despite the small variation present for the year of 2020, much due to the interpolation process, this value lies around in 5%. However, it is by analyzing the value for 2050 that is easily perceptible how ambitious the study really is regarding electricity supply/demand increase. While some studies point towards a simple growth in electricity production due to fuel shifts, or increased electrification, others address energy efficiency or include other technological options at demand side as a key part of a sustainable future, therefore, some of these studies also have lower values for electricity production for 2050.

Since the selection of studies was made based on the electricity production for 2050, it is possible that, in some cases, the value for 2020 is lower than previous one. Like in the case of "Baseline Scenario" (European Commission, 2018), presented on figure 24, the value for 2020, 3 395 TWh is higher than the next study, "EFC Technology, (EFC International, 2018) with a value of 3 242 TWh. Nevertheless, is it also important to enhance, once again, the recent year of publication of almost all studies.

## 7.2 Wind Technologies Adoption Results

To have a better understanding of the role of each technology in the long term, the third set of results that are going to be presented in this sub-chapter, reveal the projections of each wind technology electricity generation separately.

As previously mentioned, in the methodology chapter, the data used resulted in a year-by-year timeseries of values due to the interpolation of several data retrieved from different entities, studies and scenarios. In the methodology chapter it is possible to understand and follow all the steps taken as well as how the timeseries of values was retrieved, the scenario selection and other key steps.

Besides the 16 scenarios retrieved and developed, four others, resulting of the aggregation of part of the 16, were also included in this analysis. Being the Modest growth scenario the average between the first four scenarios, Intermediate growth scenario the average of the following five scenarios and Ambitious growth scenario, the average of the five followed. However, the last scenario created, entitled of Very Ambitious growth scenario, only includes the most ambitious scenario of electricity generation in 2050. Therefore, since this new scenario (Very Ambitious growth scenario) is the same as, for the European Union case, the "Navigant min gas", Navigant (2020), the most ambitious scenario of electricity generation in 2050 for the European Union case, the inclusion of such was unnecessary.

In order to better distinguish the scenarios presented in each averaged scenario, a color scheme was used. Therefore, scenarios that are included in Modest growth are presented with the green color, for Intermediate growth, these scenarios are presented in orange and, for the last aggregate of scenarios, the color blue was used. Being the last scenario the most ambitious, a distinguish had to be made. This way, the color grey was used.

Since the current thesis had the objective to further differentiate two geographical areas, both Europe and European Union, the scenario retrieval for each technology resulted in very different number of scenarios found and analyzed. It is also important to quote, once again, that the majority of the studies found, discussed and further analyzed, were only focused on the European Union region. Only a pair of studies conducted a deep breakdown on the

European level, resulting, after the scenario selection, in 2 scenarios for Onshore wind and none found for both Offshore and Small wind. Therefore, most of the effort and work dedication was focused on the European Union level. Nevertheless, all the methodology conducted was also used in the European level but with less information to test and study.

When embracing the current study, at the beginning, there was expected to be a lot more information about Onshore wind, much due to the maturity of the technology as well as the years in service that it currently has. However, after the final scenario retrieval, it was noted that, besides TAM scenarios, Offshore wind was the solution studied with more scenarios available. Totalizing 36 scenarios, 34 for the European union, 18 for Offshore, 13 for Onshore and 3 for Small wind, and only 2 for the Europe scope, Onshore only. Unexpectedly, Offshore wind scenarios came out on top.

The figures bellow, figures 26, 27, 28 and 29 portray all the scenarios developed for both Europe and European Union. Nevertheless, only figure 29 is related to Europe. Moreover, since there were only found two scenarios for Europe, both Moderate, Intermediate, Ambitious and Extremely Ambitious scenarios were not developed.

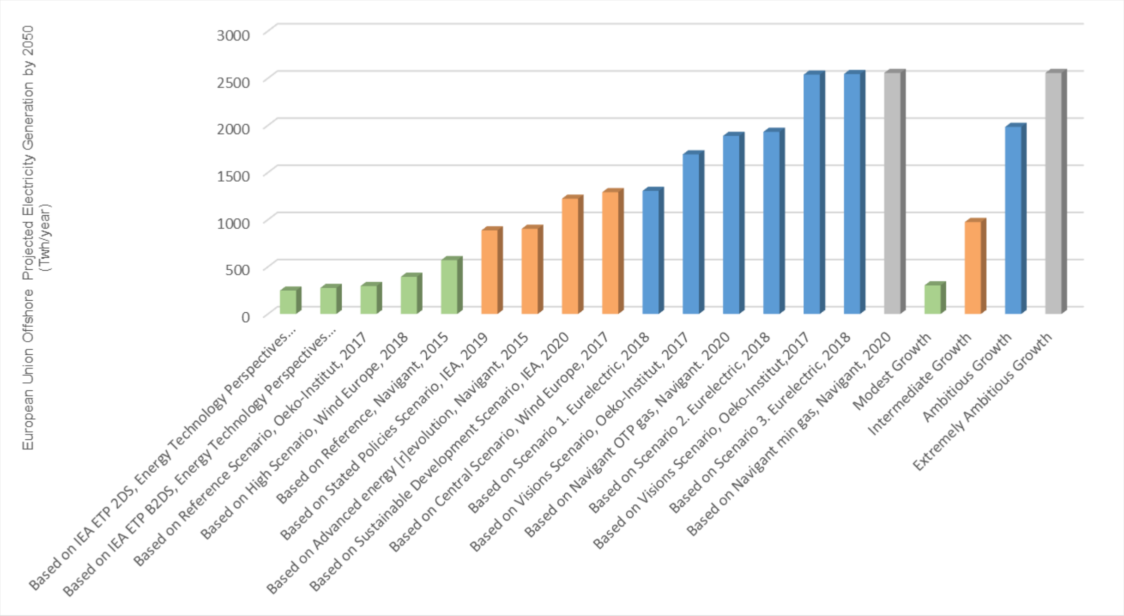


Figure 26. European Union Offshore Projected Electricity Generation by 2050 for each scenario

Furthermore, a quick glimpse around revels that the two leading technologies expect to produce almost the same amount of electricity by 2050. Both Intermediate and Ambitious scenarios have relatively the same value whereas the Modest growth scenario is quite different among this two, being much higher in the Onshore case. Nevertheless, looking only to the based scenarios, there is a presence of a ladder display in the 1 900 and 2 500 TWh production, whether in the Onshore case, the growth chart is smoother and more linear. This ladder display could be easily explained if the scenarios were from the same study or entity, however, just by a quick look, this ladder display was created with different studies and entities as well. Small wind case, a very clear difference is present between the first 13 and the last 3 scenarios. Since the first 13 are based on the onshore scenarios, a more reliable data was treated, when, compared to the last 3, growth electricity generation data that was artificially created.

Therefore, there is an immediate perception of the values discrepancy. It is relevant to state again, that the split between modest, intermediate, ambitious, very ambitious categories is based on the model user perception and to allow for a comparison between studies. Depending on the pool of scenarios available a slightly different categorization could have happened.

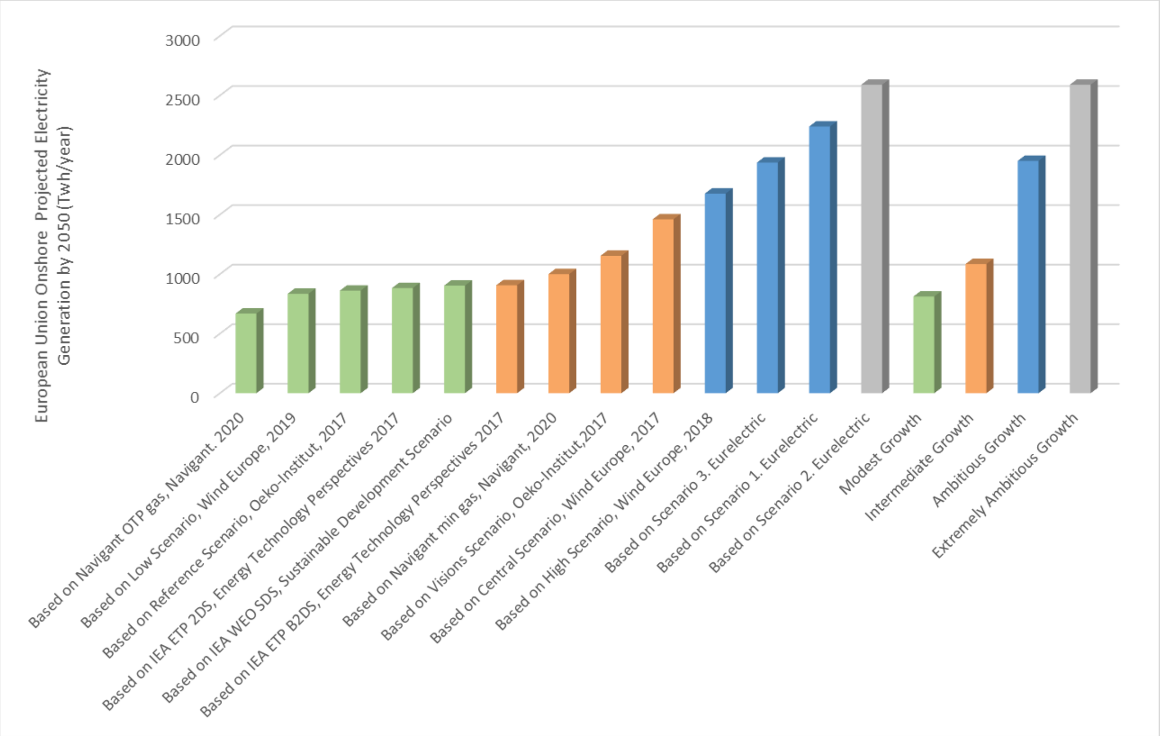


Figure 27. European Union Wind Onshore Projected Electricity Generation by 2050 for each scenario

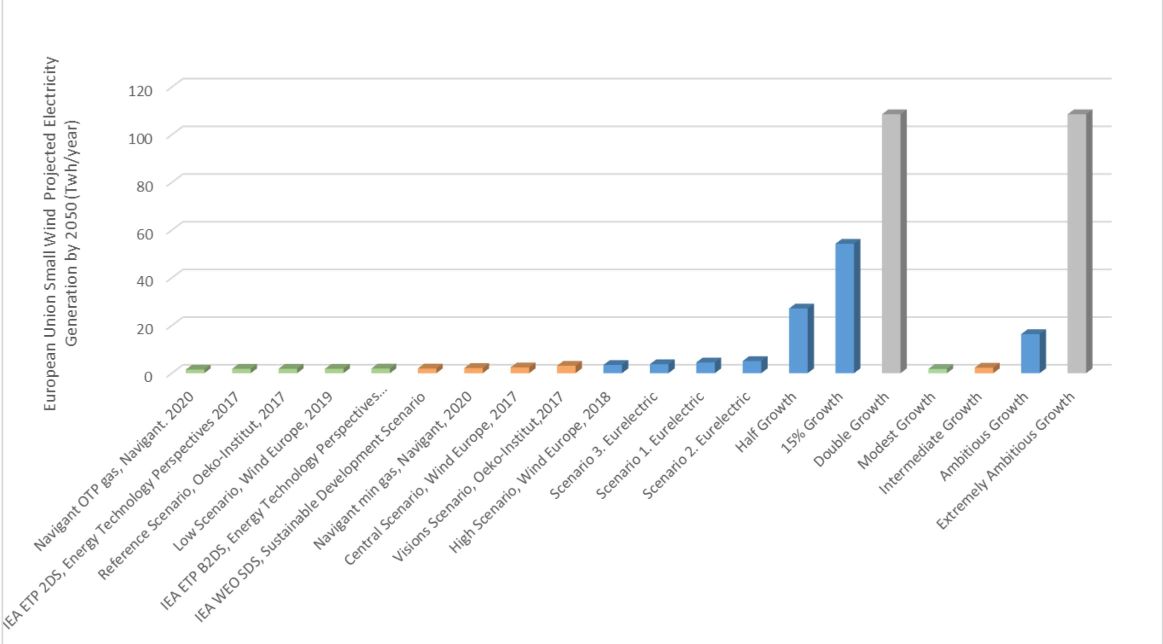


Figure 28. European Union Small Wind Projected Electricity Generation by 2050 for each scenario

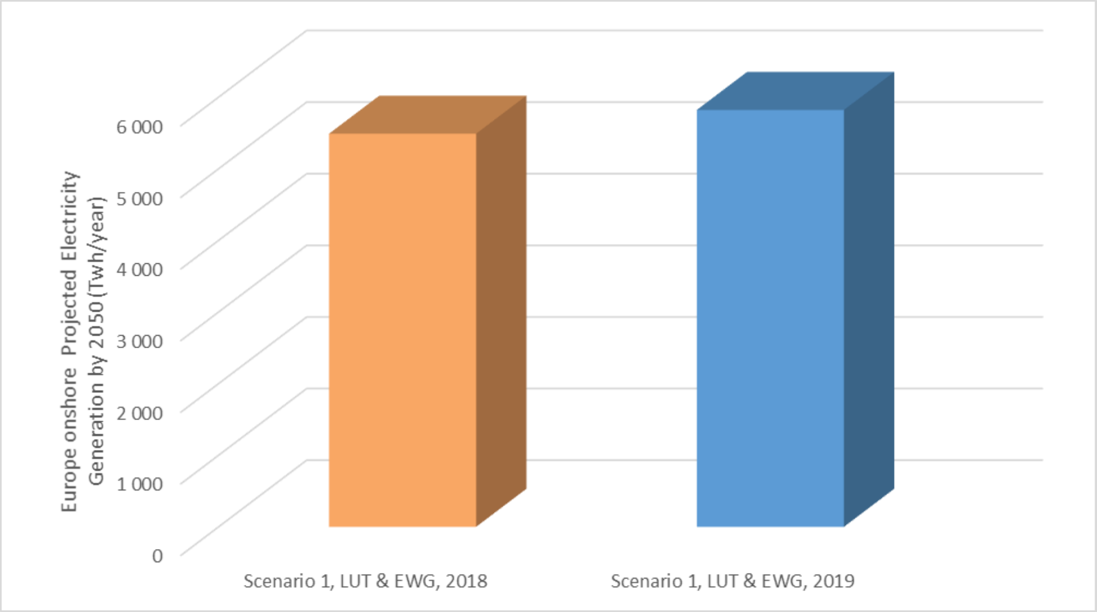


Figure 29. Europe's Wind Onshore Projected Electricity Generation by 2050 for each scenario

In the last case, since the data available was very scarce, only 2 studies from the same entity were analyzed. Therefore, the only available conclusion that is possible to retrieve from the figure above display is that, according to LUT & EWG, the Europe Onshore Projected Electricity Generation in 2050 was increased in their second study and it is expected to reach values between 5 000 – 5 500 TWh per year.

### 7.3 Variable Meta-Analysis

Starting by addressing the data from VMA, the main basis for the development of the work presented, and as the largest source of studies consulted, we began by creating tables 9, 11, 12 and 13 summaries of the various parameters analyzed, their minimum, maximum and average values for each technology previously addressed. Due to the step presented in table 7, where there was a filter (time and regional) against the pool of all data collected, the "Data Points" presented in the tables below reveal the amount used (left number) compared to the amount of data collected that was available for use (right number).

Table 9. Variable Meta-Analysis Input Data for Conventional Technologies

| Conventionals | | | | | |
|---|---|---|---|---|---|
| VMA Parameter | Unit | Data Points | Low Value | Mean Value | High Value |
| First Cost per Implementation Unit | €2021/kW | 33 / 201 | 318 | 1 540 | 2 762 |
| First Cost Learning Rate | % | | 1 | 1 | 1 |
| Lifetime Capacity | hours | 29 / 32 | 118 974 | 153 126 | 187 278 |
| Average Annual Use | hours/year | 26 / 68 | 2 714 | 4 536 | 6 358 |
| Variable Operating and Maintenance Cost (VOM) | €2021/kWh | 17 / 72 | 0.001 | 0.003 | 0.005 |
| Fixed Operating and Maintenance Cost (FOM) | €2021/kW | 24 / 147 | 18.3 | 40.32 | 62.33 |
| Fuel Price | €2021/kWh | 57 / 57 | 0.007 | 0.017 | 0.037 |

A weighted average for conventional technologies inputs was considered, in order to account for oil, coal, as gas use representation on the current electricity generation mix. Table 10 shows the weight of Conventional technologies for the year of 2018 and applied to all conventional technologies variables on the VMA.

Table 10. Weight of Conventional technologies in 2018 electricity generation mix

| Conventional Technologies | Weight |
|---|---|
| Coal | 20% |
| Natural Gas | 19% |
| Nuclear | 25% |
| Oil | 2% |

It was not considered any variation of this weight throughout the study from 2018 – 2050, guarantying a conservative approach for the established scenarios. With the increase of renewable electricity production, the weight of conventional technologies is only expected to decrease substantially.

A similar weighting scheme approach was not used for any variable of the solutions evaluated, due to uncertainty and lack of information on specific technologies current or representation (i.e. floating offshore vs. fixed offshore wind; or vertical vs horizontal axis small wind turbines).

Table 11. Variable Meta Analysis Input Data for Wind Offshore Technology

| Wind Offshore | | | | | |
|---|---|---|---|---|---|
| VMA Parameter | Unit | Data Points | Low Value | Mean Value | High Value |
| First Cost per Implementation Unit | €2021/kW | 35 / 101 | 195 | 2 764 | 3 506 |
| Learning Rate | % | 17 / 48 | 4.0 | 9.8 | 15.6 |
| Lifetime Capacity | hours | 18 / 47 | 89 301 | 96 964 | 104 628 |
| Average Annual Use | hours/year | 19 / 68 | 3 269 | 3 896 | 4 522 |
| Variable Operating and Maintenance Cost (VOM) | €2021/kWh | 5 / 11 | 0.012 | 0.032 | 0.051 |
| Fixed Operating and Maintenance Cost (FOM) | €2021/kW | 12 / 73 | 70.53 | 108.98 | 147.43 |
| Indirect GHG Emissions | $tCO_2e/TWh$ | 38 / 41 | 5 543 | 13 444 | 21 345 |

Table 12. Variable Meta-Analysis Input Data for Wind Onshore Technology

| Wind Onshore (EU) | | | | | |
|---|---|---|---|---|---|
| VMA Parameter | Unit | Data Points | Low Value | Mean Value | High Value |
| First Cost per Implementation Unit | €2021/kW | 25 / 241 | 1 390 | 1 970 | 2 550 |
| Learning Rate | % | 11 / 56 | 3.1 | 7.3 | 11.5 |
| Lifetime Capacity | hours | 13 / 29 | 63 413 | 67 737 | 72 061 |
| Average Annual Use | hours/year | 38 / 80 | 2 060 | 2 778 | 3 495 |
| Variable Operating and Maintenance Cost (VOM) | €2021/kWh | 19 / 33 | 0.015 | 0.027 | 0.038 |
| Fixed Operating and Maintenance Cost (FOM) | €2021/kW | 5 / 60 | 34.37 | 38.73 | 43.09 |
| Indirect GHG Emissions | $tCO_2e/TWh$ | 40 / 45 | 2000 | 19 834 | 40 026 |

Table 13. Variable Meta-Analysis Input Data for Small Wind Technology

| Small Wind | | | | | |
|---|---|---|---|---|---|
| VMA Parameter | Unit | Data Points | Low Value | Mean Value | High Value |
| First Cost per Implementation Unit | €2021/kW | 28 / 28 | 2 746 | 4 753 | 6 759 |
| Learning Rate | % | 20 | 4.1 | 9.7 | 15.2 |
| Lifetime Capacity | hours | 7 / 7 | 19 617 | 24 530 | 29 442 |
| Average Annual Use | hours/year | 18 / 18 | 788 | 1 249 | 24 530 |
| Variable Operating and Maintenance Cost (VOM) | €2021/kWh | 2 / 2 | 0.001 | 0.025 | 0.048 |
| Fixed Operating and Maintenance Cost (FOM) | €2021/kW | 6 / 6 | 19.23 | 42.23 | 65.23 |
| Indirect GHG Emissions | $tCO_2e/TWh$ | 23 / 26 | 400 | 49 871 | 124 807 |

As previously mentioned in the Methodology chapter, the data points presented on the previous tables are for values of Europe and European Union trough 2015 – 2020 not being considered any projection values. However, the same situation doesn't fully apply to Small wind Technology. As previously mentioned, due to the lack of information, values for other geographic regions were also included, always considering the same timeline.

After a first glance, "Indirect Greenhouse Gases Emissions" has the largest amount of data points used for almost all technologies followed by "First Cost per Implementation Unit". The hardest VMA parameter to find for this timeframe (2015-2020) and geographical area were definitely both "Variable Operating and Maintenance Cost (VOM)" as well as "Fixed Operating and Maintenance Cost (FOM)".

If we only look towards the availability of data, considering all time frame as well as all the geographical areas, "First Cost per Implementation unit" and "Fixed Operating and Maintenance Costs (FOM)", both this parameter lead the charge, revealing, once more, the detailed selection process that was conducted.

Regarding the VMA Parameter with the largest presence, it is worth noting the difference in values between the three technologies, with greater emphasis on the difference between Offshore wind and Small wind compared to the more mature technology, Onshore wind. Looking only to the mean value, Offshore technology First Cost per Implementation Unit is 69% higher compared to Onshore technology and, for Small wind, this value increases to 290%. Financially, it is easy to state that the costs for Onshore wind are substantially lower compared to the other two technologies. Nevertheless, the Lifetime Capacity as well as Learning Rate and Average Annual Use appear to be much higher in Offshore wind, which means that a substantial decrease in the respective price is expected. This higher cost for Offshore wind can be easily explained by the lack of maturity of these technologies, the higher energy transmission infrastructure connecting the offshore platform to an onshore grid, extra materials required, and other technical challenges.

Regarding Materials and jobs created by using each technology, besides the lack of information it was made possible to even differentiate the jobs created by each phase of a wind project, Construction and Installation, Manufacturing, decommissioning, between other and, for the materials aspect, it was possible to retrieve and present data for, at least, 15 different materials including rare earth metals, such Molybedenum, Zinc, Manganese, Dysprosium, etc. The values present were merely a result of the combination of all the data retrieved for this two parameters.

## 7.4 Project Drawdown RRS Model Results

Finally, the last set of results obtained were developed by using the Project Drawdown RRS model explained, in the methodology chapter. For each wind technology, 20 model runs were made, considering the 16 adoption cases from the base scenarios and four others from the created aggregate ones. Average values from the VMA analysis for all the financial, technical and emissions parameters were used for these model runs.

Later on, after the data Input, the main output results can be divided in two different categories: Emissions and Economic results. All the Economics and Environmental data retrieved refers to the cumulative cost or cost reduction and $CO_{2e}$ emissions avoided during the 30 years’ time frame line, 2020 - 2050.

### 7.4.1 Onshore Wind

All the results below portrayed are based on the comparation between conventional technologies with the impact of the solutions adoption being modelled. Therefore, all the values retrieved and further discuss are based on the comparation of the same parameters of conventional technologies.

Firstly, starting by refreshing the reader mind about the variations that sometimes occur between some scenarios, in the case of figure 30, between the last 3 cases. Since the main criteria of scenario growth selection was the Electricity Generation in 2050, there can be cases, such as the ones presented, where throughout the years, the total electricity production is higher (i.e. accumulated values). In other words, the electricity production in "Scenario 3, Eurelectric, 2018" between 2018 and 2050 was higher than "Scenario 1, Eurelectric, 2018". Nevertheless, the value of 2050 which was the only value considered for the scenarios growth setup is higher in the last one.

Taking this explanation in account, $CO_{2e}$ emissions reduction of increased adoption of wind onshore when compared to the use of conventional technologies for the same amount of electricity generated; varies roughly around 2 and 16 Gt of $CO_{2e}$. It is also important make the link between higher renewable electricity production and higher $CO_{2e}$ emissions reduction. Studies where the electricity production is bigger result in higher $CO_{2e}$ savings.

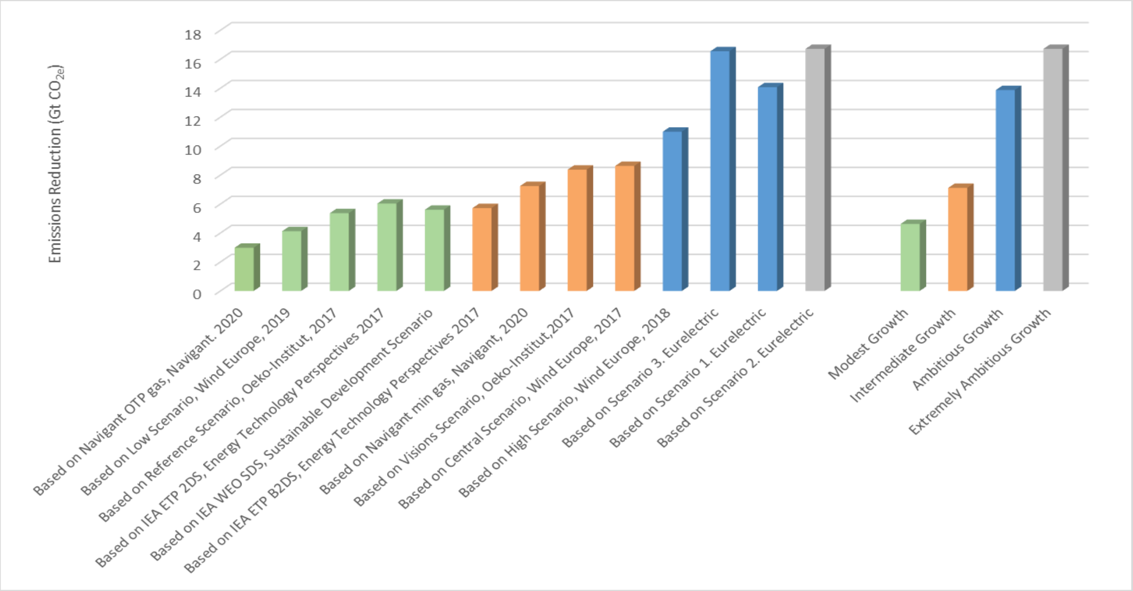


Figure 30. Emissions Reduction fom 2020-2050 for Onshore wind scenarios

According to the economic part of results present in the figure 31, one can only appreciate the scale of investment that is going to be needed in the wind industry compared to conventional technologies. As previously mentioned, a lot of studies and entities refer the leading part that both Onshore and Offshore wind will have in a near future. However, such part will only be possible with cost reduction trough out his chain. Since the data treated considered mean values from 2015 – 2020, a cost reduction in the next years will majorly change the values that are further going to be presented.

Considering a mean value of “First Cost Per Implementation Unit” of 1 970 €/kW, Marginal First Costs 2015 – 2050 could go as high as 450 billion euros, in the Extremely ambitious Scenario and as low as 100 billion euros on the least ambition one. Even more important, the mean values lies around 300 billion euros. However, considering the possible cost reduction in the studies technologies, these values can hugely decrease.

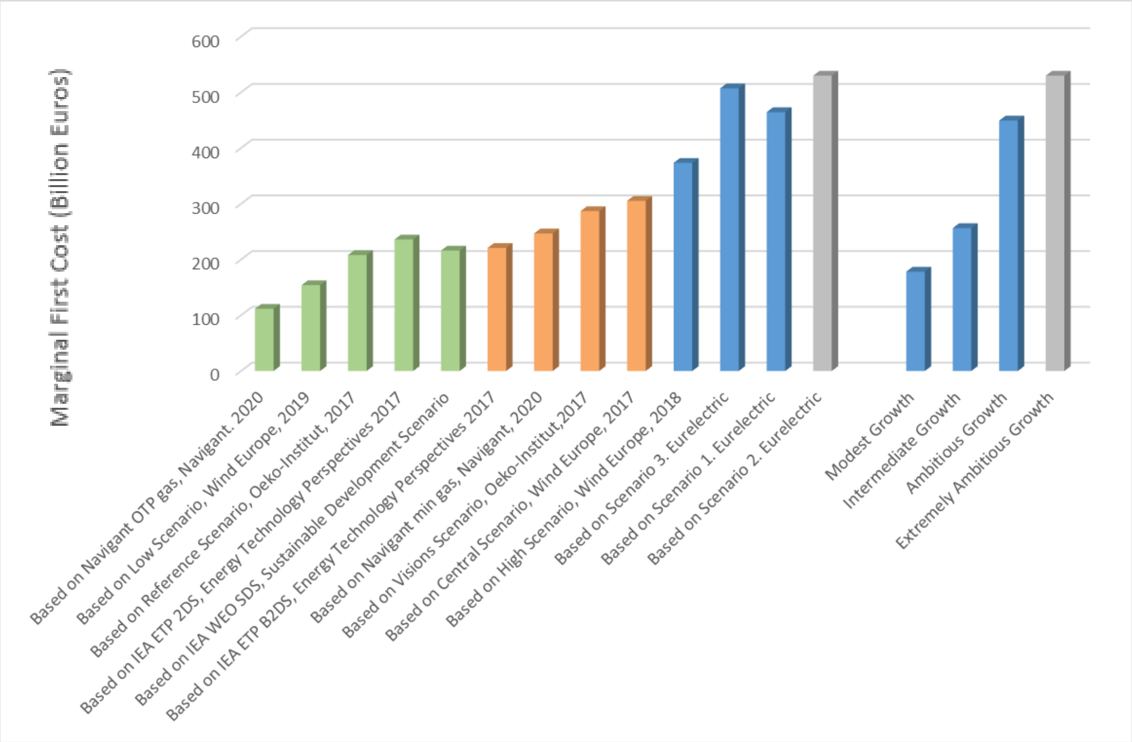


Figure 31. Marginal First Cost for Onshore Wind scenarios

For the last one, Lifetime Operating Savings (figure 32) is considered a must and a very important aspect for any investor. The increase of investors and a general search for better technology, is a crucial step towards price reduction and technology efficiency. However, all economic factor here are negative. Which means that there are no Lifetime Operating Savings, only additional costs that can go as high as 250 Billion euros and as low as 50 Billion. In order to have a look and an overview view of the main results obtained in the Project Drawdown RRS Model, Annex A - table A1 was created for the European Union.

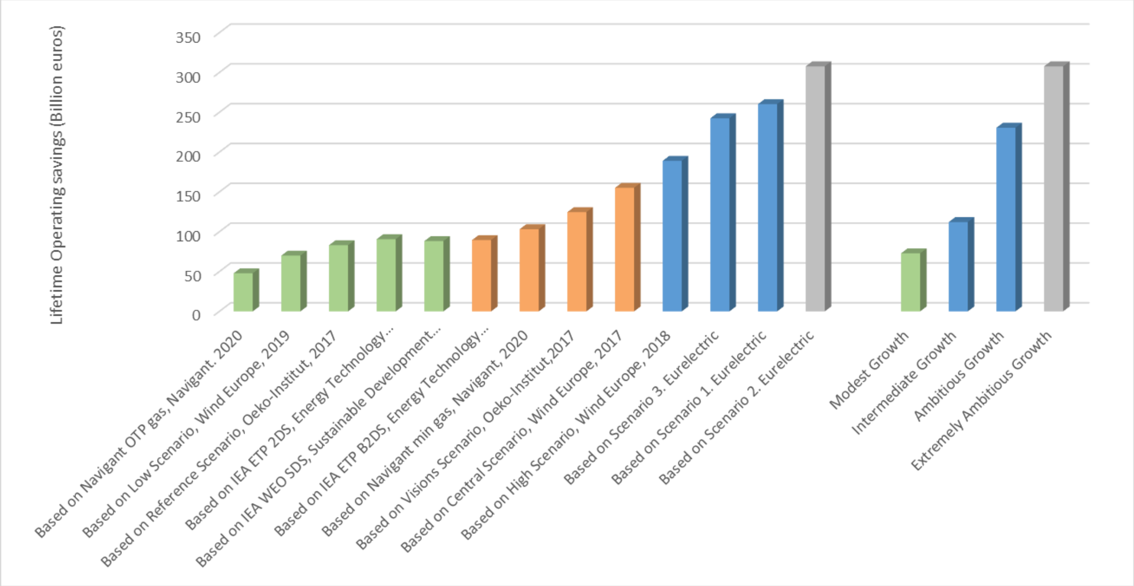


Figure 32. Lifetime Operating Saving for Onshore wind scenarios

### 7.4.2 Offshore Wind

Figure 33, once again, presents the result for Emissions Reduction but, this time, for Offshore wind technology. The environmental contribution of such technology also presents a large range of values, due to the ambitions of each scenario collected. Therefore, Offshore wind presents a potential to decrease $CO_{2e}$ emissions between three and 20 Gt, being nine gigatons the mean value.

Regarding the financial aspect of such technology, once again, there will be a need for huge efforts to address such wind electricity production. The range of value remains very similar to the Onshore case. Marginal First Cost (figure 34) between 2015 and 2050 is expected to start in 50 billion euros and achieve a high value of 400 billion while the mean value of this parameter was calculated to be 223 billion. Nevertheless, one could argue the fluctuation of value in both figures, where sometimes the value of both “Marginal First Costs” and “Emissions Reduction” increase and, in the follower year, is accompanied by a decrease. Such even occurs about four times and, like in the Onshore wind case, is a result of the scenario growth selection explain, furthermore, on the Onshore economic chapter.

As previously mentioned, a cost reduction is forecasted by several entities, that wraps up a mean value of 50% until 2050.This cost reduction will hugely affect the technology interest for new investors.

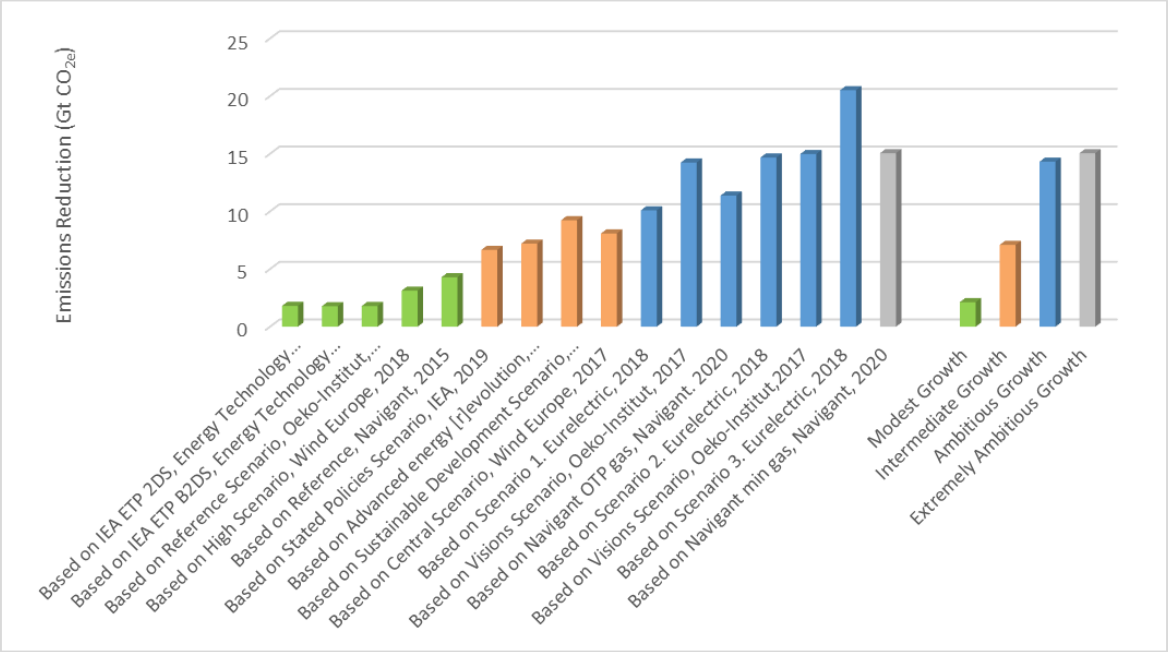


Figure 33. Emissions Reduction up to 2050 for Offshore wind scenarios

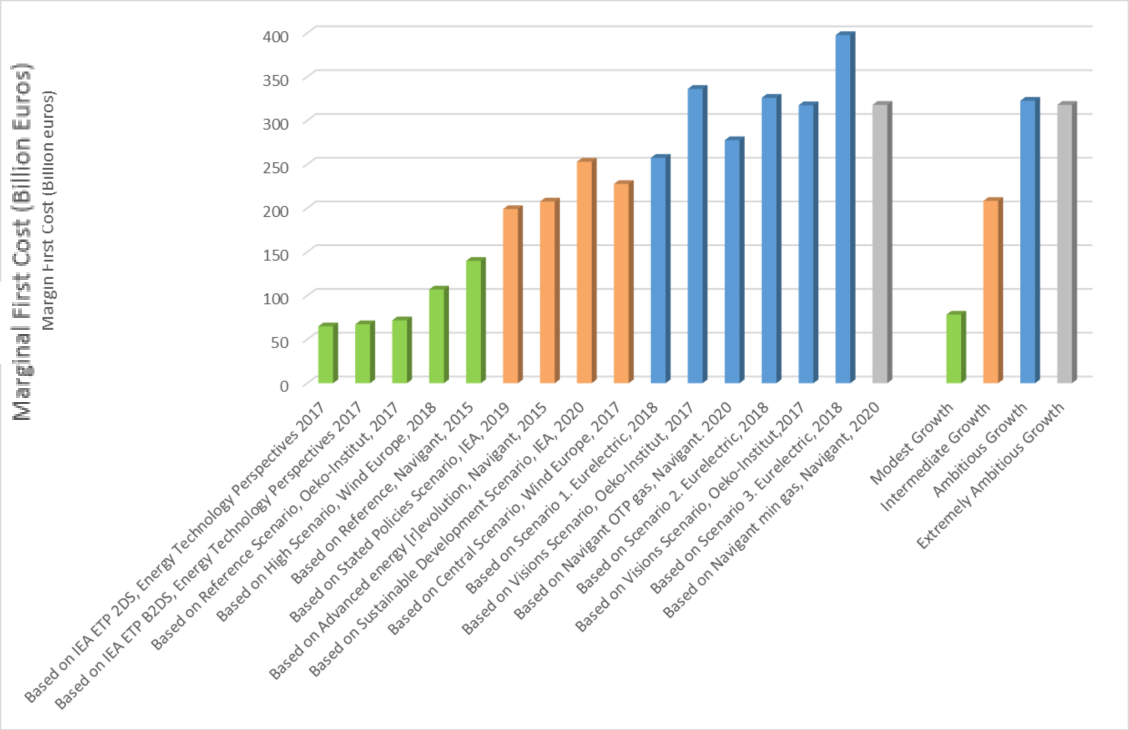


Figure 34. Marginal First Cost for Offshore Wind scenarios

Ending this subchapter with Lifetime Operating savings (figure 35), once again, this parameter comes out negative. However, it does not follow the previous trend being more homogeneous though out the scenarios. The main aspect that immediately comes to mind is the wide range of values and the huge amount of financial strength that will be needed in order to address this technology. With Lifetime Operating Savings that start in 200 billion and end in 2 400 billions euros, much has to be done regarding the decrease in “First Cost per Implementation Unit” but more importantly in the “Variable Operating and Maintenance Cost (VOM)” as well as in the “Fixed Operating and Maintenance Cost (FOM)”, the main financial aspect for the parameter in question. In order to have an overview look of the main results obtained in the Project Drawdown RRS Model, for Offshore wind, Annex A – Table A2 was created for the European Union region.

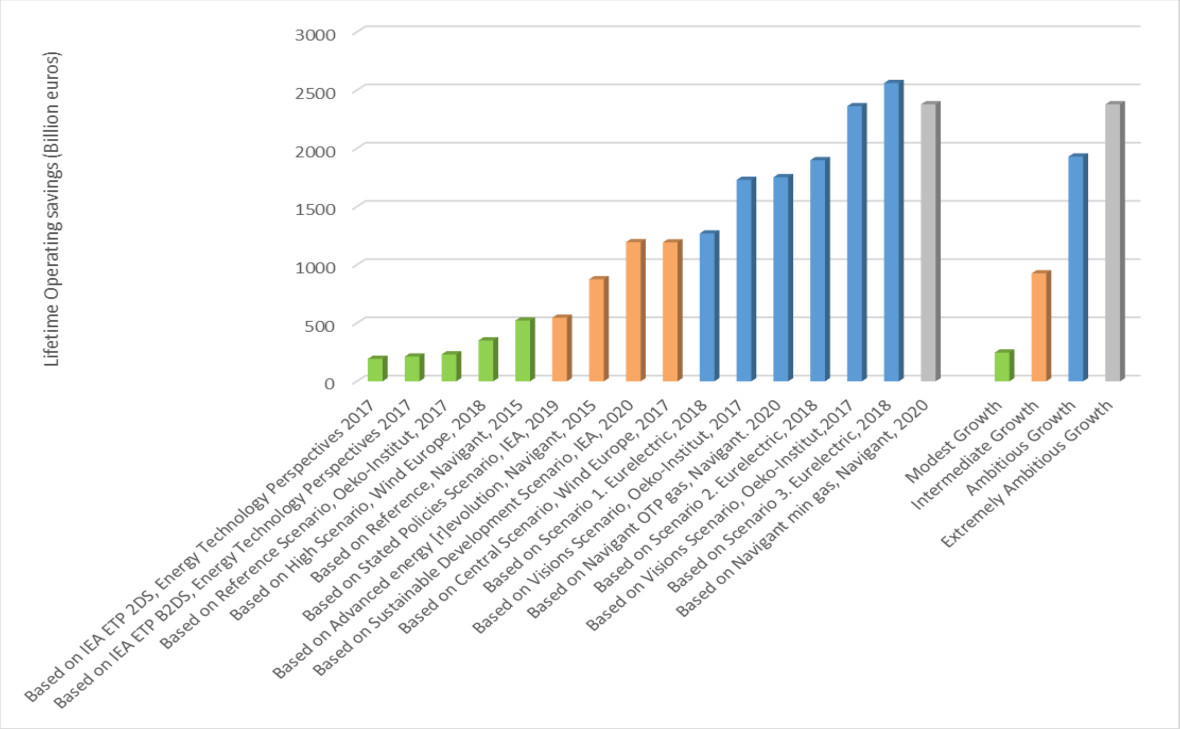


Figure 35. Lifetime Operating Saving for Offshore wind scenarios

### 7.4.3 Small Wind

Concluding with the last wind technology, the values expected are going to be much different and significantly lower than the ones presented on the previous chapters for the other utility scale level. Due to the small potential and electricity generation of small wind, the economics and GHG emissions impacts are going to be considerable reduced compared to other technologies.

Figure 36 depict that Small wind could reduce, until 2050, the emission of $CO_{2e}$ to the atmosphere in between 0.01 and 0.4 Gt on the Extreme Ambitious Growth scenario. However, by not considering the three created scenarios, the ones that present a huge discrepancy face to the others, this value would only variate between 0.01 and 0.03 Gt of $CO_{2e}$ with a mean value of 0.02, three times lower than the mean value using the 16 scenarios - 0.06 Gt of $CO_{2e}$.

These three scenarios with a very distinct assumption, do not adapt to the reality in question, nevertheless, in case of a large Small wind systems adoption, these three scenarios are the most relevant.

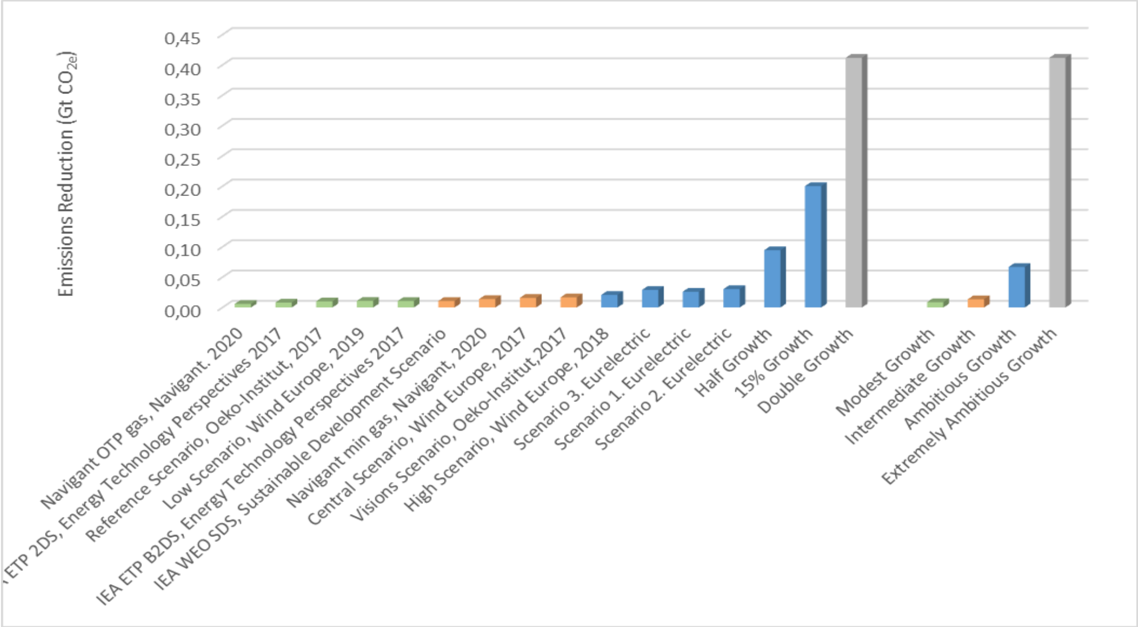


Figure 36. Emissions Reduction for Small Wind scenarios

Regarding the economic part, compared to the electricity production, Small wind Marginal Cost are actually really high. Although their “Variable Operation and Maintenance Costs” as well as their “Fixed Operating and Maintenance Costs” are relatively the same when compare to the Onshore wind technology, “First Cost per implementation Unit” presents a much higher value, two times more than Onshore wind, whereas “Lifetime Capacity” values are much lower, meaning they operate for less time, therefore, they are able to produce electricity for less time and so, the relation between gains and investment is much narrower.

Marginal First Cost (figure 37) vary between 3 billion euros, in the less ambitious case, until 200 billion in the “Double Growth” scenario. Following the previous explanation, excluding the last 3 scenarios created, “Half Growth”, “15% Growth” and “Double Growth”, this gap narrows down to a difference between three and 16 billion euros with a mean value of eight instead of 31 billion euros.

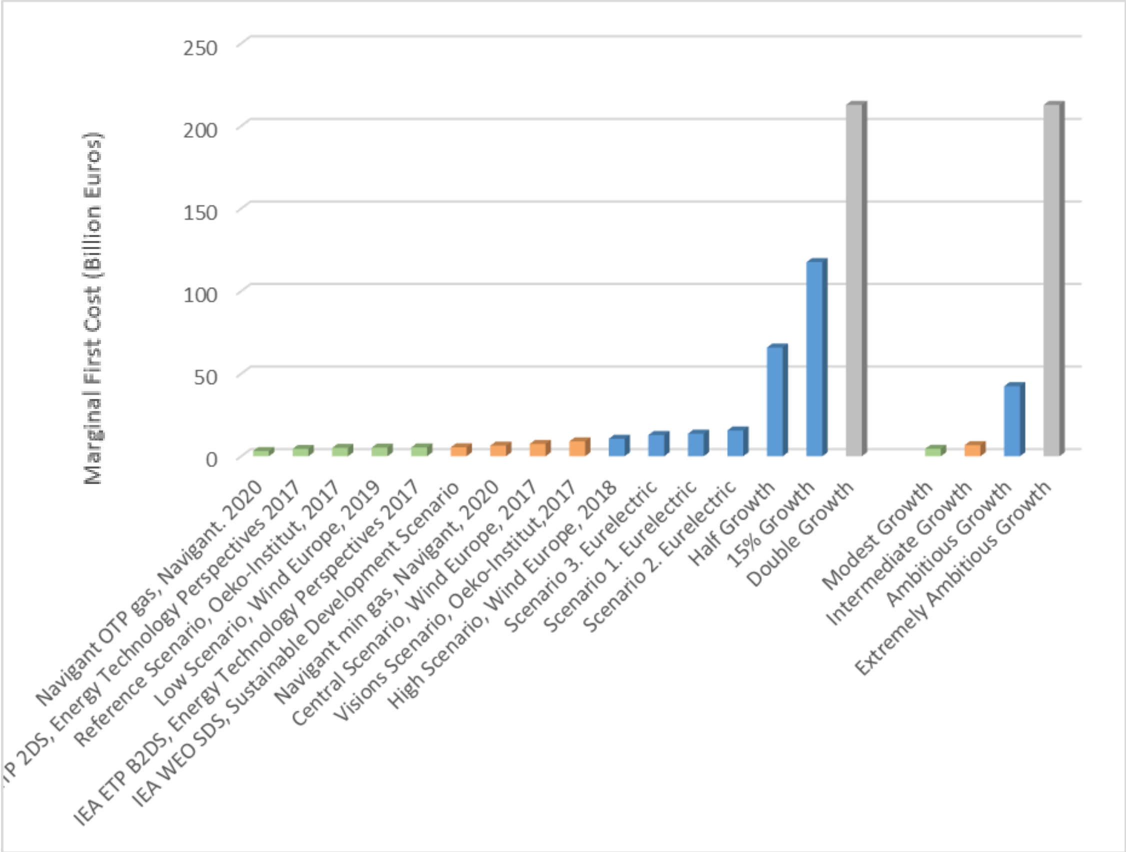


Figure 37. Marginal First Cost for Small Wind scenarios

Regarding Lifetime Operating Savings (figure 38), as expected, three studies come on top with very different values. Ranging from 0.66 billion to 79 billion euros with a mean value of 10 much due to the same over ambitious scenarios.

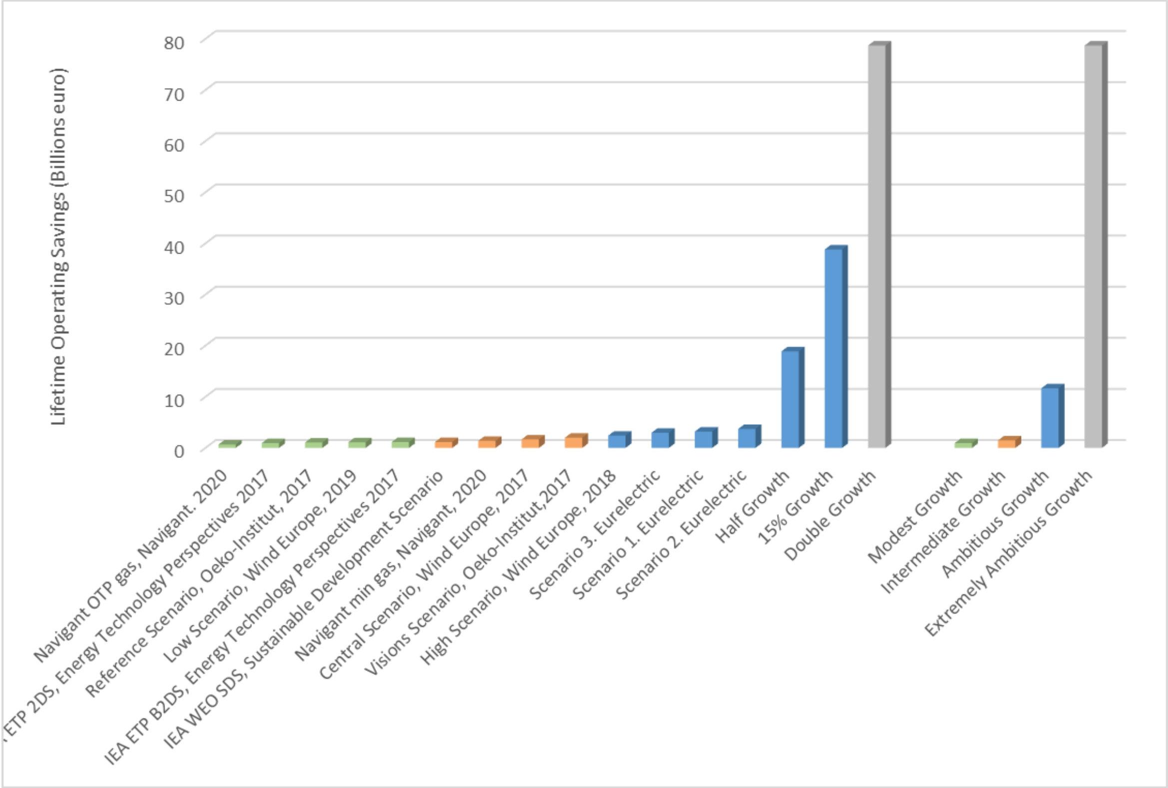


Figure 38. Lifetime Operating Saving for Small Wind scenarios

Finally, in order to have the same global look towards the main results obtained in the Project Drawdown RRS Model, for Small wind in the European Union, Annex A – table A3 was created.

### 7.4.4 Jobs and Materials

Assessing the new indicators added for this study - jobs and materials analysis. As previously mentioned, the data presented is a merely conjugation of data from many different studies, all combined and treated, resulting in the data that will be further presented. The results obtain resulted in the whitening of each technology according to the expected growth and generation for each case.

Starting with jobs parameter, in order to better distinguish and have a wider scope of interpretations, there were used 2 growth scenarios, Ambitious and Modest Growth Scenarios as well as a division between the main parts of a wind project. Table 14 and 16 reveals the combinations of all data retrieved and posterior treatment. Afterwards, presented in Table 15 and 17, a Materials analysis will be conducted, where the main materials used will be further presented in the Modest and Ambitious Growth Scenario.

After a first glance, by looking towards the Total values of both Table 14 and 16, it becomes noticeable the range of jobs that are going to be available with the continue and expansion of Onshore wind technology. Table 14 and 16 detailly reveals for the number of jobs created by the main steps of a wind project, starting with the Manufacturing and ending in the Decommissioning phase, ranging from the lowest value to the highest value retrieved. Therefore, it is important to highlight the two most important part in both an Onshore and Offshore wind project in terms of jobs generation, with Manufacturing coming on top, closely followed by Construction and Installation. These two phases represent, in the Onshore case, almost 86% of the total jobs created. A comparation between the two scenarios has to be made since Ambitious Growth Scenario Total jobs comes out as three times higher compared with the other scenario. Nevertheless, it is important to stress out that, although the electricity generation in the Ambitious scenarios is 2.4 times higher compared with the Modest scenario, in the jobs parameter, this value comes even higher.

Concluding with the materials used in the different steps of the wind part project, mainly in the construction of the several turbine components, as well in the installation process, concrete as well as steel and iron components come out on top, with roughly 85 and 21 million tons used per TW. Besides this massive numbers, that vary tremendously with the two scenarios chosen, a keynote had to be made about rare earth metals. Metals like dysprosium, molybdenum, praseodymium, between many other used, can determinate how far wind industry can grow. Being a key factor, the extraction of such materials has to follow the wind industry growth which, according to some papers and articles published ("Rethinking the use of rare-earth elements", 2018 and "The vulnerability of electric-vehicle and wind-turbine supply chains to the supply of rare-earth elements in a 2-degree scenario", 2020) it is not the case.

Due to the lack of information regarding Small wind technologies, unfortunately, the same analyze couldn't be conducted for this case. The inexistence of studies regarding jobs generation and materials used for these technologies made it impossible to further continue this data explanation.

## Table 14. Jobs created by each phase for Onshore Wind Technologies for two selected scenarios

| JOBS | | Ambitious | Modest | |
|---|---|---|---|---|
| Construction and Installation | Max | 1 920 000 | 608 000.00 | Job / TWh |
| | Min | 202 220 | 64 036.46 | Job / TWh |
| | Med | 1 460 555 | 462 509.12 | Job / TWh |
| Decommissioning | Max | 432 000 | 136800 | Job / TWh |
| | Min | 276 822 | 87660.3 | Job / TWh |
| | Med | 354 411 | 112230.15 | Job / TWh |
| Manufacturing | Max | 2 820 000 | 893 000.00 | Job / TWh |
| | Min | 259 318 | 82 117.37 | Job / TWh |
| | Med | 1 712 578 | 542 316.40 | Job / TWh |
| Operation and Maintenance | Max | 180 000 | 57 000.00 | Job / TWh |
| | Min | 87 616 | 27 745.13 | Job / TWh |
| | Med | 153 358 | 48 563.47 | Job / TWh |
| Total | Max | 5 352 000 | 1 694 800 | Job / TWh |
| | Min | 600 714 | 190 226 | Job / TWh |
| | Med | 3 419 827 | 1 082 945 | Job / TWh |

## Table 15. Materials used for Onshore Wind Technologies for two selected scenarios

| MATERIALS | | Ambitious | Modest | |
|---|---|---|---|---|
| Aluminum and aluminum alloy | Med | 1 158 154 | 366 749 | t/TWh |
| Chromium | Med | 282 000 | 89 300 | t/TWh |
| Copper | Med | 1 000 615 | 316 862 | t/TWh |
| dysprosium | Med | 6 240 | 1 976 | t/TWh |
| Electronics/electrics | Med | 540 923 | 171 292 | t/TWh |
| n (Fe), Boron (B) and other me | Med | 119 260 | 37 766 | t/TWh |
| Manganese | Med | 468 000 | 148 200 | t/TWh |
| Molybdenum | Med | 59 400 | 18 810 | t/TWh |
| Neodymium | Med | 49 423 | 15 651 | t/TWh |
| Nickel | Med | 242 100 | 76 665 | t/TWh |
| Praseodymium | Med | 7 732 | 2 448 | t/TWh |
| Steel and iron materials | Med | 67 009 231 | 21 219 590 | t/TWh |
| terbium | Med | 1 600 | 507 | t/TWh |
| concrete | Med | 274 032 000 | 86 776 800 | t/TWh |
| Zinc | Med | 3 300 000 | 1 045 000 | t/TWh |

Table 16**.** Jobs created by each phase for Offshore Wind Technologies for two selected scenarios

| JOBS | | Ambitious | Modest | |
|---|---|---|---|---|
| Construction and Installation | Max | 3 920 000.00 | 480 000 | Job / TWh |
| | Min | 220 500.00 | 27 000 | Job / TWh |
| | Med | 2 811 375.00 | 344 250 | Job / TWh |
| Decommissioning | Med | 1 465 100.00 | 179 400 | Job / TWh |
| Manufacturing | Max | 7 644 000.00 | 936 000 | Job / TWh |
| | Min | 191 100.00 | 23 400 | Job / TWh |
| | Med | 5 535 775.00 | 677 850 | Job / TWh |
| Operation and Maintenance | Max | 98 000.00 | 12 000 | Job / TWh |
| | Min | 73 500.00 | 9 000 | Job / TWh |
| | Med | 88 200.00 | 10 800 | Job / TWh |
| Total | Max | 13 127 100 | 1 607 400 | Job / TWh |
| | Min | 9 922 500 | 1 215 000 | Job / TWh |
| | Med | 11 570 533 | 1 416 800 | Job / TWh |

Table 17. Materials used for Offshore Wind Technologies for two selected scenarios

| MATERIALS | | Ambitious | Modest | |
|---|---|---|---|---|
| Aluminum and aluminum alloy | Med | 595 538 | 72 923 | t/TWh |
| Chromium | Med | 257 | 32 | t/TWh |
| Copper | Med | 332 999 | 40 775 | t/TWh |
| dysprosium | Med | 4 | 0 | t/TWh |
| Electronics/electrics | Med | 0 | 0 | t/TWh |
| Iron (Fe), Boron (B) and other metals | Med | 98 | 12 | t/TWh |
| Manganese | Med | 387 | 47 | t/TWh |
| Molybdenum | Med | 53 | 7 | t/TWh |
| Neodymium | Med | 12 256 | 1 501 | t/TWh |
| Nickel | Med | 118 | 14 | t/TWh |
| Praseodymium | Med | 5 704 | 698 | t/TWh |
| Steel and iron materials | Med | 53 372 308 | 6 535 385 | t/TWh |
| terbium | Med | 1 177 | 144 | t/TWh |
| Zinc | Med | 2 695 | 330 | t/TWh |

# 8 Discussion

This chapter presents a wide discussion regarding results contextualization as well as key factors of European Union future of electricity generation will be conducted. Furthermore, the following interpretations of results will make the bridge with the conclusion chapter.

## 8.1 Combining and Contrasting Results

Without putting aside the importance and weight of each of the technologies previously discussed and whose data was previously presented, a wider and richest observations and interpretation can be made with the combinations of these three technologies. With the aggregations and subsequent combinations of these technologies, wind electricity generation can be purely compared with solar, hydro, geothermal and non-renewable sources. Although the three wind technologies compete partly between them in the overall TAM, as an aggregate, they present several of the key factor to change and help swap the future European electricity generation mix.

Previous chapter aimed to display and have small interpretations of the results obtained, in the 20 scenarios used (16 projections + 4 aggregated-by-tier average projections), revealing the economic and emissions impact of each one. In this chapter, the target of discussion will be different. Whereas firstly a distinct interpretation was made, now, a global one will be conducted. Firstly, by comparing the technologies previously discussed and, secondly, by aggregating the wind technologies in a global one, wind.

A comparison between the three technologies is portrayed in figure 39 with the electricity generation expected for 2050 according to the different scenarios, in TWh. As expected, Onshore wind, for Europe will be, at any given moment, much higher than any other. For the European Union, both Onshore and Offshore wind display a very similar distribution throughout the scenarios, however, some less ambitious studies present, for Offshore wind lower values for electricity generation in 2050. A better view of Small wind technologies weigh is hard to find since figure 39 purely displays the comparation between this technology and the two others. Therefore, it is perceptible the small role that this technology will have in the European Union energy mix.

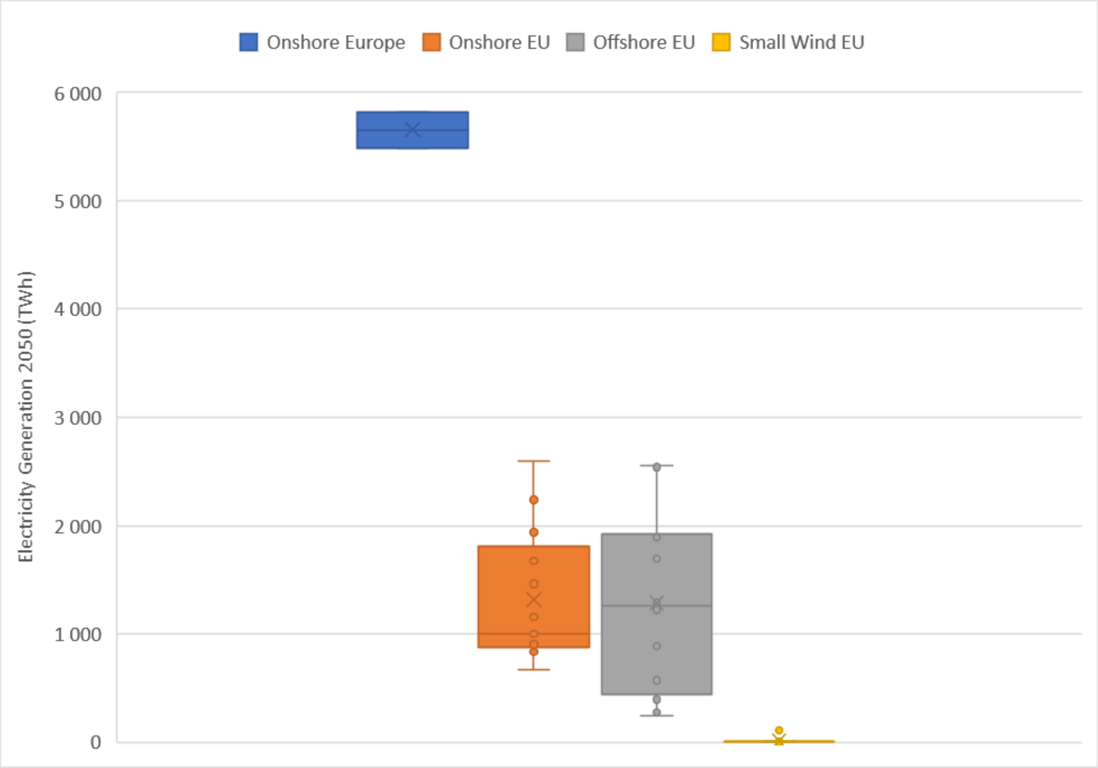
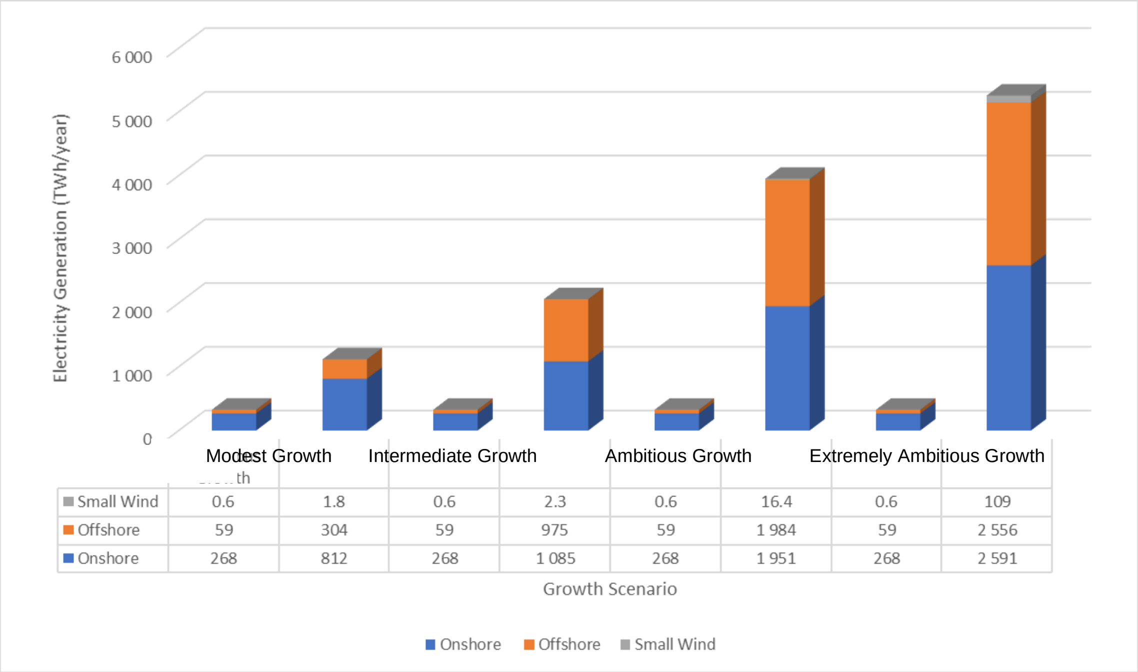


Figure 39. Electricity Generation in 2050 comparison for different regions and wind technologies

It becomes clear that there will be two major technologies in the wind industry, both Onshore wind technologies and Offshore wind technologies. In order to have a small scale of comparison, in 2018, the European Union produced roughly 60 TWh of electricity from Offshore wind and 270 TWh with Onshore wind technologies. With a Total Addressable Market of 3 275 TWh in 2018, both Offshore and Onshore represented about 1.83% and 8.24% respectively. By 2050, comparing with the Ambitious Growth scenario, there will be an increase of 33 times for Offshore wind and about 7 times for Onshore wind. Huge growth in the electricity generation of these technologies, that, with the Ambitious Growth scenario for TAM, totalizing 8850 TWh, these technologies will represent both 22.4% and 22% respectively. In other words, wind technologies have the ability to represent about 45% of the total European Union electricity generation, almost half of what will be needed.

Continuing the following analyses, now placing all the technologies in the wind aggregate, figure 40 does a small identification of the influence of each one in the 2018 -2050 electricity generation.



| | Modest Growth | | Intermediate Growth | | Ambitious Growth | | Extremely Ambitious Growth | |
|---|---|---|---|---|---|---|---|---|
| ■ Small Wind | 0.6 | 1.8 | 0.6 | 2.3 | 0.6 | 16.4 | 0.6 | 109 |
| ■ Offshore | 59 | 304 | 59 | 975 | 59 | 1 984 | 59 | 2 556 |
| ■ Onshore | 268 | 812 | 268 | 1 085 | 268 | 1 951 | 268 | 2 591 |

Figure 40. Combined Wind Technologies Electricity Generation, 2018 vs 2050

As expected, due to the decreased impact of Small wind, both Onshore as well as Offshore wind, in 2050, will represent each about 50% of the electricity generation. The only exception present is in the Modest Growth scenario where the Offshore scenarios are much more conservative. Such projections can vary immensely and are dependent of several parts. Political factors, such as incentives and wind auctions, technology development, breakthrough and sustainability use of resources need for each technology can be one of the key factors for this development.

Starting with a small comparation between the three studied technologies and, later on, with the combination of the three, it will be possible to understand the financial weigh of each one and wind technologies weight as a whole. With figure 41 it is possible to understand the big effort that is in place and that is going to be hugely reinforced over the years in other to achieve such level of electricity generation with these technologies. Starting with the Margin First Costs, Onshore wind comes on top, followed by Offshore wind and then Small wind technologies. Nevertheless, it is important to highlight the big spread in values that exist. Being this graphics made based on the Marginal First Costs for each scenario studied, for each technology, more ambitious studies, that predict a larger amount of electricity generation, will lead to higher costs. Therefore, we have spreads that can go as high as 441 billion euros and as low as 91 billion. The same can be said for the other technologies, pointing out, once more, the low impact of Small wind technologies. Regarding Lifetime Operating saving, as previously presented, all financial values came out negative, with no saving but only additional costs and, this way, figure 41 reveals the spread existing. As mentioned in the previous Offshore wind sub-chapter, due to this technology high costs, the Lifetime and Operating Saving parameter has a higher spread and a higher mean value. The most important fact to retrieve from the following graphic really is the comparing between Offshore Lifetime Operating Savings with the other technologies. Currently, Offshore wind comes as the least financial advisable technology to use in the wind sector.

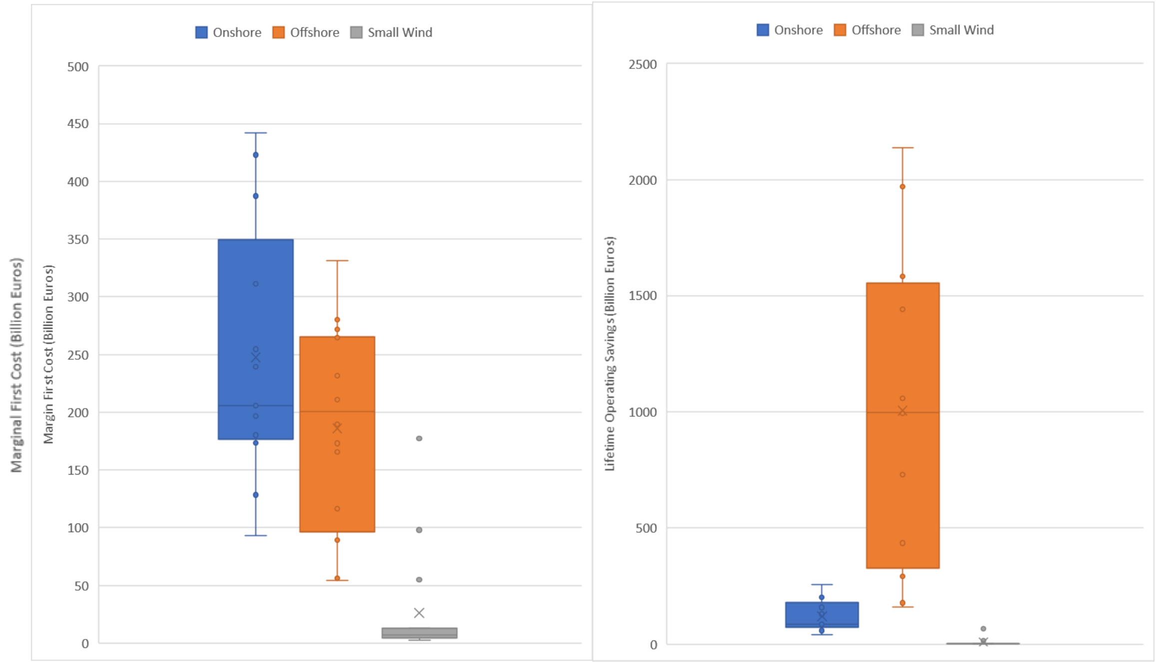
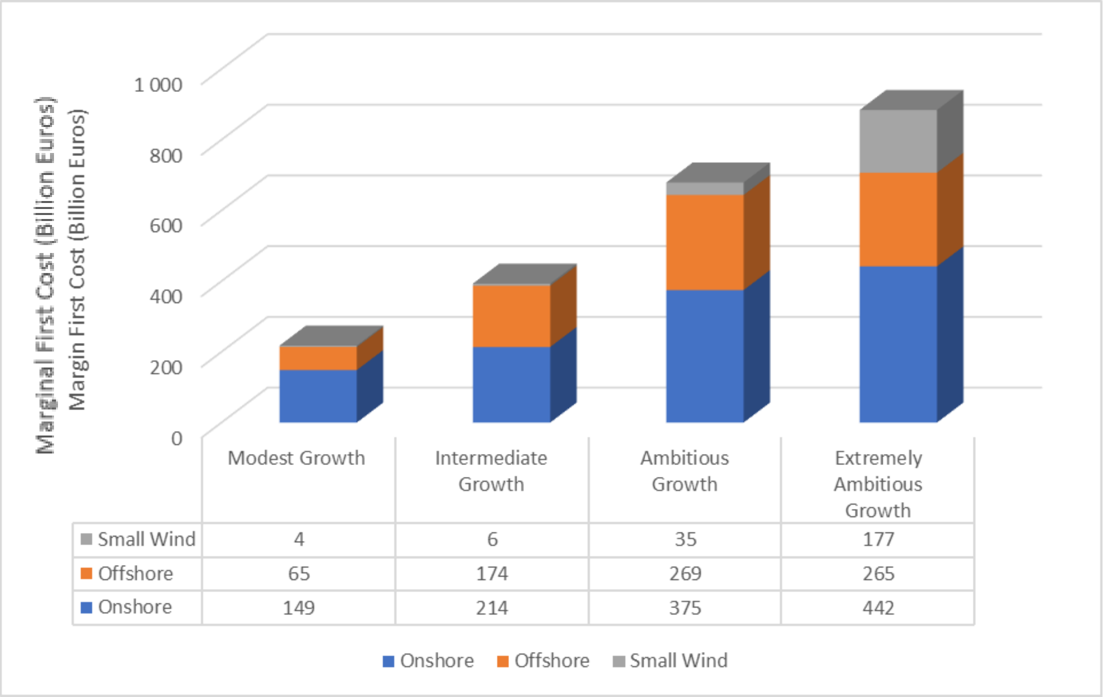


Figure 41. Marginal first Cost comparation & LifetimeOperating saving comparation



| | Modest Growth | Intermediate Growth | Ambitious Growth | Extremely Ambitious Growth |
|---|---|---|---|---|
| Small Wind | 4 | 6 | 35 | 177 |
| Offshore | 65 | 174 | 269 | 265 |
| Onshore | 149 | 214 | 375 | 442 |

Figure 42. Cumulative Wind Technologies Marginal First Cost throughout scenarios

Another key result that can be retrieved from figure 42 is the cost per TWh expected for each technology. Considering the Ambitious scenario, for Onshore wind, with 1 951 TWh of electricity generation and 231 billion euros in Lifetime Operating Savings, the price comes at 118 millions per TWh. Whereas, for the Offshore case, with a 1 984 TWh of electricity production and Lifetime Operating Savings at 1 930 billion, the price per TWh comes at roughly 1 billion euros. Finally, for the Small wind case, with roughly 16 TWh generated and Lifetime Operating Savings of 12, the price comes out at 750 millions per TWh. In a nutshell, the most economic advantageous technology is Onshore wind, with about 1/10 of Offshore wind Lifetime Operating Saving followed by Small wind with 750 millions per TWh.

Emission results are compared and presented in figure 42. Once again, Small wind technologies comes on the bottom, however, Offshore wind appears as the most relevant technology in potential $CO_{2e}$ emissions reduction. Being pushed down by some less ambitious scenarios, Offshore wind presents a wider range, however, there is a key factor to have in consideration. According to the Global Wind Energy Council, by 2050, to achieve zero emissions, Europe must deploy at least 2 000 GW of Offshore wind. In this 2 000 GW of new installed capacity, 640 GW need to be in European waters. If we consider that about 70% of Europe electricity production will come from European Union(values is expected to be much lower), converting this 640 GW to TWh by the expression $365(days) \times 24\, h/day \times Installed\ Capacity \times Capacity\ Factor$, being the capacity factor about 44%, that leaves us with a electricity generation needed of around 1 700 TWh. This value is only achieved in the twelfth scenario. Therefore, if we took this into consideration, figure 43 would show smaller spread and range of values.

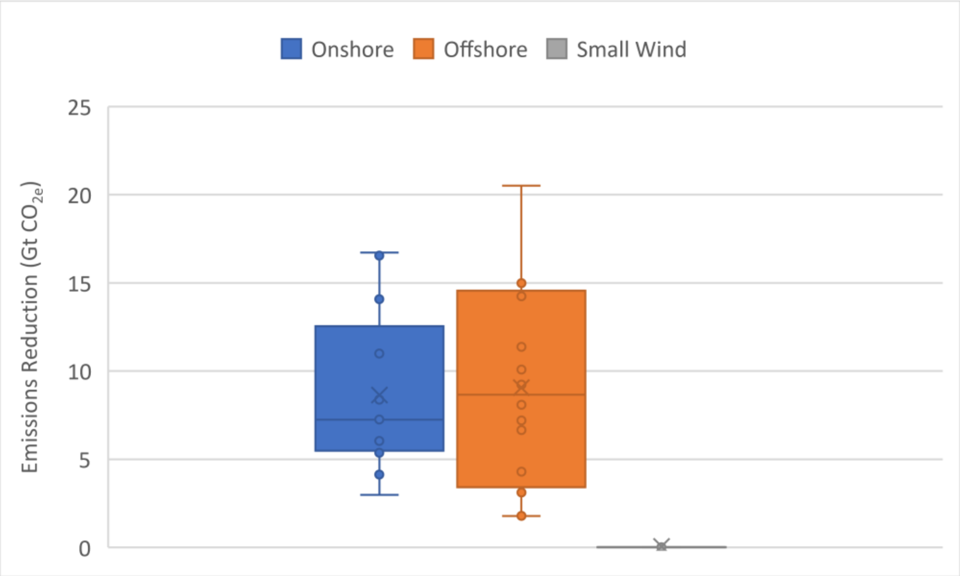
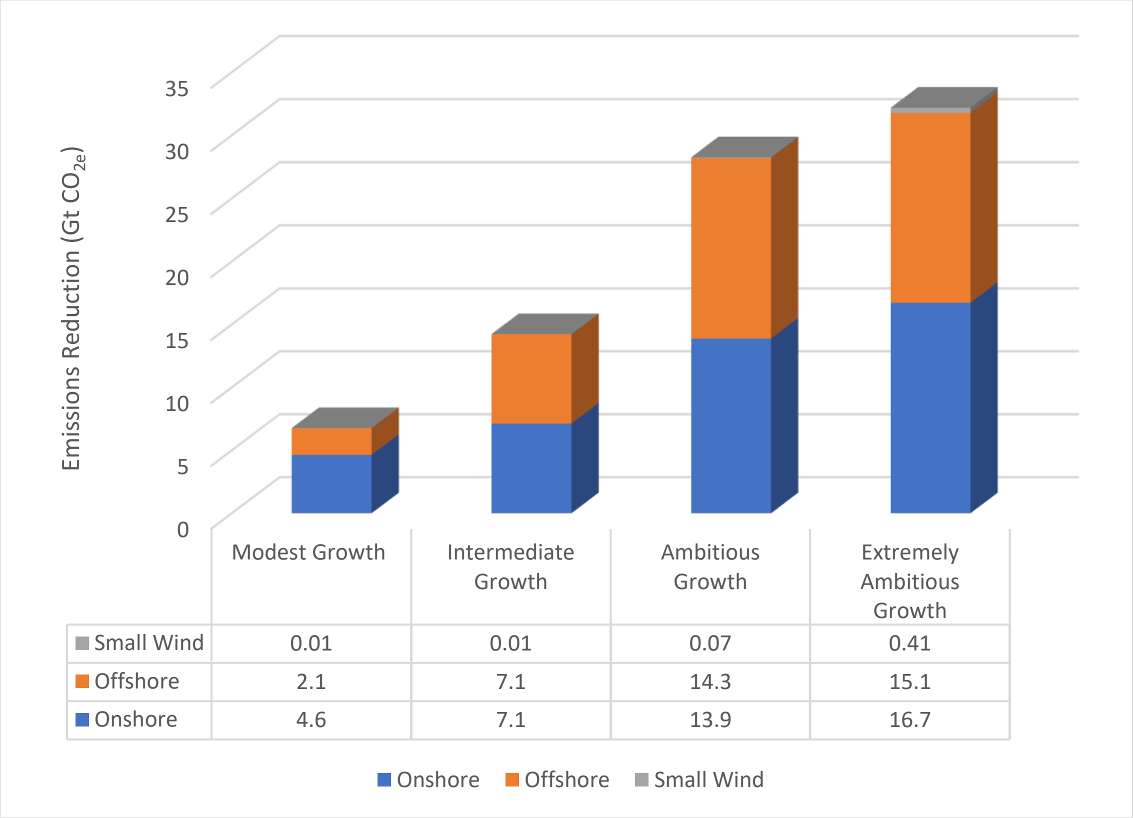


Figure 43. Emissions Reduction comparation between tecnhologies until 2050



| | Modest Growth | Intermediate Growth | Ambitious Growth | Extremely Ambitious Growth |
|---|---|---|---|---|
| ▨ Small Wind | 0.01 | 0.01 | 0.07 | 0.41 |
| 🟧 Offshore | 2.1 | 7.1 | 14.3 | 15.1 |
| 🟦 Onshore | 4.6 | 7.1 | 13.9 | 16.7 |

Figure 44. Combined Wind Technologies Emissions Reduction throughout scenarios

Figure 44 visually shows the difference between the three technologies where Onshore and Offshore wind almost represent 100% of the Emissions Reduced. Regarding total Installation costs, according to IRENA's (2019), the prices for 2050 are expected to be around 600 - 1 000 USD/kW for Onshore and 1 400 – 2 800 USD/kW for Offshore. Compared to 2018, there is a price reduction of about 57% and 56%, respectively. Another key study reviewed, "Cost development of low carbon energy technologies" by JRC (2018), reveals that their scenarios only expect a reduction between 5%-38% for Onshore wind and 16% - 61% for Offshore wind.

## 8.2 Comparison with Project Drawdown 2020 review

Having in mind the latest global study from Project Drawdown (Project Drawdown, 2020), where a deep analysis of the most impactive solutions to climate change was made and discussed, ranging from electricity, buildings, industry, transport, to less industrialized and more natural sectors such as land sinks and coastal and ocean sinks. Together, they make up the Drawdown Review Report published in 2020. Therefore, being the work developed framed within the regionalization of the Project Drawdown solutions approach, for the European Union context, a comparison of results produced by this study with the results obtained for the solutions assessed herein, from the Drawdown Global report is relevant to be made.

One must bear in mind that the benchmark that will be made isn't straightforward since electricity generation projections are very different in terms of values and will change even more as Europe's share of the global power sector changes with time. "IEA's WEO 2019 data suggest that Europe represents 16% of the global power sector in 2018, with a compound average annual growth rate of 0.7%, representing only 12% in 2040 and probably around 10% in 2050" (Silveira, 2020). Furthermore, Project Drawdown analysis comprehensively assesses all solutions of this (and others) sector (i.e., electricity generation), following an integration process and prioritizing solutions adoption to meet the TAM. "Through the process of integrating each individual solution with other solutions, the total addressable markets were adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies as well as increased electrification from other solutions such as electric cars and high-speed rail" (Project Drawdown, 2021). Since only 3 solutions are studied herein, this integration process cannot be made, with no restriction of adoption scenarios to be considered.

The following figures, 45, 46, and 47, present the main results from both Project Drawdown and the current study for the European Union; i.e. "$CO_{2e}$ Emissions Reduction in Gt (2020 – 2050)", "Cumulative First Cost (Billions €)" as well as the "Projected Electricity Generation in 2050 (TWh/y)", general parameters that reveal the European potential compared to a Global one.

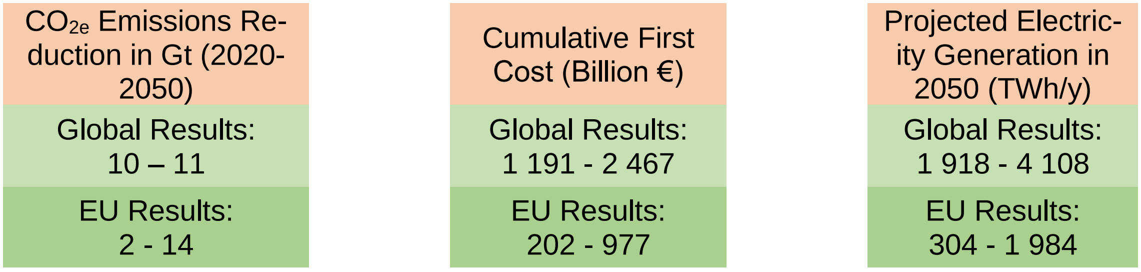
The first green row of values corresponds to the Global value retrieved from Project Drawdown technical summary for each solution. The interval of values corresponds to the PDS 1 and PDS 2, scenarios developed for the technical summary previously presented.. The second one corresponds to the results obtained in this work for both Modest and Ambitious scenarios.

| $CO_{2e}$ Emissions Reduction in Gt (2020-2050) | Cumulative First Cost (Billion €) | Projected Electricity Generation in 2050 (TWh/y) |
|---|---|---|
| Global Results:<br>47 – 148 | Global Results:<br>4 851 - 7 388 | Global Results:<br>9 052 - 19 092 |
| EU Results:<br>5 - 14 | EU Results:<br>473 - 1 086 | EU Results:<br>812 - 1 951 |

Figure 45. Onshore Wind comparison

According to Project Drawdown technical reports, Onshore wind can represent 19.8% to 26.9% of the Global Electricity Generation. Such a high value, roughly ¼ of the Global Electricity Generation, can be explained by the increase of Onshore wind importance. Moreover, for the European Union, for the year 2050, Onshore wind is expected to produce between 19.9% and 22.1%, extremely close to the Global generation.

Nevertheless, although a similar electricity-generation between these two geographical areas, the parameters used for comparison are very different from the previous ones. In this case, Onshore wind is really behind the global value interval. Considering the Ambitious Growth scenario, the upper value for the study conducted, European Union, corresponds to ¼ of all results. The weight for the European Union for each result in the Onshore wind case is more reliable than the other ones. Since there are currently about 195 countries globally, and assuming that 28 of them correspond to 25% of the total Onshore and Offshore wind electricity generation, a lot can be said about the current efforts. There exists a need to further develop such technologies and implement them in other countries as well.

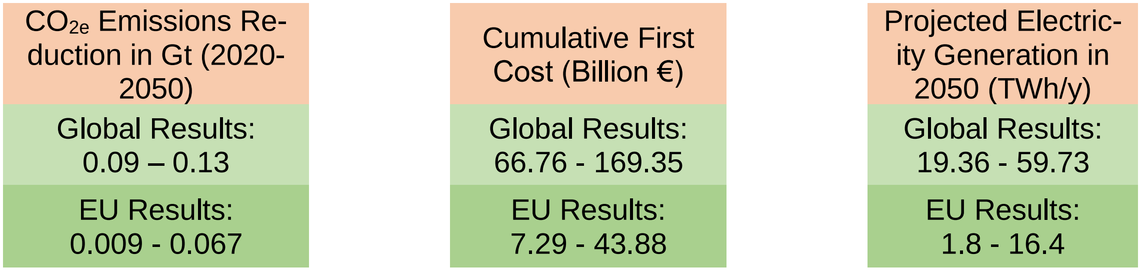


| CO$_{2e}$ Emissions Reduction in Gt (2020-2050) | Cumulative First Cost (Billion €) | Projected Electricity Generation in 2050 (TWh/y) |
|---|---|---|
| Global Results:<br>10 – 11 | Global Results:<br>1 191 - 2 467 | Global Results:<br>1 918 - 4 108 |
| EU Results:<br>2 - 14 | EU Results:<br>202 - 977 | EU Results:<br>304 - 1 984 |

Figure 46. Offshore Wind comparison

For Offshore wind technology, Project Drawdown points out a potential for 2050 of roughly 4.2% to 5.8%. Such low value can be explained with several factors ranging from the ongoing development and improvement of this technology, the years of the data used and collected, older data pointing out more costs as well as less efficiency, and, finally, the implementation and development of floating wind platforms that hugely increase the possible space in which offshore turbines can be deployed. The results obtained on a European Union level are much more optimistic, ranging from 7.5% to 22.4%.

Therefore, according to this data and adoption scenarios assumptions, European Union results surpass the Global expectation in almost all the parameters presented above. Looking at the upper end, the Ambitious Growth Scenario data, the European union overpasses the CO$_{2e}$ emissions reduction expected for the World, can generate enough electricity to meet the lower end of Project Drawdown interval, and can almost reach the lower end of the Cumulative First Cost.



| CO$_{2e}$ Emissions Reduction in Gt (2020-2050) | Cumulative First Cost (Billion €) | Projected Electricity Generation in 2050 (TWh/y) |
|---|---|---|
| Global Results:<br>0.09 – 0.13 | Global Results:<br>66.76 - 169.35 | Global Results:<br>19.36 - 59.73 |
| EU Results:<br>0.009 - 0.067 | EU Results:<br>7.29 - 43.88 | EU Results:<br>1.8 - 16.4 |

Figure 47. Small Wind comparison

Finally, the Drawdown Review emphasizes that, for 2050, Small wind is expected to provide between 0.04% - 0.08% of the global electricity generation mix, nevertheless, according to the produced study, for the European Union region, this value can range from 0.04% to 0.18% until the same deadline. Besides this small change, there is not a significant difference between values, however, the Ambitious case for the European Union is more than two times higher than the upper scenario of the global analysis.

Although the electricity generation with this technology is low, it is important to emphasize that the upper end of the interval almost collides with the lower end of the Project Drawdown study. This means that, in the Ambitious Growth Scenario, Europe could correspond to more than half of the above-outlined results. Relatively to the lower end of results acquired in this study, it is interesting to observe the recurring pattern. For each parameter, the lower end corresponds to roughly 10% of the global value.

Regarding the above comparations, a key note has to be taken into consideration. The previous ranged present in the Drawdown technical summary for each solution only used two scenarios for wind energy technologies. Therefore, Drawdown could have used scenarios that might have higher or even lower impacts. On the other hand, the analysis conducted for this comparation used a lot more scenarios for each technology, presented, therefore, ranged that might not be as accurate comparing to the Global status.

## 8.3 Sensitivity Analysis

In order to better understand the influence of each parameter used for the VMA, for both financial and emissions aspects, one of each parameters were changed at a time. This way, the different values obtained on the Drawdown RRS model according to each change, revealed the impact and where it impacted. To better understand the lower and upper end of the impact of each parameter, the swap occurred in the Drawdown RRS model, varying between the maximum and minimum number. Mean values inputs for each parameter were used for in the base runs resulting in the results presented, whereas minimum and maximum were used for this step. Since almost all data presented and previously discussed is focused in both Modest and Ambitious adoption growth scenarios, the same will occur for this Sensitivity Analysis.

The parameters that are going to be further developed are: First Cost, Lifetime, Annual Capacity, Variable Operation Cost (VOM), Fixed Operation Costs (FOM), Emissions Reduction and, finally, Fuel prices. However, in some rare cases, the methodology used doesn’t provide data that corresponds to reality. Cases that couple minimum installation costs for Wind technologies with Modest Growth Scenario are unreal since lower prices are very related with the degree of technology adoption and, in case of a lower price, an increase in production and use of technologies is expected to occur. The opposite can be said for the run that considers high adoption rate, the Ambitious Growth Scenario, with high prices. This link is very unlikely to happen because, as explained before, the technology used is much linked with the adjacent costs. Therefore, both cases are unlike to happen.

Table 18, 19 and 20, bellow portrayed, follow a very intuitive reading. On the left column it is presented both the scenario addressed as well as the value used, wither high or low value, corresponding to both maximum and minimum respectively. The second column addresses the parameter that is going to be evaluated, according to each scenario and for either high or low value. The following column correspond to the mean value of the criteria analyzed as well as the variation, the sensitivity analyses, for each one. For each technology, the first figure addresses the Modest Growth Scenario whereas the second the Ambitious.

Table 18. Sensitivity Analysis rounds results for Onshore Wind Technology

| | TW | % | Billion € | % | Billion € | % | Gt $CO_{2e}$ 2050 | % |
|---|---|---|---|---|---|---|---|---|
| | **Implementation Unit Adoption Increase in 2050 Variation** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Marginal First Cost 2015-2050 Variation** | **Lifetime Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050 Variation** | **Total Emissions Reduction** | **Total Emissions Reduction Variation** |
| **SolutionFirstCost** | 0.17 | | 240.18 | 62% | -60.79 | | 4.63 | |
| | 0.17 | | 56.99 | -62% | -60.79 | | 4.63 | |
| **SolutionLifetime** | 0.17 | | 131.58 | -11% | -62.91 | -3% | 4.63 | |
| | 0.17 | | 156.97 | 6% | -59.96 | 1% | 4.63 | |
| **SolutionAnnualCapacity** | 0.13 | -26% | 116.62 | -22% | -23.26 | 62% | 4.63 | |
| | 0.23 | 26% | 172.11 | 16% | -126.99 | -109% | 4.63 | |
| **VOM** | 0.17 | | 148.59 | | -202.48 | -233% | 4.63 | |
| | 0.17 | | 148.59 | | 80.89 | 233% | 4.63 | |
| **FOM** | 0.17 | | 148.59 | | -79.91 | -31% | 4.63 | |
| | 0.17 | | 148.59 | | -41.68 | 31% | 4.63 | |
| **EMISSIONS** | 0.17 | | 148.59 | | -60.79 | | 4.46 | -4% |
| | 0.17 | | 148.59 | | -60.79 | | 4.78 | 3% |
| **Fuel Price** | 0.17 | | 148.59 | | 36.62 | 160% | 4.63 | |
| | 0.17 | | 148.59 | | -170.38 | -180% | 4.63 | |
| | | | | | | | | |
| **SolutionFirstCost** | 0.58 | | 646.70 | 73% | -192.29 | | 13.87 | |
| | 0.58 | | 102.71 | -73% | -192.29 | | 13.87 | |
| **SolutionLifetime** | 0.58 | | 332.91 | -11% | -199.69 | -4% | 13.87 | |
| | 0.58 | | 396.86 | 6% | -189.01 | 2% | 13.87 | |
| **SolutionAnnualCapacity** | 0.46 | -26% | 278.68 | -26% | -73.71 | 62% | 13.87 | |
| | 0.78 | 26% | 524.48 | 40% | -434.37 | -126% | 13.87 | |
| **VOM** | 0.58 | | 374.71 | | -640.42 | -233% | 13.87 | |
| | 0.58 | | 374.71 | | 255.85 | 233% | 13.87 | |
| **FOM** | 0.58 | | 374.71 | | -252.74 | -31% | 13.87 | |
| | 0.58 | | 374.71 | | -131.83 | 31% | 13.87 | |
| **EMISSIONS** | 0.58 | | 374.71 | | -192.29 | | 13.36 | -4% |
| | 0.58 | | 374.71 | | -192.29 | | 14.33 | 3% |
| **Fuel Price** | 0.58 | | 374.71 | | 115.81 | 160% | 13.87 | |
| | 0.58 | | 374.71 | | -538.90 | -180% | 13.87 | |

Table 19. Sensitivity Analysis rounds results for Offshore Technology

| | TW | % | Billion € | % | Billion € | % | Gt $CO_{2e}$ 2050 | % |
|---|---|---|---|---|---|---|---|---|
| | **Implementation Unit Adoption Increase in 2050 Variation** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Marginal First Cost 2015-2050 Variation** | **Lifetime Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050 Variation** | **Total Emissions Reduction** | **Total Emissions Reduction Variation** |
| **SolutionFirstCost** | 0.06 | | 103.86 | 59% | -206.30 | | 2.12 | |
| | 0.06 | | 26.68 | -59% | -206.30 | | 2.12 | |
| **SolutionLifetime** | 0.06 | | 57.37 | -12% | -210.12 | -2% | 2.12 | |
| | 0.06 | | 73.56 | 13% | -201.02 | 3% | 2.12 | |
| **SolutionAnnualCapacity** | 0.05 | -16% | 59.92 | -8% | -168.43 | 22% | 2.12 | |
| | 0.07 | 16% | 70.36 | 8% | -250.36 | -18% | 2.12 | |
| **VOM** | 0.06 | | 65.27 | | -338.75 | -39% | 2.12 | |
| | 0.06 | | 65.27 | | -73.86 | 179% | 2.12 | |
| **FOM** | 0.06 | | 65.27 | | -273.84 | -25% | 2.12 | |
| | 0.06 | | 65.27 | | -138.76 | 49% | 2.12 | |
| **EMISSIONS** | 0.06 | | 65.27 | | -206.30 | | 2.09 | -1% |
| | 0.06 | | 65.27 | | -206.30 | | 2.16 | 1% |
| **Fuel Price** | 0.06 | | 65.27 | | -160.30 | 29% | 2.12 | |
| | 0.06 | | 65.27 | | -256.91 | -20% | 2.12 | |
| | | | | | | | | |
| **SolutionFirstCost** | 0.49 | | 515.61 | 92% | -1 608.81 | | 14.31 | |
| | 0.49 | | 22.32 | -92% | -1 608.81 | | 14.31 | |
| **SolutionLifetime** | 0.49 | | 240.46 | -11% | -1 674.27 | -4% | 14.31 | |
| | 0.49 | | 302.01 | 12% | -1 541.34 | 4% | 14.31 | |
| **SolutionAnnualCapacity** | 0.42 | -16% | 202.49 | -25% | -1 282.85 | 25% | 14.31 | |
| | 0.58 | 16% | 370.42 | 38% | -2 078.33 | -23% | 14.31 | |
| **VOM** | 0.49 | | 268.96 | | -2 641.66 | -39% | 14.31 | |
| | 0.49 | | 268.96 | | -575.96 | 179% | 14.31 | |
| **FOM** | 0.49 | | 268.96 | | -2 135.48 | -25% | 14.31 | |
| | 0.49 | | 268.96 | | -1 082.14 | 49% | 14.31 | |
| **EMISSIONS** | 0.49 | | 268.96 | | -1 608.81 | | 14.11 | -1% |
| | 0.49 | | 268.96 | | -1 608.81 | | 14.52 | 1% |
| **Fuel Price** | 0.49 | | 268.96 | | -1 250.09 | 29% | 14.31 | |
| | 0.49 | | 268.96 | | -2 003.47 | -20% | 14.31 | |

Table 20. Sensitivity Analysis rounds results for Small Wind Technology

| | TW | % | Billion € | % | Billion € | % | Gt $CO_{2e}$ 2050 | % |
|---|---|---|---|---|---|---|---|---|
| | **Implementation Unit Adoption Increase in 2050 Variation** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Marginal First Cost 2015-2050 Variation** | **Lifetime Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050 Variation** | **Total Emissions Reduction** | **Total Emissions Reduction Variation** |
| **SolutionFirstCost** | 0.00 | | 5.46 | 46% | -0.79 | | 0.01 | |
| | 0.00 | | 2.02 | -46% | -0.79 | | 0.01 | |
| **SolutionLifetime** | 0.00 | | 3.32 | -11% | -0.86 | -9% | 0.01 | |
| | 0.00 | | 4.08 | 9% | -0.67 | 14% | 0.01 | |
| **SolutionAnnualCapacity** | 0.00 | -37% | 3.13 | -16% | -0.47 | 40% | 0.01 | |
| | 0.00 | 37% | 4.14 | 11% | -1.42 | -81% | 0.01 | |
| **VOM** | 0.00 | | 3.74 | | -1.42 | -80% | 0.01 | |
| | 0.00 | | 3.74 | | -0.16 | 80% | 0.01 | |
| **FOM** | 0.00 | | 3.74 | | -1.28 | -63% | 0.01 | |
| | 0.00 | | 3.74 | | -0.29 | 63% | 0.01 | |
| **EMISSIONS** | 0.00 | | 3.74 | | -0.79 | | 0.01 | -17% |
| | 0.00 | | 3.74 | | -0.79 | | 0.01 | 9% |
| **Fuel Price** | 0.00 | | 3.74 | | -0.61 | 23% | 0.01 | |
| | 0.00 | | 3.74 | | -0.99 | -26% | 0.01 | |
| | | | | | | 1 | | |
| **SolutionFirstCost** | 0.01 | | 52.56 | 49% | -9.72 | | 0.07 | |
| | 0.01 | | 18.20 | -49% | -9.72 | | 0.07 | |
| **SolutionLifetime** | 0.01 | | 34.00 | -4% | -11.25 | -16% | 0.07 | |
| | 0.01 | | 37.21 | 5% | -8.18 | 16% | 0.07 | |
| **SolutionAnnualCapacity** | 0.01 | -37% | 3.03 | -91% | 0.37 | 104% | 0.07 | |
| | 0.02 | 37% | 54.86 | 55% | -23.83 | -145% | 0.07 | |
| **VOM** | 0.01 | | 35.38 | | -17.53 | -80% | 0.07 | |
| | 0.01 | | 35.38 | | -1.92 | 80% | 0.07 | |
| **FOM** | 0.01 | | 35.38 | | -15.84 | -63% | 0.07 | |
| | 0.01 | | 35.38 | | -3.61 | 63% | 0.07 | |
| **EMISSIONS** | 0.01 | | 35.38 | | -9.72 | | 0.06 | -17% |
| | 0.01 | | 35.38 | | -9.72 | | 0.07 | 9% |
| **Fuel Price** | 0.01 | | 35.38 | | -7.51 | 23% | 0.07 | |
| | 0.01 | | 35.38 | | -12.21 | -26% | 0.07 | |

Taking what has been shown into account, starting with table 18, the Sensitivity Analysis for Onshore wind, appear to have 2 parameters with the higher level of impact. Both Variable Operation Cost (VOM) and Fuel prices appear to lead to significative changes in, more specifically, the Lifetime Operating Savings, changes that can range from -233% to 233%, a huge discrepancy in values. Nevertheless, such a change can be easily explained for these 2 parameters. Starting with the VOM, this value appears to be one order of magnitude higher than conventional VOM and, therefore, with a low value of 0.015 €/kWh and a high value of 0.038 €/kWh, the sensitivity analysis would always present this value discrepancy and the respective influence in the various monetary parameters. Having an order of magnitude higher than conventional, since the VMA analysis is all based in the comparation between conventional technologies and wind technologies, this parameter is one with the most influence in the monetary results. Regarding fuel prices, existing only in the conventional technologies, the disclosure range, between 0.007 €/kWh and 0.037 €/kWh, will aggravate or drop the financial discrepancy present. When fuel prices are higher, wind technologies come cheaper, since the initial investment will be amortized throughout the years at a higher rate than if the fuel price was lower, leading to lower costs for conventional technologies and, for comparation, an increase in wind technologies.

As for the increase in wind technologies adoption, there is only one parameter that has influence, Capacity factor. Being the annual capacity the number of hours per year, that the technologies is producing electricity, such an increase will enhance the application of such technology for electricity producing. Without the conversion made to reveal the Annual Capacity values, the data used as based was Capacity Factor that, in a nutshell, is the unitless ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. This way it is easy to understand such change.

Variation in Marginal First Costs only occurs with the increase or decrease of parameters such as First Costs, Lifetime and Annual Capacity since the other only occur after the technology deployment and implementation. Therefore, the parameter that present the highest degree of variation, between 62 and -62% is First Cost. Being, in this case, the parameter with the highest degree of impact, other results would come out as unexpected since, due the relatively low range in Lifetime and Annual Capacity values, similar across different bibliography, the only higher degree of values range only occurs in First Cost parameter.

Finally, working the Emissions Reduction Variation, this one is only influence by the emissions parameter. Nevertheless, having a wide range of values, between 2 000 $GtCO_{2e}$ and 40 026, only a 4% change was reported in the Sensitivity Analysis data collected.

The same analysis can be made for the Ambitious Growth Scenario as well as for the other technologies (table 19 and 20). There exist slight values difference between technologies and scenarios, nevertheless, nothing of extreme importance and degree that hasn’t been previously discussed.

# 9 Conclusion

Starting by reminding the reader of this thesis objective, obtaining, through analysis and interpretation of various studies and articles, the future range of potential of wind energy technologies in a European and European Union context between the years 2020 and 2050, evaluating the decrease of $CO_2$ emissions and financial needs of their increased adoption. Followed by the identification, development and analysis of the future potential electricity generation of each wind technology - Onshore, Offshore and Small according to a different set of energy scenarios with different assumptions, models and timeframes. Finally, identifying and characterize the three different wind technologies with their technical and economic parameters to determine their long-term impact on the Europe and European Union energy systems.

The current work is only possible due to the extensive literature dedicated to energy systems analysis and wind energy technologies, developed over the last years. Due to the rapid change in the electricity generation sector, more specifically in the renewable energy sector it is important to address future expectations of technological adoption and its environmental and financial impact.

Over the last years, due to the need to reduce greenhouse gas emissions and the related climate crisis already in place, wind energy and other renewable energy sources have been increasingly studied, attracting more investments from all around the world and seeing numerous reductions in costs and new developments.

Results from the thesis point out a significant increase in different types of renewable energy with more emphasis on the wind technologies. As it was portrayed before, some studies from various entities expect that wind energy can supply roughly 50% of the European Union electricity generation. There is an expected growth for both Offshore and Onshore wind, both expected to dominate the wind electricity market. Such claims are not based on either predictions or bets but, as previously referred, on projections that account for almost all different variables present in this market. Although several results for the three technologies studied were negative, the reality isn't that dark. The fact that the studies used are prior to 2020, where costs were higher than the ones present nowadays, the conservative perspective where we did not consider technological evolution as well as the fact that the percentage of fossil fuels on the energy mix was considered constant can be the main reasons that explain these unexpected values.

This work integrates the regional efforts of solutions analysis under Project Drawdown framework to the European level. Besides wind technologies, other analysis have been developed for the other solutions (i.e. solar) presented in the Drawdown framework. With the development of such methodology for several solutions and several regions, we will be able to understand the potential of each one in different places around the globe. Therefore, the continuation of such work is of extreme importance for global awareness and regional understanding of the potential and distributions of each solution.

The results chapter highlighted the large degree of investment required when adopting each of these technologies, specifically on Offshore wind. However, with the development of this technology and the respective maturity, the price costs, as expected, will significantly decrease. As portrayed before, savings can occur using the lower end of the financial aspects, compared with conventional technologies, making wind technologies even more attractive.

The various data collected through the extensive research conducted, namely TAM and Adoptions projections, as well as all the VMA parameters previously presented and results obtained, for all the economics and environmental aspects provided by the Drawdown RRS model, can be of real use in future comparations between regions and technologies as well as a testimony and reference for the current European Union Electricity Generation mix.

From this decade forward, wind power technologies are already set to play a crucial role in the European Union electricity generation, while also being one of the technologies with great potential in most regions around Europe and with margin for cost reduction and technological development (e.g. capacity factors).

On the sensitive analysis chapter, it comes clear still the wide range existing between the upper and lower values of each technological and financial variable. This variation can be easily explained and can change the financial aspects of the three technologies discussed. Starting with more conservative studies and dated a few years later, high values for FOM, VOM, and First Costs can present values much higher than in the present day and, as such, can hugely increase costs in the financial sector. Following this thought, by using the lower end of some of the financial parameters, savings come out as positive, contrasting with the analysis conducted with the mean values.

Regarding the total values collected for the European Union, electricity generation for 2050 is expected to range between 1 116 – 5 256 TWh/y, with 812 - 2 591 TWh/y corresponding to Onshore generation, 304 - 2 556 TWh/y to Offshore generation and 0.6 - 109 TWh/y to generation through Small Wind systems. In total, wind power systems make up between 6.7 - 23.3 % of the European Union's energy mix. Over the next 30 years, these technologies are expected to reduce between 6.71 – 32.21 Gt $CO_{2e}$ with increased lifetime operating costs of around 310 – 2 700 billion €.

To have a better perception of the $CO_{2e}$ emissions reduction impact, the following assumption was made. Considering that in 2017, the EU-28 emissions represented 4 483 Mt of $CO_{2e}$, considering the same value for each year between 2020 – 2050, the amount would reach 134 490 Mt. This way, the reductions expected in the same time frame, for the study in question, between 6.71 – 32.21 Gt $CO_{2e}$, will represent roughly 4,98 – 23.95% of the emissions decrease in the European Union.

Moreover, in July 2021, the European Commission released a set of legislative proposals to ensure that the European Union meets the target of reducing net greenhouse gas emissions by 55% until 2030 compared to 1990 levels. Initially, such proposals were set to reduce GHG emissions by 45% until the same year. As such, without the publishment and analysis of documents dated so recently, one could only speculate the increase in renewable energy adoption in order to achieve such target. As such, some of the scenarios used, the more conservative ones, may not be so suitable for this rectified proposal

Nevertheless, there are areas of potential improvement. Starting with the collection of new data, from either TAM, Adoption, and even for the several VMA parameters in order to update both emissions reduction and financial results obtained in this work.

Despite the attempt to develop results and compare the European Union and Europe, the lack of data for Europe for all the wind technologies studied herein became a concern and something that restricted the continuation of such analysis. Therefore, this topic is very interesting and can be further discussed and developed.

Finally, referring to the several problems related to Small wind, due to the same lack of data, data that is certainly going to increase throughout the years, both scenarios and data retrieval was scarce and didn’t allow the same degree of detail intended.

Focusing on the numbers previously presented, and having in mind that Offshore wind can correspond roughly to 12% of the European Union electricity mix and Onshore wind 11% as well, wind technologies are on track to almost supply 23% of electricity, a value way below to the European Commission projection. Considering the research conducted by Silveira (2019), which reached an optimistic value for all Solar technologies of roughly 30%, these two technologies combined can supply around 53% of the European Union electricity generation. If these two technologies (solar and wind) can have such a high place on the electricity market, is it possible that with all the other renewable energy combined, the European Union can produce 100% of its electricity based on renewables by 2050?

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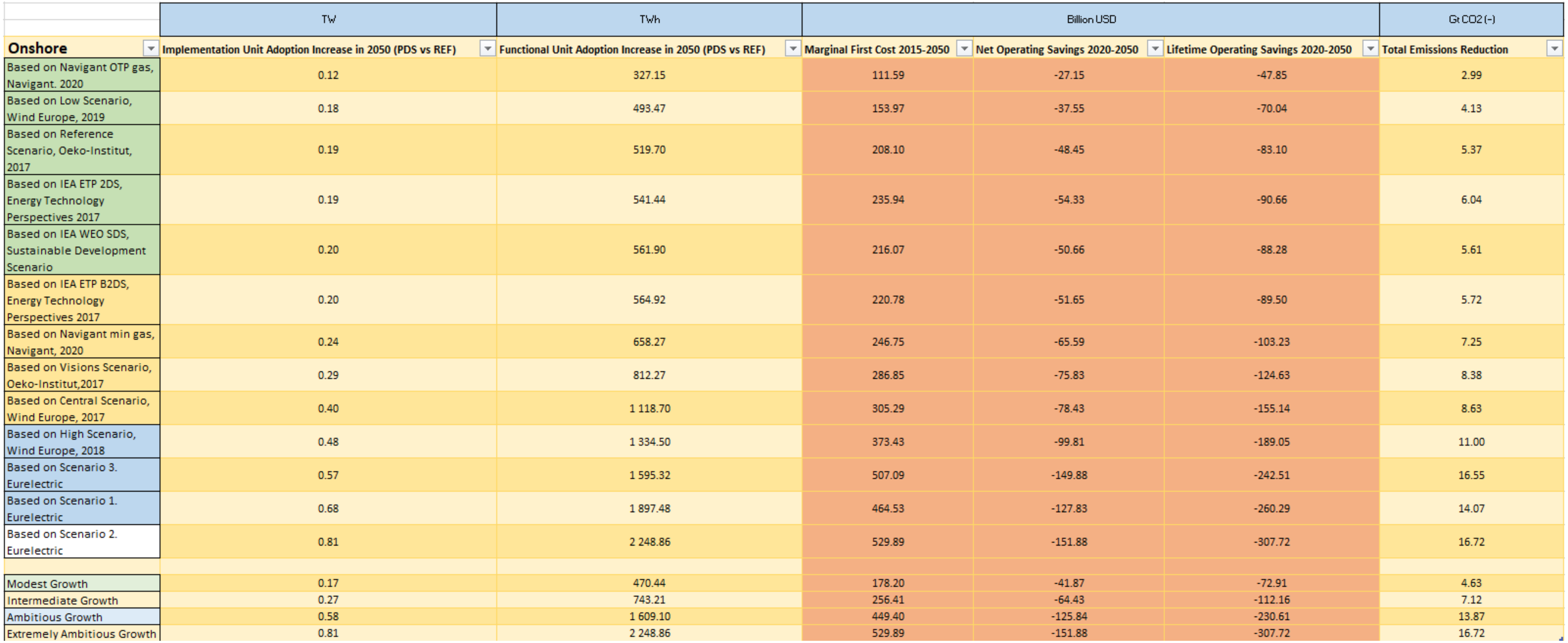
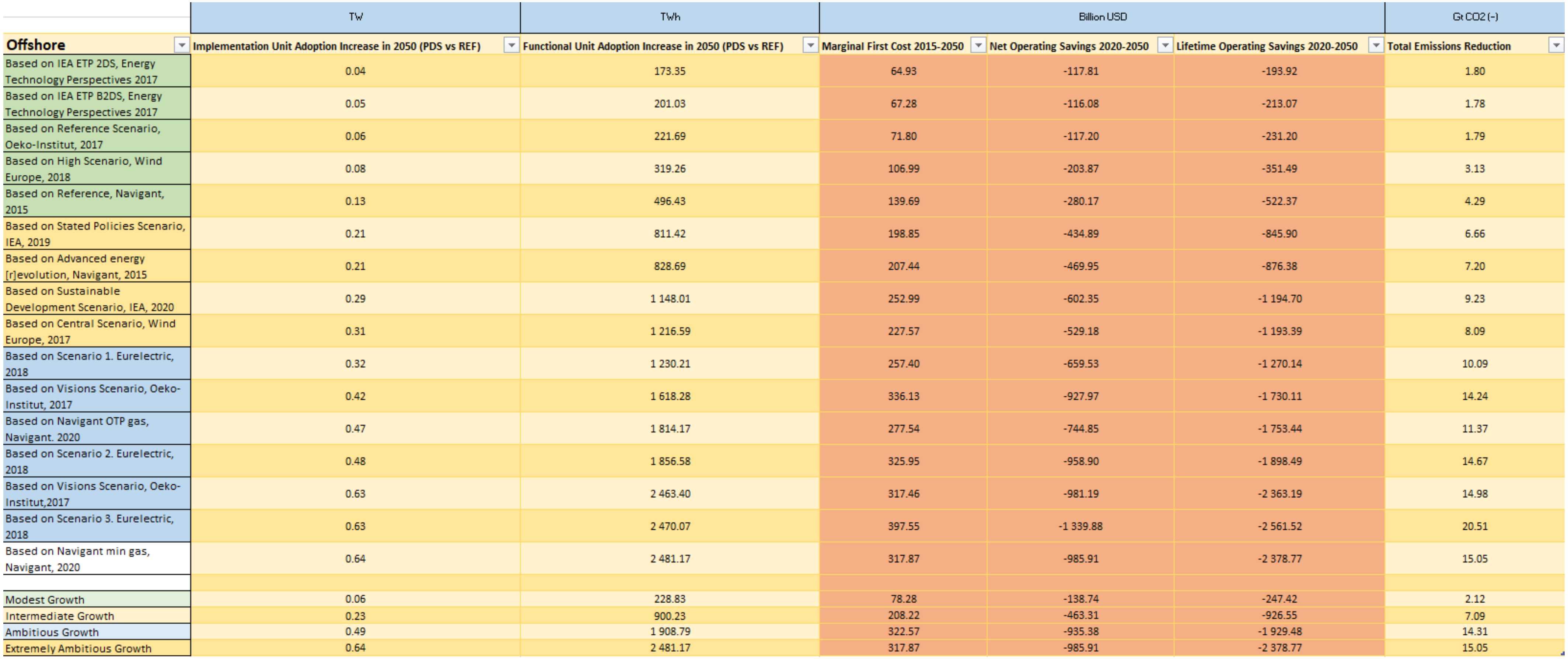
# Annexes A

Table A1: Main results obtained in the Project Drawdown RRS Model for Onshore Wind Technology, European Union



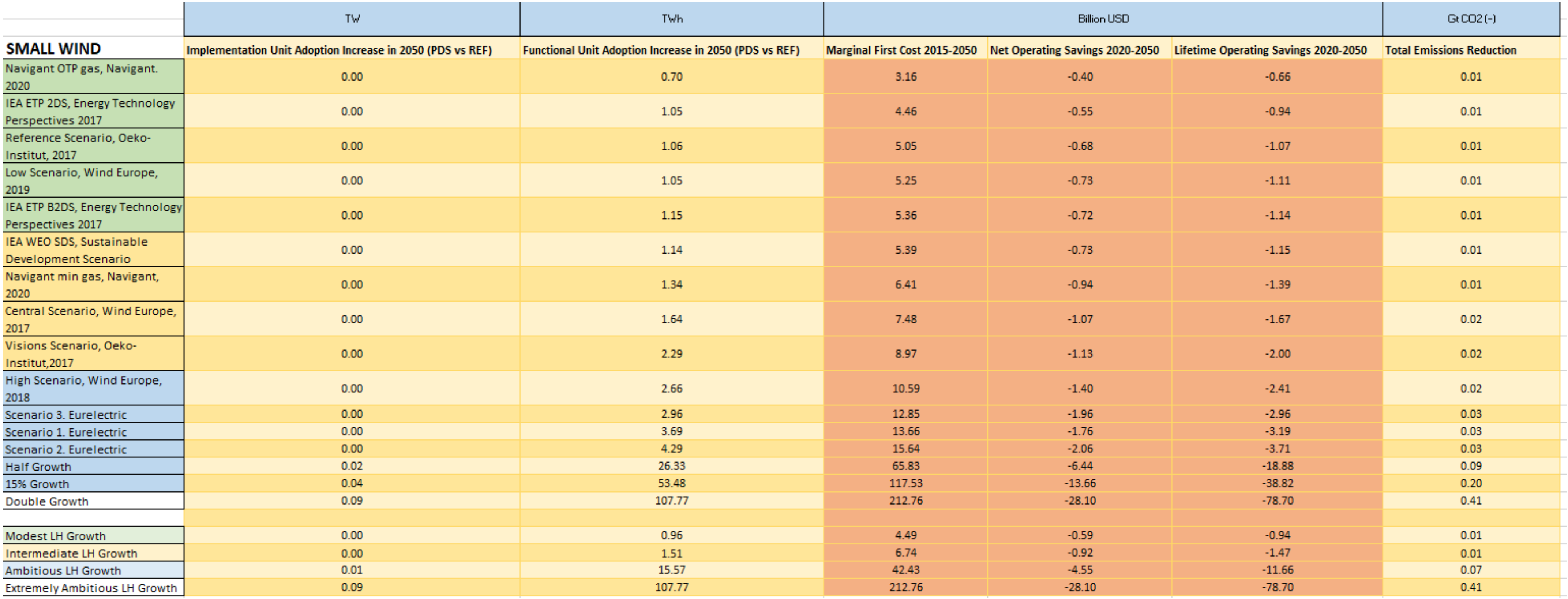
|  | TW | TWh | Billion USD |  |  | Gt CO2 (-) |
|---|---|---|---|---|---|---|
| **Onshore** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Functional Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Net Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050** | **Total Emissions Reduction** |
| Based on Navigant OTP gas, Navigant. 2020 | 0.12 | 327.15 | 111.59 | -27.15 | -47.85 | 2.99 |
| Based on Low Scenario, Wind Europe, 2019 | 0.18 | 493.47 | 153.97 | -37.55 | -70.04 | 4.13 |
| Based on Reference Scenario, Oeko-Institut, 2017 | 0.19 | 519.70 | 208.10 | -48.45 | -83.10 | 5.37 |
| Based on IEA ETP 2DS, Energy Technology Perspectives 2017 | 0.19 | 541.44 | 235.94 | -54.33 | -90.66 | 6.04 |
| Based on IEA WEO SDS, Sustainable Development Scenario | 0.20 | 561.90 | 216.07 | -50.66 | -88.28 | 5.61 |
| Based on IEA ETP B2DS, Energy Technology Perspectives 2017 | 0.20 | 564.92 | 220.78 | -51.65 | -89.50 | 5.72 |
| Based on Navigant min gas, Navigant, 2020 | 0.24 | 658.27 | 246.75 | -65.59 | -103.23 | 7.25 |
| Based on Visions Scenario, Oeko-Institut,2017 | 0.29 | 812.27 | 286.85 | -75.83 | -124.63 | 8.38 |
| Based on Central Scenario, Wind Europe, 2017 | 0.40 | 1 118.70 | 305.29 | -78.43 | -155.14 | 8.63 |
| Based on High Scenario, Wind Europe, 2018 | 0.48 | 1 334.50 | 373.43 | -99.81 | -189.05 | 11.00 |
| Based on Scenario 3. Eurelectric | 0.57 | 1 595.32 | 507.09 | -149.88 | -242.51 | 16.55 |
| Based on Scenario 1. Eurelectric | 0.68 | 1 897.48 | 464.53 | -127.83 | -260.29 | 14.07 |
| Based on Scenario 2. Eurelectric | 0.81 | 2 248.86 | 529.89 | -151.88 | -307.72 | 16.72 |
|  |  |  |  |  |  |  |
| Modest Growth | 0.17 | 470.44 | 178.20 | -41.87 | -72.91 | 4.63 |
| Intermediate Growth | 0.27 | 743.21 | 256.41 | -64.43 | -112.16 | 7.12 |
| Ambitious Growth | 0.58 | 1 609.10 | 449.40 | -125.84 | -230.61 | 13.87 |
| Extremely Ambitious Growth | 0.81 | 2 248.86 | 529.89 | -151.88 | -307.72 | 16.72 |

Table A2: Main results obtained in the Project Drawdown RRS Model for Offshore Wind Technology, European Union



| | TW | TWh | Billion USD | | | Gt CO2 (-) |
|---|---|---|---|---|---|---|
| **Offshore** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Functional Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Net Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050** | **Total Emissions Reduction** |
| Based on IEA ETP 2DS, Energy Technology Perspectives 2017 | 0.04 | 173.35 | 64.93 | -117.81 | -193.92 | 1.80 |
| Based on IEA ETP B2DS, Energy Technology Perspectives 2017 | 0.05 | 201.03 | 67.28 | -116.08 | -213.07 | 1.78 |
| Based on Reference Scenario, Oeko-Institut, 2017 | 0.06 | 221.69 | 71.80 | -117.20 | -231.20 | 1.79 |
| Based on High Scenario, Wind Europe, 2018 | 0.08 | 319.26 | 106.99 | -203.87 | -351.49 | 3.13 |
| Based on Reference, Navigant, 2015 | 0.13 | 496.43 | 139.69 | -280.17 | -522.37 | 4.29 |
| Based on Stated Policies Scenario, IEA, 2019 | 0.21 | 811.42 | 198.85 | -434.89 | -845.90 | 6.66 |
| Based on Advanced energy [r]evolution, Navigant, 2015 | 0.21 | 828.69 | 207.44 | -469.95 | -876.38 | 7.20 |
| Based on Sustainable Development Scenario, IEA, 2020 | 0.29 | 1 148.01 | 252.99 | -602.35 | -1 194.70 | 9.23 |
| Based on Central Scenario, Wind Europe, 2017 | 0.31 | 1 216.59 | 227.57 | -529.18 | -1 193.39 | 8.09 |
| Based on Scenario 1. Eurelectric, 2018 | 0.32 | 1 230.21 | 257.40 | -659.53 | -1 270.14 | 10.09 |
| Based on Visions Scenario, Oeko-Institut, 2017 | 0.42 | 1 618.28 | 336.13 | -927.97 | -1 730.11 | 14.24 |
| Based on Navigant OTP gas, Navigant. 2020 | 0.47 | 1 814.17 | 277.54 | -744.85 | -1 753.44 | 11.37 |
| Based on Scenario 2. Eurelectric, 2018 | 0.48 | 1 856.58 | 325.95 | -958.90 | -1 898.49 | 14.67 |
| Based on Visions Scenario, Oeko-Institut,2017 | 0.63 | 2 463.40 | 317.46 | -981.19 | -2 363.19 | 14.98 |
| Based on Scenario 3. Eurelectric, 2018 | 0.63 | 2 470.07 | 397.55 | -1 339.88 | -2 561.52 | 20.51 |
| Based on Navigant min gas, Navigant, 2020 | 0.64 | 2 481.17 | 317.87 | -985.91 | -2 378.77 | 15.05 |
| | | | | | | |
| Modest Growth | 0.06 | 228.83 | 78.28 | -138.74 | -247.42 | 2.12 |
| Intermediate Growth | 0.23 | 900.23 | 208.22 | -463.31 | -926.55 | 7.09 |
| Ambitious Growth | 0.49 | 1 908.79 | 322.57 | -935.38 | -1 929.48 | 14.31 |
| Extremely Ambitious Growth | 0.64 | 2 481.17 | 317.87 | -985.91 | -2 378.77 | 15.05 |

Table A3: Main results obtained in the Project Drawdown RRS Model for Small Wind Technology, European Union



| | TW | TWh | Billion USD | | | Gt CO2 (-) |
|---|---|---|---|---|---|---|
| **SMALL WIND** | **Implementation Unit Adoption Increase in 2050 (PDS vs REF)** | **Functional Unit Adoption Increase in 2050 (PDS vs REF)** | **Marginal First Cost 2015-2050** | **Net Operating Savings 2020-2050** | **Lifetime Operating Savings 2020-2050** | **Total Emissions Reduction** |
| Navigant OTP gas, Navigant. 2020 | 0.00 | 0.70 | 3.16 | -0.40 | -0.66 | 0.01 |
| IEA ETP 2DS, Energy Technology Perspectives 2017 | 0.00 | 1.05 | 4.46 | -0.55 | -0.94 | 0.01 |
| Reference Scenario, Oeko-Institut, 2017 | 0.00 | 1.06 | 5.05 | -0.68 | -1.07 | 0.01 |
| Low Scenario, Wind Europe, 2019 | 0.00 | 1.05 | 5.25 | -0.73 | -1.11 | 0.01 |
| IEA ETP B2DS, Energy Technology Perspectives 2017 | 0.00 | 1.15 | 5.36 | -0.72 | -1.14 | 0.01 |
| IEA WEO SDS, Sustainable Development Scenario | 0.00 | 1.14 | 5.39 | -0.73 | -1.15 | 0.01 |
| Navigant min gas, Navigant, 2020 | 0.00 | 1.34 | 6.41 | -0.94 | -1.39 | 0.01 |
| Central Scenario, Wind Europe, 2017 | 0.00 | 1.64 | 7.48 | -1.07 | -1.67 | 0.02 |
| Visions Scenario, Oeko-Institut,2017 | 0.00 | 2.29 | 8.97 | -1.13 | -2.00 | 0.02 |
| High Scenario, Wind Europe, 2018 | 0.00 | 2.66 | 10.59 | -1.40 | -2.41 | 0.02 |
| Scenario 3. Eurelectric | 0.00 | 2.96 | 12.85 | -1.96 | -2.96 | 0.03 |
| Scenario 1. Eurelectric | 0.00 | 3.69 | 13.66 | -1.76 | -3.19 | 0.03 |
| Scenario 2. Eurelectric | 0.00 | 4.29 | 15.64 | -2.06 | -3.71 | 0.03 |
| Half Growth | 0.02 | 26.33 | 65.83 | -6.44 | -18.88 | 0.09 |
| 15% Growth | 0.04 | 53.48 | 117.53 | -13.66 | -38.82 | 0.20 |
| Double Growth | 0.09 | 107.77 | 212.76 | -28.10 | -78.70 | 0.41 |
| | | | | | | |
| Modest LH Growth | 0.00 | 0.96 | 4.49 | -0.59 | -0.94 | 0.01 |
| Intermediate LH Growth | 0.00 | 1.51 | 6.74 | -0.92 | -1.47 | 0.01 |
| Ambitious LH Growth | 0.01 | 15.57 | 42.43 | -4.55 | -11.66 | 0.07 |
| Extremely Ambitious LH Growth | 0.09 | 107.77 | 212.76 | -28.10 | -78.70 | 0.41 |