



Vaasan yliopisto  
UNIVERSITY OF VAASA

Eetu Parkkinen

**Development of Forecasting Model for Offshore  
Wind Power Generation and Implications for  
Energy Use Planning**

School of Technology and Innovations  
Energy Technology Master's Thesis  
Master's Programme in Electrical and  
Energy Engineering

Vaasa 2025

## **Preface**

This master's thesis was commissioned by the University of Vaasa. I thank the University of Vaasa for this opportunity and the OptiDCG4H2 EU project for funding this thesis. The work on this thesis went at a brisk pace according to schedule, as I found the topic and subject area of the thesis interesting and useful for the development of offshore wind power in Finland.

I thank my thesis supervisor, Professor Xiaoshu Lu, for the opportunity to do my thesis on this interesting topic and for the good comments and feedback to improve my thesis. I also thank my thesis instructor, University Lecturer Anne Mäkiranta, for organizing the master's thesis, and for the good comments to improve my thesis.

I thank the University of Vaasa staff for their excellent teaching. The diverse courses in energy technology provided up-to-date and valuable information on matters in the energy sector, which will be useful especially in working life. Finally, I thank my fellow students for their memorable study times, my friends for their encouragement and my family for their support throughout my studies.

Vaasa 9th of May 2025

Eetu Parkkinen

---

**VAASAN YLIOPISTO****Tekniikan ja innovaatiojohtamisen yksikkö**

<b>Tekijä:</b>	Eetu Parkkinen		
<b>Tutkielman nimi:</b>	Ennustemallin kehittäminen merituulivoimatuotannolle ja vaikutukset energiakäyttösuunnitteluun		
<b>Tutkinto:</b>	Energiatekniikan diplomi-insinööri		
<b>Oppiaine:</b>	Sähkö- ja energiatekniikan maisteriohjelma		
<b>Työn valvoja:</b>	Xiaoshu Lu		
<b>Työn ohjaaja:</b>	Anne Mäkiranta		
<b>Valmistumisvuosi:</b>	2025	<b>Sivumäärä:</b>	76

---

**TIIVISTELMÄ:**

Tämän diplomityön tavoitteena on tehdä kirjallisuuskatsaus Suomen merituulivoiman potentiaalista, haasteista ja kehitysnäkymistä. Lisäksi ennustemallia tutkimalla arvioidaan merituulivoimalan energiantuotantoa, ja laaditaan energiakäyttösuunnitelma. Ennustemallin ja sen tulosten tarkoitus on esittää merituulivoiman kannattavaa potentiaalia Suomessa. Energiakäyttösuunnitelman tavoitteena on esittää kahta mahdollista sovellusta merituulivoimalan tuottamalle sähkölle: integraatio Suomen kantaverkkoon ja hyödyntäminen vedyn varastoinnissa. Lisäksi tutkielman lisätavoitteena on tehdä kirjallisuuskatsaus Suomen tuulivoiman nykytilasta, erilaisista ennustamismalleista ja erilaisista merituulivoimalan perustamistyypeistä.

Tämän diplomityön kirjallisuuskatsauksen aineisto on kerätty luotettavista, tunnetuista ja ajantasaisista lähteistä. Merituulivoimalan ennustamismallin kehittämisessä on käytetty lähteenä avoimesti saatavilla olevaa meteorologista dataa, ja avointa merituulivoimalan teknistä dataa.

Tulokset osoittavat, että Suomen merialueilla on hyvä potentiaali merituulivoimalle, sillä meren syvyys on riittävä ja merellä on hyvät tuuliolosuhteet. Pohjanlahti todettiin olevan parempi merituulivoimaloiden sijoituspaikka kuin Suomenlahti, koska siellä merituulivoimalat aiheuttavat vähemmän haittaa ihmisten toiminnalle ja luonnolle. Merituulivoimaloiden levinneisyyteen Suomessa liittyy kuitenkin paljon haasteita, joista suurimpina haasteiden aiheuttajina pidetään Itämeren merenpohjan vaihtelevuutta ja Itämeren arktisia olosuhteita. Merituulivoiman kehitysnäkymistä voitiin todeta, että ensimmäisiä suuria merituulipuistoja tulee valmistumaan vuoden 2030 jälkeen. Lisäksi on ennustettu, että merituulipuistoja tulee olemaan enimmäkseen Suomen talusvesialueella vuonna 2050. Ennustemallilla ennustettua merituulivoimalalla tuotettua sähköä tullaan energiakäyttösuunnitelman mukaan käyttämään Suomen kantaverkon sähkökysynnän kattamiseen ja vedyn tuottamiseen. Vetyä tuotettaisiin hyvin tuulisilla ajanjaksoilla, jolloin merituulivoiman sähkön tarjonta ylittää Suomen kantaverkon sähkön kysynnän. Elektrolyysillä valmistetulle vedylle on kaksi käyttövaihtoehtoa. Ensimmäisen vaihtoehdon mukaan vetyä käytettäisiin Suomen sisäisen kysynnän kattamiseen. Toisen vaihtoehdon mukaan vetyä käytettäisiin merituulivoimalan kausittaisen sähköntuotannon vaihtelevuuden tasaamiseen. Merituulivoimalalle tehdyn taloudellisen arviointitulosten mukaan merituulivoimalalla on tällä hetkellä alhaiset tasotetut energiakustannukset verrattuna tavanomaisiin voimalaitoksiin, mutta pitkä taloudellinen takaisinmaksuaika ilman taloudellista tukea.

---

**AVAINSANAT:** uusiutuvat energialähteet; tuulienergia; tuuliturbiinit; sähköverkot; vety; tasoitettu energiakustannus;

---

**UNIVERSITY OF VAASA****School of Technology and Innovations**

<b>Author:</b>	Eetu Parkkinen		
<b>Title of the thesis:</b>	Development of Forecasting Model for Offshore Wind Power Generation and Implications for Energy Use Planning		
<b>Degree:</b>	Master of Science in Energy Technology		
<b>Discipline:</b>	Master's Programme in Electrical and Energy Engineering		
<b>Supervisor:</b>	Xiaoshu Lu		
<b>Instructor:</b>	Anne Mäkiranta		
<b>Year:</b>	2025	<b>Pages:</b>	76

---

**ABSTRACT:**

The aim of this master's thesis is to conduct a literature review on the potential, challenges and development prospects of Finnish offshore wind power. In addition, a forecasting model is explored to estimate the energy production of an offshore wind turbine and to draw up an energy use plan. The purpose of the forecasting model and its results is to present the profitable potential of offshore wind power in Finland. The energy use plan aims to present two possible applications for the electricity generated by offshore wind turbine: integration into Finland's main grid and utilization for hydrogen storage. An additional goal for the thesis is to make a literature review of the current state of wind power in Finland, different forecasting models and different foundation types of offshore wind turbine.

The material for this master's thesis literature review was collected from reliable, well-known and up-to-date sources. Openly available meteorological data and open technical data from the offshore wind turbine have been used as a source in the development of the offshore wind turbine forecasting model.

Results indicate that the Finnish sea areas have good potential for offshore wind power, as the sea depth is sufficient and the wind conditions at sea are good. The Gulf of Bothnia has found to be a better location for offshore wind farms than the Gulf of Finland, because offshore wind farms there cause less harm to human activities and nature. However, the spread of offshore wind farms in Finland is associated with many challenges. The biggest challenges are the variability of the Baltic Sea seabed and the arctic conditions in the Baltic Sea. From the development prospects of offshore wind power, it could be stated that the first large offshore wind farms will be completed after 2030. It has also been predicted that offshore wind farms will mostly be in Finnish exclusive economic zone area in 2050. According to the energy use plan, the predicted electricity generated by the offshore wind turbine predicted by the forecasting model will be used to cover electricity demand of the Finnish main grid and to produce hydrogen. Hydrogen would be produced during very windy periods, when the supply of electricity from offshore wind power exceeds the electricity demand of the Finnish main grid. There are two usage options for hydrogen produced by electrolysis. The first option is to use hydrogen to cover Finland's internal demand. The second option is to use hydrogen to balance the seasonal variability of electricity generation from an offshore wind turbine. According to the results of the financial assessment conducted for the offshore wind turbine, the offshore wind turbine has currently low levelized energy costs compared to conventional power plants, but with a long financial payback period without financial support.

---

**KEYWORDS:** renewable energy sources; wind energy; wind turbines; electrical power networks; hydrogen; levelized cost of energy;

## Contents

<b>1</b>	<b>Introduction</b>	<b>11</b>
1.1	Target and research questions	11
1.2	Progress of the work.	12
<b>2</b>	<b>Wind Power</b>	<b>14</b>
2.1	Onshore Wind Power	16
2.1.1	Advantages of Onshore Wind Power versus Offshore Wind Power	16
2.1.2	Onshore Wind Power in Finland in 2024 and construction forecast in 2025	17
2.2	Offshore Wind Power	24
2.2.1	Advantages of Offshore Wind Power versus Onshore Wind Power	24
2.2.2	Offshore wind turbine support structures and concepts	25
2.2.3	Offshore Wind Power in Finland in 2024	28
<b>3</b>	<b>Finnish Offshore Wind Power Outlook</b>	<b>31</b>
3.1	Offshore Wind Power Potential in Finland	31
3.2	Offshore Wind Power Challenges in Finland	34
3.3	Development prospects	37
3.3.1	Technological development	37
3.3.2	Predicted Wind energy production in Finland	38
3.3.3	Scenarios for Offshore wind power production in Finland in 2050	40
<b>4</b>	<b>Materials and Methods</b>	<b>45</b>
4.1	Wind power forecasting and forecasting approaches	45
4.1.1	LSTM	45
4.1.2	ARIMA	46
4.1.3	WRF	46
4.1.4	AROME	46
4.1.5	Validation methods	47
4.2	Partial feasibility study	47

4.2.1	Offshore wind turbine	47
4.2.2	Location	49
4.2.3	Wind conditions	52
5	Forecasting model for Offshore wind turbine	55
5.1	Offshore wind power forecasting model	55
5.2	Wind energy use plan for Finnish electric grid and energy storage	59
5.3	Offshore wind turbine financial assessment	61
5.3.1	Levelized Cost of Energy	61
5.3.2	Financial payback period	63
5.3.3	Discussion	65
6	Conclusions	66
7	Summary	68
	References	70

## Figures

Figure 1. Flow of the master’s thesis.	13
Figure 2. Wind turbine (Thomson & Harrison, 2015).	15
Figure 3. Share of onshore and offshore cumulative capacity in Finland 2024 (Renewables Finland, 2025).	17
Figure 4. Cumulative number of installed wind turbines in Finland in 2009 – 2024 (Renewables Finland, 2025).	18
Figure 5. Installed cumulative capacity (MW) of wind turbines in Finland in 2009 – 2024 (Renewables Finland, 2025).	18
Figure 6. The average capacity of installed wind turbines (MW) in Finland (Renewables Finland, 2025).	19
Figure 7. Annual production of wind power in Finland between 1997 – 2024 (Suomen uusiutuvat, 2025).	20
Figure 8. Average hub height of installed turbines (m) in Finland between 1993 and 2024 (Renewables Finland, 2025).	20
Figure 9. Average rotor diameter length (m) of installed turbines in Finland between 1993 and 2024 (Renewables Finland, 2025).	21
Figure 10. Onshore wind turbines size comparison with Paris’s Statue of Liberty and Eiffel Tower over time in terms of hub height, rotor diameter and power rating (IEA Wind TCP, 2019).	22
Figure 11. Shares of domestic and foreign owners 2024 - cumulative capacity (Renewables Finland, 2025).	22
Figure 12. Distribution of wind turbines in Finland (Renewables Finland, 2025).	23
Figure 13. Wind power construction forecast from 1998 to 2025 (Renewables Finland, 2025).	24
Figure 14. Offshore wind turbine support structure and its main parts (de Vries et al., 2011).	26
Figure 15. Existing offshore wind turbine foundation types and their installation depth ranges (de Vries et al., 2011).	27

Figure 16. Zones of Finnish sea area (Metsähallitus, n.d).	29
Figure 17. Tahkoluoto offshore wind farm turbines (Suomen Hyötytuuli, n.d).	30
Figure 18. Tahkoluoto offshore wind farm Extension project (Tahkoluoto Offshore Oy, n.d).	30
Figure 19. The best suitable sea areas for offshore wind power in Finland. The darkest green represents the best offshore wind power area and the lightest green represents the worst offshore wind power area (Sitowise Oy, 2024, p. 21).	33
Figure 20. Finnish offshore wind power project areas in 2024 (Sitowise Oy, 2024, p. 22).	35
Figure 21. The distance travelled by ships in ice in February 2024 from Kemi and St. Petersburg to the ice-free sea (Finnish Meteorological Institute, 2024).	36
Figure 22. Forecast of Finnish electricity production and consumption (Fingrid, 2024).	39
Figure 23. Finnish Wind power forecast from 2022 to 2035 (Fingrid, 2024).	40
Figure 24. Finnish offshore wind power production in 2050 according to the first scenario. One white wind turbine 2 GW represents roughly amount of wind power in certain area (Sitowise Oy, 2024, p. 42).	42
Figure 25. Finnish offshore wind power production in 2050 according to the second scenario. One white wind turbine 2 GW represents roughly amount of wind power in certain area (Sitowise Oy, 2024, p. 44).	43
Figure 26. Offshore wind turbine (Offshore Engineer Magazine, 2020).	48
Figure 27. Technical data, project data and power curve of the Vestas V164-9.5 MW offshore wind turbine (Onea et al., 2021).	48
Figure 28. Location of offshore wind turbine in Finland (NLS, n.d).	49
Figure 29. Offshore wind turbine location distance for the land in Töjby, City of Närpiö and nature reserve owned by the Finnish state and Natura 2000 areas (Paikkatietoikkuna, n.d).	50
Figure 30. The total distance of the offshore wind turbine to the 110 kV Finnish electricity grid (Fingrid, n.d).	50

Figure 31. Offshore wind turbine location marine depth area (Paikkatietoikkuna, n.d).	51
Figure 32. Seabed map of Gulf of Bothnia and Gulf of Finland (MarineFinland.fi, n.d).	52
Figure 33. The annual average wind speed of the location of the offshore wind turbine under investigation in the maritime area of the City of Närpiö (The Finnish Wind Atlas, 2009).	53
Figure 34. Wind rose of the location of the offshore wind turbine under investigation in the maritime area of the City of Närpiö (The Finnish Wind Atlas, 2009).	54
Figure 35. Made power curve of Vestas V164-9.5 MW offshore wind turbine based on open online data (The Wind Power, 2024).	56
Figure 36. LCOE cost variations of renewable energy power plants and conventional power plants in Germany in 2024 (Kost et al., 2024).	62

## Tables

Table 1. Wind speed data and monthly hours in 2025 (The Finnish Wind Atlas, 2009).	56
Table 2. Calculated offshore wind turbine output data.	59
Table 3. Calculated offshore wind turbine LCOE.	63
Table 4. Calculated offshore wind turbine financial payback period.	64

## Abbreviations

ARIMA	autoregressive integrated moving average
cm	centimeters
CO <sub>2</sub>	carbon dioxide
€/MWh	euros per megawatt hour
GHG	greenhouse gas
GW	gigawatt
Hz	hertz
km	kilometers
km <sup>2</sup>	square kilometers
kV	kilovolt
LCOE	Levelized Cost of Energy
LSTM	long short-term memory
MW	megawatt

MWh	megawatt hour
m	meters
m/s	meters per second
NCEP	National Centers for Environmental Prediction
NM	nautical miles
Offshore	sea-based
Onshore	land-based
TWh	terawatt hour
WRF	Weather Research and Forecasting

### **Declaration of AI use**

During the preparation of this master's thesis, Eetu Parkkinen, the author of the thesis used artificial intelligence (Google Translate & MOT Translator) tools in order to develop the language of the thesis. After using Google Translate & MOT Translator, the author reviewed and edited the content and takes full responsibility for the content of the master's thesis.

## 1 Introduction

There is a growing global demand for electrical energy in the world. Renewable energy sources are playing an increasingly vital role in meeting this demand. Over the past decade, the world has raised concerns about climate change, the decline of natural resources, and emissions from energy production. It has been well established that in electricity generation, the use of fossil fuels, e.g. use of coal, causes GHG (greenhouse gas) emissions, which is a key cause of climate change (Renewables Finland, n.d).

Among renewable energy sources, wind power presents an important clean alternative. The use of wind power in energy production does not cause emissions to air, land or water. There is growing interest in constructing wind power in Finland, as it reduces Finland's CO<sub>2</sub> (carbon dioxide) emissions, is affordable, increases employment and brings real estate tax revenue to municipalities (Renewables Finland, n.d).

### 1.1 Target and research questions

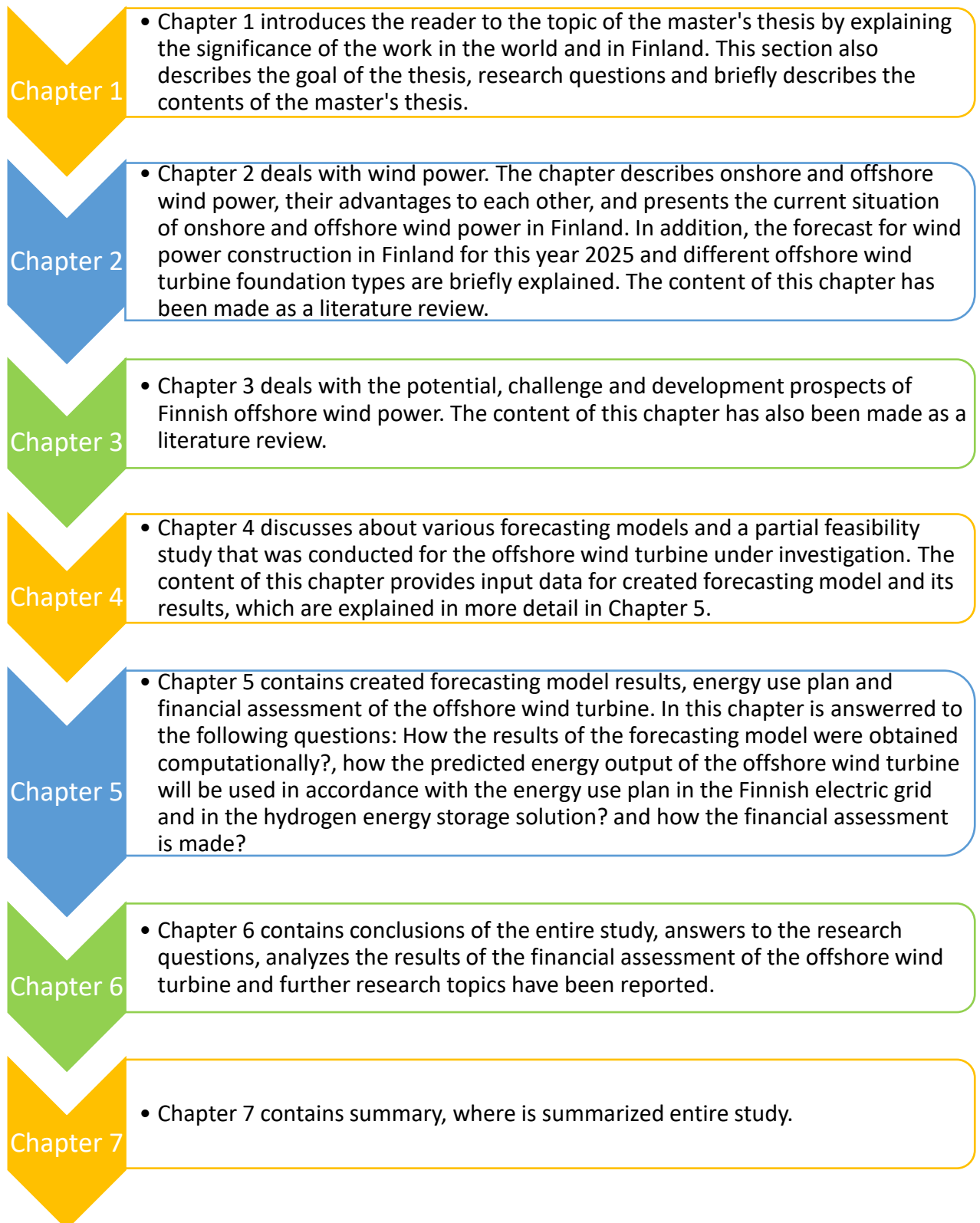
This research main goal was to conduct a literature review on the potential, challenge and development prospects of sea-based (offshore) wind power in Finland and to develop a forecasting model for offshore wind turbine for energy production. Target for forecasting model and its results were to present the profitable potential of offshore wind power in Finland and implement according to forecasting results wind energy use plan for Finnish electrical grid and hydrogen storage. In addition, as an additional objective was to conduct a literature review of the current state of wind power in Finland, various forecasting models and offshore wind turbine foundation types. Based on the above objectives, the research questions for this study were formulated, which are below:

1. What are the current opportunities and development trends for Finnish offshore wind power?

2. What challenges are associated with expanding offshore wind power in Finland?
3. How could the energy production forecast of an offshore wind turbine be utilized in Finnish electrical grid and energy storage?

## **1.2 Progress of the work.**

Figure 1 shows the flow of the master's thesis using a process diagram.



**Figure 1.** Flow of the master's thesis.

## 2 Wind Power

Wind power is generated from the wind's kinetic energy. The kinetic energy of the wind is used to rotate the blades of a wind turbine, converting the wind's kinetic energy into rotational energy. This rotational energy is then used to turn the turbine's shaft, which drives a generator to produce electricity (IRENA, 2011–2022).

Wind power is an emission-free form of energy production. Electricity generation using wind power does not cause greenhouse gas emissions into the air or water. This has a positive impact on healthcare and environmental costs related to air pollution (USDOE, 2015).

Wind energy is abundant and readily available, and it is a free source of energy that does not deplete our natural resources. Modern wind turbines have better technology and are taller than older wind turbines, meaning they can harness wind energy more efficiently in areas where wind speeds are lower. The use of free wind energy also contributes to the low operating costs of a wind power system, as no fuel is needed to produce power (USDOE, 2015).

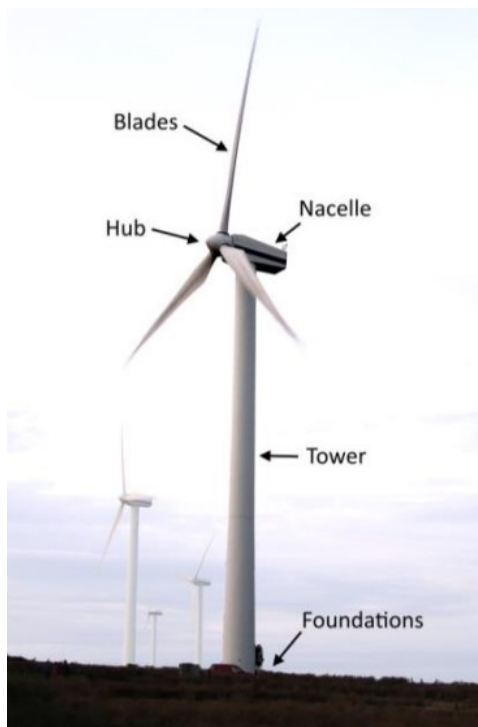
Electricity generated by wind power can be used in a variety of applications. Large-scale wind farms can supply electricity to entire communities, such as municipal facilities, while smaller wind turbines can generate power for individual consumers, such as homes (USDOE, 2015).

Wind power projects generate income for the communities, where they are located. Wind turbines generate rental income for landowners, tax revenue for the state and municipalities, and employment. Wind turbines have a small footprint, which does not greatly affect the livelihood of farmers in growing crops and grazing livestock. In addition, the development of wind energy creates thousands of long-term jobs, including in the manufacture of wind turbine components, construction and installation, maintenance

and operation, legal and marketing services, transportation and logistics services (USDOE, 2015).

Wind farms can be located on land and at sea. Wind farms on land are called onshore wind farms, while those at sea are called offshore wind farms. The technology used for electricity generation in both onshore and offshore wind turbines is essentially the same, but there are also differences between these two types of wind turbines. Specifically, they differ in terms of location, size, scale, and the transmission of the electricity they generate (National Grid, 2024).

Figure 2 shows typical wind turbine and its components, which is used on land and at sea for wind energy production (Thomson & Harrison, 2015).



**Figure 2.** Wind turbine (Thomson & Harrison, 2015).

## **2.1 Onshore Wind Power**

Onshore wind energy is the energy generated by wind turbines located on land, which use natural movement of air in energy generation. Onshore wind farms are often found in less densely populated areas, such as rural regions or fields, where buildings and obstacles do not disturb the airflow to the turbines (National Grid, 2024).

The following subsections of this chapter will discuss the advantages of onshore wind power compared to offshore wind power. In addition, the situation of onshore wind power in Finland last year 2024 and the construction forecast for this year 2025 will be discussed, of which below more widely.

### **2.1.1 Advantages of Onshore Wind Power versus Offshore Wind Power**

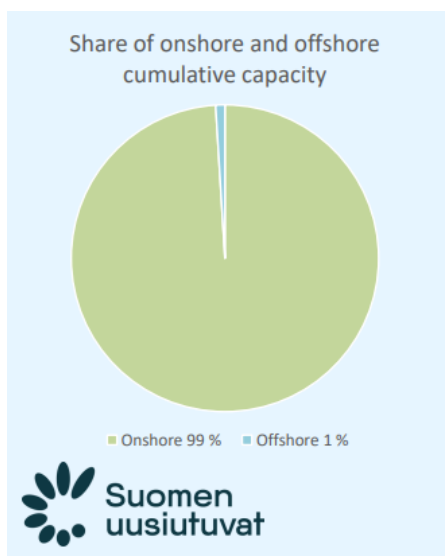
Onshore wind power has some advantages against offshore wind power, which are cost-effectiveness and faster installation and easier maintenance. In addition, onshore wind farms have advantages against other energy sources, which will be told in this section.

Onshore wind power is more cost-effective than offshore wind power, because onshore wind farms have cheaper infrastructure and lower operating costs. In addition, onshore wind farms can be built in months on a large scale and their maintenance costs are relatively cheap and cost-effective compared to offshore wind farms (National Grid, 2024).

Onshore wind farms have also advantages against other energy sources, because construction and operation of onshore wind farms is more climate-friendly than other energy sources. Farming can continue in the areas, where the onshore wind farm is built (National Grid, 2024).

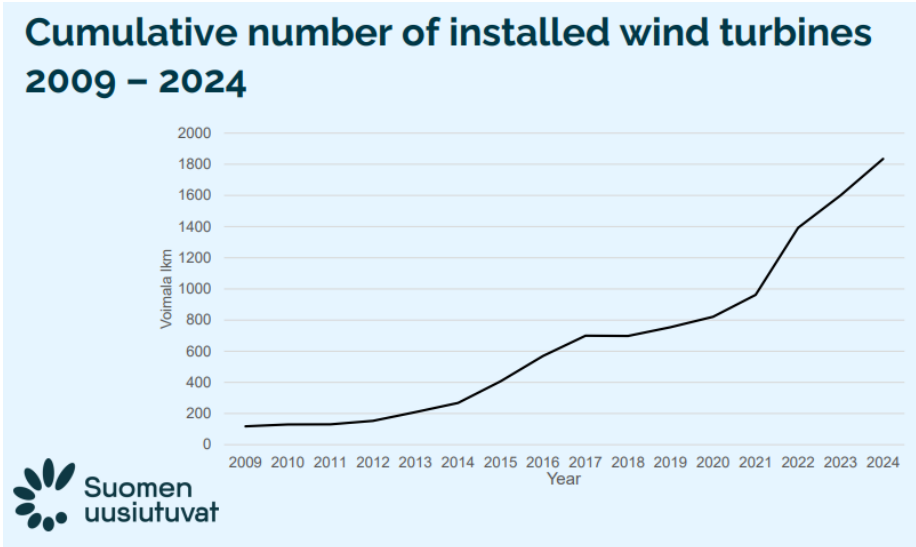
### 2.1.2 Onshore Wind Power in Finland in 2024 and construction forecast in 2025

Figure 3 shows Finland's share of onshore and offshore cumulative capacity in 2024. It can be seen from the figure that most of Finland's wind turbines are onshore wind turbines 99 %.



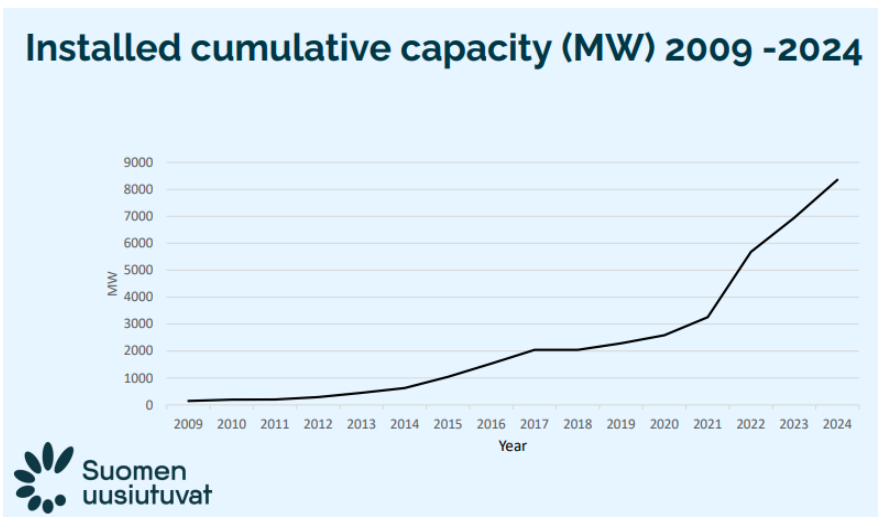
**Figure 3.** Share of onshore and offshore cumulative capacity in Finland 2024 (Renewables Finland, 2025).

Figure 4 shows cumulative number of wind turbines installed in Finland from 2009 until 2024. It can be seen from the figure that in Finland, the construction of wind power has been growing sharply from 2021 until 2024. There were 962 wind turbines installed in Finland in 2021 and 1835 in 2024 (Finnish Wind Power Association, 2022).



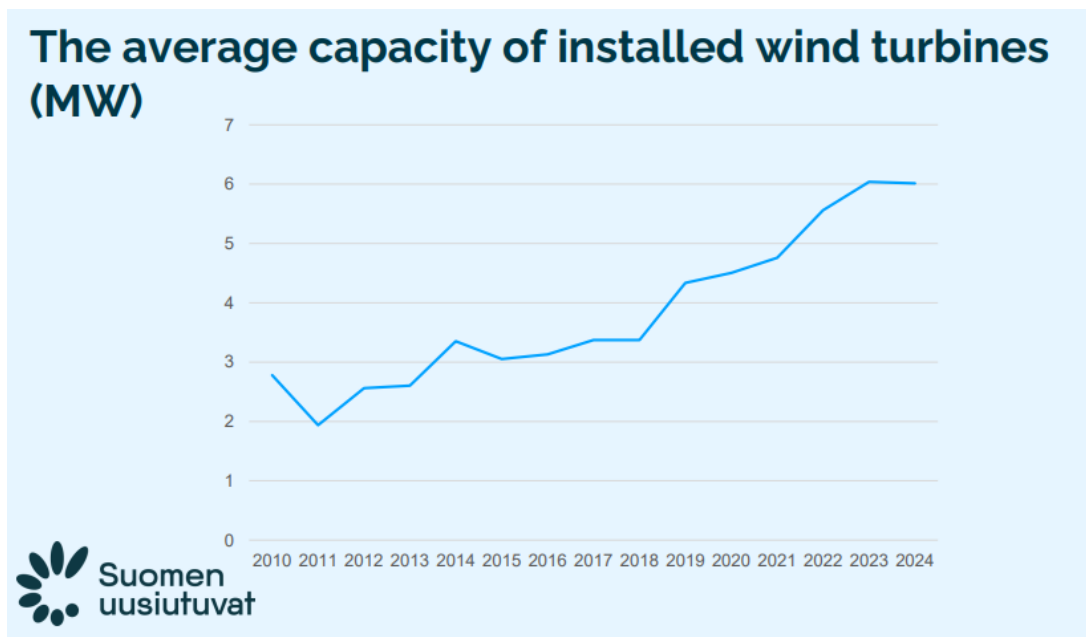
**Figure 4.** Cumulative number of installed wind turbines in Finland in 2009 – 2024 (Renewables Finland, 2025).

Figure 5 shows installed cumulative capacity MW (megawatt) of wind turbines in Finland from 2009 until 2024. It can be seen from the figure that in Finland, installed cumulative capacity has been growing continuously from 2009 to 2024. In fact, installed cumulative capacity was 147 MW in Finland in 2009 and 8358 MW in 2024 (see VTT, 2010; Renewables Finland, 2025).



**Figure 5.** Installed cumulative capacity (MW) of wind turbines in Finland in 2009 – 2024 (Renewables Finland, 2025).

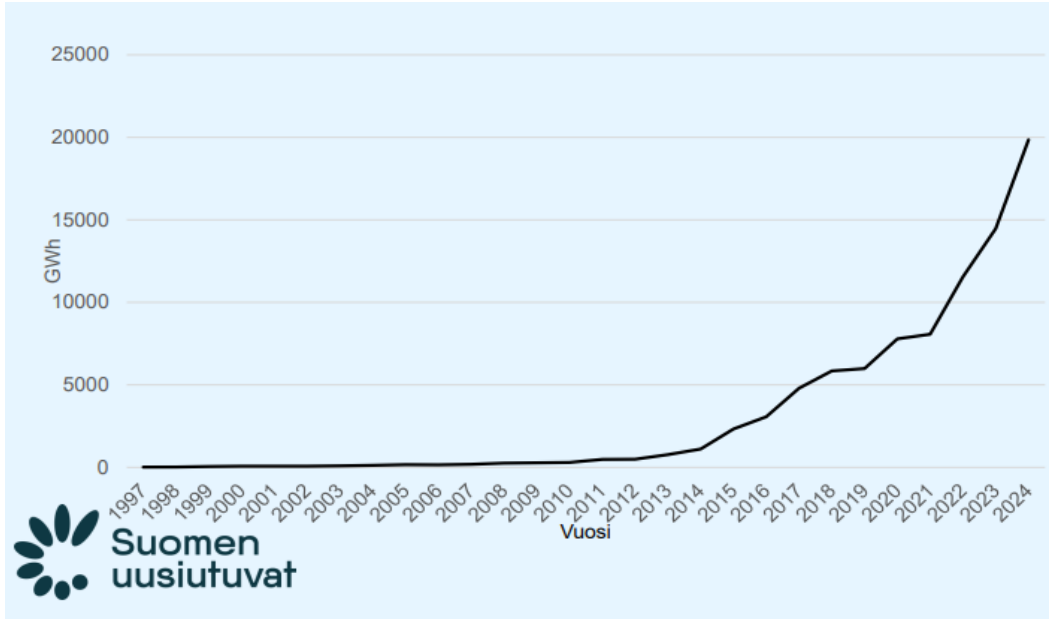
Figure 6 shows the average power development of wind turbines installed in Finland from 2010 to 2024. It can be seen from the figure that the unit power of the onshore wind turbines has increased significantly in recent years, e.g. the average power of the wind turbines installed in 2018 was 3.4 MW, while in 2023 it had increased to 6 MW. The average capacity of new onshore wind turbines installed in Finland was also approximately 6 MW in 2024 (Finnish Wind Power Association, 2019; Renewables Finland, 2025).



**Figure 6.** The average capacity of installed wind turbines (MW) in Finland (Renewables Finland, 2025).

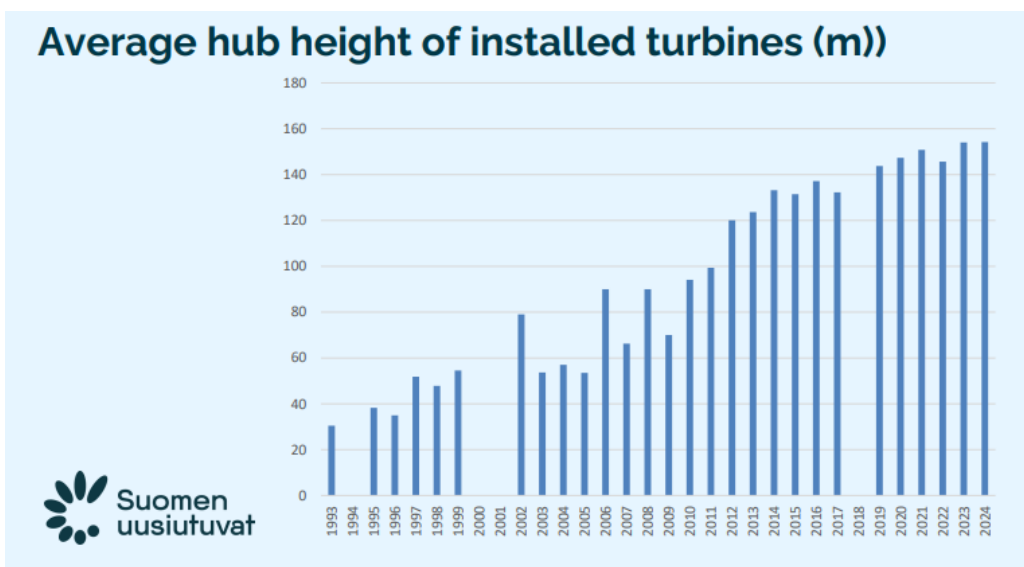
In Finland, wind power overtook hydropower for the first time in 2024 to become the second largest form of energy production. Last year, wind generated 25 % of electricity and hydro 18 % in Finland. However, the largest form of energy production in Finland is nuclear power, which generated 39 % of electricity in 2024 (Finnish Energy, 2025).

Figure 7 shows annual production of wind power in Finland between 1997 – 2024. There is exponential growth from 2014 to 2024.



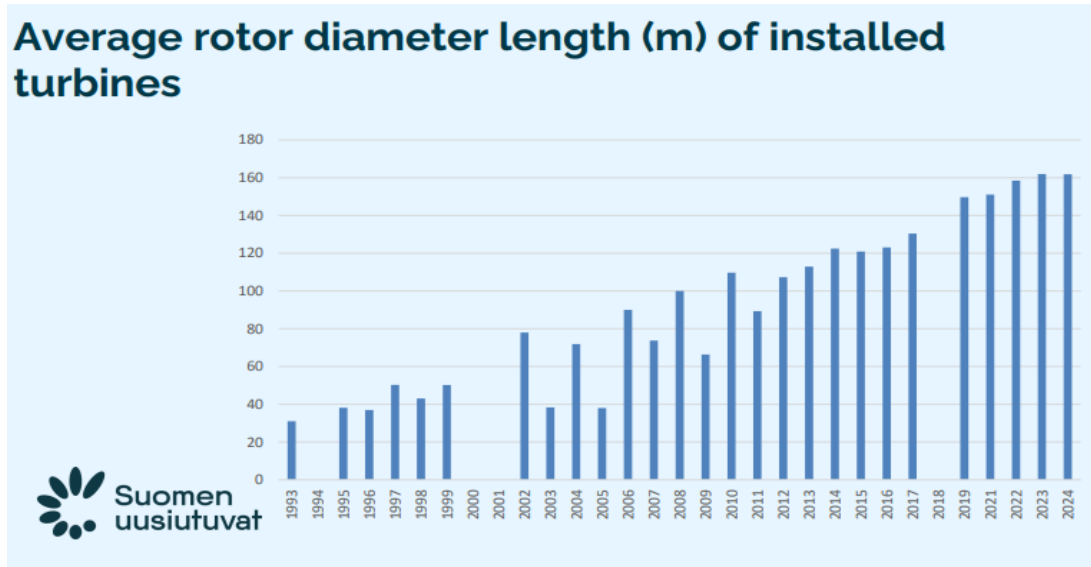
**Figure 7.** Annual production of wind power in Finland between 1997 – 2024 (Suomen uusiutuvat, 2025).

Figure 8 shows the average hub height of wind turbines installed in Finland between 1993 and 2024. It can be seen from the figure that the average hub height of a 6 MW onshore wind turbine was just under 160 m (meters) in 2024.



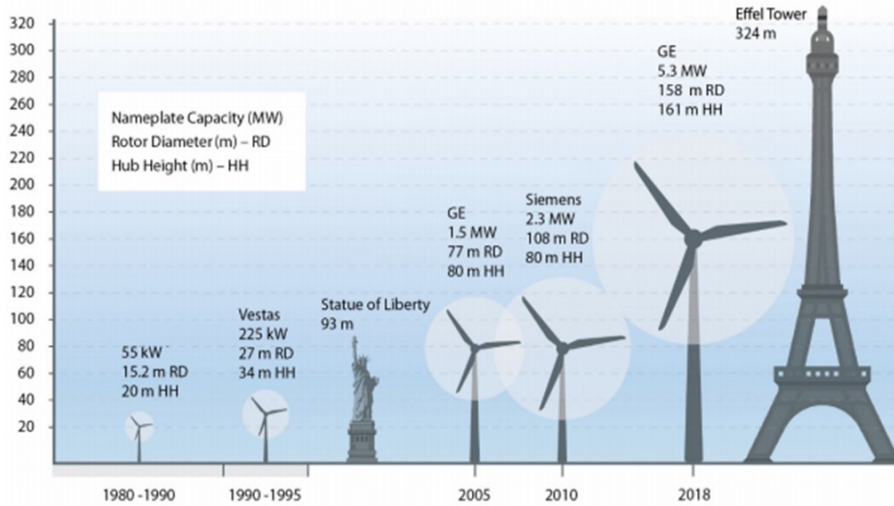
**Figure 8.** Average hub height of installed turbines (m) in Finland between 1993 and 2024 (Renewables Finland, 2025).

Figure 9 shows the average rotor diameter of wind turbines installed in Finland between 1993 and 2024. It can be seen from the figure that the average rotor diameter of a 6 MW onshore wind turbine was just over 160 m in 2024.



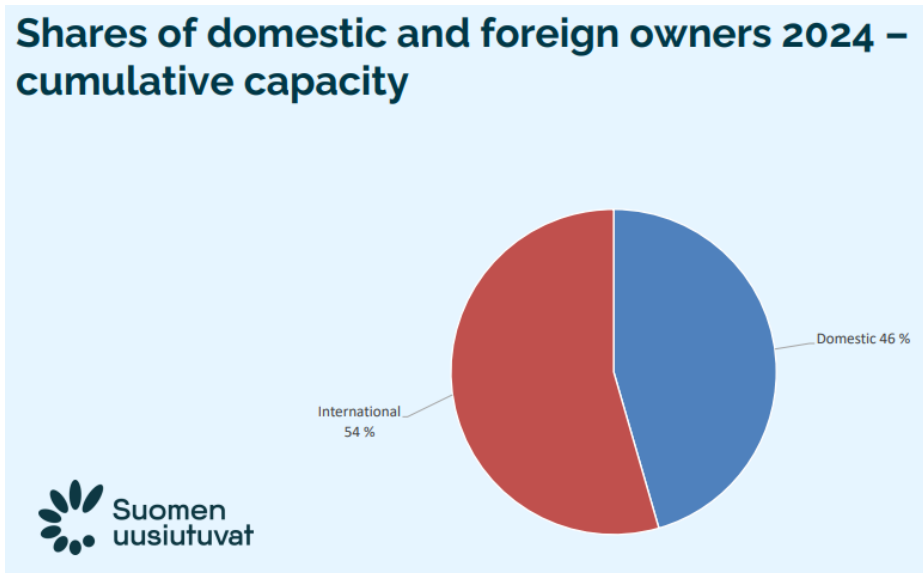
**Figure 9.** Average rotor diameter length (m) of installed turbines in Finland between 1993 and 2024 (Renewables Finland. 2025).

Figure 10 shows wind turbines size comparison to Paris's Statue of Liberty and Eiffel Tower. In Finland, the average size of a 6 MW onshore wind turbine could be compared to the Eiffel Tower in Paris, as the hub height of the average onshore wind turbine in Finland in 2024 is about half the height of the Eiffel Tower, so almost 160 m as figure 8 shows.



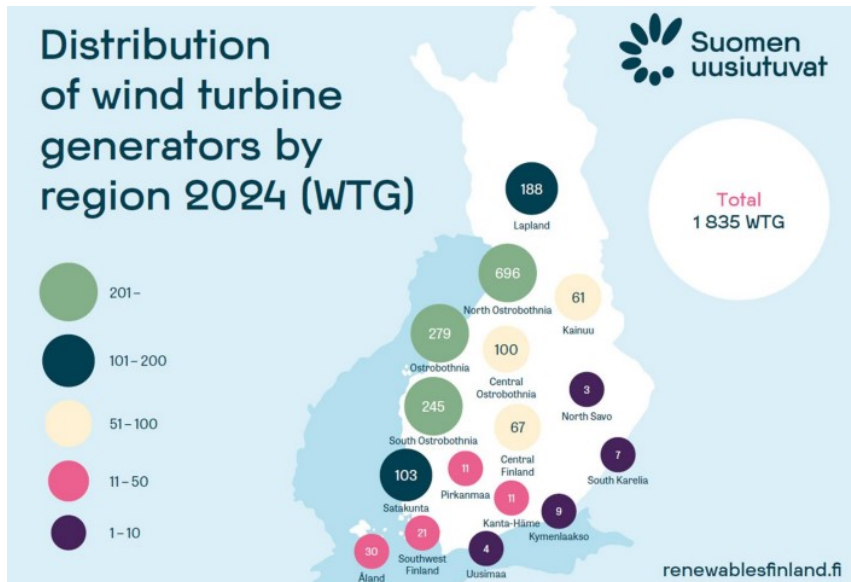
**Figure 10.** Onshore wind turbines size comparison with Paris’s Statue of Liberty and Eiffel Tower over time in terms of hub height, rotor diameter and power rating (IEA Wind TCP, 2019).

Figure 11 shows that the most Finland's wind farms are owned by foreigners 54 % and the rest by domestic owners 46 %. Thus, the construction of wind power to Finland has attracted investment interest in foreign energy investment companies.



**Figure 11.** Shares of domestic and foreign owners 2024 - cumulative capacity (Renewables Finland, 2025).

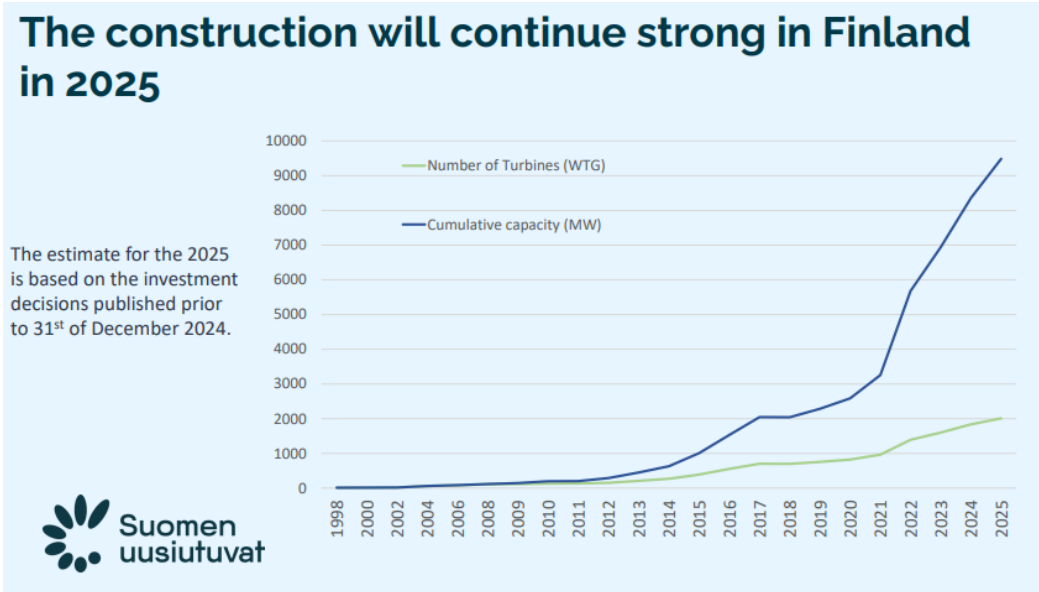
Figure 12 shows how wind turbines are distributed in Finland and shows their number of units by region. Can be seen that there is a concentration of wind power in Western Finland.



**Figure 12.** Distribution of wind turbines in Finland (Renewables Finland, 2025).

Construction of wind power is also growing in Finland this year in 2025. The production capacity of wind power is expected to be even higher this year than last year. However, the construction of wind power is delayed by investment decisions, which are affected by the current high interest rate, construction costs and the delay of new high-energy demand investments. Finland should therefore receive massive investments in new industry, which consumes a lot of electricity. Such new industry projects include, for example, hydrogen production plants and green steel factories. The realization of investments in these projects would speed up investment decisions in new wind power projects (Renewables Finland, 2024).

Figure 13 shows how wind power construction is growing in Finland from 1998 to 2025. The 2025 wind power construction estimate is based on investment decisions, which were announced in late December 2024.



**Figure 13.** Wind power construction forecast from 1998 to 2025 (Renewables Finland, 2025).

## 2.2 Offshore Wind Power

Offshore wind energy is produced from wind turbines located at sea, which use the wind blowing over the sea for energy production. Offshore wind farms are more efficient than onshore wind farms, because the wind at sea is faster, more consistent, and the air flow is not disturbed by land or man-made obstacles (National Grid, 2024).

The following subsections of this chapter discuss the advantages of offshore wind power compared to onshore wind power. They also discuss different foundation types of offshore wind turbine and the situation of offshore wind power in Finland last year 2024, of which more widely below.

### 2.2.1 Advantages of Offshore Wind Power versus Onshore Wind Power

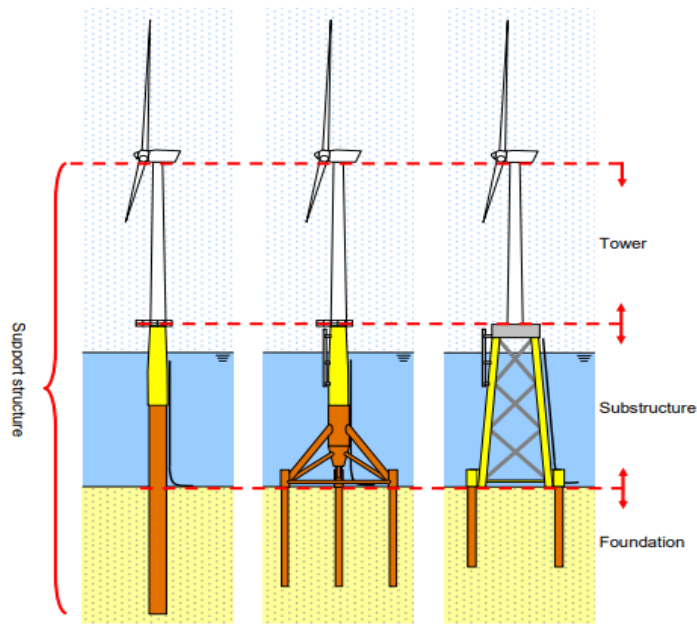
Offshore wind power has some advantages against onshore wind power, which are energy efficiency, reduced environmental impact and open space.

Offshore wind turbines energy efficiency is better at sea than on land, because wind speeds are higher, and the wind flow is more consistent than on land. This allows a smaller number of wind turbines at sea to produce the same amount of energy as would be produced by onshore wind turbines (National Grid, 2024).

Offshore wind turbines are located miles away from the coast and local populations. Restricting access to the offshore wind turbine area can even help protect the surrounding marine ecosystems. In addition, ocean regions offer the perfect location for building offshore wind farms, as there is a lot of open space. The increasing construction of offshore wind farms enables the production of cleaner and more sustainable energy (National Grid, 2024).

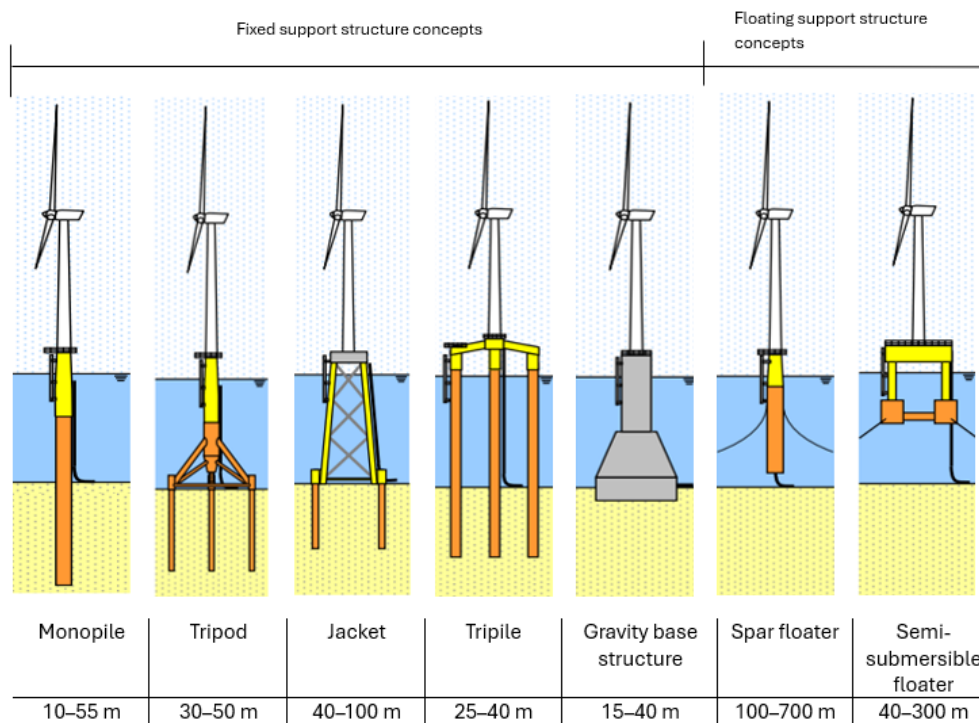
### **2.2.2 Offshore wind turbine support structures and concepts**

The purpose of the support structure of an offshore wind turbine is to keep the offshore wind turbine in place and transfer the loads applied to it to the ground. The main parts of the structure are used to carry out this important task. The main parts of the support structure are tower, substructure and foundation (de Vries et al., 2011). Figure 14 shows the support structure of the offshore wind turbine and its main parts.



**Figure 14.** Offshore wind turbine support structure and its main parts (de Vries et al., 2011).

Offshore wind turbine support structure concepts can be classified into fixed support structures and floating support structures (de Vries et al., 2011). Figure 15 shows these different offshore wind turbine support structure concepts or also so-called foundation types, and their installation depth ranges (see The Empire Engineering, 2021; Wpd, 2021; de Vries et al., 2011; Yichao et al., 2016).



**Figure 15.** Existing offshore wind turbine foundation types and their installation depth ranges (de Vries et al., 2011).

Among the fixed support structure concepts, the most commonly used in the world is the monopile foundation type. Other commonly used fixed foundation types are jacket & gravity base foundation type, of which the gravity base foundation type is the oldest of all offshore wind turbine foundation types. The use of tripods and tripiles foundation types is rare due to their lack of cost efficiency for offshore wind (The Empire Engineering, 2021).

The advantages of the spar floater support structure are the stability it creates, and the ease of design compared to the semi-submersible floater foundation type (The Empire Engineering, 2021). The downside of the spar floater support structure is its high underwater volume requirement and problems with the power export cable, which is sensitive to vibration. The spar floater floating support structure has been used by an offshore wind turbine in the Hywind project in Norwegian waters (de Vries et al., 2011).

The semi-submersible floater foundation type utilizes multiple columns and pontoons to achieve stability and buoyancy. The semi-submersible floater foundation type can be held in place, e.g. with a catenary and drag anchors. The challenges to the generalization of this foundation type are design challenges (The Empire Engineering, 2021).

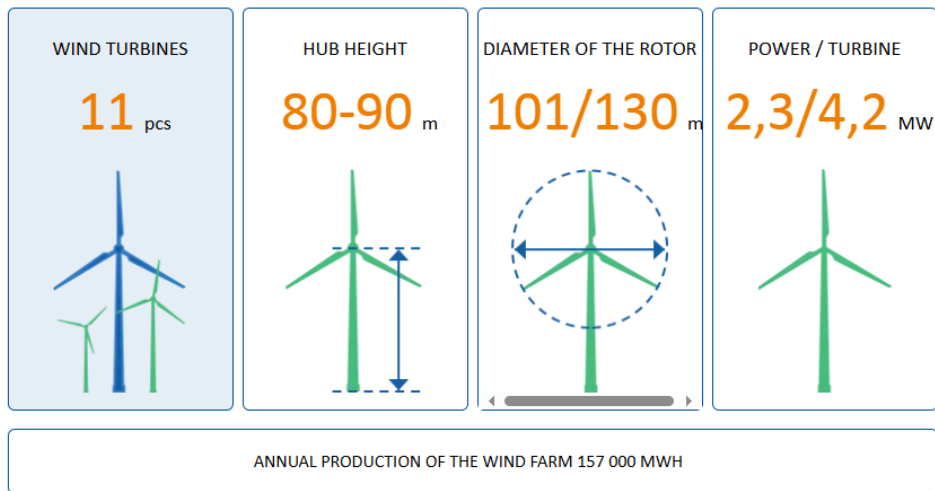
### **2.2.3 Offshore Wind Power in Finland in 2024**

Currently, only one offshore wind farm Pori Tahkoluoto is in production in Finland, located in Pori, Western Finland. In addition, there are dozens of offshore wind power projects in various stages of development in Finnish marine areas. Metsähallitus Property Development coordinates project development in the Finnish Public water areas and acts as a project developer for the preliminary study phase. There are also a few projects owned by private operators in the Finnish Public water areas. There are also projects in the Finnish exclusive economic zone, which are at different stages of the investigation (Sitowise Oy, 2024, p. 19). Figure 16 shows zones of Finnish sea area more specifically.



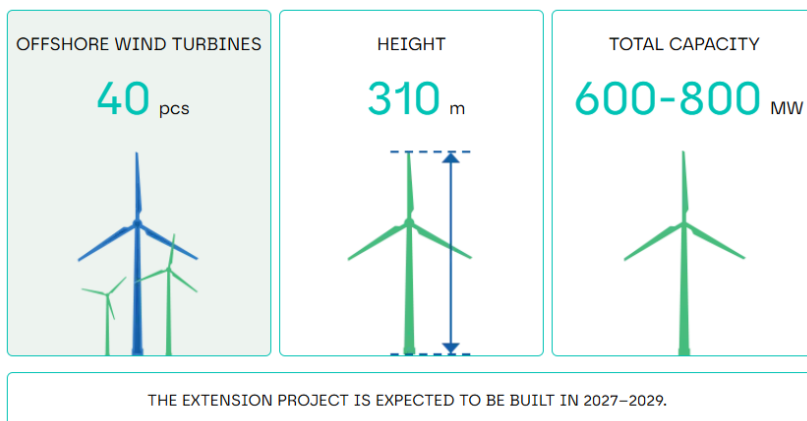
**Figure 16.** Zones of Finnish sea area (Metsähallitus, n.d).

Tahkoluoto was introduced in 2017. Tahkoluoto offshore wind farm has 11 offshore wind turbines, of which 1 has a rated power of 2.3 MW and the remaining 10 have a rated power of 4.2 MW. The total power capacity is thus 44.3 MW. Tahkoluoto offshore wind farm produces approximately 157,000 MWh (megawatt hour) of electric energy per year, which corresponds to the annual electricity needs of approximately 8,600 electrically heated detached houses. Tahkoluoto offshore wind farm is Finland's first offshore wind farm and the world's first offshore wind farm in frozen sea conditions. Tahkoluoto offshore wind farm is owned by Suomen Hyötytuuli Oy (Suomen Hyötytuuli Oy, n.d). The foundation type of the offshore wind turbines in the Tahkoluoto offshore wind farm is gravity base foundation type, as the bedrock is close to the seabed (Suomen Hyötytuuli Oy, n.d). Figure 17 shows the wind turbines of the Tahkoluoto offshore wind farm and their total annual production.



**Figure 17.** Tahkoluoto offshore wind farm turbines (Suomen Hyötytuuli, n.d).

An expansion of the Tahkoluoto offshore wind farm is also being planned. The planned expansion project will comprise a total of 40 offshore wind turbines of more than 15 MW. According to the plan, the total power output of the new offshore wind turbines will be between 600 and 800 MW. The estimated construction date is between 2027 and 2029 (Tahkoluoto Offshore Oy, n.d.). Figure 18 shows Tahkoluoto offshore wind farm Extension project. Tip-height of offshore wind turbines can be up to 310 m, which is close to Eiffel tower height, which is 324 m, as shown in figure 10.



**Figure 18.** Tahkoluoto offshore wind farm Extension project (Tahkoluoto Offshore Oy, n.d.).

### **3 Finnish Offshore Wind Power Outlook**

The sub-chapters of this chapter will discuss the potential, challenges and development prospects of Finnish offshore wind power at present and in the future, of which more widely below.

#### **3.1 Offshore Wind Power Potential in Finland**

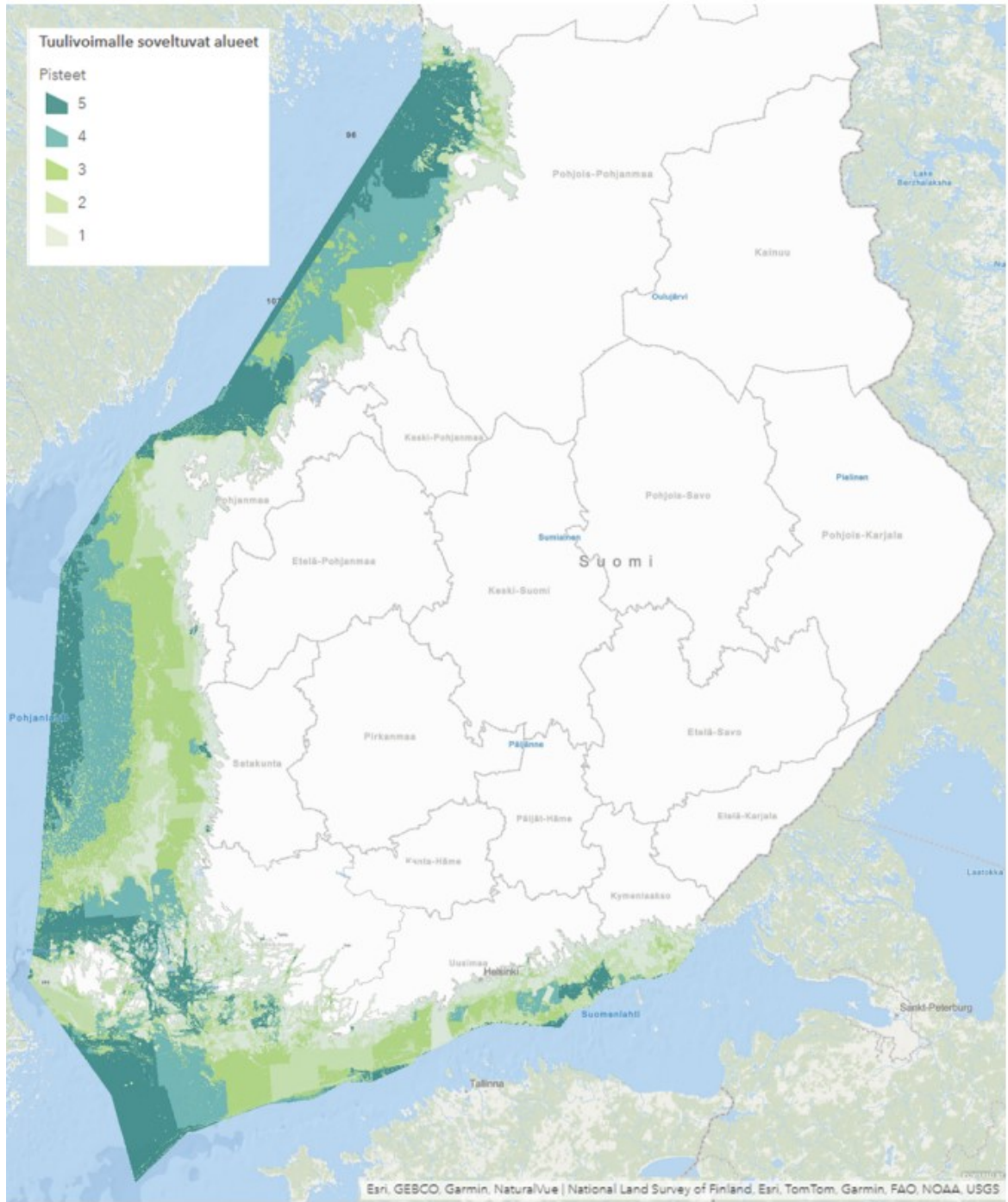
Finnish sea areas have been studied for the location of offshore wind farms. It has been found that Finnish sea areas have good potential for offshore wind power, as Finnish sea areas have good wind conditions and sufficient sea depth. However, the spread of offshore wind power projects in Finnish sea areas is influenced by investment decisions that have certain prerequisites, e.g. sufficient demand for electricity, technological development, the profitability of offshore wind power projects and changes in cost levels (Sitowise Oy, 2024, p. 10).

Sea areas suitable for Finnish offshore wind power production, namely the Gulf of Finland and the Gulf of Bothnia, have been examined. The result of the review has been that the Gulf of Bothnia is a better area for offshore wind power production, as the sea area of the Gulf of Finland has its own obstacles to exploit the offshore wind power potential. The obstacles are the needs of regional surveillance and other challenges of coordinating maritime activities (Sitowise Oy, 2024, p. 19).

The SmartSea research project was organized to find the most suitable areas for offshore wind power, and it was published in 2022. The purpose of the study was to find sea areas, where offshore wind power could be built profitably without causing major harm to people or marine nature. The study also defined areas using the Zonation approach for regional prioritization, to know where offshore wind power should not be built due to potential conflicts arising from construction. According to the study, the most suitable and extensive areas for offshore wind power are located in the Bay of Bothnia, south of the

Kvarken and in the central and southern parts of the Bothnian Sea (Sitowise Oy, 2024, p. 20).

In 2023, the Finnish Environment Institute updated the Zonation analysis data and added more data to the analysis. The new data updated nature value data, socio-cultural data and restricted areas data. The results of the new Zonation analysis resulted in a map showing the best locations for offshore wind power and cabling, so that they would cause as little harm as possible to nature and human activities (Sitowise Oy, 2024, p. 20). Figure 19 shows this map, which shows the most suitable areas for offshore wind power by changing the shade of green from darkest to lightest. The darkest shades of green indicate the best area for offshore wind power and the lightest shades of green indicate the worst.



**Figure 19.** The best suitable sea areas for offshore wind power in Finland. The darkest green represents the best offshore wind power area and the lightest green represents the worst offshore wind power area (Sitowise Oy, 2024, p. 21).

### 3.2 Offshore Wind Power Challenges in Finland

Offshore wind power has attracted interest due to tightening climate targets and growing electricity demand. However, increasing offshore wind power in Finland has its own challenges. The challenges to the use of offshore wind power in Finland can be considered the development of offshore wind power, the construction of offshore wind power and Finland's annual sea ice cover. The development of offshore wind power is more challenging, as different technology, electrical infrastructure and logistics are used in offshore wind power installation and maintenance tasks. Finland's annual sea ice cover creates its own challenges for the construction of offshore wind power, as it increases the construction and maintenance costs of offshore wind power. Therefore, the construction of offshore wind power can be considered more expensive than onshore wind power (Sitowise Oy, 2024 p. 22-24).

When planning offshore wind power to Finland, the characteristics of the Baltic Sea must be considered. The seabed of the Baltic Sea is varied and there are arctic conditions in the Baltic Sea, which is why the Baltic Sea freezes. The location of offshore wind turbines in a potential area in the Gulf of Bothnia is challenging, as the seabed in the Gulf of Bothnia is widely varied and the soil varies from soft sediments to hard rock. This creates a challenge for the layout design of the offshore wind farm and the choice of foundation solutions. Consequently, the planning of offshore wind power in the Gulf of Bothnia is very much driven by the structuralist of the base and the cost of the foundations (Sitowise Oy, 2024, p. 22-24). Figure 20 shows planned offshore wind power project areas in Finland in 2024.



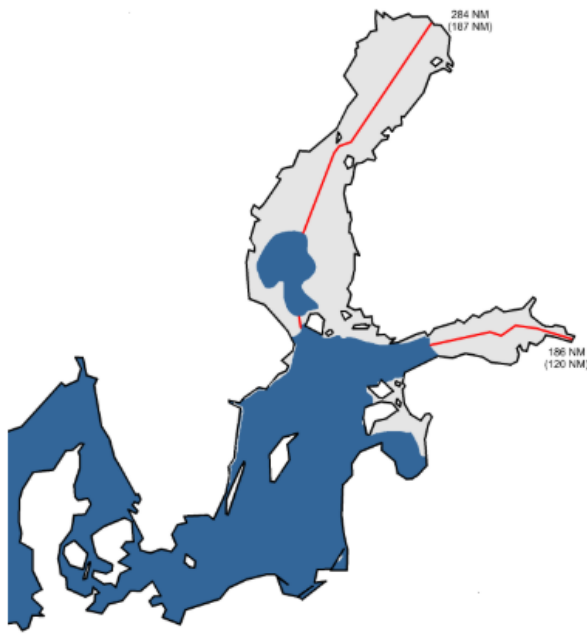
**Figure 20.** Finnish offshore wind power project areas in 2024 (Sitowise Oy, 2024, p. 22).

Arctic conditions in the Baltic Sea create challenges for offshore wind turbines. The arctic climate increases the ice mass that accumulates in the blades of the offshore wind turbine, which has an impact on the decline in the power of the offshore wind turbine and the decrease in the lifespan, if the ice mass is not removed. The ice cover of the Baltic Sea also has an impact on offshore wind turbines. When moving, ice masses in the Baltic Sea can cause damage to the towers of offshore wind turbines and accelerate the corrosion process of carbon-fibre-towered offshore wind turbines (Sitowise Oy, 2024, p. 23).

The freezing of the Baltic Sea and the arctic conditions also have a complicating effect on the maintenance of offshore wind turbines, measuring equipments and construction timing. It has been established that freezing has a detrimental effect on the operation and accuracy of measuring equipment, e.g. anemometer, wind vane, temperature sensor and ice detector operation (Sitowise Oy, 2024, p. 24). The effect of freezing on wind

speed meter performance was studied in a study commissioned by IEA Wind and found that even a small amount of ice on the wind meter's cups leads to a 30 % measurement error, when the wind speed is 10 m/s (meters per second) (Ronsten et al., 2012). When constructing an offshore wind farm, electrical cables must be placed deep enough to prevent sea ice from damaging them. Construction must also take place at a time, when the sea is not covered by ice (Sitowise Oy, 2024, p. 24).

Figure 21 shows ice situation in the Baltic Sea in February 2024. The ice was covered in 135,000 km<sup>2</sup> (square kilometers). The distance travelled by ships through ice in February 2024 from Kemi to ice-free sea was 284 NM (nautical miles), of which 187 NM was the distance travelled through over 15 cm (centimeters) thick ice. Distance travelled by ships through ice was 186 NM from St. Petersburg to ice-free sea, of which 120 NM was the distance travelled through over 15 cm thick ice (Finnish Meteorological Institute, 2024).



**Figure 21.** The distance travelled by ships in ice in February 2024 from Kemi and St. Petersburg to the ice-free sea (Finnish Meteorological Institute, 2024).

Although sea ice conditions and the impact of freezing on wind turbines have been studied, more research data and modelling are still needed, which would support offshore wind project-operators in their project development work (Sitowise Oy, 2024, p. 24).

### **3.3 Development prospects**

The sub-chapters of this development prospects chapter discuss the development prospects of offshore wind power in terms of technological development, the production forecast for Finnish offshore wind power and present two scenarios for Finnish offshore wind power energy production in 2050, of which more widely below.

#### **3.3.1 Technological development**

Technological development in offshore wind power technology has been rapid in recent years and is expected to continue in the future. Technological development in offshore wind power technology can be seen in the growth of offshore wind turbines, the development of foundation solutions, intelligent systems, ship technology and repowering (Sitowise Oy, 2024, p. 36).

The size of offshore wind turbines have been growing rapidly in recent years, from 2.9 MW in 2010 to 8.5 MW in 2021. The size of offshore wind turbines in Europe has therefore more than doubled between 2010 and 2021. Currently, 14-15 MW of offshore wind turbines are being installed in Europe, and soon 17-18 MW of offshore wind turbines are expected to be installed in 2027-2028. After 2030, it is predicted that there will be 20 MW of offshore wind turbines in Europe (PWEA, 2022). Increasing the size of an offshore wind turbines allows more energy to be produced from offshore wind power, and therefore fewer larger offshore wind turbines are needed to produce the same amount of energy as was previously produced by smaller offshore wind turbines (Sitowise Oy, 2024, p. 36).

In the future, offshore wind turbines will be set up deeper into the sea, as floating foundation solutions are predicted to become more common as a result of development and reduced cost of technology. The development of fixed ways of setting up in the deeper sea is also being developed in the future. The foundations of offshore wind turbines will be larger in the future and environmentally friendly development work will be carried out on the foundations, so that they do not cause major harm to the marine ecosystem (Sitowise Oy, 2024, p. 36).

New types of intelligent systems can be used to improve productivity and reduce costs of offshore wind turbines. Smart grid management systems can be used, e.g. to optimize the operation of offshore wind turbines to improve predictability. Intelligent systems can also, e.g. perform remote monitoring and organize predictive maintenance, extending the life of an offshore wind turbines and saving on higher maintenance costs (Sitowise Oy, 2024, p. 36).

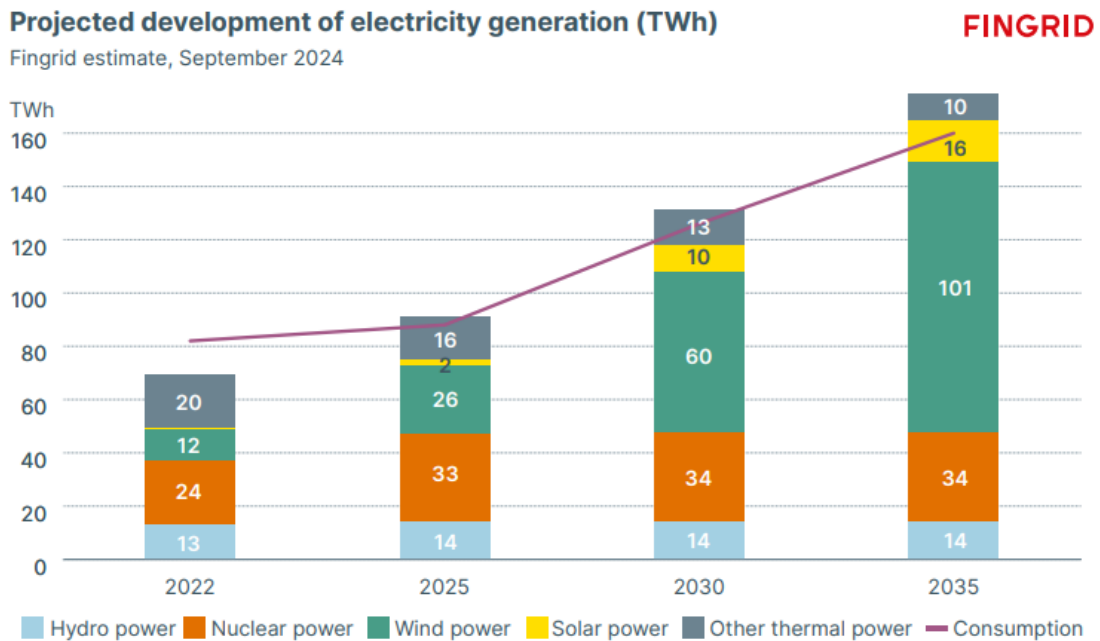
With the development of vessel technology, logistics will become better than at present. Floating installation vessels can be used to carry out installation work deeper in the sea and the carbon footprint of crew transport and service vessels can be reduced by using hybrid and electric vessels (Sitowise Oy, 2024, p. 36).

Repowering means the partial renewal of an offshore wind turbine, i.e. the renewal of blades and nacelle as they reach the end of their service life. The partial renewal will extend the entire life cycle of the offshore wind farm instead of dismantling the offshore wind turbines (Sitowise Oy, 2024, p. 36).

### **3.3.2 Predicted Wind energy production in Finland**

Currently, Fingrid's latest forecast for electricity production and consumption is Fingrid's Q3/2024 forecast report. According to the forecast, electricity production is continuously

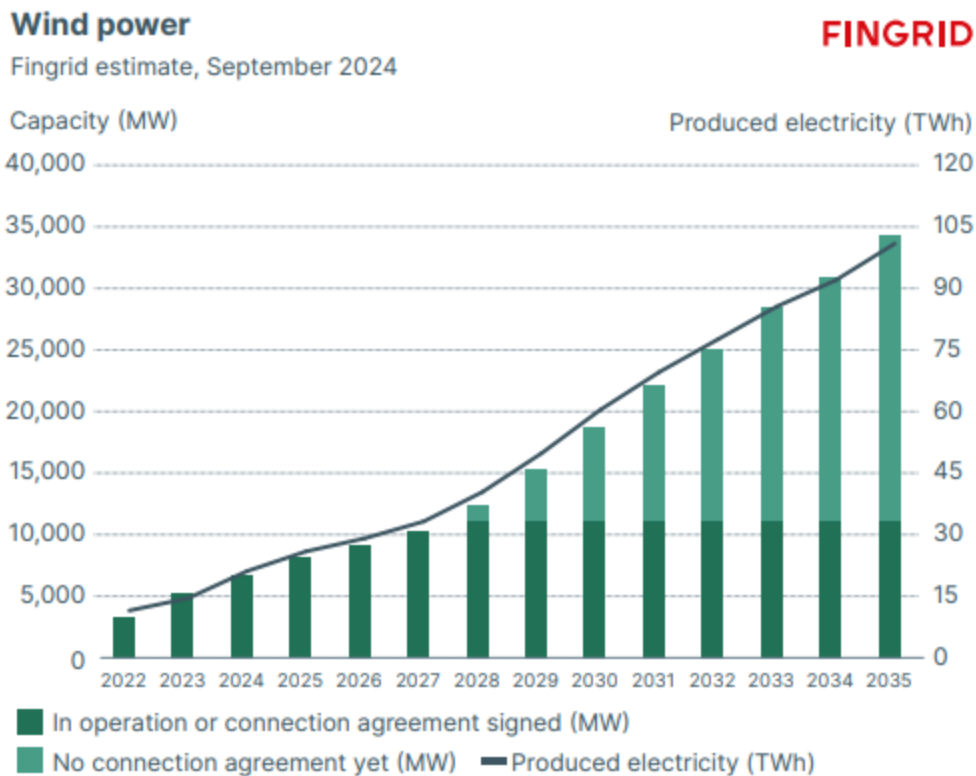
growing, as electricity production in 2025 would be approximately 90 TWh (terawatt hour), in 2030 approximately 130 TWh and in 2035 175 TWh. According to the forecast, the largest electricity production growth from 2022 to 2035 will occur in wind power. However, the condition for the realization of the wind power growth forecast is that domestic consumption would grow strongly (Fingrid, 2024). Figure 22 shows the forecast for Finnish electricity production and consumption from 2022 to 2035.



**Figure 22.** Forecast of Finnish electricity production and consumption (Fingrid, 2024).

Fingrid has predicted that wind power projects under construction and those that have already signed a connection agreement to the main grid will increase wind power capacity to about 11 GW (gigawatt) in Finland by 2027. This amount of wind power capacity would be able to produce 30–35 TWh of wind energy per year, which corresponds to approximately one third of Finland's electricity consumption. In addition, Fingrid predicts that in 2030, Finland's wind power capacity would be 19 GW and in 2035 34 GW. In 2030, the amount of energy produced from wind power would be approximately 60 TWh and in 2035, approximately 100 TWh. In 2030, the share of energy produced from wind power from total production would be 45 %. In 2035, the share of energy produced

from wind power in Finland from total production would be 55 %. Fingrid's Q3/2024 forecast also mentions that onshore wind power projects would be installed in Finland until 2030 and the first large offshore wind power projects in Finland would be completed after 2030 (Fingrid, 2024). Figure 23 shows the development of wind power in Finland from 2022 to 2035, which includes also wind power capacity and annual wind energy production.



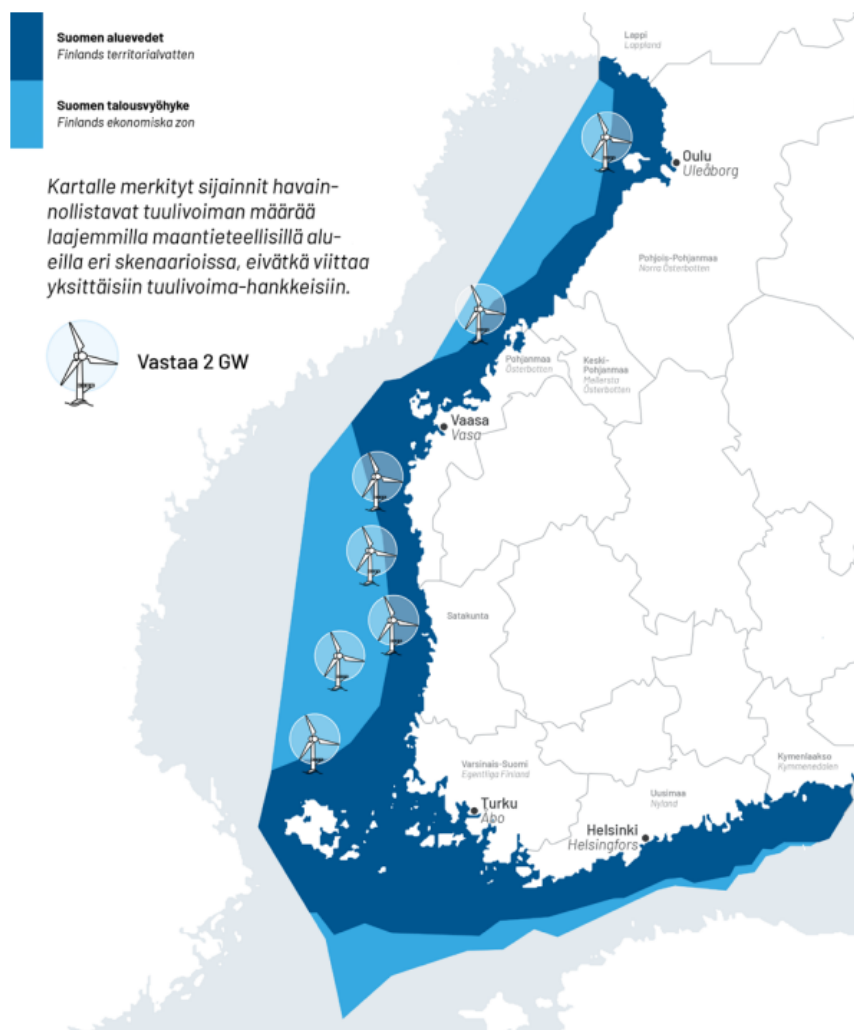
**Figure 23.** Finnish Wind power forecast from 2022 to 2035 (Fingrid, 2024).

### 3.3.3 Scenarios for Offshore wind power production in Finland in 2050

In the project report on the status and development picture of Finnish offshore wind power made by Sitowise Oy (2024, p. 39) has prepared two scenarios for the implementation of offshore wind power in Finland in 2050. The first scenario estimates the pro-

duction capacity of Finnish offshore wind power to be 15 GW in 2050. The second scenario estimates the production capacity of Finnish offshore wind power to be 26 GW in 2050. In the scenarios, offshore wind farms are located in the Gulf of Bothnia, as the Gulf of Finland has not been seen as a realistic location for offshore wind power due to the challenges of coordinating offshore wind power with other activities (Sitowise Oy, 2024, p. 39).

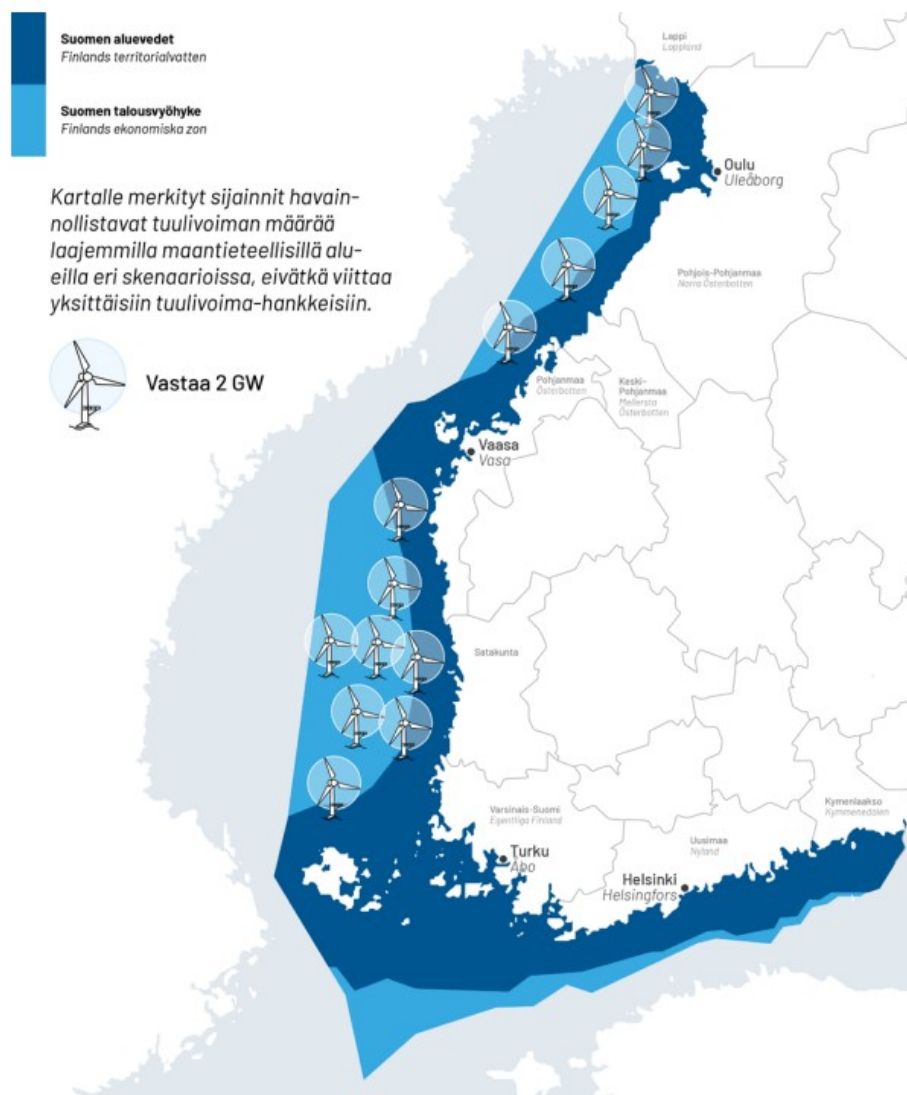
The first scenario assumed that future offshore wind energy production would be based on the current Finnish Maritime Spatial Plan 2030. In the plan, most of the offshore wind farms would be in Finnish public water areas and a small part would be in the Finnish exclusive economic zone area. Figure 24 shows roughly the amount of wind power in the Gulf of Bothnia area according to scenario 1 with a white 2 GW wind turbine, without referring to individual offshore wind power projects.



**Figure 24.** Finnish offshore wind power production in 2050 according to the first scenario. One white wind turbine 2 GW represents roughly amount of wind power in certain area (Sitowise Oy, 2024, p. 42).

In scenario 1, it was assumed that there would be sufficient growth in demand for renewable energy and large-scale industrial projects that would need a lot of renewable energy to function. It was also assumed that investments would have been made to strengthen the main grid and the connection. On the downside, it was assumed, among other things that resources would be limited for the planning, licensing and construction of offshore wind farms. Scenario 1 was presented to the authorities, and they feel that this scenario is more manageable, because it takes better account of the needs of maritime transport (Sitowise Oy, 2024, p. 43).

In scenario 2, it was assumed that energy production would be carried out extensively in the Gulf of Bothnia even outside the production area according to Finnish Maritime Spatial Plan. In this scenario, the majority of offshore wind turbines locates in the Finnish exclusive economic zone area, and a small number locates in Finnish public water areas (Sitowise Oy, 2024, p. 43). Figure 25 shows roughly the amount of wind power in the Gulf of Bothnia area according to scenario 2 with white 2 GW wind turbine without referring to individual offshore wind power projects.



**Figure 25.** Finnish offshore wind power production in 2050 according to the second scenario. One white wind turbine 2 GW represents roughly amount of wind power in certain area (Sitowise Oy, 2024, p. 44).

In scenario 2, it was assumed that positive events related to the demand for renewable energy, the regulation of the Finnish exclusive economic zone, the strengthening of the main grid and international transmission connections and the construction of offshore wind power take place, which will be told more widely below.

It was assumed that the demand for renewable energy has increased significantly and that a lot of investment decisions have been made to Finland for large-scale industrial projects that would require a lot of renewable energy to operate. Such industrial projects include hydrogen production plants, energy storage projects and transmission network development projects to neighboring countries to export energy. As a result of technological development, floating offshore wind farms are technically and economically viable and are common in deeper sea areas in the Finnish exclusive economic zone. International investors see Finland as an attractive place to develop offshore wind power due to the reform of the Finnish exclusive economic zone regulation. Many offshore wind farms are under construction by the end of 2030, and there is a demand for offshore wind power expertise in Finland. It was also assumed that investments would have been made to strengthen the Finnish grid and international transmission connections in Finland regarding the hydrogen and electricity transmission network. Hydrogen production plants and industrial plants producing synthetic fuel would be located near offshore wind farms (Sitowise Oy, 2024, p. 45).

Scenario 2 was presented to wind power operators. Wind power operators' opinion is that scenario 2 is more likely, as the areas identified in the Finnish Maritime Spatial Plan 2030 are not sufficient in terms of quantity and scope for offshore wind power to cover Finnish future demand. In addition, technological developments for the deployment of floating foundations for offshore wind turbines support the vision of locating offshore wind power deeper in the sea at the Finnish exclusive economic zone area (Sitowise Oy, 2024, p. 45).

## **4 Materials and Methods**

The sub-chapters of this chapter describe different forecasting models, the importance of wind power forecasting and about partial feasibility study for an offshore wind turbine, of which more widely below.

### **4.1 Wind power forecasting and forecasting approaches**

Wind power forecasting is important for many reasons. For grid operators, wind power forecasting is important in balancing electricity demand and supply, making optimal use of control energy, and minimizing the total energy costs of energy production. Accurate wind power forecasting can help optimize energy production to be cost-effective by optimizing wind power production according to wind conditions (OAK, 2024).

Wind farm operators can use forecasts to optimize energy production and maintenance measures to avoid potential energy production outages and maximize the profitability of the entire wind farm. In addition, accurate electricity production forecasts allow operators to keep finances under control by knowing in advance the future income and expenses from electricity production (OAK, 2024).

Forecasting approaches can be divided into forecasting models, which are used to predict the future. There are many different types of forecasting models in existence, but the following subsections of this section will briefly review at four different forecasting models, which are LSTM, ARIMA, WRF and AROME.

#### **4.1.1 LSTM**

LSTM (long short-term memory) is a forecasting model, which uses longer-term patterns to predict future patterns. The LSTM model belongs to deep learning models, and

it has ability to store and utilize non-linear and complex past data in time series predictions. LSTM models have been used in speech recognition and natural language processing due to their ability to exploit extended sequences (Demirtop & Sevli, 2024; Siami-Namini et al., 2018).

#### **4.1.2 ARIMA**

ARIMA (autoregressive integrated moving average) is known as statistical model, which is used to predict time series data. ARIMA models typically use past data points, past errors, and weighted averages and make a linear combination of them to predict future values of a time series. In addition, ARIMA models help analysts to predict future values by identifying patterns and trends in past data. Such ARIMA models have typically been used to forecast, e.g. wind speeds and solar radiation levels (Demirtop & Sevli, 2024).

#### **4.1.3 WRF**

WRF (Weather Research and Forecasting) is a numerical weather forecasting model that allows the study of the atmosphere and the making of operational forecasts for applications. The WRF model is used in a wide variety of meteorological applications at different scales from tens of meters to thousands of kilometers. The WRF model can be used to produce simulations, whose data input comes from real atmospheric conditions or idealized conditions. The WRF model is currently used in many meteorological centers, e.g. at NCEP (National Centers for Environmental Prediction) and in research institutions, e.g. at universities, laboratories and companies (UCAR, 2025).

#### **4.1.4 AROME**

AROME model is numerical weather forecasting model, which was made to enhance short-term forecasts, particularly for extreme weather events, e.g. severe thunderstorms,

fog and the impact of urban heat during heatwaves. The AROME model has a very short 48-hour forecast window, which allows it to predict weather events for the current day and tomorrow. The use of the AROME model has been popular, especially in the Mediterranean region during heavy rainfall events in the autumn (CNRM, 2014). The AROME model has been in use at Meteo-France since 2008, and it is the creator and operator of the model (Kuznetsov, 2025).

#### **4.1.5 Validation methods**

The AROME model was chosen from the forecasting models. The AROME model was chosen, because it was desired that the selected forecasting model utilizes real weather conditions from Finland's history in predicting future wind conditions. The Finnish Meteorological Institute's Finnish Wind Atlas tool has been developed for this type of wind forecasting. According to the Finnish Meteorological Institute (n.d) the AROME model has been used in the preparation of the Finnish Wind Atlas tool, which will be explained in more detail in the upcoming wind conditions section.

## **4.2 Partial feasibility study**

Partial feasibility study was carried out to determine the practical feasibility of the offshore wind turbine for the selected location. The sub-sections of this feasibility study section contain a written report on the selected offshore wind turbine, location and wind conditions, of which more widely below.

### **4.2.1 Offshore wind turbine**

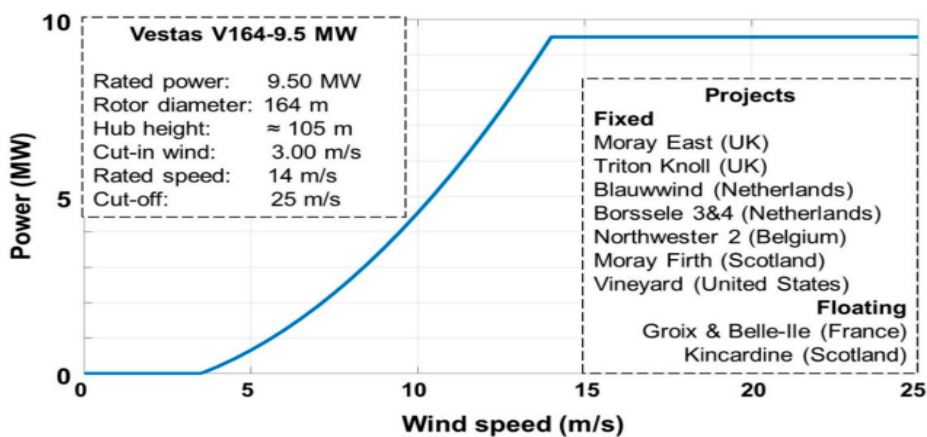
The aim was to find large Vestas's offshore wind turbine to be placed in the research area, from which the necessary information for calculating theoretical energy production

is openly available. The chosen offshore wind turbine was the Vestas V164-9.5 MW offshore wind turbine, which is shown in figure 26.



**Figure 26.** Offshore wind turbine (Offshore Engineer Magazine, 2020).

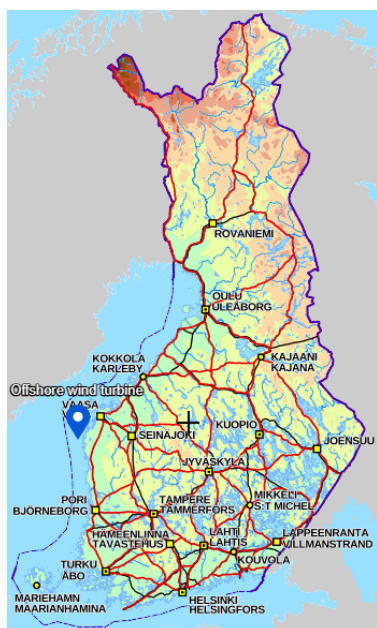
Vestas V164-9.5 MW offshore wind turbines have been implemented in many offshore wind power projects in Europe, either on fixed or floating foundations (Onea et al., 2021). The box on the right of the figure 27 shows these projects. In addition, the box on the left of the figure shows the technical data of the Vestas V164-9.5 MW offshore wind turbine, and the figure also shows the power curve of the Vestas offshore wind turbine at different wind speeds.



**Figure 27.** Technical data, project data and power curve of the Vestas V164-9.5 MW offshore wind turbine (Onea et al., 2021).

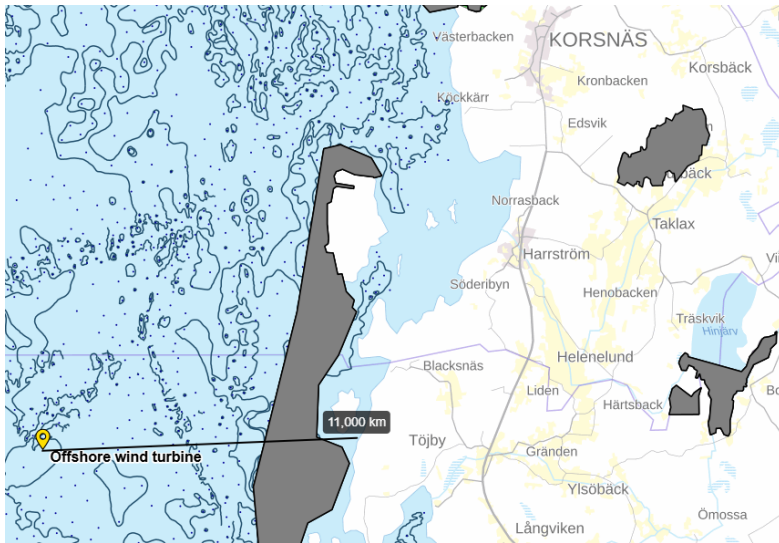
#### 4.2.2 Location

Figure 28 shows the location of Vestas offshore wind turbine under investigation in Finland. As seen, the offshore wind turbine is in the Gulf of Bothnia in Finnish public water areas, which is described in the sea area between the dark blue dotted line and the Finnish land.



**Figure 28.** Location of offshore wind turbine in Finland (NLS, n.d.).

According to the master plan of the City of Närpiö, the offshore wind turbine under investigation is in a marine area owned by the City of Närpiö near Töjby (City of Närpiö, n.d.). Figure 29 shows the distance from land to the location of the offshore wind turbine under investigation, which is 11 km (kilometers). In addition, the figure shows that the offshore wind turbine is not located in a nature reserve owned by the Finnish state or in a Natura 2000 area.



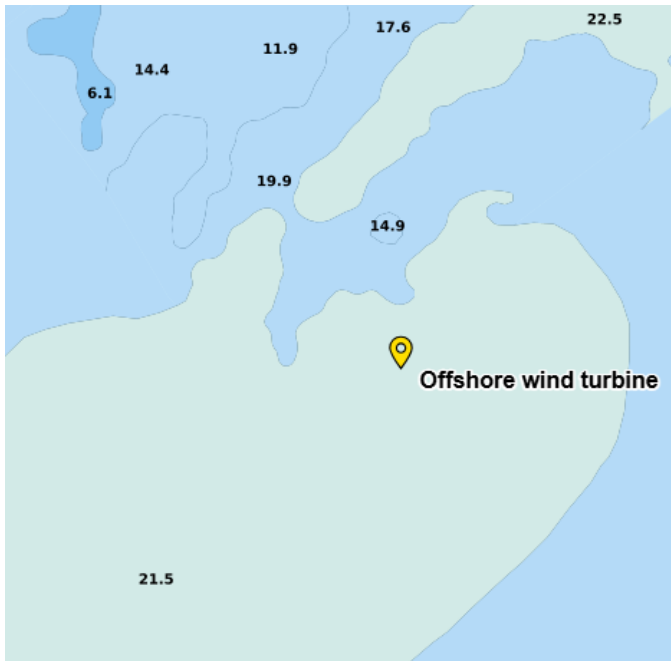
**Figure 29.** Offshore wind turbine location distance for the land in Töjby, City of Närpiö and nature reserve owned by the Finnish state and Natura 2000 areas (Paikkatietoikkuna, n.d).

Electricity produced by the offshore wind turbine is transferred to the Finnish main grid through a distribution network, which includes a 110 kV (kilovolt) electricity network (Fingrid, n.d). Figure 30 shows the coordinates of the offshore wind turbine and the total distance to the 110 kV transmission line of the Finnish distribution network, which is 18.1 km.



**Figure 30.** The total distance of the offshore wind turbine to the 110 kV Finnish electricity grid (Fingrid, n.d).

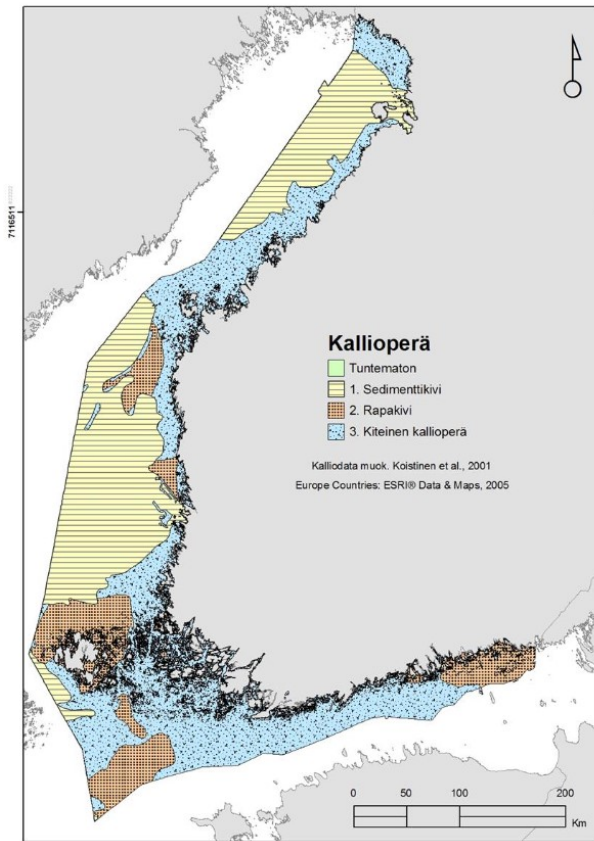
Figure 31 shows the depth of the location of the investigated offshore wind turbine in Gulf of Bothnia. The sea depth is 21.5 meters.



**Figure 31.** Offshore wind turbine location marine depth area (Paikkatiетоikkuna, n.d).

According to the National Land Survey of Finland's Paikkatiетоikkuna, the offshore wind turbine under investigation is located in a bedrock area, where the dominant rock type is Metamorphic rock, which belongs to the crystalline bedrock (Paikkatiетоikkuna, n.d; Lehtonen, 2023).

Figure 32 shows a seabed map of the Gulf of Bothnia and the Gulf of Finland. The figure shows a crystalline bedrock area, which is depicted in light blue. In addition, the figure shows that the sedimentary rock type area is depicted in yellow, weathered rock is depicted in brown, and an unknown rock type is depicted in green.



**Figure 32.** Seabed map of Gulf of Bothnia and Gulf of Finland (MarineFinland.fi, n.d).

Based on figures 31 and 32, when the sea depth and seabed bedrock of the offshore wind turbine location under investigation are known, the foundation type for the offshore wind turbine can be selected. Of the foundation methods (see figure 15), the gravity base foundation type is selected, because the sea depth is sufficient for this foundation type, and the seabed bedrock is suitable for this foundation type in the same way as in the Tahkoluoto offshore wind farm, which told earlier.

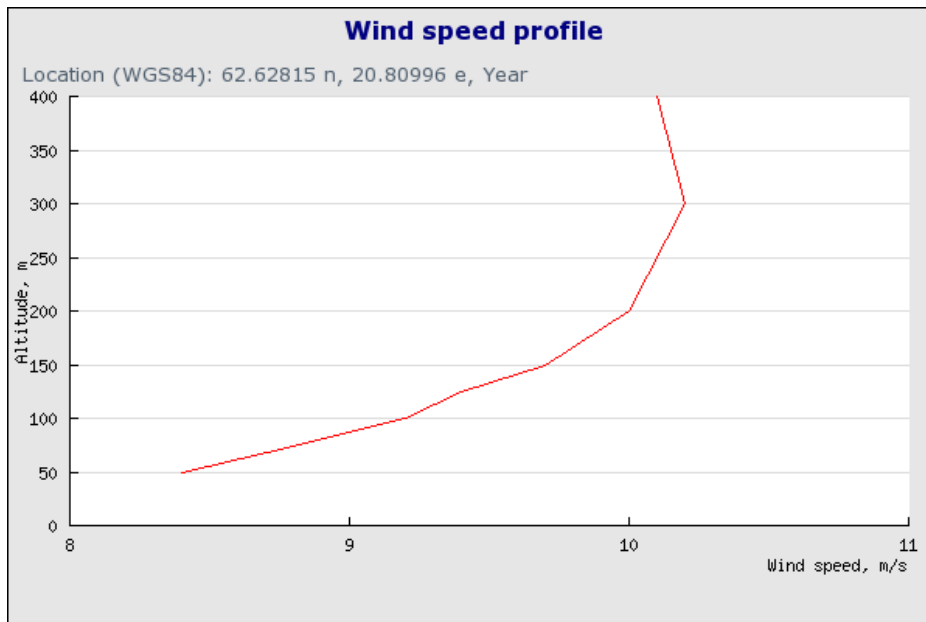
#### 4.2.3 Wind conditions

The Finnish Wind Atlas of the Finnish Meteorological Institute was used to determine the wind conditions at the location of the offshore wind turbine under study. The Finnish Wind Atlas can be used to estimate the average wind conditions in a given area in Finland

at different altitudes from 50 metres to 400 metres (Finnish Meteorological Institute, n.d.).

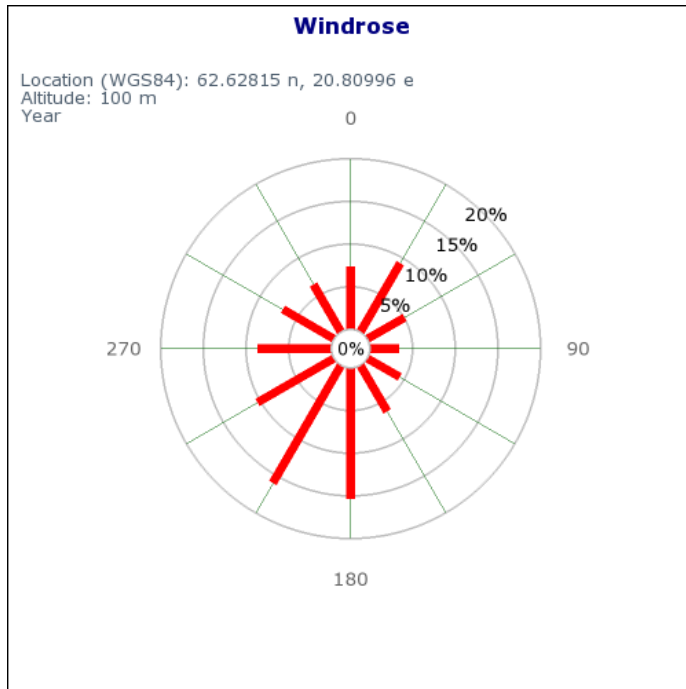
The Finnish Wind Atlas has been prepared by simulating numerical weather models from 1989–2007, and the selected weather models have examined wind conditions in Finland over the past 50 years (Finnish Meteorological Institute, n.d.).

Figure 33 shows the wind speed profile of an offshore wind turbine located in the maritime area of the City of Närpiö, which was obtained using the Finnish Wind Atlas map program. The annual average wind speed at altitude of 100 m is 9.3 m/s.



**Figure 33.** The annual average wind speed of the location of the offshore wind turbine under investigation in the maritime area of the City of Närpiö (The Finnish Wind Atlas, 2009).

Figure 34 shows a wind rose that shows the direction of the wind, from which direction the wind blows the most on average each year. The wind rose was obtained using the Finnish Wind Atlas map program. The figure shows that the wind blows the most from the southwest and south.



**Figure 34.** Wind rose of the location of the offshore wind turbine under investigation in the maritime area of the City of Närpiö (The Finnish Wind Atlas, 2009).

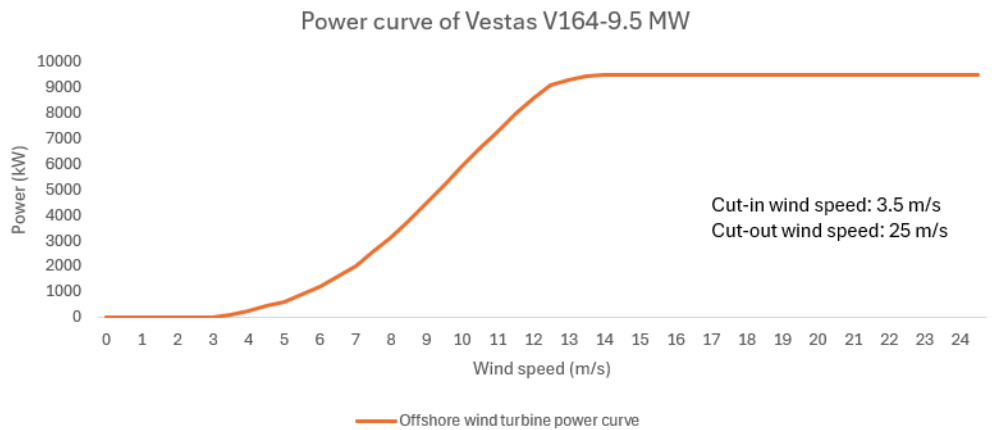
## 5 Forecasting model for Offshore wind turbine

The first subsection of this main section on the offshore wind turbine forecasting model discusses the created forecasting model and its results. The second subsection briefly discusses the energy use plan, which discusses the energy use of the predicted amount of energy in the Finnish grid and hydrogen storage. The third subsection contains offshore wind turbine financial assessment, where the economic profitability of an offshore wind turbine has been investigated using different calculation methods, of which more widely below.

### 5.1 Offshore wind power forecasting model

The Wind Power's open online data was used in creation of the forecasting model, in order to draw the power curve of the offshore wind turbine in question. The power curve was drawn, because the aim was to show the operating profile of the offshore wind turbine, i.e. the electricity production efficiency in relation to different wind speeds.

Figure 35 shows that the "Cut-in wind speed" of an offshore wind turbine is 3.5 m/s, which is when the offshore wind turbine's blades start to move, and the electricity generation starts. As the wind speed increases to 14 m/s, the offshore wind turbines generate electricity with its rated power, i.e. the turbine's maximum power, which remains the same even when the wind speed exceeds 14 m/s. The "Cut-out wind speed" of the offshore wind turbine is 25 m/s, i.e. at this wind speed the offshore wind turbine's blades will stop and the electricity production will stop to ensure safety of the offshore wind turbine (Boland Renewable Energy Co., 2024).



**Figure 35.** Made power curve of Vestas V164-9.5 MW offshore wind turbine based on open online data (The Wind Power, 2024).

Using the Finnish Wind Atlas, the average monthly wind speeds indicated in table 1 were obtained for the previously described offshore wind turbine location. In addition, the monthly hourly numbers for the year 2025 were indicated in the table. These monthly wind speeds and monthly hourly numbers were used to assist in assessing the predicted energy production of the offshore wind turbine.

**Table 1.** Wind speed data and monthly hours in 2025 (The Finnish Wind Atlas, 2009).

Finnish Wind Atlas		Monthly hours of 2025
Months	Monthly average wind speeds (m/s) at height of 100 m	Monthly hours (h) in 2025
January	11.5	744
February	10.7	672
March	8.9	744
April	8.4	720
May	8.8	744
June	8.4	720
July	7.9	744
August	7.5	744
September	9	720
October	10.2	744
November	10.2	720
December	9.7	744
Annual	9.3	8760

The monthly energy production volumes of the offshore wind turbine were obtained using the monthly average wind speed data from the Finnish Wind Atlas, and the corresponding electricity production capacity of the offshore wind turbine multiplied by the monthly number of hours. The electric energy formula according to Stein (2024) was used in the electric energy calculation (1):

$$E_{(Wh)} = P_{(W)} \cdot t_{(h)}, \quad (1)$$

where

$E_{(Wh)}$  = Energy in watt-hour [Wh].

$P_{(W)}$  = Power in watts [W].

$t_{(h)}$  = Time period in hours [h].

The calculated energy production amounts were entered in table 2 at a monthly level and the monthly energy production amounts were added together, resulting in a forecast estimate of the annual energy production amount, which was entered in the row defined in table 2 as “Annual output”.

The capacity factor of an offshore wind turbine was also calculated, as this can be used to indicate the location of the offshore wind turbine and its impact on the potential for utilizing the energy produced by the offshore wind turbine as a percentage of the maximum energy production (Kasper, n.d). The formula (2) according to Kasper (n.d) was used in the calculation of the capacity factor of the offshore wind turbine:

$$capacity\ factor = \frac{actual\ output}{maximum\ possible\ output} \cdot 100\ %, \quad (2)$$

where

*capacity factor* = Ratio of actual output and maximum output [%].

*actual output* = The amount of energy that is produced [kWh].

*maximum possible output* = Maximum amount of energy that could be produced [kWh].

To determine the capacity factor of an offshore wind turbine, the maximum energy production amount was first calculated by multiplying the hours per year, i.e. 8760 hours, by the nominal power of the offshore wind turbine, i.e. 9500 kW. The maximum energy production amount obtained was entered in table 2, which is shown in the row designated "Annual max output". Finally, the energy production amount produced during the year, which is shown in the row designated "Annual output", was divided by the maximum energy production amount, which gave us a capacity factor of 51.2 %.

Finally, the efficiency of the offshore wind turbine was calculated using a single wind speed. However, before calculating the efficiency, the total wind power had to be calculated first, which was calculated using the formula (3) according to Blackwood (2016). The wind speed used in calculating the wind power was the annual average wind speed at the location of the offshore wind turbine at a height of 100 m, i.e. 9.3 m/s.

$$P_{total} = \frac{1}{2} \cdot \rho \cdot A_T \cdot v_w^3, \quad (3)$$

where

$P_{total}$  = Wind total power in watts [W].

$\rho$  = Density of the air [ $\frac{kg}{m^3}$ ].

$A_T$  = Turbine swept area [ $m^2$ ].

$v_w$  = Upstream air velocity [ $\frac{m}{s}$ ].

After calculating the wind power, it was now possible to calculate the efficiency of the offshore wind turbine at a wind speed of 9.3 m/s, which was calculated using the formula (4) according to Blackwood (2016). The calculated efficiency was 46.9 %, which was noted in table 2.

$$\eta = \frac{P_T}{P_{total}} \cdot 100 \%, \quad (4)$$

where

$\eta$  = Efficiency of the turbine [%].

$P_T$  = Power from the turbine [W].

$P_{total}$  = Total wind power [W].

**Table 2.** Calculated offshore wind turbine output data.

Offshore wind turbine output data			
Months	Offshore wind turbine energy production (kWh)	Offshore wind turbine energy production (MWh)	Offshore wind turbine energy production (GWh)
January	5922240	5922.24	5.92224
February	4623091.2	4623.0912	4.6230912
March	3208128	3208.128	3.208128
April	2629296	2629.296	2.629296
May	3109920	3109.92	3.10992
June	2629296	2629.296	2.629296
July	2241225.6	2241.2256	2.2412256
August	1912080	1912.08	1.91208
September	3199680	3199.68	3.19968
October	4597920	4597.92	4.59792
November	4449600	4449.6	4.4496
December	4063728	4063.728	4.063728
Annual output	42586204.8	42586.2048	42.5862048
Annual max output	83220000	83220	83.22
Capacity factor	51.2 %		
Efficiency at annual average wind speed 9.3 m/s	46.9 %		

## 5.2 Wind energy use plan for Finnish electric grid and energy storage

The electricity produced by the offshore wind turbine predicted by the forecasting model can be used to cover the demand for electricity in the Finnish electricity network, i.e. the Finnish main grid, which is monitored by the Finnish transmission system operator Fingrid. Fingrid, which takes care of the electricity consumption and supply of the Finnish main grid ensures that electricity consumption and supply are kept in balance by

monitoring the frequency of the electricity network, which is allowed to vary between 49.9 and 50.1 Hz (Hertz) (Fingrid, n.d.). Electricity produced with offshore wind turbine can be used to meet the electricity needs of the whole of Finland while promoting the use of renewable energy in Finland, and to promote Finland's carbon neutrality target by 2035 (Motiva, 2025).

The electricity produced by an offshore wind turbine predicted by the forecasting model could also be used to produce hydrogen, which would support the decision-in-principle approved by the Finnish government in 2023 to make Finland a forerunner in the hydrogen economy, which would produce 10 % of the EU's pure hydrogen in 2030 (Finnish Government, 2023). The production of hydrogen took place purely by electrolysis, where hydrogen is produced by electricity produced by an offshore wind turbine by splitting water molecules into hydrogen and oxygen, from which the hydrogen would be recovered. Hydrogen could be produced at offshore wind turbine during such periods, when the electricity production from wind power exceeds the electricity demand of the Finnish main grid (Fortum, 2020). Thus, the production of hydrogen could be used to maximize the utility of the electricity produced by the offshore wind turbine together with the electricity demand of the Finnish main grid. The first alternative to the use of hydrogen would be in accordance with the decision-in-principle on hydrogen approved by the Finnish Government, i.e. produced hydrogen would be used especially to cover the demand for Finnish industry, transport and energy systems (Finnish Government, 2023). Another option would be to reuse the produced hydrogen to generate electrical energy using a fuel cell or gas turbine during windless periods, when the offshore wind turbine does not produce electricity, i.e. to balance the seasonal energy production variation of the offshore wind turbine using the emission-free energy from green hydrogen (Fortum, 2020).

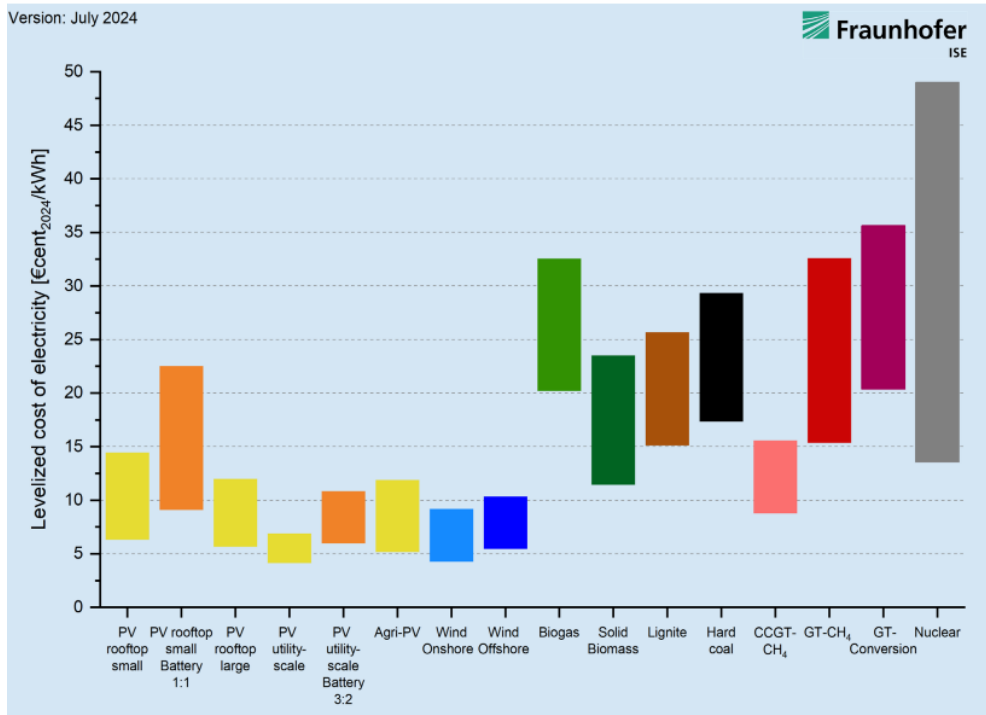
### **5.3 Offshore wind turbine financial assessment**

A financial assessment was made for the offshore wind turbine by calculating its LCOE (Levelized Cost of Energy) and financial payback period, which are discussed in more detail below.

#### **5.3.1 Levelized Cost of Energy**

LCOE is a measure that can be used to calculate the lifetime costs of a power plant per unit of energy production. The result is the present value of the construction and operating costs of the power plant over its assumed lifetime. This calculated measure can be used to compare the costs per unit of energy production of power plants using different technologies. LCOE is an important fact-based economic measure that influences decision-making and can be used to assess the economic profitability of a power plant project (USDOE, 2015).

Figure 36 shows a comparison of the LCOE of renewable energy power plants and conventional power plants in Germany in 2024. The figure shows how the LCOE of renewable energy solar and wind power plants is lower compared to the LCOE of conventional power plants, meaning that they are the most cost-effective forms of energy production in Germany in 2024. The upper limit of the LCOE range for power plants is determined by high investment costs but low electricity production. The lower limit is determined by low investment costs but high electricity production of power plants (Kost et al., 2024).



**Figure 36.** LCOE cost variations of renewable energy power plants and conventional power plants in Germany in 2024 (Kost et al., 2024).

LCOE can be calculated using the calculation formula (5) according to (Kost et al., 2024):

$$LCOE = \frac{I_0 + \sum_{t=1}^n \frac{A_t}{(1+i)^t}}{\sum_{t=1}^n \frac{M_{t,el}}{(1+i)^t}}, \quad (5)$$

where

$LCOE$  = Levelized Cost of Energy [ $\frac{\text{€cent}}{\text{kWh}}$ ].

$I_0$  = Investment costs in EUR [€].

$A_t$  = Annual total cost in EUR [€] per year.

$M_{t,el}$  = Produced amount of electricity per year [kWh].

$i$  = Real interest rate in [%].

$n$  = Economic lifetime in years.

$t$  = Year of lifetime (1, 2...n).

The LCOE for the offshore wind turbine was calculated to demonstrate its cost-effectiveness. To calculate the LCOE, the necessary input data, which are shown below, had to be determined according to formula 5. The electricity production of the offshore wind turbine was obtained from table 2. The remaining input data was obtained from online materials (Vestas, 2020 & Stehly et al., 2024). By placing the input data in formula 5., the LCOE for the offshore wind turbine was calculated, which is shown in table 3.

Input data:

$$I_0 = 35.812 \text{ million [€].}$$

$$A_t = 0.893 \text{ million [€].}$$

$$M_{t,el} = 42586204.8 \text{ [kWh].}$$

$$i = 6.76 \text{ [%].}$$

$$n = 25 \text{ years.}$$

$$t = 1 \text{ to } 25 \text{ years.}$$

**Table 3.** Calculated offshore wind turbine LCOE.

LCOE (€cent/kWh)
9.16

### 5.3.2 Financial payback period

The financial payback period refers to the time it takes for the returns from a project to cover the initial investment in the project. The financial payback period is often used to determine the payback periods for various projects. The shorter the payback period of a project, the more attractive it is to invest in it (VanLeeuwen, A., 2025).

The financial payback period can be calculated according to VanLeeuwen (2025) using the formula below (6):

$$\text{Payback Period} = \frac{\text{Initial cost}}{\text{Average annual cash flow}}, \quad (6)$$

where

*Payback Period* = Financial payback period in years.

*Initial cost* = Fixed capital costs [€].

*Average annual cash flow* = Annual average revenues [€].

The annual average economic return for the offshore wind turbine had to be determined before calculating the financial payback period. Assumption for calculating the economic return was that the future annual average market price of electricity would be the same as the average wholesale price of electricity in Finland in 2024, according to the Energateollisuus (2024), i.e. 45.6 €/MWh (euros per megawatt hour). Estimate of the annual economic return of the offshore wind turbine could now be calculated by multiplying the amount of energy produced in table 2, i.e. 42,586.2048 MWh, by the previously mentioned average wholesale price of electricity, which gave the annual average cash flow, which was entered in the input data below.

Input data:

*Initial cost* = 35.812 million [€].

*Average annual cash flow* = 1.942 millions [€].

By placing the initial data in formula 6, an estimate of the financial payback period in years for the offshore wind turbine was calculated, which is shown in table 4.

**Table 4.** Calculated offshore wind turbine financial payback period.

Financial payback period
About 18.5 years

### 5.3.3 Discussion

Investment to offshore wind power is site-dependent and offshore distance is an important influential factor in addition to the size of offshore wind turbine (Martinez, A. & Iglesias, G., 2022; Ayres, D. & Zamora, L., 2024).

Due to the very limited number of projects and available data in Finland, the calculated LCOE cannot be considered statistically reliable. More applications and data are needed to verify the estimated LCOE.

## 6 Conclusions

This study main goal was to conduct a literature review on the potential, challenge and development prospects of offshore wind power in Finland and to develop a forecasting model for offshore wind turbine for energy production. In addition, the goal was to draw up an energy use plan for electric energy generated by an offshore wind turbine, in which the use of the electricity generated is examined in the coverage of electricity demand in the Finnish main grid and in the production of hydrogen.

Based on the work, the following conclusions can be drawn:

1. Finnish sea areas have good potential for offshore wind power, when there are good wind conditions and sufficient depth of the sea. Based on the results of the Zonation analysis, the Gulf of Bothnia was found to be a better location for offshore wind farms than the Gulf of Finland, as offshore wind farms cause less harm to human activities and nature.
2. According to Fingrid's forecast, wind energy production will be the most growing of Finland's forms of energy production by 2035. However, a prerequisite for wind energy production is that domestic electricity consumption must increase a lot. In addition, Fingrid's forecast stated that the first large offshore wind farms will begin to be completed after 2030.
3. According to a project report made by Sitowise Oy (2024, p. 45), which concerned the situation and development picture of offshore wind power in Finland, it was established that Finnish wind power operators believe that the most realistic offshore wind power production scenario in 2050 is scenario 2, where offshore wind power will be built mostly in Finland's exclusive economic zone area, because this scenario can better cover Finland's future demand for electricity.
4. This study found that there are many challenges to the distribution of offshore wind turbines in Finnish sea areas. The biggest challenges come from the variability of the

seabed in the Baltic Sea and the arctic conditions of the Baltic Sea. The challenges that were discussed in more detail in this study includes, e.g. challenges to the selection of foundation solution for offshore wind turbine, challenges to layout design, sea ice, the accumulation of ice masses on the blades of offshore wind turbines, damage caused by the movement of sea ice masses to the offshore wind turbine tower, freezing of offshore wind turbine measurement equipments, construction timing, the use of different technologies, electrical infrastructure and logistics in the installation and maintenance of offshore wind turbine.

5. The electricity generation of an offshore wind turbine predicted by the forecasting model can be used to cover the electricity demand of the Finnish main grid. During very windy periods, when the electricity generated by offshore wind turbine exceeds the electricity demand of the Finnish main grid, the electricity generated by the offshore wind turbine will be used to produce hydrogen. Hydrogen produced by electrolysis would have a role in domestic use, and in balancing the seasonal variability of electricity generation from an offshore wind turbine.

6. The financial assessment carried out calculated the LCOE and financial payback period of an offshore wind turbine. The results show that an offshore wind turbine is a more cost-effective alternative to producing electricity than traditional power plants, as its calculated LCOE is lower than traditional power plants' LCOE. It was also found that an offshore wind turbine has a currently long financial payback period based solely on the income from the sale of electricity. Therefore, currently offshore wind turbine needs investment or feed-in tariff support to shorten its payback period and make its construction more profitable.

This work could be continued by conducting on-site measurements of the wind conditions at the location of the offshore wind turbine to verify the theoretical energy production estimate of the offshore wind turbine in practice. In addition, more data on Finland is needed to verify the calculated LCOE estimate of an offshore wind turbine.

## 7 Summary

This study has conducted a literature review to determine the current situation of Finnish wind power and the potential, challenges and development prospects of Finnish offshore wind power. A literature review was also conducted on various existing forecasting models, as the review created a good basis for selecting the right forecasting model for predicting the energy production of an offshore wind turbine. In addition, this study conducted a partial feasibility study for the offshore wind turbine, and based on the feasibility study data, a computational energy production forecasting model for the energy production of the offshore wind turbine was created. Finally, a short energy use plan and financial assessment was made for the selected offshore wind turbine.

Most wind turbines in Finland are currently onshore wind turbines, and a small fraction are offshore wind turbines. Finland's wind power production, wind turbine sizes and wind power construction have been growing year by year. Most onshore wind turbines are in Western Finland (Renewables Finland, 2025). There is currently only one offshore wind farm in operation in Finland, Pori Tahkoluoto, but there are numerous offshore wind power projects in the development phase in Finnish maritime areas (Sitowise Oy, 2024, p. 19).

Finnish sea areas have good potential for offshore wind turbines, because they have good wind conditions and sufficient sea depth. The Gulf of Bothnia was found to be a better location for offshore wind turbines than the Gulf of Finland. The best areas suitable for offshore wind turbines are in the Bay of Bothnia, south of the Kvarken and in the central and southern parts of the Bothnian Sea (Sitowise Oy, 2024, p. 20).

However, there are challenges associated with the generalization of offshore wind power in Finnish marine areas. The challenges will affect the development of offshore wind power, the construction of offshore wind power and the maintenance of the offshore turbines. The greatest challenges are the variability of the seabed in the Baltic Sea and the arctic conditions in the Baltic Sea (Sitowise Oy, 2024, p. 22).

According to Fingrid's forecast, large offshore wind power projects are expected to be completed in Finland after 2030 (Fingrid, 2024). According to a report made by the Sitowise Oy (2024, p. 39 & 45), there are two scenarios for the implementation of offshore wind power in Finland, of which the second scenario is considered more likely, because the areas defined in the Finnish Maritime Spatial Plan 2030 are not sufficient in quantity and scope to cover Finland's future demand for offshore wind power.

The forecasting model was made by conducting a partial feasibility study for the selected offshore wind turbine, which examined wind conditions, sea depth and seabed of the selected location. Based on these studies, the energy production of the offshore wind turbine was calculated, and the gravity base foundation type was selected. According to the energy use plan, the energy produced by the offshore wind turbine will be used in the Finnish main grid to cover electricity demand and to produce hydrogen at times, when the electricity supply of the offshore wind turbine exceeds the electricity demand of the Finnish main grid.

Finally, a financial assessment was made for the offshore wind turbine, where LCOE and financial payback period were calculated for the selected offshore wind turbine. According to the calculated results, the LCOE of the offshore wind turbine is lower compared to conventional power plants (Kost et al., 2024). However, the financial payback period of the offshore wind turbine is long based solely on the income from the sale of electricity, meaning that currently an offshore wind turbine needs financial support to be profitable to build.

This study answers the research questions and thus reached the expected outcome. The work progressed according to the planned schedule.

## References

- Ayres, D. & Zamora, L. (2024). *Renewable power generation costs in 2023*. International Renewable Energy Agency. Retrieved May 7, 2025 from [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA\\_Renewable\\_power\\_generation\\_costs\\_in\\_2023.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf)
- Blackwood, M. (2016). *Maximum Efficiency of a Wind Turbine*. *Undergraduate Journal of Mathematical Modeling: One + Two*. ResearchGate. Retrieved April 4, 2025 from [https://www.researchgate.net/publication/308179653\\_Maximum\\_Efficiency\\_of\\_a\\_Wind\\_Turbine](https://www.researchgate.net/publication/308179653_Maximum_Efficiency_of_a_Wind_Turbine)
- Boland Renewable Energy Co. (2024). *Wind Turbine Power Curve*. Retrieved April 3, 2025 from <https://bolandnewenergy.com/wind-turbine-power-curve/>
- City of Närpiö. (n.d.). *General formulas*. Retrieved March 19, 2025, from <https://www.narpes-fi.translate.google.com/translate?sl=fi&tl=en&hl=en-US>
- CNRM - Centre National de Recherches Météorologiques. (2014). *AROME*. Retrieved March 27, 2025 from <https://www.umr-cnrm.fr/spip.php?article120&lang=en>
- de Vries, W., Vemula, N., Passon, P., Fischer, T., Kaufer, D., Matha, D., Schmidt, B. & Vorpahl, F. (2011). *Project UpWind - Final report WP 4.2 Support Structure Concepts for Deep Water Sites*. Delft University of Technology. Retrieved March 20, 2025 from <https://www.upwind.eu/images/final%20report%20wp4.2.pdf>
- Demirtop, A. & Sevli, O. (2024). *Wind speed prediction using LSTM and ARIMA time series analysis models: A case study of Gelibolu*. ResearchGate. Retrieved March 26, 2025 from [https://www.researchgate.net/publication/382074163\\_Wind\\_speed\\_prediction\\_using\\_LSTM\\_and\\_ARIMA\\_time\\_series\\_analysis\\_models\\_A\\_case\\_study\\_of\\_Gelibolu](https://www.researchgate.net/publication/382074163_Wind_speed_prediction_using_LSTM_and_ARIMA_time_series_analysis_models_A_case_study_of_Gelibolu)
- The Empire Engineering. (2021). *Guide to Offshore Wind Foundations*. Retrieved March 20, 2025 from [https://www.empireengineering.co.uk/wp-content/uploads/2021/08/The\\_Empire\\_Engineering\\_Guide\\_to\\_Offshore\\_Wind\\_Foundations\\_eBook-1.pdf](https://www.empireengineering.co.uk/wp-content/uploads/2021/08/The_Empire_Engineering_Guide_to_Offshore_Wind_Foundations_eBook-1.pdf)

- Energiateollisuus. (2024). *Sähkön hintatilastot 2024*. Retrieved April 28, 2025 from <https://energia.fi/tilastot/sahkotilastot/sahkon-hintatilasto/>
- Fingrid. (n.d). *Electricity system of Finland*. Retrieved March 31, 2025 from <https://www.fingrid.fi/en/grid/development/electricity-system-of-finland/>
- Fingrid. (n.d). *Finnish grid*. Retrieved March 31, 2025 from <https://karttapalaute.fingrid.fi/?link=hDzo>
- Fingrid. (n.d). *Maintenance of power balance*. Retrieved April 9, 2025 from <https://www.fingrid.fi/kantaverkko/sahkonsiirto/kulutuksen-ja-tuotannon-tasapainon-yllapito/>
- Fingrid. (2024). *Prospects for future electricity production and consumption*. Retrieved March 12, 2025, from <https://www.fingrid.fi/globalassets/dokumentit/en/news/prospects-for-future-electricity-production-and-consumption.-fingrids-forecast-q3-2024.pdf>
- Finnish Energy. (2025). *Sähkön vuosi 2024: päästöt vähenivät 25 %, hinta palautui normaalitasolle, sähkön tuotannossa uusia ennätyksiä*. Retrieved March 4, 2025 from <https://energia.fi/tiedotteet/sahkon-vuosi-2024-paastot-vahenivat-25-hinta-palautui-normaalitasolle-sahkon-tuotannossa-uusia-ennatyksia/>
- Finnish Government. (2023). *Government adopts resolution on hydrogen – Finland could produce 10% of EU's green hydrogen in 2030*. Retrieved April 9, 2025 from <https://valtioneuvosto.fi/-/1410877/hallitus-hyvaksyi-periaatepaatoksen-vedysta-suomella-edellytykset-valmistaa-10-prosenttia-eu-n-vihreasta-vedysta-2030>
- The Finnish Wind Atlas. (2009). Finnish Meteorological Institute. Retrieved March 24, 2025 from <http://tuuliatlas.fmi.fi/en/>
- Finnish Meteorological Institute. (n.d.). *Wind Atlas - wind energy resources on the map of Finland*. Retrieved March 24, 2025 from <https://en.ilmatieteenlaitos.fi/wind-atlas>
- Finnish Meteorological Institute. (2024). *Ice season 2023/2024 was long*. Retrieved March 10, 2025, from <https://en.ilmatieteenlaitos.fi/ice-winter-2023-2024>

- Finnish Wind Power Association. (2019). *Wind power in Finland 2018*. Retrieved March 4, 2025 from [https://suomenuusiutuvat.fi/media/sty-vuosiraportti-2018\\_public-en.pdf](https://suomenuusiutuvat.fi/media/sty-vuosiraportti-2018_public-en.pdf)
- Finnish Wind Power Association. (2022). *Wind power in Finland 2021*. Retrieved March 4, 2025 from [https://suomenuusiutuvat.fi/media/tuulivoima\\_vuositilastot\\_2021\\_in\\_english-2.pdf](https://suomenuusiutuvat.fi/media/tuulivoima_vuositilastot_2021_in_english-2.pdf)
- Fortum. (2020, September 4). Vetytalous tulee – ennemmin tai myöhemmin. *ForTheDoers-blogi*. Retrieved April 9, 2025 from <https://www.fortum.fi/tietoa-meista/blogi/forthedoers-blogi/vetytalous-tulee-ennemmin-tai-myohemmin>
- IEA Wind TCP. (2019). *Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology*. Retrieved March 4, 2025 from <https://www.nrel.gov/docs/fy19osti/72437.pdf>
- IRENA - International Renewable Energy Agency. (2011–2022). *Wind energy*. Retrieved February 19, 2025, from <https://www.irena.org/Energy-Transition/Technology/Wind-energy>
- Kasper, D. (n.d). *Wind Energy and Power Calculations*. The Pennsylvania State University. Retrieved April 3, 2025 from <https://www.e-education.psu.edu/emsc297/node/649>
- Kost, C., Müller, P., Sepúlveda Schweiger, J., Fluri, V. & Thomsen, J. (2024). LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES. Fraunhofer Institute for Solar Energy Systems ISE. Retrieved April 24, 2025 from <https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html>
- Kuznetsov, I. (2025). *What is AROME weather model and how it works*. Windy Weather World Inc. Retrieved March 27, 2025 from <https://windy.app/blog/arome-weather-model.html>
- Lehtonen, E. (2023). *Peruskallio – Suomen kallioperätermistön tarpeeton kivijalka?* Geological Society of Finland. Retrieved March 25, 2025 from [https://www.geologinenseura.fi/sites/geologinenseura.fi/files/geologi\\_-\\_artikkelit/geologi\\_3\\_2023\\_s108\\_116.pdf](https://www.geologinenseura.fi/sites/geologinenseura.fi/files/geologi_-_artikkelit/geologi_3_2023_s108_116.pdf)

- MarineFinland.fi. (n.d). *Characteristics of the seafloor*. Retrieved March 24, 2025 from <https://www.marinefinland.fi/en-US/Nature-and-how-it-changes/The-unique-Baltic-Sea/Characteristics-of-the-sea-floor>
- Martinez, A. & Iglesias, G. (2022). *Site selection of floating offshore wind through the levelised cost of energy: A case study in Ireland*. ResearchGate. Retrieved May 7, 2025 from <https://www.researchgate.net/publication/360913565-Site-selection-of-floating-offshore-wind-through-the-levelised-cost-of-energy-A-case-study-in-Ireland>
- Motiva. (2025). *Uusiutuva energia Suomessa*. Retrieved April 9, 2025 from <https://www.motiva.fi/ratkaisut/uusiutuva-energia/uusiutuva-energia-suomessa?view-status=preview>
- National Grid. (2024). *Onshore vs offshore wind energy: what's the difference?* Retrieved February 20, 2025 from <https://www.nationalgrid.com/stories/energy-explained/onshore-vs-offshore-wind-energy>
- NLS – National Land Survey of Finland. (n.d). *MapSite*. Retrieved March 19, 2025, from <https://asiointi.maanmittauslaitos.fi/karttapaikka/?lang=en>
- OAK - Operis Analysis Kit. (2024). *How is Wind Power Forecasting Done?*. Retrieved March 27, 2025 from <https://www.operisanalysiskit.com/modelling-insights/how-is-wind-power-forecasting-done/>
- Offshore Engineer Magazine. (2020). *Final Turbine Installed at Borssele III/IV Offshore Wind Farm*. Retrieved March 18, 2025, from <https://www.oedigital.com/news/483537-final-turbine-installed-at-borssele-iii-iv-offshore-wind-farm>
- Onea, F., Rusu, E. & Rusu, L. (2021). *Assessment of the Offshore Wind Energy Potential in the Romanian Exclusive Economic Zone*. ResearchGate GmbH. Retrieved March 17, 2025, from <https://www.researchgate.net/figure/Power-curve-of-the-Vestas-V164-95-turbine-including-some-technical-data-left-side-and-fig4-351600993>

- Paikkatietoikkuna. (n.d). National Land Survey of Finland. Retrieved March 25, 2025 from <https://kartta.paikkatietoikkuna.fi/?lang=en>
- PWEA - Polish Wind Energy Association. (2022). *Offshore wind vessel availability until 2030: Baltic Sea and Polish perspective*. Retrieved March 11, 2025, from <https://windeurope.org/wp-content/uploads/files/policy/topics/offshore/Offshore-wind-vessel-availability-until-2030-report-june-2022.pdf>
- Renewables Finland. (n.d). *Miksi tuulivoimaa*. Retrieved March 7, 2025, from <https://suomenuusiutuvat.fi/tuulivoima/miksi-tuulivoimaa/>
- Renewables Finland. (2024). *Wind power becoming the largest renewable electricity producer in 2024*. Retrieved March 5, 2025 <https://suomenuusiutuvat.fi/en/wind-power-becoming-the-largest-renewable-electricity-producer-in-2024/>
- Renewables Finland. (2025). *Wind power in Finland in 2024*. Retrieved March 4, 2025 from <https://suomenuusiutuvat.fi/media/wind-power-stats-fin-2024.pdf>
- Ronsten, G., Wallenius, T., Hulkkonen, M., Baring-Gould, I., Cattin, R., Durstewitz, M., Krenn, A., Laakso, T., Lacroix, A., Tallhaug, L., Byrkjedal, Ø. & Peltola, E. (2012). *State-of-the-Art of Wind Energy in Cold Climates*. IEA Wind. Retrieved March 10, 2025, from [https://suomenuusiutuvat.fi/media/state-of-the-art-of-sota\\_weincc\\_2012\\_approved.pdf](https://suomenuusiutuvat.fi/media/state-of-the-art-of-sota_weincc_2012_approved.pdf)
- Siami-Namini, S., Tavakoli, N., Siami Namin, A. (2018). *A Comparison of ARIMA and LSTM in Forecasting Time Series*. National Science Foundation. Retrieved March 26, 2025 from <https://par.nsf.gov/servlets/purl/10186768>
- Sitowise Oy. (2024). *Merituulivoiman tilanne- ja kehityskuvan kokonaistarkastelu*. Ministry of the Environment Finland. Retrieved March 6, 2025, from [https://api.hankeikkuna.fi/asiakirjat/f2abcca7-500a-4bbc-98af-4980fcdab344/1516d4df-ec95-40c9-8bb0-757110d95e04/JULKAISU\\_20240529073855.pdf](https://api.hankeikkuna.fi/asiakirjat/f2abcca7-500a-4bbc-98af-4980fcdab344/1516d4df-ec95-40c9-8bb0-757110d95e04/JULKAISU_20240529073855.pdf)
- Stehly, T., Duffy, P. & Mulas Hernando, D. (2024). *Cost of Wind Energy Review: 2024 Edition*. National Renewable Energy Laboratory. Retrieved May 5, 2025 from <https://www.nrel.gov/docs/fy25osti/91775.pdf>
- Stein, Z. (2024). *Watt-Hour (Wh)*. Carbon Collective Corporation. Retrieved April 4, 2025 from <https://www.carboncollective.co/sustainable-investing/watt-hour-wh>

- Suomen Hyötytuuli Oy. (n.d). *Tahkoluoto offshore wind farm*. Retrieved March 6, 2025. <https://hyotytuuli.fi/tuulivoima/tahkoluodon-merituulipuisto/>
- Suomen Hyötytuuli Oy. (n.d). *Offshore wind power*. Retrieved March 24, 2025 from <https://hyotytuuli.fi/en/offshore-wind-power/>
- Suomen uusiutuvat. (2025). *Tuulivoima Suomessa 31.12.2024*. Retrieved March 5, 2025 from [https://suomenuusiutuvat.fi/media/tuulivoima\\_vuositilastot-2024-1.pdf](https://suomenuusiutuvat.fi/media/tuulivoima_vuositilastot-2024-1.pdf)
- Tahkoluoto Offshore Oy. (n.d.). *Laajennushanke*. Retrieved March 6, 2025, from <https://tahkoluoto-offshore.fi/hankkeet/laajennushanke/>
- Thomson, R. & Harrison, G. (2015). *Life Cycle Costs and Carbon Emissions of Onshore Wind Power*. ClimateXChange. Retrieved March 13, 2025, from [https://www.climateexchange.org.uk/wp-content/uploads/2023/09/main\\_report\\_-\\_life\\_cycle\\_costs\\_and\\_carbon\\_emissions\\_of\\_onshore\\_wind\\_power.pdf](https://www.climateexchange.org.uk/wp-content/uploads/2023/09/main_report_-_life_cycle_costs_and_carbon_emissions_of_onshore_wind_power.pdf)
- UCAR – University Corporation for Atmospheric Research. (2025). *Weather Research & Forecasting Model (WRF)*. Retrieved March 27, 2025 from <https://www.mmm.ucar.edu/models/wrf>
- USDOE - United States Department of Energy | Office of Indian Energy. (2015). *Levelized Cost of Energy (LCOE)*. Retrieved April 22, 2025 from <https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf>
- USDOE - United States Department of Energy. (2015). *Wind Energy Benefits*. Retrieved February 20, 2025 from <https://www.nrel.gov/docs/fy15osti/62823.pdf>
- VanLeeuwen, A. (2025). *Know the Significance of Payback Period. Preferred CFO*. Retrieved April 28, 2025 from: <https://preferredcfo.com/insights/determining-payback-period-of-business-investment>
- Vestas. (2020). *First ever V164-9.5 MW turbine installed on a floating wind project*. Retrieved April 22, 2025 from: <https://www.vestas.com/en/media/mwow-press-releases/2020/first-ever-v164-9-5-mw-turbine-installed-on-a-floating-wind-proj>
- VTT Technical Research Centre of Finland. (2010). *Tuulivoiman tuotantotilastot*. Retrieved March 4, 2025 from <https://suomenuusiutuvat.fi/media/2009.pdf>

- The Wind Power. (2024). V164/9500. Retrieved April 3, 2025 from [https://www.thewindpower.net/turbine\\_en\\_1476\\_mhi-vestas-offshore\\_v164-9500.php](https://www.thewindpower.net/turbine_en_1476_mhi-vestas-offshore_v164-9500.php)
- Wpd. (2021). *Eystrasalt Offshore – Kuulemisperuste*. Retrieved March 20, 2025 from [https://ym.fi/documents/1410903/0/UUSI%20SUOMENNOS%20Eystrasalt\\_samradsunderlag\\_Kuulemisasiakirja\\_211019.pdf/9d4a5c17-625b-7a05-b940-9329d8237ec7/UUSI%20SUOMENNOS%20Eystrasalt\\_samradsunderlag\\_Kuulemisasiakirja\\_211019.pdf#page=31&zoom=100,91,125](https://ym.fi/documents/1410903/0/UUSI%20SUOMENNOS%20Eystrasalt_samradsunderlag_Kuulemisasiakirja_211019.pdf/9d4a5c17-625b-7a05-b940-9329d8237ec7/UUSI%20SUOMENNOS%20Eystrasalt_samradsunderlag_Kuulemisasiakirja_211019.pdf#page=31&zoom=100,91,125)
- Yichao, L., Sunwei, L., Qian, Y. & Daoyi, C. (2016). *Developments in semi-submersible floating foundations supporting wind turbines: A comprehensive review*. ScienceDirect. Retrieved March 20, 2025 from <https://www.sciencedirect.com/science/article/pii/S1364032116001398>