DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

Department of Mechanical and Aerospace Engineering

Calibration of uncertainty on weather forecasting for a North Atlantic offshore wind farm case study

Author: Lucas Beaury

Supervisor: Nicolas Kelly

A thesis submitted in partial fulfilment for the requirement of degree in
Master of Science in Renewable Energy Systems Analysis & the Environment

August 2021

This thesis contains confidential information and should not be released publicly

Student No. 202086287

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Lucas Beaury Date: 08/17/2021

Abstract

Offshore wind development falls within a worldwide turnover regarding decarbonised electricity production, as part of global plans to reach carbon neutrality. Marine operations involved during construction, installation, operation, and maintenance of offshore wind farms are highly sensitive to weather. This is why, a detailed knowledge of local weather conditions onsite is required to avoid additional weather stand-by costs and risks for the different stakeholders that might slow down the expansion of offshore wind projects.

This thesis focuses on the alpha factor methodology, currently used by the offshore wind industry to assess uncertainty on weather forecasts. Current application of this method almost systematically involves tabulated alpha factors determined for North Sea conditions. Proposed study investigates a calibration of alpha factors for a future North Atlantic offshore wind farm located close to the French coastline in *Saint-Nazaire*. The idea here is to compare generic and specific values to provide recommendations to the industry on this particular case study.

Methodology followed in this study first includes a research and literature review of related topics to both weather forecasts and uncertainty assessment. Second step is then specific to alpha factors methodology: understanding overall aspects and theoretical methods of calculation. Thereafter, the third step focuses on a practical calculation of alpha factors for the case study of *Saint-Nazaire*, through the creation of a python code and an Excel sheet containing local measurements and weather forecasts data. Finally, last step runs a sensitivity analysis of parameters influencing alpha factors such as seasons, forecasted periods, or operational limits, and lastly compares these specific values to tabulated alpha factors.

Calibration of alpha factors to the *Saint-Nazaire* case study shows that alpha factors depend on various parameters identified in the sensitivity analysis, as well as the method of forecasts used. Results indicate an overall overestimation of actual uncertainty on significant wave height forecasts from tabulated alpha factors, which is logical regarding the adverse conditions of weather in North Sea.

Concerning study undertaken on the case study of *Saint-Nazaire*, specific alpha factors are less restrictive compared to generic values. Sensitivity analysis suggests a seasonal influence and better predictions for long-range forecasting. However, studying input data for several years and extended periods of forecasts would be beneficial to refine the conclusions obtained in the thesis.

Acknowledgements

I would like to offer my sincere thanks and appreciation to my former teacher and project supervisor Dr. Nicolas Kelly for all his guidelines provided through the project. I am very grateful for his time, valuable insights, suggestions, and opinions he gave to help me both on the project definition and development.

I would like to thank the entire installation offshore wind department team of EDF Renewables for their welcome, caring, and also availability to support my work, which makes this project what it is now. I am particularly thankful to Sébastien Jubé for his explanations on alpha factors and sharing relevant documentation linked to the subject. I am also very grateful to Maud Lamaze, Richard Mansion, Niels Nederstigt, and Virak Sar for their advice on my project and availability to raise suggestions and support my work.

More generally I would like to thank all the teachers and classmates that I met during my MSc at the University of Strathclyde. Despite the specific health situation, I spent a rewarding exchange program, increasing considerably my understanding of sustainable and energetic issues, which leads me to end my studies peacefully.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description	Units
H_{max}	Maximum wave height at a given location.	m
H_s	Mean height of the highest one third of the waves passing at a given location.	m
$h_{s,meas}$	Local Hs value measured onsite.	m
$h_{s,thr}$	Operational wave height criterion.	m
$h_{s,wf}$	Local Hs value forecasted.	m
n	Number of sea states.	Ø
T_C	Contingency period.	h
T_{FP}	Forecast period, or lead time.	h
T_p	Waves peak period.	s
T_{POP}	Planned operational period.	h
T_z	Waves zero up-crossing period.	s
OP_{LIM}	Operational limiting criteria.	Not fixed
OP_{WF}	Forecasted operational criteria.	Not fixed

V_d	Average wind speed value over a defined time period.	m/s

1.0 Introduction

As stated in the Paris Agreement in 2015, more and more countries plan to reach carbon neutrality by 2050. While the world population keeps increasing, leading to always more demands and pressure on the environment, an urgent turnover is necessary to reduce pollution produced by the current and future supply of human needs. Within this context, the world has experienced a switch in means of producing energy, especially with the use of renewables. Among these carbonless technologies of power generation, offshore wind turbines have been used since 1991, but only scaled-up worldwide after 2010 due to technological advances and massive cost reductions. Ongoing research on this topic focuses on more ambitious designs of turbines located further from the coast, at great depths, with higher electricity generation and lower costs of construction and operation. In that respect and in order to guarantee complete control during all stages of an offshore wind project, including construction, installation and operation, detailed knowledge of the weather conditions is required. Furthermore, weather is a key feature in decision-making of offshore projects, hence it is crucial to have accurate forecasting with the smallest uncertainties possible of the upcoming local weather conditions.

1.1 Context of offshore wind expansion

1.1.1 Brief history

While the first onshore wind turbine was built in 1978 in Denmark with a capacity of 2 MW, the first offshore wind farm was erected in 1991. This farm, also located in Denmark, was composed of 11 turbines for a total capacity of 5MW. It was mostly perceived as a demonstration project as many people were sceptical about its potential. [1] That is why, until 2001, the development of an offshore wind turbines industry was quite slow with only a few small projects located in Denmark, the UK, Sweden, and the Netherlands. Concerning technologies, it was built with concrete foundation close to the coast in shallow water.

At the dawn of the 21st century, the offshore wind industry started moving forward. Indeed, projects became more ambitious compared to their predecessors, both in terms of size and technologies involved. For instance, in 2002, Horns Rev 1 was commissioned by the Danish government and was composed of 80 wind turbines for a total production of 94.8 MW. [2] The water depth was comprised between 6 to 14 meters, and it was the first time that a submarine cable was used to transfer electricity to the coast, located 21 km away. At the same time, the UK started a massive installation of offshore wind farms such as in 2013 with London Array, a park comprising 175 turbines for a total capacity of 630 MW. [3] This increase in production may be explained by higher turbines (turbines' hub up to 90 m over the sea) thanks to significant improvements in the design.

In order to keep the development of offshore wind turbines industry growing and with regards to the financial crisis, the costs of offshore wind energy had to be reduced. Therefore, after 2012, a target of less than 100€/MWh by 2020 was set by the Danish government (respectively 100£/MWh for the UK government). [1] Thus, new turbine designs were investigated, such as lighter foundations for monopile, the most common type of foundation, with a reduction of the required quantity of steel. This also marks the beginning of investigating new designs for foundations, with the pilot floating wind farm Hywind, located in Scotland and built in 2017. [4]

As the cost was progressively reduced with the development of new offshore wind farms, even more ambitious projects started emerging all over the world. Indeed, Europe is nowadays no longer the only producer of offshore wind energy, as many offshore wind farms were built in Asian countries such as China in 2010 [5] or more recently in India, Japan, South Korea, and Taiwan, as well as the US in 2016. [6] This globalization of offshore wind production is planned to keep increasing exponentially over the next few years, on coasts shown on Figure 1.

Figure 1: Potential future and current areas for offshore wind energy over the world [1]

1.1.2 Motivations & future perspectives

While global demand in energy is growing with the increase of the world population and rise of the average standard of living, consequences on the environment are drastic. To tackle these new challenges, the Paris Agreement set national objectives in December 2015, to reduce global emissions as soon as possible. [7] In response, some countries such as Germany or China planned to reach carbon neutrality by 2050. Electricity and heat alone accounted for about 31% of global manmade greenhouse gas emissions in 2013. [8] When also considering the energy use in other sectors like transportation, it is crucial to control the carbon footprint of energy production. To address the objectives defined on an international scale, the production of energy needs to be completely decarbonised. In that respect, the part of renewables in the world's energy production has increased and will continue to do so in the future.

Among the development of renewables, offshore wind turbines experienced an exponential development over the past few years. Whereas some countries, such as the UK or Denmark, already have a significant part of their energy mix supplied by offshore wind, others are currently making huge investments on offshore wind projects, such as France, China, or the US. Figure 2 shows the expected global offshore wind growth to 2030.

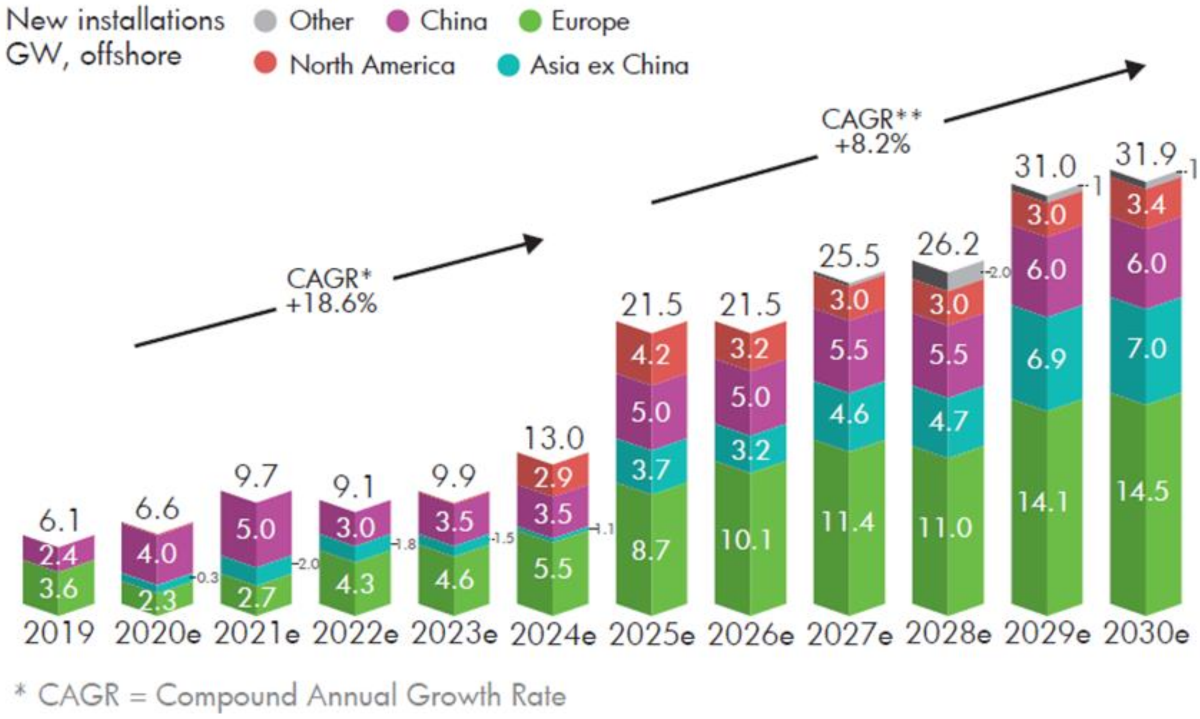
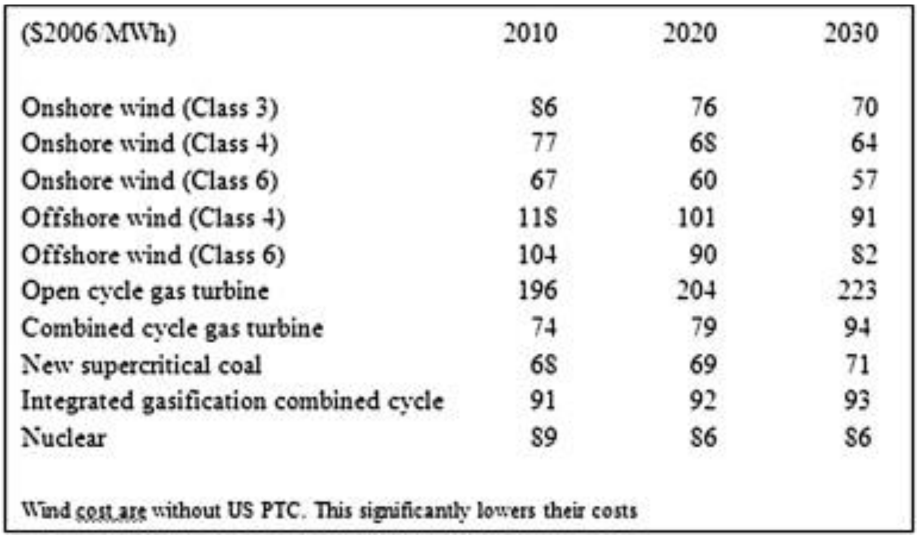


Figure 2: Global offshore wind planned growth from 2019 to 2030 [49]

Besides reducing carbon emissions compared to fossil fuel-based energy, offshore wind, like other renewables, ensures a production with local resources directly available on-site. Renewables offer some independence whereas fossil fuel-plants often require imports of specific resources like coal, gas, or uranium. This makes renewables reliable sources of energy production regarding the market, emphasised by the possibility of economic and geopolitical crises like the oil shocks of 1973 and 1979 which threatened the energy sector all over the world. [9] Another key element in the recent development of renewables is the massive cost reduction they allow. As shown on Table 1, the future levelized costs of different generating technologies are compared between 2010 and 2030. The levelized cost of power can be perceived as an economic indicator which depends on construction, operating and fuel costs. For example, renewables have high construction costs but limited operating and fuel costs, contrary to fossil fuel-based technologies, which are cheaper to build but much more expensive to operate. By 2030, onshore and offshore wind should become cheaper than fossil fuel-based technologies.

Table 1: Levelized cost comparison between different technologies, between 2010 and 2030 [10]



($2006/MWh)	2010	2020	2030
Onshore wind (Class 3)	86	76	70
Onshore wind (Class 4)	77	68	64
Onshore wind (Class 6)	67	60	57
Offshore wind (Class 4)	118	101	91
Offshore wind (Class 6)	104	90	82
Open cycle gas turbine	196	204	223
Combined cycle gas turbine	74	79	94
New supercritical coal	68	69	71
Integrated gasification combined cycle	91	92	93
Nuclear	89	86	86

Wind cost are without US PTC. This significantly lowers their costs

Within renewables, wind energy has undergone the fastest development, which can be explained by both the availability of wind resources around the world, and the great cost-efficiency ratio due to a quick maturity of this technology. [10] The large majority of wind energy is currently provided by onshore turbines. However, this trend is set to change as offshore wind projects are massively being developed. The main advantages of offshore wind compared to onshore are large available spaces, reduction of visual and noise impacts, and better wind conditions. Indeed, wind speed gradually increases with the distance to shore, and decreased turbulences also enhance the efficiency and reduce the fatigue loads on wind turbines. [11] Nevertheless, as shown in Table 1, offshore wind is more expensive than onshore wind, mainly due to marine foundations and cables. Installation and maintenance are also more complicated, mainly because of weather conditions, which lead to delay and higher costs for both construction and operation phases.

1.1.3 Importance of weather forecasting

Weather is a key feature involved in the entire lifecycle of an offshore wind turbine, both on duration of operations and power generation. That is why it is essential to be able to accurately predict the local weather conditions around a wind farm.

First, all construction phases are driven by the weather conditions. Whether it is the building of the foundations or the assembly of other components such as the turbines, all stages involve huge transport and lifting devices. Those activities present high risks, both for safety and in financial terms. Therefore, weather conditions should remain under defined limits, in order to safely control operations and reduce risks as much as possible. In addition, unknown or incorrect climatic conditions might reduce the overall accuracy of operations, which could lead to failure. Forecasting weather also intervenes upon the planification of a project. An error in the weather forecast can delay the operations, which will lead to additional costs for the project holder.

Following installation, weather forecasting is again crucial for maintenance and operation, as it is worth up to 30 % of the total costs of an offshore project. [12] Planning normal maintenance at times when weather conditions are optimal minimises the costs and reduces risks for technicians during transfer operations. Another interest of accurate weather forecasting is to determine the upcoming energy production of an offshore wind farm. This is particularly useful for the integration of renewables within national grids. Indeed, one of the most significant issues with traditional renewables such as offshore wind, is the intermittency and difficulty to predict their output power generation. Increasing the prediction horizon makes the energy production of offshore wind more reliable in such a way that it can be extended on the market at a larger scale.

1.2 Aim and objectives

Overall aim of the present paper is to improve accuracy of weather forecasting for each phase of the lifecycle of an offshore wind farm. The idea is to support the current development of this power generation technology by reducing the potential costs and risks related to weather uncertainties.

First objective is to give the background of offshore wind energy and determine the current state of the art for the methods of weather forecasting. In that respect, the purpose is to summarise industrial and on-going research materials to precisely explain how forecasts are currently being generated by the industry. The intent is to cover all topics related to weather forecast and uncertainty reduction so that the readers can understand the main issues revolving around this subject.

The weather forecast method selected for further analysis is based on the alpha factors. This method is currently being used by the offshore wind industry to assess the uncertainty on forecasted key weather parameters. Thus, the second objective is to analyse and describe the alpha factor method, and to explain its current application in the industry in a way that is easily understandable for non-expert readers.

The third objective is to calculate the alpha factors on a defined case study. The selected one is a future offshore wind farm of *Saint-Nazaire* conducted by EDF Renewables. [13] The goal is to use onsite meteorological and forecasted data, to determine alpha factors calibrated to this precise location. Two different calculation methods for alpha factors are described and one is practically investigated in this present paper.

Finally, the last objective is to analyse the differences between calibrated alpha factors for a specific project, compared to generic values that are almost systematically used within actual projects. Thus, the comparison includes generic and specific alpha factors calculated by the original method. At the end of the day, recommendations to the industry are provided after analysing the results.

1.3 Plan

After explaining the context of offshore wind, the aim and objectives of the study were described within the present introduction, followed by a literature review focusing on the background of weather forecasting for offshore wind applications. Within this section, a description of offshore wind farms and weather influence on offshore projects is given, before listing sources of meteorological data, current methods of weather forecast and uncertainty study, and finally introducing the *Saint-Nazaire* case study. The third section covers the research undertaken, including a short precision of objectives and applied methodology, before explaining alpha factors theory and selected parameters for the study. Then, two calculation methods used to generate calibrated alpha factors are described and a practical application is carried out for the case study of *Saint-Nazaire* in the last part of the section. The fourth section first provides expected results, then a sensibility analysis focuses on influential parameters regarding alpha factors calibration. Finally, tabulated and calibrated alpha factors are compared, and recommendation towards the industry is expressed. The conclusion sums up the main information presented in the report and discusses further work useful to go forward.

2.0 Literature Review

The literature review aims to introduce the work achieved within the context of ongoing research on weather forecasting for offshore wind applications. First, the background of offshore wind farms is described with a quick review of the current main designs of wind turbines. Then, still in the context of offshore wind, the relevant parameters for assessing weather conditions are listed, and a classification of marine operations is made according to their weather sensitivity. The next two sections provide information on the state-of-the-art on meteorological sources of data and weather forecast methods that are currently being used by the offshore wind industry. After uncertainty study of forecasts is described within a dedicated section, the last one introduces the offshore wind project of *Saint-Nazaire*, that is the case study used as reference in the present paper.

2.1 Background of the study

2.1.1 Offshore wind farm

An offshore wind farm aims to collect energy from wind and deliver it to the national grid. In other words, it can be described as a power plant converting wind mechanical power into electricity, that can then be used to supply energy demand. The layout of a typical wind farm is shown on Figure 3.

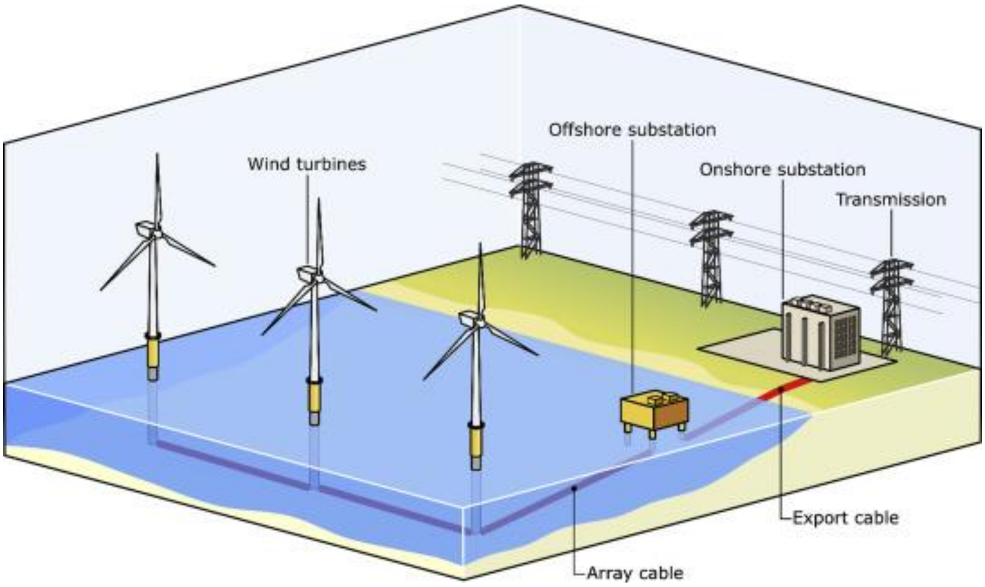


Figure 3: Layout of a typical offshore wind farm [16]

The main parts of an offshore wind farm are the wind turbines, the array and export cables and the two offshore and onshore substations. First, the key components are the wind turbines, which are devices responsible for transforming kinetic energy from the wind into electricity. Their design, size and power output delivery vary according to the environmental conditions such as distance from the shore or water depth. The number of turbines within an offshore wind farm also differs from a few turbines to 174 turbines at a time. [15] Further details on the main wind turbine designs are given in the next section. All turbines are interconnected with each other through an array cable, which is almost systematically submarine. Then, the power produced by the turbines is transferred to the offshore substation where voltage is stabilised and prepared for export to the shore. Transmission from the offshore substation to the shore is provided by the export cable. Located at the end of this cable, the onshore substation ensures that the electricity generated by the wind turbines is properly added to the national grid. For small wind farms, there can only be one onshore substation without any offshore substation.

2.1.2 Main designs of wind turbines

As stated above, conception of wind turbines can lead to several designs. Even if the three-bladed rotor driving a horizontally mounted generator is the most widely spread system of wind turbines, there are also innovative designs such as vertical axis turbines. [16] The main components of a wind turbine are shown on Figure 4.

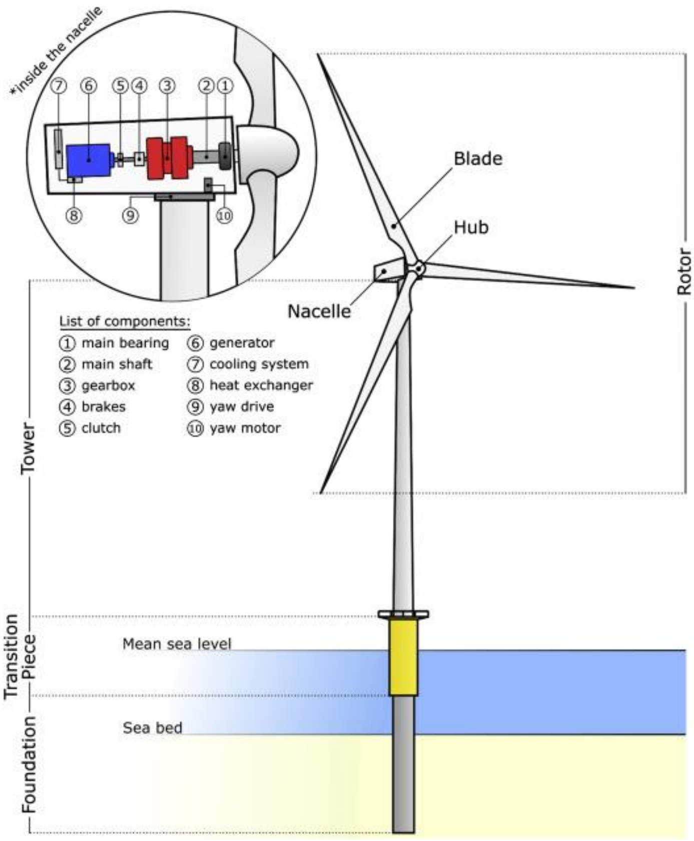


Figure 4: Main components of a wind turbine [16]

A wind turbine is composed of three different parts: a tower, a transition piece, and a foundation. First, the tower is responsible for the generation of electricity through the rotor converting wind energy, which is itself comprised of a nacelle, blades, and a hub. Then, a transition piece allows to link the tower with the foundation. It acts as the junction ensuring that the tower is correctly installed on the foundation. Finally, the foundation is located below sea level. This part sticks in the ground and provides stability for the whole structure of the turbine. Figure 5 lists the main types of foundations used to support offshore wind turbines.

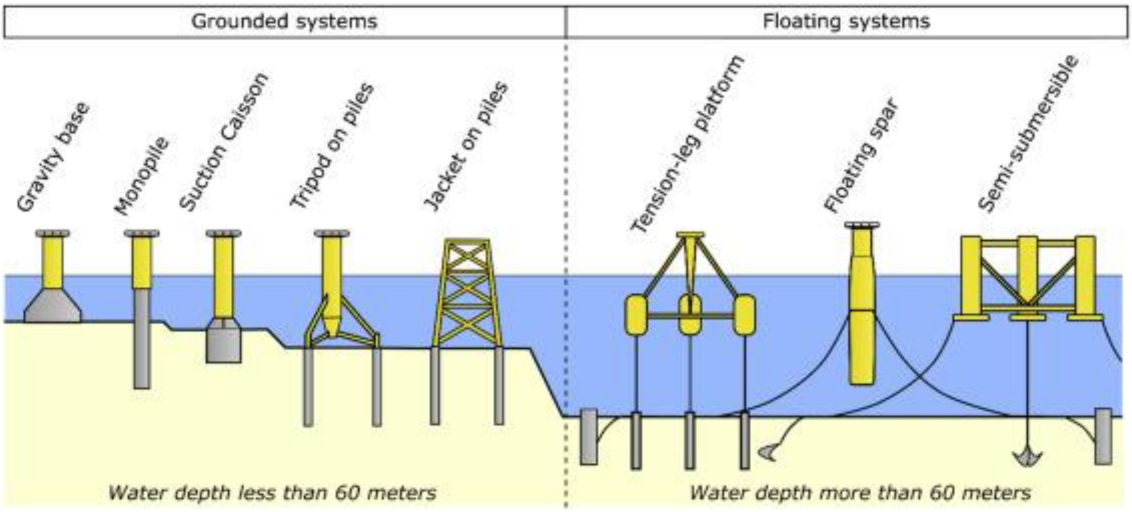


Figure 5: Common types of foundations used to support offshore turbines [16]

The choice of a certain type of foundation mostly depends on the water depth range, and it may significantly impact the costs and the viability of a project. Grounded systems are restricted to projects with a water depth that does not exceed 60 meters, whereas floating systems can go far beyond this limit. Among all types of foundation, monopiles are the most largely used design, involved in 80.6% of European offshore projects in 2018. [17] The main reason for their popularity is due to advantageous costs of construction and installation compared to other designs. However, the limit depth for monopile designs lies around 30 meters, meaning that other systems need to be investigated for greater depths. Such projects are often located further from the shore and eventually involve higher wind speed with less turbulences. In this context, the jacket, gravity base, tripod, and tripile designs account for respectively 8.6%, 6.0% 2.5% and 1.6% of all European offshore wind project in 2018. [17] Floating designs so far only represent prototype projects which still lack maturity to scale up. Indeed, the main costs are, in decreasing order, related to the manufacturing, maintenance, and installation. Among floating systems, the semi-submersible is the cheapest and its competitiveness will certainly be improved progressively as the costs are minimised in the future. [18]

2.2 Weather influence on offshore wind

2.2.1 Relevant weather parameters

The weather may significantly impact the planification of offshore operations, both for installation and maintenance. Indeed, inadequate weather conditions can delay operations as the risk for workers' safety or material degradations become too high. That is why it is crucial to accurately forecast the local wind, waves, and current profiles. The relevant parameters that are generally measured in the offshore industry are given below for each one of the categories based on the DNV GL standards, which is the competent authority in charge of describing all the requirements of offshore wind projects. [19]

Wind parameters

Wind conditions are particularly important to determine the practicability of offshore operations, for example lifting of equipment. The wind speed as well as its direction have to be known to be able to correctly plan such operations. The most important parameter is usually the wind speed at 10 meters high V_d. It can be given as the mean value, either each minute, each 10 minutes, or each hour. The selected time period depends on the type of operations and the precision that is required.

Wave parameters

Wave conditions may also significantly impact the process of offshore operations. In this case, the significant and maximum height, mean or peak period and wave direction have to be measured and forecast. The most usual parameters used in the industry are H_s, T_z and T_p.

- H_s corresponds to the mean height of the highest one third of the waves passing at a given location, which is used by most of the mariners. [19]
- T_z and T_p respectively refer to the zero up-crossing period and the peak period of the waves. In other words, T_z is the average wave period while T_p is the period of the highest frequency of waves. [21]

It is important to mention that often, the full spectrum of the wave energy distribution is determined by measurements.

Current parameters

Another decisive parameter for the viability of offshore operations is the water current speed. For most operations, only the surface current is required. However, some tasks such as drilling and laying of the foundations require knowing current depth values. In this case, weather buoys are equipped with a laser doppler current meter and used to determine the current profile depending on water depth. [22]

Other parameters

The description of weather conditions should also include a general description mentioning sun, rain, snow, lighting, or ice. Visibility, temperature, and barometric pressure are parameters that also need to be measured. Particularly for sensitive operations, tide variations, storm surge and risk of gust should also be considered.

2.2.2 Classification of offshore operations

In practice, offshore operations are classified according to their sensitivity to environmental conditions. This classification imposes the accuracy and the level of uncertainty allowed for weather forecasts. According to the DNV GL standards [19], three different levels can be defined for weather forecasts. Each one of these levels is described below and some examples of marine operations are given for illustration purposes.

Level A1/A2 – Major marine operations highly sensitive to environmental conditions

This category includes all offshore operations that are highly sensitive to weather conditions and involve significant features. For all these operations, a dedicated meteorologist needs to analyse the weather information and forecasts, coming from at least two independent sources. A meteorologist may also be required on site for some specific operations, classified as A1. Level A2 regroups the remaining operations involving less important features and does not require an onsite meteorologist. This category includes for instance, offshore float over, multi barge towing, jack-up rig moves, sensitive laying operations and most of the offshore installation operations. Figure 6 shows Gravity Based Structure (GBS) tow-out operation while Figure 7 represents mating operation of a blade.

Figure 7: Installation of GBS support structures in Thornton Bank offshore wind farm [51]

Figure 6: Installation of blades at SeaMade, Belgium's largest offshore wind farm [52]

Level B – Environmental sensitive operations of significant value or consequences

Level B category refers to moderate sensitivity marine operations that have an important value or consequences on the installation. These operations do not require a dedicated meteorologist but still a minimum of two independent sources of weather forecasts. This is for example the case of small tow-out operations, weather routed sea transports, offshore lifting, subsea installation, semi-submersible rig moves and standard laying operations. Figure 8 exposes the use of Remotely Operated Vehicle (ROV) to carry out subsea operations while Figure 9 shows the transport of blades in a cargo.

Figure 9: ROV used to take subsea pictures of offshore wind foundation [53]

Figure 8: Transportation of blades to offshore wind site [54]

Level C – Conventional marine operations little sensitive to weather conditions

This last category concerns activities with a low sensitivity to environmental conditions. Contrary to levels A and B, only one source of weather forecasts is enough. For instance, level C includes onshore/inshore lifting, load-out operations, short tows in sheltered waters or in harbour tows and standard sea transports without any specified wave restrictions. Figure 10 shows the offloading of incoming wind farm modules using two cranes.

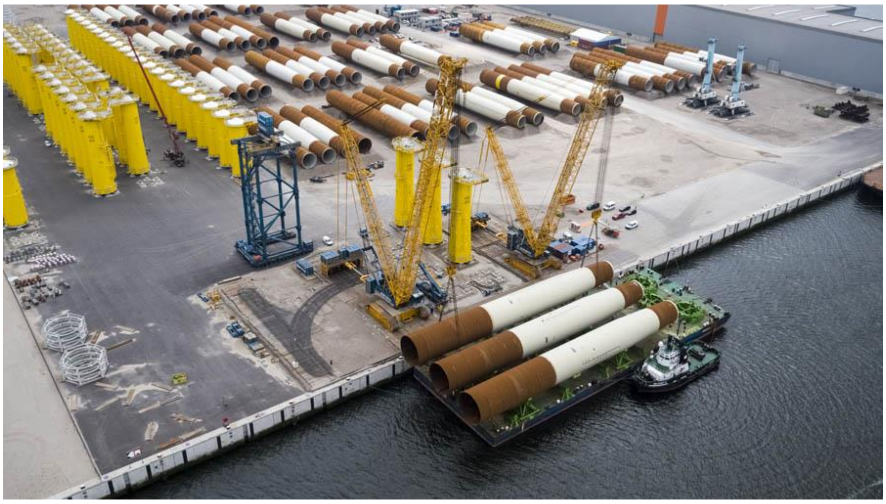


Figure 10: Offloading of offshore wind towers and placing into position on the quay in Rotterdam [55]

2.3 Sources of meteorological data

2.3.1 Observations

The first type of meteorological data comes from observations. This includes actual measurements of weather parameters like temperature, humidity, precipitation, air pressure, wind speed and direction. Different types of weather instruments may be used to collect information on specific weather parameters. Some are basic such as thermometers to measure temperature, barometers for pressure, rain gauges for precipitation or anemometers for wind speed. Others are more sophisticated but more precise and effective. For instance, a radiosonde or "weather balloon" can be used to determine both temperature, pressure, and relative humidity at different elevations. [23] Wind speed and direction, as well as risk of tornado, can be measured precisely using wind profilers or doppler radars. [24] Within the rest of this section, examples of observation devices that are currently being used in the offshore wind industry are given for illustrative purposes.

<u>World Meteorological Organisation</u>

The World Meteorological Organisation (WMO) network is used to collect, exchange, and distribute weather data sets coming from different parts of the world. In particular, the Global Telecommunication System (GTS) is the communication and data management component that ensures near real time access to weather information. GTS is composed of surface synoptic observations, ship and platform observations, upper winds observations, upper temperature soundings, aircraft reports, and severe weather bulletins received from various sources. [25] This network provides major support to access and share global weather data.

<u>Onsite observations</u>

Contrary to GTS, local observation of data can also be performed directly close to the site. This option includes weather stations located onshore near the offshore wind park or sea sensors directly located into the park. In this case, metocean buoys are installed on site to assess local weather conditions as accurately as possible.

<u>Satellite imagery LRIT / HRIT systems</u>

Satellite imagery, especially Long-Range Identification and Tracking (LRIT) and High-Rate Information Transmission (HRIT) systems, provide huge sources of data to assess weather conditions. Updates are made every fifteen minutes and then coupled with the high quality and wide range of data available, which leads to large improvements for prediction of severe weather conditions. These systems include for example atmospheric motion vectors, cloud analysis and height, global instability index, tropospheric humidity. [25] Figure 11 shows the display and processing of weather satellite imagery using the Dartcom iDAP software.

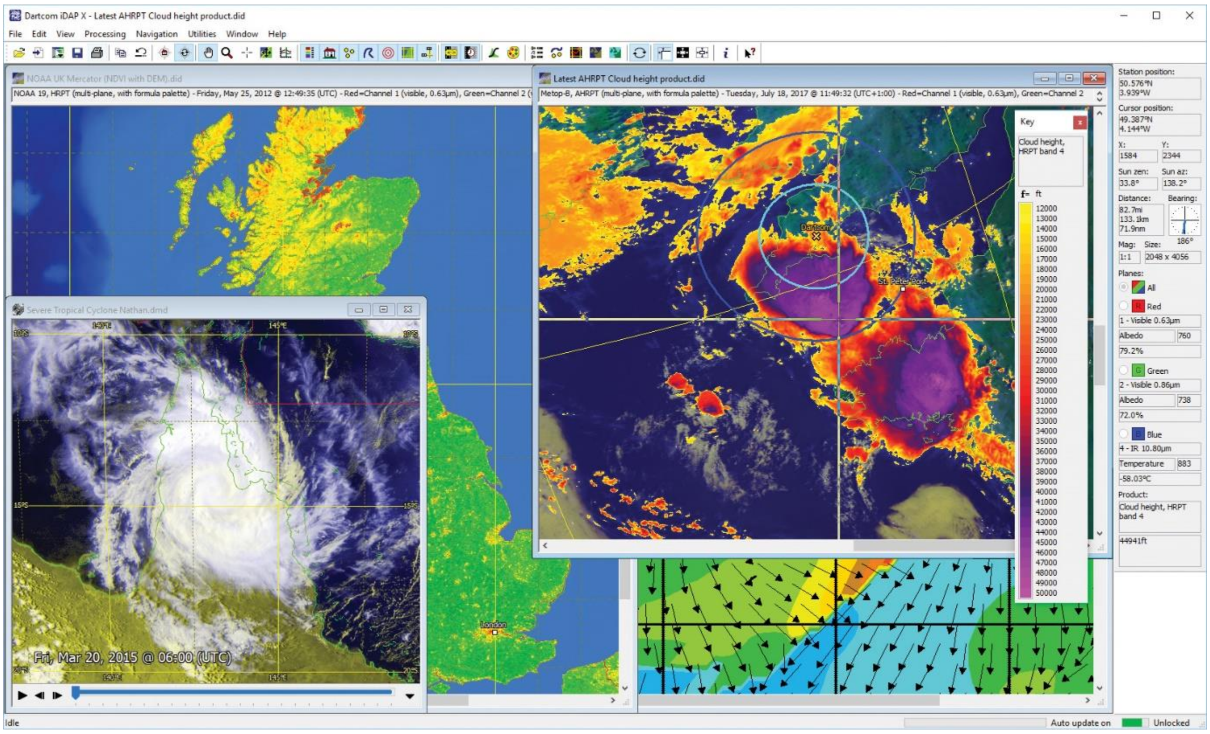


Figure 11: Weather satellite imagery display and processing using the Dartcom iDAP software [56]

2.3.2 Numerical models

Another source of meteorological data originates from numerical simulations. In this case, simulations are based upon models that accurately describe the evolution of weather parameters in time. Atmospheric and wave models are commonly used by the offshore wind industry.

Atmospheric models

Various atmospheric models are used by the offshore wind industry. Nevertheless, they are all mathematical models comprising the key dynamical equations which govern atmospheric motions. They consider in particular solar radiation, moist processes, heat exchange with the soil and ocean, convection, turbulences, and interactions with vegetation. These models are typically able to predict large scale phenomena such as storms or hurricanes, as well as microscale tornadoes. For instance, the National Center for Environmental Prediction (NCEP GFS), [26] the European Center for Medium range Weather Forecast (ECMWF), [27] and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), [28] have developed atmospheric models used in practice for weather forecast.

Swell & Wave model

Global models provide valuable data to assess the weather conditions close to site and accurately predict the main changes. However, each nearshore location is unique and relying on generic models may not be suitable to precisely assess the local behaviours of swell and wave. That is why meteorologists tend to develop nearshore models for site-specific wind, wave, and swell characteristics. Indeed, water depth or complexity of bathymetry impact swell diffraction, meaning that special care needs to be taken to choose a relevant location for the model. Sandbanks also cause high or long waves to break early, or induce waves to bend, adding complexity to models. They usually consider wind sea generation, on-linear waves interaction and dissipation, and also wave shoaling, breaking and refraction. [29]

2.3.3 Software

Within the offshore wind industry, many programmes are used to help in the preparation of weather forecasts. They allow visualisation at various locations and perform analysis of all data models. The software can be run with different inputs like measurements, outputs from weather models, satellite images, or even a combination of both. The main interest is to have a tool to help with data analysis, and to improve accuracy as much as possible. [25]

2.4 Current methods for weather forecast

2.4.1 Classification of forecast

Weather forecast methods are whether deterministic or probabilistic. A deterministic approach relies on a cause-effect relationship to predict the weather analysis. Then, the forecast only depends on the meteorologist’s skills in interpreting the global level of understanding of the phenomenon, the accuracy of the chosen models, and the precision of observations. Conversely, a probabilistic approach is based on different methods to establish an event occurrence/magnitude probability. The main difference with the deterministic approach is that, in the case of a probabilistic approach, uncertainty of the prediction is considered. Both methods have multiple subsets, the most important ones are described in the next subsections. [30] However, in practice a combination of different methods is used by meteorologists to come up with their weather forecast.

Range types are another crucial aspect in the classification of forecasts. Forecasting of the weather within the next six hours is called nowcasting. In this time range, the precision allows to predict small events such as local showers and thunderstorms. Short-range forecast refers to a weather prediction for a time period up to 48 hours, while medium-range forecast stands for a period between three days to one week in advance. After seven days, the forecasts are considered as long-range, and are usually less accurate than short-range forecasts. [30]

2.4.2 Persistence method

Persistence forecasting is the simplest method to predict weather conditions. In fact, the forecast is only based on the current day weather conditions to forecast the conditions of the following day. The accuracy of this method is highly sensitive to the stability of the current weather pattern. In other words, if weather conditions change significantly from day to day, the persistence method may give wrong forecasts, thus it would be preferable to use another method instead. Even if the persistence method might appear useful for short-range weather predictions, it is actually one of the most useful methods to predict long-range forecasts. Indeed, for instance, a hot and dry month is often followed by another hot and dry month, which means that persistence method has an interest for monthly and seasonal predictions. [31]

2.4.3 Synoptic method

Synoptic weather forecasting is the traditional method to determine weather predictions. It is primarily based on the analysis of all data collected from observations made by meteorologists. In practice, meteorologists realise a series of synoptic charts every day such as the one shown on Figure 12. This chart includes various elements such as pressure patterns, warm and cold fronts, and troughs. The idea is to provide an average view of the changes of weather conditions in space.

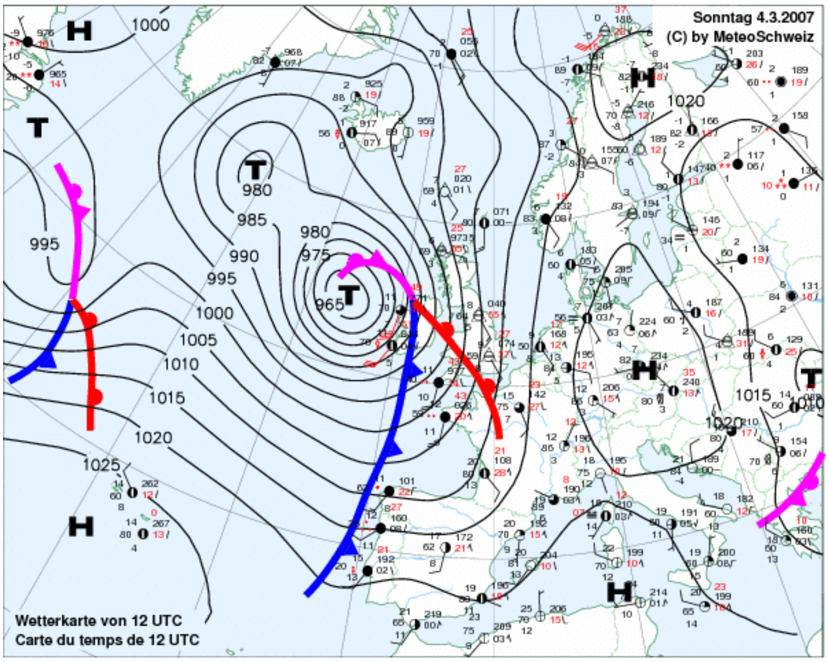


Figure 12: Typical synoptic chart from a "Surada" windstorm in Northern Spain [57]

2.4.4 Numerical Method

Numerical method involves the use of supercomputers to run models with many atmospheric variables and equations, in order to generate forecast of the future weather conditions. The Numerical Weather Prediction (NWP) takes as input observation variables such as temperature, pressure, wind, and rainfall. Then, theoretical models of the atmosphere and physical equations are solved by computer at each nodal point for a short period of time (typically 10 minutes). An iterative process is used to generate forecast for 24h, 48h or 72h. The NWP method highly depends on the precision of models used in the programme. Quantity and quality of data available have also a significant impact on the accuracy of this method. However, the NWP method is probably one of the best methods for short-range forecasting. [31]

2.4.5 Statistical Method

Statistical methods are often used as support to numerical methods. The idea here is to analyse past records of weather data such as for instance average temperatures, average rainfall, or average snowfall to define what the weather is “supposed to be like” at a certain time of the year. The main goal of statistical methods is to identify indicators of past weather record data that are relevant for future predictions. Then, the key issue is to establish correct assumptions for the weather forecast. However, some factors like climate change might distort the statistical analysis as past weather record data can be different from current weather conditions. [31]

2.5 Uncertainty study

2.5.1 Key dimensions of uncertainty

Uncertainty goes beyond the simple concept of an analysis of a probability distribution. It is a major part of daily life, used to make decisions and balance consequences that are the most suitable, both financially, rationally, for safety or even pleasure. In order to classify the different types of uncertainty, its three fundamental dimensions are investigated below.

Nature

First, an uncertainty can be characterised according to the nature of the judgement which is made. This dimension corresponds to all possibilities covered by the uncertainty and the related questions. For instance, the modal uncertainty is defined as what is feasible and what could logically happen. This is the traditional approach to model decision-making process when thinking about the different choices available and the consequences following each possibility. The agent might be unaware of certain states and/or consequences. Then, empirical uncertainty refers to the correct perception of what is the actual status. Even if the agent is aware of all possible states, described by modal uncertainty, they might still be unsure about what the actual state is or what the other states could have been. Finally, normative uncertainty addresses the question of which state would be the best. Indeed, once the modal and empirical uncertainties are solved, the agent knows the actual state and what other states could have been, but they are still not confident about the value attached to each one of the states. [33]

Object

The second dimension of uncertainty is related to the objects of judgements made by the agent. In other words, this refers to the features of reality that the agent focuses on. Factual uncertainty only concerns the actual world, while counterfactual uncertainty is about the non-actual world. This distinction can also be expressed by the perspective: factual uncertainty means that the agent is looking for the understanding of what the things are, whereas for counterfactual uncertainty, the question is about what the things could or would have been if the actual state were different from what it is. [33]

Severity

The last characteristic refers to the difficulty of the agent who has to make a judgement on the different possible states. This may be due to the coherence or the large quantity of available data, but also to the level of judgement and understanding that the agent has on this data. Ignorance is when the agent is not able to make any judgement on the relevant information. Then, severe uncertainty refers to a partial or imprecise judgement, while a mild uncertainty corresponds to a precise judgement with sufficient information. Finally, certainty is when the value of a judgement is fully known. [33]

2.5.2 Methods for quantification of uncertainty

This section does not give a mathematical description of the quantification of uncertainty but only explains key concepts from the main used methods. More details on the calculation are given in the case of alpha factors in section 3.4 and a complete description of other quantification methods can be found in referenced literature. [34]

First, for many decisions, forecasts are used to determine what is more likely to happen, but it is also necessary to know what might happen. The range of all possible outcomes refers to the uncertainty of a decision, characterised by the three dimensions covered in section 2.5.1. In statistics, uncertainty on possible outcomes or forecasts is described as a probability distribution, and quantification of uncertainty means analysing this distribution to produce accurate predictions. There are two main approaches, based on a direct or indirect study. [34]

The direct approach aims to determine the probability that the forecasts exceed a certain limit value or are included in an interval. If the purpose is to know the risk of going above (or below) a threshold limit, the cumulative distribution function gives the chance that the outcome exceeds (respectively is inferior to) a fixed boundary. In case the agent wants to determine if the outcomes are included in an interval, a quantile regression can be performed to produce confidence intervals that include a fraction of all possibilities. [34]

Rather than directly studying the forecast distribution, the indirect approach focuses on errors between the forecasts and “real values” (for example measurements). This method requires more work than a direct approach but is particularly useful to assess and improve a forecast procedure. It is used for the calculation of alpha factors described in the third section. However, a distinction needs to be made between estimation and residual errors. The estimation error defines the theoretical part of the difference between observed values (measurements) and expected values (forecasts). It can be caused by various reasons, but the agent may have an impact on this error by selecting different forecast models or measurement devices. On the contrary, residual errors cannot be improved, as they represent the observable part of the difference between observed values and expected values due to the selected sample. [34] In this paper, this distinction is not considered, and the “error” refers to the sum of estimation and residual errors.

2.5.3 Applications in weather forecast

Assessing uncertainty in weather forecasting can be done by several methods. The most usual one is to use alpha factors that directly quantify the uncertainty. [18] This is the method studied in the present paper. More details on the exact characterisation and calculation of alpha factors are available in the third section.

Even if assessment of uncertainty on weather forecasts should always be required, the Marine Warranty Surveyor (MWS), the competent authority in charge of reviewing the proper execution of offshore wind projects to reduce the risks for contractors, might authorise exceptions. For instance, the accuracy of forecasting might be considered enough, especially when local data is available and high-resolution models are used such as SWAN modelling or Kalman filtering systems. [35]

2.6 *Saint-Nazaire* case study

2.6.1 Background of the project

As one of the first countries to set out ambitious objectives for energy transition, France plans to reach carbon neutrality by 2050 with the legislation of its 2019 Energy and Climate Act. [33] To achieve this long-term target, part of the budget is being allocated to support the energy transition each year, which is the reason why the development of renewable projects, and more particularly offshore wind farms, is economically feasible and encouraged by the French government.

France already has a very low-carbon electricity mix, mainly thanks to nuclear production. Indeed, the French nuclear fleet is the second largest in the world, behind the US. As shown on Figure 13, 70.6% of the electricity generated came from nuclear plants in 2019. The remaining part was mostly produced by hydro (11.2%), natural gas (7.2%), wind energy (6.3%), solar energy (2.2%), and biofuels (1.8%). [34] For the past three decades, the part of fossil fuels in the French energy mix has decreased while natural gas and wind energy have scaled up. This switch can easily be explained by a substitution of fossil fuels energy, large emitter of greenhouse gases, by lower or carbon free sources of energy production. During this time period, the maximum hydro capacity was almost reached, explaining why the part of hydro has decreased a bit since 2004. Indeed, the global electricity production kept increasing whereas no new major hydro features were developed. A similar analysis can be conducted with nuclear energy, as few new installations were realised within the past few years.

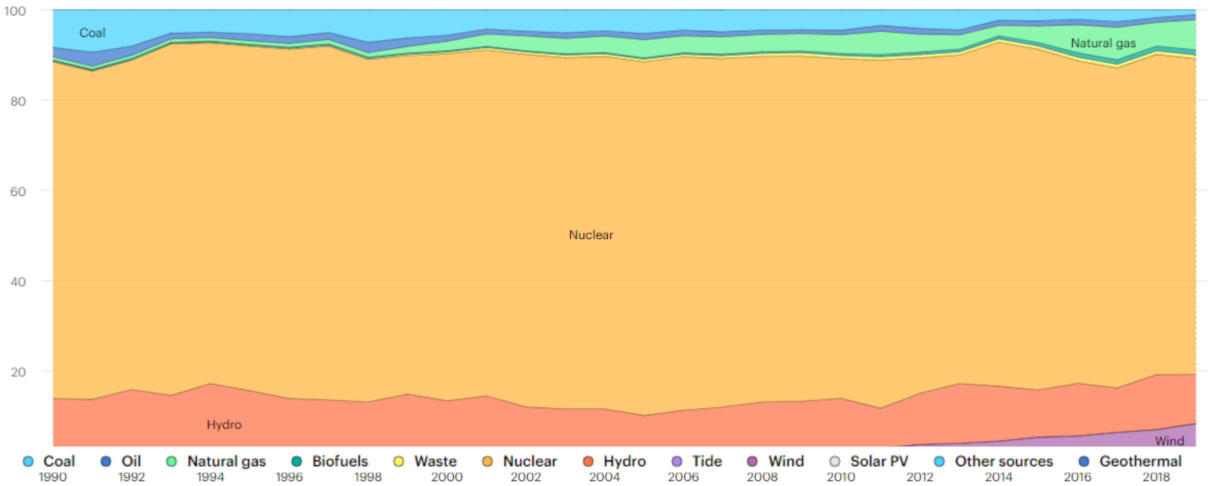


Figure 13: Energy generation by source in France from 1990 to 2019 [36]

Another goal of the Energy and Climate Act is to reduce the part of nuclear power from 70% to 50% in the French electricity mix by 2035. [34] The main reason behind this decision is that many reactors are close to their lifetime operational limit, meaning that they need to be replaced by new installations. In this context, renewables such as offshore wind have a huge potential in the future of the French energy mix due to their flexibility compared to nuclear, and with the recent important cost reductions.

2.6.2 Project description

To scale up offshore wind, the French government launched a tender for the development, construction, and operation of offshore wind farm projects on the 11th of July 2011. EDF Renewables was awarded on the 23rd of April 2012 three sites (*Fécamp*, *Courseulles-sur-Mer* and *Saint-Nazaire*) for a total of about 1.5 GW. They represent the first offshore wind projects for the company in France.

In particular, the project of *Saint-Nazaire* is composed of 80 offshore wind turbines with an individual power generation of 6 MW and a total production of 480 MW. The *Saint-Nazaire* wind farm is located around 35 km from the city of *Saint-Nazaire*, halfway between the *Belle-île* and *Noirmoutier* islands. The exact location is shown on Figure 14. One offshore substation is also planned to be built, and the turbines will be located from 12 to 20 km from the shore. The total area is over 78 km² with water depths ranging from 12 to 25 m.

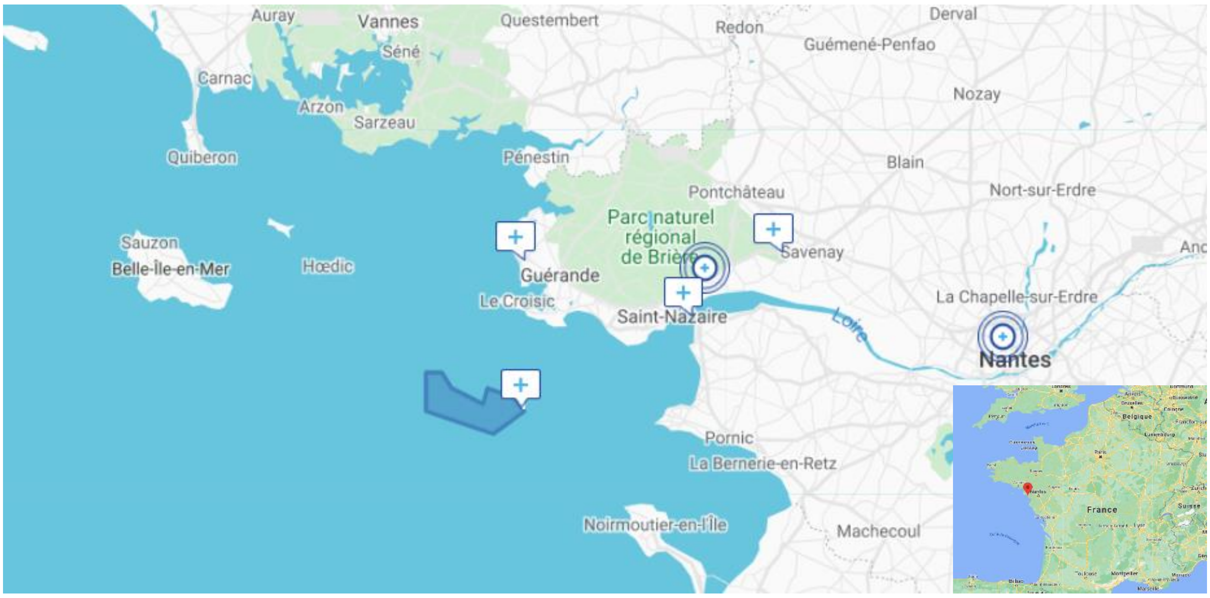


Figure 14: Saint-Nazaire windfarm location [13]

Construction started on the 1st of January 2021 with the first installation of a monopile foundation and should normally be completed by the end of 2022. Afterwards, commissioning of the park will allow the wind generation to connect to the national grid.

2.6.3 Weather data collection and forecast on site

As already explained, construction requires accurate assessment of the weather conditions. That is why two metocean buoys were installed on both sides of the *Saint-Nazaire* project location, for an operational duration of around three years and a half. Figure 15 shows a picture of a similar buoy as the ones installed in *Saint-Nazaire*. The purpose of these devices is to measure the relevant weather parameters onsite. More precisely, they measure the current profile speed and direction every five minutes, the directional waves with the parameters already described in section 2.2.1 such as H_s, T_p or the wave spectra frequency every thirty minutes, and meteorological parameters such as wind speed and direction, barometric pressure, and air temperature every ten minutes.

Figure 15: Metocean buoy installed in Saint-Nazaire [58]

In addition to the on-site measurement devices, a weather forecast service has been contracted. This service involves weather forecast specialists and a meteorologist on-site as an option in case of sensitivity to weather operations (see section 2.2.2). The metocean buoys are used as reference to validate and calibrate the forecast model. Then, it should ensure a good accuracy level of forecasts for at least the following parameters: H_s, wind speed 10min averaged at 10m, wave peak period, and depth averaged current speed. Four actualised weather forecasts are produced a day, for at least the five upcoming days, and with a time resolution that depends on both forecast parameters and time extension of forecast. A confidence factor is given for the forecast data provided as well as a risk value for some wind and wave parameters (e.g. 10% excess probability = 90-percentile).

3.0 Research Undertaken

The research undertaken is the central part of the present paper. Work that has been done during the study is described within this section. Afterwards, readers should precisely understand the main topic of study and be aware of the methodology followed. First, the aim and methodology section recaps and specifies overall objectives already covered in part 1.3. Then, an introduction to alpha factors explains main concepts and its current use in the industry, as well as alternatives for response forecasts. After the description of selected parameters and sources of data for the study, two methods for the calculation of alpha factors are detailed. Finally, a practical calibration process of alpha factors for the *Saint-Nazaire* case study is related in the last part.

3.1 Aim & Methodology

3.1.1 Summary of the issue

Overall objectives of the study are already explained in part 1.3 of the introduction. However, this ongoing section clarifies objectives with more details covered within the literature review, in order to give a precise and concise recap of the addressed issue. As previously described, offshore operations require a detailed knowledge of weather conditions onsite. This is why incorrect predictions on forecasts can lead to additional costs and risks for the different stakeholders.

How to manage uncertainty on forecasts? This is the simple question that leads all decisions made for offshore wind projects. The dilemma here is to correctly balance between optimism and pessimism in order to evaluate the actual weather conditions of upcoming operations. Indeed, too much optimism on weather forecasts means additional weather stand-by during operations, leading to delay and extra costs. On the contrary, high pessimism can cause huge unnecessary weather stand-by provisions. It also reduces the operation window, which means a higher density during summer period when weather usually allows many operations.

3.1.2 Methodology

The current study is restricted to alpha factors' method used to assess uncertainty on weather forecasts. The first step is to do research on this method and analyse its current application in the offshore wind industry. Tabulated values of alpha factors are used on almost every project. The second step is to understand the calculation process behind these factors, and to collect the required information to be able to do this calculation on a case study. The third step focuses on generation of new alpha factors values calibrated to the *Saint-Nazaire* project, which aims to determine the difference regarding generic values on this specific example. Finally, the last step is to investigate a sensitivity analysis of parameters influencing alpha factors such as seasons, forecasted period or limits considered.

3.2 Introduction to alpha factors

3.2.1 Presentation

Alpha factors only stand for uncertainty on a weather forecast for a defined operation and planned period. To clarify a bit more this definition, the DNV GL standards characterises the alpha factor with equation 1. [18]

$$OP_{WF} = \alpha \times OP_{LIM} \quad (1)$$

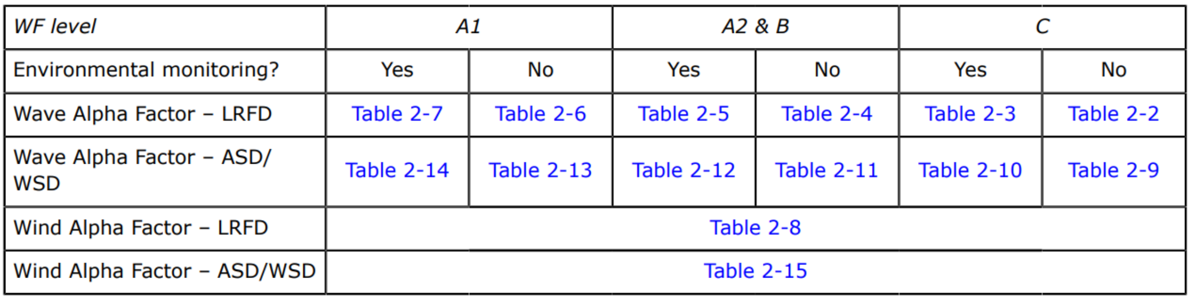
OP_{LIM} is the operational limiting environmental criteria that is described for each marine operation. This is the minimum operational parameter between environmental design criteria, maximum wind and waves parameters that allow a safe work or vessel transfer, specific weather restrictions due to equipment involved, or any other additional limits. With other words, it can be defined as the most limiting parameter of an operation. OP_{WF} is the defined forecast of this operational criteria.

With this characterisation, alpha factors downgrade the operational limiting environmental criteria to its forecast to account for uncertainty of predictions. As a result, the alpha factor directly corresponds to the ratio between the operational limit considered and its forecast, between 0 and 1. An alpha factor equal to 0 implies a huge difference between forecast and operational limit, while a 1 value represents a perfect forecast, which is the ideal case where there is no uncertainty at all.

3.2.2 Tabulated values

Within the DNV GL standards, tabulated values for alpha factors are given. They result from the calculation of alpha factors for several projects, using the method described in part 3.4.2. First, Table 2 shows which table includes the tabulated alpha factors to consider. This selection depends on the level of sensitivity to weather of the operation considered (see section 2.2.2 for more details), onsite environmental monitoring systems (see section 2.4.4) and finally operational limiting environmental criteria. More particularly, there are tables tabulated for wave and wind operational limits. For each weather parameter, two design methods are considered: the Load and Resistance Factor Design, or LRFD, and the Allowable Stress Design, or ASD (same as Working Stress Design or WSD). LRFD refers to a design factor specific to the type, load, and failure mode of a defined situation, [37] while ASD is only based on the verification that maximum stress is below an allowable value. [38] Even if both methods are used in the industry, LRFD is more recent than ASD but is slightly more used, which can be explained by the specificities included within this method.

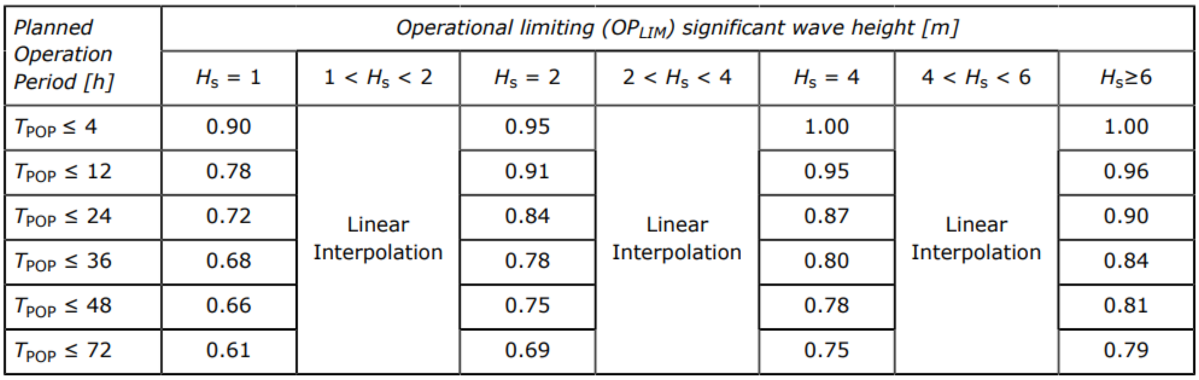
Table 2: Selection of Alpha Factor table [18]



WF level	*A1*		*A2 & B*		*C*	
Environmental monitoring?	Yes	No	Yes	No	Yes	No
Wave Alpha Factor – LRFD	Table 2-7	Table 2-6	Table 2-5	Table 2-4	Table 2-3	Table 2-2
Wave Alpha Factor – ASD/ WSD	Table 2-14	Table 2-13	Table 2-12	Table 2-11	Table 2-10	Table 2-9
Wind Alpha Factor – LRFD	Table 2-8					
Wind Alpha Factor – ASD/WSD	Table 2-15					

To specify a bit more, Table 3 gives an example of a table containing tabulated alpha factors for waves using the LRFD method for level A1 operations, in the case of environmental monitoring. As shown below, the operational limiting environmental criteria considered is the significant wave height H_s. For wind, the speed V_d represents the operational limiting environmental criteria, compared to half of the 10-year return wind speed, which means maximum wind speed expected to be witnessed once at the studied location. [39]

Table 3: LRFD Alpha Factor for waves, Level A1 – with environmental monitoring [18]



Planned Operation Period [h]	*Operational limiting (OP_{LIM}) significant wave height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 4$	0.90	Linear Interpolation	0.95	Linear Interpolation	1.00	Linear Interpolation	1.00
$T_{POP} \leq 12$	0.78		0.91		0.95		0.96
$T_{POP} \leq 24$	0.72		0.84		0.87		0.90
$T_{POP} \leq 36$	0.68		0.78		0.80		0.84
$T_{POP} \leq 48$	0.66		0.75		0.78		0.81
$T_{POP} \leq 72$	0.61		0.69		0.75		0.79

Before explaining the method to read this table, one last term needs to be explained: T_{POP}. It refers to the planned operation period, which means the theoretical duration of operation, usually in hours. In the case of forecasts, T_{POP} also stands for the predicted period covering the weather predictions. For example, if T_{POP} equals 24 hours, the forecasts should at least be produced the day before the start of operations (more precisely 24 hours before). As already seen in section 2.4.1, the accuracy of forecasts often decreases over time, leading to choosing forecasts as close as possible to the start of operations.

Once everything is explained, this table can be read easily. As described above, each line refers to a maximum period covered by forecasts, while each column appoints a maximum value for the operational limiting environmental criteria, here H_s. The intersection corresponds to the tabulated alpha factor value for these two parameters. For example, tabulated alpha factor values for a planned operation up to 24 hours and an H_s limit of 1 m is 0.72, still for a 24-hours prediction horizon but for an H_s limit of 4 m, it increases to 0.87. For intermediate wave heights, linear interpolation should be used. [40]

Within a table, longer planned periods for operation reduce the values of alpha factors because of uncertainty increasing for longer weather forecasts. On the contrary, higher wave height limit values minimise global strength, meaning larger variations allowed and less uncertainty on forecasts with alpha factors closer to 1.

Among several tables, the presence of environmental monitoring logically reduces uncertainty on weather forecasting, which implies higher values of alpha factors. Weather sensitivity level also impacts alpha factors values with a global increase from level A1 to C. However, this improvement mostly concerns long planned periods and is not as significant below 24 hours. Finally, ASD/WSD alpha factors are smaller than corresponding LRFD values, due to higher precision involved in the LRFD method.

3.2.3 Framework for use of response forecasts

As previously described, tabulated alpha factors values are almost systematically used to assess uncertainty on weather forecasts. However, alternative methods exist depending on the statistical weather data available. In this case, new sets of alpha factors can be generated in response to measurements made on site. This key topic was discussed within a Join Industry Project (JIP) on reliability of weather forecasts. [41] JIP is a global workshop, which involves several actors from the offshore industry, such as EDF Renewables or DNV GL, and aims for a global technological improvement for the sector as a whole. Three alternate methods have been investigated and are briefly described below.

Establishing uncertainty adjustment factor

This first method mainly relies on tabulated alpha factors introduced in part 3.2.2. However, the intent is to consider an uncertainty adjustment factor (named β) to model more accurately a situation. As a result, the characterisation equation of uncertainty on weather forecasts is replaced by equation 2.

$$OP_{WF} = \alpha \times \beta \times OP_{LIM} \quad (2)$$

The alpha factor considered here remains the same compared to tabulated values described in parts 3.2.1 and 3.2.2. Introducing a beta factor mostly aims to account for various adjustments regarding monitoring, weather forecast levels and also response forecasting available onsite. Thus, to establish beta factors, it is necessary to quantify those impacts on uncertainty, based on general evaluations of several locations. [41]

Project specific alpha factors

Contrary to tabulated alpha factors and adjustments with beta factors, this second method is totally specific to a single project. The idea here relies on a case-by-case calculation of alpha factors for each project. In that respect, statistically representative historical forecast data and measurements of project location are used as basis for the generation of specific alpha factors. This is the selected method covered in the present paper: details on calculation are given in section 3.4 and a calibration is performed for the case study of *Saint-Nazaire* in part 3.5.

Ensemble forecast

The last method which has been investigated completely differs from both previously described methods. Here alpha and beta factors are no longer applied, as uncertainty on forecast only depends on specified levels of confidence. This method stands for high accuracy weather forecasts where uncertainties are quantified within the model. In this case, uncertainty identification arises from a combination of factors such as input parameters, simulation models, type of operation, ensemble techniques and consequences of failure considered. This method echoes high resolution models mentioned in section 2.5.3. [34]

3.3 Selected parameter for the study

3.3.1 Restriction to wave height

According to the DNV GL standards, [18] wave height highly restricts offshore wind operations. This is why many tables account for uncertainty in the forecast of this specific parameter. The H_s value is chosen for the present study, both because of its significance on offshore operational limitations and due to the large quantity of tabulated values available for comparison. However, this section aims to question this choice.

Wave conditions often follow a predefined pattern, called wave spectrum, such the one-peak JONWAP wave spectrum [42] or the two-peaks Torsethaugen wave spectrum. [43] Representing this pattern requires two main parameters: the significant wave height H_s and the peak period T_P (or zero up-crossing period T_z). Figure 16 shows uncertainty respectively for wave height and peak period for 24 hours and 72 hours prediction horizons. In addition to uncertainty on H_s, forecasted wave periods differ from actual measurements. As a result, uncertainty on wave period is not taken into account by alpha factors and might be relevant to consider for highly sensitive operations such as installation of foundations.

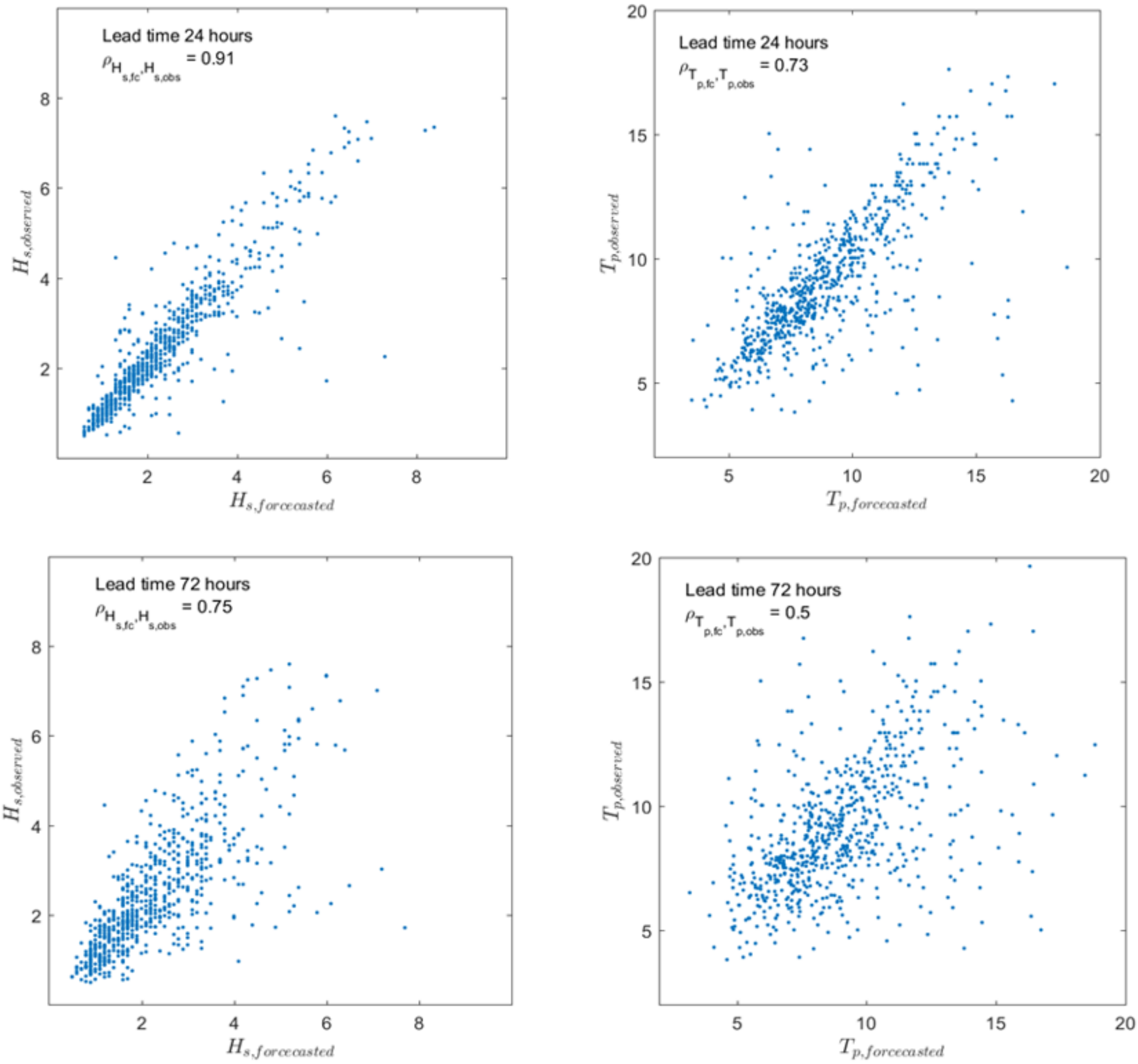


Figure 16: Comparison of uncertainty for T_p and H_s forecasts [41]

Besides, alpha factors also do not account for uncertainty on wave directions, as well as swell influence and deviation, which are usually included in model assumptions and simplifications. Thus, alpha factors only consider uncertainty on wave height, and it can be argued that their present calculation does partially cover the uncertainty on wave forecasts.

3.3.2 Sources of data

As already mentioned in section 2.6.3, two metocean buoys are installed in Saint-Nazaire and constitute local measurement devices. This measure data is provided by NortekMed, [44] while weather forecast is realised by MeteoGroup. [45]

Weather measures

Acquisition of local weather parameters is realised every thirty minutes and historical data is available remotely. The measurements include maximum and significant wave heights, as well as zero up-crossing and peak periods. There are also other parameters related to wave direction or wind and current profiles. Figure 17 shows measured significant and maximum wave heights from one of the two buoys installed in *Saint-Nazaire* over a month in July 2021.

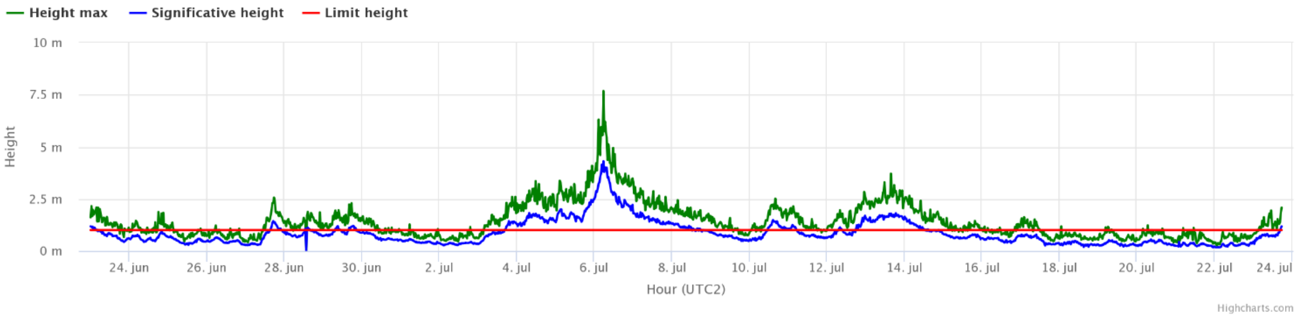
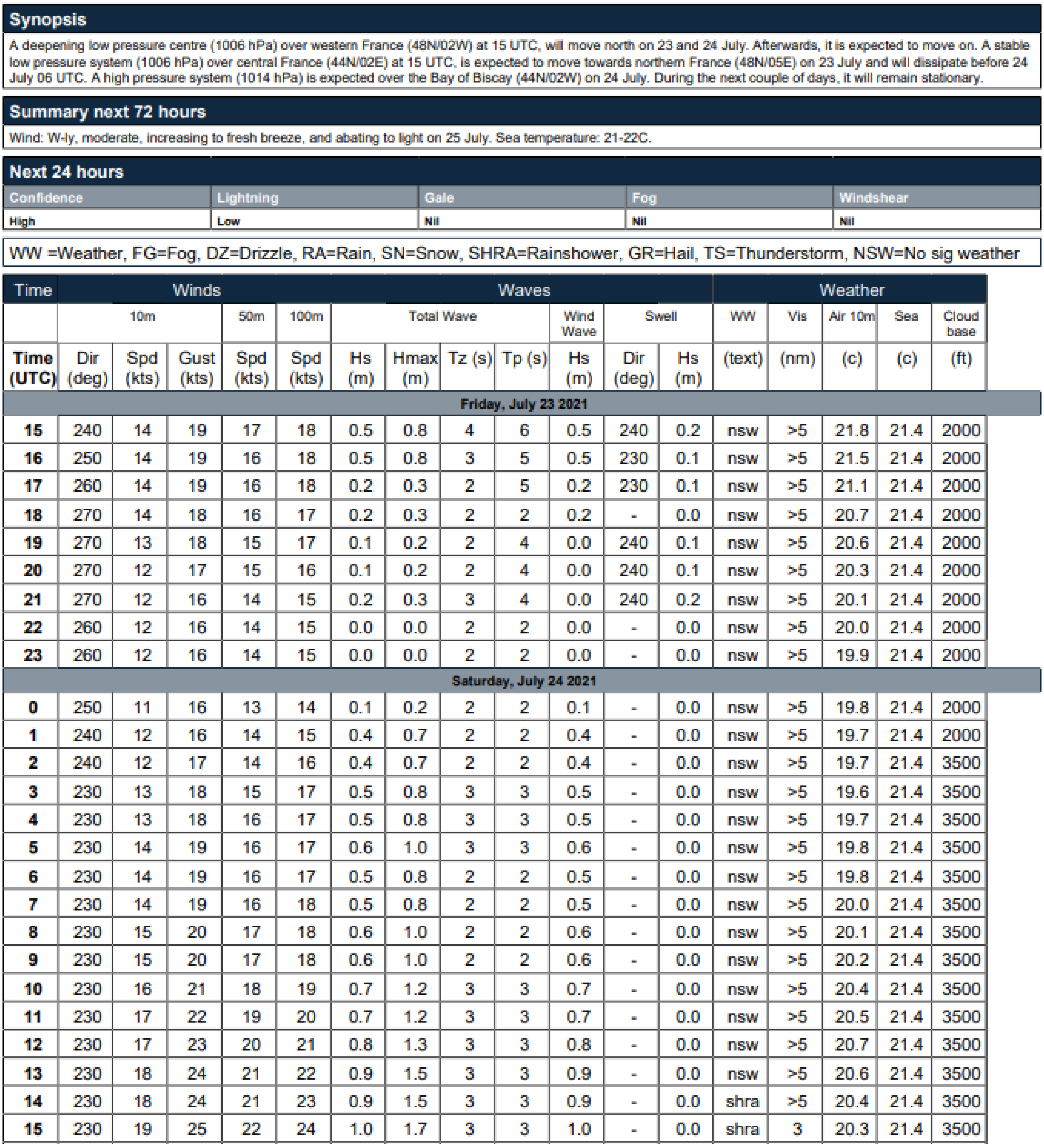


Figure 17: Significant and maximum wave heights from measurements realised in Saint-Nazaire in July 2021 [44]

The operational criterion is set here to 1m (red line on Figure 17). After exporting this data on Excel, it is possible to examine the wave profiles compared to defined limits. These measures correspond to the input data used in part 3.5.1.

Weather forecast

As mentioned in section 2.6.3, four weather forecasts are produced a day for *Saint-Nazaire*. Figure 18 shows an extract of the weather forecast table for the upcoming days issued on Friday 23rd of July at 4pm.



Synopsis

A deepening low pressure centre (1006 hPa) over western France (48N/02W) at 15 UTC, will move north on 23 and 24 July. Afterwards, it is expected to move on. A stable low pressure system (1006 hPa) over central France (44N/02E) at 15 UTC, is expected to move towards northern France (48N/05E) on 23 July and will dissipate before 24 July 06 UTC. A high pressure system (1014 hPa) is expected over the Bay of Biscay (44N/02W) on 24 July. During the next couple of days, it will remain stationary.

Summary next 72 hours

Wind: W-ly, moderate, increasing to fresh breeze, and abating to light on 25 July. Sea temperature: 21-22C.

Next 24 hours

Confidence	Lightning	Gale	Fog	Windshear
High	Low	Nil	Nil	Nil

WW =Weather, FG=Fog, DZ=Drizzle, RA=Rain, SN=Snow, SHRA=Rainshower, GR=Hail, TS=Thunderstorm, NSW=No sig weather

Time	Winds					Waves							Weather				
	10m			50m	100m	Total Wave				Wind Wave	Swell		WW	Vis	Air 10m	Sea	Cloud base
Time (UTC)	Dir (deg)	Spd (kts)	Gust (kts)	Spd (kts)	Spd (kts)	Hs (m)	Hmax (m)	Tz (s)	Tp (s)	Hs (m)	Dir (deg)	Hs (m)	(text)	(nm)	(c)	(c)	(ft)
Friday, July 23 2021																	
15	240	14	19	17	18	0.5	0.8	4	6	0.5	240	0.2	nsw	>5	21.8	21.4	2000
16	250	14	19	16	18	0.5	0.8	3	5	0.5	230	0.1	nsw	>5	21.5	21.4	2000
17	260	14	19	16	18	0.2	0.3	2	5	0.2	230	0.1	nsw	>5	21.1	21.4	2000
18	270	14	18	16	17	0.2	0.3	2	2	0.2	-	0.0	nsw	>5	20.7	21.4	2000
19	270	13	18	15	17	0.1	0.2	2	4	0.0	240	0.1	nsw	>5	20.6	21.4	2000
20	270	12	17	15	16	0.1	0.2	2	4	0.0	240	0.1	nsw	>5	20.3	21.4	2000
21	270	12	16	14	15	0.2	0.3	3	4	0.0	240	0.2	nsw	>5	20.1	21.4	2000
22	260	12	16	14	15	0.0	0.0	2	2	0.0	-	0.0	nsw	>5	20.0	21.4	2000
23	260	12	16	14	15	0.0	0.0	2	2	0.0	-	0.0	nsw	>5	19.9	21.4	2000
Saturday, July 24 2021																	
0	250	11	16	13	14	0.1	0.2	2	2	0.1	-	0.0	nsw	>5	19.8	21.4	2000
1	240	12	16	14	15	0.4	0.7	2	2	0.4	-	0.0	nsw	>5	19.7	21.4	2000
2	240	12	17	14	16	0.4	0.7	2	2	0.4	-	0.0	nsw	>5	19.7	21.4	3500
3	230	13	18	15	17	0.5	0.8	3	3	0.5	-	0.0	nsw	>5	19.6	21.4	3500
4	230	13	18	16	17	0.5	0.8	3	3	0.5	-	0.0	nsw	>5	19.7	21.4	3500
5	230	14	19	16	17	0.6	1.0	3	3	0.6	-	0.0	nsw	>5	19.8	21.4	3500
6	230	14	19	16	17	0.5	0.8	2	2	0.5	-	0.0	nsw	>5	19.8	21.4	3500
7	230	14	19	16	18	0.5	0.8	2	2	0.5	-	0.0	nsw	>5	20.0	21.4	3500
8	230	15	20	17	18	0.6	1.0	2	2	0.6	-	0.0	nsw	>5	20.1	21.4	3500
9	230	15	20	17	18	0.6	1.0	2	2	0.6	-	0.0	nsw	>5	20.2	21.4	3500
10	230	16	21	18	19	0.7	1.2	3	3	0.7	-	0.0	nsw	>5	20.4	21.4	3500
11	230	17	22	19	20	0.7	1.2	3	3	0.7	-	0.0	nsw	>5	20.5	21.4	3500
12	230	17	23	20	21	0.8	1.3	3	3	0.8	-	0.0	nsw	>5	20.7	21.4	3500
13	230	18	24	21	22	0.9	1.5	3	3	0.9	-	0.0	nsw	>5	20.6	21.4	3500
14	230	18	24	21	23	0.9	1.5	3	3	0.9	-	0.0	shra	>5	20.4	21.4	3500
15	230	19	25	22	24	1.0	1.7	3	3	1.0	-	0.0	shra	3	20.3	21.4	3500

Figure 18: Extract of weather forecasts issued on Friday 23rd of July [45]

Just as measures, forecasts also include the main relevant weather parameters such as H_s, H_{max}, T_z and T_p, but also additional data on wind and swell for instance. In addition, there is also a synopsis which sums up upcoming weather changes and a description of the upcoming 72 hours weather conditions. For the next 24 hours, a confidence interval and risks of lighting, gale, fog, and windshear are specified. This is the data used for forecasts in part 3.5.1.

3.4 Calculation methods of alpha factors

3.4.1 Notations and preamble

First, basic notations involved in calculation of alpha factors are introduced:

- $h_{s,meas}$ refers to historical measurements of wave significant height realised onsite during a given time period.
- $h_{s,wf}$ corresponds to historical forecasts of wave significant height for the same location during a given time period.
- n stands for the number of sea states during a given time period.
- T_{FP} represents the duration covered by forecasts, or lead time, i.e., delay from the last issuance of forecasts achievement to the effective period that has been forecasted. In practice, this duration should add the planned period of operations T_{POP} and the contingency time T_C that is supposed to cover uncertainties between effective duration of operations compared to predicted duration. More details on this calculation are given in the DNV GL standards. [18]

Equation 3 describes the statistical error ε considered bins of $h_{s,meas}$ and $h_{s,wf}$, more details are available in section 2.5.3. This difference is calculated for different lead times (12h, 24h, 36h, 48h and 72h).

$$\varepsilon = h_{s,wf} - h_{s,meas} \quad (3)$$

The mean error (bias) and sample standard deviation are respectively defined by equations 4 and 5. With N the number of sea states considered in each group, corresponding to the number of values.

$$M_{err} = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_i \quad (4)$$

$$S_{err} = \sqrt{\frac{\sum_{i=1}^{N}(\varepsilon_i - M_{err})^2}{N-1}} \quad (5)$$

All these notations allow to define the probability density of forecast uncertainty for a given h_s measured value, which is assumed to follow the normal distribution described in equation 6. [41]

$$f_{wf}(x|H_s) = \frac{1}{\sqrt{2\pi}\,\sigma(H_s)} e^{-\frac{1}{2}\left(\frac{x-\mu(H_s)}{\sigma(H_s)}\right)^2} \quad (6)$$

With the mean value and standard deviation respectively given by equations 7 and 8.

$$\mu(H_s) = H_s - M_{err} \quad (7)$$

$$\sigma(H_s) = S_{err} \quad (8)$$

Then, it is assumed that the maximum wave height for a given H_s and X=x follows a Rayleigh distribution, as expressed in equation 9. [41]

$$F_{Hmax}(H_{max}|x, H_s) = \left[1 - exp\left(-2\left(\frac{H_{max}}{x(H_s)}\right)^2\right)\right]^n \quad (9)$$

In the JIP project, the number of sea states is given by equation 10. [41]

$$n = \frac{T_{FP}}{T_{z,mean}} \quad (10)$$

Here $T_{z,mean}$ refers to the average of the upper and lower limits defined in the rules given by the DNV GL in 1996, given by equation 11. [46] Justifications for establishing this formula are not addressed in the present paper, but its practical determination is detailed in section 3.5.3.

$$T_{z,mean} = \frac{1}{2}(2.52{H_s}^{0.52} + 13) \quad (11)$$

Finally, an ultimate result useful before describing the alpha factor calculation methods concerns the H_{max} probability distribution. During operations, having a probability of exceedance a maximum wave height limit equals to *q* is defined by equation 12 for a given significant wave height H_s.

$$1 - F_{Hmax}(H_{max}|H_s) = q \quad (12)$$

A combination of equations 9 and 12, leads to equation 13 providing, any calculations made, the maximum wave height limit for the probability and significant wave height considered.

$$H_{max} = H_s\sqrt{-\frac{1}{2}ln(1 - (1 - q)^{1/n})} \quad (13)$$

3.4.2 Original method

This section relates the standard procedure to calculate alpha factors and keeps using notations defined in section 3.4.1. This method applies to a defined forecast duration T_{FP} and an operational criterion $h_{s,thr}$ corresponding to the significant wave height limit considered for the ongoing operation. Figure 19 shows a graphical representation of the original method, which is detailed below. [41]

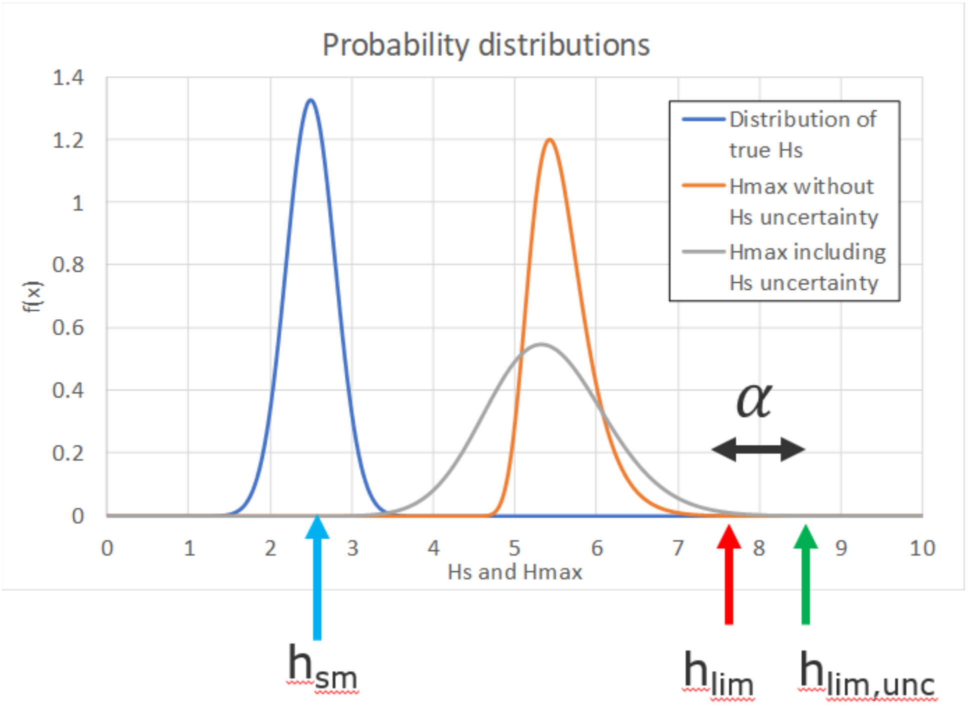


Figure 19: Graphical description of the original method for alpha factors calculation [47]

The first step is to calculate h_{lim} defined using equation 14.

$$P\left(H_{max} > h_{lim} \middle| h_{s,thr}\right) = 1 - P\left(H_{max} \leq h_{lim} \middle| h_{s,thr}\right) = q \quad (14)$$

This value stands for the height limit beyond which the probability of maximum waves being above this value is equal to q during a forecasted period T_{FP} for a defined $h_{s,thr}$. According to the DNG GL standards, q is chosen equal to 10^{-4}. [18] Mathematically speaking, h_{lim} represents the (1-q) quantile of the H_{max} distribution over the forecasted period, which means that a (1-q) fraction of the height of maximum waves is below h_{lim} while q (e.g. 10^{-4}) is above this limit.

Equation 14 is a direct application of equation 12 using the distribution function, which means that h_{lim} can be expressed with equation 15.

$$h_{lim} = h_{s,thr}\sqrt{-\frac{1}{2} ln(\, 1 - (1 - q)^{1/n})} \quad (15)$$

Then, the second step is to calculate $h_{lim,unc}$ using equation 16.

$$P\left(H_{max} > h_{lim,unc} \middle| h_{s,thr}\right) = q \quad (16)$$

This value has the same interpretation as h_{lim}. However, this time, uncertainty on the H_{max} distribution is considered. Practically, the calculation is done through equation 17 and uses the normal error and Hmax distributions respectively defined by equations 6 and 9.

$$P\left(H_{max} > h_{lim,unc} \middle| h_{s,thr}\right) = \int P\left(H_{max} > h_{lim,unc} \middle| h_{s,wf}\right) \cdot f_{wf}\left(h_{s,wf} \middle| h_{s,thr}\right) \cdot dh_{s,wf} \ (17)$$

Finally, once equation 16 is solved, alpha factor is obtained using equation 18.

$$\alpha = \frac{h_{lim}}{h_{lim,unc}} \ (18)$$

The value found corresponds to a defined forecast period and a given operational limit and is tabulated to a precise case study. Repeating the above procedure allows to generate a branch of tabulated alpha factors for several forecast periods, as well as other operational limits, which is the methodology used to generate the tables of values in section 4.3.1. Please note that q could also be a relevant parameter to run a sensibility analysis for but it is not covered within this paper.

3.4.3 Revised method

This section describes a revised method to calculate alpha factors discussed during the JIP on reliability weather forecasting. [46] As well as the original procedure, this method stands for a defined forecast duration T_{FP} and an operational criterion $h_{s,thr}$. Figure 20 shows a graphical representation of the revised procedure, which is detailed below. [41]

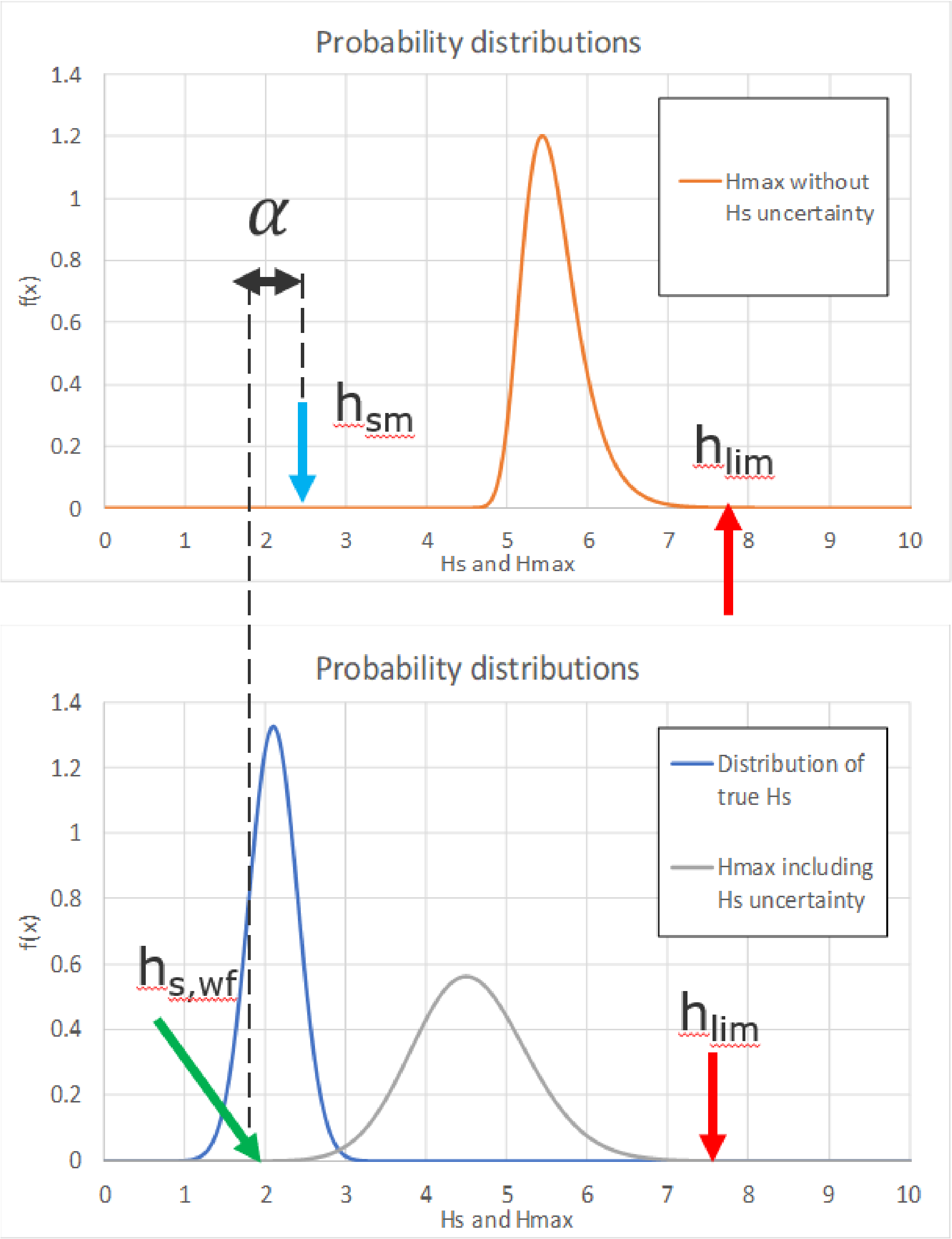


Figure 20: Graphical description of the revised method for alpha factors calculation [47]

The first step remains the same as in the original procedure, h_{lim} is calculated using equation 15 for a probability q sets equal as 10^{-4}. Once h_{lim} is determined, $h_{s,thr,wf}$ can be calculated with equation 19.

$$P\left(H_{max} > h_{lim} \middle| h_{s,thr,wf}\right) = q \quad (19)$$

The adopted point of view here differs from the original procedure where the idea is to keep studying the H_{max} distribution. Conversely, the revised procedure focuses on the H_s weather forecast distribution. Equation 20 gives the practical calculation of $h_{s,thr,wf}$.

$$P\left(H_{max} > h_{lim} \middle| h_{s,thr,wf}\right) = \int P(H_{max} > h_{lim}|x) \cdot f\left(x \middle| h_{s,thr,wf}\right) \cdot dx \quad (20)$$

This last equation helps understanding the mathematical meaning of $h_{s,thr,wf}$. Indeed, it can be defined as the theoretical operational criterion that should be considered to allow a fraction q of maximum waves to exceed h_{lim}. Contrary to the original method, this limit is no longer chosen regarding the uncertainty on maximum waves distribution but directly on the forecast significant wave height $h_{s,wf}$. To clarify, $h_{s,thr,wf}$ corresponds to the operational criterion that should be considered instead of $h_{s,thr}$ in order to include uncertainty of forecasts.

Finally, once equation 19 is solved, the alpha factor is obtained using equation 21.

$$\alpha = \frac{h_{s,thr,wf}}{h_{s,thr}} \quad (21)$$

This new alpha factor compares the « true » operational criterion $h_{s,thr}$ used as a fixed parameter in the original method to the calculated operational criterion $h_{s,thr,wf}$ that should be theoretically considered on forecasts. Like the original method, repeating the above procedure allows to generate a branch of tabulated alpha factors.

However, this method is not investigated within this paper. Compared to the original methods, it benefits from directly focusing on the significant wave heights, which is logical as this is the most used parameter through marine operations.

3.5 Practical application for *Saint-Nazaire* case study

3.5.1 Collection and classification of input data

As stated in section 3.3.2, weather measures are available online and can be directly exported to Excel for a chosen period of time. This is a bit different for forecasts where an API is required to upload data into Excel. An Excel document called "A1-BeauryInputs" is available in Appendix and includes all the work described within this section. Dedicated datasheets named "Measures" and "Forecasts" respectively give inputs data used for the calibration of alpha factors to the case study of *Saint-Nazaire*. Study only focuses on significant wave heights, meaning that other parameters included in these datasheets have not been analysed. Records of weather measures and forecasts respectively start on the 1st of January 2020 and the 16th of December 2019. Thus, input data used in the study covers a one year and a half total duration.

Then after data collection, the next step concerns formatting. Indeed, forecasts need first to be assigned with measures which they apply. These bins of forecast with corresponding measure allow to calculate the statistical error on wave height predictions. After that, bins are classified regarding several parameters: season (Winter, Spring, Summer, Autumn), wave height group (0-1m, 1-2m, 2-3m, 3-4m, 4-5m, 5-6m, 6->m) and forecasted period (4h, 12h, 24h). Please note that the inputs considered do not provide forecasted periods exceeding 24 hours. These classified bins of values are available in “Winter”, “Spring”, “Summer”, and “Autumn” datasheets. Another classification realised concerns forecasts produced after the 1st of May 2021, which uses a new high-resolution method. [45] Corresponding bins are available in the “New forecasts method” datasheet and assessing the effectiveness of this method is one of the objectives investigated.

Before going further, the readers need to be aware of limiting points concerning the data available. Indeed, due to changing patterns in forecast inputs, only a forecasted period of 4 hours is available during summer. More generally, 12-hours and 24-hours forecasts include less values than 4-hours forecasts. This is also the case for wave height groups above 4 meters, mainly because of the low likelihood of extreme conditions at the *Saint-Nazaire* location. These last points make sense regarding the sensitivity analysis conducted in section 4.2.

3.5.2 Generation of error distribution

Once data is collected and formatted in different groups, it is possible to calculate the statistical error using equation 3 for each bin of forecast and measure. For each group defined according to the season, wave height group and forecasted period, mean error and standard deviation can be respectively determined with equations 4 and 5. These values are accessible in a dedicated datasheet called “Mean & Standard deviation” and are listed in section 4.1.1.

Then, the distribution of statistical errors can be generated for each group previously defined, using a normal distribution with mean value and standard deviation respectively given by equations 7 and 8. Figure 21 shows an example of error distribution for the group with significant wave heights between 1 and 2 meters and a forecasted period of 4 hours during winter.

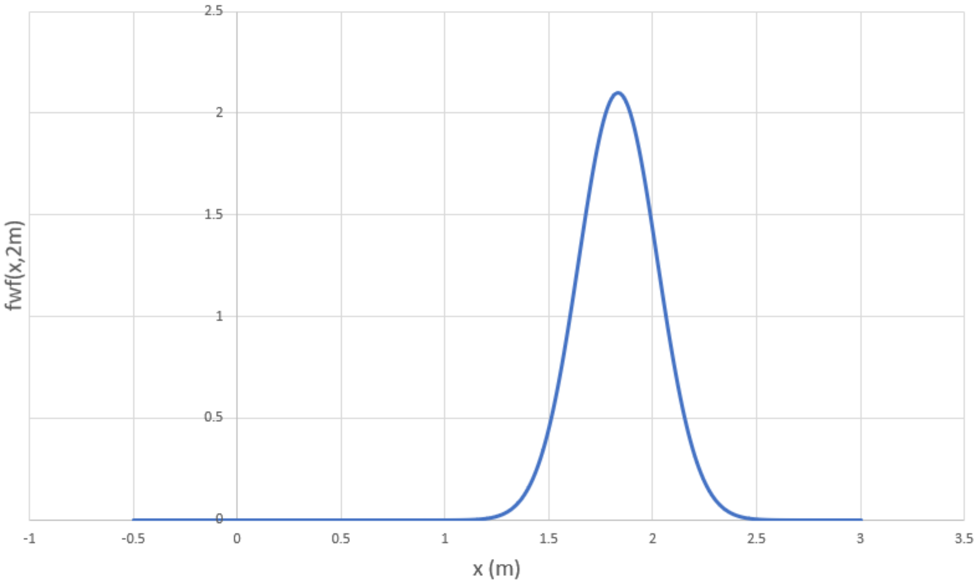


Figure 21: Statistical error for the subgroup (Winter, 1 < h_s < 2m, T_{FP} = 4h)

3.5.3 Alpha factor calculation

After statistical errors are generated for each subgroup, next step corresponds to the actual calculation of alpha factors for *Saint-Nazaire* case study. In that respect, a python script was developed and is available as Appendix. This code is not analysed in details, only a description of key stages is provided:

- Useful parameters are first imported in the code. This includes mean, standard deviation, forecast period and operational criterion of each subgroup. Upper boundary of H_s interval considered is chosen as operation criterion. Value of probability *q* used in the calculation is also defined.

- Number of sea states *n* is then calculated using equations 10 and 11.

- Both h_s and H_{max} distributions are then defined using equations 6 and 9, respectively normal and Rayleigh distributed. Please note that the h_s function returns a random value following a normal distribution with defined parameters.

- Boundaries involved in alpha factor original calculation, h_{lim} and $h_{lim,unc}$, are then determined. Integrals included in equations 12 and 16 are numerically computed using *Monte-Carlo* integration method. [48]

- Finally, each alpha factor derived from the ratio of each bin of h_{lim} and $h_{lim,unc}$ previously determined.

Alpha factors are reported in a dedicated datasheet, and results are discussed in the next section.

4.0 Results & Discussion

The results and discussion section aims to present key findings of the study and also provide a critical analysis and interpretation regarding results. First, a section gives an overview of expected alpha factor values by focusing on the geographical context of *Saint-Nazaire* and the error distributions between forecasts and measures. Calibrated alpha factors are then listed and explained through a sensitivity analysis assessing the seasonal influence as well as choices made concerning operational criteria and forecasted periods. Finally, comparison of these results with tabulated alpha factors is proceed before giving overall interpretations and recommendations to the offshore wind industry.

4.1 Expectations

4.1.1 *Saint-Nazaire* situation

As introduced in section 3.5.2, the future offshore wind farm of *Saint-Nazaire* is located in the Atlantic Ocean close to the French coastline. Local conditions are characterised by wind and current that usually come straight from the Ocean. However, tabulated alpha factors have been calculated for North Sea conditions. This location is known for having strong currents with a high turbidity water. Indeed, there are more sources of disturbance in the case of North Sea conditions, meaning it can be expected to get higher uncertainties in forecasts for North Sea marine operations. Thus, alpha factors calibrated for *Saint-Nazaire* case study are planned to be less restrictive than tabulated values. This affirmation is discussed in section 4.3.

4.1.2 Analysis of error distributions

In this section, means and standard deviations of error distribution for each subgroup are analysed in order to identify possible trends as regards to influencing factors. Figure 22 shows bias for the different subgroups mentioned in section 3.5.1. Please note that values of bias are listed in the “Mean & Standard deviation” datasheet.

First, seasons (represented by colours on Figure 22) seem to have an impact on error values, with higher mean errors during winter and lower ones during summer. Spring and autumn bias are bounded by winter and summer values, slightly higher in autumn compared to spring. Besides, bias usually gets higher as measured significant wave height increases (except for spring), meaning that forecasts might underestimate high significant wave heights. However, high wave height groups are often composed of a few values (less than five), thus a more in-depth study is required to determine if it is a default of the forecasted method used. Dependency with the forecasted period is not really clear on Figure 22. Finally, the new forecast method seems to have low bias compared to summer and spring. At this stage this new method seems to be slightly more accurate than the previous one.

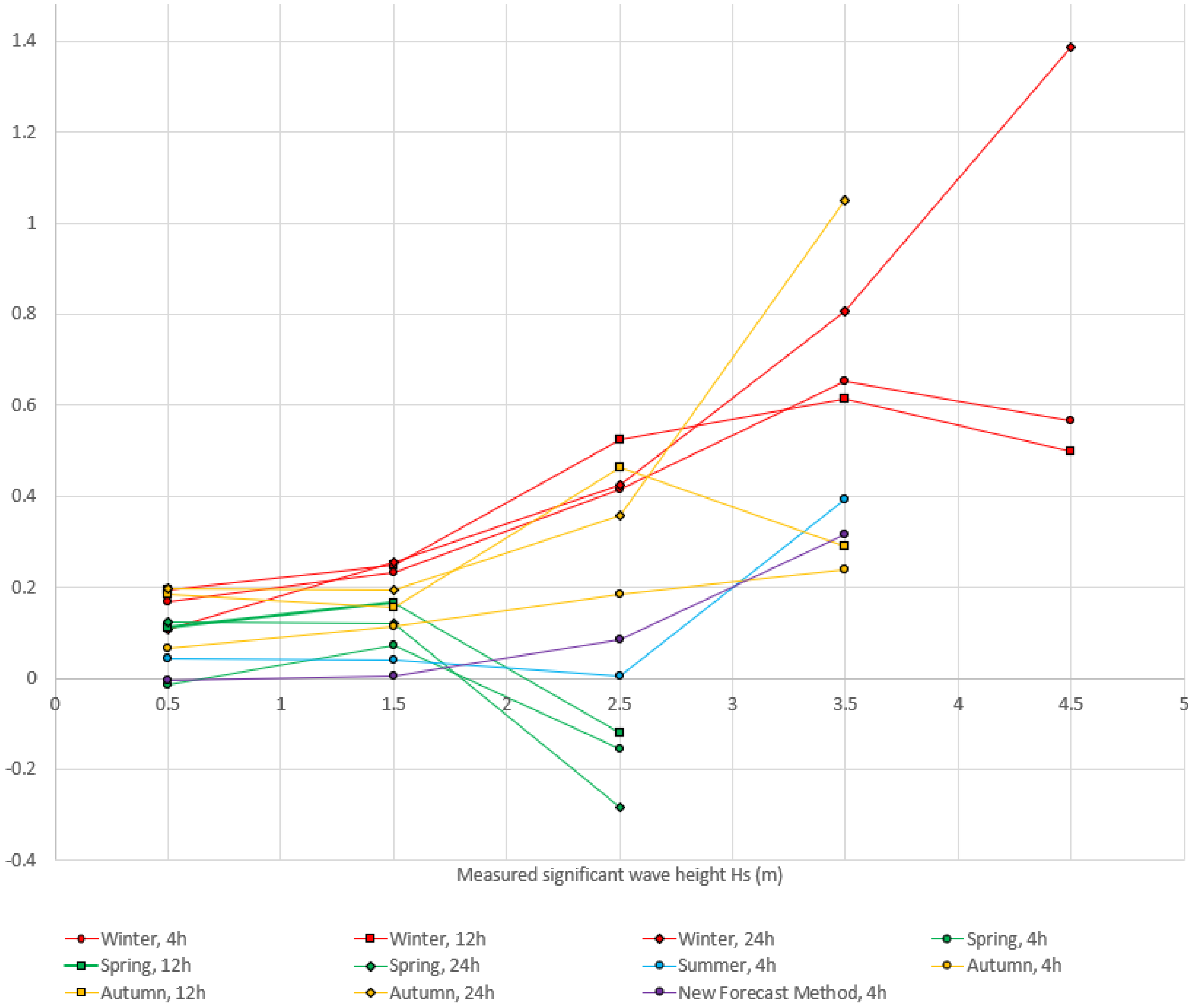


Figure 22: Bias for each subgroup according to the measured significant wave height

Figure 23 shows standard deviations for the different subgroups defined in section 3.5.1. Interpretation here is less straightforward than for bias. Standard deviations seem not to have a clear seasonal dependency. Concerning forecasted periods and significant wave heights, two opposite effects make the identification of influence harder. Indeed, as stated in section 2.4.1, forecasts should become less precise as long as periods of forecast increase, meaning higher standard deviations. However, due to limited amount of data available for high wave height groups and 12h and 24h forecast periods, standard deviations have unpredictable variations. Finally, standard deviations of the new forecast method seem quite low compared to other groups.

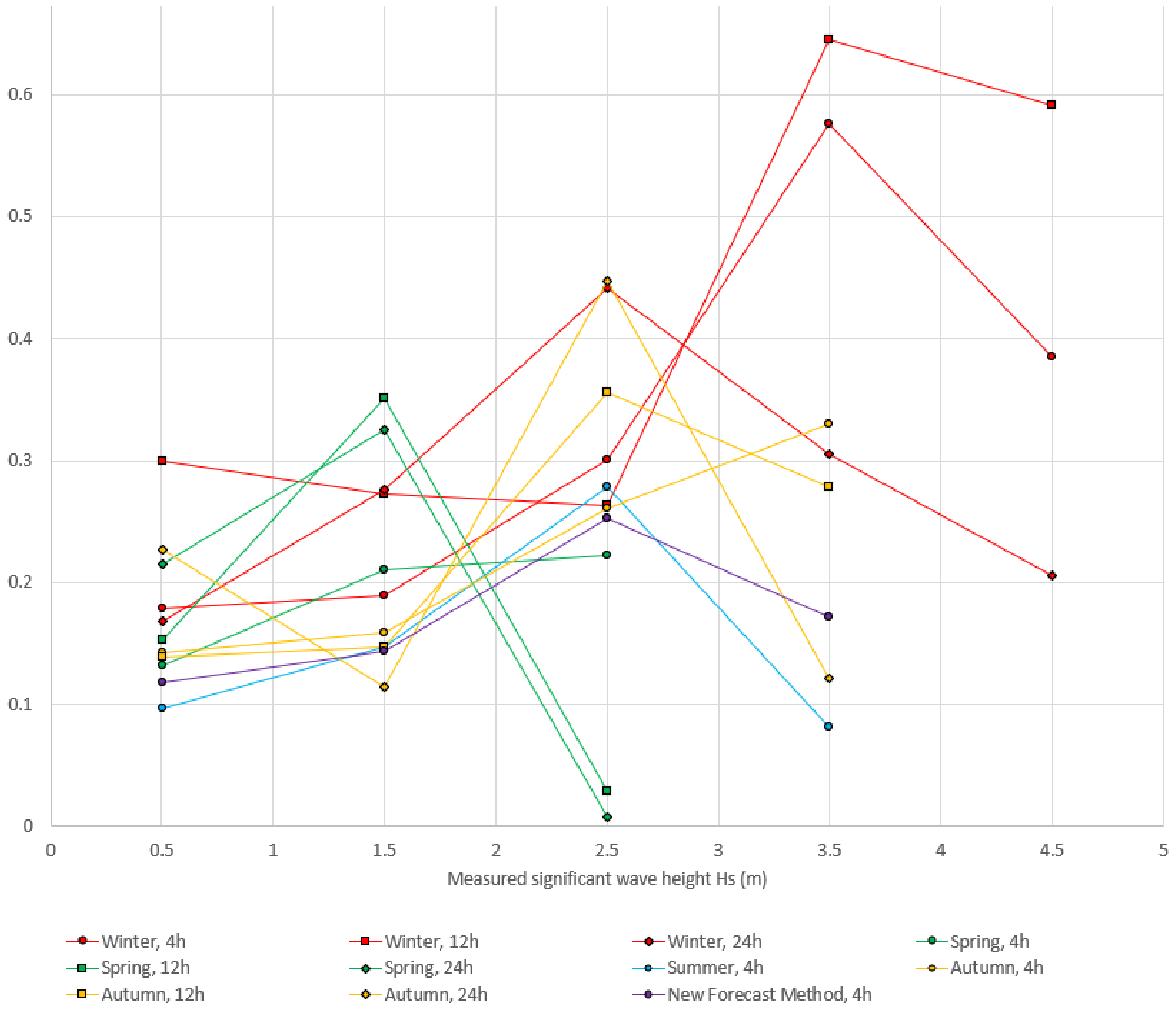


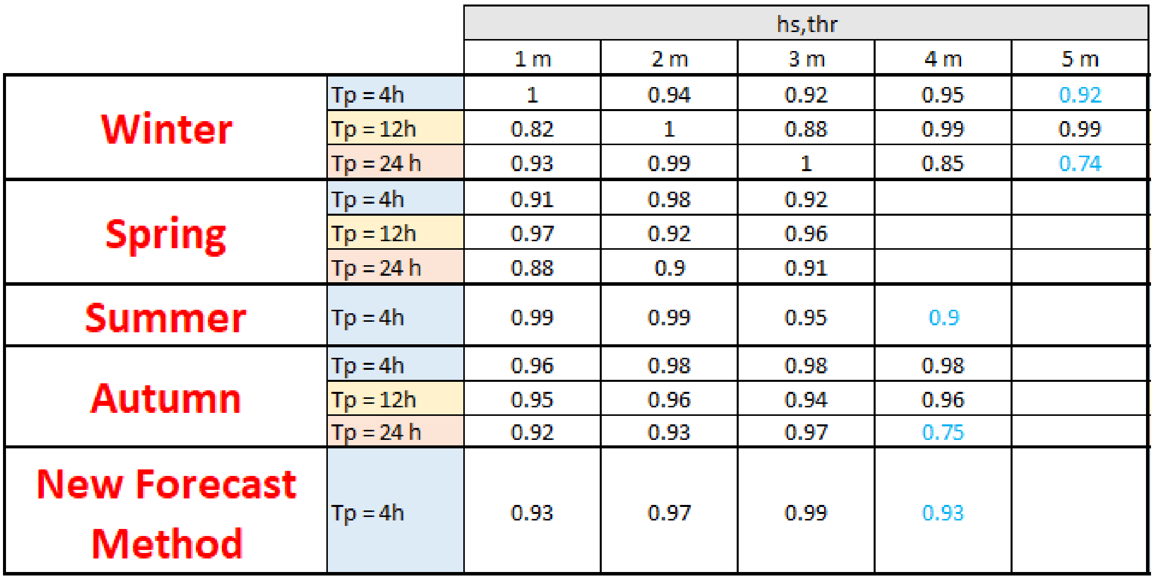
Figure 23: Standard deviations for each subgroup according to the measured significant wave height

4.2 Sensitivity analysis

4.2.1 Tabulated alpha factors

As explained in section 3.5.3, a python code (available in “A2-BeauryAlphaFactor Calculation”) was used to calculate the alpha factors calibrated to the case study of *Saint-Nazaire*. Table 4 shows alpha factors determined for each subgroup considered using the original method of calculation. Boundary values (h_{lim} and $h_{lim,unc}$) involved in the calculation are available in the “Alpha Factors” datasheet. These values are classified according to their season, forecasted period and wave height group. As already mentioned in section 3.5.1, only a 4-hour forecasted period is available during summer and for the new method of forecast. Furthermore, few data are available for high wave height groups. Alpha factors written in blue stand for calculation with a limited amount of data (less than five values), which means that special care needs to be applied regarding their interpretation.

Table 4: Calibrated alpha factors for each subgroup considered



		hs,thr				
		1 m	2 m	3 m	4 m	5 m
Winter	Tp = 4h	1	0.94	0.92	0.95	0.92
	Tp = 12h	0.82	1	0.88	0.99	0.99
	Tp = 24 h	0.93	0.99	1	0.85	0.74
Spring	Tp = 4h	0.91	0.98	0.92		
	Tp = 12h	0.97	0.92	0.96		
	Tp = 24 h	0.88	0.9	0.91		
Summer	Tp = 4h	0.99	0.99	0.95	0.9	
Autumn	Tp = 4h	0.96	0.98	0.98	0.98	
	Tp = 12h	0.95	0.96	0.94	0.96	
	Tp = 24 h	0.92	0.93	0.97	0.75	
New Forecast Method	Tp = 4h	0.93	0.97	0.99	0.93	

4.2.2 Seasonal influence

Seasons have an influence on bias of error distribution, then it should also impact resulting alpha factors. Figure 24 exposes seasonal influence on calibrated alpha factors for a forecasted period equal to four hours. Alpha factors are generally higher in summer and lower in winter. This result seems logical as weather conditions are generally easier to predict and less turbulent in summer rather than during winter. Autumn has intermediate values of alpha factors while spring is the season with largest variations. One possible reason for these variations might be the presence of storms which occurred during the studied period and leading to unpredictable changes in wave patterns. Finally, a study over several years would be useful to confirm if forecast models are actually more accurate in summer than in winter, and more generally account effectively for specific changes of weather conditions.

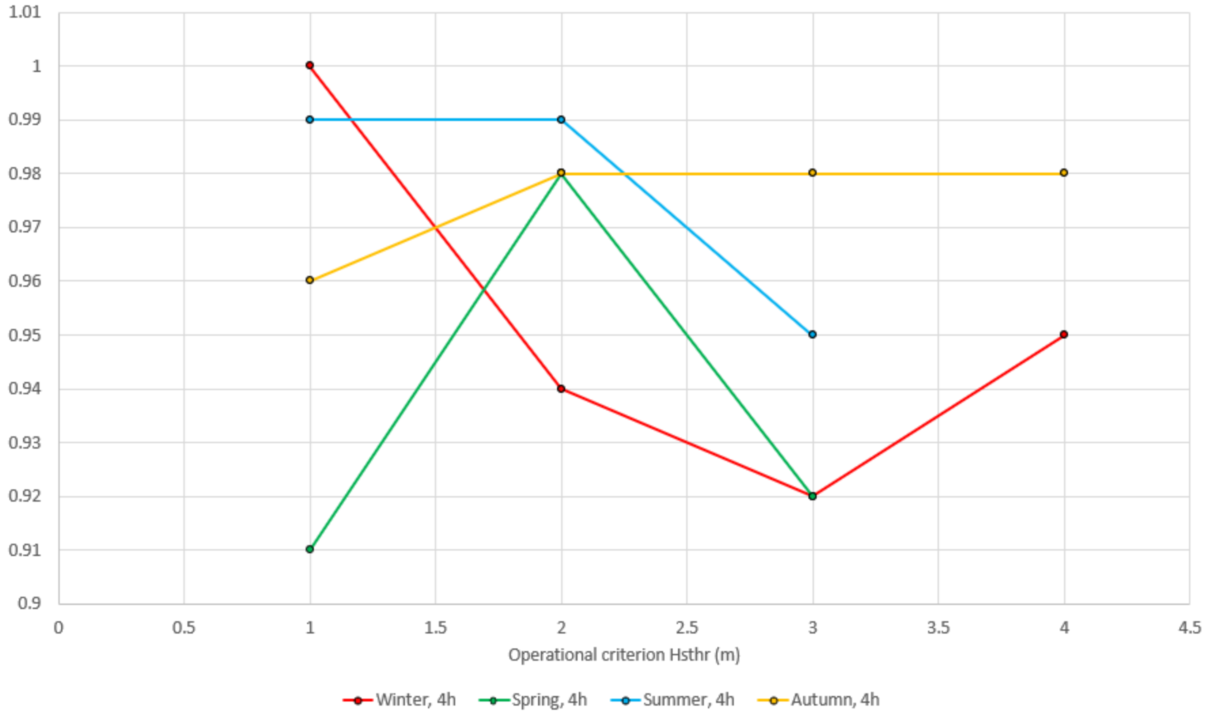


Figure 24: Influence of season on calibrated alpha factors with a 4-hour forecasts period

4.2.3 Sensitivity to period of forecasts

Longer forecast periods are supposed to reduce alpha factors due to larger uncertainties on long-range forecasts. Figures 25, 26 and 27 respectively show alpha factors for winter, spring, and autumn. In practice, it is not always the case, and 24-hour forecasts are sometimes more precise than 12-hour or 4-hour predictions. Overall, the lowest values correspond to 24-hour forecasts while 4-hour forecasts are the best or intermediary in terms of accuracy. This analysis is highly dependent on the pattern selected to collect data, meaning additional data with a standard pattern should be used to refine the analysis. Besides, even a 24-hour prediction is considered as short-range forecasts, then extending the study to forecasted periods up to 72 hours should be valuable to get a complete understanding of the influence of this parameter on alpha factors.

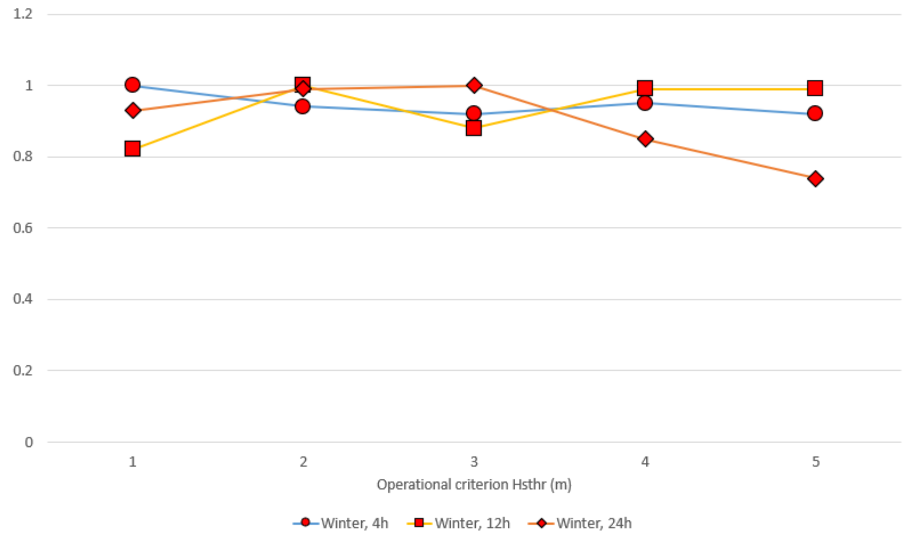


Figure 27: Calibrated alpha factors in winter according to their forecasts period

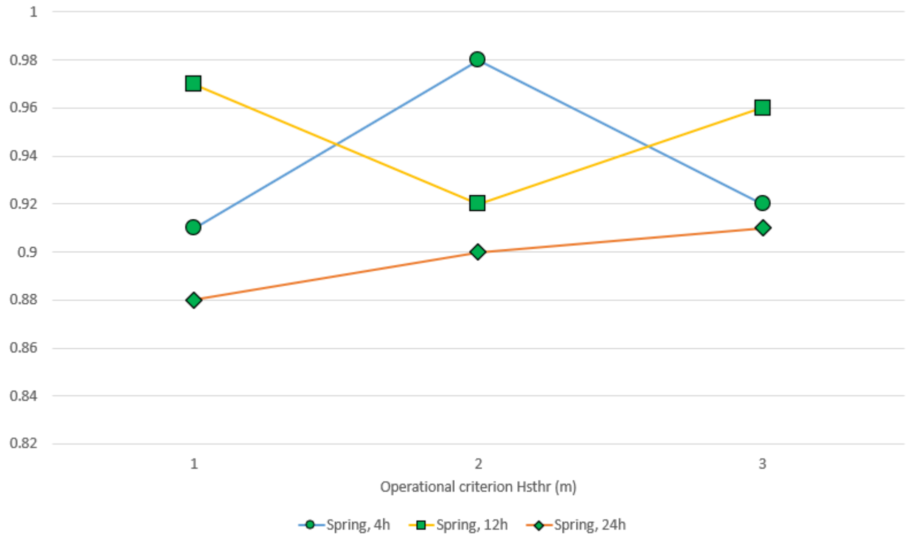


Figure 25: Calibrated alpha factors in spring according to their forecasts period

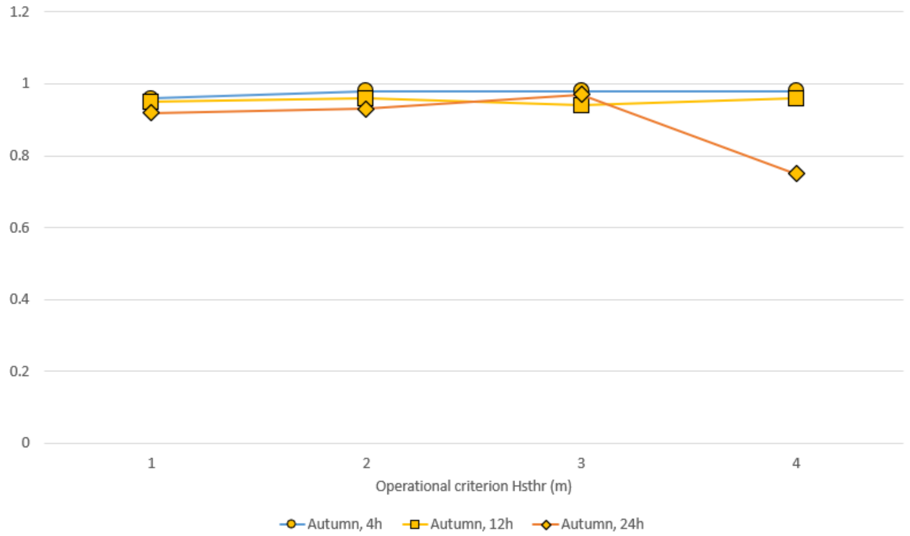


Figure 26: Calibrated alpha factors in autumn according to their forecasts period

4.2.4 Sensitivity to operational criterion

No clear patterns are identified concerning the sensitivity to operational significant wave height criterion. Compared to tabulated values studied in section 3.2.2, alpha factors clearly increase for high wave height groups considered. This trend is not as obvious for the calibrated values provided in table 4. Various reasons might explain this difference. First, weather forecast models used in *Saint-Nazaire* might predict accurately small variations of wave height but are not able to forecast huge variations due to storms for instance. Another reason might concern the dataset studied, including most of the values for (0 – 1m) and (1 – 2m) h_s groups and less data for other groups, mainly because of the low occurrence of high waves at the location of *Saint-Nazaire*. As a result, uncertainties on higher height groups are boosted by the few amounts of data available.

4.2.5 Sensitivity to new forecasting method

Figure 28 compares alpha factors calculated with the new forecasting method, in summer and spring with a forecasted period of 4 hours. Summer and spring are used as references because the new method is studied from the 1st of May until 29th of July 2021. For low height wave values, the new method seems less accurate, while for high values, uncertainties on forecasts are reduced. Only three months of data is too short to provide a more detailed analysis. Studying the influence of this new method over a complete year would be beneficial to determine its effectiveness during other seasons such as in winter. In addition, this study only considers a 4-hour forecasted period, assessing this method for longer forecasts would also be interesting, especially considering the reduction of accuracy for long-range forecasting.

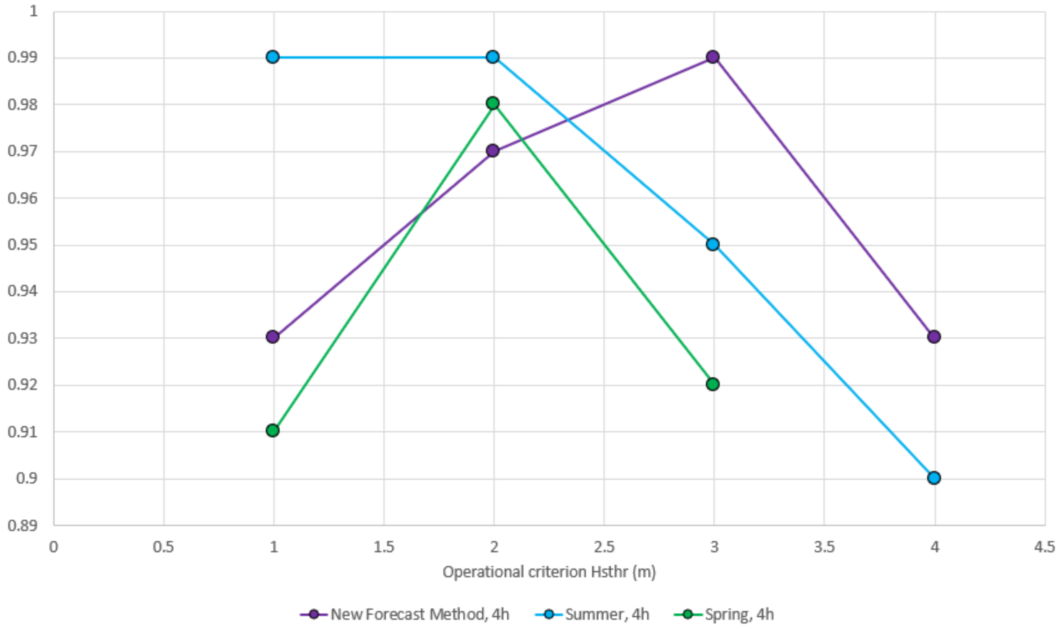


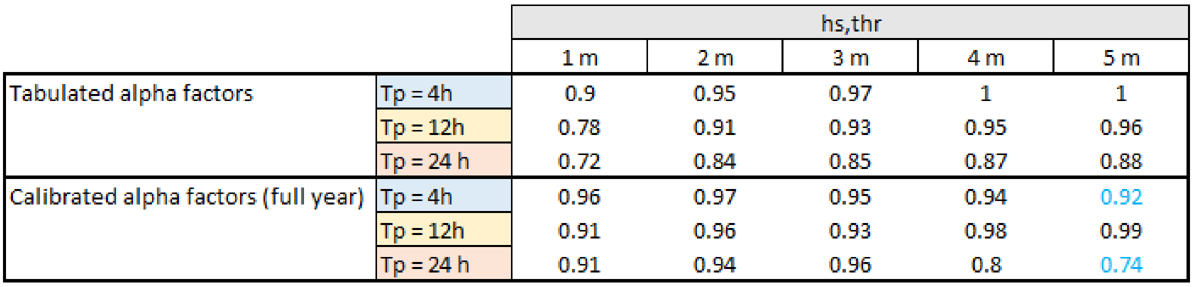
Figure 28: Calibrated alpha factors respectively for the new forecasting method, in summer, and spring

4.3 Comparison between tabulated and calibrated alpha factors

4.3.1 Comparison

Tabulated alpha factors selected for comparison correspond to level A1 operations using LRFD and with environmental monitoring. [18] This choice is justified by the presence of environmental monitoring on site and because LRFD method is more commonly used than ASD/WSD. Selection of sensitivity to weather is based on the most restrictive criterion, corresponding to level A1 (see section 2.2.2 for details). Table 5 lists tabulated alpha factors considered and average calibrated alpha factors through the whole year.

Table 5: Tabulated and calibrated alpha factors



		hs,thr				
		1 m	2 m	3 m	4 m	5 m
Tabulated alpha factors	Tp = 4h	0.9	0.95	0.97	1	1
	Tp = 12h	0.78	0.91	0.93	0.95	0.96
	Tp = 24 h	0.72	0.84	0.85	0.87	0.88
Calibrated alpha factors (full year)	Tp = 4h	0.96	0.97	0.95	0.94	0.92
	Tp = 12h	0.91	0.96	0.93	0.98	0.99
	Tp = 24 h	0.91	0.94	0.96	0.8	0.74

Difference between tabulated and calibrated alpha factors is shown on Figure 29 for the different forecasted periods studied (4h, 12h and 24h). First, calibrated factors are almost systematically under tabulated values, meaning that uncertainty on forecasts is lower in the case of *Saint-Nazaire*. This makes sense considering that weather conditions are more favourable in the case study than for North and Norwegian sea, where tabulated values were determined. However, for high wave heights values, uncertainties are more significant for calibrated factors, mainly because of the low quantity of data available. Finally, the difference is more significant for 12-hour and 24-hour forecasted periods, suggesting that calibration especially impacts uncertainties for long-range forecasting. This justifies running a study with longer forecast periods, as less uncertainties on this type of forecast would be particularly useful to plan operations as soon as possible.

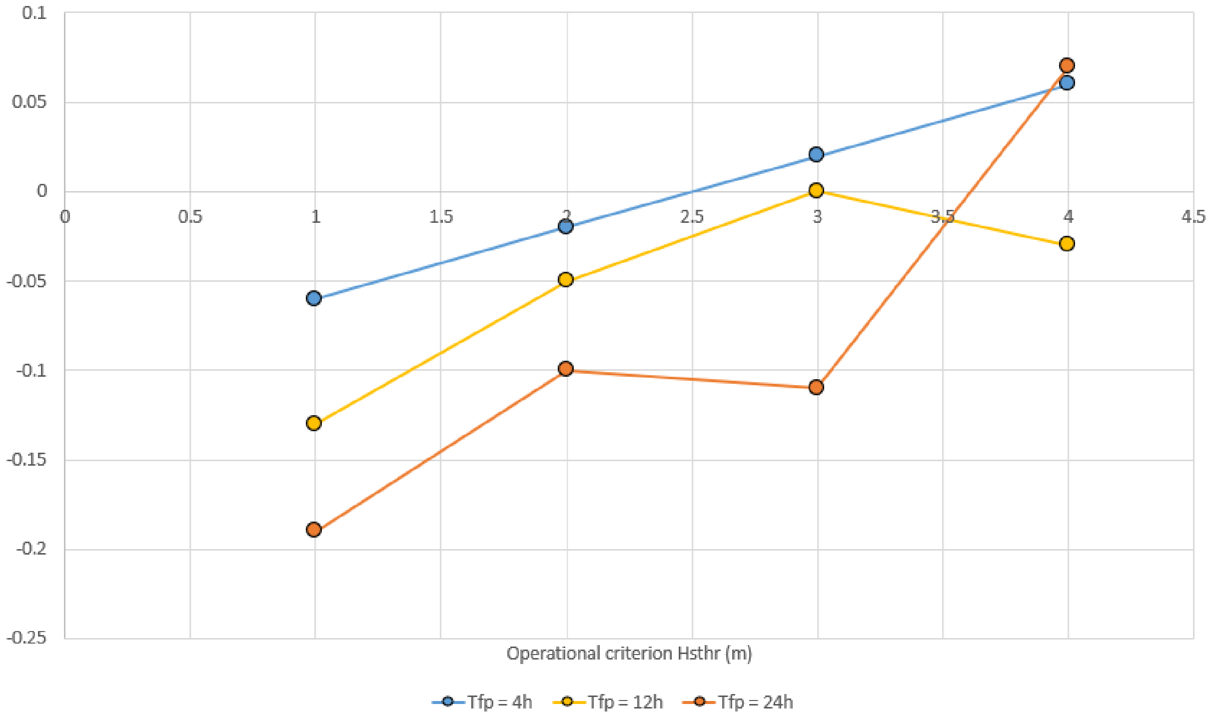


Figure 29: Difference between tabulated and calibrated alpha factors (tabulated – calibrated)

4.3.2 Recommendations towards industry

Investigation through the calibration of alpha factors to the *Saint-Nazaire* case study first shows that it is possible to calculate specific alpha factors as long as enough measures and forecasts are available onsite. “Enough” data depends here on the expectations of the analysis. For instance, if the calibration only aims to determine the difference with tabulated factors or to verify the effectiveness of a forecasting model, one year might be enough. Otherwise, if seasonal impacts need to be quantified precisely, an analysis of several years would be more suitable. However, in any case, proceeding an analysis only based on a couple of months does not consider seasonal variations, which might lead to risks of misestimation.

Concerning the case study of *Saint-Nazaire*, results show that tabulated alpha factors overestimate actual uncertainty on forecasts. In addition, it suggests that uncertainty on long-range forecasts could be significantly reduced, allowing sooner prevision of marine operations.

Calibrated alpha factors provided in this paper lack of input data, especially for long-range forecasting periods and high significant wave heights. Defining a new pattern to collect weather forecasts would allow to get more data and give additional weight to the calibrated factors found.

Finally, concerning the new method of forecast, investigation shows that this method seems slightly better than previous method. However, increasing the time period of study is necessary before reaching further conclusions regarding whether alpha factors are still required or not.

5.0 Conclusions

Overall, the present study focuses on the correct assessment of uncertainty in weather forecasting in the context of offshore wind. First, the background of the study is introduced, and key topics related to weather forecasting are described. Literature review addresses different sources of influence impacting accuracy of weather forecasts such as weather parameters, types of offshore operations, sources of meteorological data, and methods of uncertainty quantification.

Selected method to assess uncertainty on weather forecasts is based on alpha factors. A description of this method is provided in the research undertaken section. Current projects almost systematically use tabulated values, leading to misestimation of uncertainty regarding specific projects. Among adjustment factors and ensemble forecasting, direct calibration of alpha factors to project is studied, including description of two procedures of calculation.

Practical determination of specific alpha factors is proceeded for the future wind farm of *Saint-Nazaire*. Original method of calculation is investigated in the present paper and only applies for the significant wave height parameter. Measured and forecasted data involved in the calibration are based on local records over a one year and a half time period. A sensitivity analysis identifies the dependency of alpha factors regarding seasons, forecasting periods, operational criteria, and methods of forecasts used.

Comparison between tabulated and calibrated alpha factors for the specific *Saint-Nazaire* case study is made in the results and discussion section. At the end of the day, analysis suggests that, for the case study, calibrated alpha factors are actually less restrictive than tabulated values determined for North Sea weather conditions.

Finally, several topics can be subject to future work:

- Concerning the alpha factor methodology of calculation, only the original method is investigated. Studying the revised method would be valuable, especially as it directly focuses on the significant wave height distribution.
- Uncertainty is only studied on wave height, but actual uncertainty also exists on wave frequency, or wind and current speeds, which could be subject of other studies.

- Probability *q* involved in alpha factors calculation was fixed to 10^{-4} but questioning this value could significantly reduce the uncertainties currently considered.
- Linear interpolation used for intermediary values in DNV GL tabulated alpha factors can also be reviewed. In that respect, alpha factors could be divided into smaller H_s groups (e.g., every 0.5 or 0.25m).
- Calibration made for *Saint-Nazaire* case study suggests that uncertainty is overestimated for long-range forecasting periods, verifying this hypothesis could be beneficial.
- Studying input data for over several years would refine the analysis, especially to accurately assess seasonal and forecasting method influences on alpha factors.

6.0 References

[1] Ørsted, “Making green energy affordable,” 2019. [Online]. Available: https://orsted.com/-/media/www/docs/corp/com/explore/making-green-energy-affordable-june-2019.pdf. [Accessed 08 06 2021].

[2] Vattenfall, “Horns Rev 1,” 2021. [Online]. Available: https://powerplants.vattenfall.com/horns-rev/. [Accessed 08 06 2021].

[3] LondonArray, “About London Array,” 2020. [Online]. Available: https://londonarray.com/. [Accessed 08 06 2021].

[4] Equinor, “Hywind Scotland,” 2021. [Online]. Available: https://www.equinor.com/en/what-we-do/floating-wind/hywind-scotland.html. [Accessed 08 06 2021].

[5] Y. Feng, Y. Qiu and Z. Junwei, “Study of China's first large offshore wind project,” Beijing, 2014.

[6] Wikipedia, “Block Island Wind Farm,” 2021. [Online]. Available: https://en.wikipedia.org/wiki/Block_Island_Wind_Farm. [Accessed 08 06 2021].

[7] Europa, “Paris Agreement,” 2016. [Online]. Available: https://ec.europa.eu/clima/policies/international/negotiations/paris_en. [Accessed 08 06 2021].

[8] Center for climate and energy solutions, “Global Emissions,” 2019. [Online]. Available: https://www.c2es.org/content/international-emissions/. [Accessed 08 06 2021].

[9] J. D. Hamilton, “Historical Oil Shocks,” *Handbook of Major Events in Economic History,* 1 February 2011.

[10] M. D. Esteban, J. J. Diez, J. S. Lopez and V. Negro, “Why offshore wind energy?,” *Renewable Energy,* pp. 444-450, February 2011.

[11] M. Bilgili, A. Yasar and E. Simsek, “Offshore wind power development in Europe and its comparison with onshore counterpart,” *Renewable and Sustainable Energy Reviews,* pp. 905-915, February 2011.

[12] J. J. Nielsen and J. D. Sorensen, “On risk-based operation and maintenance of offshore wind turbine components,” *Reliability Enginneering & System Safety,* pp. 218-229, January 2011.

[13] EDF Renewables , “Parc éolien en mer de St Nazaire,” 2021. [Online]. Available: https://parc-eolien-en-mer-de-saint-nazaire.fr/le-parc-eolien-en-mer/presentation-projet/. [Accessed 16 June 2021].

[14] Ørsted, “Hornsea One,” 2021. [Online]. Available: https://hornseaprojectone.co.uk/. [Accessed 24 June 2021].

[15] P. Dvorak, “VertAx Wind (vertical axis turbine) signs C-Gen (generator) agreement with University of Edinburgh,” 8 December 2017. [Online]. Available: https://www.windpowerengineering.com/vertax-wind-vertical-axis-turbine-signs-c-gen-generator-agreement-university-edinburgh/. [Accessed 24 June 2021].

[16] G. Nikitas, S. Bhattacharya and N. Vimalan, “16 - Wind Energy,” *Future Energy (Third Edition),* pp. 331-355, 2020.

[17] L. Castro-Santos and V. Diaz-Casa, “Life-cycle cost analysis of floating offshore wind farms,” *Renewable Energy* , pp. 41-48, June 2014.

[18] DNV GL, “Marine operations and marine warranty,” 2020.

[19] Ocean Weather Services, “A Mariner's Guide to Waves,” [Online]. Available: http://oceanweatherservices.com/featured_blog_posts/a_mariners_guide_to_waves. [Accessed 28 June 2021].

[20] Copernicus Marine In Situ Team, “Copernicus In Situ TAC, Real Time Quality Control for WAVES,” 2020.

[21] Y. Agrawal and W. Terry, “Laser doppler velocimetry on the sea floor,” in *IEEE,* Hilton Head, 2003.

[22] National Weather Service, “Radiosonde Observation,” National Oceanic and Atmospheric Administration, [Online]. Available: https://www.weather.gov/upperair/factsheet. [Accessed 10 July 2021].

[23] National Weather Service, “Using and Understanding Doppler Radar,” [Online]. Available: https://www.weather.gov/mkx/using-radar. [Accessed 10 July 2021].

[24] Global MeteOcean, *Weather Forecasts and associated services,* 2019.

[25] Météo Centre, “NCEP-GFS,” 2021. [Online]. Available: https://meteocentre.com/numerical-weather-prediction/forecast-systems.php?lang=fr&mod=gfs. [Accessed 10 July 2021].

[26] ECMWF, “Advancing global NWP through international collaboration,” [Online]. Available: https://www.ecmwf.int/. [Accessed 10 July 2021].

[27] Fleet Numerical Meteorology and Oceanography Center, [Online]. Available: https://www.metoc.navy.mil/fnmoc/fnmoc.html. [Accessed 10 July 2021].

[28] MeteoGroup, *Weather Forecasting Services - Technical Proposal,* 2019.

[29] Tornado, “Deterministic vs Probabilistic Forecasting,” [Online]. Available: http://tornado.sfsu.edu/geosciences/classes/m698/Determinism/determinism.html. [Accessed 11 July 2021].

[30] A. Balasubramanian, "Weather Forecasting," *Technical Report,* February 2016.

[31] University of Illinois, "Persistence Method," [Online]. Available: http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fcst/mth/prst.rxml. [Accessed 11 July 2021].

[32] R. Bradley and M. Drechsler, "Types of Uncertainty," *The First Six Articles Belong to the Special Issue: RADICAL UNCERTAINTY,* pp. 1225-1248, December 2014.

[33] Donskerclass, "Uncertainty Quantification," [Online]. Available: https://donskerclass.github.io/Forecasting/Uncertainty.html. [Accessed 16 July 2021].

[34] DTN, "Alpha factor EDF," 2020.

[35] French Government, *Energy and Climate Act,* 2019.

[36] IEA, "France," 30 March 2021. [Online]. Available: https://www.iea.org/countries/france. [Accessed 13 July 2021].

[37] T. V. Galambos, "Load and Resistance Factor Design," AMERICAN INSTITUTE OF STEEL CONSTRUCTION.

[38] W. Lin and T. Yoda, "Chapter Two - Bridge Planning and Design," *Classifications, Design Loading, and Analysis Methods,* pp. 31-58, 2017.

[39] M. Laapas, I. Lehtonen, A. Venäläinen and H. Peltola, "The 10-Year Return Levels of Maximum Wind Speeds under Frozen and Unfrozen Soil Forest Conditions in Finland," *Climate,* pp. 7-62, 30 April 2019.

[40] Wikipedia, "Linear interpolation," 25 June 2021. [Online]. Available: https://en.wikipedia.org/wiki/Linear_interpolation. [Accessed 19 July 2021].

[41] Alpha-factor Joint Industry Project group, "Building a Framework for use of Response Forecasts," 26 November 2019.

[42] K. &. a. Hasselmann, "Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP)," *Deutsche Hydrographische Zeitschrift,* 1973.

[43] K. Torsethaugen, "Two peak wave spectrum model," *Norwegian Marine Technology Research Institute,* Jannuary 1993.

[44] Nortekmed, "Weather measurements for Saint-Nazaire," 2021. [Online]. Available: http://nortekmed.dyndns.org/SNA-SOUTHWEST/Register/Login.aspx. [Accessed 22 July 2021].

[45] Meteogroup, "Weather forecasts for Saint-Nazaire," 2021. [Online]. Available: https://offshore.meteogroup.com/ocw/#app. [Accessed 22 July 2021].

[46] DNV GL, "Rules for Planning and Execution of Marine Operations," 1996.

[47] DNV GL, “Alpha factors, revised procedure,” 2020.

[48] J. Collot, “Technique de calcul de type Monté-Carlo,” 2001.

[49] GWEC, “Global Offshore Wind Report 2020,” 2020.

[50] EDF Renewables, “Provence Grand Large,” 2021. [Online]. Available: https://www.provencegrandlarge.fr/. [Accessed 17 June 2021].

[51] M. D. Esteban, B. Counago, J. Lopez-Gutierrez, V. Negro and F. Vellisco, “Gravity based support structures for offshore wind turbine generators: Review of the installation process,” *Ocean Engineering*, pp. 281-291, 1 December 2015.

[52] DEME Group, “Turbine installation at Belgium's largest offshore wind farm crosses the finish line,” 01 December 2021. [Online]. Available: https://www.deme-group.com/news/turbine-installation-belgiums-largest-offshore-wind-farm-crosses-finish-line. [Accessed 30 June 2021].

[53] Catapult, “Rovco,” 20 April 2021. [Online]. Available: https://ore.catapult.org.uk/stories/rovco/. [Accessed 30 June 2021].

[54] K. Wallis, “UHL looks to fill looming offshore wind vessel shortage,” 31 August 2021. [Online]. Available: https://www.joc.com/breakbulk/project-cargo/uhl-looks-fill-looming-offshore-wind-vessel-shortage_20200831.html. [Accessed 30 June 2021].

[55] Sarens, “Maasvlakte 2 Terminal Project,” 22 July 2019. [Online]. Available: https://www.sarens.com/about/projects/maasvlakte-2-terminal-project.htm. [Accessed 30 June 2021].

[56] Dartcom, “IDAP/MacroPro Software,” 2021. [Online]. Available: https://www.dartcom.co.uk/products/idap-macropro-software/overview. [Accessed 10 July 2021].

[57] V. Carracedo, D. Liano, J. G. Codron and D. Rasilla, “Recent climate variability trends and wildfire occurrence in Cantabria (Northern Spain)”.

[58] Nortek, “Technical Proposal,” Toulon, 2018.

7.0 Appendices

7.1 Excel Input Datasheet for the *Saint-Nazaire* case study

Excel datasheet submitted with the present thesis as a separate document named “A1-BeauryInputs”.

7.2 Python Script used for Alpha factors calculation via original method

Python code submitted with the present thesis as a separate document named “A2-BeauryAlphaFactorCalculation”

DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

Student No. 202086287