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Department of Mechanical and Aerospace Engineering

Met-Ocean Conditions and Weather Window Analysis Of Falck Renewables ScotWind Zones

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Signed: Christopher Del Valle Date: 12.08.22

Abstract

To successfully install, operate and maintain offshore marine renewables, such as floating offshore wind, they must be available and safely accessible regularly and predictably. This project set out to analyse and understand various trends, variances and outliers related to the met-ocean conditions experienced within three ScotWind zones awarded to Falck Renewables. ERA5 Reanalysis data was obtained and analysed over a thirty year period, with particular attention given to two key variables – Significant Wave Height (Hs) and Mean Wind Speed. Hs and Wind Speed were found to be relatively comparable in all three locations, though in particular for the two sites codenamed "Cygnus" and "Orion".

This study highlights the need for further research determining specific weather-windows for each of the ScotWind zones analysed, in order to accurately inform future installation, operation and maintenance strategies.

Acknowledgements

This thesis is the result of the author's original research, however; significant academic, emotional and moral support was provided to the author by a number of individuals.

The author would like to thank Dr Paul Gerard Tuohy for providing considerable guidance and support throughout the academic year, including consistently reaching out throughout the duration of this MSc project to offer support. Dr Tuohy approachable manner coupled with his knowledge and passion for all things sustainability and engineering made studying this course an exceptionally valuable experience.

In addition, the author would like to thank Dr David McMillan for instilling a real passion for the offshore wind industry and harnessing energy from wind in general. Dr McMillan's own enthusiasm for the subject alongside his utilisation industry links reinforced the real-world applications of often theoretical concepts. "The Place of Useful Learning".

Thank you to Jade McMorland for kindly offering to share some of her expertise, knowledge and time in the preliminary and early stages of building this project, which was both extremely generous and instructive.

Finally, the author would like to express their immense gratitude and appreciation for Eilidh Boa. Without Eilidh's unconditional guidance, support, encouragement and patience, applying for a place on an MSc programme and subsequently completing a full-time MSc course whilst working full-time jobs throughout would truly never have been possible.

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Nomenclature & Abbreviations

Symbol/Abb.	Description	Units
GW	Gigawatt	N/A
MW	Megawatt	N/A
CfD	Contract for Difference	N/A
CES	Crown Estate Scotland	N/A
SMP	Sectoral Marine Plan	N/A
SNMP	Scottish National Marine Plan	N/A
CTV	Crew Transfer Vessel	N/A
SOV	Service Operation Vessel	N/A
Tp	Peak wave period	Seconds (s)
Hs	Significant Wave Height	Metres (m)
FOW	Floating Offshore Wind	N/A
UK	United Kingdom	N/A

2.0 Introduction

The United Kingdom is currently considered to be a world leader in offshore wind energy, second only to China in terms of the overall capacity of wind turbines currently in operation and the total number of wind turbines installed [1]. By the end of 2021, the top three countries worldwide in terms of installed offshore wind capacity were China, the United Kingdom and Germany with market shares of 48.4%, 21.9% and 13.5% respectively [2].This represents a massive shift in the offshore wind landscape, as China installed an impressive 16.9GW of capacity in 2021 alone, increasing their total capacity from less than 10GW at the end of 2020 to 26.4GW at the end of 2021 [3]. Until 2015, offshore wind was very much a European play. Europe's total global share of offshore wind capacity fell from a peak of 91% in 2012 to 50% in 2021, with the UK's share of capacity falling from a peak of 53% in 2012 to 22% in 2021 [4].

Despite the UK losing its pole position in terms of market share in offshore wind with the growth and emergence of new markets, the UK still currently has the world's second-largest project pipeline currently in place at 91GW according to a RenewableUK EnergyPulse market intelligence report [5] released in June 2022. This comes as the global pipeline of offshore wind projects which are operational, under construction, consented or being planned has approximately doubled in the last year from 429GW in 2021 to 846GW in June 2022 [6].Europe has a combined pipeline of 350GW of the global total of 846GW [6],with current projections from ORE Catapult suggesting that 47% of the total cumulative offshore wind installed globally will be located throughout Europe [7].

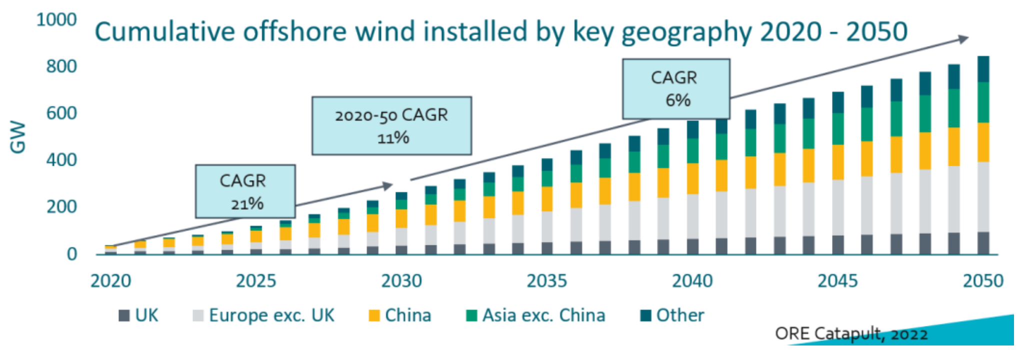


Figure 1: Cumulative offshore wind installed by key geography 2020-2050
(Image credit: ORE Catapult) [4]

These projections and the healthy offshore wind project pipeline currently existing within the UK suggest that the offshore wind industry is likely to continue to make great strides in the coming years and decades. In July 2021, three commercial-scale floating wind demonstration projects were selected for lease in the Celtic Sea [8]. In July 2022, the results of the fourth round of the Contracts for Difference (CfD) scheme were announced with 7GW of offshore wind capacity allocated [9]. In February 2022, the UK Government announced that annual CfD auctions would be held from 2023 onwards to accelerate the scale-up of UK renewable energy supplies [10]. Finally, in January of 2022, Crown Estate Scotland (CES) announced the outcome of its application process for ScotWind leasing: totalling 25GW in capacity across 17 projects [11]. The Crown Estate has additionally made plans for the second phase of up to 4GW of floating wind in the Celtic Sea. In April 2022, the UK Government presented plans to increase its 2030 offshore wind target from 40GW to 50GW (of which 5GW will be floating wind) [12].

As part of the 25GW awarded within Crown Estate Scotland's ScotWind process, 10 of the 17 projects are intended to utilise floating technology – amounting to 15GW in total [11].Falck Renewables, an experienced onshore wind developer yet a newcomer in the offshore wind industry, alongside a consortium of affiliated organisations were successfully awarded three of these project option areas [11]. All three of these potential projects awarded to Falck Renewables will employ floating platforms and technology, and present significant technical and practical obstacles that must be considered and overcome to ensure success.

1.1 Background Context and Problem Description

1.1.1 Scotland

Scotland has access to some of the greatest potential wind resource in Europe, with some studies suggesting 25% of the total wind resource for the entire continent [13] and others, such as the Scottish Government, suggesting that perhaps as much as 33% of Europe's potential offshore wind resource is within the UK – with the majority of that resource falling within Scottish waters [14]. It is certainly true that the UK and Scotland's potential wind resource is amongst the highest in Europe, this is due to a variety of factors. In addition to a strong and consistent wind resource, Scotland also enjoys a significantly sizeable coastline and over 900 islands. These geographical features have provided an abundance of coastal waters which are further complimented by the bathymetry surrounding Scotland to create some favourable conditions for the development of offshore wind – particularly on the east coast of Scotland, where the seabed has been identified as particularly suitable due to its gently shelving nature[15]. In addition, more of Scotland's considerable offshore potential may be able to be exploited as floating platforms and turbine technologies become more viable. The Floating Offshore Centre of Excellence believes this decade is poised to see floating offshore wind enter a global commercial phase and start to emerge as a major contributor to carbon-free power generation. Of all markets expected to benefit from and embrace floating offshore wind in the near-term (2022-2030), the UK was found to be the most well-placed globally at the moment based on a number of factors including Technical & Policy Drivers, Investment Landscape and Market Speed Facilitators[7].

Alongside Scotland's fortunate geographical location and unique meteorological conditions, Scotland also has a significant Oil & Gas industry and workforce that has primarily existed and operated in the north-east of the country, with Oil and Gas exploration being considered a major activity in Scottish waters since the late 1960s [16]. Whilst oil and gas production has increased since 2014, long-term forecasts expect production to decline and eventually end in the next 20-30 years [16]. This presents a significant opportunity for Scotland and its population, as many of the necessary skills, experience and assets required to successfully operate a sizeable exploratory Oil & Gas industry are transferable to the offshore marine wind industry. Many argue Scotland is ideally placed to capitalise on its offshore renewable wind potential, and might even see an "oil-style" boom reminiscent of the 70s in the coming decades [17].

2.1.1 ScotWind

The publication of the Sectoral Marine Plan (SMP) for Offshore Wind Energy 2020 [18] provided the necessary spatial framework to allow Crown Estate Scotland to launch its first leasing round for commercial-scale wind energy projects in Scottish waters, since powers were devolved, in June of 2020 [19]. The Sectoral Marine Plan for Offshore Wind Energy 2020 was developed to be consistent with the objectives and principles set out within Scotland's National Marine Plan (SNMP) and the UK Marine Policy Statement. Scotland's National Marine Plan sets out legislation and requirements pertaining to the management of Scottish inshore waters (up to 12 nautical miles from shore) and offshore waters (12-200 nautical miles from shore) [20]. The Sectoral Marine Plan 2020 defined commercial-scale offshore wind development as any project capable of generating more than 100MW of electricity [18]. The Sectoral Marine

Plan for Offshore Wind Energy also assumed an average deployment density of 5MW/km2 overall, considering all 15 initial proposed development zones within Scottish waters.

However, very few people, if anyone, anticipated the sheer scale of the announcement made by CES in January of 2020 regarding the outcome of ScotWind. 17 successful option areas were awarded totalling an amount of 25GW to an array of applicants and stakeholders throughout the wind and wider energy industry that included well-known offshore wind industry players such as Iberdrola, SSE and Vattenfall, large oil and gas energy giants such as Shell and bp and consortiums of organisations with experience in other renewable sources like onshore wind and solar energy, such as Falck Renewables [11].

Falck Renewables were successfully awarded three option areas within ScotWind. Of these three potential projects, Orsted (formerly DONG Energy) are an affiliate for one of them – NE3, codename "Cygnus". Given Orsted's proven track record in offshore wind [Orsted] and the fact that they did not win any other ScotWind projects, it is assumed by many that Orsted will take the lead in delivering and planning this project. Falck Renewables, on the other hand, are untested as of yet in the offshore wind space. Whilst Falck has considerable experience working with onshore wind development, this is their first venture into the offshore wind industry. Skipping fixed-bottom, all three of Falck's ScotWind projects are utilising floating wind foundations[11].

Floating wind is still a relatively nascent technology, with only three currently operational floating wind farms in the world – two of which are located in Scotland, with the final floating offshore wind farm located in Portuga [21]. It is therefore imperative that Falck Renewables thoroughly consider all factors related to their ScotWind offshore wind zones if they wish to succeed in their ambitious venture into the offshore wind industry.

2.2 Project Aims and Deliverables

2.2.1 Aims

2.2.2 Deliverables

This project intends to produce the following deliverables:

- Histogram of Significant Wave Height (Hs) for each site

- Comparison of Significant Wave Height (Hs) for all three sites
- Histogram of Wind Speed at Hub Height for each site
- Comparison of Wind Speed at Hub Height for all three sites
- Histogram of Wind Speed at 10m for each site
- Comparison of Wind Speed for all three sites
- Seasonal analysis of Significant Wave Height (Hs) for each site
- Average monthly analysis of Significant Wave Height (Hs) for each site
- Monthly analysis of Average / Maximum / Minimum Significant Wave Height (Hs) over time for each site
- Monthly analysis of Wind Speed at Hub Height for each site
- Monthly analysis of Wind Speed at Hub Height for all three sites
- Estimation of access levels for O&M vessels

2.2.3 Approach

1. Conduct a thorough review and analysis of existing literature
2. Conduct site-specific research into the three ScotWind areas awarded to Falck Renewables
3. Obtain and collect appropriate data to conduct met-ocean condition and weather-window analysis of ScotWind areas awarded to Falck Renewables

4. Conduct data analysis logically, beginning with analysis specific to particular sites and datasets. Following this, combine and compare various sites across a variety of metrics and parameters.

3.0 Literature Review

The advent and expansion of floating offshore wind as a sector within offshore marine renewable power generation has and is allowing previous inaccessible or prohibitively costly sites for turbine placement to become accessible and cost-effective [22]. The success of the 30MW Hywind, the world's first floating wind farm [23] has been unprecedented – with Hywind successfully achieving the highest average capacity factor for any wind farm in the UK [24], has been met with excitement from the industry. In addition to Hywind, Kincardine Offshore Windfarm Ltd. became the world's largest fully operational floating wind farm in October 2021, consisting of six turbines for a total site capacity of 50MW [25]. According to a report published in 2017 by Wind Europe, 80% of the total offshore wind resource in Europe is located in waters with depths of 60m and greater, where traditional fixed-bottom wind is not economically attractive [26].

To harness this potential untapped wind resource, floating offshore wind turbines are the likely solution. In these increased water depths, a fixed monopile / jacket foundation ceases to become a viable, cost-effective solution due to the loads imparted on the structure and the incurred sizes and costs required to counteract these [22]. The Carbon Trust estimates that up to 70GW of FOW could be operational globally by 2040 [27]. The Global Wind Energy Council's Global Offshore Wind Report 22 believes the UK and several other nations are ideally placed to continue to scale-up and lead in terms of growth within floating offshore wind in the coming decade, however, several drivers and constraints must be considered to allow this, such as: site conditions, supply chain and infrastructure and the transmission grid [10]. Significant investment in researching optimal site conditions (including wind speeds and bathymetry), an overhaul of current port facilities and domestic industrial capabilities alongside considerations regarding building of new substations close to connection points and mass upgrades to current transmission grid capabilities [10].

Further areas of concern surrounding the widespread adoption of floating systems is the introduction of new challenges and constraints – such as an increased distance to shore and harsher natural operating environment [28]. In addition, NREL identified key challenges such as wave sensitivity, maintainability, anchor cost/complexity, mooring cost/complexity and turbine motion that must be addressed for the FOW sector to succeed and thrive [29]. Jade McMorland et al argue that another operational challenge is lack of available data due to the infancy of the industry [28].

This lack of available data within the industry is acute, with very few to no reliable real-time resources available publicly. Public data that is available tends to exist in the form of vague datasets from resources such as ERA5, the latest climate reanalysis produced by ECMWF, providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty [30]. McMorland et al have conducted a review of FOW O&M models and highlights a number of models that are adaptations of existing models for fixed-bottom wind and a few others that have been designed specifically for FOW [28].

4.0 Methods and Materials

4.1 Site Research

All three of the options areas awarded to Falck Renewables were researched thoroughly utilising a number of publicly available resources, such as CES' ScotWind: Map of Option Areas [19], CES' List of Successful Project Partners [11], CES' Interactive Map [31], the European Marine Observation Data Network [32], Marine Scotland's Interactive Map Tool [33] and LAUTEC ESOX [34]. In addition, the published Supply Chain Development Statements relevant to each of Falck Renewables option areas were reviewed: E3 (GEMINI) [35], NE3 (CYGNUS) [36] and NE6 (ORION) [37].

Information collected from the above resources included: site location, site capacity (MW), site area (km^2), turbine foundation type, bathymetry and distance from the nearest port.

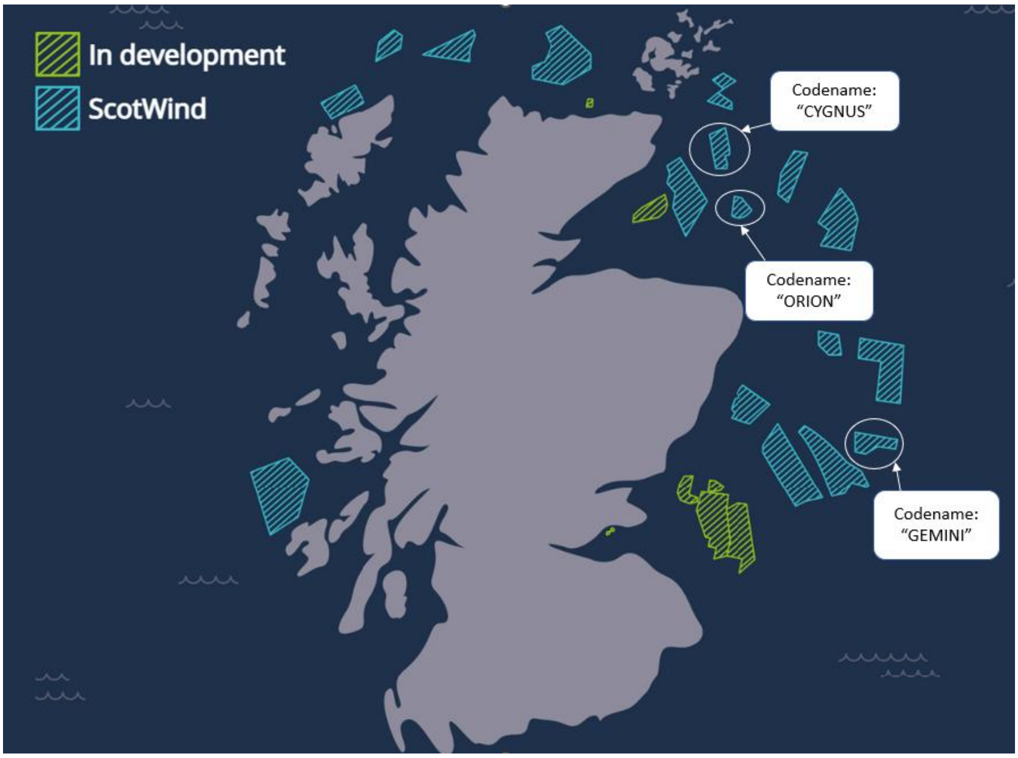


Figure 2: Map of Scotland's Offshore Wind Developments – annotated with three Falck Renewables Sites (Image credit: Crown Estate Scotland)

Table 1: Falck Renewables ScotWind Option Zones

ZONE	AREA (KM^2)	CAPACITY (MW)	FOUNDATION	DISTANCE TO NEAREST PORT
GEMINI	280	1200	Floating	170km (Montrose)
CYGNUS	256	1000	Floating	64km (Wick)
ORION	134	500	Floating	60.5km (Fraserburgh)

4.2 Data Collection

Historical datasets were collected utilising Lautec ESOX's map function. ESOX utilises ERA5 reanalysis data which is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union's Copernicus Climate Change Service (C3S) [38]. Each dataset location in the ESOX map is the centroid of an area with a width of 0.25 x 0.25 degrees and the data at each point is representative of this grid box area, resulting in a spatial resolution of approximately 10 to 30 km, depending on latitude [34].

Eight datasets in total were obtained for analysis. The datasets collected from ESOX for the purposes of this study cover a thirty-year period in an hourly timestep from 01.01.1990 – 31.12.2019, and contain four met-ocean variables: mean with wind speed at 10m above ocean surface, mean wind speed at 100m above ocean surface, significant wave height and peak wave period.

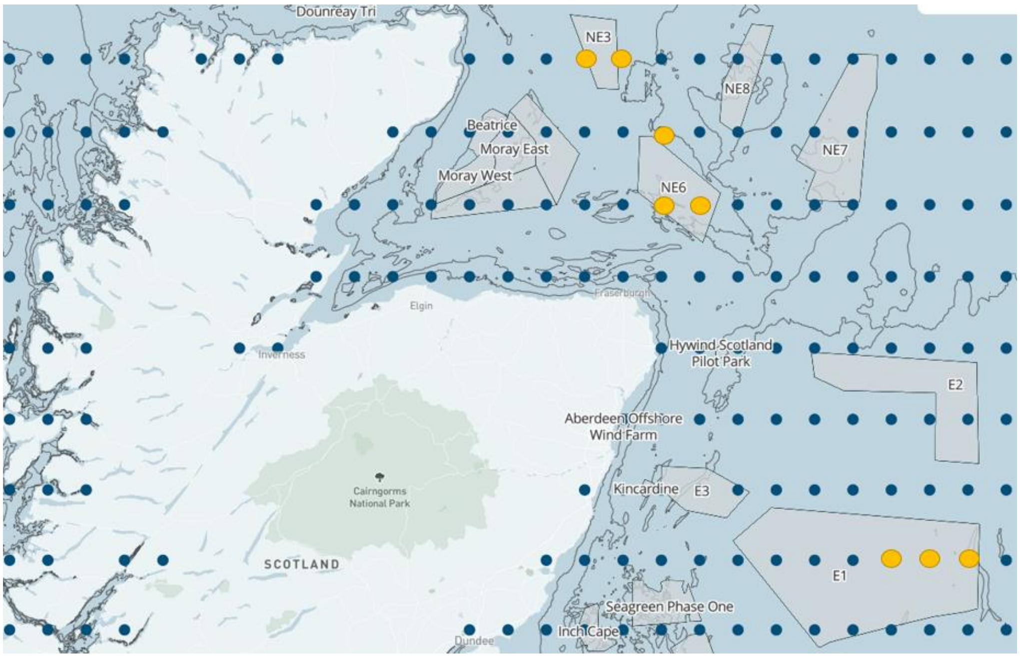


Figure 3: ESOX Map Grid - Showing data points used for each Falck Renewables ScotWind Zone (Yellow) and Bathymetry
(Image credit: Lautec ESOX) [34]

Three datasets were obtained for sites “Gemini” and “Orion”. For site “Cygnus”, two datasets were obtained. This was due to the variation in site area size – “Gemini” and “Cygnus” greater area sizes were assumed to warrant more data to ensure representative results. Coordinates and links to each datapoint can be found in the table below:

Table 2: Dataset Latitudes, Longitudes and Links

Site	Datapoint Latitudes	Datapoint Longitudes	Link to Datapoints
Gemini (E1)	56.75	-0.25	https://esox.lautec.com/map/?location=56.75/-0.25&zoom=8
Gemini (E1)	56.75	0	https://esox.lautec.com/map/?location=56.75/0.00&zoom=8
Gemini (E1)	56.75	0.25	https://esox.lautec.com/map/?location=56.75/0.25&zoom=8
Cygnus (NE3)	58.50	-2.0	https://esox.lautec.com/map/?location=58.50/-2.00&zoom=8
Cygnus (NE3)	58.50	-2.25	https://esox.lautec.com/map/?location=58.50/-2.25&zoom=8
Orion (NE6)	58.00	-1.50	https://esox.lautec.com/map/?location=58.00/-1.50&zoom=8

Orion (NE6)	58.00	-1.75	https://esox.lautec.com/map/?location=58.00/-1.75&zoom=8
Orion (NE6)	58.25	-1.75	https://esox.lautec.com/map/?location=58.25/-1.75&zoom=8

4.3 Data Analysis

Each of the datasets was analysed utilising Microsoft Excel, in a logical step-wise manner.

4.3.1 Site Specific

All eight datasets were analysed individually and, in their entirety, to provide representative illustrations of the frequency that each met-ocean variable present fell within various notable ranges throughout a thirty-year timeframe at each node. Graphs depicting Mean Significant Wave Height Frequency, Mean Peak Wave Period Frequency, Mean Wind Speed Frequency at 10m and Mean Wind Speed Frequency at 100m were then illustrated in histogram format for each of the datasets.

Following this, pivot tables were created for each dataset to allow for further analysis seasonally, yearly, monthly and hourly across all variables over the thirty-year timeframe specific to each site.

4.3.2 Site Comparison

Following this, datasets specific to certain sites were then merged with one another and averaged to achieve a representative portrayal of typical conditions that may be found within each site. These new datasets were then utilised to compare each of the Falck Renewables sites, “Gemini”, “Cygnus” and “Orion”, with each other directly. Each of the four variables present within the datasets was compared across each site over a thirty-year timeframe to highlight occurrences of each met-ocean variable within notable ranges.

Following this, further comparative analysis of significant wave height and maximum mean wind speed at 100m was conducted across all three sites. Pivot tables were created to allow for monthly comparison. Maximum and minimum monthly significant wave height and wind speed at 100m graphs were created to illustrate the variance in what were assumed to be the most important variables for offshore wind farm developers.

4.4 Assumptions

For the purposes of this study, a number of assumptions were made – based on literature wherever possible:

- CTV Hs Limit: 1.5m-2m [28], [39]
- SOV Hs Limit: 2.5-4m [28], [39]
- Spring: March, April and May
- Summer: June, July and August
- Autumn: September, October and November
- Winter: December, January and February

These assumptions were utilised to estimate weather-based availability from significant wave height and to illustrate variations in various met-ocean conditions between seasons.

5.0 Results

5.1 Gemini

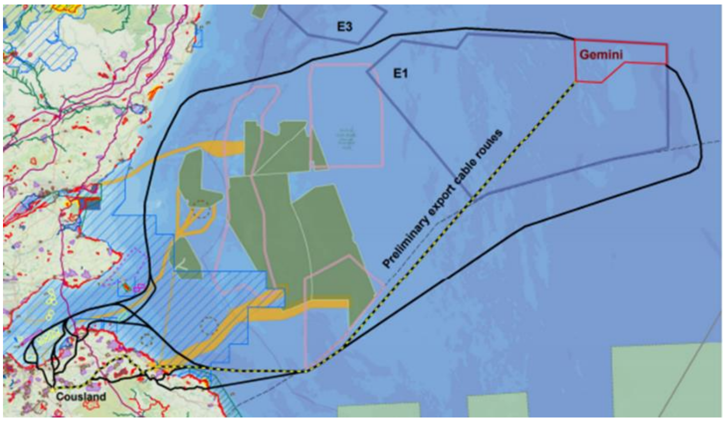


Figure 4: "Gemini" ScotWind Option Area
Image Credit: Obtained from Supply Chain Development Statement Outlook Area 3

Gemini is located in a region of the ocean where the depths of the ocean floor range from 50m-100m throughout, according to EMODnet, Marine Scotland and Lautec ESOX.

5.1.1 Dataset (56.75, 0.00)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 46.2%-65.2% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 78.1%-95% of any given year, assuming a Hs limit of 2.5-4m.

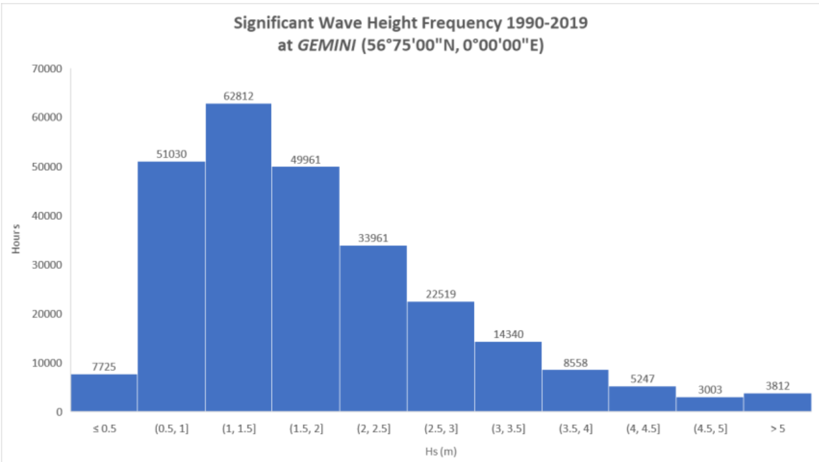


Figure 5: Significant Wave Height Frequency 1990-2019 – Gemini (56.75, 0.00)

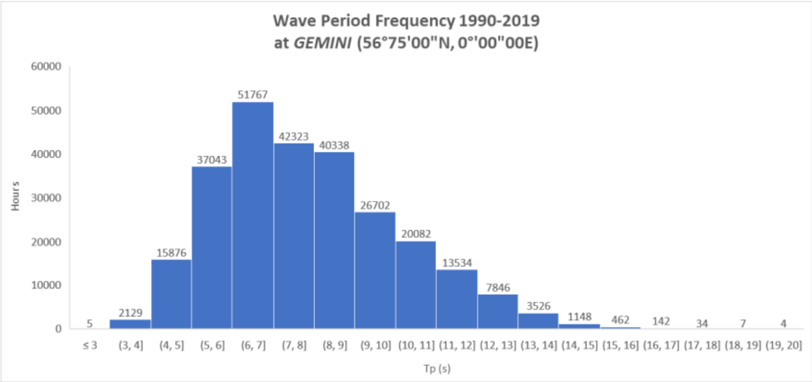


Figure 6: Wave Period Frequency 1990-2019 – Gemini (56.75, 0.00)

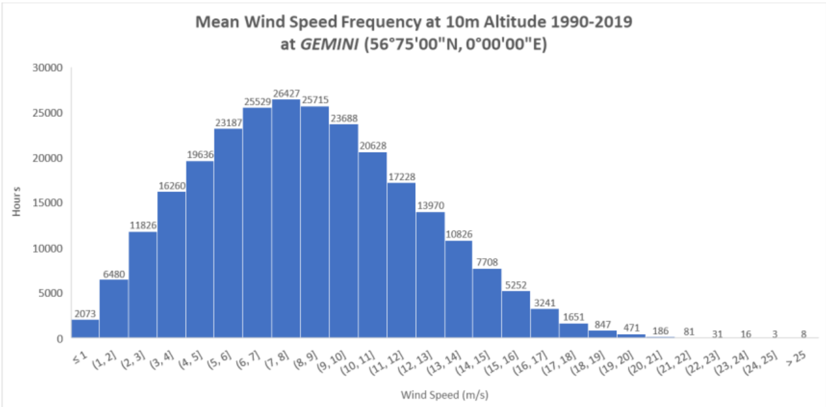


Figure 7: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Gemini (56.75, 0.00)

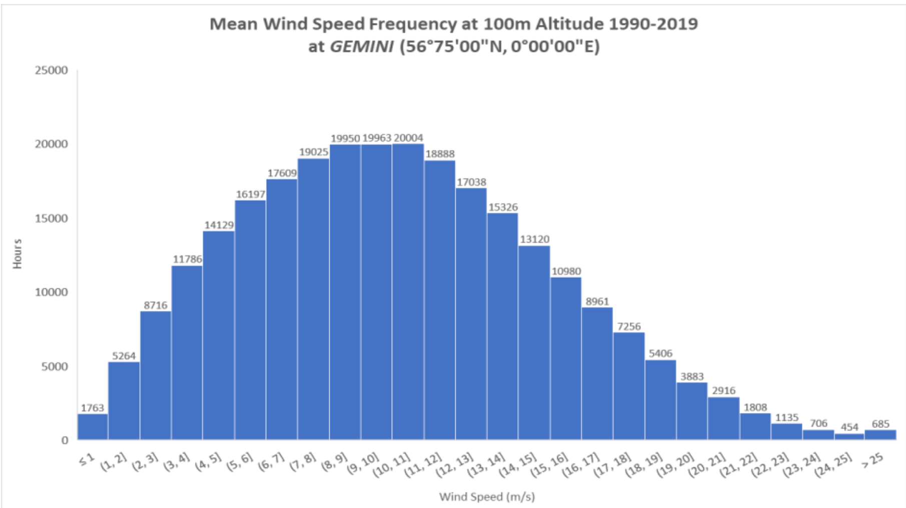


Figure 8: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Gemini (56.75, 0.00)

5.1.2 Dataset (56.75, 0.25)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 45.4%-64.4% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 77.4%-95.1% of any given year, assuming a Hs limit of 2.5-4m.

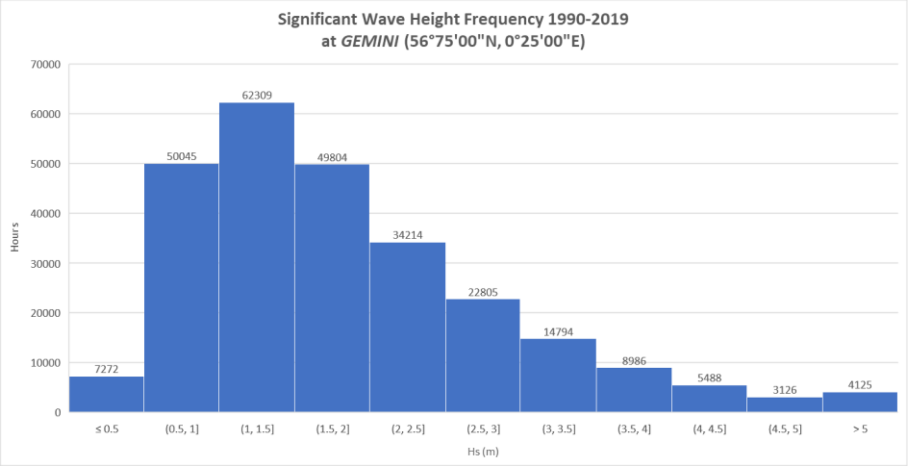


Figure 9: Significant Wave Height Frequency 1990-2019 – Gemini (56.75, 0.25)

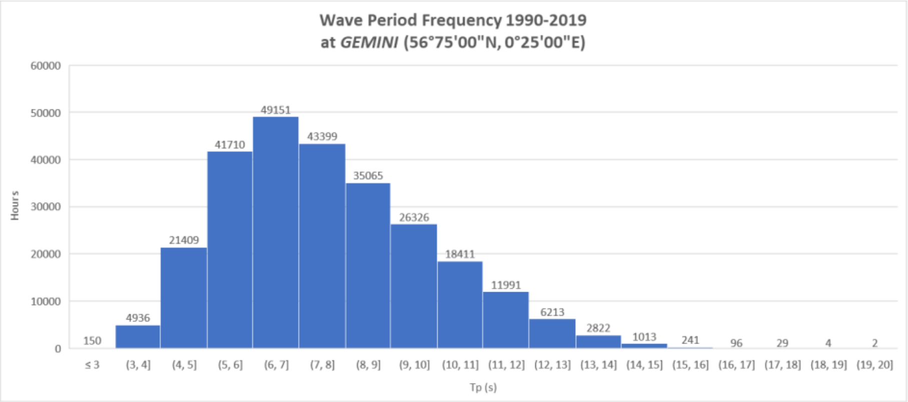


Figure 10: Wave Period Frequency 1990-2019 – Gemini (56.75, 0.25)

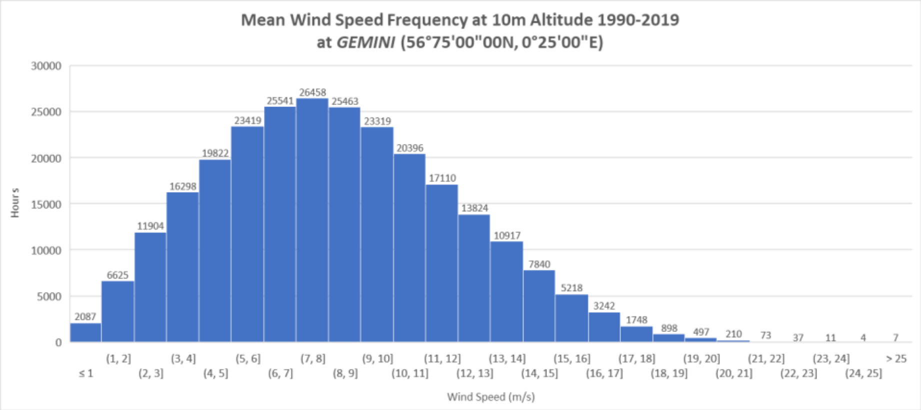


Figure 11: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Gemini (56.75, 0.25)

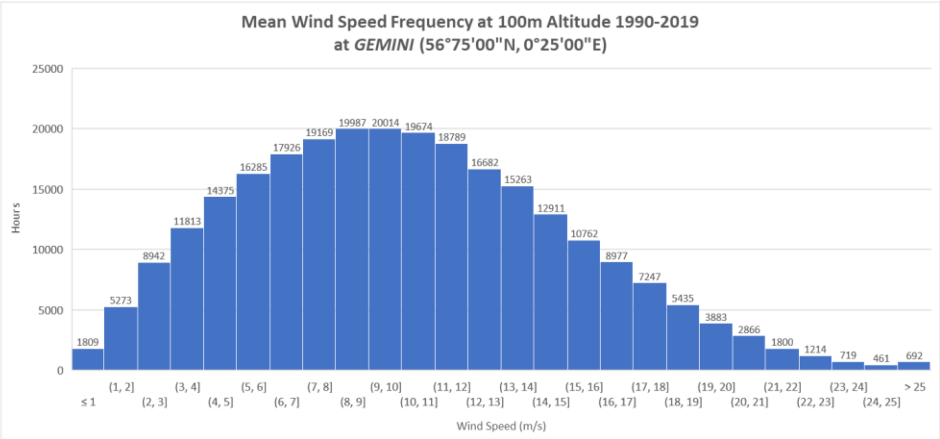


Figure 12: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Gemini (56.75, 0.25)

5.1.3 Dataset (56.75, -0.25)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 47.6%-66.6% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 79.3%-95.8% of any given year, assuming a Hs limit of 2.5-4m.

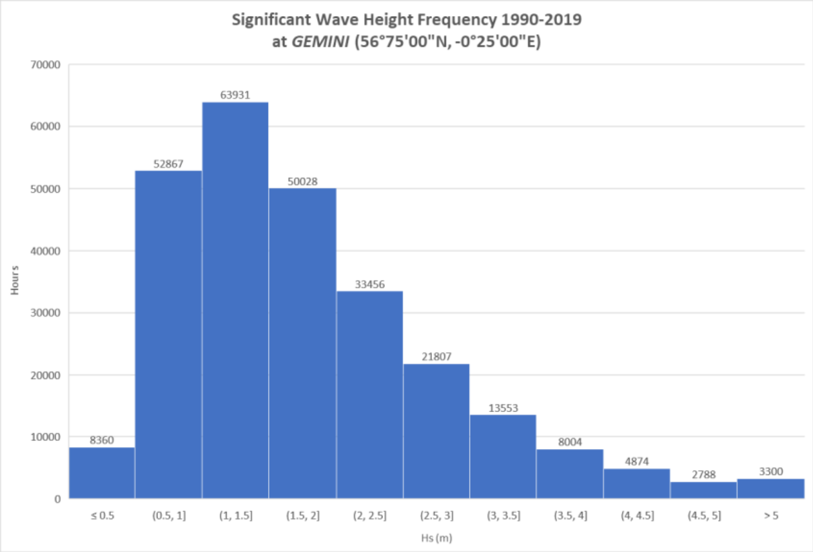


Figure 13: Significant Wave Height Frequency 1990-2019 – Gemini (56.75, -0.25)

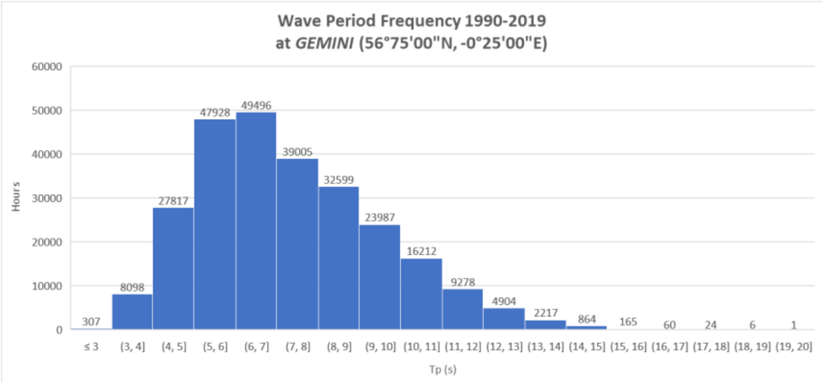


Figure 14: Wave Period Frequency 1990-2019 – Gemini (56.75, -0.25)

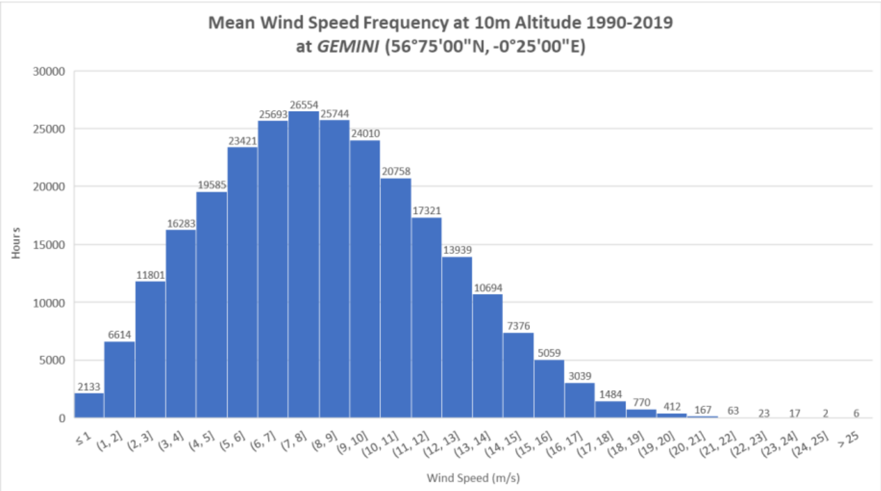


Figure 15: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Gemini (56.75, -0.25)

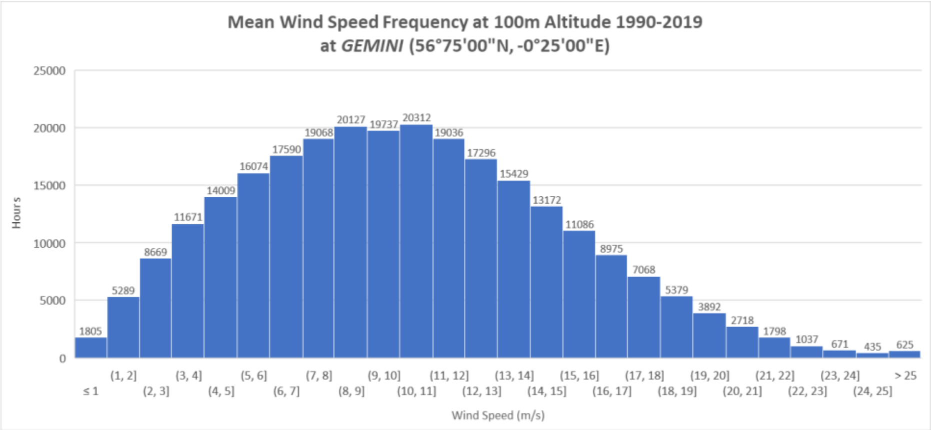


Figure 16: Mean Wind Speed Frequency at 100m Altitude 1990-2019 (56.75, -0.25)

5.1.4 Gemini: Site-Wide

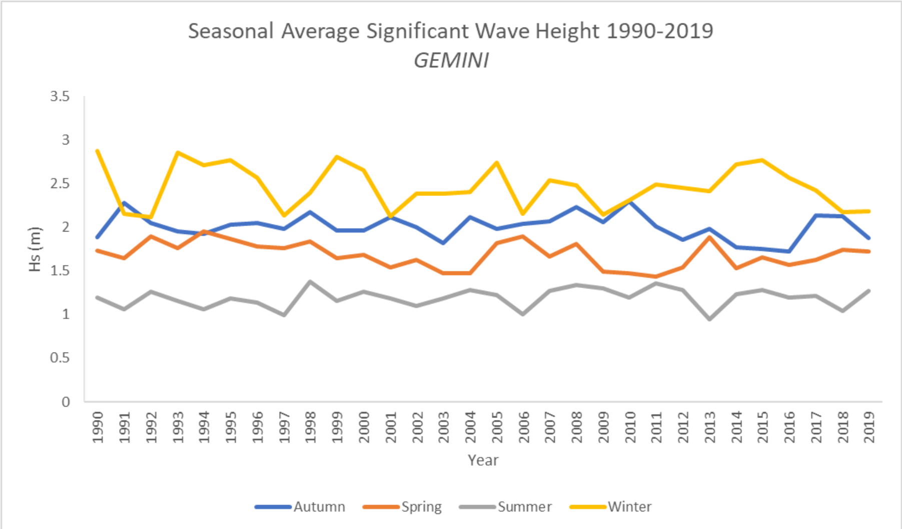


Figure 17: Seasonal Average Significant Wave Height 1990-2019 – Gemini

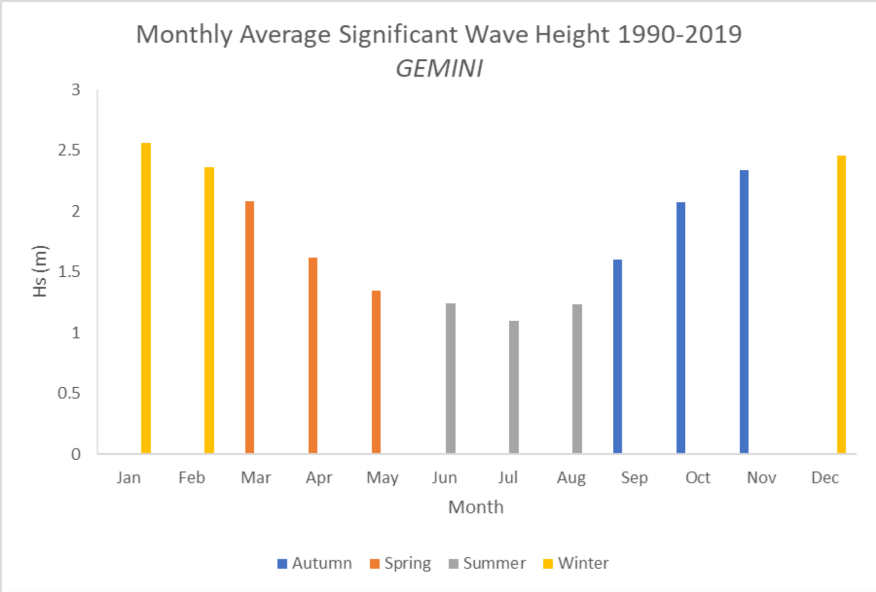


Figure 18: Monthly Average Significant Wave Height 1990-2019 – Gemini

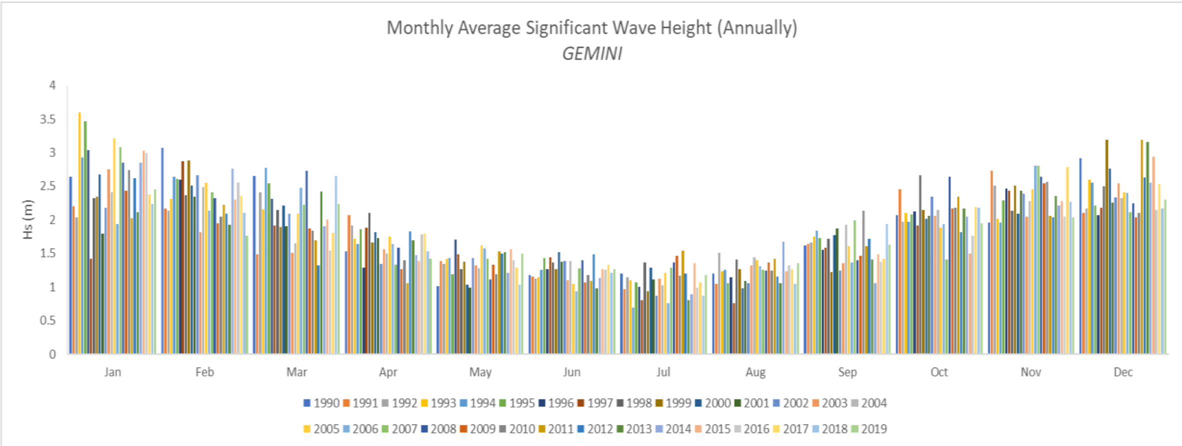


Figure 19: Monthly Average Significant Wave Height 1990-2019 - Gemini

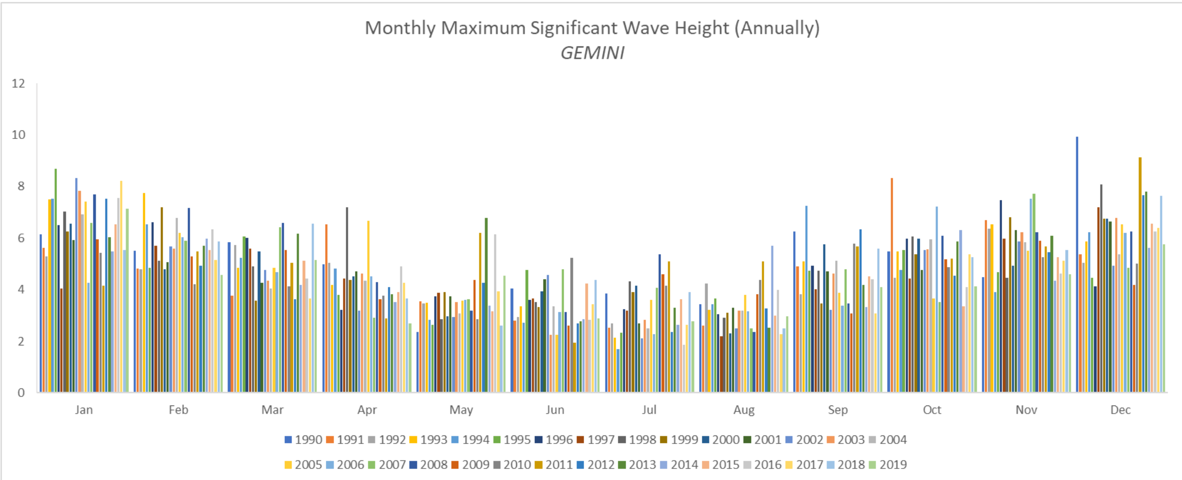


Figure 20: Monthly Maximum Significant Wave Height 1990-2019 - Gemini

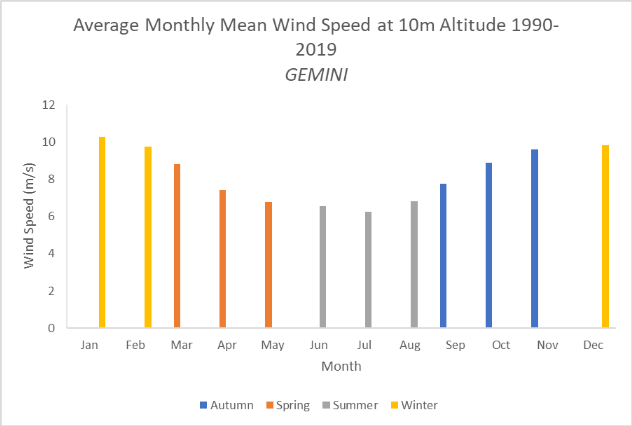


Figure 21: Average Monthly Mean Wind Speed at 10m Altitude 1990-2019 - Gemini

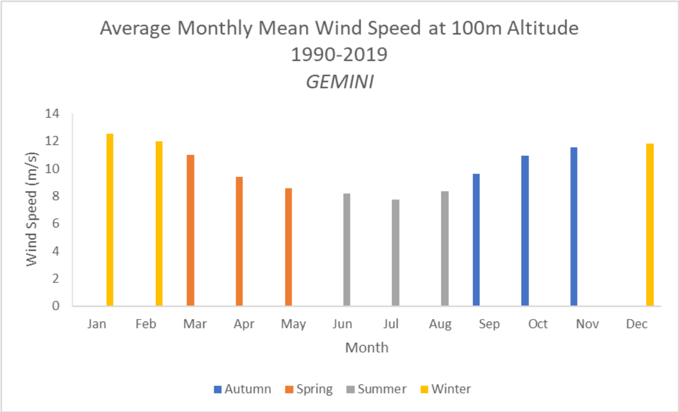


Figure 22: Average Monthly Mean Wind Speed at 100m Altitude 1990-2019 - Gemini

5.2 Cygnus

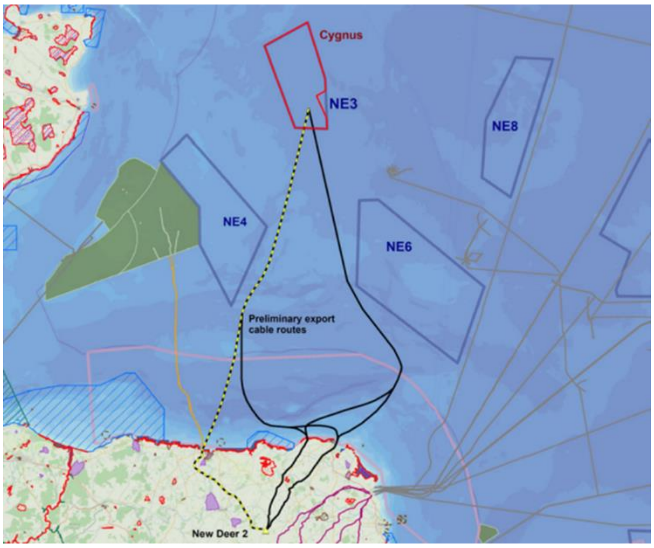


Figure 23: "Cygnus" Scotwind Option Area
Image Credit: Obtained from Supply Chain Development Statement Outlook Area 8

Cygnus is located in a region of the ocean where the depths of the ocean floor range from 50m-100m throughout, according to EMODnet, Marine Scotland and Lautec ESOX.

5.2.1 Dataset (58.50, -2.00)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 49.95%-69.2% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 81.45%-96.5% of any given year, assuming a Hs limit of 2.5-4m.

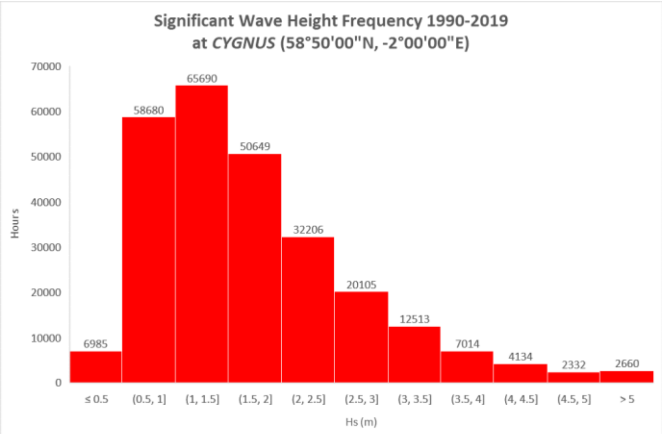


Figure 24: Significant Wave Height Frequency 1990-2019 – Cygnus (58.50, -2.00)

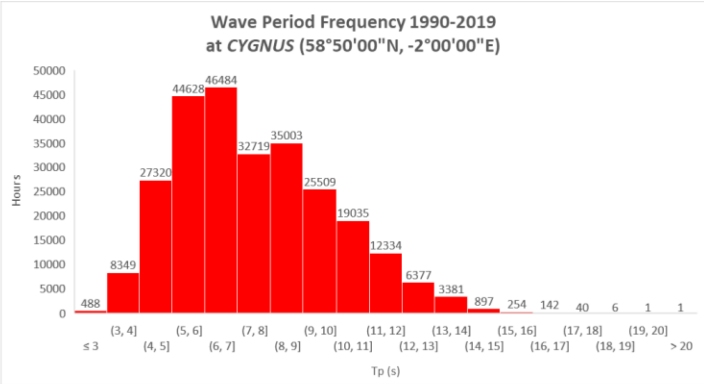


Figure 25: Wave Period Frequency 1990-2019 – Cygnus (58.50, -2.00)

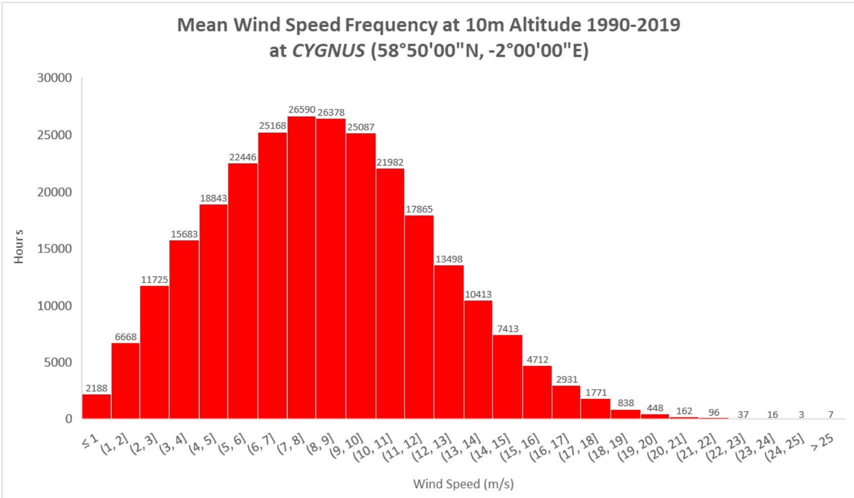


Figure 26: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Cygnus (58.50, -2.00)

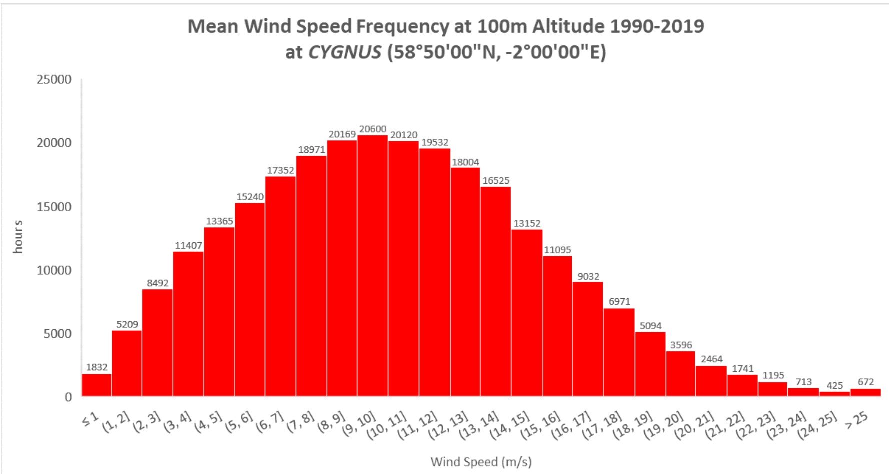


Figure 27: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Cygnus (58.50, -2.00)

5.2.2 Dataset(58.50, -2.25)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 46.2%-65.2% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 78.1%-95% of any given year, assuming a Hs limit of 2.5-4m.

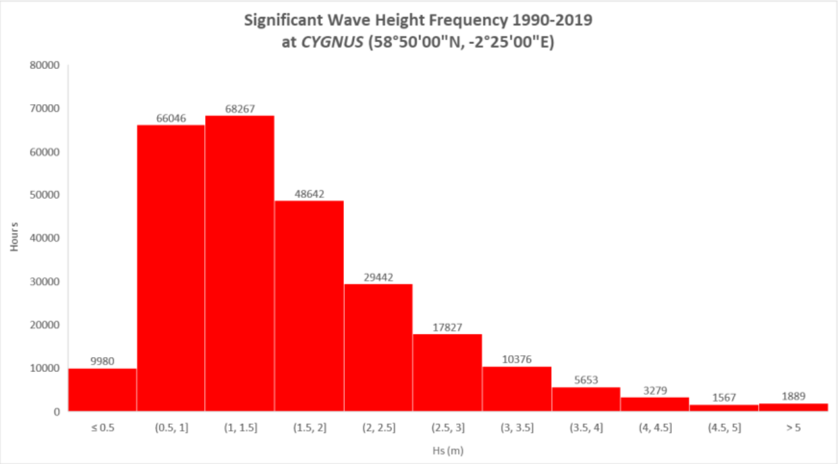


Figure 28: Significant Wave Height Frequency 1990-2019 – Cygnus (58.50, -2.25)

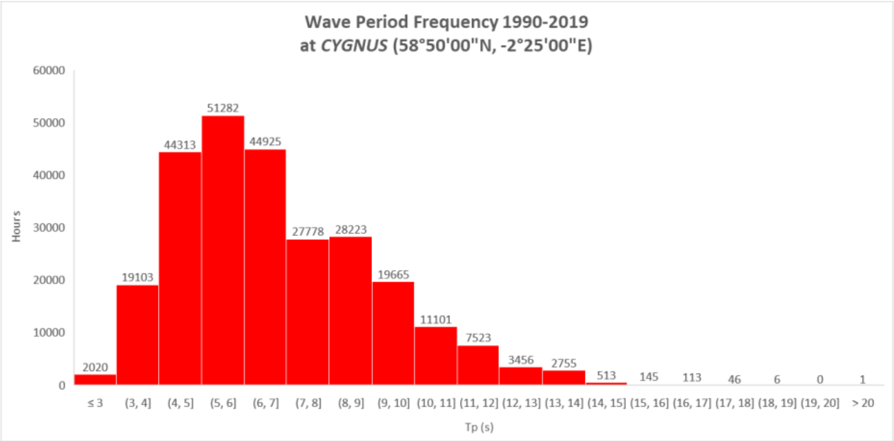


Figure 29: Wave Period Frequency 1990-2019 – Cygnus (58.50, -2.25)

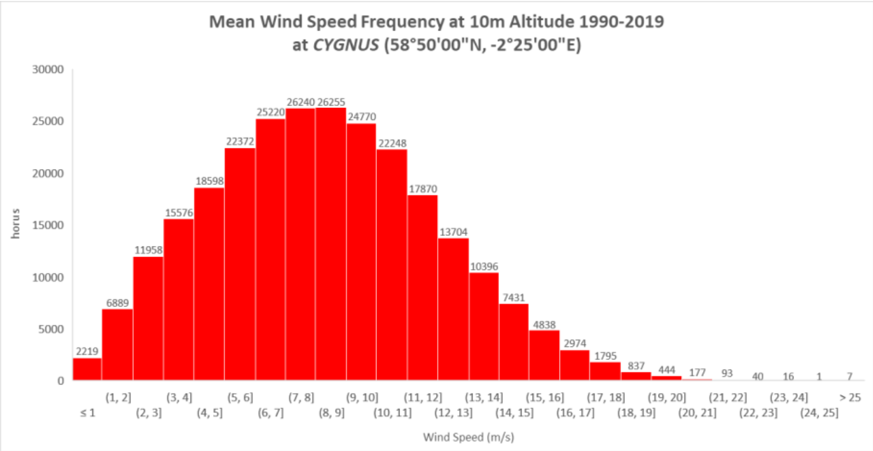


Figure 30: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Cygnus (58.50, -2.25)

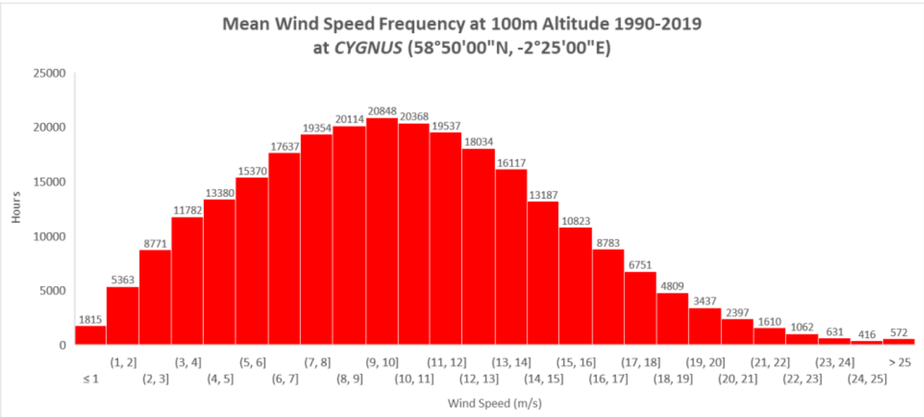


Figure 31: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Cygnus (58.50, -2.25)

5.2.3 Cygnus: Site-Wide

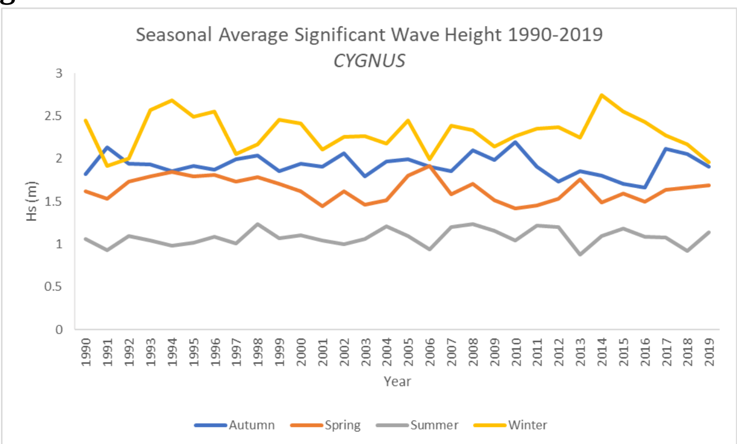


Figure 32: Seasonal Average Significant Wave Height 1990-2019 - Cygnus

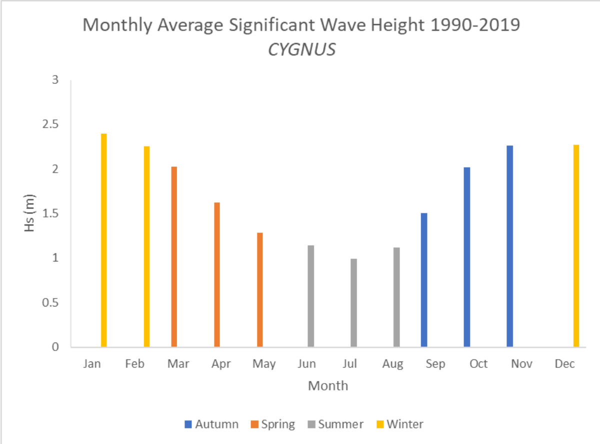


Figure 33: Monthly Average Significant Wave Height 1990-2019 - Cygnus

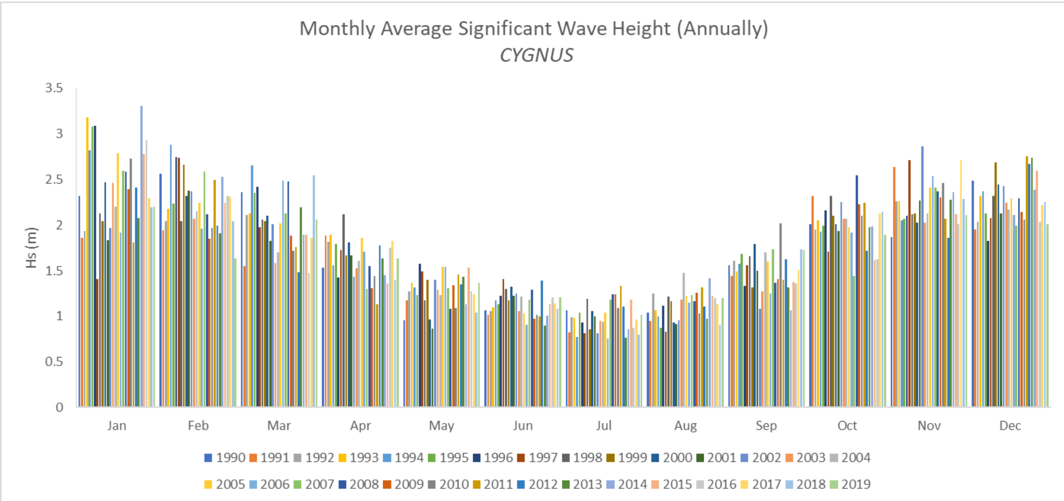


Figure 34: Monthly Average Significant Wave Height 1990-2019 - Cygnus

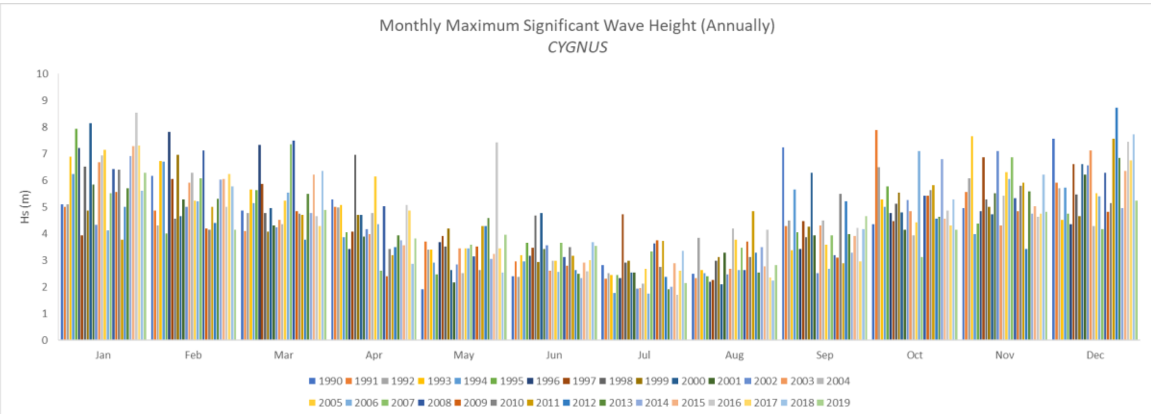


Figure 35: Monthly Maximum Significant Wave Height 1990-2019 - Cygnus

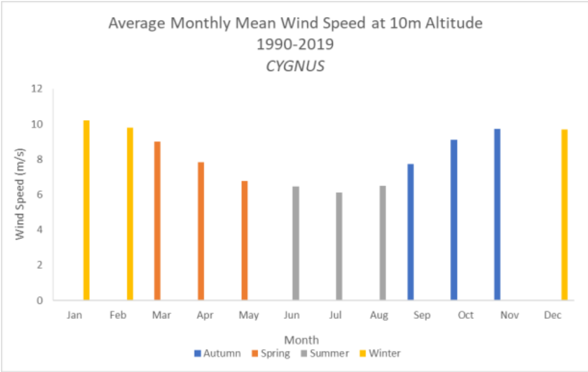


Figure 36: Average Monthly Mean Wind Speed at 10m Altitude 1990-2019 - CYGNUS

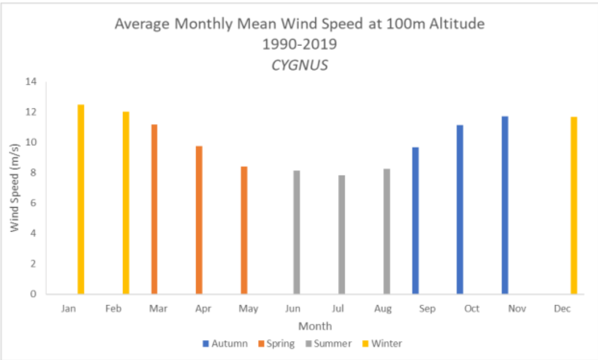


Figure 37: Average Monthly Mean Wind Speed at 100m Altitude 1990-2019 - Cygnus

5.3 Orion

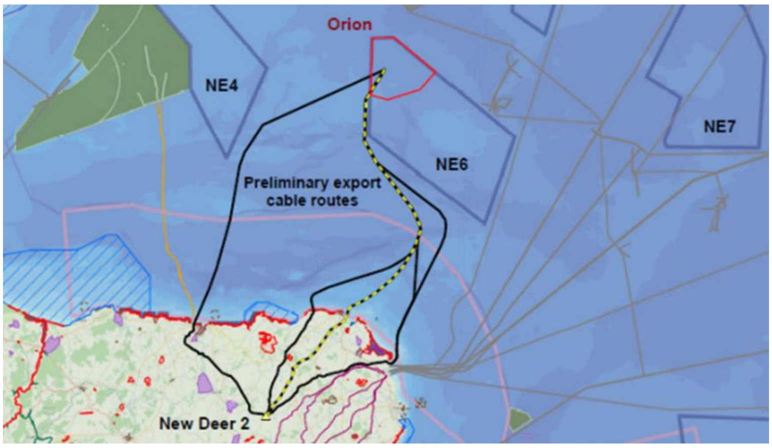


Figure 38: "Orion" ScotWind Option Area
Image Credit: Supply Chain Development Statement Outlook Area 10

Orion is located in a region of the ocean where the depths of the ocean floor range from 50m-100m throughout, according to EMODnet, Marine Scotland and Lautec ESOX.

5.3.1 Dataset (58.00, -1.50)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 50.3%-68.9% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 81.1%-96.2% of any given year, assuming a Hs limit of 2.5-4m.

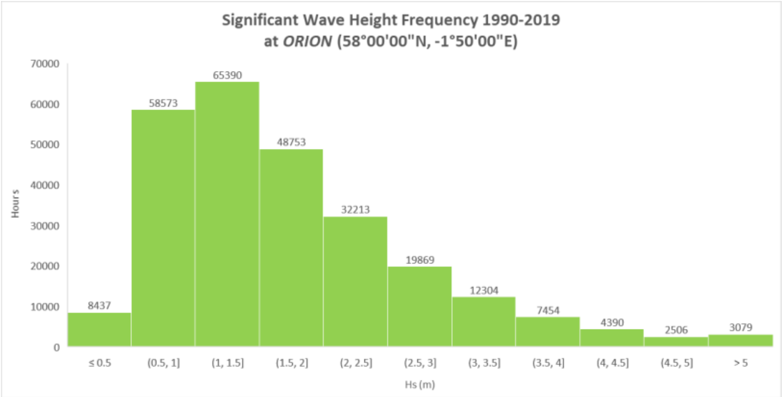


Figure 39: Significant Wave Height Frequency 1990-2019 – Orion (58.00, -1.50)

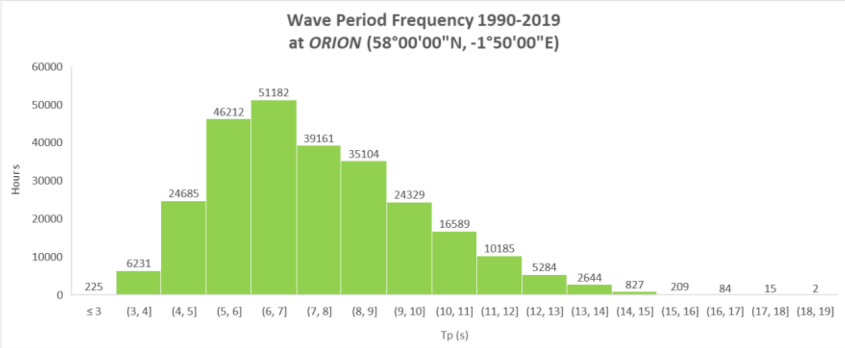


Figure 40: Wave Period Frequency 1990-2019 – Orion (58.00, -1.50)

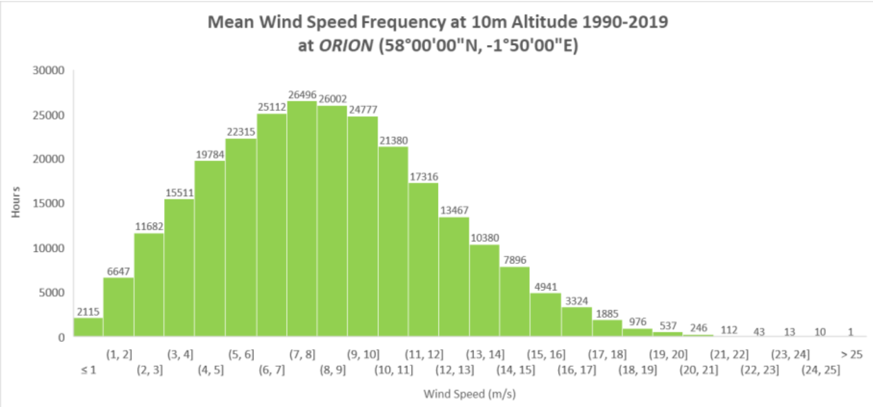


Figure 41: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Orion (58.50, -1.50)

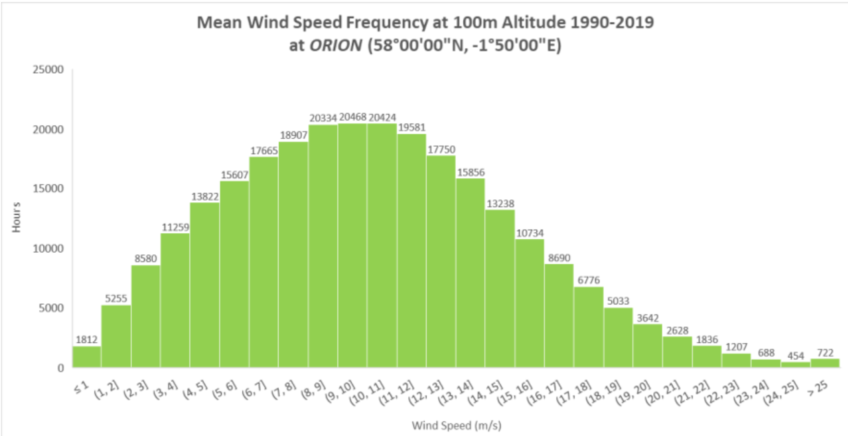


Figure 42: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Orion (58.50, -1.50)

5.3.2 Dataset (58.00, -1.75)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 54.1%-64.9% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 83.7%-97% of any given year, assuming a Hs limit of 2.5-4m.

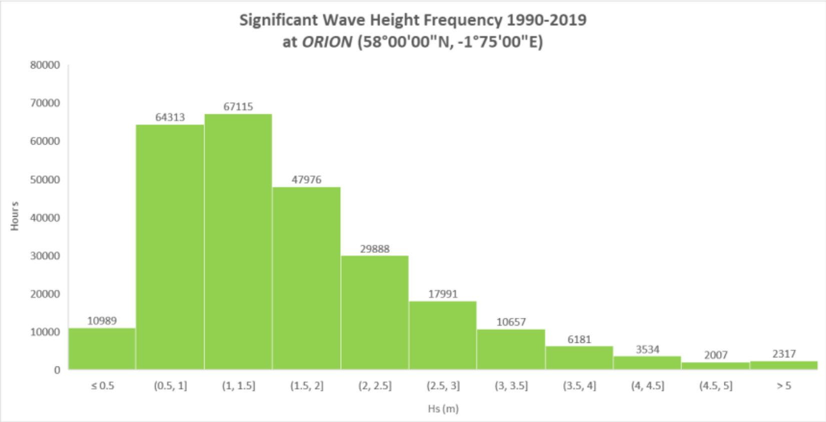


Figure 43: Significant Wave Height Frequency 1990-2019 – Orion (58.00, -1.75)

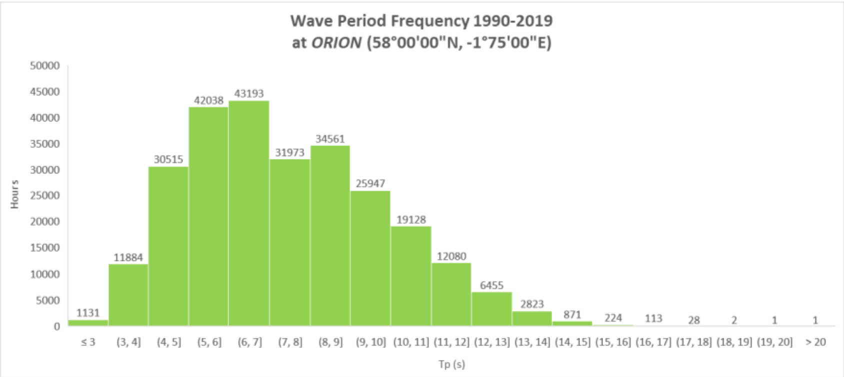


Figure 44: Wave Period Frequency 1990-2019 – Orion (58.00, -1.75)

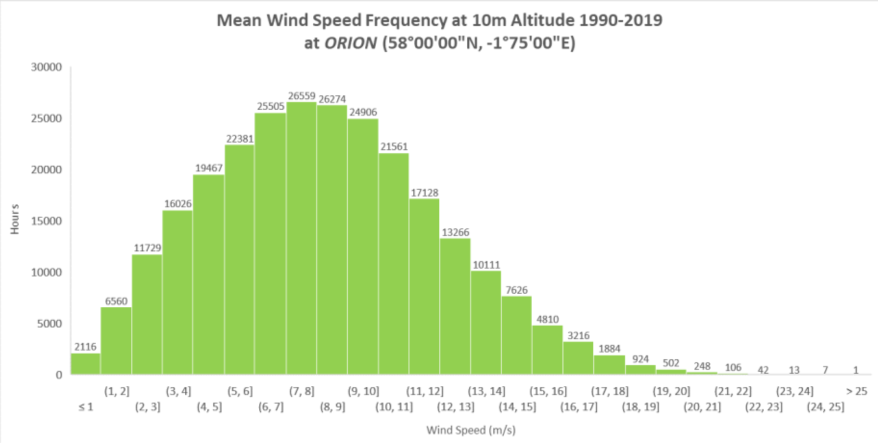


Figure 45: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Orion (58.00, -1.75)

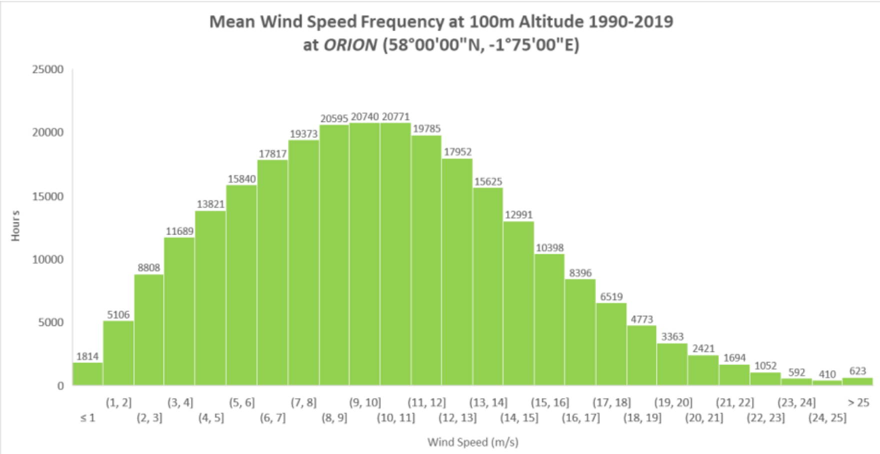


Figure 46: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Orion (58.00, -1.75)

5.3.3 Dataset (58.25, -1.75)

Given the distribution of significant wave height illustrated below, a CTV could expect to be able to operate safely for 50.08%-69.1% of any given year, assuming a Hs limit of 1.5-2m. An SOV could operate safely for 81.3%-96.4% of any given year, assuming a Hs limit of 2.5-4m.

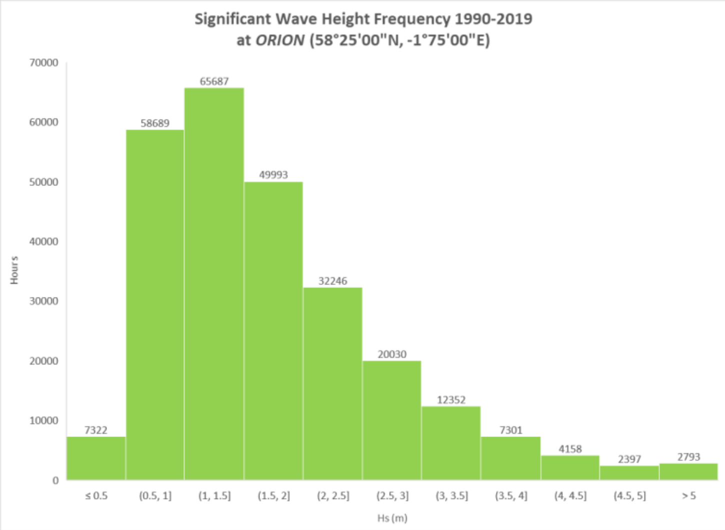


Figure 47: Significant Wave Height Frequency 1990-2019 – Orion (58.25, -1.75)

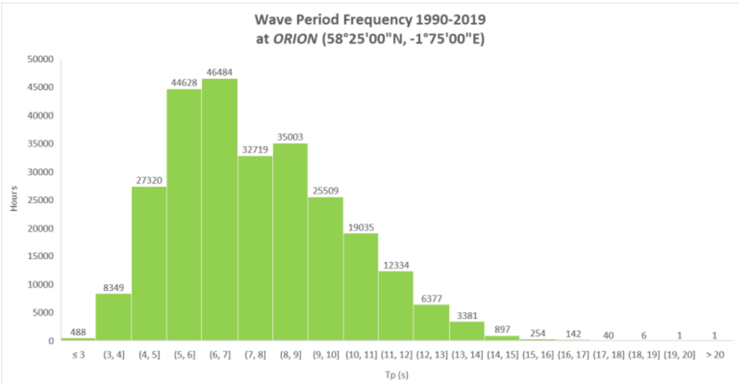


Figure 48: Wave Period Frequency 1990-2019 – Orion (58.25, -1.75)

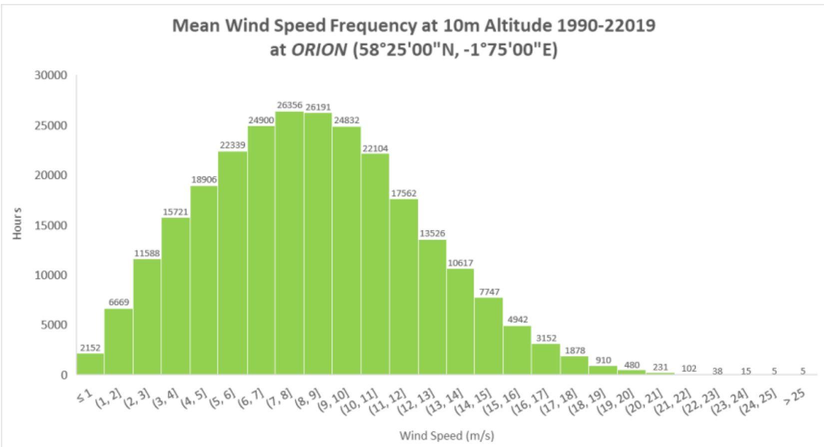


Figure 49: Mean Wind Speed Frequency at 10m Altitude 1990-2019 – Orion (58.25, -1.75)

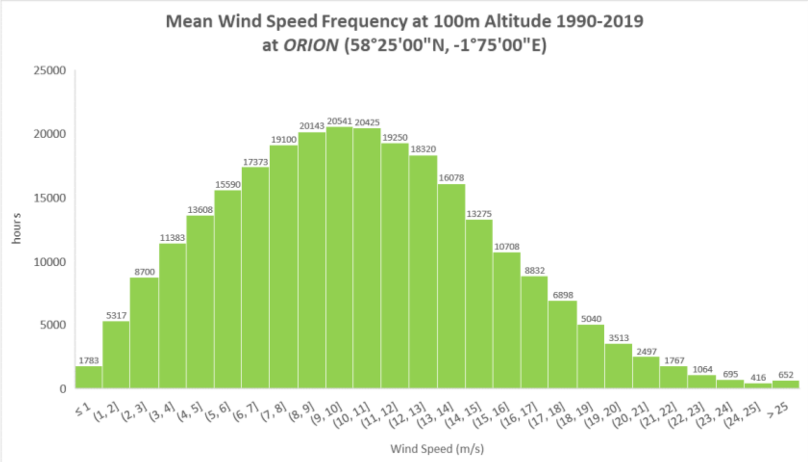


Figure 50: Mean Wind Speed Frequency at 100m Altitude 1990-2019 – Orion (58.25, -1.75)

5.3.4 Orion: Site-Wide

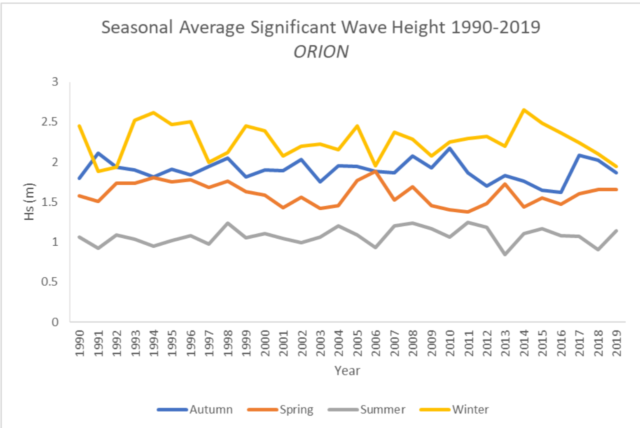


Figure 51: Seasonal Average Significant Wave Height 1990-2019 - Orion

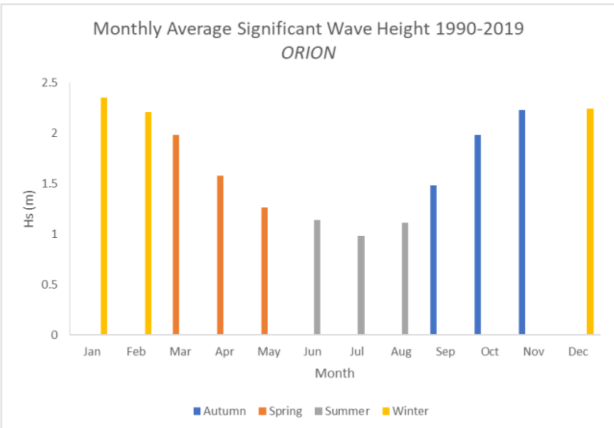


Figure 52: Monthly Average Significant Wave Height 1990-2019 – Orion

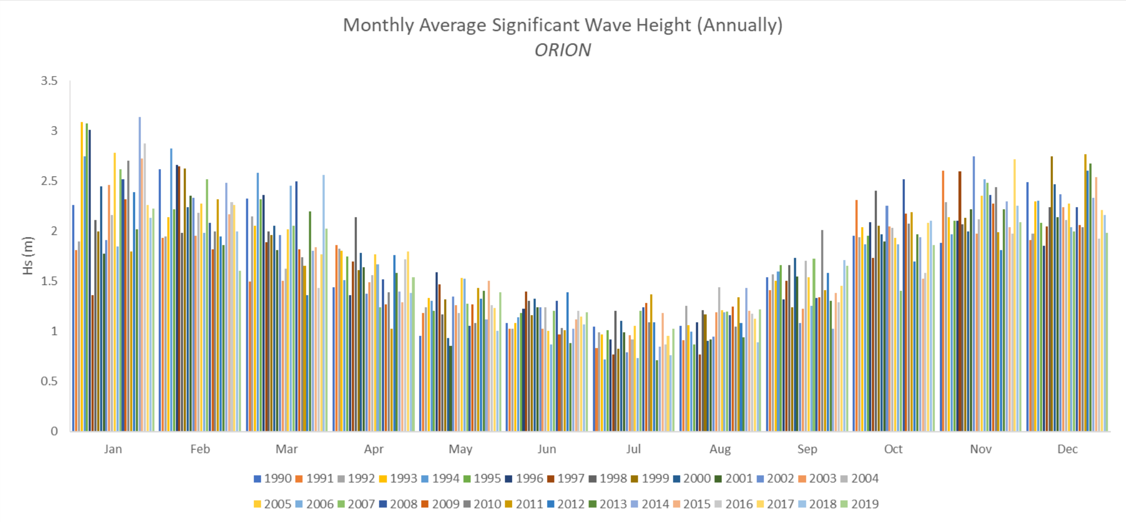


Figure 53: Monthly Average Significant Wave Height 1990-2019 - Orion

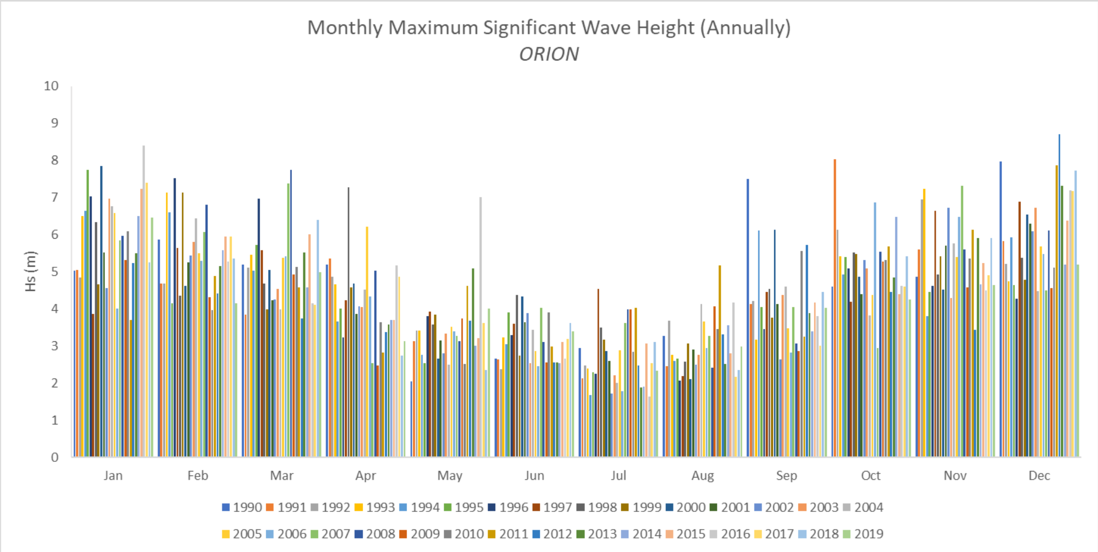


Figure 54: Monthly Maximum Significant Wave Height 1990-2019 - Orion

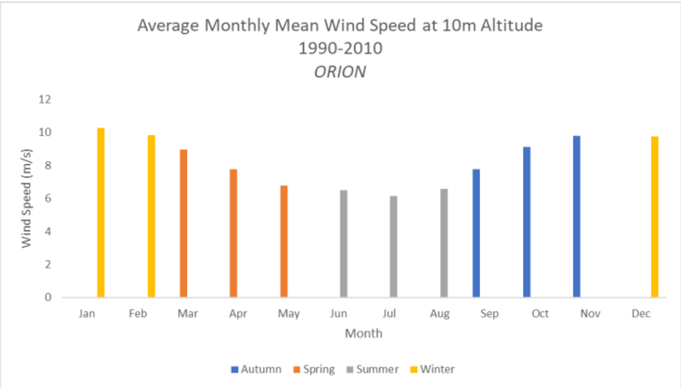


Figure 55: Average Monthly Mean Wind Speed at 10m Altitude 1990-2019 – Orion

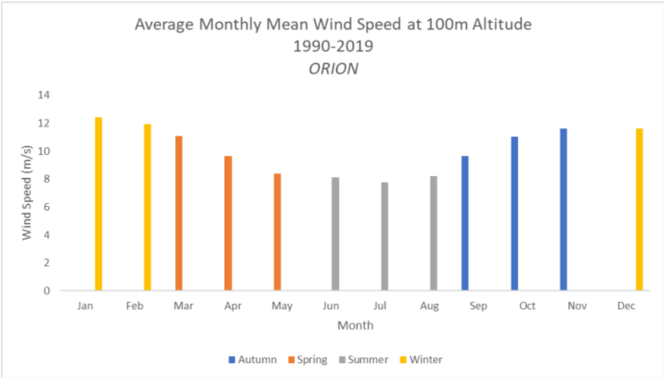


Figure 56: Average Monthly Mean Wind Speed at 100m Altitude 1990-2019 - Orion

5.4 Site Comparison

5.4.1 Significant Wave Height Frequency

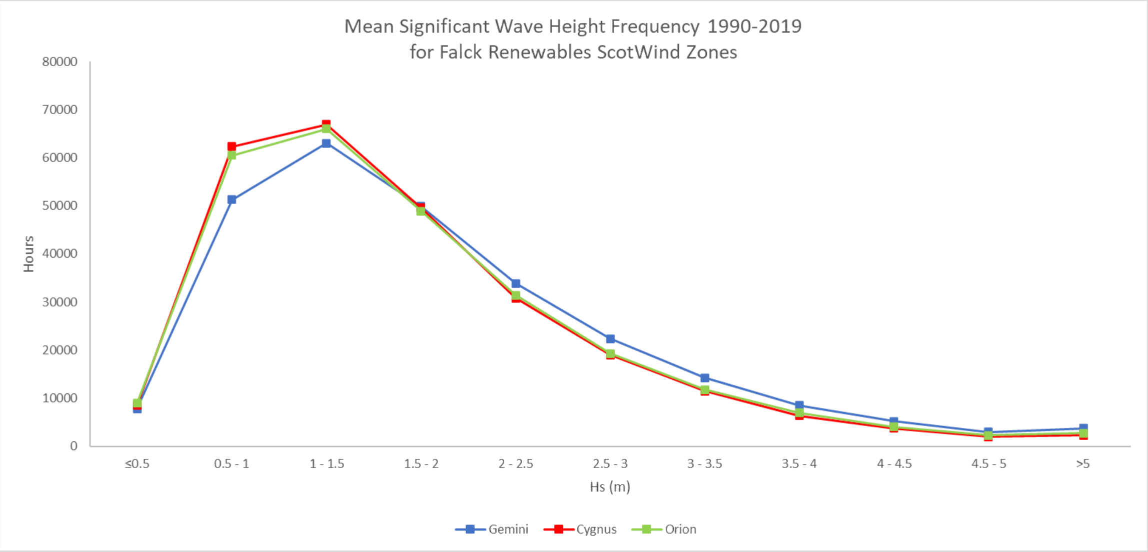


Figure 57: Mean Significant Wave Height Frequency for Falck Renewables ScotWind Zones 1990-2019

5.4.2 Peak Wave Period Frequency

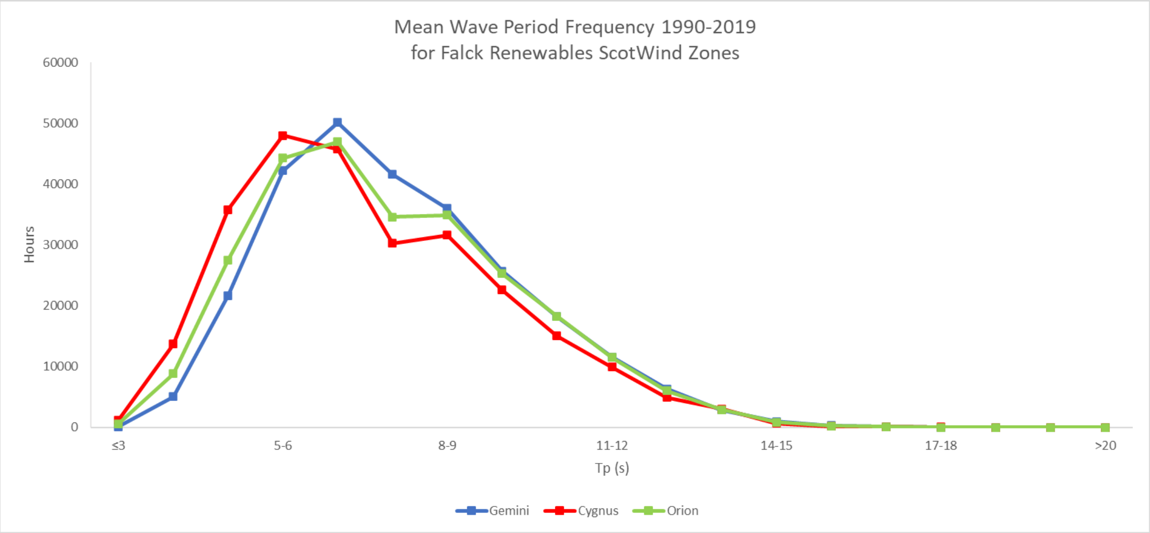


Figure 58: Mean Peak Wave Period Frequency for Falck Renewables ScotWind Zones 1990-2019

5.4.3 Wind Speed at 10m Altitude Frequency

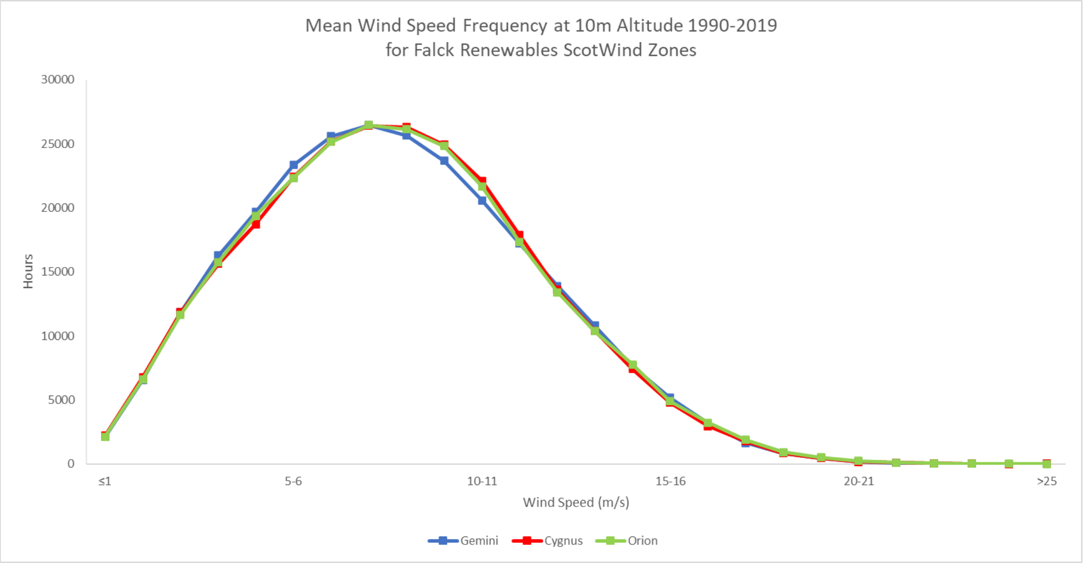


Figure 59: Mean Wind Speed Frequency at 10m Altitude for Falck Renewables ScotWind Zones 1990-2019

5.4.4 Wind Speed at 100m Altitude Frequency

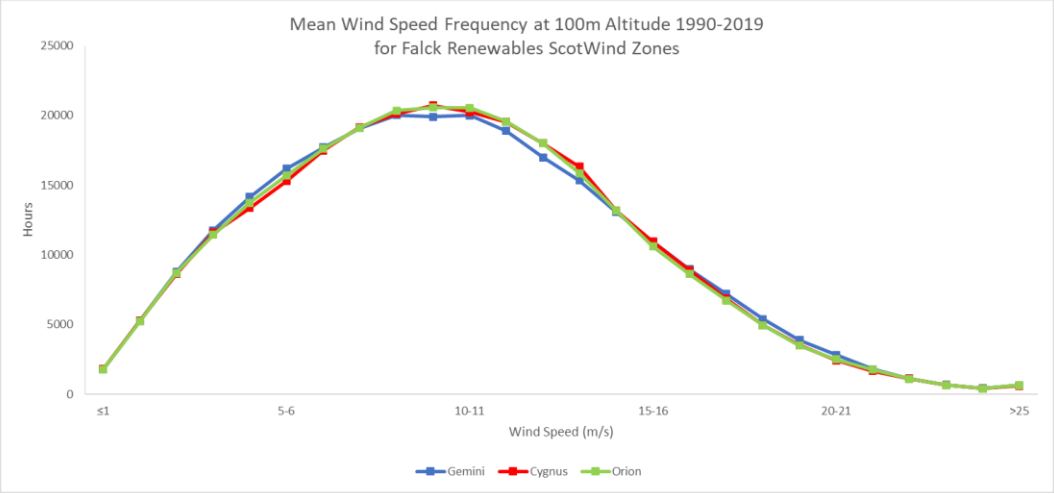
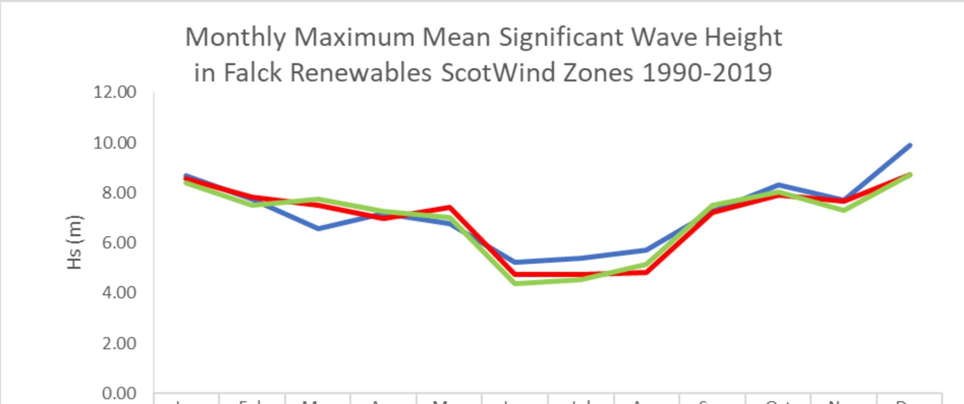


Figure 60: Mean Wind Speed Frequency at 100m Altitude for Falck Renewables ScotWind Zones 1990-2019

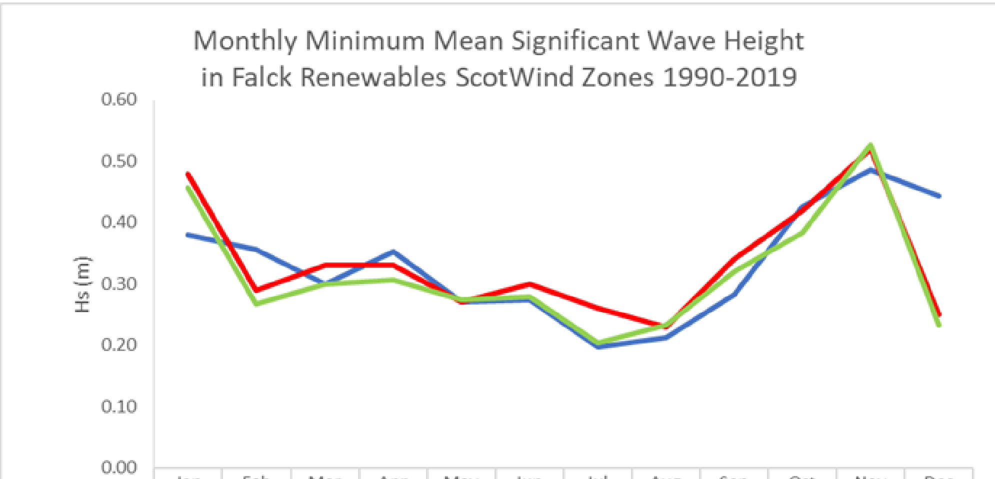
5.4.5 Monthly Maximum Significant Wave Height



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gemini	8.67	7.74	6.58	7.18	6.78	5.22	5.38	5.71	7.26	8.33	7.72	9.92
Cygnus	8.54	7.81	7.49	6.96	7.42	4.76	4.73	4.84	7.24	7.89	7.65	8.73
Orion	8.40	7.52	7.76	7.27	7.02	4.38	4.55	5.17	7.51	8.03	7.31	8.71

Figure 61: Monthly Maximum Mean Significant Wave Height in Falck Renewables ScotWind Zones 1990-2019

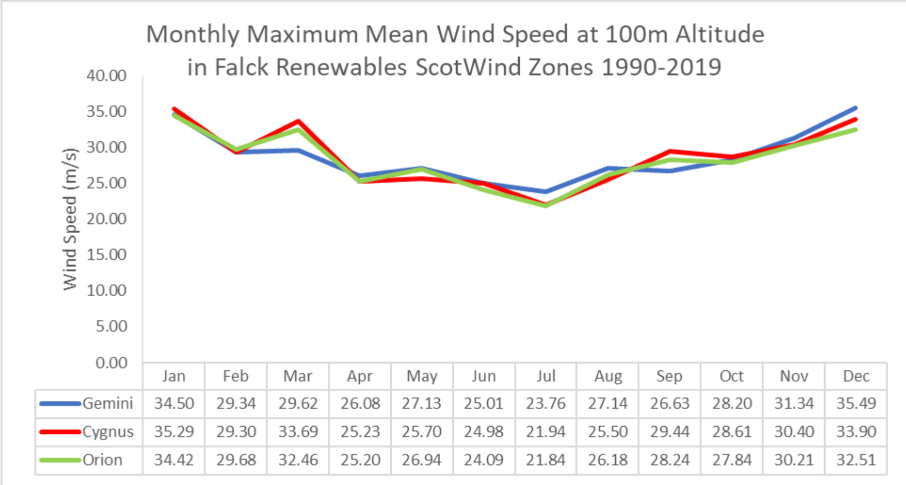
5.4.6 Monthly Minimum Significant Wave Height



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gemini	0.38	0.36	0.30	0.35	0.27	0.27	0.20	0.21	0.28	0.43	0.49	0.44
Cygnus	0.48	0.29	0.33	0.33	0.27	0.30	0.26	0.23	0.34	0.42	0.52	0.25
Orion	0.46	0.27	0.30	0.31	0.27	0.28	0.20	0.23	0.32	0.38	0.53	0.23

Figure 62: Monthly Minimum Mean Significant Wave Height in Falck Renewables ScotWind Zones 1990-2019

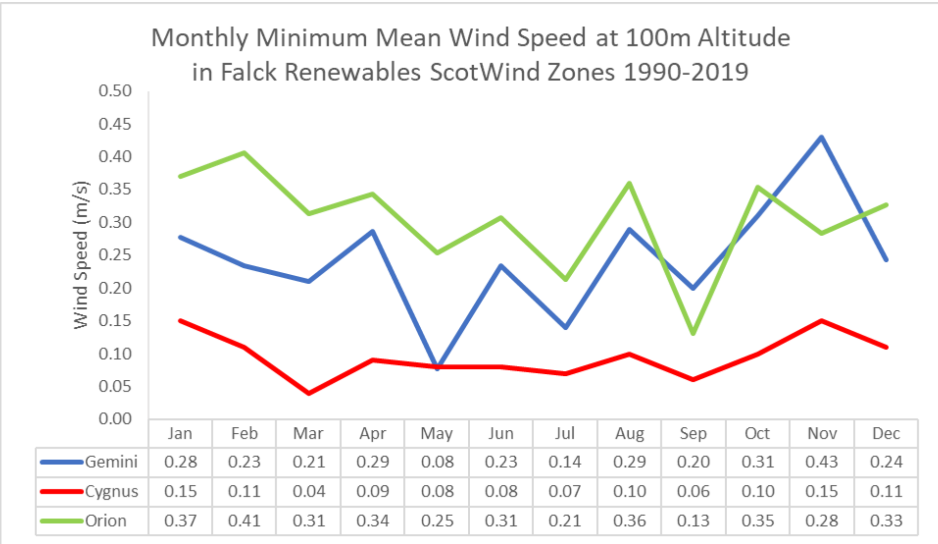
5.4.7 Monthly Maximum Wind Speed at 100m Altitude



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gemini	34.50	29.34	29.62	26.08	27.13	25.01	23.76	27.14	26.63	28.20	31.34	35.49
Cygnus	35.29	29.30	33.69	25.23	25.70	24.98	21.94	25.50	29.44	28.61	30.40	33.90
Orion	34.42	29.68	32.46	25.20	26.94	24.09	21.84	26.18	28.24	27.84	30.21	32.51

Figure 63: Monthly Maximum Wind Speed at 100m Altitude in Falck Renewables ScotWind Zones 1990-2019

5.4.8 Monthly Minimum Wind Speed at 100m Altitude



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gemini	0.28	0.23	0.21	0.29	0.08	0.23	0.14	0.29	0.20	0.31	0.43	0.24
Cygnus	0.15	0.11	0.04	0.09	0.08	0.08	0.07	0.10	0.06	0.10	0.15	0.11
Orion	0.37	0.41	0.31	0.34	0.25	0.31	0.21	0.36	0.13	0.35	0.28	0.33

Figure 64: Monthly Minimum Mean Wind Speed at 100m Altitude in Falck Renewables ScotWind Zones 1990-2019

6.0 Discussion

6.1 Significant Wave Height

In terms of site comparison, given the relatively close proximity between all three of Falck Renewables ScotWind Zones – Gemini, Cygnus and Orion – the distribution of significant wave height values, shown in *Figure 54*, was extremely similar. Cygnus and Orion in particular were very closely aligned, whereas Gemini interestingly experienced small, yet markedly higher Hs values overall. This is particularly interesting given that Gemini is located further south and further east than both of its neighbours.

The "Seasonal Average Significant Wave Height 1990-2019" graphs shown in *Figure 16, Figure 30* and *Figure 48* for sites Gemini, Cygnus and Orion respectively showed a very typical pattern throughout all sites. Summer was almost without exception the calmest season of the any year, experiencing low Hs values throughout, whilst Winter typically acted as it's inverse in that it was almost without exception the season that experienced the highest average significant wave height values. Spring and Autumn were often interchangeable, though higher Hs values seem to be more likely in Autumn than Spring.

Figure 58 and *Figure 59* show the maximum and minimum mean significant wave height values recorded in each month. These are interesting in that they show extreme outliers can and often do occur in every month and season of the year.

The analysis of significant wave height (Hs) frequency throughout every site and subsequent calculation of weather-based availability of CTV's and SOV's showed that due to Gemini experiencing markedly higher Hs values distributed from 1.5m upwards, CTV's and even SOV's to a certain extent will be slightly less viable as an O&M strategy than they could be at either Orion or Cygnus. This, however, is likely to be a non-factor in terms of CTV operations being unsuitable for the site due to the Gemini zone being located at such a great distance from shore and from the nearest port [40].

Figures 18 & *19*, *32* & *33* and *50* & *51* depict monthly maximum and average recorded values for significant wave height for every year from 1990-2019. Despite significant outliers existing throughout both graph types, particularly the figures illustrating maximum values, it is clear that whilst there is incredible variability in the Hs values that appear month to month and year to year, there is very much a general and predictable pattern that emerges when viewing datasets representing a long timeframe such as thirty years.

Despite many of the successes and interesting results from looking into significant wave height in this manner, a major limitation of this analysis method is the failure to capture daily variability in Hs. In particular, greater analysis of the percentage of hours on a month to month and season to season basis featuring significant wave heights greater than 1m, 1.5m, 2m and 2.5m would be extremely beneficial. This would be exceptionally helpful alongside analysis that worked to ascertain specific months or times of year where weather-windows of at least 6h, 12h, 24hr and 48hr may exist for essential installation and maintenance operations to be carried out [41]. Hs is considered to be the single most important met-ocean variable to consider in any offshore operational setting – referred to as the “primary parameter” by O’Connor [42]. Hs is often viewed as the determining factor when it comes to gaining access to a site or not gaining access – Hs limits are typically written into vessel contracts [28].

6.2 Peak Wave Period

In *Figure 55*, Analysis of peak wave period, Tp, across all three sites showed the greatest levels of variance of any of the met-ocean conditions considered in this study. With that said, the results remain broadly similar with the main variance occurring in the range of Tp = 4s - 8s. Peak wave period is important to be considered when associated with high Hs levels. When acting in concert, the dynamic response and safety of personnel on board a vessel can be impacted according to Walker et al [43].

6.3 Wind Speed at 10m

After Significant Wave Height, mean wind speed is considered to be the next key factor and consideration in terms of met-ocean conditions linked to offshore wind operations. Wind Speed at 10m above sea surface is primarily a consideration for operations that involve crane or jack-up operations [42]. *Figure 56* compares the mean wind speed frequency at 10m altitude throughout all Falck Renewables sites, and shows remarkable congruity in terms of distribution of mean wind speeds throughout a thirty-year timespan. O’Connor conducted a case-study utilising an existing offshore wind installation (jack-up) vessel, the MPI Resolution, which features an operational wind speed limit of up to 16m/s [44]. Utilising its operational wind speed limit of 16m/s, the MPI Resolution would be safe to operate in 96.7% of the mean wind speeds experienced at 10m altitude at any of the Falck Renewable ScotWind zones. This is important when considering that the MPI Resolution was the world’s first purpose-built vessel for installing offshore wind turbines and was put into service in 2014.

Wind Speed is also an important factor to consider in terms of maintenance: maintenance can easily be scheduled during times of low mean wind speeds, as well as allowing for unscheduled maintenance to be undertaken if necessary [40]. In addition to maintenance, mean wind speed data is vital for overall monitoring and control of assets such as wind turbines.

6.4 Wind Speed at 100m

Figure 57 shows the mean wind speed frequency at 100m altitude – the contrast between speeds experienced at 100m altitude is vast when compared to *Figure 56* depicting the mean wind speed frequency at 10m. For Gemini, Cygnus and Orion, *Figures 20* & *21*, *32* & *33* and *50* & *51* respectively show an approximate 20% increase in average monthly wind speed across all three sites. In addition, *Figures 60 & 61* show the enormous variations that exist between maximum and minimum mean wind speeds – even at 100m altitudes.

Wind speed at 100m altitude is particularly important for wind turbines, as wind power generation increases with the cube of the wind speed. Therefore, doubling the wind speed can provide eight times the power output [45]. A currently operational floating wind farm, Hywind in Scotland, consists of six Siemens SWT-6.0-154 turbines. These turbines possess a cut-in speed of 4m/s, a rated wind speed of 13m/s, a cut-out wind speed of 25m/s and are touted to survive in winds of up to 70m/s [46]. At 6MW capacity, these turbines are already dated (indeed, Kincardine Offshore Windfarm has already installed floating turbines at 9.5MW in capacity [25]) – however, this simply shows the capability of floating wind technology and the significant opportunity present for Falck Renewables to exploit the offshore wind resource present in the option areas utilising floating technology.

Analysis of thirty years of time-step data in and around their allocated ScotWind zones has reinforced the potential for consistent, clean, green renewable energy generation available utilising next-generation floating offshore wind technology.

7.0 Future Work & Limitations

This project, whilst quite successful in thoroughly assessing the variations and consistencies over time in some met-ocean conditions and parameters, was severely limited in its very rudimentary weather-window analysis.

In future, further work could be conducted to assess monthly access levels, typical waiting periods and longest waiting periods for a variety of weather window lengths (6hr, 12h, 24hr, 48hr) across a variety of Hs thresholds (1m, 1.5m, 2m, 2.5m etc.).

In addition, obtaining and considering additional wave data is becoming increasingly important for floating offshore wind modelling and is lacking in existing models [28].

This work would greatly benefit Falck Renewables and their consortium, and serve to inform their installation strategy alongside their future operations & maintenance strategies. Current recommendations within the industry include focusing on expanding the weather windows for transporting/towing offshore wind floating foundations, simplification of installation methodology to reduce time spent offshore and a reduction of risks to personnel working offshore during installation and maintenance [22].

8.0 Conclusions

In conclusion, this project successfully obtained and subsequently analysed historical met-ocean data and identified various trends, variances and outliers amongst a number of met-ocean parameters for each of the ScotWind sites awarded to Falck Renewables. A strong emphasis and focus was placed upon analysis of significant wave height (Hs) and mean wind speed. This was due to both of these parameters appearing persistently throughout available literature as the key parameters to consider when installing, operating and maintaining assets in an offshore environment.

Hs was found to be extremely comparable in all three sites studied, though in particular for the sites codenamed “Cygnus” and “Orion”. Significant seasonal variation was observed in Hs values, with Summer returning the lowest values on average and Winter the greatest on average. However, considerable deviation from this rule was observed, particularly in some of the analysis highlighting the maxima and minima occurrences of Hs by month throughout the data spanning 1990-2019. These deviations can likely be explained by exceptionally strong storms and surges. The statements that are true for Hs are also true, by and large, for wind speed. It was found that whilst data can be utilised to model and predict parameters such as Hs and wind speed to reasonable degree of accuracy; their nature is extremely volatile and variable.

In future, deeper analysis of the met-ocean conditions and in particular, weather windows, for each of the Falck Renewables ScotWind zones would be extremely beneficial in informing future installation, operation and maintenance strategies. Cross-verification of the ERA5 Reanalysis data with a new dataset would also provide a significant level of validation to the results of this study.

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