Funded by the European Union

SUREWAVE

Deliverable number: D2.1

SUREWAVE- Structural Reliable Offshore Floating PV Solution Integrating Circular Congrete Floating Breakwater

Title: Use case scenario basis for typical, rough location

Disclaimer:

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Funded by the European Union

Funded by the European Union

SUREWAVE

Deliverable details

WP	2	
Task	D2.1	Use case scenario basis for typical, rough location

Dissemination level	PU		**Due delivery date**	
Deliverable type	R		**Actual delivery date**	31.01.2023

Lead beneficiary	**SINTEF**
Contributing beneficiaries	

Document Version	**Date**	**Author**	**Comments** [1]
1.0	03.01.2023	Balram Panjwani	Draft version
1.1	20.01.2023	Bjørn Riise	First version
1.2	24.01.2023	Virgile Delhaye	Revision-1
1.3	25.01.2023	Joep van der Zanden	Revision-2
2.0	30.01.2023	Bjørn Riise	Second version
2.1	31.01.2023	Tim Bunnik	Revision-1
3.0	31.01.2023	Balram Panjwani	Final version

Dissemination level	
PU	Public- fully open
SEN	SEN = Sensitive – limited under the conditions of the Grant Agreement
EU classified	EU classified – restraint – UE/EU-restricted, confidential, secret-UE/EU secret under Decision 2015/444
Deliverable type	
R:	Document, report (excluding the periodic and final reports)
DEM:	Demonstrator, pilot, prototype, plan designs
DEC:	Websites, patents filing, press & media actions, videos, etc.
OTHER:	Software, technical diagram, etc.

[1] Creation. modification. final version for evaluation. revised version following evaluation. final

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

EXECUTIVE SUMMARY

A set of Metocean design criteria, based on three sites located in European Waters, for further use in the SUREWAVE project work, have been defined. The locations, as listed in Table 1, are chosen to include both mild and harsh environmental conditions, including wave directionality and conditions where wind U_W > 25 m/s, current U_C > 1.2 m/s, and maximum wave height H_{max} > 14 m have been considered.

Table 1 Relevant locations in semi-open European waters

Region	Coordinates	Water depth (m)	$H_{S,median}$ (m)	Extreme values; R = 50 years			
				H_S (m)	T_P (s)	u_W (m/s)	
Baltic Sea	54°12'N 4°24'E	16	0.6	4.4	9.6	22.4	Mild
Western Mediterranean	39°00'N 0°00'E	38	0.5	7.0	11.7	20.8	Mid
Greater North Sea	56°54'N 5°00'E	49	1.6	12.3	14.8	26.0	Harsh

Deliverable Review

	Reviewer #1: Bjørn Riise			Reviewer #2: Virgile Delhaye		
	Answer	**Comments**	**Type***	**Answer**	**Comments**	**Type***
1. Is the deliverable in accordance with						
(i) The Description of Work?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒ Yes ☐ No		☐ M ☐ m ☐ a
(ii) The international State of the Art?	☐ Yes ☐ No	*Not applicable for this deliverable*	☐ M ☐ m ☐ a	☐ Yes ☐ No	*Not applicable for this deliverable*	☐ M ☐ m ☐ a
2. Is the quality of the deliverable in a status						
(i) That allows it to be sent to European Commission?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒ Yes ☐ No		☐ M ☐ m ☐ a
(ii) That needs improvement of the writing by the originator of the deliverable?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☒ No		☐ M ☐ m ☐ a
(iii) That need further work by the Partners responsible for the deliverable?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☒ No		☐ M ☐ m ☐ a

* Type of comments: M = Major comment; m = minor comment; a = advice

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Table of Contents

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

1. Introduction

The SUREWAVE project is developing a breakwater concept for floating photovoltaic (FPV), suited for offshore conditions, typically with wind speed > 25 m/s, current >1.2 m/s, and wave height > 14 m.

The objective of this document is to define a set of Metocean design criteria, based on sites located in European Waters, for further use in the SUREWAVE project work. The locations are chosen to include both mild and harsh environmental conditions, including wave directionality and locations where the wind U_W > 25 m/s, the current U_C > 1.2 m/s, and the maximum wave height H_{max} > 14 m.

The present work comprises:

- chose a set of relevant locations,
- provide hindcast data for the locations, and
- establish a set of Metocean design criteria in agreement with DNV RP0584

Further design criteria are described in the project deliverable D2.3 "High level understanding of the system general loads".

The project work and deliverables focus on chosen critical elements and it is not providing a full set of design criteria. Furthermore, the document, data, and results are for project use only, and any use of the data and/or results takes place without any form of guarantee. Partners outside the SUREWAVE consortium require written permission to use the data.

Table 2 lists applicable rules and regulations, standards, recommended practices, and other relevant references. Where no specific design criteria have been defined, the design should comply with DNV-RP-0584 or other applicable Norwegian standards and regulations. In case of a conflict between documents, this should be discussed and a solution should be agreed on. Typically, the hierarchy is as follows: applicable rules and regulations, company-specified criteria, and DNV-RP-0584.

Table 2 Applicable rules, regulations, standards, recommendations, and references

- DNV-RP-0584, Design, development and operation of floating solar photovoltaic systems
- DNV-RP-C205, Environmental loads and conditions
- Haver, S., and Winterstein, S. R. (2008), Environmental Contour Lines: A Method for Estimating Long Term Extremes by a Short Term Analysis, DOI: https://doi.org/10.5957/SMC-2008-067)
- NORSOK N-003:2017, Actions and action effects
- M. Dörenkämper, D. van der Werf, K. Sinapis, M.M. de Jong, W. Folkerts (2019), Influence of Wave Induced Movements on the Performance of Floating PV Systems, 36th European Photovoltaic Solar Energy Conference and Exhibition, 1759 – 1762 (doi:10.4229/EUPVSEC20192019-6DO.9.1)

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

2.Methodology

Hindcast data

The European Centre for Medium-Range Weather Forecasts (ECMWF) provides the ERA5 hourly hindcast data. For each of the chosen locations data with a time step of 3 hours and for a total of 25 years have been obtained and used to establish the wind and wave criteria.

Directional dependence

Directions are given in degrees clockwise from (true) north. For wind and waves the directions are taken from the data. I.e., wind and waves of 90 degrees are coming from the east.

The wave data are grouped into 8 directional sectors, each with a size of 45 degrees, defined by their mid-point. I.e., sector 0 is spanning from -22.5 to 22.5 degrees and has a midpoint at the north, while sector 90 spans from 67.5 to 112.5 degrees and has a midpoint at the east.

Long-term variability and definition of extremes

To account for the long-term variability the contour line method (IFORM approach ref. Haver, Winterstein 2008, and DNV-RP-C205 section 3.6 Long term wave statistics and section 3.7.2 Metocean contours) have been used to establish the H_S - T_P dependence for the extreme values.

Extreme wind

Based on the hindcast data a long-term model (Weibull is established for each location, providing U_W (1-hour average), where extreme values for return periods of 1, 5, and 50 years.

The Weibull distribution is given by

$$F_{U_W}(u_W) = 1 - \exp\left(-\left(\frac{u_W-\gamma}{\alpha}\right)^{\beta}\right),$$

Where; β is Shape parameters in Weibull distribution; u_W is one-hour average velocity; γ is the location parameter in the 3-parameter Weibull distribution; α is the scale parameters in the Weibull distribution

A logarithmic wind speed profile can be taken for neutral atmospheric conditions which is expressed as

$$u_W(z) = \frac{u^*}{k_a} \cdot \log\left(\frac{z}{z_0}\right)$$

where k_a = 0.4 is von Karman's constant, z is the height and z_0 is the roughness length. For offshore locations, the roughness parameter z_0 typically varies between 0.0001 m in open sea without waves and 0.01 m in coastal areas with onshore wind. The roughness parameter for offshore locations may be solved implicitly from the following equation (DNV-RP-C205).

$$z_0 = \frac{A_C}{g} \cdot \left(\frac{k_a u_W(z)}{\log\left(\frac{z}{z_0}\right)}\right)$$

where g is the acceleration of gravity and A_C is Charnock's constant. A_C is usually higher for "young" developing and rapidly growing waves than for "old" fully developed waves. For open sea with fully developed waves, A_C = 0.011-0.014 is recommended.

As an alternative to the logarithmic wind profile, a power law profile may be assumed. The wind speed *u* as a function of height above mean water level *z* is given by (DNV-RP-C205)

$$u_W(z) = u_w(z_{ref}) \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha},$$

where α=0.12, and $u_W(z_{ref})$ is the velocity at the reference height z_{ref} = 10 m

Extreme waves

Based on the hindcast data a long-term joint model (Weibull, Lognormal) is established for each location, providing H_S - T_P (3-hour sea states) contours where extreme sea states can be extracted for return periods of 1, 5, and 50 years. Where H_S is a significant wave height and T_P is the wave period

Applying binned sea state data, the marginal long-term variability for H_S is modeled using a Weibull distribution, and the conditional long-term variability for T_P is modelled using a lognormal distribution and subsequently the Metocean contours are found.

The Weibull distribution is given by

$$F_{H_S}(h_S) = 1 - \exp\left(-\left(\frac{h_S-\gamma}{\alpha}\right)^{\beta}\right),$$

and the lognormal distribution is given by

$$f_{T_P|H_S}(t_P|h_S) = \frac{1}{\sigma t_P\sqrt{2\pi}} \exp\left(-\frac{(\ln t_P-\mu)^2}{2\sigma^2}\right),$$

were

$$\mu = E[\ln T_P] = a_0 + a_1 H_S^{a_2}, \text{ and}$$
$$\sigma = std[\ln T_P] = b_0 + b_1 \exp(b_2 H_S).$$

The parameters for the Weibull (γ, α, β) and lognormal distributions (a_0, b_1, b_2 b_0) are found by the least square fitting to the data. The parameter b_0 is defined from both the data and engineering judgment. The parameter a_0 is found from the omnidirectional data. Both the Weibull and the lognormal distribution parameters are listed below for the chosen locations (see Table 5, Table 12, and Table 18).

The characteristic largest crest-to-trough wave height $H_{max,c}$ in a stationary sea state of duration t may be taken as

$$H_{max,c} = 0.5 H_S \sqrt{(1-\rho)\ln(t/T_Z)} \;; \text{ where } \rho = 0.73,\ t = 3 \text{ hour},$$

and the most probable individual wave period $T_{H\,max}$ = 1.16T_Z. Considering a return period of 50 years for the harshest locations $H_{max,c}$ > 14 m.

For reference, the steepness curve as found in DNV-RP-C205 is given by

$$S_P = \frac{2\pi}{g}\frac{\mathrm{H_S}}{T_P^2}; S_P = \frac{1}{15} \text{ for } T_P \le 8\ s, S_P = \frac{1}{25} \text{ for } T_P \ge 15\ s, \text{and linearly interpolated in between}$$

Where S_P is Average wave steepness; T_P is peak period

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Operational data

For fatigue analyses the 25 years' time-series can be used either directly or using binned data.

Wave spectra

For irregular waves, the wind sea and swell should be based on a JONSWAP spectrum given by (DNV-RP-C205)

$$S_J(\omega) = A_\gamma \frac{5}{16} \cdot H_S^2 \cdot \omega_P^4 \cdot \omega^{-5} \exp\left(-\frac{5}{4} \cdot \left(\frac{\omega}{\omega_P}\right)^{-4}\right) \cdot \gamma^{\exp\left(-0.5 \cdot \left(\frac{\omega - \omega_P}{\sigma \cdot \omega_P}\right)^2\right)},$$

where

$$\sigma = 0.07\ for\ \omega \leq \omega_P,\ \sigma = 0.09\ for\ \omega > \omega_P, \text{and } A_\gamma = 1 - 0.287 \cdot \ln\gamma.$$

ω = Wave angular frequency
ω_P = Angular spectral peak frequency
σ = Spectral width parameters
γ = Non-dimensional peak shape parameter
A_γ = Normalizing factor.

If not specified the peak shape parameter γ for wind sea is found based on H_S and T_P and they are given by

$$\gamma = 5 \ \text{ for } \ T_P/\sqrt{H_S} \leq 3.6,$$

$$\gamma = \exp\left(5.75 - 1.15\frac{T_P}{\sqrt{H_S}}\right) \text{ for } 3.6 < T_P/\sqrt{H_S} < 5, \text{and}$$

$$\gamma = 1 \ \text{ for } \ 5 \leq T_P/\sqrt{H_S},$$

while for swell

$$\gamma = 10$$

To include the effect of separate wind sea and swell, two separate JONSWAP spectra should be used. The individual significant wave height and gamma should be found as proposed by Torsethaugen and Haver (2004), also given in DNV RP-C205, appendix A. The distinction between wind and swell dominate sea states is given by

$$T_f = a_f H_S^{1/3}, \text{with } \mathrm{a_f} = 5.3$$

The factor $\mathrm{a_f}$ depends on the fetch length

For wind-dominated sea ($T_P \leq T_f$)

$$H_{S1} = r_{pw} H_S, \qquad T_{P1} = T_P, \qquad \gamma = 35(1 + 3.5\exp(-H_S))\left(\frac{2\pi H_{S1}}{gT_P^2}\right)^{0.857}$$

$$H_{S2} = \sqrt{1 - r_{pw}^2} H_S, \qquad T_{P2} = T_f + 2, \qquad \gamma = 1, \qquad \text{and}$$

$$r_{pw} = 0.7 + 0.3\exp(-\left(2\frac{T_f - T_P}{T_f - 2\sqrt{H_S}}\right)^2).$$

While for swell-dominated sea ($T_P > T_f$)

$$H_{S1} = r_{ps} H_S, \qquad T_{P1} = T_P, \qquad \gamma = 35(1 + 3.5\exp(-H_S))\left(\frac{2\pi H_{S1}}{gT_P^2}\right)^{0.857}(1 + 6\frac{T_P - T_f}{25 - T_f})$$

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

$$H_{S2} = \sqrt{1 - r_{ps}^2} H_S, \qquad T_{P2} = a_f H_{S2}^{1/3}, \qquad \gamma = 1, \qquad \text{and}$$

$$r_{ps} = 0.6 + 0.4 \exp\left(-\left(\frac{T_P - T_f}{0.3(25 - T_f)}\right)^2\right).$$

Where;
H_{S1} is Primary peak
H_{S2} is Primary peak

Extreme current

For a return period of 50 years a current velocity u_C = 1.2 m/s, with a constant vertical profile, should be applied. For a return period of 5 years a 10 percent reduction, i.e., u_C = 1.08 m/s, may be used.

Current from all directional sectors should be combined with waves from all directional sectors. 50 years current should be combined with 5 years wind and waves, and that 5 years current should be combined with 50 years wind and waves. See Table 3 for design values.

Table 3 Current velocity u_C which should represent return periods of 5 and 50 years.

Return period	Velocity, u_C (m/s)
50 years	1.2
5 years	1.08

Marine growth

For design analyses a layer of marine growth should be included. If found and available, site-specific data should be used. If the site-specific data are not available then data, as given in Table 3, from NORSOK N-003 may be used. Table 4 provides the maximum thickness and density as a function of water depth. For further details and values for deeper waters see NORSOK N-003 section 6.11.1.

The mass of marine growth should be added to both the structural mass and the hydrodynamics added mass in the analysis. Both zero and maximum thicknesses should be assessed. For fatigue analyses the thickness may increase linearly to the given value over a period of 2 years. Otherwise, the most severe of zero and maximum thickness should be applied.

Table 4 Marine growth, thickness and density, as a function of water depth.

Water depth (m)	**Thickness (mm)**	**Density kg/m3**
Above +2	0	-
-15 to +2	60	1325
-30 to -15	50	1325
-40 to -30	40	1325
-60 to -40	30	1100
-100 to –60	20	1100

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

3. Site-specific wind and wave conditions

General

Although SUREWAVE developing an FPV concept for harsh offshore conditions (wind speed > 25 m/s, current >1.2 m/s, and wave height > 14 m), the concept needs to be evaluated in mild conditions which are more frequent than the harsh conditions. Considering the different regions of semi open waters around European, as shown in Figure 1, a total of three locations are evaluated and used to establish a set of design conditions. The three chosen locations are defined as mild, mid, and harsh conditions, as listed in Table 5.

Figure 1 European waters

Table 5 Relevant locations in semi-open European waters

Region	Coordinates	Water depth (m)	$H_{S,median}$ (m)	Extreme values; R = 50 years			
				H_S (m)	T_P (s)	u_W (m/s)	
Baltic Sea	54°12'N 4°24'E	16	0.6	4.4	9.6	22.4	Mild
Western Mediterranean	39°00'N 0°00'E	38	0.5	7.0	11.7	20.8	Mid
Greater North Sea	56°54'N 5°00'E	49	1.6	12.3	14.8	26.0	Harsh

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Baltic Sea 54°12'N 14°24'E (Mild)

The location 54°12'N 14°24'E in the Baltic Sea region is shown in Figure 2, and the directional significant wave heights H_S for that location are shown in Figure 3.

Figure 2 Location 54°12'N 14°24'E, in region Baltic

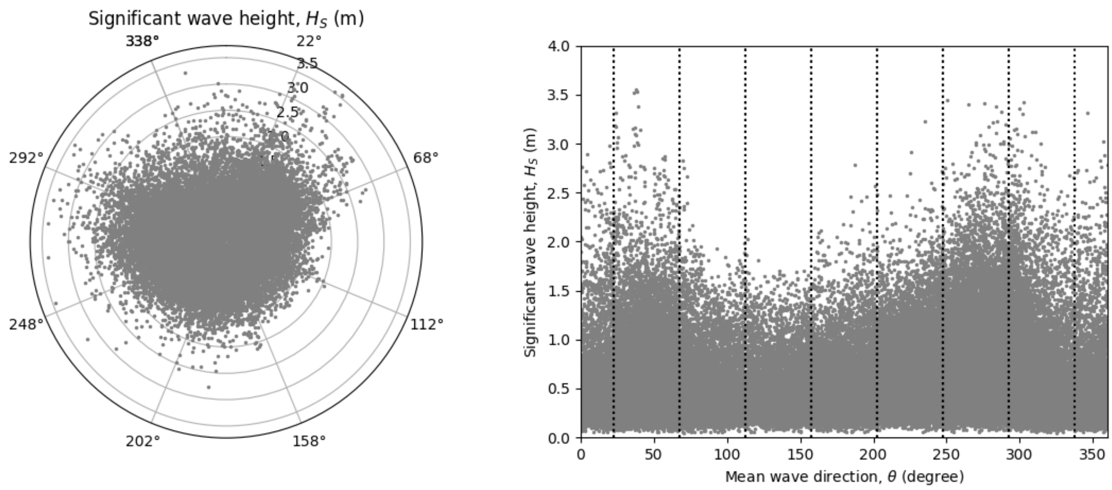

Figure 3 Directional wave data for for location 54°12'N 14°24'E, in region Baltic Sea, significant wave height H_S (m) as a function of mean wave direction ϴ (°).

Firstly, all wave data are applied to establish an omnidirectional joint model, as shown in Figure 4. These parameters and extreme values as listed in Table 6, Table 7, and Table 8.

It is found challenging to find a good fit for the steepest waves (left side of the contour), and it is found acceptable to use the least conservative of the calculated contour line and the DNV steepness curve.

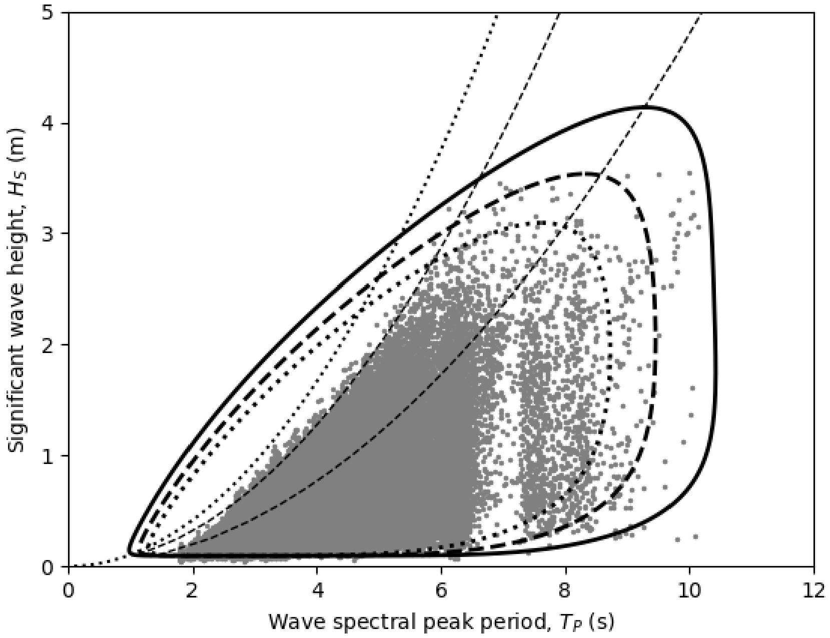

Figure 4 Omnidirectional scatter diagram (H_S-T_P) and joint distribution model (Weibull – Lognormal) for location 54°12'N 14°24'E, in region Baltic Sea. Contour lines for R = 1 year (dotted line), 5 years (dashed line) and 50 years (solid line) and DNV RP-C205 steepness criteria (dotted line) and DNV RP-0584 lower and upper bound (dashed line).

Table 6 Omnidirectional distribution parameters for H_S-T_P joint model (Baltic Sea 54°12'N 14°24'E (Mild))

Weibull			**Lognormal**					
α	**β**	**γ**	***a_0***	***a_1***	***a_2***	***b_0***	***b1***	***b_2***
0.636	1.339	0.094	0.6813	0.794	0.4703	0.025	0.244	-0.3322

Table 7 Omnidirectional extreme sea state (H_S-T_P) values (Baltic Sea 54°12'N 14°24'E (Mild))

	R = 1 year		**R = 5 years**		**R = 50 years**	
	H_S	***T_P***	***H_S***	***T_P***	***H_S***	***T_P***
Fit to all data	3.1	7.5	3.5	8.2	4.1	9.2

*Table 8 Omnidirectional peak period **T_P** estimates for given significant wave height **H_S** (Baltic Sea 54°12'N 14°24'E (Mild))*

H_S (m)	T_P (s)			T_P (s); return period, R (years)			*Steepness criteria (RP-C205)*
	Mean	Median	Mode	R = 1	R = 5	R = 50	
0.5	3.6	3.5	3.3	1.6	1.5	1.3	2.2
1	4.5	4.4	4.2	2.3	2.1	1.9	3.1
1.5	5.2	5.2	5	3.1	2.8	2.6	3.8
2	6	5.9	5.8	4	3.7	3.4	4.4
2.5	6.8	6.7	6.6	5.2	4.8	4.3	4.9

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

3	7.5	7.5	7.4	6.8	6	5.4	5.4
3.5	8.3	8.3	8.2			6.7	5.8
4	9.1	9.1	9			8.3	6.2

Secondly, the directional data are used to establish a directional joint model for the waves, with parameters listed in Table 9 , and extreme values listed in Table 10. Also included in the table are omnidirectional extreme values as found from the integrated annual probability of exceedance from all directional sectors.

Table 9 Directional sectors and joint distribution model parameters for HS-TP, location 56°54'N 5°00'E

Sector			**Distribution parameters**								
Centre	**Boundaries**	**Prb.**	**Weibull**			**Lognormal**					
Θ_C (°)	**(Θ_L - Θ_U] (°)**	**(%)**	**α**	**β**	**γ**	***a_0***	***a_1***	***a_2***	***b_0***	***b1***	***b_2***
0	-22.5 - 22.5	8.5	0.613	1.23	0.051	0.6813	0.9214	0.3736	0.025	0.2998	-0.7768
45	22.5 - 67.5	17.9	0.533	1.152	0.148	0.6813	0.9779	0.3954	0.025	0.3438	-0.7789
90	67.5 - 112.5	9.1	0.463	1.224	0.116	0.6813	0.761	0.5084	0.025	0.339	-0.4594
135	112.5 - 157.5	6.8	0.524	1.559	0.07	0.6813	0.5997	0.6456	0.025	0.2373	-1.395
180	157.5 - 202.5	9.6	0.493	1.284	0.128	0.6813	0.63	0.5761	0.025	0.1359	-0.9651
225	202.5 - 247.5	12.4	0.689	1.528	0.087	0.6813	0.6393	0.5278	0.025	0.1551	-1.0548
270	247.5 - 292.5	19.5	0.856	1.588	0.073	0.6813	0.7426	0.4377	0.025	0.2887	-1.0759
315	292.5 - 337.5	16.1	0.619	1.261	0.105	0.6813	0.8534	0.4007	0.025	0.2376	-1.0014

Table 10 Directional sectors and extreme sea states (HS-TP) location 56°54'N 5°00'E

Sector			**H_S (m) and T_P (S); Return period R**							
Centre	**Boundaries**	**Prb.**	**R = 1 year**		**R = 5 years**		**R = 50 years**		**ULS[1)]**	
Θ_C (°)	**(Θ_L - Θ_U] (°)**	**(%)**	***H_S***	***T_P***	***H_S***	***T_P***	***H_S***	***T_P***	***H_S***	***T_P***
0	-22.5 - 22.5	8.5	2.5	7.2	3.1	8	3.9	9.1	4.3	9.7
45	22.5 - 67.5	17.9	2.8	8.5	3.3	9.6	4.1	11.0	4.4	9.6
90	67.5 - 112.5	9.1	2.0	5.8	2.4	6.5	3.0	7.5	3.4	8.1
135	112.5 - 157.5	6.8	1.6	4.4	1.9	4.9	2.2	5.4	2.4	5.8
180	157.5 - 202.5	9.6	2.0	5.1	2.4	5.7	3.0	6.5	3.3	6.9
225	202.5 - 247.5	12.4	2.3	5.3	2.7	5.8	3.2	6.4	3.4	6.7
270	247.5 - 292.5	19.5	2.8	6.4	3.2	6.8	3.8	7.5	4.1	7.8
315	292.5 - 337.5	16.1	2.7	7.1	3.2	7.8	4.0	8.7	4.4	9.6
Omni (integrated)			3.2	7.7	3.7	8.5	4.4	9.6		

1) Minimum of calculated equivalent characteristic(R=200) value and the omni-directional value, R=50 (N-003)

Thirdly, all wind data are applied to establish a marginal distribution as shown in Figure 5, with parameters and extreme values as listed in Table 11.

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

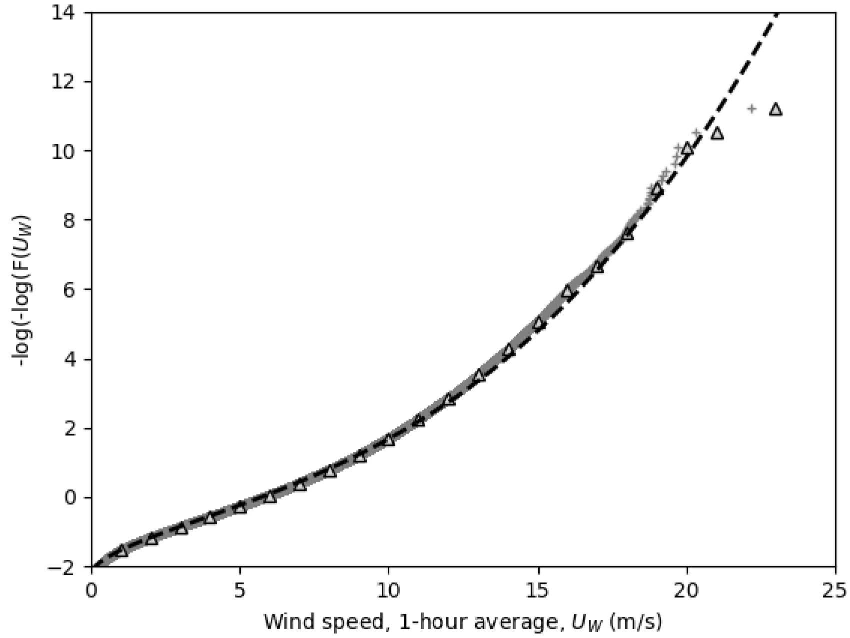

Figure 5 Marginal distribution of 1-hour average wind speed U_W for location the Region Greater North Sea, 56°54'N 5°00'E

Table 11 Omnidirectional distribution parameters and extreme values for 1 hour wind speed

Weibull parameters			**U_w(m/s); return period**		
α	**β**	**γ**	***R = 1 year***	***R = 5 years***	***R = 50 years***
8.233	2.526	-0.312	19.4	20.7	22.4

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Western Mediterranean 39°00'N 0°00'E (Mid)

The location 39°00'N 0°00'E in the Western Mediterranean region is shown in Figure 6, and the directional significant wave heights H_S for that location are shown in Figure 7.

Figure 6 Location 39°00'N 0°00'E, in region Western Mediterranean.

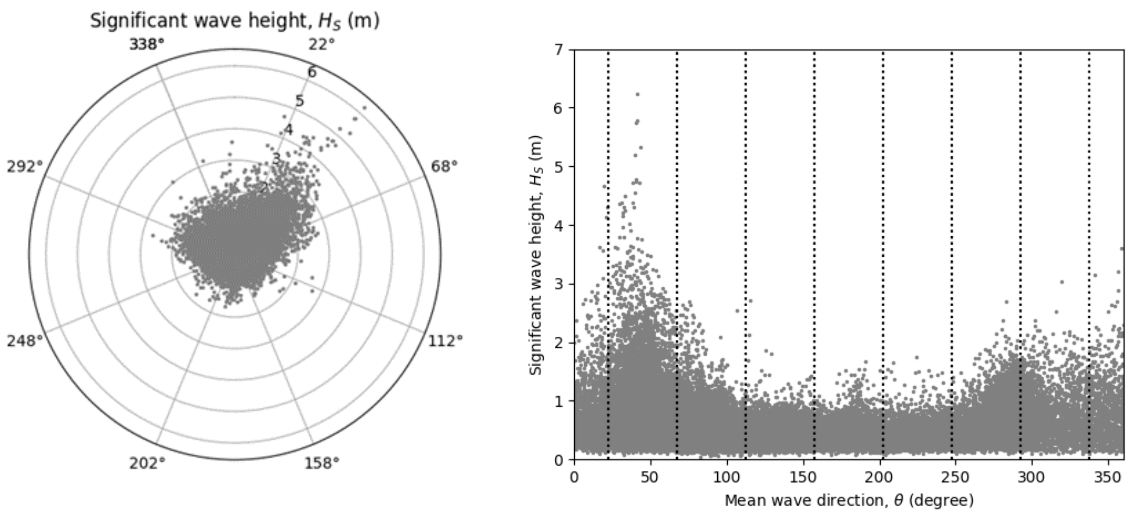

Figure 7 Directional wave data for for location 39°00'N 0°00'E, in region Western Mediterranean, significant wave height H_S (m) as a function of mean wave direction ϴ (°).

Firstly, all wave data are applied to establish an omnidirectional joint model, as shown in Figure 8, and with parameters and extreme values as listed in Table 12, Table 13, and Table 14.

It is found challenging to find a good fit for the steepest waves (left side of the contour), and it is found acceptable to use the least conservative of the calculated contour line and the DNV steepness curve.

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

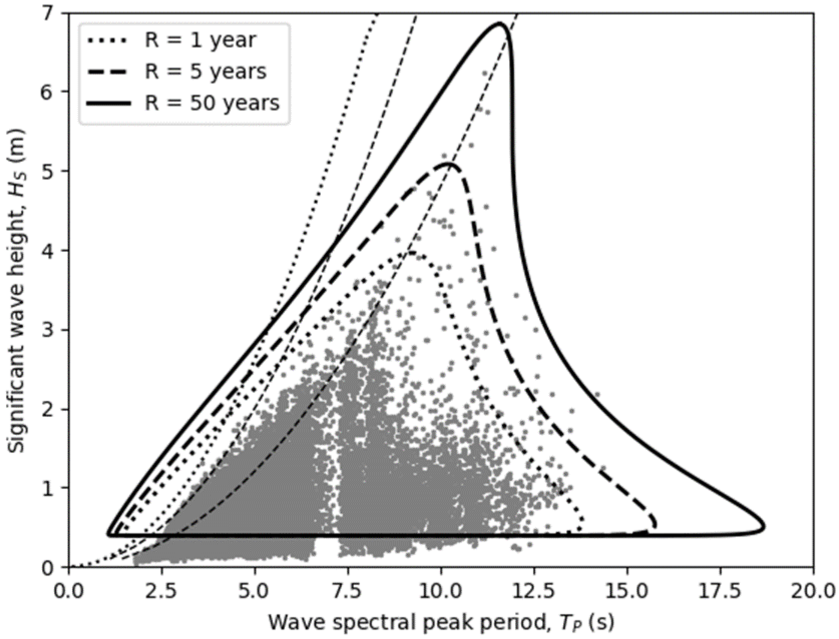

Figure 8 Omnidirectional scatter diagram (H_S-T_P) and joint distribution model (Weibull – Lognormal) for location 39°00'N 0°00'E, in region Western Mediterranean. Contour lines for R = 1 year (dotted line), 5 years (dashed line) and 50 years (solid line) and DNV RP-C205 steepness criteria (dotted line) and DNV RP-0584 lower and upper bound (dashed line).

Table 12 Omnidirectional distribution parameters for H_S-T_P joint model (Western Mediterranean 39°00'N 0°00'E (Mid))

Weibull			Lognormal					
α	**β**	**γ**	***a_0***	***a_1***	***a_2***	***b_0***	***b1***	***b_2***
0.163	0.673	0.392	0.0187	1.7219	0.1792	0.025	0.3566	-0.3853

Table 13 Omnidirectional extreme sea state (H_S-T_P) values (Western Mediterranean 39°00'N 0°00'E (Mid))

	R = 1 year		**R = 5 years**		**R = 50 years**	
	H_S	***T_P***	***H_S***	***T_P***	***H_S***	***T_P***
Fit to all data	4.0	9.1	5.1	10.1	6.8	11.6

*Table 14 Omnidirectional peak period **T_P** estimates for given significant wave height **H_S***

H_S (m)	T_P (s)			T_P (s); return period, R (years)			*Steepness criteria (RP-C205)*
	Mean	Median	Mode	R = 1	R = 5	R = 50	
0.5	4.9	4.7	4.2	1.6	1.4	1.2	2.2
1	5.9	5.7	5.3	2.5	2.2	1.9	3.1
1.5	6.7	6.5	6.2	3.5	3.1	2.7	3.8
2	7.3	7.2	6.9	4.5	4	3.6	4.4
2.5	7.9	7.8	7.6	5.5	5	4.5	4.9

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

3	8.4	8.3	8.1	6.6	6	5.4	5.4
3.5	8.9	8.8	8.7	7.7	6.9	6.2	5.8
4	9.3	9.3	9.2		7.8	7	6.2
4.5	9.7	9.7	9.6		8.7	7.8	6.6
5	10.2	10.1	10.1		9.8	8.6	6.9
5.5	10.6	10.5	10.5			9.3	7.3
6	11	10.9	10.9			10	7.6
6.5	11.3	11.3	11.3			10.8	7.9

Secondly, the directional data are used to establish a directional joint model for the waves, with parameters listed in Table 15, and extreme values listed in Table 16. Also included in the table are omnidirectional extreme values as found from the integrated annual probability of exceedance from all directional sectors.

Table 15 Directional sectors and joint distribution model parameters for H_S-T_P, location 56°54'N 5°00'E.

Sector			Distribution parameters								
Centre	Boundaries	Prb.	Weibull			Lognormal					
Θ_C (°)	(Θ_L - Θ_U) (°)	(%)	α	β	γ	a_0	a_1	a_2	b_0	$b1$	b_2
0	-22.5 - 22.5	3.5	0.429	0.906	0.345	0.0187	1.6793	0.1821	0.025	0.487	-0.5864
45	22.5 - 67.5	27.2	0.240	0.717	0.521	0.0187	1.7976	0.1545	0.025	0.3723	-0.4346
90	67.5 - 112.5	30.5	0.096	0.681	0.397	0.0187	1.7174	0.1602	0.025	0.3358	-0.7289
135	112.5 - 157.5	17.1	0.017	0.475	0.470	0.0187	1.6694	0.2387	0.025	0.3173	-0.5109
180	157.5 - 202.5	7.1	0.117	0.839	0.324	0.0187	1.7597	0.2735	0.025	0.3173	-0.5109
225	202.5 - 247.5	4.0	0.113	0.811	0.362	0.0187	1.8728	0.3454	0.025	0.3158	-0.3468
270	247.5 - 292.5	7.6	0.387	1.230	0.345	0.0187	1.4373	0.2428	0.025	0.3642	-1.0842
315	292.5 - 337.5	3.0	0.722	1.538	0.124	0.0187	1.4768	0.2137	0.025	0.4974	-1.1668

Table 16 Directional sectors and extreme sea states (H_S-T_P) location 56°54'N 5°00'E.

Sector			H_S (m) and T_P (S); Return period R							
Centre	Boundaries	Prb.	R = 1 year		R = 5 years		R = 50 years		ULS[1)]	
Θ_C (°)	(Θ_L - Θ_U) (°)	(%)	H_S	T_P	H_S	T_P	H_S	T_P	H_S	T_P
0	-22.5 - 22.5	3.5	2.7	7.6	3.6	8.5	4.9	9.6	5.8	10.3
45	22.5 - 67.5	27.2	3.9	9.4	5.1	10.3	7.0	11.5	7.0	11.7
90	67.5 - 112.5	30.5	2.0	6.9	2.6	7.5	3.5	8.3	4.1	8.8
135	112.5 - 157.5	17.1	1.3	6.0	1.8	6.9	2.7	8.4	3.4	9.5
180	157.5 - 202.5	7.1	1.2	6.4	1.5	7.3	2.0	8.5	2.3	9.2
225	202.5 - 247.5	4	1.1	7.2	1.5	8.6	2.0	10.9	2.3	12.4
270	247.5 - 292.5	7.6	1.9	5.4	2.2	5.8	2.7	6.4	3	6.7
315	292.5 - 337.5	3	2.0	5.7	2.5	6.1	3.0	6.6	3.3	6.9
Omni (integrated)			4.0	9.2	5.2	10.2	7.0	11.7		

1) Minimum of calculated equivalent characteristic (R=200) value and the omni-directional value R=50 (N-003)

Thirdly, all wind data are applied to establish a marginal distribution as shown in Figure 9, with parameters and extreme values as listed in Table 17.

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

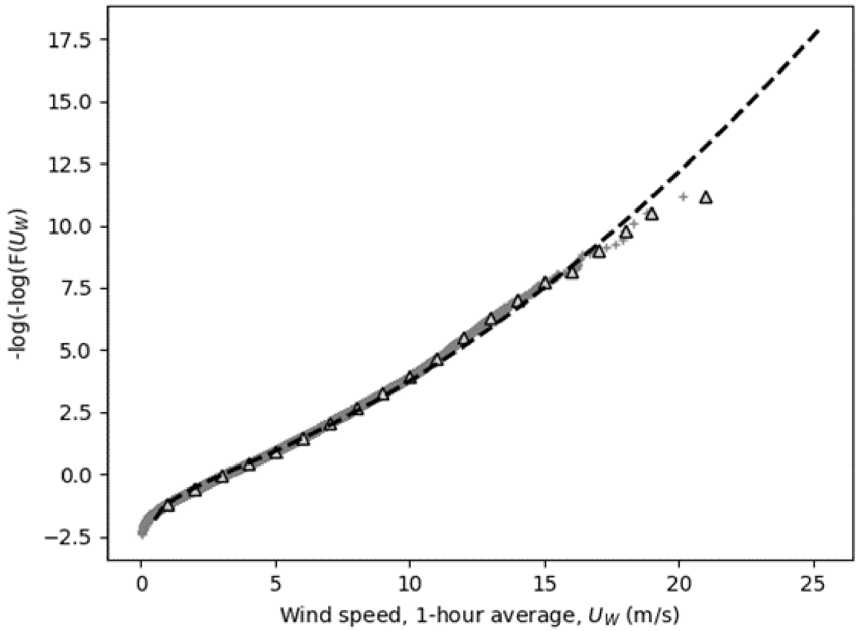

Figure 9 Marginal distribution of 1-hour average wind speed U_W for location the Region Greater North Sea, 56°54'N 5°00'E

Table 17 Omnidirectional distribution parameters and extreme values for 1 hour wind speed

Weibull parameters			***U_w(m/s); return period***		
α	**β**	**γ**	***R = 1 year***	***R = 5 years***	***R = 50 years***
4.257	1.636	0.417	16.8	18.5	20.8

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

Greater North Sea - 56°54'N 5°00'E (Harsh)

The location 56°54'N 5°00'E in the Greater North Sea region is shown in Figure 10 and the directional significant wave heights H_S for that location is shown in Figure 11. This is probably a location where offshore wind farms will be installed.

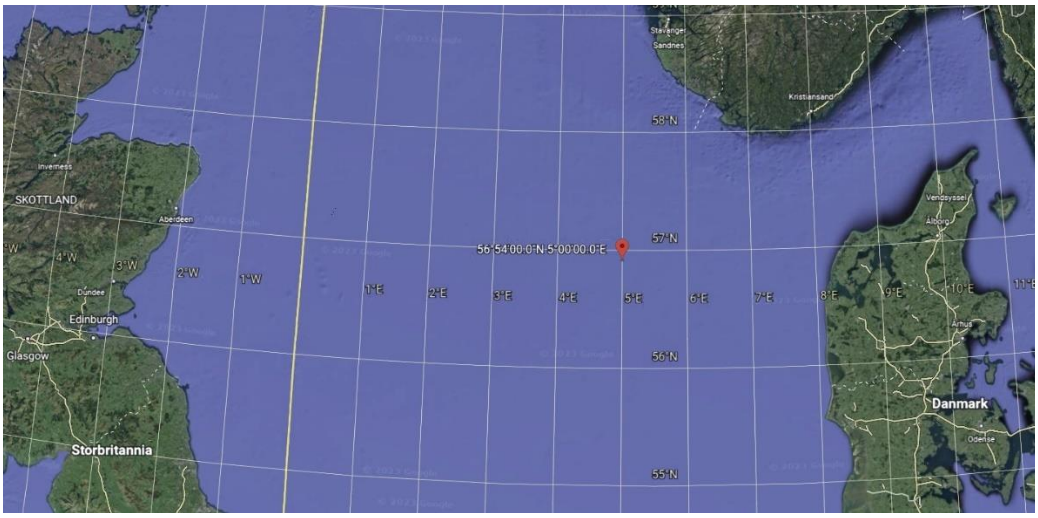

Figure 10 Region Greater North Sea, location 56°54'N 5°00'E (red mark)

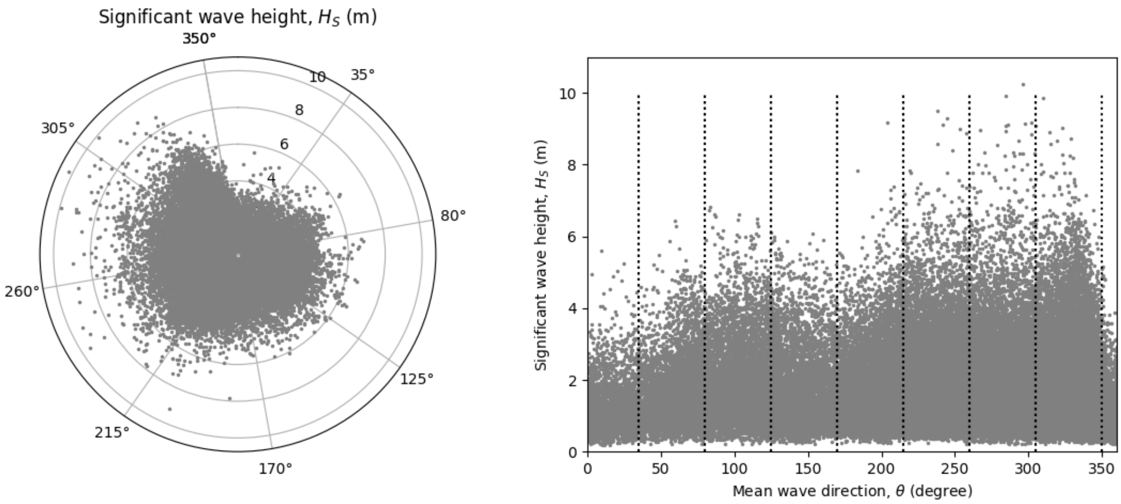

Figure 11 Directional wave data for location 56°54'N 5°00'E, significant wave height HS (m) as a function of mean wave direction ϴ (°). European waters

Firstly, all wave data are applied to establish an omnidirectional joint model, as shown in Figure 12, and with parameters and extreme values as listed in Table 18, Table 19, and Table 20.

It is found challenging to find a good fit for the steepest waves (left side of the contour), and it is found acceptable to use the least conservative of the calculated contour line and the DNV steepness curve.

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

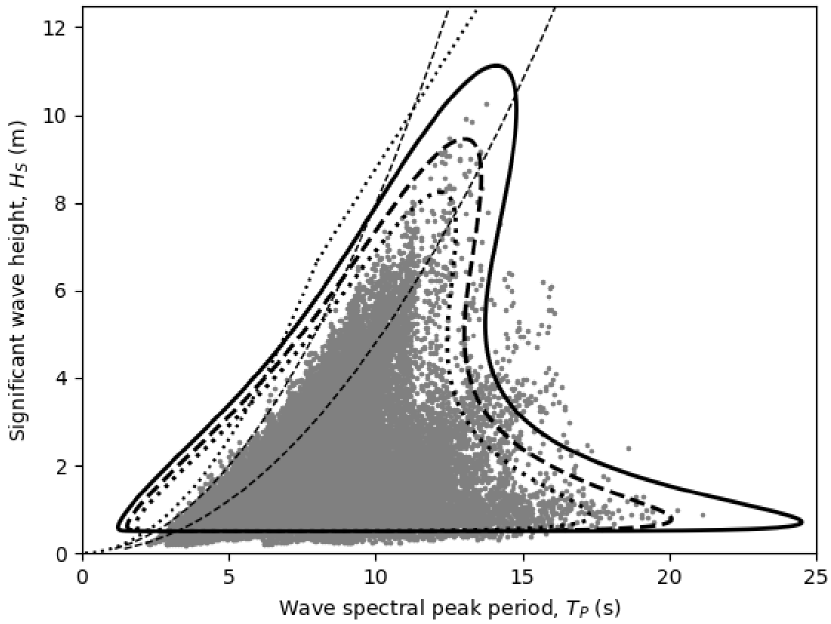

Figure 12 Omnidirectional scatter diagram (H_S-T_P) and joint distribution model (Weibull – Lognormal) for location the Region Greater North Sea, 56°54'N 5°00'E (harsh conditions). Contour lines for R = 1 year (dotted line), 5 years (dashed line) and 50 years (solid line) and DNV RP-C205 steepness criteria (dotted line) and DNV RP0584 lower and upper bound (dashed line).

Table 18 Omnidirectional distribution parameters for H_S-T_P joint model (Greater North Sea - 56°54'N 5°00'E (Harsh))

Weibull			**Lognormal**					
α	**β**	**γ**	***a_0***	***a_1***	***a_2***	***b_0***	***b1***	***b_2***
1.484	1.258	0.50	1.0802	0.718	0.3238	0.0565	0.4409	-0.5339

Table 19 Omnidirectional extreme sea state (H_S-T_P) values (Greater North Sea - 56°54'N 5°00'E (Harsh))

R = 1 year		**R = 5 years**		**R = 50 years**	
H_S	***T_P***	***H_S***	***T_P***	***H_S***	***T_P***
8.2 m	12.2 s	9.5 m	13.0 s	11.1 m	14.1 s

Table 20 Omnidirectional peak period TP estimates for given significant wave height HS

***H_S* (m)**	***T_P* (s)**			***T_P* (s); return period, R (years)**			***Steepness criteria (RP-C205)***
	Mean	**Median**	**Mode**	**R = 1**	**R = 5**	**R = 50**	
1	6.3	6	5.5	2.1	1.9	1.6	3.1
1.5	6.9	6.7	6.3	2.8	2.5	2.2	3.8
2	7.4	7.2	6.9	3.6	3.3	2.9	4.4
2.5	7.9	7.7	7.5	4.4	4.1	3.7	4.9
3	8.3	8.2	8	5.1	4.8	4.4	5.4
3.5	8.7	8.6	8.5	5.9	5.5	5.2	5.8
4	9.1	9.1	9	6.6	6.2	5.9	6.2
4.5	9.5	9.5	9.4	7.2	6.9	6.5	6.6

5	9.9	9.9	9.8	7.8	7.5	7.1	6.9
5.5	10.3	10.2	10.2	8.4	8.1	7.6	7.3
6	10.7	10.6	10.6	9	8.6	8.2	7.6
6.5	11	11	10.9	9.5	9.1	8.7	7.9
7	11.4	11.3	11.3	10.1	9.6	9.1	8.2
7.5	11.7	11.7	11.6	10.7	10.2	9.6	8.5
8	12.1	12	12	11.5	10.7	10.1	8.8
8.5	12.4	12.4	12.3		11.3	10.6	
9	12.7	12.7	12.7		11.9	11	
9.5	13.1	13	13			11.5	
10	13.4	13.4	13.3			12.1	
10.5	13.7	13.7	13.7			12.7	
11	14	14	14			13.6	

Secondly, the directional data are used to establish a directional joint model for the waves, with parameters listed in Table 21, and extreme values listed in *Table 22*. Also included in the table are omnidirectional extreme values as found from the integrated annual probability of exceedance from all directional sectors.

Table 21 Directional sectors and joint distribution model parameters for HS-TP, location 56°54'N 5°00'E

Sector		Distribution parameters								
Centre	Boundaries	Weibull			Lognormal					
Θ_C (°)	(Θ_L - Θ_U] (°)	α	β	γ	a_0	a_1	a_2	b_0	*b1*	b_2
12.5	-10 – 35	0.792	1.083	0.50	1.0802	0.7655	0.2806	0.025	0.4235	-0.3338
57.5	35 – 80	1.340	1.379	0.50	1.0802	0.5737	0.4395	0.025	0.2389	-0.4661
102.5	80 – 125	1.562	1.383	0.50	1.0802	0.5238	0.4564	0.025	0.2074	-0.5230
147.5	125 – 170	1.382	1.346	0.50	1.0802	0.5600	0.4244	0.025	0.2514	-0.5010
192.5	170 – 215	1.142	1.142	0.75	1.0802	0.6817	0.3263	0.025	0.4936	-0.7977
237.5	215 – 260	1.269	1.111	0.75	1.0802	0.6743	0.3427	0.025	0.4359	-0.6846
282.5	260 – 305	1.245	1.057	0.75	1.0802	0.7989	0.2666	0.025	0.3425	-0.3612
327.5	305 – 350	1.237	1.134	0.75	1.0802	0.8932	0.2291	0.025	0.3652	-0.2960

Table 22 Directional sectors and extreme sea states (HS-TP) location 56°54'N 5°00'E

Sector			H_S (m) and T_P (S); Return period R							
Centre	Boundaries	Prb.	R = 1 year		R = 5 years		R = 50 years		ULS (R = 200)	
Θ_C (°)	(Θ_L - Θ_U] (°)	(%)	H_S	T_P	H_S	T_P	H_S	T_P	H_S	T_P
12.5	-10 – 35	5.1	4	9.1	5	9.8	6.5	10.7	7.3	11.2
57.5	35 – 80	6.0	4.9	9.3	5.9	10.3	7.1	11.5	7.9	12.2
102.5	80 – 125	7.4	5.8	9.5	6.9	10.4	8.3	11.7	9.2	12.4
147.5	125 – 170	7.0	5.3	9.2	6.3	10	7.7	11.2	8.5	11.8
192.5	170 – 215	11.2	6.1	10.1	7.3	10.9	9.1	12	10.1	12.6
237.5	215 – 260	17.0	7.3	11.2	8.8	12.2	10.9	13.6	12.2	14.4
282.5	260 – 305	17.3	7.8	11.7	9.5	12.6	11.9	13.8	13.3	14.5
327.5	305 – 350	28.9	7.4	12.1	8.8	12.8	10.7	13.7	11.8	14.2
			8.6	12.4	10.1	13.4	12.3	14.8		

Thirdly, all wind data are applied to establish a marginal distribution as shown in Figure 13, with parameters and extreme values as listed in Table 23.

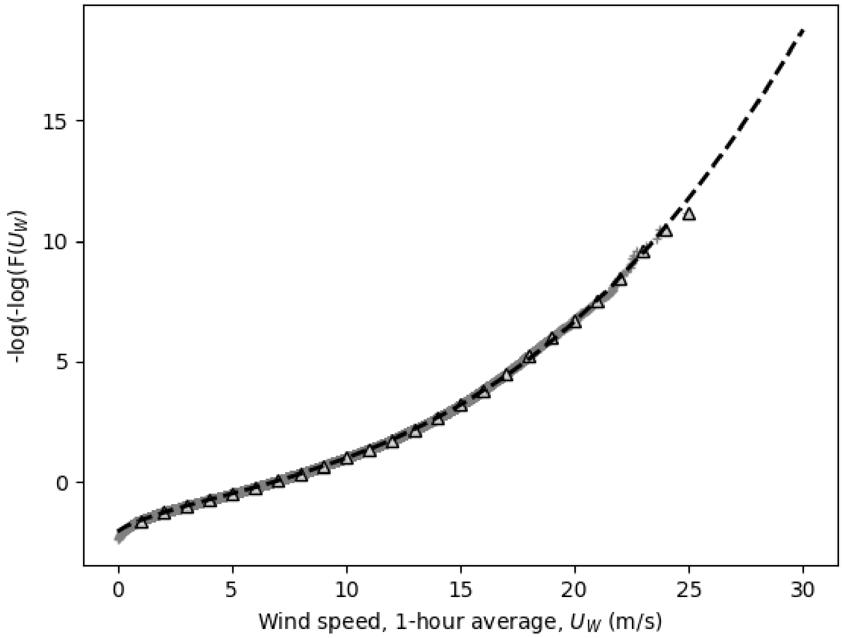

Figure 13 Marginal distribution of 1-hour average wind speed U_W for location the Region Greater North Sea, 56°54'N 5°00'E

Table 23 Omnidirectional distribution parameters and extreme values for 1 hour wind speed

Weibull parameters			***U_W(m/s); return period***		
α	**β**	**γ**	***R = 1 year***	***R = 5 years***	***R = 50 years***
9.882	2.605	-0.465	22.6	24.1	26.0

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

4. Power production estimate

For each of the locations, a power production estimate for a total of 18000 PV units has been calculated including wave corrected performance ratio (WCPR). The calculations have firstly been carried out by PVsyst[2] for a fixed system as summarized in Table 24, and secondly, the calculated production estimate has been adjusted according to the WCPR, as summarized in Table 25. The WCPR has been found based on the work carried out by Dörenkämper et. al (2019) where the decrease in production was estimated for three different locations.

Table 24 Power production estimate for the relevant locations in semi-open European waters, fixed system

Region	Coordinates	Nominal power (kWp)	Energy production in year 1 (kWh)	Yield (KWh/kWp)
Baltic Sea	54°12'N 4°24'E	9679	8972433	927
Western Mediterranean	39°00'N 0°00'E	9679	12640774	1306
Greater North Sea	56°54'N 5°00'E	9679	8691742	898

Table 25 Power production estimate for the relevant locations in semi-open European waters, incl. WCPR

Region	Coordinates		$H_{S,\ R=50}$ (m)	$H_{S,med}$ (m)	WCPR[1)] (%)	Energy production in year 1 (kWh)	Yield (KWh/kWp)
Baltic Sea	54°12'N 4°24'E	Mild	4.4	0.6	7.4	8311739	859
Western Mediterranean	39°00'N 0°00'E	Mid	7.0	0.5	7.2	11732939	1212
Greater North Sea	56°54'N 5°00'E	Harsh	12.3	1.6	9.2	7893701	816

1) Based on Dörenkämper et. al (2019), inter- and extrapolated values.

All the data on these three locations will be uploaded in SUREWAVE project folder.

5. References

1. DNV-RP-0584, Design, development and operation of floating solar photovoltaic systems
2. DNV-RP-C205, Environmental loads and conditions
3. Haver, S., and Winterstein, S. R. (2008), Environmental Contour Lines: A Method for Estimating Long Term Extremes by a Short Term Analysis, DOI: https://doi.org/10.5957/SMC-2008-067)

[2] https://www.pvsyst.com/

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.

4. NORSOK N-003:2017, Actions and action effects
5. M. Dörenkämper, D. van der Werf, K. Sinapis, M.M. de Jong, W. Folkerts (2019), Influence of Wave Induced Movements on the Performance of Floating PV Systems, 36th European Photovoltaic Solar Energy Conference and Exhibition, 1759 – 1762 (doi:10.4229/EUPVSEC20192019-6DO.9.1)
6. https://www.pvsyst.com/

The SUREWAVE project has received funding from the European Union's Horizon Europe Research and innovation funding programme under GA No. 101083342.