Sample of Irregularity and Seasonality of Waves Based on Calculation of Sea Wave Potential in the Latvian EEZ

In natural conditions, including the Baltic Sea coast of Latvia, waves are irregular. Wave height, period and wave propagation are random variables.

Key Parameters of Waves and Calculation Results of Wave Potential

By selecting a sufficiently short time interval and a sufficiently small surface area of the sea, for example 1m x 1m, we can assume that the changes in these parameters can be described by means of probability theory as a stationary random process. In this case, the wavelength energy density spectrum is the most appropriate for calculating the energy potential [1]. This spectrum is characterized by parameters that are used in the calculation of wave potential below:

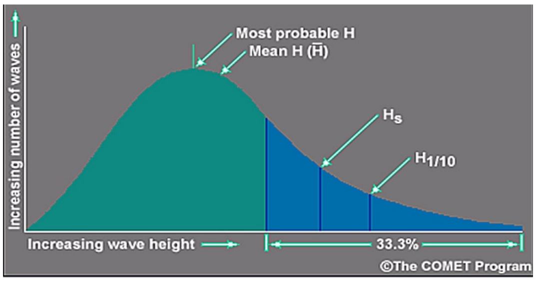
H_s – Characteristic wave height, often referred to as *swh* (significant wave height),

T_z – Zero crossing = T_e (s) according to data provided by data providers,

T_p – Their period of peak energy (s) in the spectrum,

θ_{vid} – Average angle of wave propagation direction.

swh is a wave parameter in meters that characterizes irregular wave surface fluctuations (Fig. 1) [2].



1. Fig. Illustration of characteristic wave height definition [2]

The average wave time T_z is a wave parameter in seconds that characterizes fluctuations in the surface of irregular wave water as well as the spectrum of energy density. Since $Tz \leq Te$, their expressions use a wave of energy and power estimation. Here is the average energy period of the wave energy spectrum, which is connected by the moments of the 1-st and 0-th order of the energy density spectrum:

$$T_e = m_{-1} / m_0, \qquad (1)\ [20]$$

Variata's k-th spectral moment is a specific constant determinative value of a point set to be used in mechanics and statistics where *k* can be: - 4, -3, 0, 1, 2, 3, 4.

The main direction of the *mwd* (Mean wave direction) is the wave parameter in degrees, which characterizes the fluctuation of the surface of irregular wave water and the spectrum of energy direction.

Description of Start Data Used in the Calculation

The following criteria were chosen to select checkpoints [3]:

1. Water area "A" (Fig. 2) – The Eastern part of the Baltic Sea in the waters of the *EEZ* of Latvia is approximately 216 km long and 95 km wide;

2. *SW* and *W* winds in this area are dominant [4];

3. Six checkpoints were selected in the Baltic Sea area "A" near the coast of Latvia;

4. Fixed checkpoint coordinates and depths (Table 2). Visualization of control points has been created (Fig. 2.).

As we do not have local technical tools to provide data for the correction of this spectrum parameter, we will use the characteristic parameters of the wave energy density spectrum [3] (H_s *(swh)*, T_z and *mwd* data) – an illustrative example of the data record is in table 1.

1. Table

Wave data

Year	Month	Date	hr.	min.	*mwd*	*swh*
2010.	1	1	0	0	328	0.699
2010.	1	1	1	0	328	0.668
2010.	1	1	2	0	328	0.637

Data are given for six control points (Fig. 2.). Data are given 24 hours a day, every day of the month and every month for five years (2010 – 2014). Assuming that the meteorological and hydrological conditions in our chosen area are sufficiently homogeneous, the calculation results can be attributed to the adjacent sea area +/- 5km. *DMI* data are about 10 km in step [5]. *mwd* values are viewed every 1 in the 360˚ spectrum.

2. Table

Coordinates of selected control points and depths of the aquatorium [3]

Control point	*Lat*	*Lon*	Depth, m
P1	56.100	20.833	24
P2	56.500	20.833	24
P3	57.000	21.167	24
P4	57.400	21.333	56
P5	57.600	21.667	21
P6	57.700	24.167	31
P7	56.400	20.810	24

Fig. 2. Illustrative placement of control points that have been calculated [3]

2.4.3. Results of Calculation of Wave Energy Potential

Results were obtained in area "A" (Figure 2) – 6.51 TWh / year [3] (Table 3).

3. Table

Detailing calculations of Baltic wave energy potential in the Baltic Sea

Names of calculations	Control points						
	P1	P2	P3	P4	P5	P6	P7
E monthly depending from H_{si} / T_e (kWh)	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014
E monthly depending from H_{si} / T_e (%)	2010-2014	2010-2014	2010-2014.	2010-2014	2010-2014	2010-2014	2010-2014
E time distribution (kWh / m)						2010.12.	
P depending from H_{si} (W / m)	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014	2010-2014
P time distribution (W / m)	2010-2014						
Distribution of waves by λ intervals	2011						
E P5 distr. by *mwd* & month. (kW / m)					2010-2014	2010-2014	2010-2014
E P5 distr. by month. (kW / m)					2010.		
E P5, P6, P7 distr. by month. (kW / m)					2010-2014	2010-2014	2010-2014
E P6 distr. by *mwd* & month. (kW / m)					2010-2014	2010-2014	2010-2014
E P7 distr. by *mwd* & month. (kW / m)					2010-2014	2010-2014	2010-2014

Additional calculations – 13 point-to-point projections of wave power and main energy and energy directions per month / year, polygon curve processing, theoretical potential on line P1 - P5, polygon curve processing potential with *cos* θ on line P1 - P5, polygon curve potential with δ angle filter for the projections of the sectored baselines P1 - P5 and the projection of the baseline projections of the "A" sub-area of the area to the baseline lines.

Wave energy has seasonal dependence (by months) on wave height and period.

Calculated at wave specific energy control points P1, P2, P3, P4, P5, P6 and P7 by months and years (Table 4). The results are grouped by mean T_e and H_{si} intervals (Table 5, Table 6). It is important how long and how much energy waves occur during the year (Figure 3).

4. Table

Fragment of the wave specific energy table from control point P1 May 2010.

Date	hr.	min.	*mwd*	*swh*	*Tz*	*E*(kWh / m)
1	0	0	245	1,367	5,055	4.537
1	1	0	245	1,438	5,184	5.149
1	2	0	246	1,481	5,262	5.544

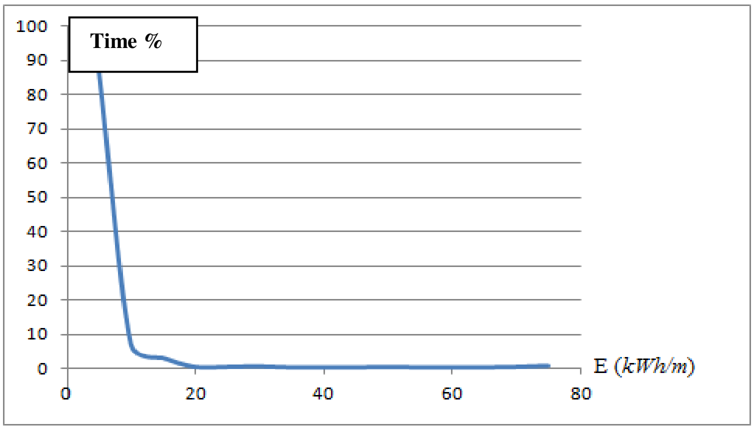


Fig. 3 Distribution of specific energy of waves during Dec. 2010. contr. point P5 (kWh / m)

5. Table

Wave specific energy depending on H_{si} and T_e control point P1 May 2010.

	1m wide wave energy at control point P1 May 2010, kWh / m											**Total**
	Te average per hour											**kWh / m**
Hsi	**2.00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	
0.20	0.14	0.31	0.77	-	-	-	-	-	-	-	-	**1.21**
0.30	1.35	5.32	4.61	1.93	-	-	-	-	-	-	-	**13.21**
0.40	2.59	12.39	4.58	3.38	1.77	-	-	-	-	-	-	**24.71**
0.50	0.28	7.98	4.14	7.20	6.01	-	1.79	1.13	-	-	-	**28.54**
0.60	-	5.58	4.14	5.15	6.97	1.39	-	-	-	-	-	**23.25**
0.70	-	1.83	14.74	9.69	5.10	1.03	-	-	-	-	-	**32.39**
0.80	-	-	11.04	18.16	11.59	24.06	1.55	1.60	1.75	-	-	**69.75**
0.90	-	-	10.82	22.69	15.70	25.67	-	4.33	3.95	-	-	**83.17**
1.00	-	-	-	11.71	18.89	20.76	8.75	-	-	-	-	**60.10**
1.10	-	-	-	13.79	21.90	24.26	8.33	-	-	-	-	**68.29**
1.20	-	-	-	-	12.87	15.01	19.62	-	-	-	-	**47.51**
1.30	-	-	-	-	6.45	21.00	23.63	-	-	-	-	**51.08**
1.40	-	-	-	-	-	16.25	14.28	4.95	-	-	-	**35.48**
1.50	-	-	-	-	-	13.92	37.25	22.75	-	-	-	**73.92**
1.60	-	-	-	-	-	-	12.10	6.51	14.19	7.94	-	**40.73**
1.70	-	-	-	-	-	-	-	14.43	-	8.87	-	**23.30**
1.80	-	-	-	-	-	-	-	8.25	-	-	20.66	**28.91**
1.90	-	-	-	-	-	-	-	9.58	10.36	23.17	-	**43.10**
2.00	-	-	-	-	-	-	-	-	11.23	11.85	-	**23.08**
Total												**771.72**

Distribution of specific E_w depending on H_{si} and T_e at control point P1 May 2010 (%)

	Distribution of specific wave energy by H_{si} and T_e													**Total**
	T_e average per hour													**%**
H_{si}	**2,00**	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	**7.50**	**8.00**	
0.30	-	0.00	0.01	0.01	0.01	.-	-	-	-	-	-	-	-	**0.03**
0.40	0,00	0.05	0.04	0.02	0.05	0.01	0.04	0.01	-	-	-	-	-	**0.22**
0.50	0,01	0.05	0.06	0.06	0.12	0.07	-	0.04	0.04	-	-	-	-	**0.45**
0.60	-	0.11	0.20	0.09	0.14	0.08	-	-	0.02	0.05	-	-	-	**0.70**
0.70	-	0.07	0.32	0.26	0.13	0.16	0.03	-	-	0.11	-	-	-	**1.09**
0.80	-	-	0.22	0.36	0.13	0.29	-	0.04	-	0.10	-	-	-	**1.15**
0.90	-	-	0.06	0.29	0.32	0.38	0.35	0.06	-	0.06	0.07	-	-	**1.59**
1.00	-	-	0.12	0.23	0.41	0.90	0.93	-	0.08	-	0.17	-	-	**2.84**
1.10	-	-	-	0.60	0.56	1.06	1.60	0.39	0.19	-	0.21	-	-	**4.59**
1.20	-	-	-	0.27	0.94	1.55	1.79	0.20	-	0.11	0.38	-	-	**5.23**
1.30	-	-	-	0.15	0.44	1.17	1.40	0.36	0.13	-	0.45	-	-	**4.11**
1.40	-	-	-	-	0.23	1.19	1.63	1.10	1.08	0.64	0.18	-	-	**6.05**
1.50	-	-	-	-	-	0.25	2.18	0.81	0.17	0.18	0.42	-	-	**4.01**
1.60	-	-	-	-	-	0.31	1.80	1.24	-	0.20	0.47	-	-	**4.03**
1.70	-	-	-	-	-	0.16	1.92	2.49	0.89	0.24	0.75	-	-	**6.45**
1.80	-	-	-	-	-	-	1.92	2.99	1.46	-	-	-	-	**6.36**
1.90	-	-	-	-	-	-	0.94	3.59	2.51	0.30	0.31	-	-	**7.65**
2.00	-	-	-	-	-	-	0.24	4.06	2.50	0.99	-	-	-	**7.79**
2.10	-	-	-	-	-	-	-	2.24	1.35	0.76	-	-	-	**4.35**
2.20	-	-	-	-	-	-	-	0.70	1.90	0.82	0.43	-	-	**3.85**
2.30	-	-	-	-	-	-	-	-	1.24	2.22	-	-	-	**3.45**
2.40	-	-	-	-	-	-	-	-	0.43	2.86	-	-	-	**3.28**
2.50	-	-	-	-	-	-	-	-	-	3.17	-	0.61	-	**3.78**
2.60	-	-	-	-	-	-	-	-	0,53	0.55	1.23	-	-	**2.31**
2.70	-	-	-	-	-	-	-	-	-	-	0.71	-	-	**0.71**
3.00	-	-	-	-	-	-	-	-	-	-	-	0.86	-	**0.86**
3.10	-	-	-	-	-	-	-	-	-	-	-	0.92	-	**0.92**
3.20	-	-	-	-	-	-	-	-	-	-	-	1.03	-	**1.03**
3.30	-	-	-	-	-	-	-	-	-	-	-	-	1.08	**1.08**
3.40	-	-	-	-	-	-	-	-	-	-	-	1.16	3.59	**4.75**
3.50	-	-	-	-	-	-	-	-	-	-	-	-	2.57	**2.57**
3.60	-	-	-	-	-	-	-	-	-	-	-	-	2.73	**2.73**
%	**0.01**	**0.29**	**1.03**	**2.35**	**3.48**	**7.57**	**16.76**	**20.30**	**14.51**	**13.36**	**5.79**	**4.58**	**9.97**	**100.00**

Calculate the specific wave power at hourly intervals at control points P1, P2, P3, P4, P5, P6 and P7 W / m (Table 7). The results are grouped by H_{si} intervals (Table 8).

7. Table

P1 of the Table for Calculating the Specific Power of Waves February 2010

Date	hr.	min.	*mwd*	*swh*	*Tz*	Power W / m
1	0	0	214	0.690	3.86	0.25
1	1	0	214	0.670	3.93	0.24
1	2	0	218	0.639	4.09	0.22
1	3	0	226	0.605	4.34	0.21
1	4	0	229	0.595	4.50	0.21
1	5	0	229	0.601	4.55	0.22
1	6	0	230	0.601	4.65	0.22
1	7	0	234	0.585	4.85	0.22
1	8	0	238	0.565	5.05	0.21
1	9	0	240	0.548	5.17	0.21
1	10	0	242	0.529	5.25	0.20
1	11	0	243	0.509	5.27	0.18
1	12	0	243	0.488	5.25	0.17
1	13	0	243	0.468	5.20	0.15
1	14	0	244	0.453	5.03	0.14

8. Table

Results of specific power calculations depending on H_{si} P1 control point (02. 2010.)

No.	H_{si} intervals (m)	H_{si} (m)	Av. *P* (W / m)	Time (h)	Time (%)
1	0.1	0.2	0.01	68.00	10.12
2	0.2	0.3	0.02	77.00	11.46
3	0.3	0.4	0.04	75.00	11.16
4	0.4	0.5	0.09	106.00	15.77
5	0.5	0.6	0.14	99.00	14.73
6	0.6	0.7	0.20	56.00	8.33
7	0.7	0.8	0.31	27.00	4.02
8	0.8	0.9	0.40	32.00	4.76
9	0.9	1.0	0.51	33.00	4.91
10	1.0	1.1	0.64	21.00	3.13
11	1.1	1.2	0.82	14.00	2.08
12	1.2	1.3	1.04	13.00	1.93
13	1.3	1.4	1.21	15.00	2.23
14	1.4	1.5	1.52	5.00	0.74
15	1.5	1.6	1.61	5.00	0.74
16	1.6	1.7	1.99	10.00	1.49
17	1.7	1.8	2.23	2.00	0.30
18	1.8	1.9	2.70	4.00	0.60
19	1.9	2.0	3.20	5.00	0.74
20	2.0	2.1	3.57	5.00	0.74
Average *P* per month			**0.33**	**672.00**	**100.00**

To determine the wavelength distribution by wavelengths, the average wavelengths of the control point P1 for 2011 were calculated (Table 9) (Figure 4).

Distribution of average wavelengths by length at control point P1 (Depth – 24 m) 2011.1.11.

Wave type	*λ* intervals	Number of waves, *n*
Deep water waves	10	11756
	20	25339
	30	56848
	40	69666
Medium water waves	50	52639
	60	57537
	70	58439
	80	39799
	90	24944
	100	23056
	110	16235
	120	11827
	130	8907
	140	2732
	150	3356
Deep water waves		**163609**
Medium water waves		**299471**

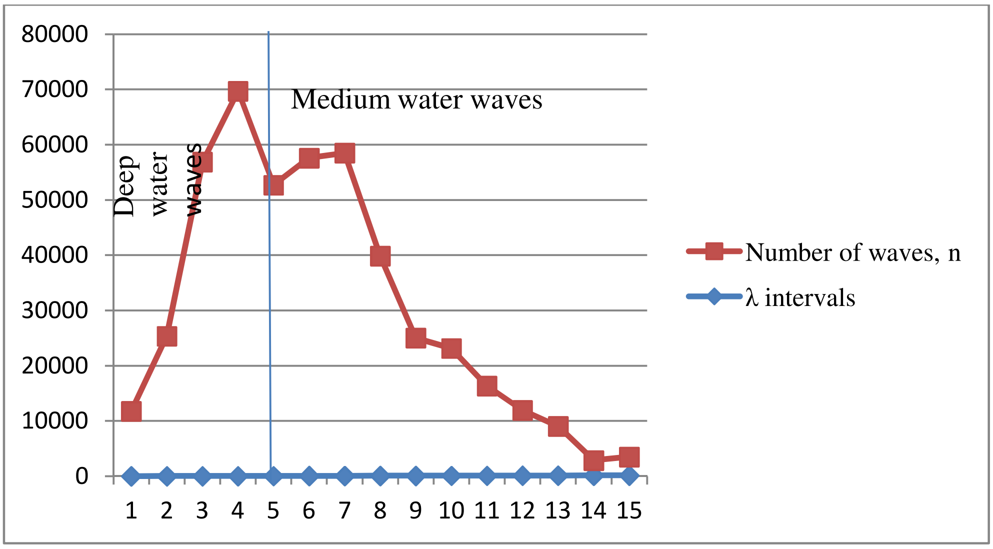
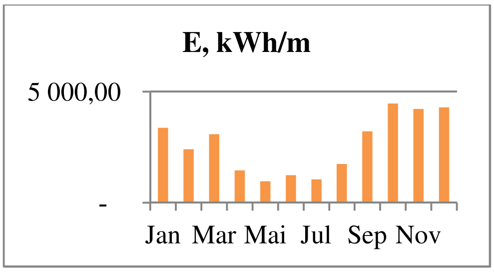


Fig. 4 Distribution of mean wavelengths by length at control point P1 (depth 24m) in 2011

The energy breakdown by month is shown in Fig. 5.

Distribution of energy potential by month will be important for energy conversion (Fig. 5).



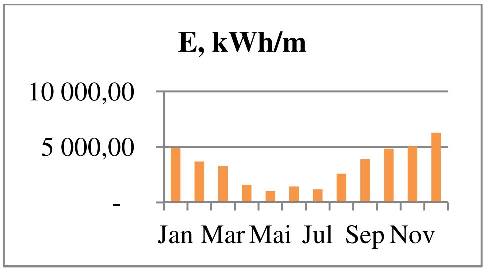


Fig. 5 Monthly distribution of specific energy (kWh / m) of control points P5 and P7 [6]

Calculated and grouped by *mwd* groups (Direction +/- 22, 5°) Baltic Sea's Latvian *EEZ* energy potential based on control point P5 data (Table 10) (Fig. 6).

10. Table

Energy calculation based on control point P5, P6 and P7 (Z_0 method [10])

	N	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	**Total, kWh/m**
P5	903.28	1 088.58	263.98	242.51	575.79	13 872.39	7 527.08	7 064.72	31 538.34
P6	404.53	185.04	224.14	293.47	3 361.94	4 006.71	3 655.91	1 808.86	13 940.58
P7	3 392.68	336.40	218.43	459.77	3 157.73	10 209.42	16 707.20	5 210.83	39 692.46
%	8.55	0.85	0.55	1.16	7.96	25.72	42,09	13.13	100.00
Dist.,km	95	100	216	199	95	100	216	199	
TWh	**0.32**	**0.03**	**0.05**	**0.09**	**0.30**	**1.02**	**3.61**	**1.04**	**6.46**

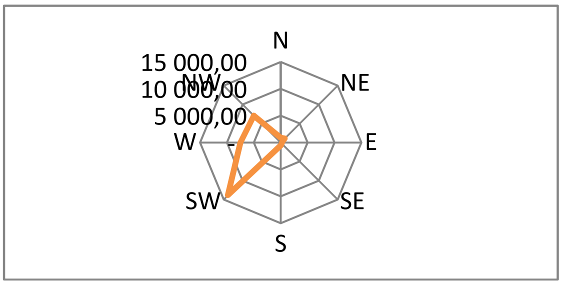


Fig. 6. Average specific energy potential at control point P5 (Depth 21m) (2010 – 2014) (kWh / m)

Distribution of control points P5, P6 and P7 year's (average from 2010 to 2014) specific energies by directions to the Baltic Sea the graphic image of the Latvian *EEZ* is shown in Fig. 7. [6].

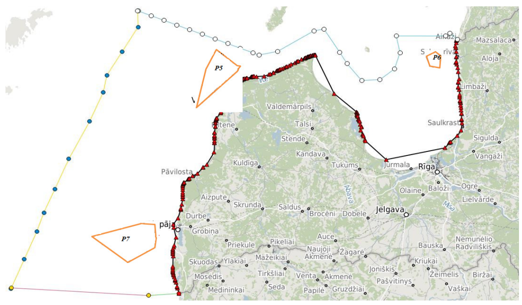


Fig. 7. Distribution of P5, P6 and P7 control points (average from 2010 to 2014) specific energies by directions to the Baltic Sea Latvian *EEZ* graphic (kWh / m) [6]

Calculations of specific energies at control points P5, P6 and P7, were also made in the direction of directions each month from 2010 – 2014.

Control points P1; P2; P3; P4; P5 and P7 calculated, aggregated monthly data on specific potential, as well as interpolation of these results, estimation of specific energy potential at points P1 – P19 (Fig. 8.).

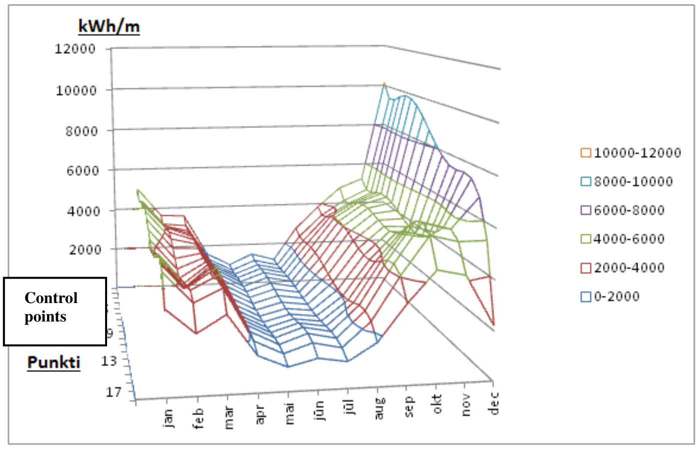


Fig. 8. Monthly average (2010 – 2014) specific energy potential averaged over months at points P1 - P19 (kWh / m) [3]

SOURCES OF INFORMATION

[1] Owerwiew of Ocean Wave Statistics., Ch.4 Spectral analisys. https://upcommons.upc.edu/bitstream/handle/2099.1/6034/06.pdf?sequence=7

[2] DMI Ocean and Ice services, DMI WAM model http://ocean.dmi.dk/models/wam.uk.php;

[3] J. Beriņš, J. Beriņš, A. Kalnačs. „Viļņu enerģijas potenciāla noteikšana Latvijas EEZ". "Latvijas fizikas un tehnikas žurnāls" 2016. gada 3. Nr.

[4] Soomere T., Keevallik S., Anistropy of moderate and strong winds in the Baltic Proper., 35 Proc. Estonian Acad. Sci. Eng., 2001, 7, 1, p.35–49;

[5] DMI Ocean and Ice services, DMI WAM model http://ocean.dmi.dk/models/wam.uk.php

[6] MK noteikumi. Nr.779 (17.08.2010.). „Noteikumi par bāzes līniju punktu koordinātēm".