RIGA TECHNICAL UNIVERSITY

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OCEAN AND MARINE ENERGY OPTIONS AND DEVELOPMENT

Summary of the Doctoral Thesis

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Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 2 July 2019 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Jānis Beriņš ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; five chapters; Conclusions and Suggestions; one appendix; 83 figures; 28 tables; the total number of pages is 184. The Bibliography contains 256 titles.

CONTENT

1. INTRODUCTION

1.1. Position of Problem

Researching the composition of gas bubbles in polar glaciers, scientists have found that the concentration of CO_2 in them varies. Analysing ice samples, it has been found that the world temperature tends to follow the carbon dioxide content of the atmosphere.

Using the glacial analysis method, it can be concluded that the CO_2 content has never been more than 280 parts per million molecules over the last 800 000 years. However, recently this figure has reached 390 parts and continues to grow rapidly. Such CO_2 growth contributes to the greenhouse effect and climate changes. Since the 1950s, world temperature has increased by 0.44 °C (0.8 °F), as a result observations show a significant increase in the level of natural disasters [1] and imbalance of different water states. Part of this phenomenon is caused by the use of fossil energy sources.

World energy consumption depends on the population and the level of technical development of society. There are three UN forecasts for population change (Fig 1.1) [2]. World population has risen approximately six times in the 200 years between 1800 and 2000 (Fig. 1.1) [2].

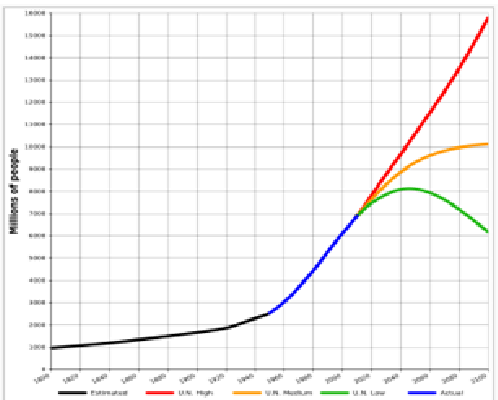


Fig. 1.1. UN population forecasts (million people) [2].

Total world energy consumption in 200 years (1820–2020) has risen about 22 times, and uses of new forms of energy are being discovered during this period (Fig. 1.2) [3].

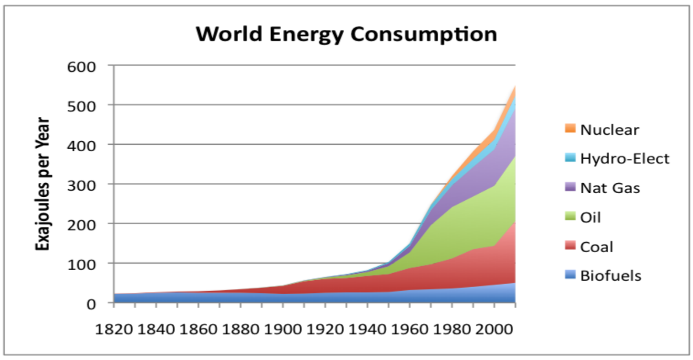


Fig. 1.2. Structured energy consumption in the world (EJ per year) [3].

If around 1800 the average per capita energy consumption was 2.5×10^{11} J, then around 2000 it became 5.5×10^{12} J. Following this trend, energy consumption per capita will continue to increase. According to the UN World Population Forecasts, the world will face the challenges of acquiring new forms of energy. The graph (Fig 1.3) [3] shows that a significant part of the current energy mix (natural gas, oil, coal, nuclear) is dominant in the overall energy. This means that these sources will have to be replaced by others in order to meet growing public demand for the required amount of energy. The worrying fact is that the consumption of fossil fuels, in fact, continues to grow faster than the use of renewable and nuclear energy (Fig. 1.3) [3].

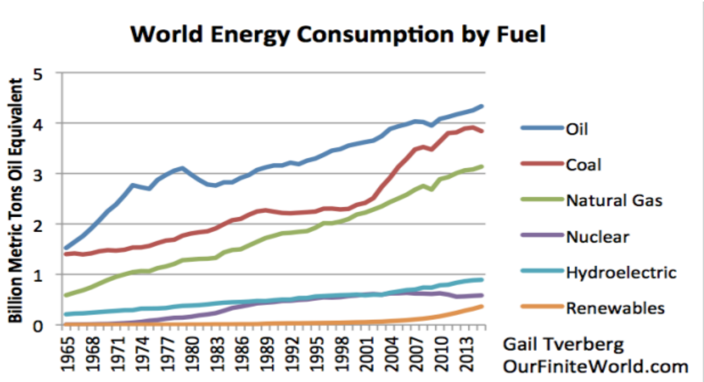


Fig. 1.3. Global energy consumption (oil equivalent of billion tonnes) [3].

The role of renewable energy sources will increase in the future. Wave potential is one of those energy forms. New efficient conversion facilities need to be developed so that waves become an important energy sector.

1.2. Aims and Tasks of the Thesis

The aims of the Doctoral Thesis are to evaluate the possibilities of wave energy acquisition at a significant level for society based on the development history of the industry and its perspectives and contribute to solving major tasks.

Tasks of Thesis

1. To evaluate the wave energy potential of the world and of the Latvian Exclusive Economy Zone (EEZ).
2. To define the factors influencing wave energy transformation.
3. To assess the design of the World wave power plants.
4. To classify the reviewed equipment.
5. To choose one of the types of equipment and justify the choice.
6. To develop a new model and test it in laboratory environment.
7. To define the development perspectives of the developed model.
8. To provide a techno-economic assessment at the pre flexibility stage of the use of wave energy on the basis of the potential of the Latvian EEZ of the Baltic Sea.

1.3. Research Tools and Methods

Literature sources have been used to justify the work, to obtain the necessary analyses and classifications, and to make the equations for calculations. The database of the calculated wave hour spectral parameters of SWAN modelling programs was used in the Thesis. MS *Excel* tools were used to evaluate the wave potential, process the wave stand experimental results and perform calculations related to the *JVS* (sea/ocean wave powerstation) technically economical evaluation and to obtain the results of the graphical images: sorting of results, one-dimensional and two-dimensional histograms, window interpolation, Fourier rapid digital transformation. Visualization tools have been used to illustrate the long-term direction of wave potential with the wave power line baseline projection (*VEVPP*) method developed for this purpose.

The type of equipment was selected by reviewing the existing invention by sorting (classifying) the equipment according to certain characteristics and analysing the test results. Dimensions of its model were selected according to our capabilities in the laboratory. An experimental method was used to test the machine model. A similar approach is described in the article "Coupling Methodology for Studying the Far Field Effects of the Wave Energy Converter Arrays over a Varying Bathymetry" [4], [5], where other devices are being tested, but the principle of the experiment remains. An experimental base was created: wave pool, wave receiver with measuring equipment for recording and processing wave parameters (computer, laser meters). The "black box" principle was used to determine the absorbed wave energy. The model was tested in a special turbine bench in a wave laboratory. Laboratory wave parameter (H and T) measurements were obtained and data recorded by automatic WEB-camera image digital pre-processing using specially-designed tools based on the *Java* application.

The efficiency of the wave turbine model was assessed by processing and analysing visual information and bench data.

1.4. Results of the Work

The results of the Doctoral Thesis are manifested in accomplishing the set tasks.

1. Estimation of World wave energy potential and wave potential of the Latvian EEZ of the Baltic Sea has been made.
2. Factors affecting wave energy transformation are defined.
3. Technology developments in 137 different wave power plants have been considered.
4. The equipment in question has been classified.
5. One type of equipment has been selected and the justification of the choice is given.
6. A wave laboratory has been established and the parameters that have to be improved have been identified.
7. A new model of equipment has been developed, tested in a laboratory environment and results have been obtained.
8. Improvable parameters of the developed model are defined.

9. Techno-economic evaluation of the potential sea wave power station in the Latvian EEZ of the Baltic Sea has been made.

1.5. Scientific Novelty of the Thesis

1. A new scientific-research-wave laboratory structure for purposes to test the models of wave transforming has been based substantiated.
2. The capabilities of the wave laboratory have been examined and its advantages and disadvantages, as well as the ways of addressing/mitigation of these weaknesses have been demonstrated.
3. Two self-regulating blade mechanisms for working wave-kinetic turbines have been developed.
4. The task of developing a self-regulating blade has been defined.
5. A new method for calculating the potential of waves – *VEVPP* – has been developed.

1.6. Practical Use of the Work

The practical significance of the work is as follows.

1. The newly developed *VEVPP* method can be used for more accurate estimation of wave potential.
2. It is possible to continue the development of wave-kinetic turbines to the *TRL* 9.
3. Knowledge has been obtained for creating a new laboratory with more accurate test performances.

1.7. Approbation of the Work

The main results of the work have been published and two of them have been discussed in international conferences. The development and testing of the model for wave transformation and the development of the *VEVPP* method have been funded by a private company.

1.8. Conferences

1. J. Beriņš, J. Beriņš. Wave Energy Factors and Development Perspective in Latvia, 56th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga 14 Oct., 2015. (IEEE, Xplore, SCOPUS).
2. J. Beriņš. Technical Analysis of the Economic Viability of Sea Wave Power Stations, 57th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga, 14 Oct., 2016. (IEEE, Xplore, SCOPUS).

1.9. Publications

In the context of the Doctoral Thesis the following articles have been published.

1. J. Berins, A. Grickus, A. Kalnacs. Wave Energy Conversion-Overview and Perspectives. Published at www.aplacetoinvest.com .
2. J. Beriņš, J. Beriņš. Wave Energy Factors and Development Perspective in Latvia 56th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga 14 Oct. 2015. (IEEE, Xplore, SCOPUS).
3. J. Beriņš. Technical Analysis of the Economic Viability of Sea Wave Power Stations, 57th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga, 14 Oct., 2016. (IEEE, Xplore, SCOPUS).
4. J. Beriņš, J. Beriņš, A. Kalnačs. Wave Energy potential in the Latvian EEZ, Latvian Journal of Physics and Technical Sciences, 2016. No. 3.
5. J. Beriņš, J. Beriņš. New Hydrokinetic Turbine for Free Surface Gravitational Wave Transformation, Latvian Journal of Physics and Technical Sciences, 2017. No. 4.
6. J. Beriņš, J. Beriņš. Measurements of Wave Power in Wave Energy Converters Effectiveness Evolution, Latvian Journal of Physics and Technical Sciences, 2017. No. 4.

1.10.Patents

A patent has been received on the topic of the promotion work: Patent No. LV 14059, Wave Energy Conversion Device.

2. CHARACTERISTICS OF WAVE ENERGY POTENTIAL

2.1. Research on Wave Energy Potential in the World, the Baltic's and Latvia

Scientists who have studied the potential of surface water gravity waves in the world have estimated them at 8000 TWh per year, up to 80 000 TWh per year [6]. According to some sources [7], [8], the wave potential of the World Sea (shelf) near the shore is 29 500 TWh per year (Table 2.1) [8].

Table 2.1

Distribution of Wave Energy in the World by Region [8]

Part of the World	**Wave energy TWh per year**
West Europe and North Europe	2800
Mediterranean and Archipelagos of the Atlantic	1300
North America and Greenland	4000
Central America	1500
South America	4600
Africa	3500
Asia	6200
Australia, New Zeeland and Pacific Islands	5600
Total	**29 500**

U. Henfridsson et al. [9] summarize promising areas in the North Sea and interesting parts of the Baltic Sea [9]. The publication shows a visible wave energy diagram in the Baltic Sea (Fig. 2.1) [9].

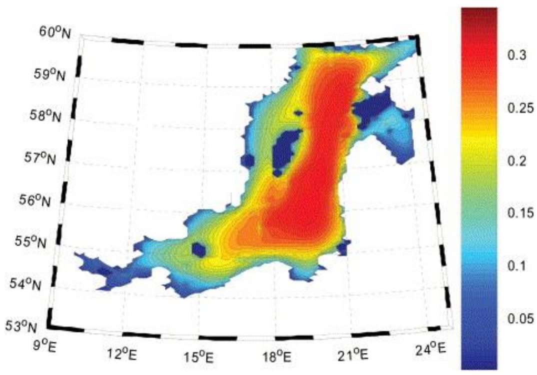


Fig. 2.1. Wave energy density map in the Baltic Sea (Wh/m^2) [9].

T. Soomere and M. Eelsalu [10] have described a study of both the theoretical amount of wave energy and its practically available part in a medium-depth aquatorium on the Baltic Sea's East coast. The 38-year average wave power is 1.5 kW/m, but in some places it reaches 2.55 kW/m, in the Gulf of Finland and in the Gulf of Riga – 0.7 kW/m. The most important factor and their conclusion is that this water area has an uneven distribution of wave energy during the year. The work presents the visualization of the medium depth wave power of the Baltic coast (Fig. 2.2) [10].

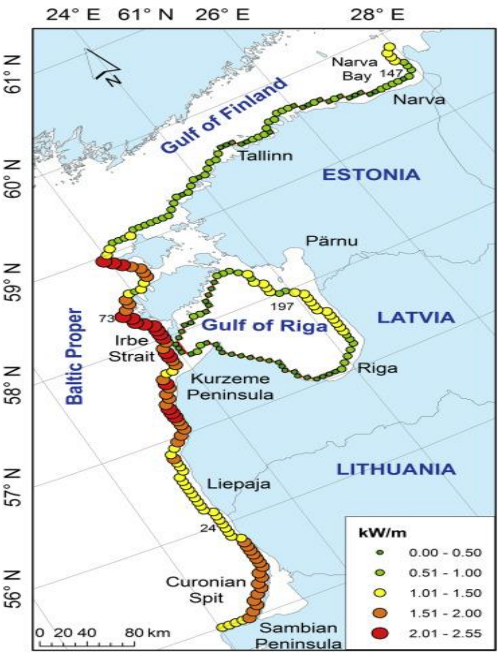


Fig. 2.2. Visualization of the medium depth wave power of the Baltic coasts according to Tarmo Soomere and Maris Eelsalu [10].

Egidijus Kasiulis, Petras Punys and Jens Peter Kofoed [11] argue that the increasing interest in wave energy and developing wave energy converters could also attract more interest to the Baltic Sea. Wave energy flow to the annual wave height on the Lithuanian coast ranges from 1.6 kW/m high intensity to 0.4 kW/m per year of low intensity, which makes the coastal energy potential of the coastline of Lithuania comparable to that of other semi-enclosed seas in Europe.

J. Greivulis, A. Avotiņš and L. Kalniņš [12] have reflected on the analysis of two wavelength parameters H and T and wind speed in the region. They have proved that it is necessary to take into account the direction of the waves and believe that the wave potential in the part of the aquatorium considered is sufficient to develop marine energy converters.

2.2. Methodology for Calculating Wave Energy Potential in the World, the Baltic's and Latvia

G. Mork and others calculate the wave potential based on data from a global wave model (validated and calibrated against satellite altimeter data) and geothermal data (WorldWaves database). First, the theoretical potential was calculated using all available wave data, and in the second step, areas with very low power levels ($P \leq 5$ kW/m) were excluded. In the third step, the areas affected by sea ice were assessed [6].

The method of T. Soomere is described in [10] as a study of input data for the period from 1970 to 2007 from 3 nautical miles (5.5 km). Data is listed every 1 hour. The depths of the aquatorium, where the data are calculated, are from 7 m to 48 m by geostatic wind measurements. It should be noted here that due to this depth range, some of the measurements do not reflect the deep-water wave scene. This is evident in the wavelength performance of the Baltic Sea and the Baltic coasts of Latvia and Lithuania (Fig. 2.2).

U. Henfridsson et al. [9] analyse examples of possible wave power plants in the Baltic Sea and the Danish part of the North Sea using wind-wave retransmission data to calculate wave energy by classical irregular wave relationships.

Egidijus Kasiulis, Peter Punys and Jens Peter Kofoed [11] assess the wave energy potential on the Lithuanian coast using available multiannual visual observations. However, the article does not explain in more detail the visual measurement algorithm, the coordinates of the measurement points and the depths of the aquatorium.

The potential of waves in the Baltic Sea region of Latvia has been studied by the previously mentioned Estonian academic Sommere and Latvian scientists J. Greivulis, A. Avotiņš and L. Kalniņš [12], claiming that they have used the wave height and period of Ventspils measurement station to obtain the results of their wave heights and periods with observations made twice a day. The article does not specify the coordinates of the measurement points, the depth(s) and how these parameters have been identified. It does not cover the data of the dominant wave directions.

2.3. Wave Energy Assessment Method in the Latvian EEZ of the Baltic Sea

The Naive method can be used to predict the potential of waves in the future. The Naive method is based on the average values of historical data, assuming that the future will be similar to the past. Different methods are used to characterize the wave energy potential.

The simplest method is to calculate the specific power of the waves and the specific energy of the waves at separate points in the area [13], [14].

Another method is to draw a notional wave receiver line (straight line or multiple slits for flat-rolled angles) at sea [10] and calculate the total energy flow through a vertical plane passing through this line of conditional receivers in one direction. Each wave direction energy flow and wave direction energy in the distance unit will decrease $\cos\theta$ times, respectively, θ – the angle whose wave front is formed by the imaginary receiver line.

The third method, where the vertical surface of an imaginary receiver in the space at the depth of energy release, serves the boundaries of the whole area. The total energy flow per year (TWh) is determined by the average wave power P_{vid} (kW/m) or the wave energy flow through this surface – the methodology of Electric Power Research Institute (EPRI) [15]. These methods have gaps [16].

In order to evaluate as accurately as possible the potential of the Baltic Sea in the Latvian EEZ, we developed a new method. This method is based on input wave parameters (*swh*, T_z and *mwd*) from the Danish Meteorological Institute (DMI), which are given in text files every hour for five years (2010–2014). These data are calculated by DMI using the SWAN program designed to calculate these wave parameters from satellite data (wind direction and wind strength). The SWAN program also provides for the correction of the above-mentioned results, which is introduced by the measurement of the nearest dipper wave data and the comparison of the wind parameters above it and some others (Fig. 2.3).

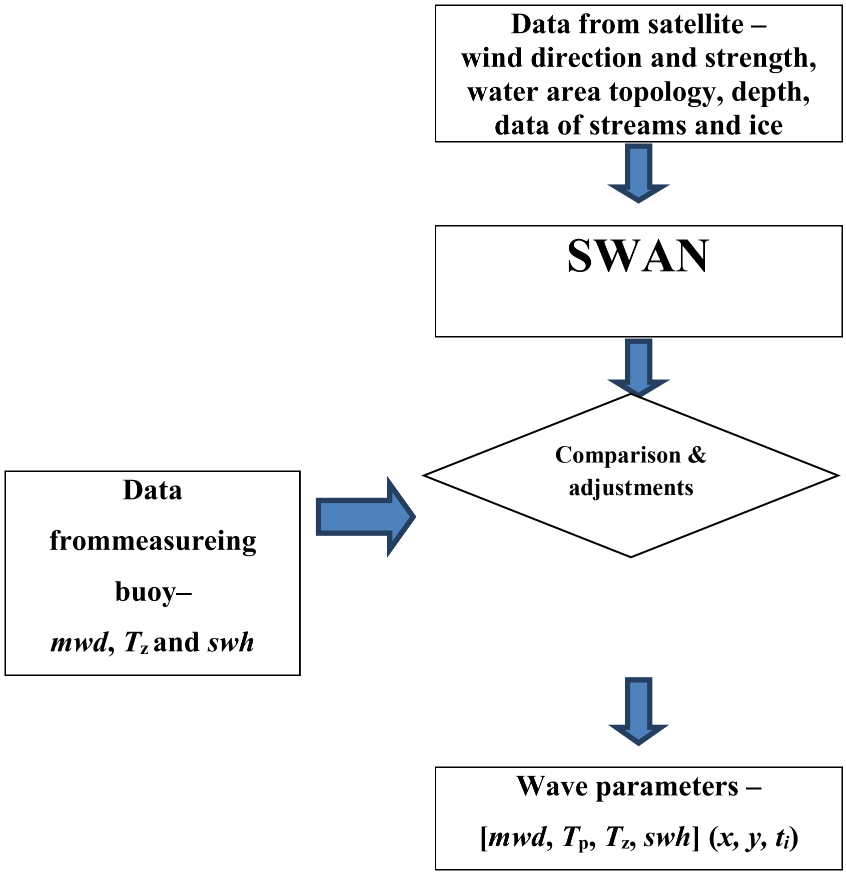


Fig. 2.3. DMI wave input data generation scheme.

Power and energy are calculated from wave parameter data.

To mitigate the weaknesses of the above methods in the wave power estimation, we propose a *VEVPP* method [16] whose initial calculations correspond to the classic irregular wave calculations (Fig. 2.4).

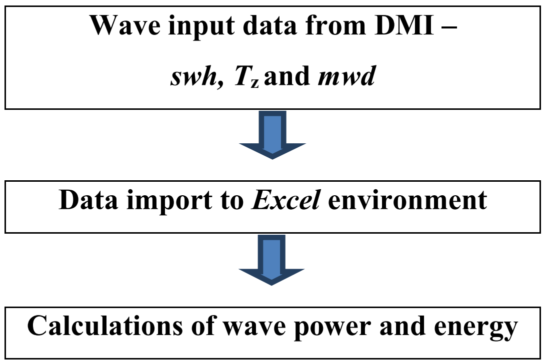


Fig. 2.4. Initial processing and calculations of wave data.

1. From the energy spectrum by integrating in the frequency range [0; ∞] we calculated the average wavelength energy density of J_{vid} in the area of 1 m^2 [18]:

$$J_{\mathrm{vid}} = \rho g \int_0^{\infty} S(f)\mathrm{d}f = \rho g m_0 = \frac{\rho g (H_{m0})^2}{16} = \frac{\rho g (H_s)^2}{16}, \quad (2.1)$$

where ρ – seawater density (kg/m^3);

g – free fall acceleration (m/s^2);

f – wave frequency (Hz);

$S(f)$ – spectrum function of wave energy;

m_0 – 0-th spectral moment;

$H_{m0} = H_s$ – characteristic wave height (m).

2. In the Baltic Sea Area "A" perpendicular to 8 traditional wind and wave directions (PV_{xx}, where xx = (N, NE, E, SE, S, SW, W, NW) we set the lines perpendicular to the directions (Fig. 2.5) [16], [17].

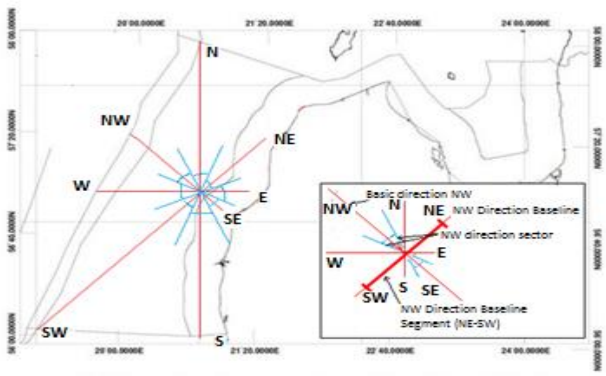


Fig. 2.5. Basic wave directions and cuts of basic lines in aquatorium "A" [16], [17].

Thus, summing the wave direction of the energy (1.1) over time interval Δt in each of the checkpoints by sector, the wave energy of non-duplicate directions is counted.

$$\dot{E}_n(Km, PV_{xx}) = \Delta t \cdot \frac{\rho g^2}{64\pi} \sum_{i=1}^{n} IF(mwd_i, PV_{xx\min}, PV_{xx\max})(T_{ei}(H_{si})^2), \quad (2.2)$$

where Km –charestiristic of controlpoint (kW/m);

PV_{xx} – one of the main directions xx (N, NE, E, SE, S, SW, W, NW);

$PV_{xx\min}$ – minimum limit for basic PV_{xx} sector;

$PV_{xx\max}$ – maximum limit for PV_{xx} sector;

H_{si} – significant wave height in the i-th time interval (m);

T_{ei} – average energy period(s) of wave energy density spectrum.

The annual wave energy potential of control point Pm for a 1 m wide wave $\dot{E}_g$ is calculated as follows:

$$\dot{E}_{g,m,xx,yy} = \sum_{n=1}^{12} (E_n, m, xx, yy), \quad (2.3)$$

where m – No of controlpoint;

E_g – annual wave energy.

3. We integrated the direction of the reference line control points into the corresponding energy by integrating its specific energy function within the distance projection. Thus, the integration process is reduced to the use of trapezoidal method [20].

$$E_{xxyy}(\mathrm{K1}, \mathrm{K5}) = \sum_{m=1}^{m+1=5} E(\Delta L(m, m+1)_{xx}) =$$

$$= \sum_{m=1}^{m+1=5} \frac{\dot{E}_n(Km) + \dot{E}_n(Km+1)}{2} \cdot \Delta L(m, m+1)_{xx}, \tag{2.4}$$

where m is a serial number (1, 2, 3, 4, 5, 7) of check point $\mathrm{P}m_{xx}$; and $\Delta L(m, m+1)$ is the distances between these point projections on the base line, taking into account the coordinates of the azimuth and control points of the baselines (Table 2.3).

4. Knowing the potential of wave energy in the control area where control points P1; P2; P3; P4; P5 and P7 are located, which are marked by the projections of the checkpoints on the base lines of the direction (Fig. 2.6), and knowing that the control area forms a significant, but not all, part of the analysed area and that the distribution of wave energy in time and space is dispersed homogeneously, it is possible to estimate the amount of PV_{xx} energy for each by increasing proportionally the ratio of the direction of the reference line PN_{yy} and the sum of the respective projection sections of control points $L(\mathrm{P1}, \mathrm{P5})_{yy}$.

5. The total monthly/annual wave potential is the sum of 8 potentials.

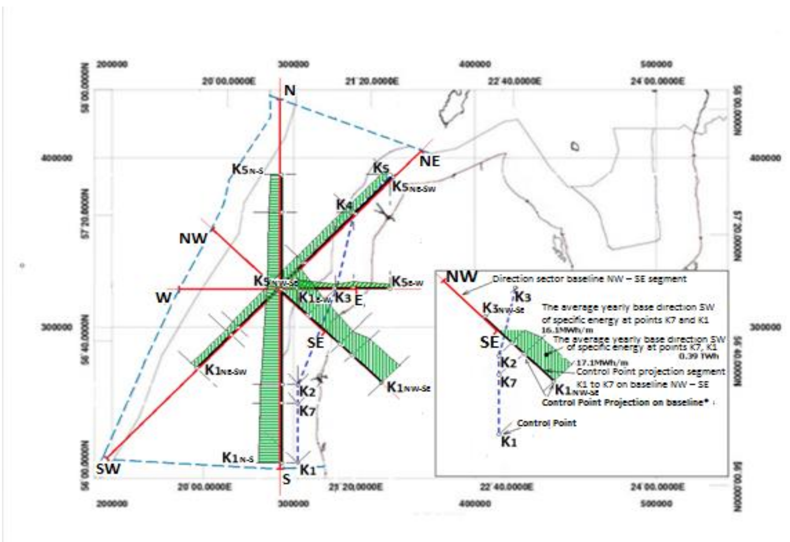


Fig. 2.6. Wave annual average energy projections in the Baltic Sea area "A" [17], [19].

Since the *VEVPP* method includes calculations related to the dependence of the result on the multiple control point placement plane, we used a simpler area wave energy estimation method chosen for the checkpoint (P7, the average annual average energy of an average close to the point of the control point to be analysed) in a special way and extended to the whole area. Its many time interval Δt components $\dot{E}_n(\Delta t_n, \theta_n)$ are sorted and summed by *mwd* by eight basic directions of the PV_{xx} (xx = N, NE, E, SE, S, SW, W, NW) 45° sectors, obtaining 8 average specific energies $\dot{E}_{g7,xx}$ components. Each component is multiplied by one of the corresponding lengths of the four baseline sections PN_{yy}, thus obtaining an approximation of the area energy eight-axis distribution E_{g7} (PV_{xx}, PN_{yy}) (yy = N-S, NE-SW, E-W, NW-SE) whose components are summed up in the average annual energy potential of an area in the Latvian EEZ.

The method differs from others by selection of basic base directions ±22.5°, and by these sectors the specific power and specific energy of the control points are summed. Then there are polygons around the checkpoints that cover the area of the aquatorium, if it is necessary to mathematically model additional control points and sum up the results.

2.4. 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.

2.4.1. 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 × 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 [18]. This spectrum is characterized by parameters that are used in the following calculation of wave potential:

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 – period of peak energy 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. 2.7) [19].

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 $T_z \leq T_e$, 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 1st and 0th order of the energy density spectrum [20]:

$$T_e = \frac{m_{-1}}{m_0}. \tag{2.5}$$

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 *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.

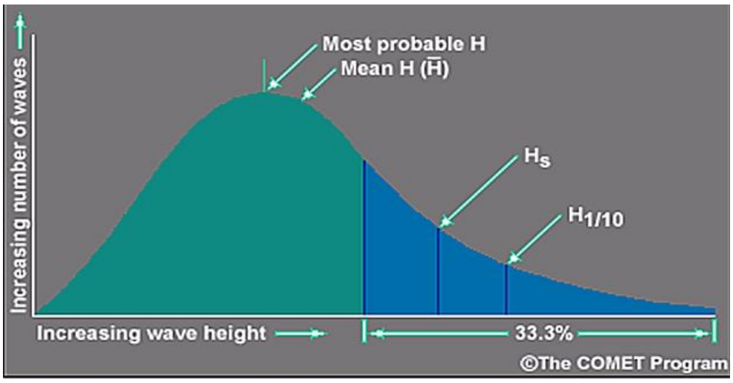


Fig. 2.7. Illustration of characteristic wave height definition [19].

2.4.2. Description of Start Data Used in the Calculation

The following criteria were chosen to select the checkpoints [16].

1. Water area "A" (Fig. 2.10) – 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 [21].
3. Six checkpoints were selected in the Baltic Sea area "A" near the coast of Latvia.
4. Checkpoint coordinates and depths were fixed (Table 2.3). Visualization of control points has been created (Fig. 2.10).

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 [16] (H_s (*swh*), T_z and *mwd* data) – an illustrative example of the data record is given in Table 2.2.

Table 2.2

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. 2.8). 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 ±5 km. DMI data are about 10 km in step [22]. *mwd* values are viewed every 1° unit in the 360° spectrum.

Table 2.3

Coordinates of Selected Control Points and Depths of the Aquatorium [16]

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. 2.8. Illustrative placement of control points that have been calculated [16].

2.4.3. Results of Calculation of Wave Energy Potential

Results were obtained in area "A" (Fig. 2.10) – 6.51 TWh per year [16] (Table 2.4).

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 cosθ 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.

Calculations were made at wave specific energy control points P1, P2, P3, P4, P5, P6 and P7 by months and years (Table 2.5). The results are grouped by mean T_e and H_{si} intervals (Tables 2.6 and 2.7). It is important how long and of how big energy waves occur during the year (Fig. 2.9).

Table 2.4

Detailed Calculations of 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**

Table 2.5

Fragment of the Wave Specific Energy Table From Control Point P1 on May 2010

Date	**h**	**min**	***mwd***	***swh***	T_z	***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

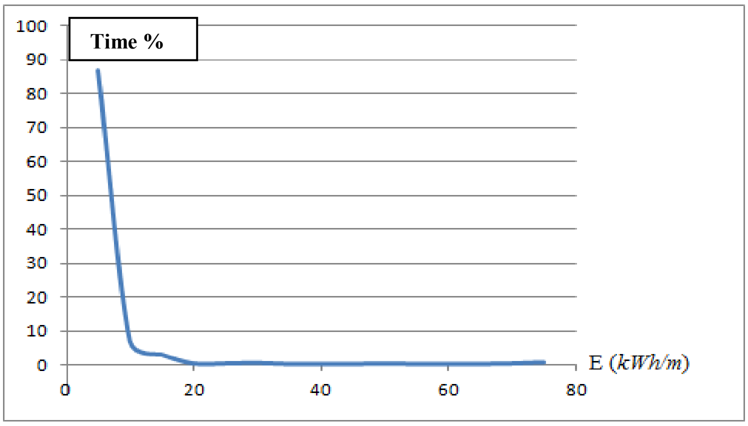


Fig. 2.9. Distribution of specific energy of waves during Dec. 2010, contr. point P5 (kWh/m).

Table 2.6

Wave Specific Energy Depending on H_{si} and T_e at Control Point P1 in May 2010

	1 m wide wave energy at control point P1 May 2010, kWh/m											**Total**
	T_e average per hour											**kWh/m**
H_{si}	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	
0.2	0.14	0.31	0.77	–	–	–	–	–	–	–	–	**1.21**
0.3	1.35	5.32	4.61	1.93	–	–	–	–	–	–	–	**13.21**
0.4	2.59	12.39	4.58	3.38	1.77	–	–	–	–	–	–	**24.71**
0.5	0.28	7.98	4.14	7.20	6.01	–	1.79	1.13	–	–	–	**28.54**
0.6	–	5.58	4.14	5.15	6.97	1.39	–	–	–	–	–	**23.25**
0.7	–	1.83	14.74	9.69	5.10	1.03	–	–	–	–	–	**32.39**
0.8	–	–	11.04	18.16	11.59	24.06	1.55	1.60	1.75	–	–	**69.75**
0.9	–	–	10.82	22.69	15.70	25.67	–	4.33	3.95	–	–	**83.17**
1.0	–	–	–	11.71	18.89	20.76	8.75	–	–	–	–	**60.10**
1.1	–	–	–	13.79	21.90	24.26	8.33	–	–	–	–	**68.29**
1.2	–	–	–	–	12.87	15.01	19.62	–	–	–	–	**47.51**
1.3	–	–	–	–	6.45	21.00	23.63	–	–	–	–	**51.08**
1.4	–	–	–	–	–	16.25	14.28	4.95	–	–	–	**35.48**
1.5	–	–	–	–	–	13.92	37.25	22.75	–	–	–	**73.92**
1.6	–	–	–	–	–	–	12.10	6.51	14.19	7.94	–	**40.73**
1.7	–	–	–	–	–	–	–	14.43	–	8.87	–	**23.30**
1.8	–	–	–	–	–	–	–	8.25	–	–	20.66	**28.91**
1.9	–	–	–	–	–	–	–	9.58	10.36	23.17	–	**43.10**
2.0	–	–	–	–	–	–	–	–	11.23	11.85	–	**23.08**
Total												**771.72**

Table 2.7

Distribution of Specific Energy of Waves E_w Depending on H_{si} and T_e at Control Point P1 in May 2010 (%)

	Distribution of specific wave energy by H_{si} and T_e													**Total**
	T_e average per hour													**%**
H_{si}	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	
0.3	–	0.00	0.01	0.01	0.01	–	–	–	–	–	–	–	–	**0.03**
0.4	0,00	0.05	0.04	0.02	0.05	0.01	0.04	0.01	–	–	–	–	–	**0.22**
0.5	0,01	0.05	0.06	0.06	0.12	0.07	–	0.04	0.04	–	–	–	–	**0.45**
0.6	–	0.11	0.20	0.09	0.14	0.08	–	–	0.02	0.05	–	–	–	**0.70**
0.7	–	0.07	0.32	0.26	0.13	0.16	0.03	–	–	0.11	–	–	–	**1.09**
0.8	–	–	0.22	0.36	0.13	0.29	–	0.04	–	0.10	–	–	–	**1.15**
0.9	–	–	0.06	0.29	0.32	0.38	0.35	0.06	–	0.06	0.07	–	–	**1.59**
1.0	–	–	0.12	0.23	0.41	0.90	0.93	–	0.08	–	0.17	–	–	**2.84**
1.1	–	–	–	0.60	0.56	1.06	1.60	0.39	0.19	–	0.21	–	–	**4.59**
1.2	–	–	–	0.27	0.94	1.55	1.79	0.20	–	0.11	0.38	–	–	**5.23**
1.3	–	–	–	0.15	0.44	1.17	1.40	0.36	0.13	–	0.45	–	–	**4.11**
1.4	–	–	–	–	0.23	1.19	1.63	1.10	1.08	0.64	0.18	–	–	**6.05**
1.5	–	–	–	–	–	0.25	2.18	0.81	0.17	0.18	0.42	–	–	**4.01**
1.6	–	–	–	–	–	0.31	1.80	1.24	–	0.20	0.47	–	–	**4.03**
1.7	–	–	–	–	–	0.16	1.92	2.49	0.89	0.24	0.75	–	–	**6.45**
1.8	–	–	–	–	–	–	1.92	2.99	1.46	–	–	–	–	**6.36**
1.9	–	–	–	–	–	–	0.94	3.59	2.51	0.30	0.31	–	–	**7.65**
2.0	–	–	–	–	–	–	0.24	4.06	2.50	0.99	–	–	–	**7.79**
2.1	–	–	–	–	–	–	–	2.24	1.35	0.76	–	–	–	**4.35**
2.2	–	–	–	–	–	–	–	0.70	1.90	0.82	0.43	–	–	**3.85**
2.3	–	–	–	–	–	–	–	–	1.24	2.22	–	–	–	**3.45**
2.4	–	–	–	–	–	–	–	–	0.43	2.86	–	–	–	**3.28**
2.5	–	–	–	–	–	–	–	–	–	3.17	–	0.61	–	**3.78**
2.6	–	–	–	–	–	–	–	–	0,53	0.55	1.23	–	–	**2.31**
2.7	–	–	–	–	–	–	–	–	–	–	0.71	–	–	**0.71**
3.0	–	–	–	–	–	–	–	–	–	–	–	0.86	–	**0.86**
3.1	–	–	–	–	–	–	–	–	–	–	–	0.92	–	**0.92**
3.2	–	–	–	–	–	–	–	–	–	–	–	1.03	–	**1.03**
3.3	–	–	–	–	–	–	–	–	–	–	–	–	1.08	**1.08**
3.4	–	–	–	–	–	–	–	–	–	–	–	1.16	3.59	**4.75**
3.5	–	–	–	–	–	–	–	–	–	–	–	–	2.57	**2.57**
3.6	–	–	–	–	–	–	–	–	–	–	–	–	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**

The specific wave power at hourly intervals at control points P1, P2, P3, P4, P5, P6 and P7 W/m was calculated (Table 2.8). The results are grouped by H_{si} intervals (Table 2.9).

Table 2.8

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

Date	h	min	*mwd*	*swh*	T_z	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

Table 2.9

Results of Specific Power Calculations Depending on H_{si} at Control Point P1 in February 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 control point P1 for 2011 were calculated (Table 2.10), (Fig. 2.10). The energy breakdown by month is shown in Fig.1.12. Distribution of energy potential by month will be important for energy conversion (Fig. 1.15).

Table 2.10

Distribution of Average Wavelengths by Length at Control Point P1 (Depth 24 m) in 2011

Wave type	**λ intervals**	**Number of waves *n***
Deep water waves	10	11 756
	20	25 339
	30	56 848
	40	69 666
Medium water waves	50	52 639
	60	57 537
	70	58 439
	80	39 799
	90	24 944
	100	23 056
	110	16 235
	120	11 827
	130	8907
	140	2732
	150	3356
Deep water waves		**163 609**
Medium water waves		**299 471**

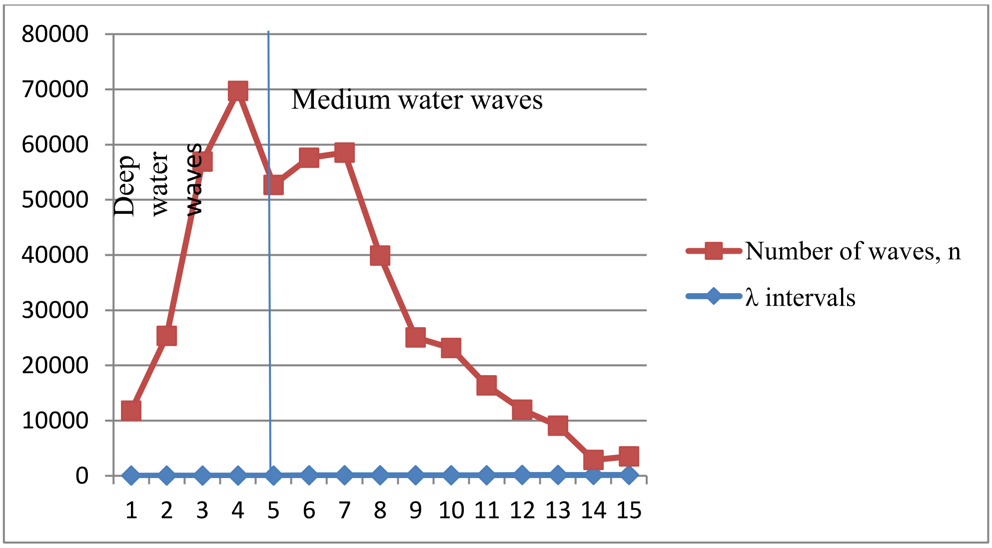
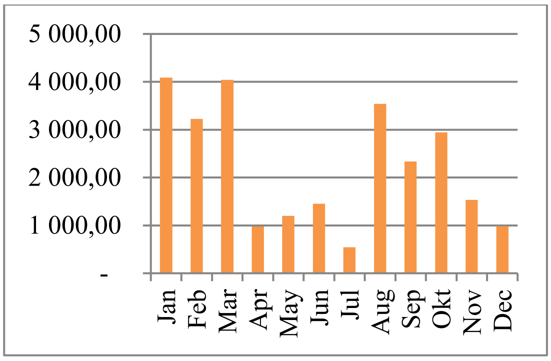


Fig. 2.10. Distribution of mean wavelengths by length at control point P1 (depth 24 m) in 2011.

The energy breakdown by month is shown in Figure 2.11. Distribution of energy potential by month will be important for energy conversion (Fig. 2.14).



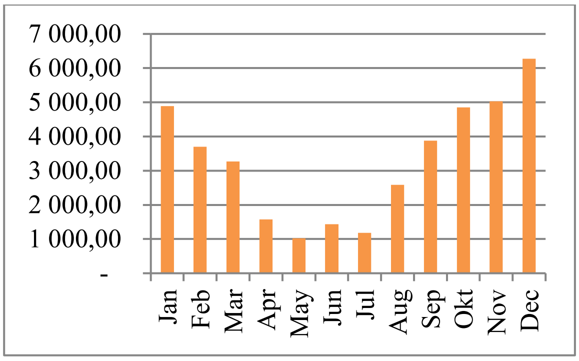


Fig. 2.11. Monthly distribution of specific energy (kWh/m) of control points P5 and P7 [17].

Energy potential in the Latvian EEZ of the Baltic Sea was calculated and grouped by *mwd* groups (Direction ±22.5°) based on control point P5 data (Table 2.11, Fig. 2.12).

Table 2.11

Energy Calculation Based on the Data at Control Points P5, P6 and P7 (Z_0 method [10])

	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Total, kWh/m**
P5	903.28	1088.58	263.98	242.51	575.79	13 872.39	7527.08	7064.72	31 538.34
P6	404.53	185.04	224.14	293.47	3361.94	4006.71	3655.91	1808.86	13 940.58
P7	3392.68	336.40	218.43	459.77	3157.73	10 209.42	16 707.20	5210.83	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**

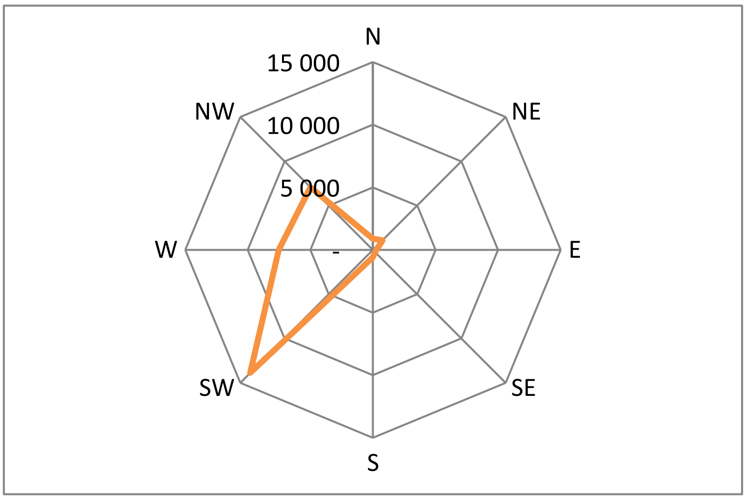


Fig. 2.12. Average specific energy potential at control point P5 (Depth 21m), (2010–2014), (kWh/m).

The graphic image of distribution of specific energies per year (average from 2010 to 2014) at control points P5, P6 and P7 by directions in the Latvian EEZ of the Baltic Sea is shown in Figure 2.13 [17].

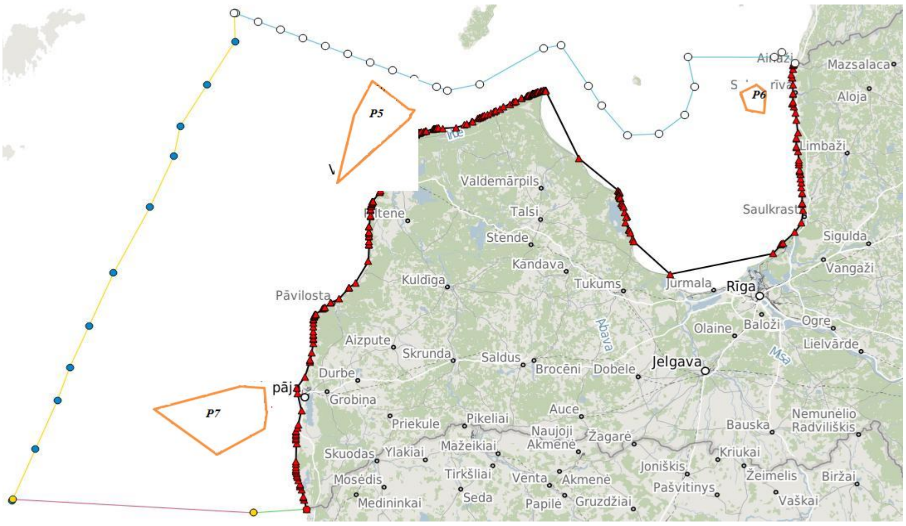


Fig. 2.13. Distribution of specific energies per year (average from 2010 to 2014) at control points P5, P6 and P7 by directions in the Latvian EEZ of the Baltic Sea (kWh/m) [17].

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

Control points P1, P2, P3, P4, P5, and P7 were calculated, monthly data on specific potential were aggregated, and by interpolation of these results estimation of specific energy potential at points P1–P19 was done (Fig. 2.14).

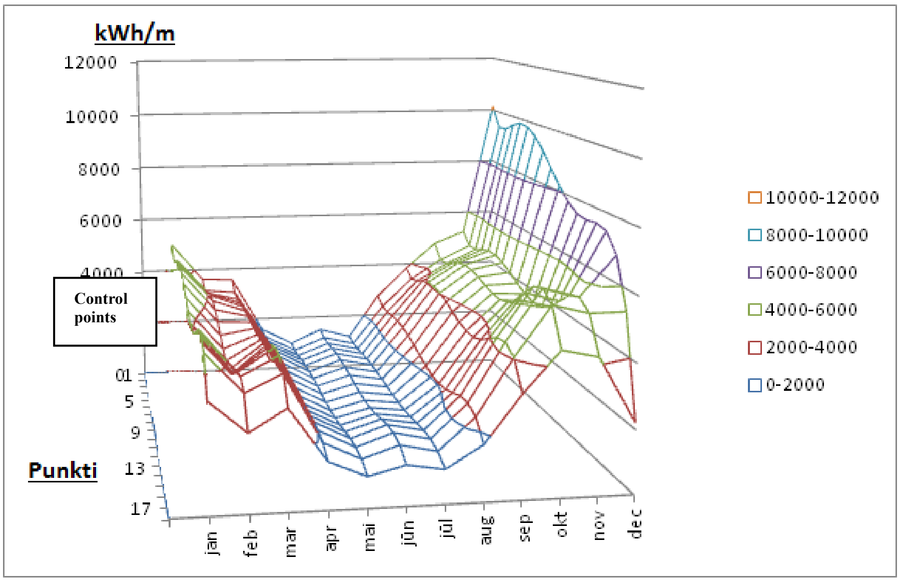


Fig. 2.14. Monthly average (2010–2014) specific energy potential averaged over months at points P1– P19 (kWh/m) [16].

3. CHOICE OF ENERGY CONVERSION EQUIPMENT

3.1. Equipment Review

The World's first wave power plant was Akuacadura (Portugal). It used three Pelamis wave energy converters with a total installed power of 2.25 MW. The power plant started producing electricity in July 2008 [23]. The wave power device Islay LIMPET was installed and connected to the national network in 2000 and is the world's first commercial wave-powered installation. Scotland established a 3 MW wave power plant in Scotland on 20 February 2007 [24].

Bombora Wave Power [25] is located in Perth (Western Australia) and is currently developing a flexible membrane converter – mWave [26]. The CETO wave power plant on the western coast of Australia operates to demonstrate commercial viability and has been further developed following an environmental impact assessment [27], [28]. Two fully submerged buoys attached to the seabed transform ocean energy into hydraulic pressure on land. It drives the electric generator as well as produces fresh water [29], [30]. Ocean Power Technologies (OPT Australasia Pty Ltd.) is a 19 MW wave power plant connected to the network near Victoria (Portland) [31]. By the end of 2013, Oceanlinx planned to establish a commercial scale demonstration device for Port MacDonnell (off the coast of South Australia). This device, called GreenWAVE, has an electrical capacity of 1MW [32]. Reedsport, Oregon is a commercial wave power station on the US West Coast, near Reedsport (Oregon). The first phase of this project was designed for ten PB150 PowerBuoys or 1.5 MW [33], [34]. The Azura wave power unit is a 45-ton wave power converter located 30 meters deep in the Kaneohe Bay [35]. Eugen Rusu provides information on wave states and the efficiency of wave transformation in three different types of coastal environment: coastal ocean, island environment and marine environment. The review evaluates several types of converters that cover a wide range of existing offshore installations [36]. The author believes that the future belongs to converters with variable capacity. Authors V. Jayashankar, K. Mala, S. Kedarnath, J. Jayaraj, U. Omezhilan, and V. Krishna [37] highly appreciate the prospects of oscillating columns for commercial production of electricity. Equipment with an average energy of 24 kW/m and the ability to produce 100 GWh in two years is described. Simulations show that turbine efficiency can exceed 60 % (10–100 %) of rated power. It has been shown that a wavelength of about 660 m with 11 turbine generators is sufficient to meet the design requirements and an average wave efficiency of about 36 %. Of course, 60 % has a high efficiency factor, but the machine is massive and therefore thought to be expensive (Fig. 3.1).

Fig. 3.1. Indian wave power converter (OWC) [37].

Obviously, efficiency is calculated not from the power of the wave, but from the average air flow capacity.

3.2. Equipment Classification

There are around 240 different projects in the world. The equipment differs according to the operating principles by which it can be classified. The *ITTC* article [38] provides an evaluation of wave transformers depending on whether the structure is fixed or floating.

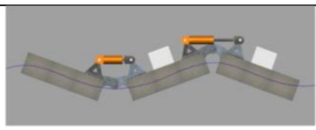
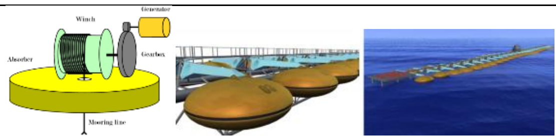
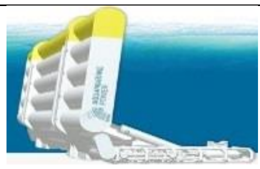
In the *IRENA* article [39], the basic principle of the classification of equipment is also depending on whether the structure is fixed or floating and then further expanded according to the location of the site.

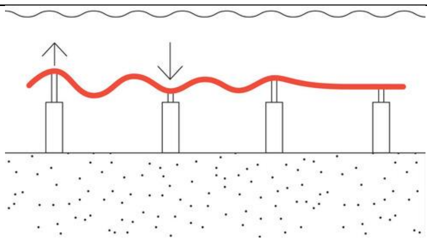
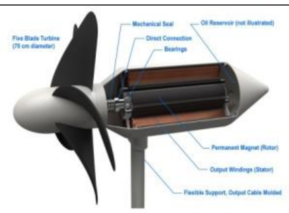
We offer to classify the equipment according to the principle of operation and compare how they respond to our criteria and options of location in particular zone (shallow-water, medium-depth and deep-water zones) (Table 3.1).

We offer to evaluate wave transformation equipment by operating principle and placement area – shallow (Sh), medium (M) and deep (D) water areas (Table 3.1).

Table 3.1

Classification of Wave Conversion Equipment

	Type	Illustration	Sh	M	D
1	Surface damper [40]			×	×
2	Float type absorber [41]–[43]		×	×	×
3	Fluctuating wave stream converter [44]		×		

4	Air pressure camera [45]		×	×	×
6	Overflow converter [50]		×	×	×
7	Underwater pressure difference receiver [46], [47]		×	×	
8	Air bubble engine [48]			×	×
9	Rotating mass [49]			×	×
10	Flow turbine with horizontal axis [50]		×	×	
11	Flow turbine with vertical axis [51]		×	×	×

3.3. Converter Model

3.3.1. Analysis of the Examined Equipment

According to the review of the equipment, we can conclude that all the equipment can work in the middle depth zone. The following criteria for the operation of prospective equipment can be set as additional criteria:

1) the ability to change the depth of immersion and/or the simplicity of this option;
2) positioning of the machine against *mwd* and/or the ease of positioning.

Let us evaluate the equipment according to these two criteria (Table 3.2).

Based on data in Table 3.1, position 7 (Underwater Pressure Differential Converters) and 11 (Flow Turbine with Vertical Axis) isworth considering. To select the more promising of these two types of equipment, we will set additional criteria:

1) the ability to lock the receiver to the required depth;
2) the ability to convert wave energy into rotational motion.

Let us compare the two types of equipment chosen on the basis of these criteria (Table 2.2).

Table 3.2

Evaluation of Wave Conversion Devices by their Possibility of Fixing the Receiver to a Specific Depth and Possibilities to Convert Wave Force to Rotational Movement

No	Type of the transformer	Option to fix	Option to get rotation
7	Underwater differential	Complicated	Complicated
11	Turbine with vertical axis	Easier to deal with	Simple

The selected machine is thus a turbine with a vertical axis.

3.3.2. Justification of the Chosen Equipment

The justification of the chosen equipment is based on an analysis of its performance.

Despite the fact that the turbine diameter is also limited by the vector velocity of its rim, this type of turbine does not need a positioning mechanism with respect to *mwd*. This means that in the illustrated block diagram of Figure 3.2, position 2 in the particular mechanism is already incorporated in the mechanism itself. These types of turbines can be combined with offshore wind parks, for which a patent application has been prepared in the context of the promotion work.

For any newly developed device, it is necessary to estimate the most important parameters that determine the advantage of this equipment before performing the *TRL* 9 stage. Let us define the following parameters:

1) expected capital expenditures (*CAPEX*);
2) expected operating expenses (*OPEX*);
3) efficiency curve of the device.

CAPEX has to be divided into two components, as part of this item can be credit interest, the rates of which depend only on the financial market, but not on the technical solution. Of course – the total amount of credit interest depends on the amount of the loan in the investment. Therefore, the second part of *CAPEX* – investment is important. Perhaps the most successful investment appraisal is the depreciation of the plant, as it depends on the initial investment and the depreciation period.

OPEX depends on the cost of maintenance (*TA*) and repair (*R*).

The machine utilization rate curve will depend on how efficiently it transforms the forces in the waves at the specific wave potential conditions.

Taking into account the parameters defined above, the model chosen by the equipment mentioned in the survey is a turbine with a vertical rotary axis and self-adjusting blades (SAB) (Fig. 3.2).

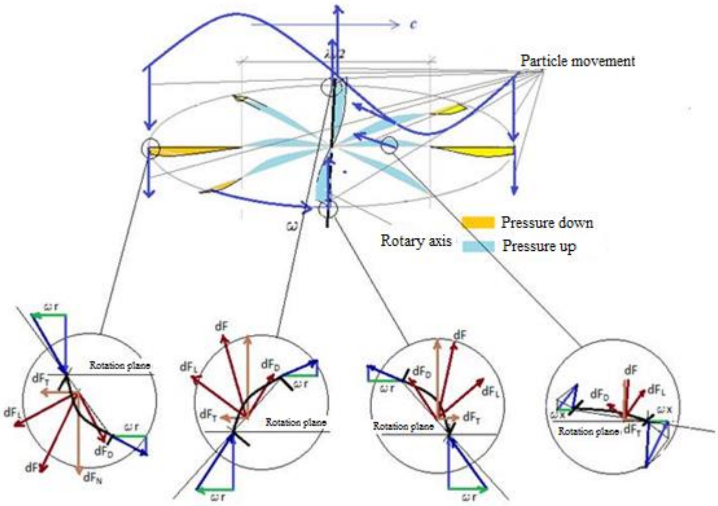


Fig. 3.2. Turbine with vertical rotary axis and SAB.

4. LABORATORY AND TESTING OF WAVE CONVERSION MODEL

4.1. Description of the Laboratory

In order to be able to make waveform conversion models, a laboratory was established, which included 1.25 m deep, 1 m wide and 10 m long pool. The pool was equipped with wave generators, wave conversion model installation equipment, wave parameter measurement and data archiving equipment with two computer programs and a wave suppressor (Fig. 4.1) [52].

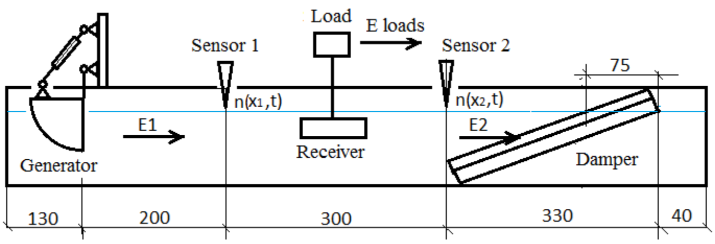


Fig. 4.1. Principal scheme of laboratory components [52].

In addition, the wave pool is equipped with water supply, drainage and side monitoring equipment and some handheld gauges and a photo/video camera.

4.1.1. Wave Generator

For generating the waves, we created a generator, by means of which wave parameters *T* and *H* can be adjusted (Fig. 4.2).

Fig. 4.2. Wave generator.

The operating modes of the distributor are set with the processor (Fig. 4.3), thus setting the frequency and distance of the pendulum stroke.

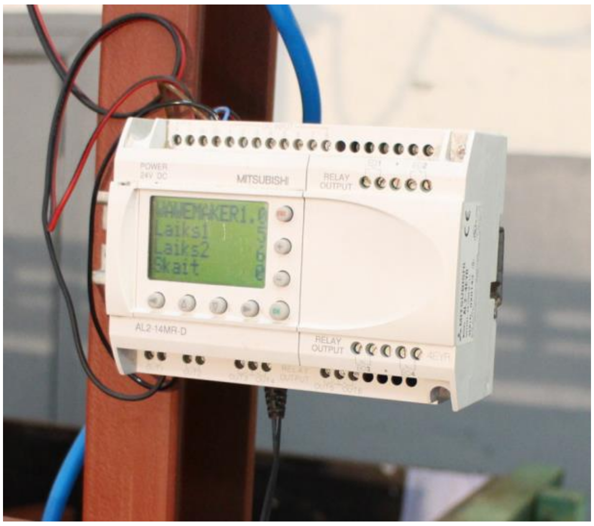


Fig. 4.3. Processor.

4.1.2. Wave Parameter Measurement and Data Archiving Equipment

Wave parameter measurement and archiving equipment consists of:

1) two foam floats that copy water surface fluctuations (Fig. 4.4);
2) two laser sensors that detect float oscillations and transmit signals to the processor (Fig. 4.5);
3) data analyser for receiving and processing signals and archived data (Fig. 4.6);
4) two computer programs for receiving, processing and archiving data installed in the data capture/processing processor.

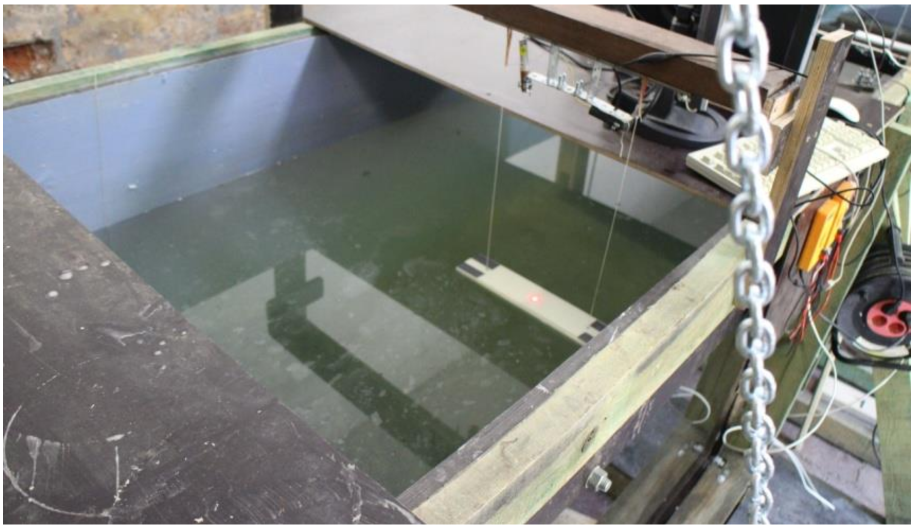


Fig. 4.4. Float.

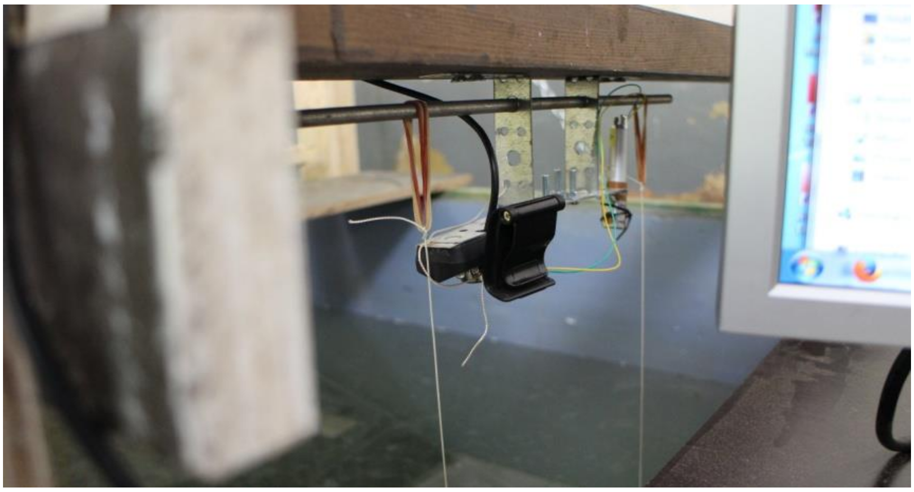


Fig. 4.5. Laser sensor.

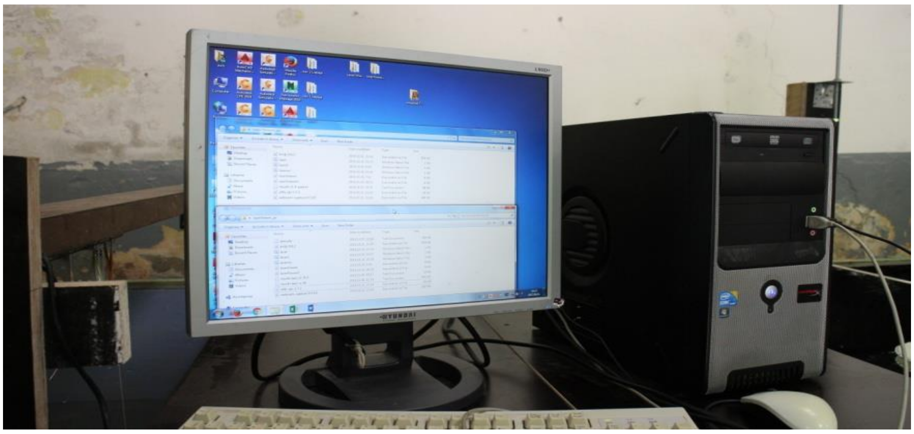


Fig. 4.6. Data analyser.

4.1.3. Computer Programs

4.1.3.1. Laser Beam Coordinate Image Processing Program

A WEB-camera image processing algorithm was created and a program for determining the coordinates of the measurement laser beam in angular units to record them and register in the absolute time of the computer was created. *Jawa script* programming language was used. The text of the program is a formal record of the data processing algorithm. The structure and language of the program is shown in Figure 4.7.

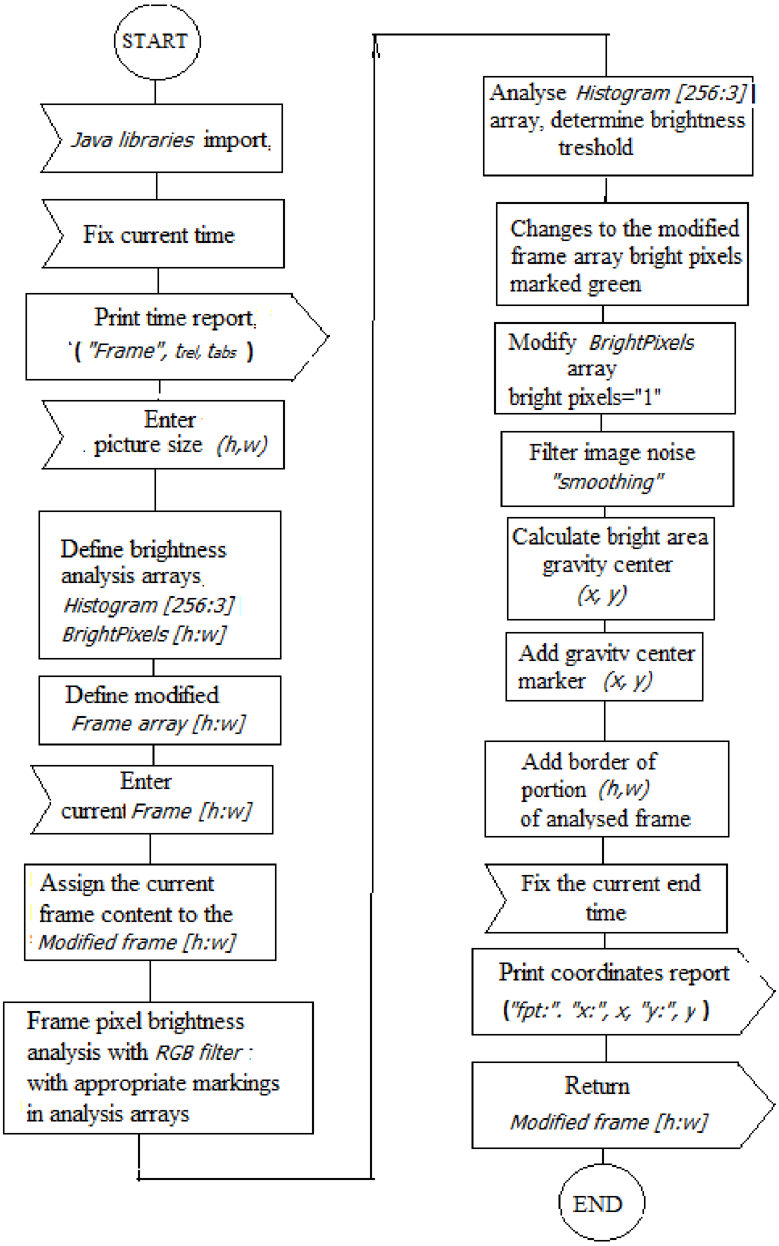


Fig. 4.7. Description of the structure diagram and language of the laser beam coordinate image processing program.

4.1.3.2. WEB-camera Image Data Capture Program

WEB-camera image data capture program was created, the text of which describes its algorithm. The description of the structure diagram and language is shown in Figure 4.8. With the program the compilers helped to convert the text of the program into a working program code or program that collected and processed the measurement data for obtaining intermediate results.

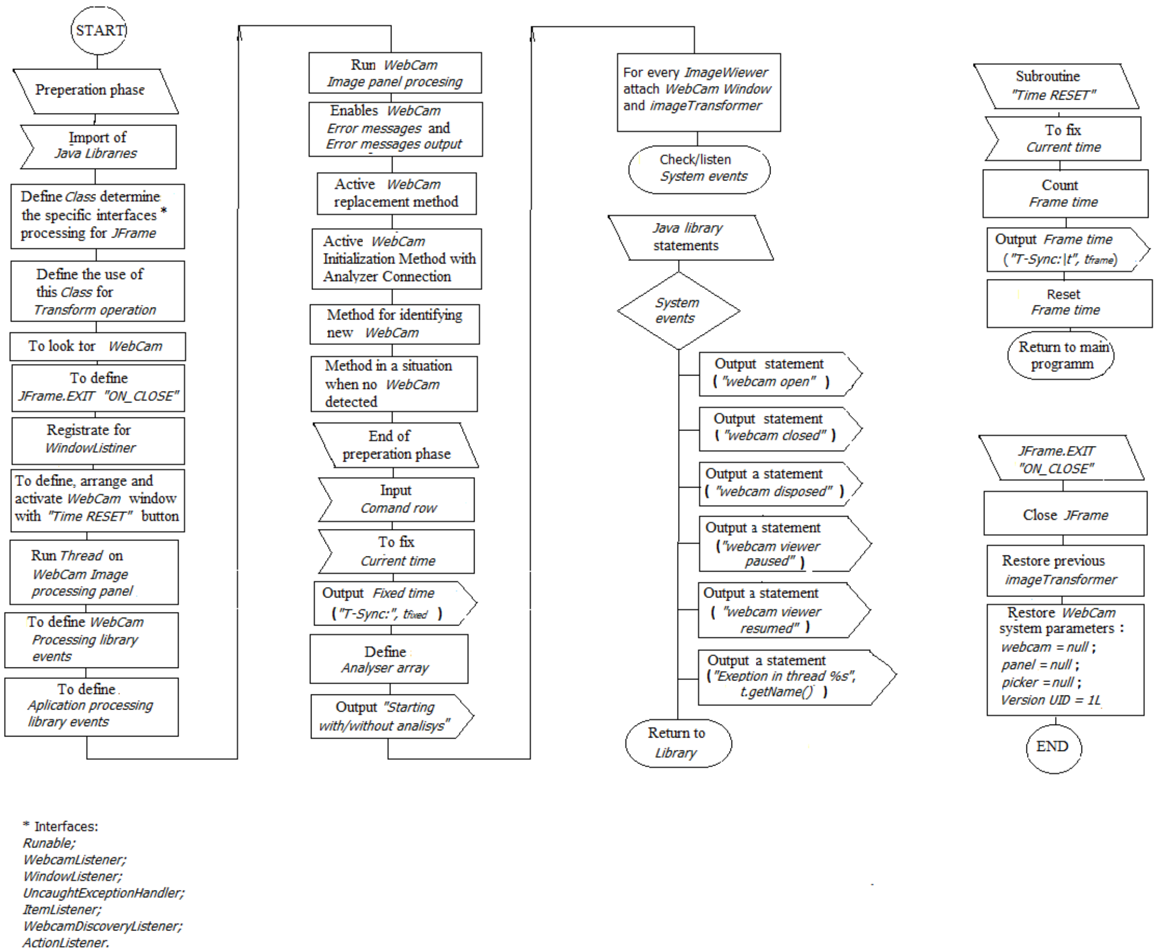


Fig. 4.8. Description of the structure and language of the WEB-camera image data capture program.

4.1.4. Wave Damper

The wave damper was made of a frame with a sieve, which can be adjusted with a hand winch. On a sieve with a thickness of about 10 cm, 2–4 cm fractions of dolomite were deposited (Fig. 4.9).

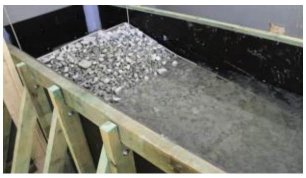


Fig. 4.9. Wave damper.

4.2. Implementation of the Pilot Project

4.2.1. Model Solution of the Pilot Project

An image of an axial self-regulating blade hydro-kinetic turbine (*APRLHK* turbine) was developed (Fig. 4.10).

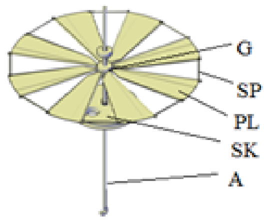


Fig. 4.10. APRLHK turbine construction: G – bearing; SP – tensioning rubber; SAB – self-adjusting blade; SK – pulley; A – axis.

The vertical rigid axle A (Fig. 4.10) was fitted with bearings and interconnected by a pulley SK *APRLHK* for mechanical loading of turbines and a turbine wheel with SAB acting on the wave force.

4.2.2. Choice of the Pilot Project Implementation Method

An experimental method was chosen for the pilot project. Laboratory experiments with a model turbine were used to research the turbine in action and clarify its parameters.

So far, hydro-kinetic turbines were known to operate in variable direction streams with SAB, which used a ring to form the outer diameter of the turbine to provide the movements needed to support one hinge group. These types of turbines had a disadvantage – the support ring was a significant additional resistance and also increased the turbine mass.

The *APRLHK* turbine with sail type SAB was developed in the pilot project. It does not need a ring.

Wave converter models and a laboratory where waves with variable parameters can be created were created to perform the experiment.

4.2.3. Tests

The work describes how the test procedure was followed, what tools were used, how the measurement, calibration, measurement processing, results analysis, and the wave parameter measurement works were performed. The recorded data was recorded and archived. Observations were described. Wave process analysis scheme (Fig. 4.11) was developed and used [52].

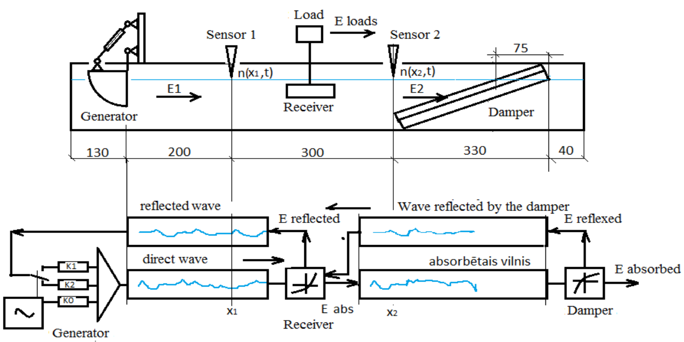


Fig. 4.11. Wave process analysis scheme [52].

Window interpolation was used for measurement processing. The interpolation window is shifted by one step ($i + 1$) and the calculations of the polynomial coefficients are repeated until the entire interpolation segment is processed (Fig. 4.12).

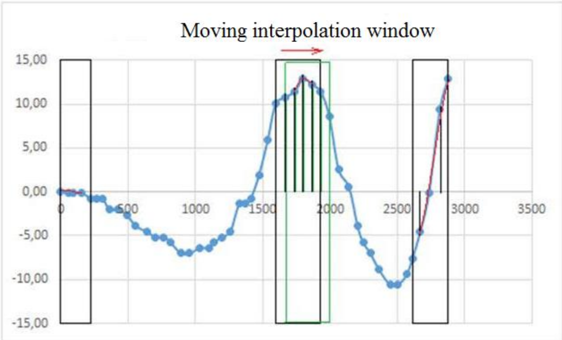


Fig. 4.12. Interpolation window in interpolation segment.

4.2.4. Modelling Results

Various results were obtained from the *APRLHK* turbine testing with different types of SAB (Table 4.1; Fig. 4.13).

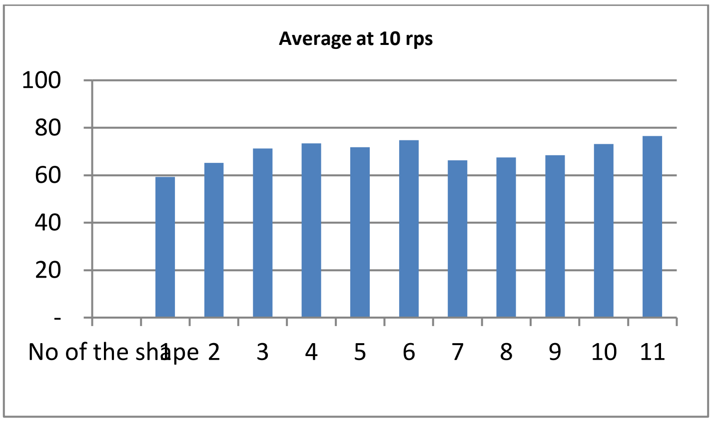


Fig. 4.13. Test results of the *APRLHK* turbines in which they perform 10 revolutions

On the basis of the entrance data, the most successful *APRLHK* turbine power at various revolutions was calculated (Fig. 4.14).

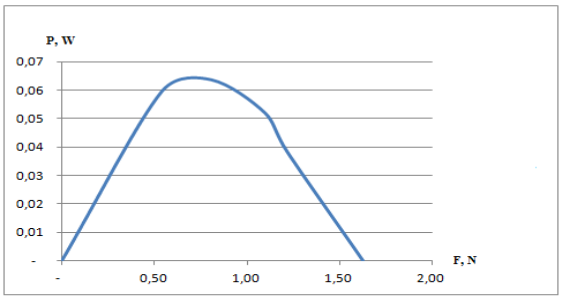


Fig. 4.14. Calculation results of turbine power P(W) at different loads.

Wave parameters were measured with sensors A and B and the wavelengths and absorbed capacities were calculated from these parameters (Table 4.1). Calculations of power of turbines with blade profile No. B-1 and turbine utilization factor were performed (Table 4.1).

Table 4.1

Power and Utilization Factor Calculations of Turbines With Blade Profile No. B-1

***w*, rps**	***F*, N**	***r*, m**	***v*, m/s**	***P*, W**	**$P_{(AK)}$, W**	**η_T, %**
–	1.63	0.15	–	–	0.736	–
0.03	1.22	0.15	0.03	0.04	0.736	5.43
0.05	1.10	0.15	0.05	0.05	0.736	6.79
0.08	0.81	0.15	0.08	0.06	0.736	8.15
0.12	0.54	0.15	0.11	0.06	0.736	8.15
0.17	–	0.15	0.16	–	0.736	–

Symbols in Table 4.1:

w – turbine speed (rps);
F – turbine braking load force (N);
r – braking load application shoulder (m);
v – vector velocity (m/s);
P – braking power (W);
$P_{(AK)}$ – corrected wave power before loaded turbine (W);
η_T – turbine utilization rate (%).

Now we can create turbines with blade profile No. B-1 turbine utilization factor η_T depending on rpm. (Fig. 4.15).

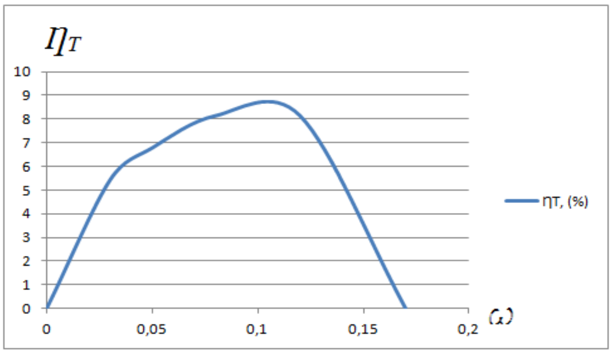


Fig. 4.15. The characteristic curve of the turbine utilization factor η_T, depending on rpm.

5. WAVE STATION OPTIMIZATION

Developing the *JVS*, there is a need for technology that can easily identify the economic consistency of power plant construction with existing impact factors – wave power potential, *JVS* performance, electricity prices, connection to distribution networks (*ST*), efficiency of *JVS* equipment, different costs, grants and legal aspects, etc. Due to the fact that *JVS* influence factors are sufficient, in addition, they are in many cases variable, and then they need to be optimized with the aim of forecasting profits (Fig. 5.1).

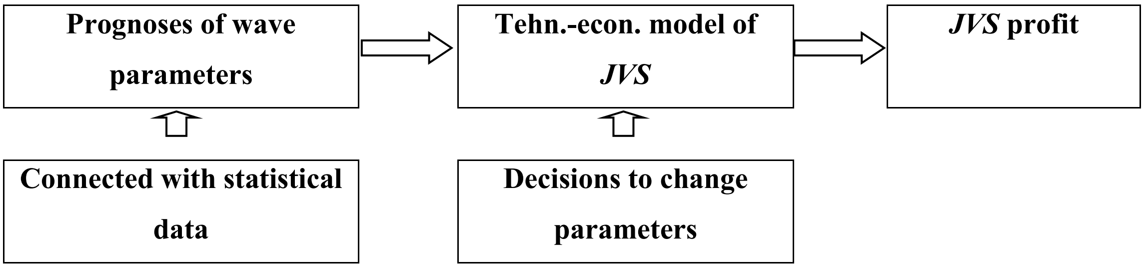


Fig. 5.1. Principal scheme of *JVS* optimization.

The *JVS* optimization tool could be a specially designed computer program, the use of which would become useful after obtaining *JVS* design research data. Prior to design, data relating to the use of this computer program would include at least the identification of impact factors and the *JVS* sketch design. Let us classify this computer program as a *JVS* optimization computer program (*OD*) and define its purpose: "The best parameters of the target function – the highest production".

5.1. Optimal Position of *JVS*

In order to optimize the *JVS*, feasibility studies have to be carried out in order to choose a construction site, to calculate the wave energy potential, to choose the type and capacity of the technology, the connection scheme for the electricity grid, as well as to assess the necessary capital expenditures and the amount of energy produced, the revenue from its sale, and production costs. Power plant planning is done in the context of profit maximization. Several economic criteria are used to do this, such as net present value (NPV), internal rate of return (IRR), payback time, average cost of energy in LCOE [53], [54]. With multiple or many variables, the number of variants can be very large, making it more difficult to choose the right solution. In practice, the impact factors of the project are complemented, at least, by a diagram of energy directions, the results of negotiations with investors, equipment suppliers and builders. Some of the parameters not initially covered become known and there is a need to review the feasibility study.

In this chapter, only NPV and LCOE are used, with the algorithms described in the work.

Optimization tasks are stochastic functions:

$E\ (NPV\ (Tdarb.))\ D_{\max}$;

$E\ (LCOE\ (Tdarb.))\ D_{\min}$.

The essence of stochastic tasks is complex because it requires the use of statistical data on input processes (including but not limited to correlations). Let us note that long-term forecasts need to be created, which cause difficulties. They (long-term forecasts) must be made/compiled according to appropriate planning or proper evaluation of any project.

When evaluating the economic efficiency of a power plant, a scenario approach is used and random variables with average times are used [54]. There is a known method for assessing the effectiveness of *JVS*, based on the annual breakdown of seasons (winter, spring, autumn and summer) and the selection of typical days (work or holiday) for each season. In this case, the daily averages are used and the revenue is calculated for each season based on the number of days. Another method is based on the annual breakdown by month and the corresponding average value [53], [54] for calculating cash flow. The disadvantage of these methodologies is that it is impossible to consider the actual production of *JVS* electricity and the real price changes in market conditions that occur every hour.

5.2. Technical and Economical Assessment of *JVS* in the Latvian EEZ in the Baltic Sea

Considering the data of the Latvian EEZ wave potential calculation [16] in the Baltic Sea as described in Chapter 1 of this work, we will look at it from a 200 km long (consisting of several stages with different input parameters) *JVS* perspective. Let us take the standard calculation method Nett Present Value (NPV) as the basis for calculations and use Expression (4.1) to calculate the input potential of the electricity generated in the calculations of the generated electricity, as they were historically in 2011, using the naive forecasting method.

JVS utilization factor includes the multiplication of several coefficients from the transformation of the wave power to energy connection *ST*.

In this calculation, we will consider/analyse only the process in which wave energy is transformed into electricity.

The coefficient η_T is used to determine this transformation characterized by equitation

$$\eta_T = \eta_V \eta_H \eta_P \eta_F \eta_L \eta_M \eta_E \, , \tag{5.1}$$

where η_V – coefficient of kinetic energy distribution in volume;

η_H – separation ratio of horizontal flow (0.5);

η_P – flow utilization factor for estimating the flow of the flow through the turbine (Beitz/Glauerts 0.5926);

η_F – form factor ($\pi/4$);

η_L – turbine hydraulic efficiency;

η_M – mechanical efficiency (bearing, seal 0.95);

η_E – efficiency ratio of the electric generator.

Morozov's equation [55] describes the relationship of model T1 of the known *APRLHK* turbine and geometrically similar turbines T2 with diameter D_2 as in subsection 3.2.1. (Table 3.1)

$$\eta_{L2} = \left(1 - (1 - \eta_{L1})\sqrt[5]{\frac{D_1}{D_2}}\right),\tag{5.2}$$

where η_{L2} – efficiency coefficient of a geometrically similar turbine;

η_{L1} – efficiency ratio of known turbine;

D_1 – diameter of the known turbine (0.9 m);

D_2 – diameter of the geometrically similar turbine.

Assuming that η_{T1} and η_{T2} expressions are based on Equation (5.1), and dividing both parts of these equations with each other, we will express them as Equation (5.3):

$$\frac{\eta_{T1}}{\eta_{T2}} = \frac{\eta_{L1}}{\eta_{L2}}.\tag{5.3}$$

From (4.3) we will express η_{L1} of the known turbines:

$$\eta_{L1} = \frac{\eta_{T1}}{\eta_V\eta_H\eta_P\eta_F\eta_L\eta_M\eta_E},\tag{5.4}$$

where all the values on the right of the equation are known. Thus, knowing η_{L2}, η_{L1} and η_{T1} from Expression (4.1), the coefficient of utilization of the geometrically similar turbine η_{T2} is calculated.

On the basis of the data of the Latvian EEZ in the Baltic Sea wave potential data described in Chapter 1 of the work at control points P1, P2, P3, P4, P5 and P7 at the turbine with $D = 9$ m and $\eta_{T2} = 0.25$, we will make economic calculations.

In order to find out the greatest energy probability we will multiply the corresponding wave power with the time that these waves exist and rank in increasing order of energy value. Approximately 70 % of wave power is in the range up to 39 kW/m (Table 5.1).

Technically, the *JVS* turbine power range is limited and the rest of the wave energy is within a wave power range that is far from 39 kW/m. In this interval, the *JVS* will continue to work in a submerged position. Let us choose the maximum power of the *JVS* turbine at *jvl-A, (*where *A* – amplitude) at a power of 39 kW/m. In this range, the dependence of the specific amount of wave energy E_v (kWh/m) on the specific wave power P_V (kW/m) is shown in Figure 5.2.

Technically, the *JVS* turbine power range is limited and the rest of the wave energy is within a wave power range that is far from 39 kW/m. In this interval, the *JVS* will continue to work in a submerged position. Let us choose the maximum power of the *JVS* turbine at *jvl* at a power of 39 kW/m. In this range, the dependence of the specific amount of wave energy E_v (kWh/m) on the specific wave power P_V (kW/m) is shown in Figure 5.2.

Table 5.1

Dependence of Incoming Wave Energy E_v on Wavelength Average Power P_v at Control Point P1

E_v (kWh/m)	Average power P_v (kW/m)	% of the total energy E_v
522	37	
585	**39**	
883	35	
914	33	
966	23	
1052	29	
1070	27	
1396	11	
1442	17	
1545	25	
1595	21	
1643	15	
1869	19	
3052	1	
3079	3	
31 508		**70.05**

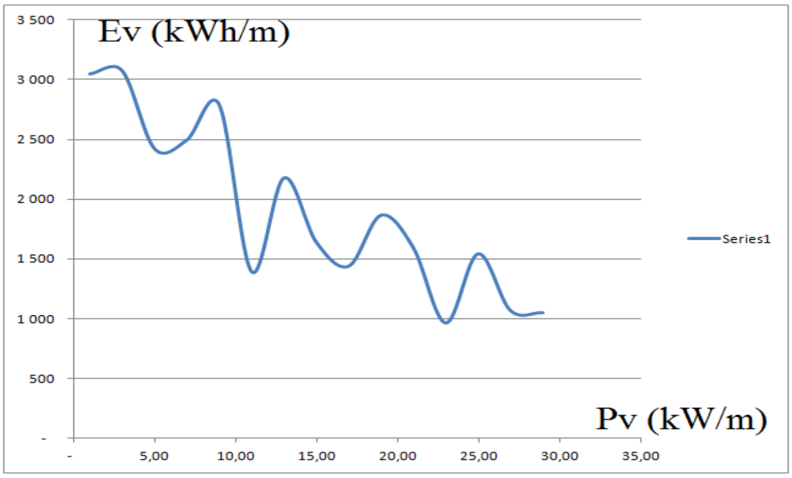


Fig. 5.2. Dependence of specific wave energy E_v (kWh/m) on specific average wave power P_v (kW/m).

The full spectrum of the control wave P1 annual specific energy E_v (kWh/m) is shown in Figure 5.3.

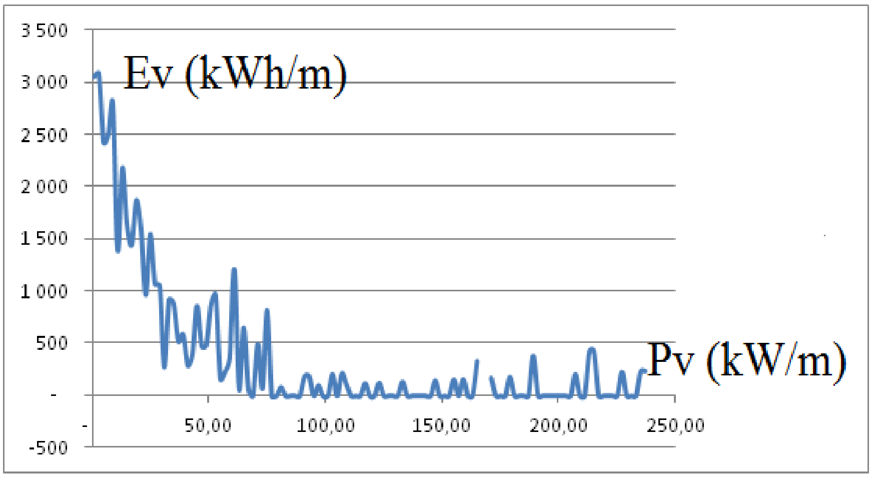


Fig. 5.3. Distribution of full wave specific energy E_v (kWh/m) at the control point P1 depending on wave specific power P_v (kW/m).

Based on the data of wave potential in the Latvian EEZ in the Baltic Sea (described in Chapter 1) at control points P1, P2, P3, P4, P5 and P7 at the turbine with D = 9 m and η_{T2} = 0.25, we will make economic calculations for possible *JVS*, which is characterized by distances depending on input data and existing navigation situation.

1. With P1 characteristics, the *JVS* is 19.4 km long.
2. With P7 characteristics, the *JVS* is 24.85 km long.
3. With P2 characteristics, the *JVS* is 55.60 km long.
4. With P3 characteristics, the *JVS* is 61.73 km long.
5. With P4 characteristics, the *JVS* is 25.18 km long.
6. With P5 characteristics, the *JVS* is 13.65 km long.

Specific investment forecasts are shown in Table 5.2. Estimates of electricity prices were used in the calculations, as shown in Table 5.3.

Table 5.2

Specific Investment Forecasts

Item	Investments, EUR
Price of turbine	7000.00
Installation costs	10 000.00
Infrastructures costs	9000.00
Infrastructure installation	12 000.00
Total for 1 turbine	38 000.00

Table 5.3

Episode of Electricity Wholesale Price Forecasts in EUR/kWh

Year									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0.0152	0.0060	0.0173	0.0268	0.0412	0.0225	0.0059	0.0338	0.0072	0.0170
0.0249	0.0212	0.0164	0.0167	0.0066	0.0203	0.0206	0.0101	0.0101	0.0336
0.0070	0.0086	0.0029	0.0137	0.0239	0.0232	0.0224	0.0209	0.0009	0.0092
0.0171	0.0109	0.0086	0.0027	0.0115	0.0172	0.0301	0.0214	0.0095	0.0213
0.0131	0.0026	0.0140	0.0151	0.0147	0.0364	0.0208	0.0016	0.0227	0.0247
0.0026	0.0138	0.0191	0.0220	0.0194	0.0206	0.0144	0.0024	0.0097	0.0349
0.0144	0.0312	0.0169	0.0377	0.0208	0.0214	0.0478	0.0267	0.0343	0.0478

The interest rate, discount rate and duration of the planning period are shown in Table 5.4.

Table 5.4

Interest Rate, Discount Rate and Duration of the Planning Period

Item	Value
Interest rate	2.60 %
Discount rate	2.00 %
Period	25 years

5.3. Results

Calculation results are shown in Table 5.5. Symbols used in Table 5.5:

P_{Vmax} – the maximum available power of the incoming waves in kW/m;

P_{Tmax} – maximum power of the turbine in kW;

E_{EL} – annual electricity production in TWh.

In the technical project, the maximum electrical power of turbine will be standardized and will therefore differ from the theoretically calculated one. The NPV forecast for *JVS* P1 is shown in Figure 5.4.

Table 5.5

Results of the Technical and Economical Calculation of *JVS* Modelled in the Latvian EEZ in the Baltic Sea

	P1	**P2**	**P3**	**P4**	**P5**	**P7**	**Total**
P_{Vmax}, kW/m	39	33	34	37	30	34	
P_{Tmax}, kW	88	75	76	84	67	77	
***JVS* length, km**	19.40	55.60	61.73	25.18	13.65	24.85	**200.41**
E_{EL}, TWh	0.19	0.52	0.55	0.26	0.11	0.23	**1.86**
Number of turbines	2155	6178	6859	2798	1517	2761	**22 268**
Investments, mil. EUR	81.89	234.76	260.64	106.32	57.65	104.92	**846.18**
LCOE with loan, EUR/kWh	0.100	0.099	0.102	0096	0.105	0.100	**0.100**
LCOE without loan, EUR/kWh	0.092	0.091	0.093	0.089	0.096	0.092	**0.092**

Symbols used in Table 5.5:

P_{Vmax} – the maximum available power of incoming waves in kW/m;

P_{Tmax} – maximum power of the turbine in kW;

E_{EL} – annual electricity production in TWh.

In the technical project, the maximum electrical power of the turbines will be standardized and will therefore differ from the theoretically calculated one. The NPV forecast for *JVS* P1 is shown in Figure 5.4.

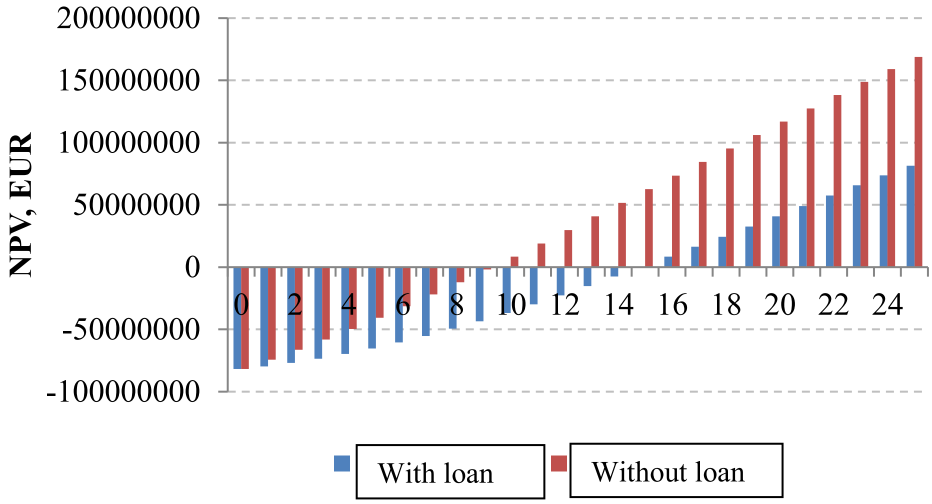


Fig. 5.4. NPV forecast for *JVS* stage P1.

Similar NPV projections were also calculated for the remaining *JVS* stages.

6. FUTURE WORK

The wave energy transformation research laboratory must be improved by making the pool 30 m long, 1.5 m deep, and 1.5 m wide. It would extend the wave damper to at least 7 m and improve the wave generator thus reducing the reflection from the wave damper and wave generator and "softening" the effect of the water ejected by the wave generator.

The *APRLHK* turbine must be manufactured with SABs that provide the direction of the jet flow perpendicular to the turbine axis. Torque differences between different turbines in the SAB should be minimized. The hydrodynamic properties of SAB should be improved and it should be studied in more detail how the wave E_k is captured in wave phases, how to smooth out the torques between the different blades of the turbine and the same blade, how to choose blade materials to balance their weight with strength. The dependence of *APRLHK* efficiency on its diameter, and wavelength should be experimentally confirmed.

A simulation environment for different models should be created.

It is necessary to develop a turbine immersion depth change mechanism for the continuation of safe operation of power plants above the designed wave parameter range.

Alternative methods of creating a receiver that moves parallel to the waves (z axis) should be considered.

A *JVS* optimization computer program should be purchased, if necessary completed, as a commercial pre-design/business plan tool that would take into account the following factors:

- sketch project estimates;
- possibility to enter 10-year data for the water area under review with the required number of checkpoints for the grid with standard (if necessary changeable) mesh size;
- identification of wave potential density to determine the optimal converter size and to calculate the generator's power;
- loss in networks from converter to connection;
- energy profiles to be accumulated/sold;
- the phenomenon of change of wave directions;
- expenditure (*R*, *TA*, insurance, administration, other expenses, unplanned expenses, etc.);
- conversion factor curves;
- the kinetic energy utilization rate depending on the position of the immersion level of the converter.

7. CONCLUSIONS AND PROPOSALS

The results of the Doctoral Thesis show the following.

1. In recent decades, the concentration of carbon dioxide in the atmosphere has increased to a level that has not been experienced during the past 800 000 years. This causes climate change in the form of natural anomalies and disasters. Replacing fossil energy sources with renewable energy could alleviate this problem.
2. At the same time, there are different attitudes to the available wave energy potentials in the world – some places already create an environment for this type of energy, whereas elsewhere, its potential is not rated as highly.
3. The use of the wave potential of each country is determined not only by its laws, the decision making is largely determined by the relevant governments and parliaments and their understanding of the potential of waves and their use.
4. Using different wave potential calculation methods, obtained results can vary by a factor of 10.
5. More precise methods should be used in the pre-design stage of *JVS*.
6. The most important characteristics of wave energy potential are *H, T*, wavelength λ, *mwd*, *h*, as well as tidal dynamics and wave power distribution over time.
7. When assessing the potential of the waves, it is important to realize how the aquatorium is divided into zones (deepwater, coastal and shallow water) and the energy density in these areas. Ignoring this distribution, significant differences in calculated wavelength results may occur. An important indicator in collecting wave potential is the distribution of energy over time.
8. Example of calculation in the Latvian EEZ in the Baltic Sea [16] shows the following.
   - 8.1. In the Gulf of Riga, the amount of wave energy per 1 m wavelength is about 3 times less than the corresponding indicator in the Latvian EEZ in the Baltic Sea region. It is considered that the main causes are differences in wavelength and ice conditions.
   - 8.2. At least 90 % of wave power in the Baltic Sea in the EEZ of Latvia comes from the Southwest-West and North-West directions.
   - 8.3. The complex distribution of energy directions indicates that the potential *JVS* placement will depend on the angle of action of their receivers.
   - 8.4. Calculating the wave energy potential of the Baltic Sea area "A" with the *VEVPP* method the result is 6.51 TWh per year. Applying a comparative assessment derived from the simplified calculation method Z_0, based on the principle of different checkpoint placement, it averages to 6.46 TWh per year (–0.77 %). The obtained results are close, which means that the wave power calculation is plausible. The wave energy projection method is more even compared to traditional methods and more accurately lists the different directions of energy in the area.
   - 8.5. *VEVPP* serves to determine more precisely the area of the receiver line or other *JVS* in the area and the subsequent estimation of potential perceptual energy.

9. For optimal placement of *JVS* equipment, input data on generating wave potential is required. These data are coordinates, depths, tidal registers, *H*, *swh* and *T*, linked to specific times.
10. For optimal design of the *JVS*, it is necessary to have data on how the wave potential changes in its interaction with the equipment. Such data can be obtained by modelling *JVS* with specific equipment.
11. Wave directions will always be an impact factor for any *JVS*.
12. Wave energy imbalance will lead to the need to sell and/or store the converted energy.
13. It is possible to combine wave energy with some of the types of energy available in the summer, such as solar energy.
14. There is interest in wave technology in the world. At the moment, there is no recognised technology that gives all the benefits. There is no method for choosing technical equipment.
15. A turbine with a vertical axis and self-adjusting blades could be a perspective wave energy conversion device.
16. Differences in the wavelength characteristics of different waters and of the same aquatorium, as well as changes in energy prices, call for consideration to be given to the development of conversion facilities that could easily expand or reduce the *JVS*.
17. It is worth classifying wavelength conversion devices according to their applicability in shallow water, medium depth and deep water.
18. It is possible to create a wave energy receiver that, without a special component or node, performs certain functions of the *JVS* input block diagram, such as positioning the machine around the *z* axis (*APRLHK* turbine).
19. It is worth classifying wave converters depending on the ability to protect them from excessively powerful waves.
20. The wave laboratory should look for solutions to reduce reflection from the wave generator and both ends of the pool. This could be achieved by inserting at least 7 m of shredder at both ends of the pool and changing the design of the wave generator. Reducing the reflection would make it possible to get more accurate measurements.
21. Wave energy capture is complicated by its particle motion trajectories and wave characteristics – refraction, diffraction, reflection and overlap. It is also complicated by the uneven wave spectrum.
22. When using the wave energy transformation process in the *APRLHK* turbine, in order to increase its efficiency, it is necessary to ensure that the same turbines SAB operate simultaneously in wave phases with different direction flows. The accuracy of the turbine blade position to sense the wave power depends on the following factors (and more).
    22.1. Freedom of movement of the blade around its bearing axis.
    22.2. Flexibility of the blade itself.
    22.3. Length of the longest edge of the blade.
23. New technology solutions are required to minimize the simultaneous exposure of counter-current wave forces on the turbine blade.

24. Turbine works more efficiently if:
    24.1. Its axis does not move in a vertical dimension.
    24.2. The density of the material of the blade is equal to the bulk density of the turbines working environment.
    24.3. The blade's free edge does not form a bag shape, so that it does not form pockets that interfere with the flow of water.
25. In the process of wave energy transformation, the *APRLHK* turbine, in order to increase its efficiency, must ensure that the same turbine SABs operate simultaneously in wave phases with different directional flows.
26. When designing the *JVS* work equipment, not only water density and temperature must be taken into account but also changes in these parameters.
27. *JVS* equipment must be sufficiently shielded from the corrosive effects of saltwater and a series of variable loads.
28. The *JVS* equipment generators will have a number of specific requirements.
29. The tried-and-tested *APRLHK* turbine model produces about 31 % power loss of wave. Part of this loss is due to wave refraction, some – due to the unnecessary torque difference between the individual turbine branches, and only part is useful energy conversion.
30. By approving the work-based calculations with the corresponding results of the *APRLHK* turbine *TRL* 9 tests and sketch project estimates, it may prove that the wave potential of the Latvian EEZ in the Baltic Sea is an important source of renewable energy in its volume of about 1.86 TWh per year. However, one has to take into account the energy imbalances of waves, which means that this energy will also have to be sold or accumulated.
31. Optimization of the *JVS* requires the use of a special *OD* that can be used to process the factors specific to these plants.
32. Before the use of *OD*, the following pre-design work must be carried out on *JVS*:
    32.1. Input data for the wave potential of the selected aquatorium should be obtained;
    32.2. An *OD* complementary aquatorium map with permitted Marine Space Plan (MSP) version and depth records should be obtained;
    32.3. Records of energy use ratios must be obtained for the entire electricity chain, starting with the generated electricity and ending with the electricity sold at the accounting point;
    32.4. A *JVS* sketch project based business plan with all expected costs should be worked out.
33. Preliminary technical and economic calculation of the *JVS* under the conditions of the Latvian EEZ in the Baltic Sea highlights the topicality of the problem of uneven waves.

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