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Assessment of energy resources of Polish Baltic Sea areas

Ocena zasobów energetycznych polskich obszarów Morza Bałtyckiego

Maciej Kałas, Piotr Piotrowski

Department of Operational Oceanography of the Maritime Institute in Gdańsk, Poland

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Abstract: The article presents spatial characteristics of energy fluxes recorded in the area of the Polish Exclusive Economic Zone (EEZ) in the four-year period of 2013–16. Data presented in this work are based on results of forecast calculations with application of numerical models of the atmosphere (HIRLAM) and sea (WAM and HIROMB). Conducted analyses were concerned with dynamics of physical phenomena above the sea surface (wind), on its surface (wind waves motion), and in its near-surface layer up to 4 m (seawater flows). Physical energy resources connected with these processes for subsequent four years were computed and compared with the amount of annual electricity output generated by conventional and renewable sources of energy. Such an analysis of estimated energy resources reveals that the resource are highly differentiated in terms of space and in individual years, and significantly exceed the annual production of Polish power plants.

Keywords: renewable energy resources, wind, wave motion, water flows, Polish marine areas of the Baltic Sea

Streszczenie: Praca przedstawia charakterystykę rozkładów przestrzennych strumieni energii, jakie w latach 2013–16 związane były z obszarem polskiej strefy odpowiedzialności na Bałtyku (EEZ). Przedstawione dane uzyskano korzystając z wyników obliczeń prognostycznych operacyjnych modeli numerycznych: atmosfery (HIRLAM) oraz morza (WAM i HIROMB). Wykonane analizy dotyczyły dynamiki zjawisk fizycznych nad powierzchnią morza - wiatru, na jego powierzchni - falowania wiatrowego oraz w jego przypowierzchniowej warstwie (do 4 m) – przepływów wody. Oszacowano fizyczne zasoby energii związane z wymienionymi procesami dla czterech kolejnych lat i porównano je z wielkościami rocznej produkcji energii elektrycznej ze źródeł konwencjonalnych i odnawialnych. Analiza tak otrzymanych wielkości pokazuje, że zasoby energii są znacząco zróżnicowane przestrzennie jak i w poszczególnych latach i znacząco przewyższają możliwości produkcyjne polskich elektrowni.

Słowa kluczowe: zasoby energii odnawialnej, wiatr, falowanie, przepływy wody, polskie obszary morskie na Bałtyku

Introduction

Areas of the Baltic Sea under the jurisdiction of the Republic of Poland (Polish EEZ) are inherently associated with atmospheric and hydrological processes generating significant amounts of energy. In line with ongoing development in the field of energy production and construction of associated installations, it will be possible to use these potential resources for economic purposes. This article presents the authors' trials at estimation of their values by means of analysing dynamic and energetic parameters of the phenomena with respect to:

- wind at the altitude of 10 m ASL;
- surface wave motion;
- water flows in the near-surface layer of the sea (up to the depth of 4 m).

They are important phenomena and processes, constantly present in the marine environment though with changing intensity. They have the energy potential which may turn them, sooner or later, into reserves of "pure" energy obtained from unconventional, renewable sources, production of which does not involve CO_2 emission.

Information presented herein allows estimating potential physical energy resources produced in the Polish marine areas in connection to above-mentioned hydrometeorological phenomena. The results were elaborated taking into account the basic physical characteristics of these processes and their changeability over the years. Near-water atmospheric layer (wind), sea surface (wave motion) and near-surface layer of the water column within 4 m depth (water flows) were all taken into consideration. Spatial dis-

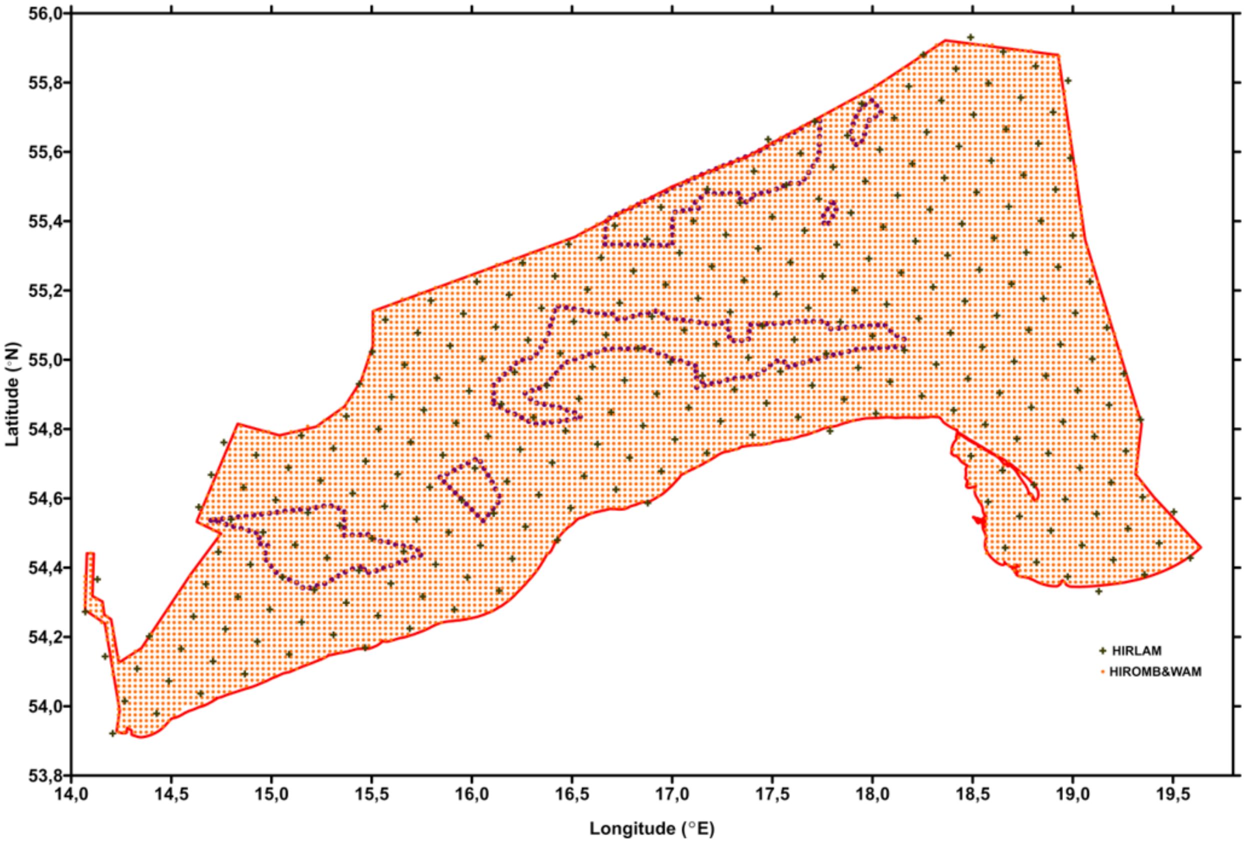

Fig 1. Grid points of the HIRLAM model (black crosses) and the WAM and HIROMB models (orange dots) in the Polish marine areas, for which the energy fluxes were calculated, with the areas allotted for construction of marked wind farms (purple dotted line)

tribution of energy fluxes associated with these processes over the entire area of the Polish EEZ was presented as well. This way, an important criterion allowing assessment and choice of areas of the sea showing the greatest energy potential with reference to three analysed sources, and which are most suitable for power production installations (e.g. offshore wind farms).

Computed values obtained from analysed renewable sources of energy were compared with current values of electricity produced in Poland over the past years by power plants and stations of various types.

It is worth noting that similar assessments, but only for wind energy, were performed for the sea areas of neighbouring Baltic countries (incl. Hasager et al. 2011, Lizuma et al. 2013, Uiboupin et al. 2013).

Numerical forecast models as a source of information on energy resources of marine areas

Energy resources of the Polish exclusive economic zone (EEZ) associated with phenomena occurring in sea (wind wave motion, water flows) and over its surface (wind) cannot be assessed accurately not only because of a highly variable intensity of hydrometeorological processes recorded in different seasons of the year and in subsequent years, but rather due to the fact that unlike on the land, in the open sea there is no permanent network of observation and measurement stations placed in the optimum and most representative places (Gajewski 2016, Kałas 2016). Hence, we do not have at our disposal a sufficient amount of reliable data from *in situ* recordings carried out for sufficiently long periods of time, which are necessary for performance of such analyses.

Usage of data from calculations of numerical models of atmosphere and the sea, however, provides such an opportunity (Kałas, 2002a). Taking this into account, forecast information obtained from operational marine models was applied to ensure reliable data on energy potential of the Polish marine areas. Although forecasts for course of phenomena at sea are unavoidably characterised by certain stated level of generalisation and inaccuracy, in the operational mode they still provide precise information on physical parameters of the atmosphere and the sea from an appropriately dense grid of measurement points covering the entire Polish marine area of the Baltic Sea (Figure 1). It is also possible to make hindcast computations which allows obtaining sufficiently long homogeneous data strings. Analyses are usually conducted on data collected at 1 h interval. A number of validation analyses of forecasting models performed with reference to various places at sea confirm compatibility of data obtained from these models with observations registered at sea at the same time (e.g. Kałas 2002b, 2004, 2010, 2012, Staśkiewicz 2008). Therefore, these data may be considered as a reliable source of information of weather conditions prevailing in the areas of the open sea in a given period of time.

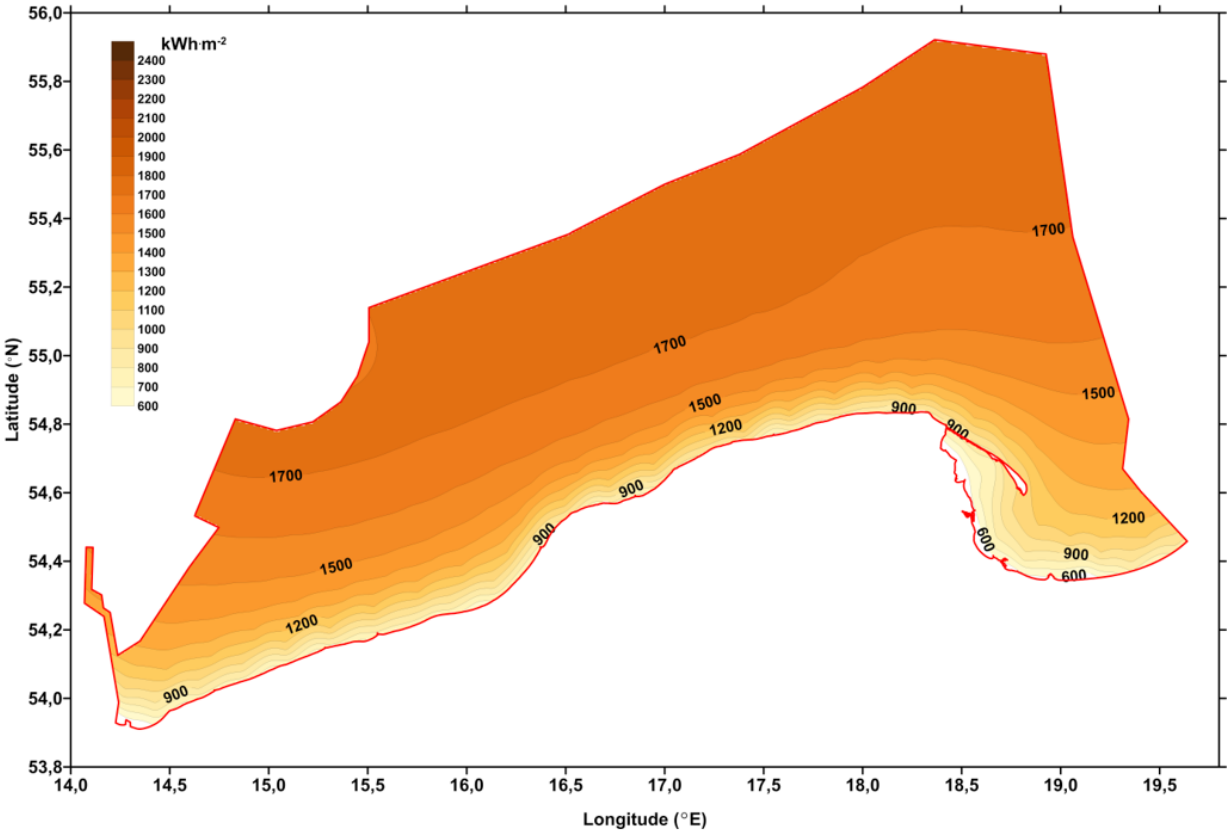

Fig. 2. Average wind power density distribution over the Polish areas of the Southern Baltic in 2013

When elaborating this article, forecasts from models offering possibly the shortest lead-time (usually in the range of up to 6 hours). Adequately, information of this kind was used in assessment of:

- wind conditions – calculated with use of the atmospheric model **HI**RLAM11 (HIgh Resolution Limited Area Model) providing calculations on a 11 km at the SMHI (Sweden) (HIRLAM)
- wave motion parameters – computed from the wind wave model WAM (WAve Model) providing calculations on a 1 Nm at the Maritime Institute in Gdańsk (Kałas, 1998)
- Distribution and magnitude of sea currents – calculated from the high resolution hydrodynamic model for the Baltic Sea HIROMB (HIgh ResOlution Model for the Baltic Sea) calculated on a 1 Nm grid at the SMHI (Sweden) (HIROMB, Funquist, Kleine, 2007).

Energy fluxes over the Polish marine areas of the Baltic Sea

Levels of annual average energy output were calculated for each grid point of the above mentioned models (Figure 1) taking into account three basic processes connected indispensably with the sea areas under the jurisdiction of Poland. Obtained values were next used in presenting spatial distribution of hourly average values of the energy fluxes (expressed in MWh m^{-2}) for each year of the investigated time period.

Wind

The amount of energy generated by wind blowing over the sea surface depends, first of all, on the air masses flow rate which increases with growing distance from the water surface. Assuming that surface of the sea corresponds to roughness class of 0–1, power density of energy flux generated by flow of air stream over a surface area unit (1 m^2) in a period of 1 hour were calculated for each grid point in the atmospheric model HIRLAM (located every 11 km). As a result, value equal:

$E = 2.205*V^3$ (in kWh m^{-2})

was obtained, where: V – wind speed (in m/s), accepted as a constant value for the accepted time interval (1 h), measured at the standard height of 10 m ASL, assuming constant density of air equal to 1.225 kg·m^{-3} (Kałas, 2003)

Figures 2–5 present average power density distribution over the entire Polish marine areas (in kWh m^{-2}) at the height of 10 m ASL, in four subsequent years of the 2013–16 period.

1.2 Wave motion

Wave motion development which is described by parameters such as lengths of escalation, duration and attenuation of wave phenomena, is associated primarily with the impact

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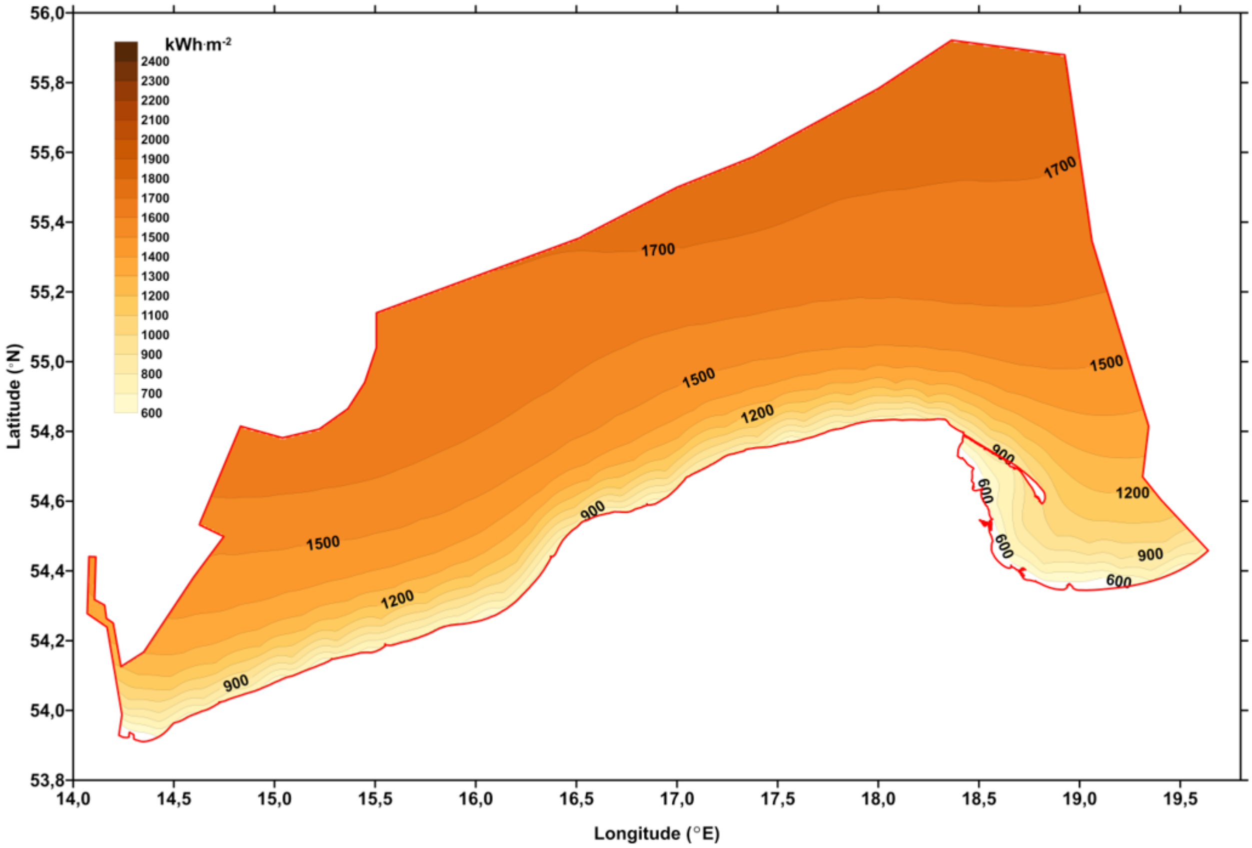

Fig. 3. Average wind power density distribution over the Polish areas of the Southern Baltic in 2014

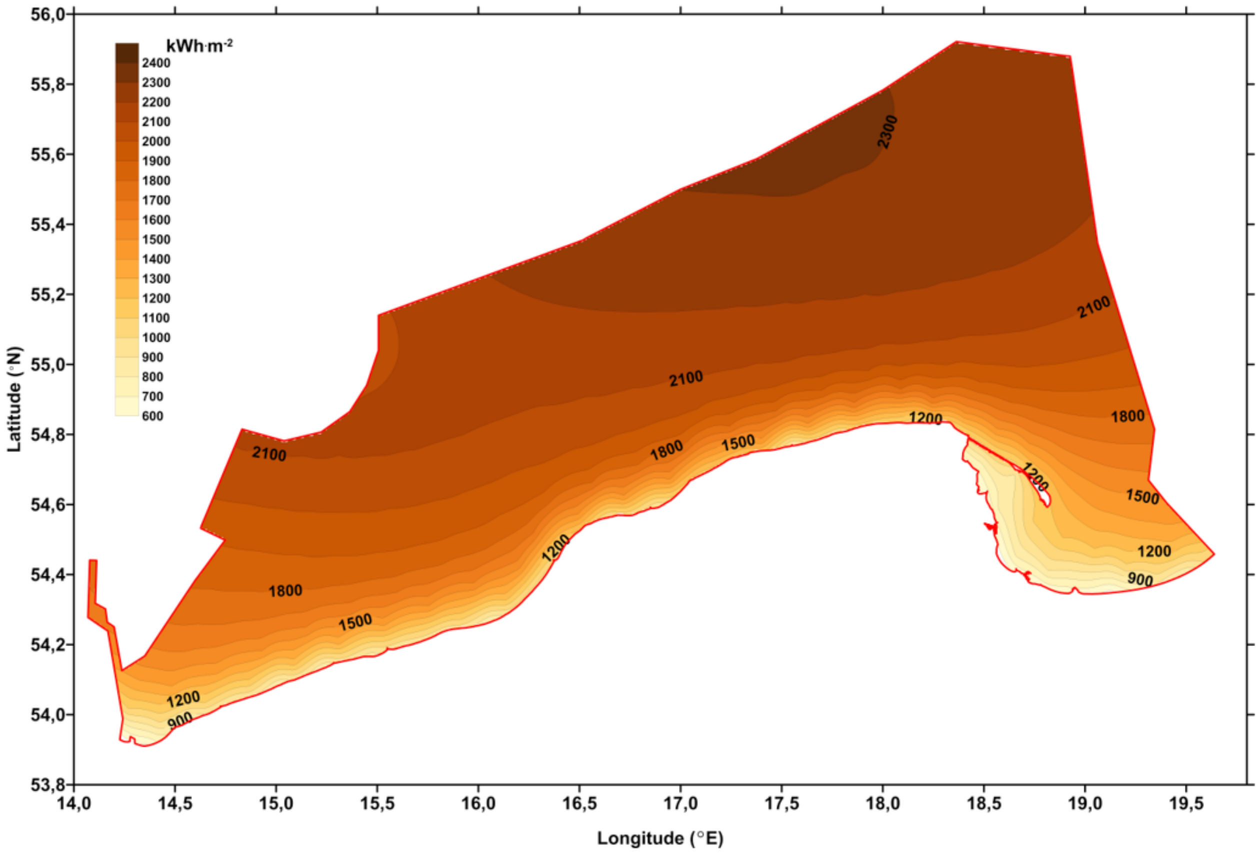

Fig. 4. Average wind power density distribution over the Polish areas of the Southern Baltic in 2015

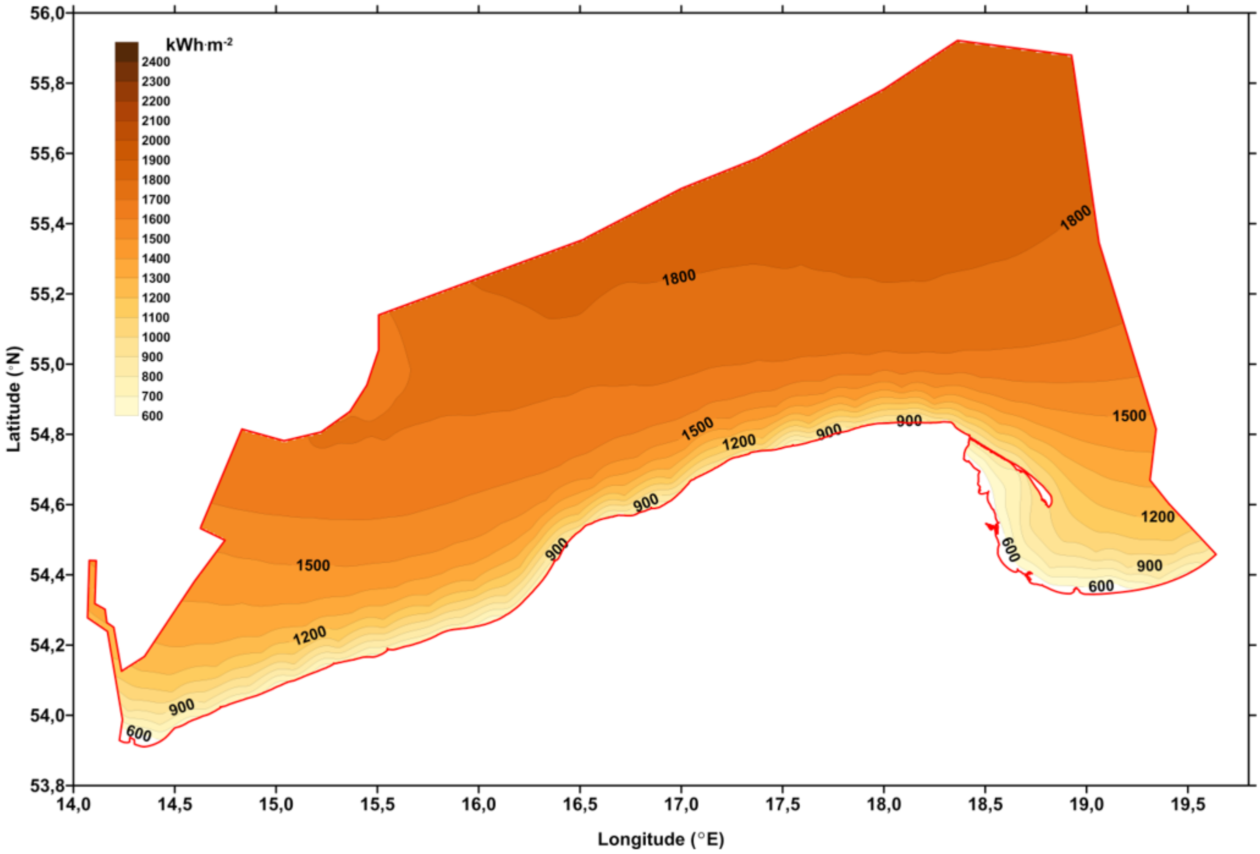

Fig. 5. Average wind power density distribution over the Polish areas of the Southern Baltic in 2016

of wind field on the sea surface in the entire area of the Baltic Sea. Wave height-which decides on the amount of energy generated by the wave, depends first of all on the current (both instantaneous and maximal) speed of wind in the near-water layer, duration, and the flow direction of air masses-which decide on extent of wind impact along the Polish coast. In case of the observed height of wave motion also depth distribution and relief of the seabed, distance from the shoreline and the average depth of the sea area are important factors. Assuming that wave motion is of sinusoidal character and that the highest energy is associated with significant waves (Massel, 1992, Rodrigues, 2008), average wave motion energy per a surface area unit of the wavefront (1 m^2) in an hour were calculated for each grid point of the wind wave motion model WAM (on a 1 Nm), (1 m^2). As a result, energy equal:

$$E = 13.871 * H^2 \text{ (in kW m}^{-2}\text{)}$$

was obtained, where: H is the significant wave height (in m) for each point of the model located at the sea, calculated at one time interval of time (of 1 h), with the assumed fixed seawater density of 1025 kg·m^{-3}

The following figures (Figures 6–9) present spatial distribution of the average wind wave motion power density (in kWh m^{-2}) over the entire Polish marine area in four subsequent years of the 2013–16 period.

1.3 Sea currents

Just like in the case of wind wave motion appearing and developing on the sea surface, rate and direction of water flow across the entire cross-section of the water column depend first of all on the wind field prevailing in the entire sea area at a given time. Only the sea areas where current distribution is stable, not changing for a longer period of time, may be distinguished. As the biggest water flow velocities characterise the water-atmosphere contact zone, and they decrease significantly with increasing depth, calculations of what amount of energy these flows may generate were limited to the depth of 4 m, which was accepted as the lower limit of the near-surface water layer. This way, homogeneous data could be obtained for practically entire Polish area of the Baltic Sea. Average power density of energy flux generated by flow of water mass across a surface area unit (1 m^2) in 1 hour period were calculated for each grid point in the model HIROMB (located every 1 Nm). As a result, value equal:

$$E = 1809 * V^3 \text{ (in kWh·m}^2\text{)}$$

was obtained, where: V is the averaged value of water flow velocity in the layer form the surface to the depth of 4 m BSL calculated for each point of the model located at sea, with the accepted time interval of time (of 1 h), and fixed seawater density of 1025 kg·m^{-3} assumed.

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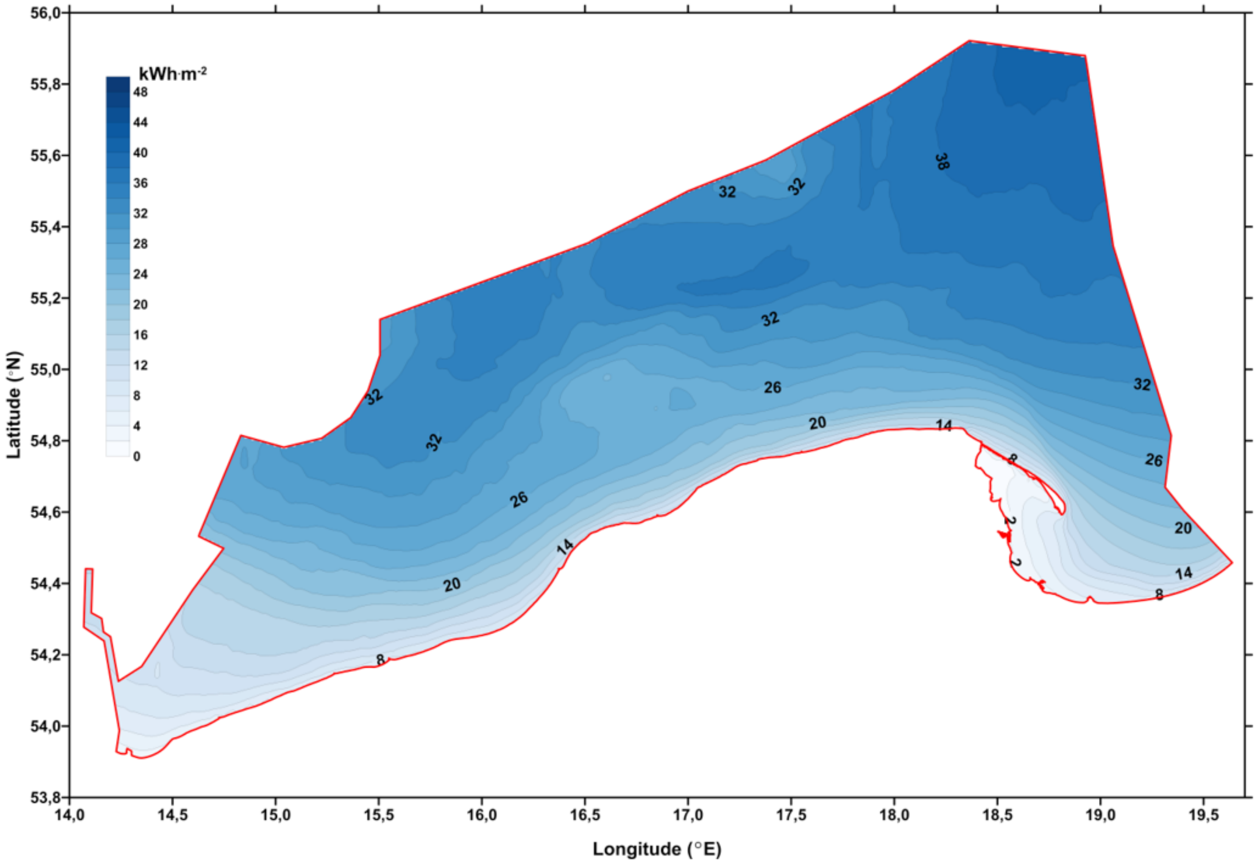

Fig. 6. Average wind wave motion power density distribution over the Polish areas of the Southern Baltic in 2013

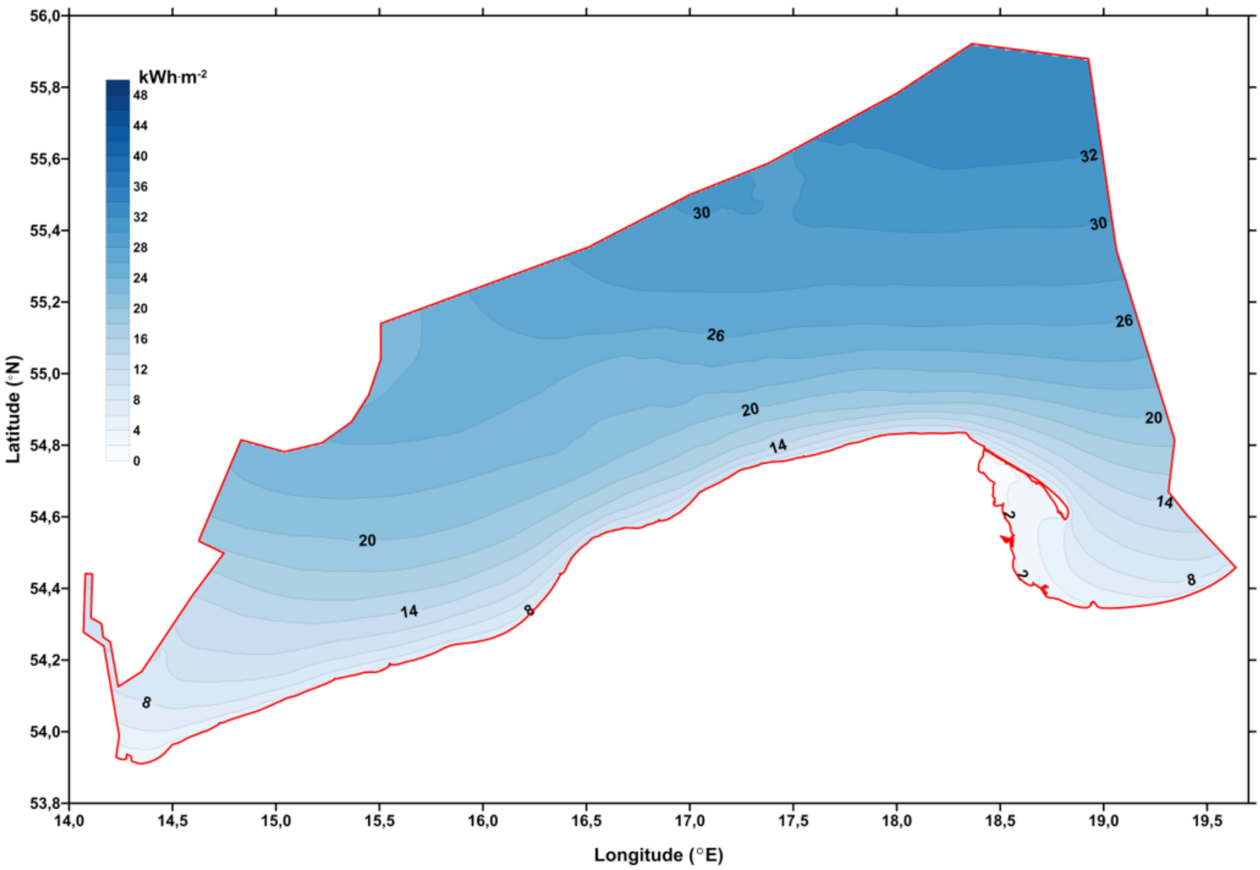

Fig. 7. Average wind wave motion power density distribution over the Polish areas of the Southern Baltic in 2014

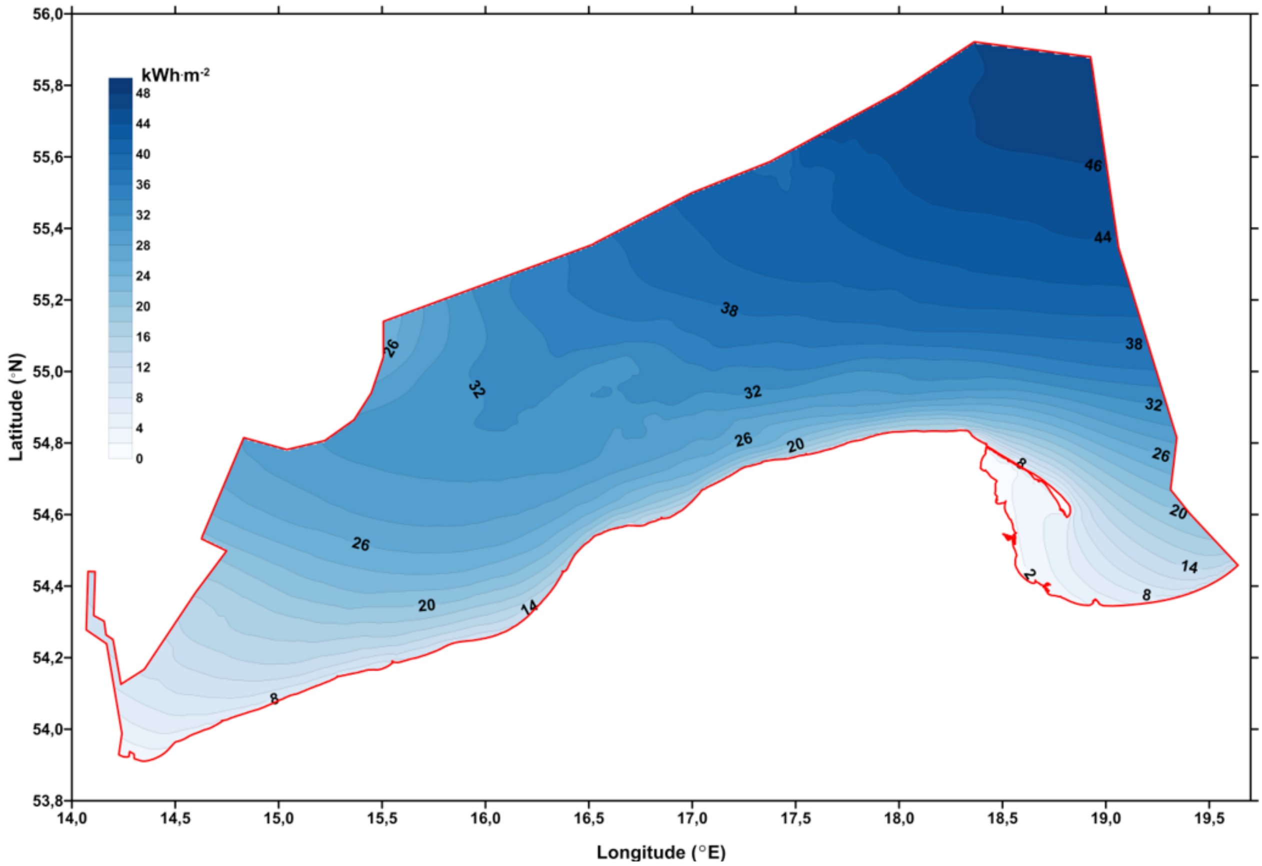

Fig. 8. Average wind wave motion power density distribution over the Polish areas of the Southern Baltic in 2015

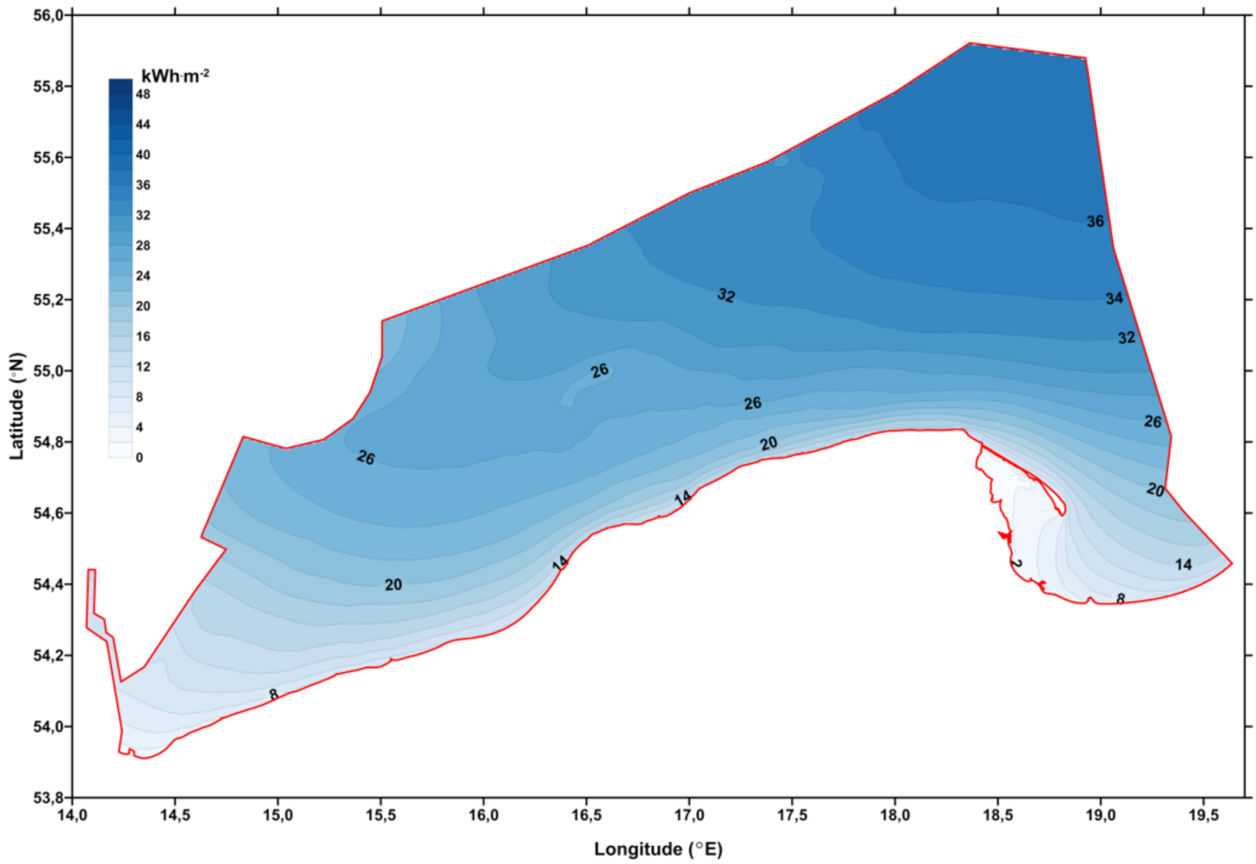

Fig. 9. Average wind wave motion power density distribution over the Polish areas of the Southern Baltic in 2016

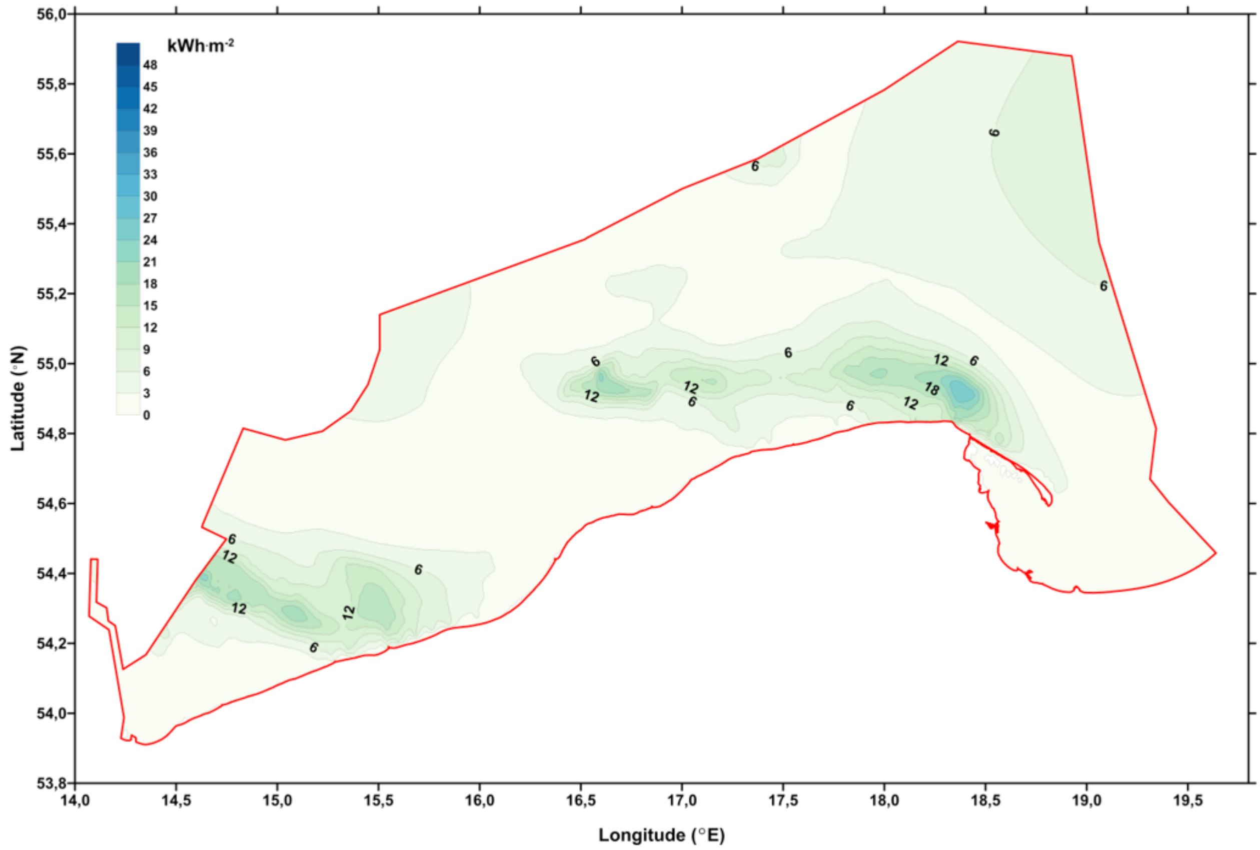

Fig. 10. Distribution of average water flow power density in the surface layer of the sea in the Polish areas of the Southern Baltic in 2013

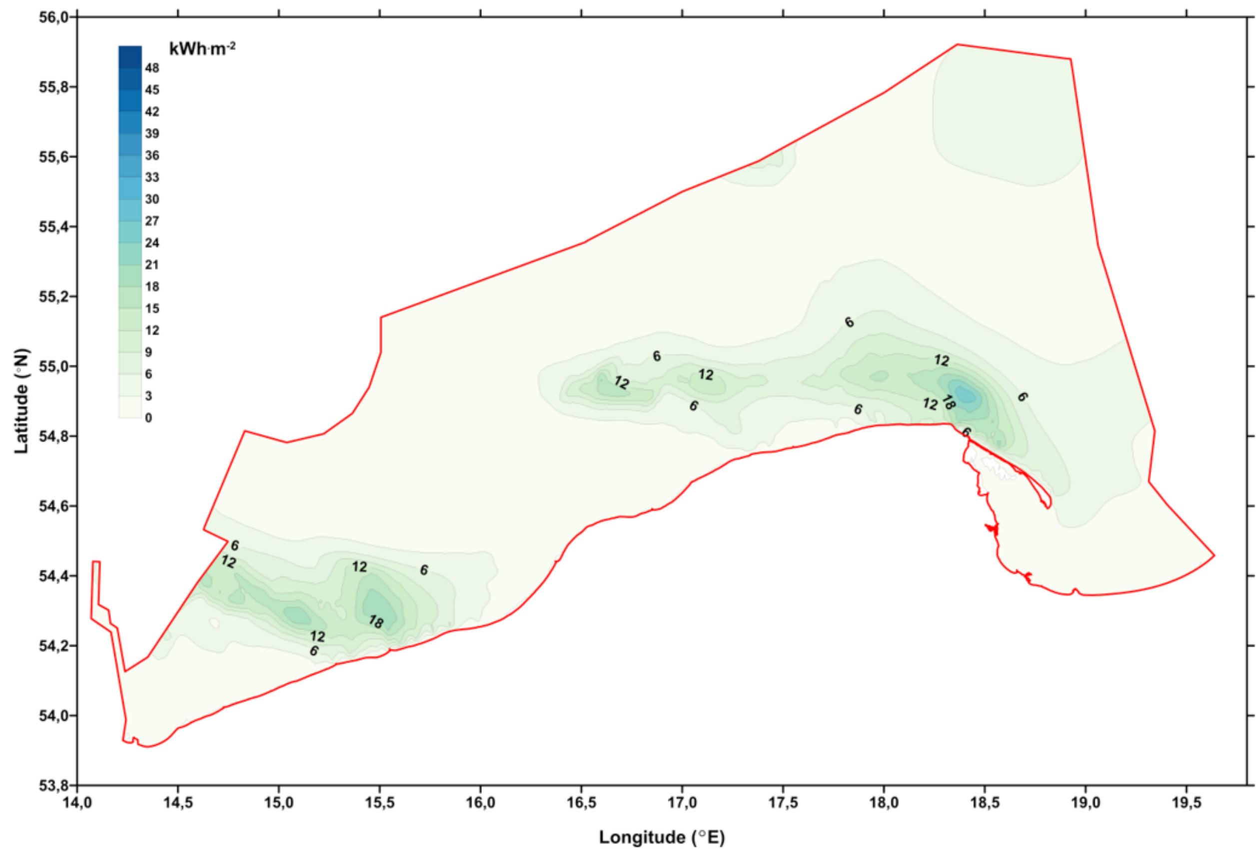

Fig. 11. Distribution of average water flow power density in the surface layer of the sea in the Polish areas of the Southern Baltic in 2014

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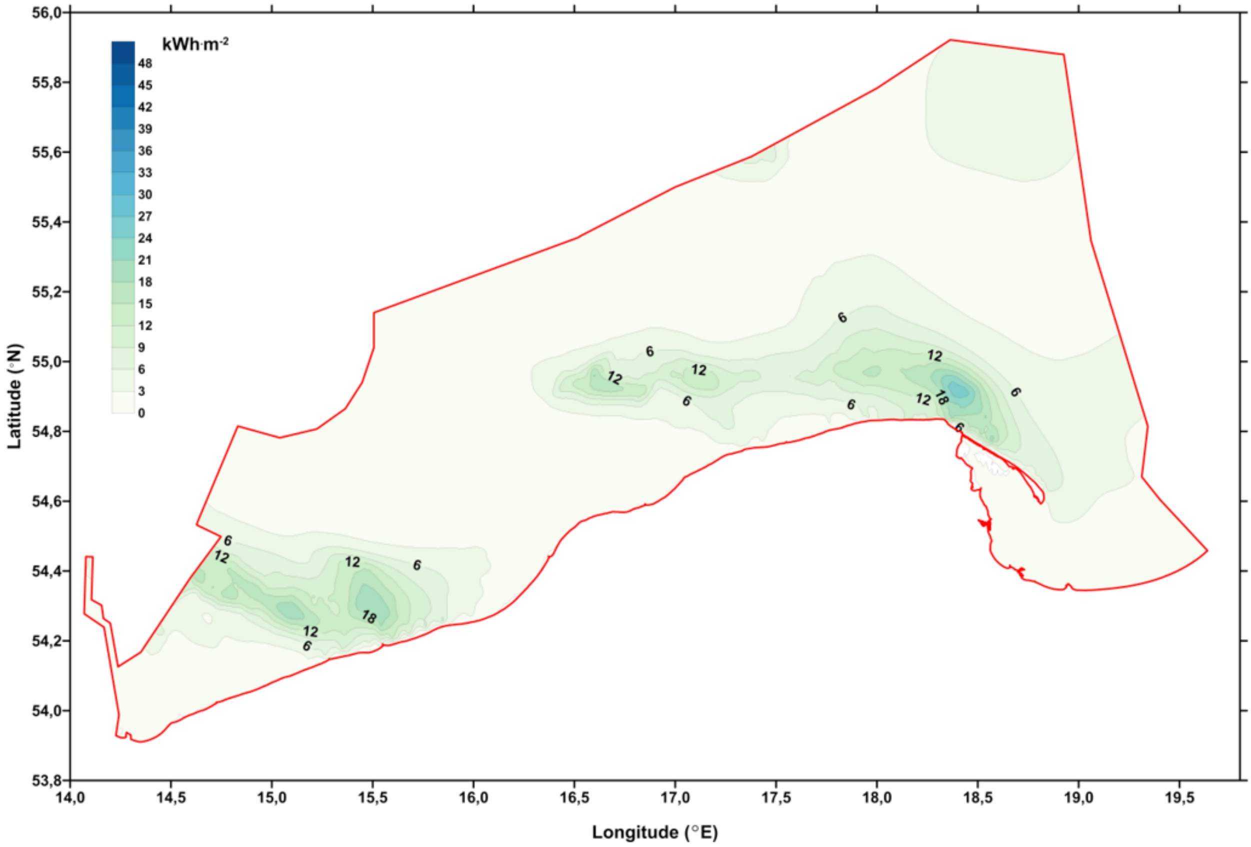

Fig. 12. Distribution of average water flow power density in the surface layer of the sea in the Polish areas of the Southern Baltic in 2015

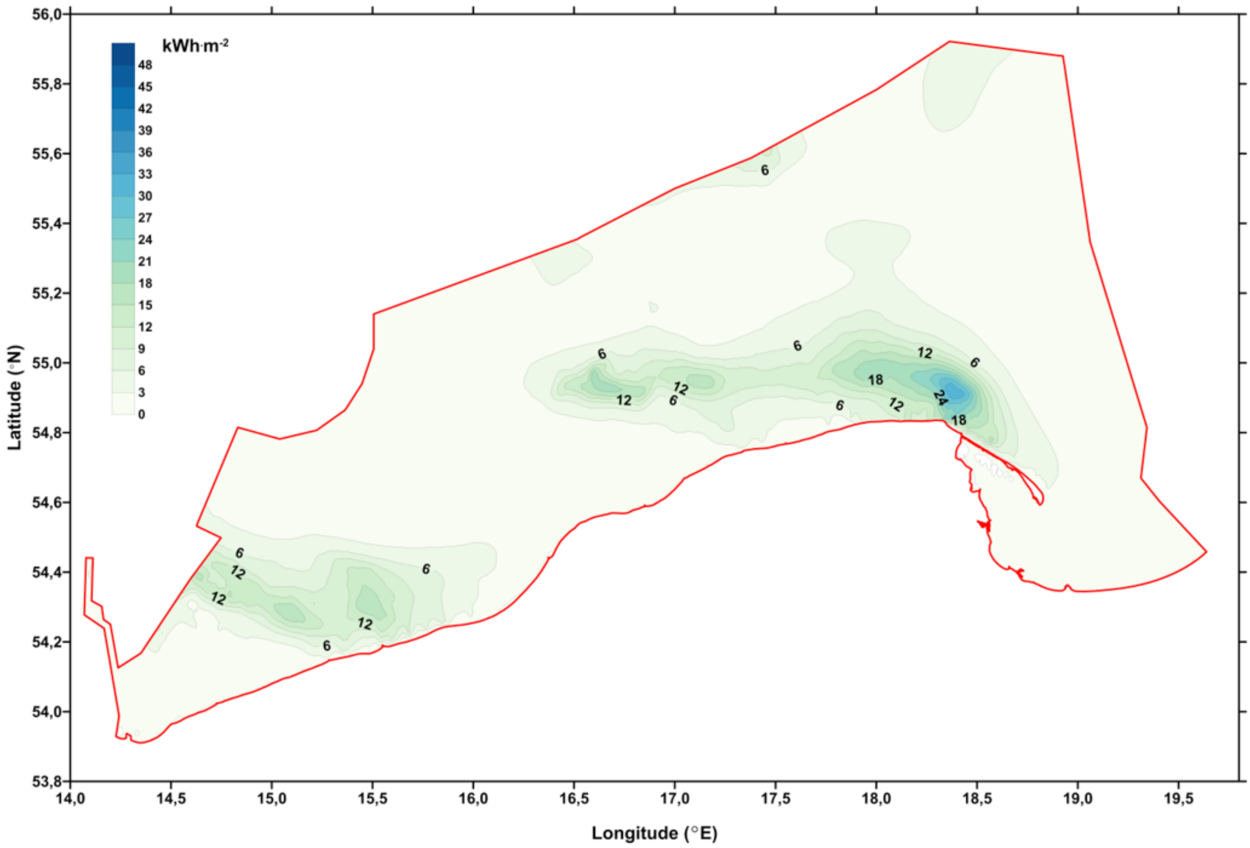

Fig. 13. Distribution of average water flow power density in the surface layer of the sea in the Polish areas of the Southern Baltic in 2016

Tab. I Energy fluxes above the sea areas under Polish jurisdiction in 2013–16 in relation to wind fields, water flows in the near-surface layer and wind wave motion (in MWh m^{-2}) and total annual resources of energy generated by each of these phenomena (in EWh)

	UNIT	WIND				CURRENTS				WAVES			
		2013	2014	2015	2016	2013	2014	2015	2016	2013	2014	2015	2016
Amount grid nets		281	281	281	281	9897	9897	9897	9897	9911	9911	9911	9911
Minimum	MWh.m^{-2}	3217,8	3213,7	3740,0	2980,3	0,0	0,0	0,0	0,0	3,4	3,6	4,7	4,0
Maximum	MWh.m^{-2}	15683,2	15303,8	20339,9	16187,5	237,2	227,4	367,4	283,2	358,9	269,5	412,1	331,3
Mean	MWh.m^{-2}	13299,1	12680,2	16714,5	13542,1	36,6	32,8	40,5	31,3	238,3	173,4	264,6	224,5
Total energy	EWh	452,2	431,1	568,3	460,4	1,2	1,1	1,4	1,1	8,1	5,9	9,0	7,6

Source: Authors' own calculations

The following figures (Figures 10–13) present spatial distribution of average water flow power density in the surface layer of the sea (in kWh m^{-2}) over the entire Polish marine area in four subsequent years of the 2013–16 period.

Energy resources of the Polish marine areas

Our calculations provided information which allowed calculating magnitude and present spatial distribution of energy resources generated in a period of 1 year by the sea phenomena occurring in the 2013–2016 period. Both, the entire area of the Polish EEZ and selected sea areas intended as prospective wind energy sector investment areas were investigated (Figure 1). Although certain differences in levels of energy output generated in association with the discussed sea phenomena between individual years became apparent, the general characteristics of these wind fields remains basically unchanged (Figure 2–13).

Table I presents the basic statistical parameters of annual energy fluxes computed for the entire Polish area of the Baltic Sea, generated by the three discussed physical phenomena in subsequent years and it accounts for the real course of hydrometeorological conditions in each of the analysed years (in MWh·m^{-2}). Additionally, information on estimated values of total annual energy output from the Polish EEZ (in EWh) was added.

Energy fluxes above the sea areas under Polish jurisdiction in 2013–16 in relation to wind fields, water flows in the near-surface layer and wind wave motion (in MWh m^{-2}) and total annual resources of energy generated by each of these phenomena (in EWh)

Calculations presented above indicate that amount of energy generated by wind are significantly higher than in similar assessments associated with the water mass dynamics on the sea surface. In this regard, it should also be noted that our computations allow for wind speed parameters associated at the standard height of 10 m ASL. As rotors of wind power stations are usually at the altitude of about 100 m ASL where mean levels of wind speed are much higher, the actual available wind energy resources that may be possibly used in power production may be also much higher. Power production technologies applied nowadays in the wind power sector are advanced, and so values presented above indicate that the Polish sea areas are a very promising source of renewable energy of this kind.

Taking into account dynamics of the water masses movement and the flow in the surface layer of the sea, resources of energy associated with phenomena taking place in this layer constitute about 0.25% (water flows) and about 1.6% (wave motion) in relation to wind power resources (referring to the altitude of 10 m ASL). Hence, taking into account the current advancement of adequate generators allowing utilisation of these resources in production of electric power, significance of these resources in terms of power production on an industrial scale be considered insignificant these days.

Our analyses reveal that wave power resources are slightly larger than those of water flow power. Spatial distribution is distinctly associated with bathymetric and morphometric conditions of the Polish marine areas in this case. It reveals that the most considerable resources of wave motion power are available in the areas separated from the coast by a great distance. This adverse factor makes the prospect of utilising these renewable energy resources more and bleaker.

When investigating distribution of energy flux associated with surface water masses flows, it may be noticed that the flux is highly heterogeneous. Areas where water flow power levels are the most considerable are concentrated in two regions. The first of them is on the Słupsk Bank and further, in the sea areas located to the north of Rozewie and along the Hel Peninsula, where it borders with significant depressions in the seabed in the region of the Gdańsk Deep. The second one is located in the western part of the Polish zone, to the north of the Oderbank and it spreads along the south-western edge of an area characterised by greater depths which is associated with the Bornholm Deep (Figure 14). Big values of energy fluxes were recorded in the area of the Southern Middle Bank. Sizes of the water flow energy fluxes tend to change in individual years, but areas where the highest values can be recorded are still in the presented regions of the sea (Figures 10–13).

As the figure presented below shows (Figure 14), these parts of the sea are located in areas with relatively small depths (about 20 m at maximum) which may be considered in the future as potential

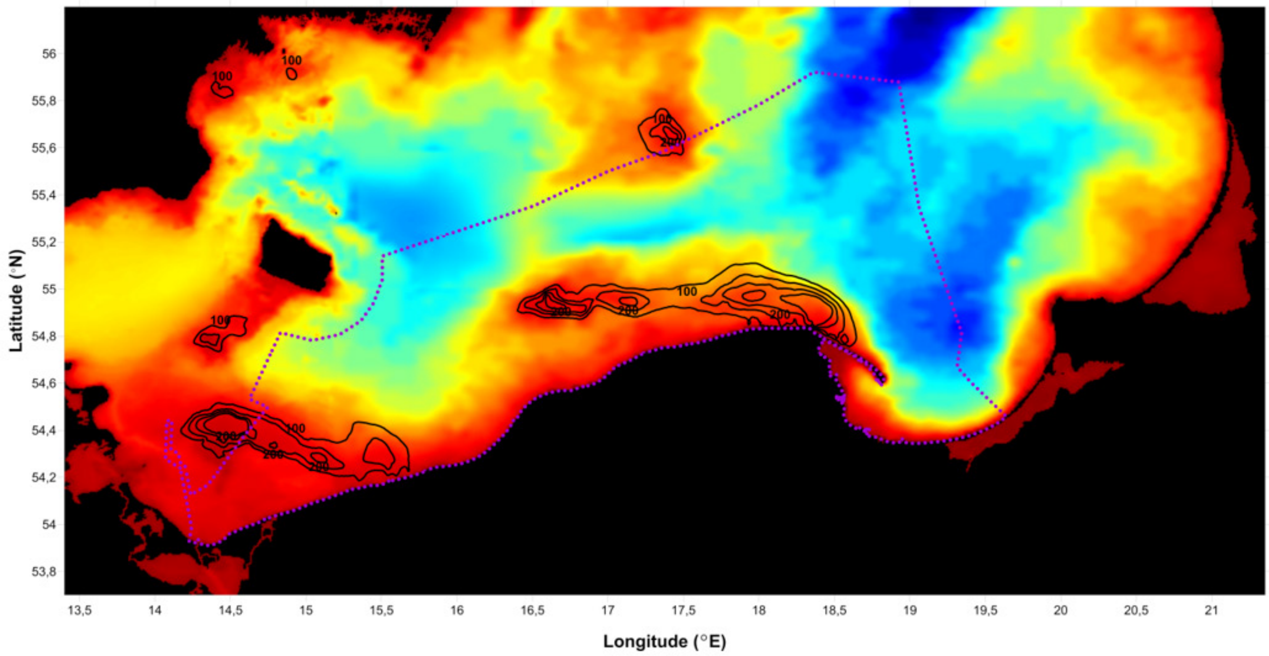

Fig. 14. Areas of the sea covered by the Polish EEZ in which the highest levels of surface water flow energy fluxes are recorded a year (over 100 MWh m^{-2} for conditions calculated in 2015); dotted line marks the boundary of the Polish marine areas

Tab. II. Energy fluxes in concession areas under the Polish jurisdiction recorded in 2013–16 in relation to wind fields, water flows in the near-surface layer and wind wave motion (in MWh m^{-2}) and total annual resources of energy generated by each of these phenomena (in EWh)

	UNIT	WIND				CURRENTS				WAVES			
		2013	2014	2015	2016	2013	2014	2015	2016	2013	2014	2015	2016
Amount grid nets		25	25	25	25	1105	1105	1105	1105	1105	1105	1105	1105
Minimum	MWh.m^{-2}	13239,357	12487,545	16298,617	13093,235	10,489	8,012	8,722	7,028	162,333	121,450	170,764	155,246
Maximum	MWh.m^{-2}	15375,697	14382,261	19173,141	15704,212	132,876	135,294	215,785	143,177	316,779	261,820	393,034	317,743
Mean	MWh.m^{-2}	14526,671	13559,950	18056,795	14597,455	39,046	37,334	51,559	39,110	250,120	193,117	290,366	244,296
Total energy	EWh	43,943	41,019	54,622	44,157	0,118	0,113	0,156	0,118	0,757	0,584	0,878	0,739

Source: Authors' own calculations

areas of experimental surveys associated with energy acquisition from renewable sources. Such option is even more probable due to the fact that most of these sea areas are allotted to construction of wind farms.

Energy resources of the selected investment areas in the Polish EEZ

Over the past few years, a rapidly growing interest in possibilities of utilising energy from renewable sources was observed concerning both the open sea areas and the coastal zone. Various concepts of development and site selection possibilities connected first of all with utilisation of wind power (wind farms) are being analysed in terms of e.g. planning spatial development and sustainable development of the Polish marine areas (Niecikowski, 2008, Gilbert, 2008, Zimna, 2013, Blažauskas, 2013).

The Ministry of Maritime Economy and Inland Waterways methodically designates areas in the sea areas under the Polish jurisdiction which may be the subject of applications for permit for the erection and use of artificial islands, constructions and equipment submitted by potential investors (BPI of the Ministry of Maritime Economy and Inland Navigation). Basing on the published site selection data on such fields of the sea, concession areas intended primarily for construction of offshore wind farms were marked in the map in the form of envelopes (Figure 1). Adequate calculations of annual energy resources associated with the analysed phenomena were made for these areas as well (Table II). However, it must be strongly pointed out that the computed wind, wave or current energy resources are of the overall and theoretical energy resources, treated as a physical phenomena that exist on the sea areas designated for renewable energy projects. Practically, it is possible to use only a small part of these resources, but they are still significant.

Comparison of data presented in Table I, and Table II reveals that about 10% of calculated energy resources of the Polish economic zone of the Baltic Sea is associated with the designated concession areas, which cover about 11% of the Polish EEZ. At the same time, energy resources are distributed in these areas more evenly than in case of the entire Polish EEZ.

Energy fluxes in concession areas under the Polish jurisdiction recorded in 2013–16 in relation to wind fields, water flows in the near-surface layer and wind wave motion (in MWh m^{-2}) and total annual resources of energy generated by each of these phenomena (in EWh)

Energy resources of the Polish marine areas in relation to electricity production in Poland

To illustrate the scale of energy resources generated on a yearly basis by wind phenomena above the sea surface and surface and near-surface water layers dynamics, and to balance it against the production capacity of the power generation sector in Poland, statistical data on annual electricity production in Poland in 2013–16 (in GWh) were compared in Table III. This period of time corresponds to the ones for which the computations presented in this article were made, which offers a chance at making certain comparisons.

Data presented below indicate that if only annual energy resources from concession areas at sea are taken into account (in relation to wind energy at the altitude of 10 m ASL) then yearly output of electricity produced by all types of power stations in Poland is from 0.30 to 0.38 % of these resources. This example shows the magnitude of the renewable energy resources that still wait to be used.

Summary and conclusions

The analysis of estimated energy resources associated with occurrence in the Polish marine areas of the most important physical phenomena and processes in the near-water layer of the atmosphere (wind) and the surface layer of the sea (wave motion and water flow) presented in this article reveals that obtained values are highly differentiated, both in terms of

Table III. Annual power output generated in Poland in 2013–16 (in GWh) in total and broken by individual methods of energy production

NO.	TYPE	2013	2014	2015	2016
1	total production	162.501	156.567	161.772	162.626
1.1	professional power plants	147.435	140.290	141.901	140.727
1.1.1	water-power plants	2.762	2.520	2.261	2.399
1.1.2	thermal power plants	144.673	137.770	139.640	138.328
1.1.2.1	hard coal power plants	84.566	80.284	81.883	81.348
1.1.2.2	brown coal power plants	56.959	54.212	53.564	51.204
1.1.2.3	gas power plants	3.149	3.274	4.193	5.776
1.2	renevable power plants	72	73	73	146
1.3	wind power plants	5.823	7.184	10.041	11.623
1.4	industrial power plants	9.171	9.020	9.757	10.130

Source: Monthly reports on operations of the National Power System (KSE) and the Balancing Market (PSE)

space as well as with respect to the individual years. This variability is aptly illustrated in figures with spatial distribution of energy fluxes associated with investigated physical phenomena recorded in the period of 2013–2016.

This compilation allows us to identify places in the sea offering the greatest possibilities for production of energy from renewable energy sources presented herein. Usage of wind energy resources seems to be the most promising option. Utilising of energy resources consisting in wave motion and water flow dynamics seems to be still a distant reality.

At the same time, compilation of annual power output of energy produced in Poland allows us to assess scale and magnitude of renewable energy sources of the Polish marine areas and how small percentage of them has been put to use so far. Although our computations of energy resources for the Polish sea areas are of the overall and theoretical energy resources it one can notice, that the yearly production of the Polish energetic system represents only tiny fraction of the resources existing in nature – of wind it is about 10^{-4} percent and of waves and currents about 10^{-3} percent.

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Corresponding author: Piotr Piotrowski; Department of Operational Oceanography of the Maritime Institute in Gdańsk; e-mail: ppiotrowski@im.gda.pl

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