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Assessing temporal complementarity of solar, wind and hydrokinetic energy

Jakub Jurasz[1,a], Adam Piasecki[2] and Marcin Wdowikowski[3]

[1]*AGH University, Department of Management Engineering, 30-067, Gramatyka St., Cracow, Poland*
[2]*AGH University, Department of Economics, Finance, and Environmental Management, 30-067, Gramatyka St., Cracow, Poland*
[3]*Institute of Meteorology and Water Management - National Research Institute, 01-673 Warsaw, Podleśna 61 Street, Poland*

Abstract. Renewable energy sources (RES) exhibit various characteristics when it comes to their availability in time and space domain. Some are characterised by significant variability and limited predictability. This makes their integration to the power grid a complicated task. Temporal and spatial complementarity of RES is perceived as one of the possible ways to facilitate the process of integration. This paper investigates the concept of temporal complementarity of solar wind and hydrokinetic energy in case of two sites in Poland. Obtained results indicate existence of some beneficial complementarity on inter-annual and annual time scale. Combination of those three RES in one hybrid system makes power source more reliable.

1 Introduction

In case of some power systems (e.g. Germany [1], California [2], Denmark [3]) RES start to play a very significant role and strongly contribute to the reduction of: greenhouse gasses emissions and dependence on conventional fuels. However their integration to the power grid comes with additional challenges – resulting mainly from RES variability in time and space. Jones [4] addressed those problems and exemplified them based on several case studies – both from practical and theoretical point of view. Issue of RES integration draw much attention in the most recent literature. Highly cited work of Jacobson and Delucchi [5] pointed to seven ways of efficient design and operation of variable renewable energy (VRE) in power systems. To VRE one may classify *inter alia* photovoltaics (PV), wind turbines (WT) and hydrokinetic turbines (HKT). Naturally their variability is different in scale, frequency and predictability. One of the approaches recommended by [5] is to design power systems in such a way that it utilizes energy sources which are complementary one to another.

For the best of the authors' knowledge so far conducted research did not investigate the complementarity of those three energy sources. Several papers addressed wind and solar complementarity in different parts of the world: China [6], Mediterranean Islands [7], Germany [8], Italy [9], Iberian Peninsula [10] and India [11]. Hydropower (using height difference in contrary to hydrokinetic which utilizes flow speed), solar and wind complementarity has been investigated in case of: Brazil [12], Northeast Brazil [13] and one city in Poland (Piła) [14]. Conclusions coming from all above mentioned papers indicate, that wind and solar energy exhibit strong complementarity from the perspective of their annual variability patterns. Usual abundance of solar energy during dry period may result in improving water budged – meaning that water can be stored in reservoirs and do not have to be used for propelling water turbines (this beneficiary aspect of resources complementarity has been pointed by [13]).

This study deals with small scale PV, WT and HKT power sources which can be used by for domestic purposes. Hydrokinetic turbines are usually perceived from the perspective of large-scale technologies which use the energy of waves, tides and ocean currents. However there is a huge potential of using this technology by applying it to the energy of flowing water. Vermaak et al. [15] gave a thorough analysis and review of current technology status and trends of micro-hydrokinetic turbines for rural applications. Authors point to the fact that there are significant gaps in literature when it comes to the technical, economic and environmental aspects of utilizing HKT. Those gaps may be one of the reasons why this technology keeps in the background.

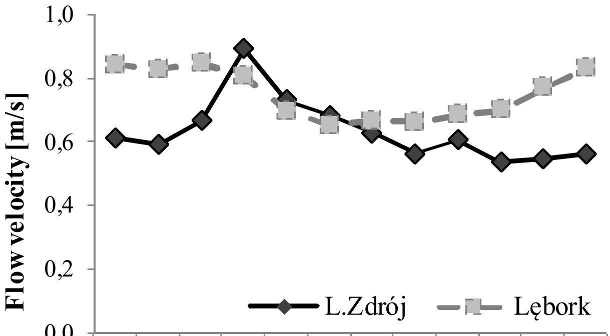
The goal of this study was twofold. First it aimed at analysing the complementarity of mentioned energy sources from the perspective of various time scales. This analysis was divided into two subsections: potential energy and energy generated from power sources based on their individual characteristics. Secondly it investigated the behaviour of PV-WT-HKT hybrid power source from the perspective of hourly energy generation values.

2 Methods and data

Two sites in Poland were selected for the purpose of this study. The first one is a small city Lądek Zdrój (50.34N, 16.88E) which is situated in Southern part of Poland,

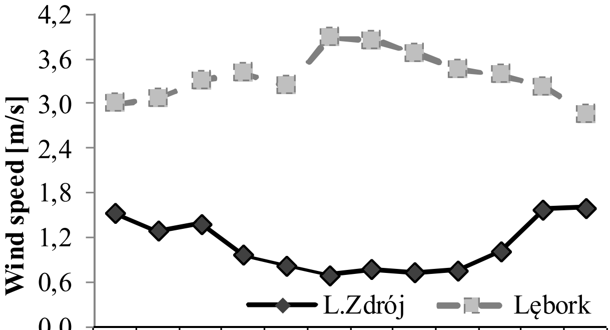
[a] Corresponding author: jakubkamiljurasz@gmail.com

Lower Silesia Voivodeship. Lębork a slightly bigger city (54.53E, 17.74E) is the second site and lies in Northern Poland, Pomeranian Voivodeship. Those both sites are characterised by the fact that the Institute of Meteorology and Water Management (IMGW) is making there measurements of basic meteorological and hydrological parameters such as wind speed and flow rate. It is important to note, that the rivers in both sites have different regimes and pattern of annual flow (see Figure 1) additionally both exhibit various annual patterns of wind speed, as shown on Figure 2. When it comes to the solar energy, the values of mean hourly irradiation observed in those two locations are almost the same. Those recorded in Lądek Zdrój are by 5% greater than those from Lębork, respectively 1.62 kWh/m^2/day and 1.55 kWh/m^2/day.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Nov	Oct	Dec
L.Zdrój	0,61	0,59	0,67	0,90	0,73	0,69	0,63	0,56	0,61	0,54	0,55	0,56
Lębork	0,85	0,83	0,85	0,81	0,70	0,65	0,67	0,67	0,69	0,70	0,77	0,84

Figure 1. Mean monthly flow velocity in Lądek Zdrój and Lębork. Values were calculated based on 2006-2015 time series of hourly meter readings.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Nov	Oct	Dec
L.Zdrój	1,53	1,29	1,39	0,97	0,83	0,70	0,77	0,73	0,76	1,03	1,58	1,60
Lębork	3,02	3,09	3,33	3,42	3,25	3,90	3,86	3,69	3,48	3,40	3,24	2,87

Figure 2. Mean monthly wind speed in Lądek Zdrój and Lębork. Values were calculated based on 2006-2015 time series of hourly meter readings.

In both cases data on flow rate (later recalculated into flow velocity based on method described in following paragraph) and wind speed has been downloaded from IMGW NRI databases. Wind speed is measurements are taken at 10 meters and this height has been assumed to be the height of small wind turbine rotor. Irradiation time series have been obtained from SoDa Solar Radiation Data (http://www.soda-pro.com/) which provides access to a broad range of services and web services related to *inter alia* meteorological data. Time series from SoDa did not have any missing observations, therefore were treated as a benchmark for the two remaining. Both in case of Lądek Zdrój and Lębork some values of flow rate and wind speed were missing. When a single value was missing and its predecessor and successor were available then it was replaced by the mean of those two mentioned. However if missing values represented longer continuous time series subset, then the whole period was removed from further analysis. In result, considering 2006-2015 times series with hourly time step in case of Lądek Zdrój 1034 values records were removed whereas in case of Lębork this number was greater and amounted to 3068. Those values constitute to respectively 1.2% and 3.5% of total number of observations.

2.1 Flow rate and flow velocity

River flow rate (Q) also known as a river discharge, in simple form of hydraulic relationship, is described as an exponential equation – rating curve [20, 21]:

$$Q = \alpha\,(h - e)^{\beta} \tag{1}$$

where: h is the river depth or gauge height of the water surface (cm), e is gauge height of effective zero flow (cm), α, β are the equation parameters depend on the river channel shape. Flow rate is given in cubic meters per second unit (m^3s^{-1}).

Stage-discharge relations for opened channel stations with uniform flow can be governed by the Manning equation, as it applies to the reach of controlling channel downstream from a gauge [20, 21]:

$$Q = n^{-1} A R^{2/3} S^{1/2} \tag{2}$$

where A is cross-section area, in square meters (m^2), R is hydraulic radius, in meters (m), S is friction slope, and n is channel roughness.

In Manning's formula, combination of n, R and S values gives a local river flow velocity computed in a specific time. Stage-discharge, rating curve, stage-velocity or discharge-velocity relationships can be developed using hydrometric field measurements [22]. Comparison between rating curve, stage-velocity plots and approximation of flow rate data series gives flow velocity series. In this paper hourly flow velocity series were approximated for two water gauges Lądek Zdrój and Lębork for 2006-2015 time period.

Because of the natural cycle of the analyzed part of rivers as well as the purpose of this research, the ranges of used flow velocity values were limited to the average conditions of flow rate. In order to do so, flow rate data series in 2006-2015 period were compared to the characteristic value of *average of maximal annual flows* (SWQ), which for Lądek Zdrój and Lębork were 50.5 m^3s^{-1} and 14.2 m^3s^{-1} respectively. Every value from data series higher than SWQ was removed from the string to further computations. Using SWQ flow series threshold ensures that extreme values derived by natural and unpredictable flooding are excluded (have no influence) from the analysis.

2.2 Potentially available energy

The energy accumulated in flowing air masses (E_W) can be calculated based on formula [16]:

$$E_W = 0.5 \cdot A \cdot \rho_{air} \cdot v_{wind}^3 \cdot t \tag{3}$$

where: A is the wind turbine area (m^2), ρ_{air} is the density of air (1.2 kg/m^3), v_{wind} is the current wind speed (m/s) and t is the time.

The energy which can be generated by a perfect hydrokinetic system (E_{HKT}) can be expressed as [17]:

$$E_{HKT} = 0.5 \cdot A \cdot \rho_w \cdot v_{water}^3 \cdot t \tag{4}$$

where: A is the hydrokinetic turbine area (m^2), ρ_{water} is the density of water (1000 kg/m^3), v_{water} is the current water flow speed (m/s) and t is the time.

Potential of solar energy has been directly taken from irradiation time series.

2.3 Power sources characteristics

In order to simulate energy generation from wind and hydrokinetic turbines their power curves were applied (see Figure 3 and 4).

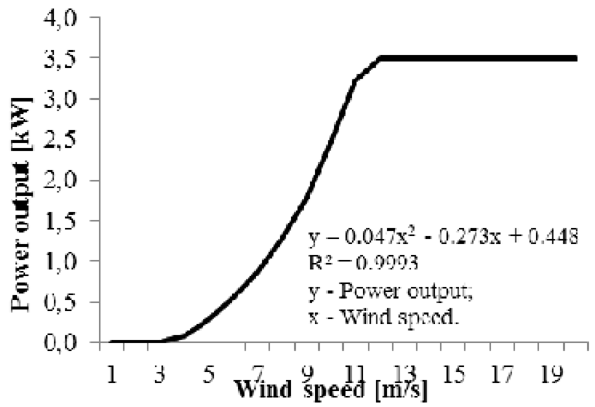


Figure 3. 3.5 kW Sonkyo Windspot HAWT power curve. Second degree polynomial approximates power output for wind speed ranging from 4 m/s to 12 m/s. Data source [18].

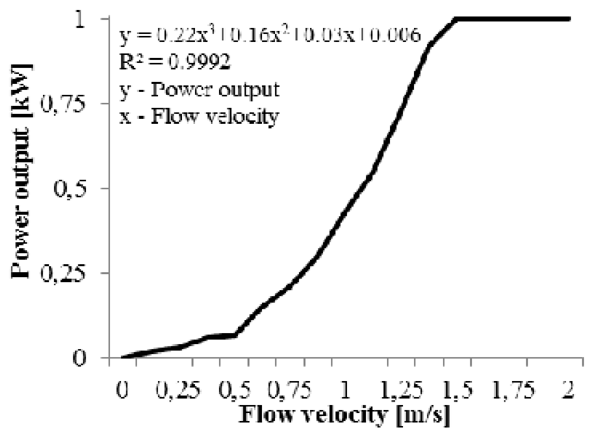


Figure 4. 1.0 kW DHT power curve. Third degree polynomial approximates power output for wind speed ranging from 0 m/s to 1.5 m/s. Data source [19].

Small scale units were selected because of the assumption that they will be used for household purposes. In case of hydrokinetic turbine its energy output has been multiplied by 3.5, because its nominal power is 1 kW and the goal was to make it comparable with wind turbine. The nominal power of PV installation has been assumed to be also 3.5 kW. Energy generation from PV system has been calculated based on formula:

$$E = \frac{G\, P^{PV}}{STC} \eta^{PV} \tag{5}$$

where: E – energy yield [kWh], G – global irradiation [kWh/m^2], P^{PV} – nominal power of PV installation [kW] η^{PV}- overall efficiency [%], STC – standard testing conditions irradiance [kW/m^2].

3 Results and discussion

This section is divided into three parts which describe obtained results. Two first sections deal with complementarity of: potential energy and energy generated based on power sources individual characteristics.

3.1 Complementarity of potential energy

As it has been already said, considered in this study energy sources tend to vary in time and space. Figures 5-8 illustrate this variability over seven consecutive days for both sites in January and June. Please note that the maximal available energy per hour is three times smaller in January than in June. Figures 5-8 additionally indicate that the energy from coming from flowing water has bigger potential than other two energy sources to operate as a base load power unit.

Table 1 summarizes basic statistical parameters of solar, wind and hydrokinetic energy time series over the year 2014. One statistical measure which is not sensitive to the range of time series values and therefore enables comparison among those energy sources is the coefficient of variation (CV) defined as a ratio of the standard deviation to the mean. Values of CV in Table 1 indicate that in case of Lądek Zdrój solar energy is the one with lowest variability, whereas in Lębork it is hydrokinetic energy. In both sites wind energy have the greatest value of CV. Differences in CV values in case of hydrokinetic energy can be attributed to the regimes of those rivers. Biała Lądecka River in Lądek-Zdrój has a mountainous catchment with a relatively rapid outflow. Biała Lądecka catchment is in addition six times smaller than the lowland catchment of Łeba River which flows through Lębork.

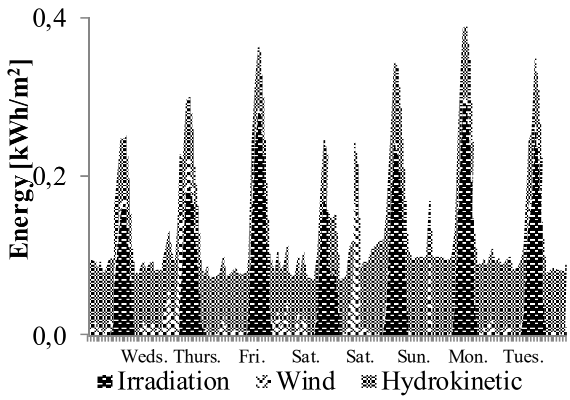


Figure 5. Energy available from an area of 1 square meter during first seven days of the year 2014 in Lądek Zdrój.

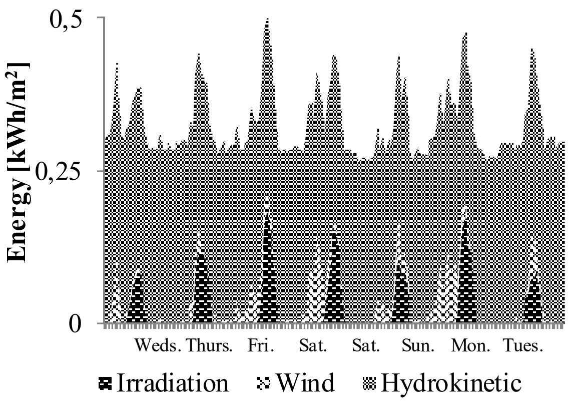


Figure 6. Energy available from an area of 1 square meter during first seven days of the year 2014 in Lębork.

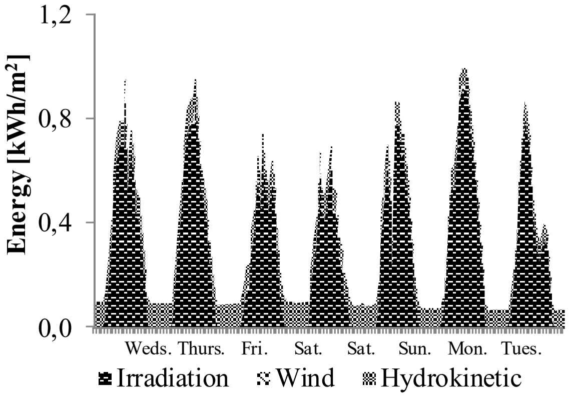


Figure 7. Energy available from an area of 1 square meter over the period 18-24.06.2014 in Lądek Zdrój.

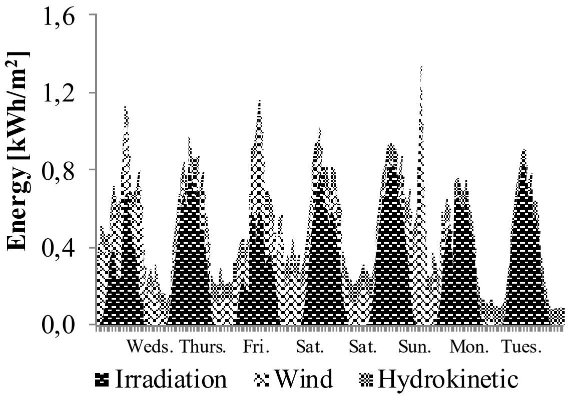


Figure 8. Energy available from an area of 1 square meter over the period 18-24.06.2014 in Lębork.

From the perspective of hybrid power source design and optimisation the potential and temporal complementarity of energy sources play crucial role. Perfect temporal complementarity can be described as a situation when dwindling amount of energy available from one source is instantaneously replaced by energy available from another one. A statistical parameter which is often used to calculate this phenomenon is correlation coefficient (CC) which gives values between +1.0 and -1.0 inclusive. Already mentioned perfect temporal complementarity is observed when the value of CC is equal to -1.0.

Table 1. Statistical parameters of investigated time series in over the year 2014.

	Lądek Zdrój		
	Irradiation	Wind	Hydrokinetic
Mean [kWh]	0.139	0.005	0.130
StD [kWh]	0.215	0.017	0.261
CV [%]	154.2	298.3	200.6
Var [kWh^2]	0.046	0.000	0.068
	Lębork		
	Irradiation	Wind	Hydrokinetic
Mean [kWh]	0.136	0.056	0.159
StD [kWh]	0.213	0.125	0.095
CV [%]	156.1	221.2	60.0
Var [kWh^2]	0.213	0.125	0.095

key: StD – standard deviation, CV – coefficient of variation, Var – variation.

Tables 2-5 present values of CCs calculated for various time steps. Values above diagonal (filled with 1.0) refer to Lądek Zdrój, whereas those bellow to Lębork. In case of annual sums of potentially available energy (Table 1) only hydrokinetic and solar (here denoted as irradiation) in Lębork exhibited beneficiary negative CC value. It means that during "sunnier" years one should expect lower potential of hydrokinetic energy. Moderate dependence (CC value of 0.478) can be also observed in case of wind energy and irradiation in case of Lądek Zdrój – this means that a year abundant with wind energy may be also have good potential for solar energy.

Table 2. Temporal complementarity based on annual sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	0.478	-0.296
Wind power	-0.316	1.000	-0.200
Hydrokinetic	-0.633	-0.044	1.000

Table 3. Temporal complementarity based on monthly sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	-0.590	0.172
Wind power	0.363	1.000	-0.178
Hydrokinetic	-0.480	-0.211	1.000

Table 4. Temporal complementarity based on daily sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	0.013	0.011
Wind power	-0.228	1.000	-0.018
Hydrokinetic	0.034	-0.027	1.000

Table 5. Temporal complementarity based on hourly values

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	0.013	0.011
Wind power	0.054	1.000	-0.018
Hydrokinetic	-0.186	-0.043	1.000

Table 3 focuses on monthly sums of individual parameters. Interesting value of CC (from the perspective of complementarity) occurs in case of wind and solar energy (Lądek Zdrój) and solar and hydrokinetic energy in Lębork. Both exhibit moderately negative values, which implies that they may be to some extent complement one another. Analysis conducted from the perspective of daily sums and hourly values of irradiation, wind and hydrokinetic energy did not reviled any significant correlation between those time series. This indicate that the complementarity on a daily and hourly time scale does not exist. But one must bear in mind, that those energy sources will still exhibit some individual daily patterns of available energy as it is the case of monthly values (see Figures 9-10).

3.2 Complementarity of energy considering power sources characteristics

Potential energy of wind, solar radiation and flowing water differes from the energy which can be derived from generators using them. This is due to the individual characteristics of: PV modules or wind and hydrokinetic turbines. For example wind turbine is characterized typicaly by three values of wind speed. One is know as *cut-in* speed – that is when blades start to rotate, *rated* speed – when turbine generated power at its rated capacity and finally *cut-off* speed when the wind velocity is to fast and blades have to be stoped from safety reasons. Thats the main reason is why not whole potential wind energy can be converted into electricity.

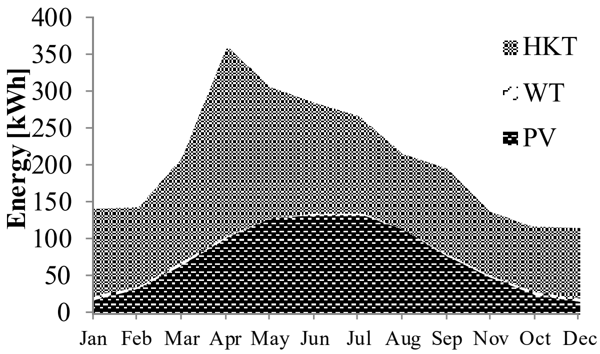


Figure 9. Mean monthly sum of energy generated per kW of installed capacity of given power source in Lądek Zdrój.

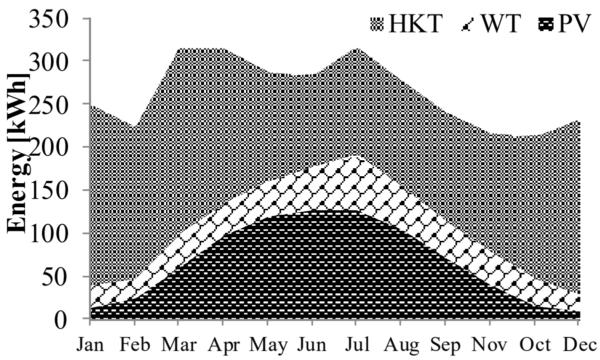


Figure 10. Mean monthly sum of energy generated per kW of installed capacity of given power source in Lębork.

Additionally please take a look at power curves depicted in Figures 1-2 and exponent for speed in formulas 1-2. Basically if wind speed increasy two times, then the energy output may increase eight times. Presented above short characteristic of wind turbines principles of operation are the main reason for conducting the analysis of CC values once again. This time for time series exhibiting energy generated. Figures 9-10 depict mean monthly sums of energy generated from different power sources with rated capacity of 3.5 kW each. A peak observed in Figure 9 in case of HKT can be attributed to thew (Lądek Zdrój is situated in Kłodzka Basin sourounded by Śnieżnik Masiff and Złote Mountains).

Comparison of values presented in Tables 2-5 and Tables 6-9 shows a significant increase in the correlation coefficient between hydrokinetic and solar energy in case of Lądek Zdrój (Table 6) which was calculated based on annual sums. The value of this CC i s greatest of all observed. It indicates that a year with smaller sums of irradiation may be also a year with greater availability of hydrokinetic energy. One more change was observed in case of daily sums in Lębork. The CC value between irradiation and hydrokinetic energy has significantly decreased. It is still rather relatively low, but may indicate that during sunny day energy generation from hydrokinetic turbine may be lower, this may be of course not the case of for example spring when irradiation and temperatures above 0°C might lead to thaw and greater energy yield from HKT.

Table 6. Temporal complementarity based on annual sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	0.194	-0.692
Wind power	-0.289	1.000	-0.049
Hydrokinetic	-0.596	-0.097	1.000

Table 7. Temporal complementarity based on monthly sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	-0.522	0.205
Wind power	0.369	1.000	-0.149
Hydrokinetic	-0.463	-0.218	1.000

Table 8. Temporal complementarity based on daily sums

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	-0.192	0.076
Wind power	0.139	1.000	-0.021
Hydrokinetic	-0.385	-0.069	1.000

Table 9. Temporal complementarity based on hourly values

Lądek Zdrój/ Lębork	Irradiation	Wind	Hydrokinetic
Irradiation	1.000	-0.030	0.029
Wind power	0.055	1.000	-0.012
Hydrokinetic	-0.190	-0.056	1.000

3.3 Energy generation values

Using hybrid renewable system when energy sources do not perfectly complement one another will entail usage of energy storage device. In case of small residential hybrids usually acid-lead or lithium-ion batteries would be applied. However batteries are costly and their longevity depends on their operation regime. It is not recommeded to deeply discharge them. Combining different power sources, which are to some extent complementary may enable battery bank capacity redcution and prolong its operation. Assuming that load is continuous (there are no periods with zero load) please take a look at Figures 11-18. If battery bank is being charged only from one source of energy (e.g. PV or WT) there will often occure situations when there is energy demand but it all must be covered from battery bank. This is the case especialy for WT in Lądek Zdrój or PV in both locations. The former results from daily availability of solar energy, which for each point on the Earth can be calculated based on clear-sky models.

Figures 17-18 indicate that combining all those energy sources makes energy more available – meaning that it is generated almost all the time. However volume of its generation may be sometimes relatively small.

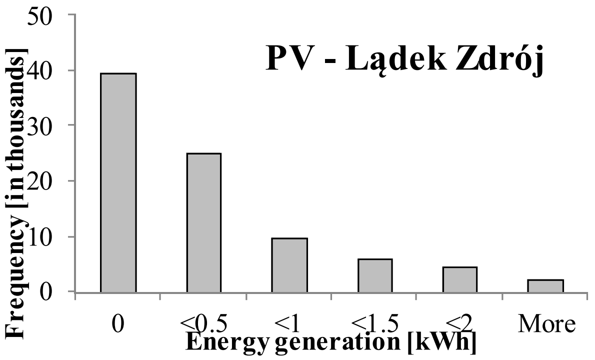


Figure 11. Histogram of energy generation values from PV in Lądek Zdrój covering period 2006-2015.

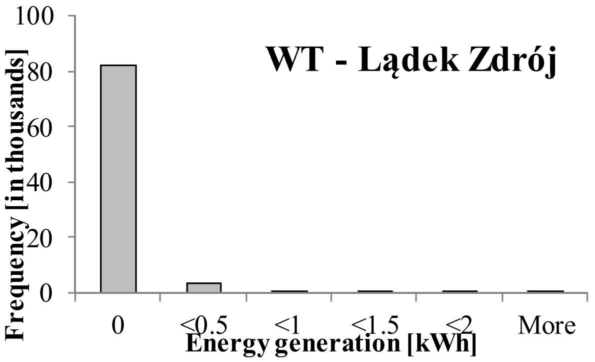


Figure 12. Histogram of energy generation values from WT in Lądek Zdrój covering period 2006-2015.

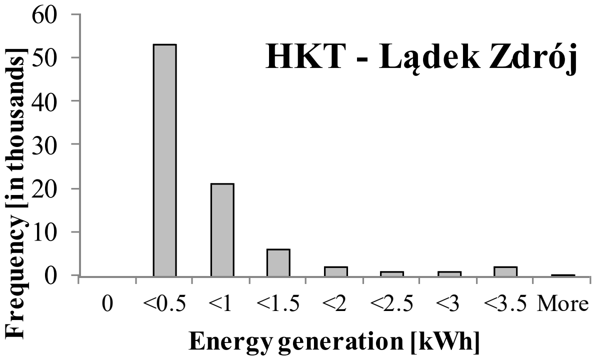


Figure 13. Histogram of energy generation values from HKT in Lądek Zdrój covering period 2006-2015.

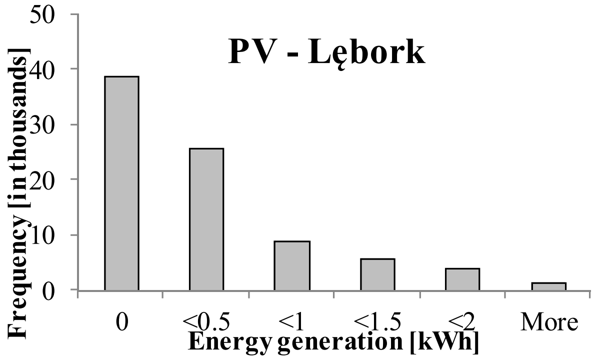


Figure 14. Histogram of energy generation values from PV in Lębork covering period 2006-2015.

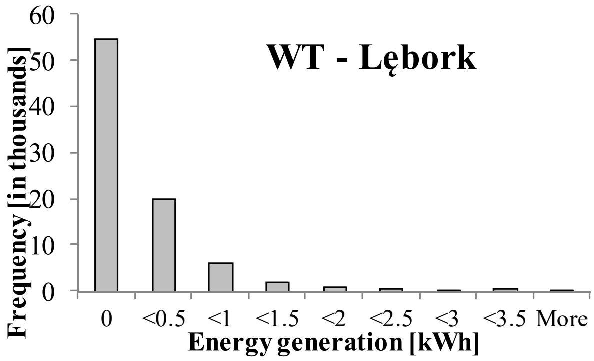


Figure 15. Histogram of energy generation values from PV in Lębork covering period 2006-2015.

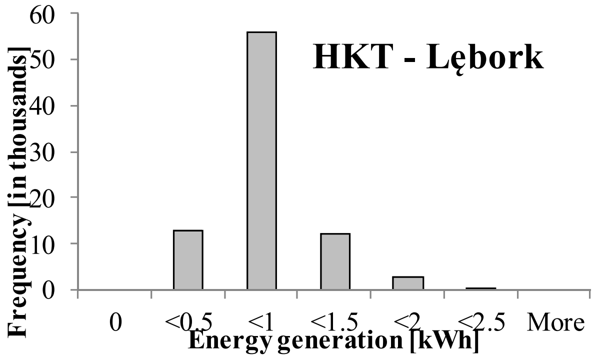


Figure 16. Histogram of energy generation values from HKT in Lądek Zdrój covering period 2006-2015.

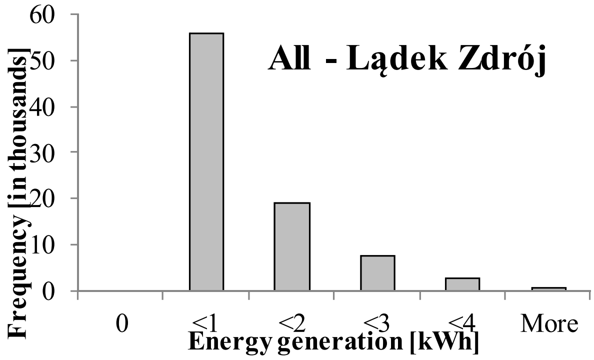


Figure 17. Histogram of energy generation values from PV-WT-HKT (3.5 kW per each source) in Lądek Zdrój covering period 2006-2015.

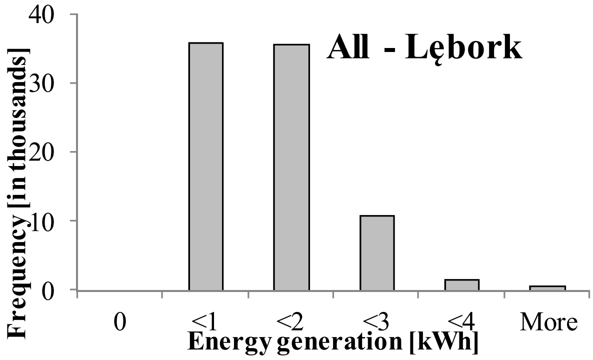


Figure 18. Histogram of energy generation values from PV-WT-HKT (3.5 kW per each source) in Lębork covering period 2006-2015.

4 Conclusions

According to the authors' knowledge the study described in this paper was the first one ever conducted. There are many papers which dealt with energy sources complementarity. However only several studies investigated this concept from the perspective of three types of energy sources. Additionally instead of hydrokinetic so far conducted research concentrated on large-scale hydropower which utilizes the potential energy of falling water masses. Results obtained from this analysis point to a moderate complementarity between solar and wind, solar and hydrokinetic energy on the annual and monthly time scale. Values of complementarity indices are not as spectacular as in referenced papers. This may be due to the fact that this study focused on small scale power sources, and to some extent the potential of wind energy may be distorted. Wind speed values were taken from measurements conducted 10 meters above the ground level, whereas industrial wind turbines are utilizing winds which are blowing 100 meters or more above the ground and are more stable. However obtained results indicate that development of polish energy sector should be to some extent based on RES that complement each other despite the fact that in some situations energy yield from a given source in certain locations may not be economically justified. What is more, in order to overcome problems (namely variability in energy output) encountered in case of power sources utilizing single RES one may use complementary energy sources such as wind and solar – as for example shown in [23].

After conducting this analysis there seems to be several interesting directions for future research. First of all, more sites representing various wind availability patterns and river regimes should be analyzed. Secondly a study should be conducted in order to determine the minimal needed storage capacity considering standard household load profile and various combinations of power sources.

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