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Assessment of Climatological Impact on Renewable Energy Sources in the Gulf of Finland

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ABSTRACT
Study of the joint daily variability of wind speed and solar activity in the Gulf of Finland and its impact on renewable energy sources. The combined distribution of the daily mean insolation and wind speeds shows that insolation has a much stronger seasonal cycle than wind, due to the tilt of the Earth's rotation. Weak anticorrelation dependences of the air masses movement and solar insolation are obtained, additionally weak tendency between windy days and cloudiness is obtained. The influence of external factors on the variability of total output power of ground-based wind turbines and solar photovoltaic panels is investigated. To a small extent, wind turbines are able to complement the generation of renewable energy sources: 15 % –30 % wind turbines and 70 % –85 % solar photovoltaics is preferable ratio of renewable energy sources. The study aims to demonstrate the potential of hybrid renewable energy sources in severe weather conditions, the possibilities for increasing and optimizing energy generation.

Keywords: *Renewable energy, Photovoltaics, Hybrid renewable energy systems, Wind turbines, Correlation of climatic parameters, Optimization of renewable energy systems.*

1. INTRODUCTION

Moving away from traditional fossil resources and tendencies towards less pollution from burning fossil fuels will lead the world to a low-carbon future. In solar photovoltaic (PV) technology, significant progress has been made in using a powerful, clean and sustainable energy source to meet the energy demands of humankind [1, 2]. But in some remote regions, climatic restrictions can affect the operation of photovoltaic systems. Northern regions and regions of sub-continental, continental and sub-arctic climatic zones cannot fully rely on photovoltaic systems. In this study, we explore the possibilities of introducing photovoltaic systems with additional renewable energy sources.

Wind and solar energy are highly variable and extremely unstable [3,4]. Variability of output parameters can be affected by weather fluctuations on timescales ranging from minutes and hours, to days and seasons, and even to climatic changes occurring over many years and decades. Therefore, for the rational and efficient use of renewable energy, it is important to understand the relationship between the energy generated by wind and solar PV modules, and the degree of variability due to which it is possible to balance the lack of energy in one source with another. This has important practical implications in terms of demand for energy storage and/or reserve capacity (i.e., gas or nuclear power plants), as well as for operational requirements of electrical networks.

There are many studies on the assessment of the external factors impact, interchangeability, forecasting and optimization of variable weather conditions, which directly affect the performance of electricity generation using renewable energy sources (RES). The authors of the study, using the example of Italy [5], found that the specific locations of the study sites are weakly associated with changes in the predicted values of energy generation in Italy. In other work of the authors Heide et al. [6, 7] modelled the demand for energy consumption in Europe, in terms of energy storage and balancing, in accordance with a hypothetical scenario of using renewable energy sources. This study was compiled on the basis of the forecast of energy production from wind and solar energy according to consumption, using data from 2000–2007. Based on the results of this study, conclusions were drawn about the possibility of an optimal balance of wind and solar potential, which requires large storage volumes to meet demand. They show that the volatility of RES can be balanced out by storing excess energy. Other studies have also focused on finding the optimal mix of wind and solar energy for different regions and using data covering different periods [8–10], and studies usually show that the inclusion of several types of RES reduces the volatility in electricity generation, reducing the need for storing excess energy [11, 12].

Analysis of articles devoted to the climatic investigation of the Gulf of Finland demonstrated it as a region with a high wind potential [13]. The Gulf of Finland is quite shallow: its average depth is 40 meters, and in the area of the Neva Bay is about 8 meters. Therefore, most of its territory is unsuitable for sailing and remains unused. However, such conditions are enough for the installation of wind turbines, since the depth to which the wind turbine mast can be installed does not exceed 30 meters. There are technologies for installing “wind turbines” at great depths, the so-called floating wind turbines, but the cost of their installation is much higher than in the case of fixed alternatives.

Biggest part in climate formation is devoted to Gulf of Finland roles [14]. Seasonal dynamics of air temperature over the water area is typical for temperate latitudes. The lowest air temperatures are observed in February, and the highest in July. The average monthly air temperature in July-September and March-April is practically the same throughout the bay. In July 17–18 ºC, in August 16.5-17.5 ºC, on September 11–12 ºC, on March 1–2 ºC, on April 2–3 ºC. On average, westerly, south-westerly and southerly winds prevail over the bay during the year (their frequency exceeds 50%), as a rule, the strongest ones. Less common are east and north winds [15]. The general character of circulation processes in the atmosphere over the North-Eastern regions of the Baltic Sea is determined by the influence of the transfer of air masses from the Atlantic Ocean.

The main differences of this study are in considering the Gulf of Finland as a region with a high wind potential, making it possible to compensate the lack of solar activity. Prior to this, the Gulf of Finland region was not considered for the introduction of renewable energy sources, therefore, the main focus of the study is focused on the complementarity of solar-wind energy, without introducing the features of the distribution of the energy supply network in various countries of the region under consideration. Also, a more generalized approach to considering climatological impacts is associated with the constant development of power supply networks, which can limit and make information irrelevant.

2. METHODOLOGY

Most of the local variability in solar illumination is directly related to the tilt of the Earth's axis of rotation in relation to its orbit. This leads to a change in both the total number of hours of daylight and the total intensity of the incident radiation (number per unit area). These “astronomical” factors have two key characteristics: they are completely predictable and dominate the seasonal variability of illumination.

To eliminate the seasonal influence of the inclination of the Earth's rotation on illumination, an additional parameter was introduced that describes the amount of illumination reaching the surface without the influence of cloudiness [16]. For this, the ratio of the total (global) incident illumination G to the daily average descending illumination in a clear sky (no clouds), G_{cs}, was considered. Then we can assume that the ratios of these brightness are the same; let's call this value the surface cleanliness:

$$k_S = \frac{G}{G_{cs}} \quad (1)$$

This contrasts with the traditional definition of the (global) clearness index kT, which is the ratio of surface illumination to that obtained in the upper atmosphere, that is, before any kind of atmospheric absorption. In our study, we want to compare the illumination obtained on the surface with that which would be obtained on the surface in a clear (cloudless) sky, that is, in the absence of the dominant meteorological factor, clouds coverage.

Additionally, the approximate power generation capacities were calculated by solar PV elements and wind generators both at individual points in the region and as the region average, dividing them into separate seasons (winter / spring / summer / autumn).

3. RESULTS AND DISCUSSION

3.1. Distribution of daily mean values

During the analysis of the wind potential of the region under consideration, 5 points were selected on the map with the most different indications of wind activity. Meteorological stations were taken as geographic points. The list of points under consideration is presented in the Table 1.

Table 1. Meteorological stations in the investigated region

Station index	Geographic location	Measurement period
26045	Kunda, Estonia	01.01.2003-31.12.2012
2976	Kotka, Finland	01.01.2001-01.01.2011
22897	Ozerki, Leningrad Region, Russian Federation	01.01.2003-15.06.2004 31.08.2012-31.12.2012
22892	Vyborg, Leningrad region, Russian Federation	01.01.2003-31.12.2012
26063	Saint Petersburg, Russian Federation	01.01.2003-31.12.2012

Figure 2 shows the distribution of wind speed throughout the year at the points under consideration. As you can see, the highest wind speeds reach in the west and northwest of the Gulf of Finland. At selected points, using NASA's POWER (Prediction of Worldwide Energy Resources) Single Point Data Access Viewer, the average daily climatological data for the period 2015–2020 were obtained: global insolation, clear sky insolation, wind speed at an altitude of 10 m. Based on this information, the dependences of the joint distribution of wind and solar potential were constructed in the considered geographical points.

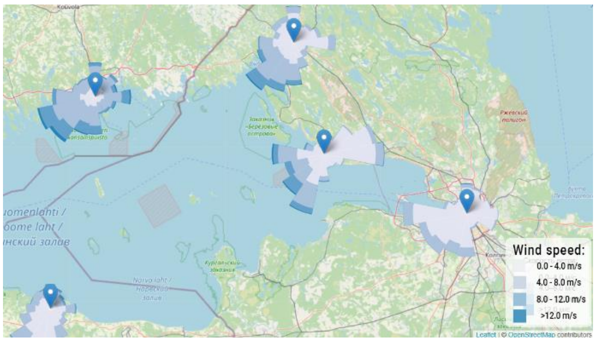

Figure 1. Map of the considered points of the Gulf of Finland [13].

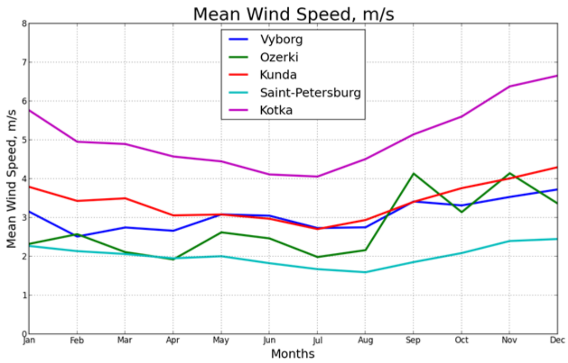

Figure 2 The graph of the distribution of the average annual wind speed in the study region [13].

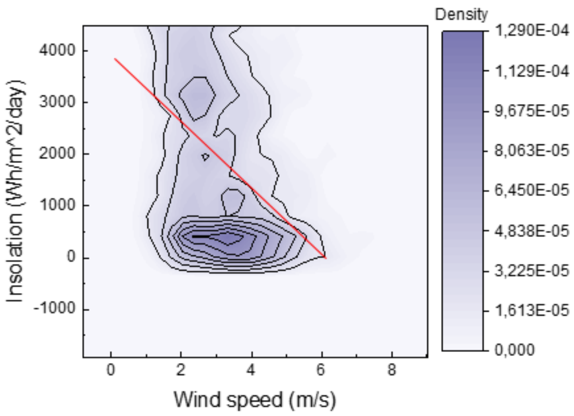

Figure 3 Joint distribution of the average daily wind speed at a height of 10 m and the total incident surface illumination in the Gulf of Finland.

The results of the joint distribution based on the readings of five geographic points demonstrate a general anticorrelation of the dependence of the surface irradiance (insolation) from the wind speed; this is also confirmed by the Pearson correlation, where the value of ρ = -0.37 corresponds to the inverse relationship. The red line represents the linear regression of the values. A similar study of the distribution of the cleanliness index and wind speed at a height of 10 m (Figure 4) confirms this statement.

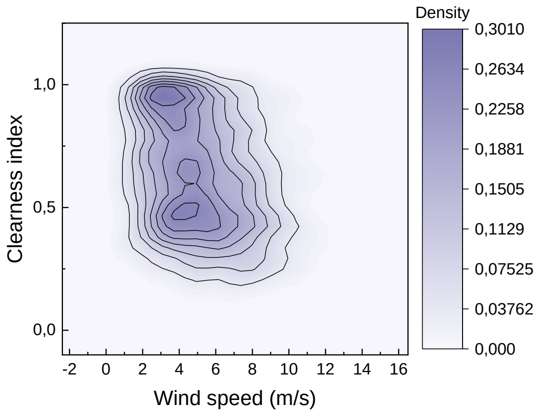

Figure 4 Dependence of the Clearness index and the wind speed in the region under consideration.

Additionally, the work investigated the joint distribution of climatic parameters by "seasons". The division into seasons was, according to the meteorological definition, “seasons.” This means that winter season consists of the months December, January, February. This is due to seasonal lags, limiting temperature response, and other climatic changes throughout the year, which can affect changes in illumination reaching the upper atmosphere.

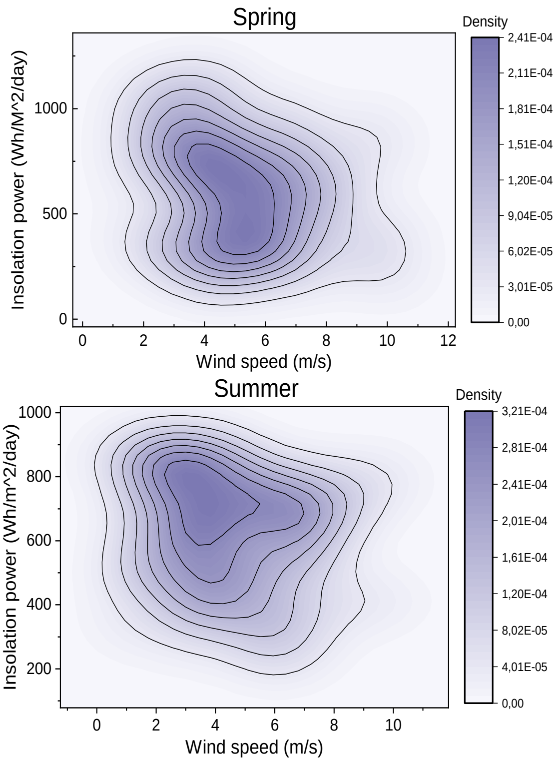

Figure 5. Average seasonal values of insolation distribution in different seasons from wind speed in the investigated region

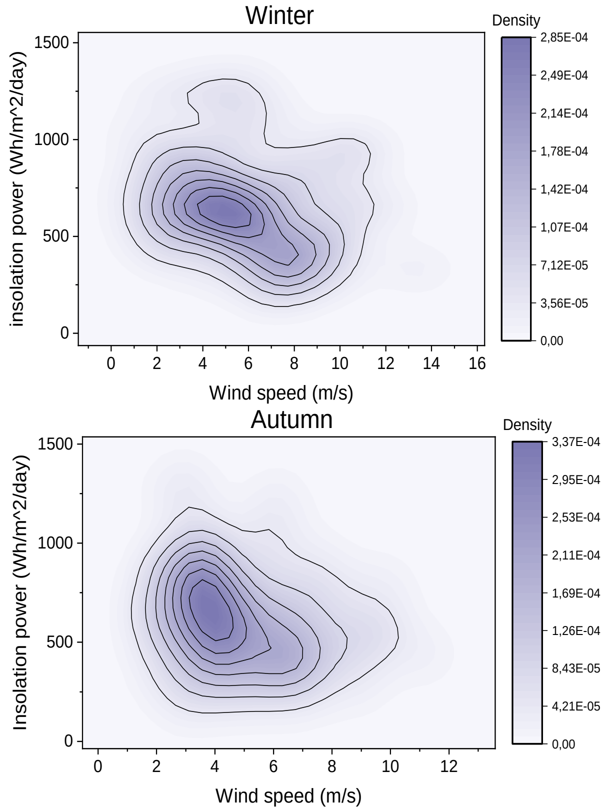

Figure 6 Average seasonal values of insolation distribution in different seasons from wind speed in the investigated region.

The following results were obtained for the joint distribution of wind speed in the region from the total insolation on the surface, shown in Figure 5, 6.

Based on Figure 5, 6, despite the overall higher solar activity in summer and spring, the largest range of values of wind and solar potential is achieved precisely in winter. The more dynamic atmosphere of changes in winter allows more parameters to be included in the distribution, complementing the lack of solar activity. This means that the Pearson correlation value will be closer to zero in winter than in summer, which leads to a greater dependence of the number of cloudy days and wind speed.

Based on the data obtained, it is possible to form an approximate forecast of electricity generation using solar photovoltaics and wind turbines.

3.2. Wind turbine

Most wind turbines use a power curve with certain critical wind speeds when the turbine starts generating energy ('cut-in', Uci), when it is mechanically limited by its operating or rated power (U_r) and when the wind turbine is cut off for safety reasons in strong winds (cut-out, U_{co}). For most wind turbines, the height of which does not exceed 10 m, the power curve corresponds to Figure 7.

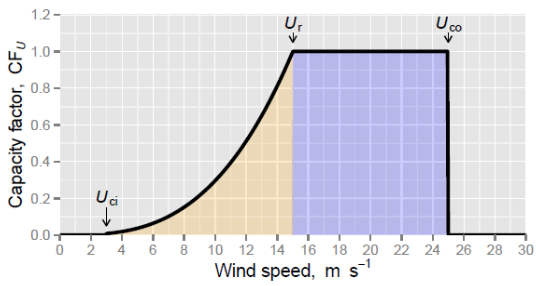

Figure 7 Power curve of the wind generator, orange power means the initial wind speeds for generating electricity, the blue area means operating wind speeds.

$$P_r = \frac{1}{2}\eta U \rho \pi R^2 U^3 \quad (2)$$

$$P_U = \begin{cases} 0, & U < U_{ci} \\ P_r\left(\frac{U}{U_r}\right)^3, & U_{ci} \le U \le U_r \\ P_r, & U_r \le U \le U_{co} \\ 0, & U > U_{co} \end{cases} \quad (3)$$

In most cases, it is not necessary to indicate the efficiency η or the blade radius R, if the wind power factor $CF_U = P_u/P_r$ is calculated instead. In this case, a minimum of information about the turbine is required, leaving the results more general. It is important to note that this article only uses daily average wind speeds for this estimate, when in fact the power curve wind speed thresholds are defined for instantaneous wind speeds. The power curve shown is only an approximation of the actual behavior of the wind turbine. All turbines exhibit significant power output scatter depending on their rated power curves [16, 17].

3.3. Photovoltaics

The power output of a solar PV panel depends on both the total incident insolation *G* and the ambient temperature *T*. In case of PV elements, the power of the photovoltaic panel will be determined by the expression:

$$CF_G = \frac{P_G}{P_{STC}} \equiv \eta_{REL}(G,T)\frac{G}{G_{STC}} \quad (4)$$

In this case, the output power of the photovoltaic panel will directly depend on the ambient temperature T, its illumination G. G_{STC} P_{STC} are the parameters of insolation and power of the panel under standard operating conditions of the photovoltaic panel, respectively. Using the values of the NASA POWER Access Viewer, the amount of incident light and air temperature at a height of 2 m, it is possible to estimate the power generated by the solar panel.

As seen on Figure 8, the prevalence of low wind speeds for longer periods and limited solar activity throughout the year greatly reduce the overall output performance of hybrid systems. Compensation for shortages of certain types of energy must be done rationally, and the ability of solar cells to compensate for lulls in wind energy in winter must be balanced against the risk of increased volatility in summer. As a result, significant variability of wind resources during winter periods is compensated by an increase in average wind speed during winter periods.

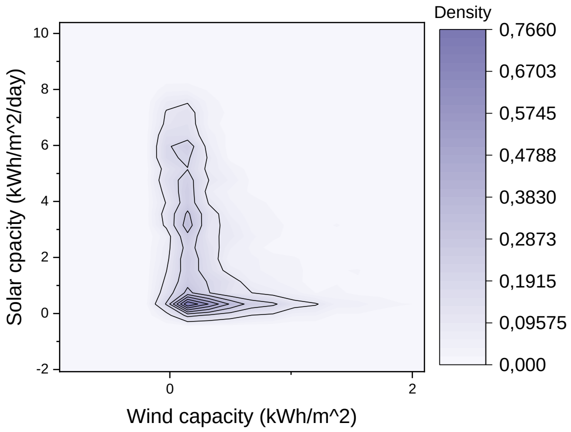

Figure 8 Joint distribution of average daily production rates of solar photoconverters and wind turbines.

4. CONCLUSION

This work considered the potential of the Gulf of Finland as a region for the introduction of renewable energy sources. A solution was proposed to use wind turbines in conjunction with photovoltaic panels. A hybrid approach to the use of renewable sources makes it possible to compensate for the shortage of one of the resources during periods of variable climatic conditions. The study of the region showed that there is a dependence in which solar activity decreases in winter periods and the production of solar energy using photovoltaics. However, in winter periods the average wind speed increases, which makes it possible to implement wind generators.

During the study, it was revealed that the average daily insolation throughout the year in the Gulf of Finland weakly correlates with the wind speed. Pearson correlation value is $\rho \approx -0.37$, which is associated with the cyclical movement of air masses and periods of insolation changes throughout the year. With the exclusion of the influence of the variability of insolation (clear sky insolation only), the correlation dependences remain.

It has been shown that the bulk of electricity is actively generated during most of the year (spring - summer) while the wind generator is active during winter. Accordingly, when solving the issue of optimizing and balancing the components of hybrid systems, the main emphasis should be placed on photovoltaics, devoting at least 60% of overall electricity generation. With the right approach and stimulation of the development of wind and renewable energy in general, even in a short period of winter, it is possible to obtain high efficiency rates due to a wide range of average wind speeds and high average wind speeds.

In further studies, we plan to perform more detailed modeling of the operational features of hybrid renewable energy systems. In order to do this, we want to include modeling software and experimental data on climatic parameters to get as close as possible to real production rates and values.

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