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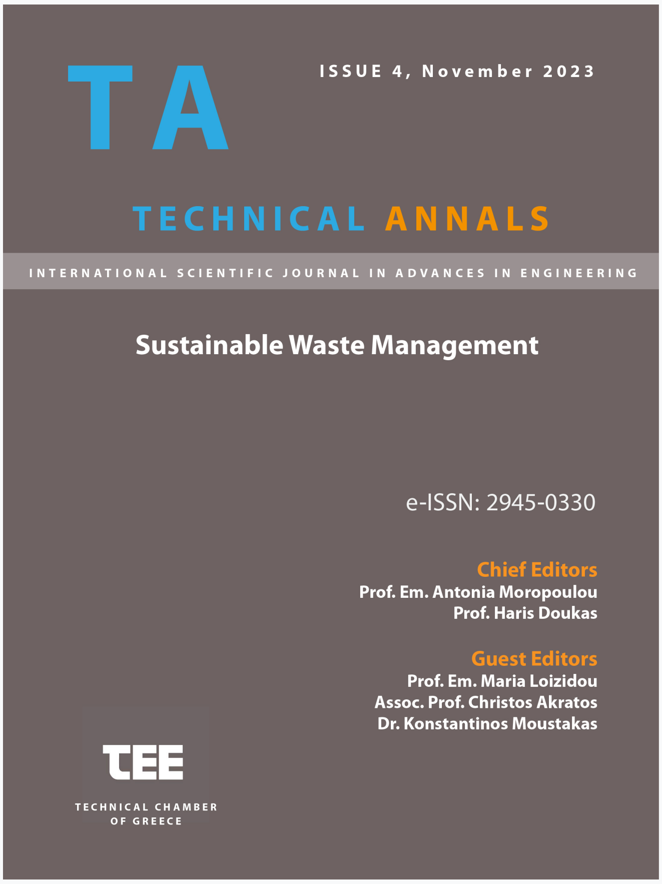

Exploring the Feasibility of Solar and Wind Energy Utilization in Poland: A Hybrid Energy Mapping Approach

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Exploring the Feasibility of Solar and Wind Energy Utilization in Poland: A Hybrid Energy Mapping Approach

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Abstract. Poland is obliged to reach the target of 21% share of renewable energy sources in gross final energy consumption by 2030. Thus, it makes it necessary and obligatory for the country to expand its wind and solar power generation. This research presents the preliminary process of creating the hybrid energy map for the country that would make it simpler both for the government and the enterprises to choose the available siting location. Geodata is assessed along with the siting constraints in a spatial analysis by using Geographic Information System (GIS), encompassing infrastructural constraints, land use, and renewable energy resources. The final outcome of the paper is the visual hybrid energy map of Poland showing the available space for both wind and solar farms.

Keywords: hybrid energy map, Poland, GIS, wind power, solar power.

1 Introduction

1.1 Problem background

Nowadays, climate issues are one of the most important topics being discussed worldwide. The problems with energy supply and use are not only just related to global warming, but also to environmental concerns such as air-pollution, forest destruction, and ozone depletion [1]. It is a serious problem, and it requires a massive transformation of the world's energy infrastructure - ideally to 100% clean, renewable energy (RE) producing zero emissions, as suggested by Jacobsen et al [2]. It is extremely clear that faster expansion of renewable energy systems is a necessary requirement for a sustainable energy future [3]. That is why there are currently five main support mechanisms of electricity from renewable energy sources (RES) in the EU that are implemented: investment subsidies, fixed price mechanisms, fixed premium mechanisms, quota system based on auctions or tradeable green certificates [4]. As a result, the EU introduced a renewable energy directive EU 2018/2001/EU.

Due to the before mentioned directive from EU 2018/2001/EU, Poland received a new bidding RE target of 21% share of RES in gross final energy consumption by 2030 (EU, 2018). The gross final energy consumption includes the aggregate consumption in the electricity sector, heating, and cooling sector, as well as for transport purposes. The target for 2020 is 15% [6]. According to Główny Urząd Statystyczny, Poland has reached 12.18% share of RES in 2019 [7]. However, Figure 1 shows that the total installed capacity of RES in 2019 was 20.1% including biomass and biogas.

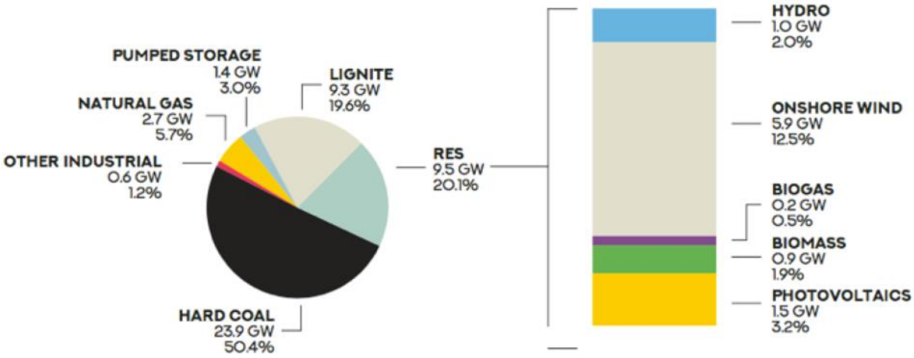

Fig. 1. Installed Capacity in the Polish system at the end of 2019 [8]

The focus of this study is based on Poland which has an area of 306 230 square kilometres and almost 38 million inhabitants [9]. It is a rather low-lying country with 91% of its territory lying below 300m above sea level [10]. Poland is the 9th largest country in Europe and has a variety of geographical characteristics. Its coastline measures approximately 1,000km and is located in the north part of the country. Most of the country consists of many lakes and low hills. However, to the south of central lowlands the terrain rises slowly and becomes dominated by highlands. Along the southern border stretches the mountains. Only 3% of Polish territory is elevated higher than 500m above the sea level [10].

Figure 1 illustrates an overview of the installed capacity in the Polish system in 2019. According to the Główny Urząd Statystyczny, at the end of 2019 there has been a total installed capacity of 47,378 MW. It can be clearly seen that Poland remains dependent on thermals. Hard coal and lignite account for almost 70% of the total capacity. As this study focuses on wind and solar systems it is worth to take a look at them. Onshore wind installations account for 12.5% and photovoltaics to 3.2%. The current situation in Poland moves towards more renewable solutions but regrettably the hard coal and lignite are still the biggest players.

1.2 Problem formulation and research questions

The problem formulation and research questions justify the existence of this paper. In order for the reader to clearly understand and recognise the drive and the motivation of this report the problem formulation and research questions should be as detailed as possible.

Poland needs to create an energy infrastructure that has to comply with the EU directive and help the country reach its target of 21% share of RES by 2030. That can be done by developing the renewable energy sources. The main challenge identified by the author was to preliminary recognise the potential and available onshore wind power and solar power unit locations in Poland with consideration of possible constraints.

What are the prime locations in Poland with the greatest potential for wind and solar power generation?

Analysing the potential space for hybrid uses of solar and wind energy in Poland.

The main research question aims to identify the most suitable locations through geodata. In order to answer this question geodata will be collected and a map will be created with the use of GIS. The desired goal of the research is a hybrid energy map of Poland, where the available space for wind and solar farms siting is shown. In order to reach the outcome other sub questions shall be answered. The following research questions will narrow down the study and help answering the main problem.

1. What is the current status of renewable energy in Poland?
2. What are the advantages of utilizing hybrid resources, specifically wind and solar, such as a hybrid energy map for Poland?
3. Which constraints, including infrastructural elements like roads, railways, and water bodies, as well as land use factors such as buildings, were considered in mapping the potential areas suitable for hybrid energy use in Poland?

1.3 Methodology

This section's purpose is to outline and argue for the methodological choices, techniques and considerations that form the foundation of the report and its results. This paper uses both quantitative and qualitative data and is a combination of a theoretical research and data analysis. As a starting point, quantitative data is being collected and analysed using a numerical analysis. Furthermore, it is supported by desk research, gathering open-source, and free geodata.

The selection of mixed-method approach has been made to enable the researcher to answer the research questions in a more reliable way [11]. Hybrid solar-wind map has been conducted within the use of QGIS tool and previously collected geodata. In the following section a short introduction to Geographical Information System is given as it is the main application used in this paper.

1.4 Use of Geographical Information System

Use of QGIS software is the base of this report. It is used to collect and analyse geodata and visualise the developed artefact, the hybrid energy map of Poland. Thus, this section will explain how Geographical Information System (GIS) will enable the researchers to accomplish it.

According to (ERIS, 2020), GIS is a framework used by thousands of organizations in virtually every field. It helps them to make various maps that can communicate, perform analysis and share information around the world. There are obviously different ways to use GIS in many different areas and industries. However, this paper will aim to use GIS to create the final artefact by overlaying different constraint layers on top of each other in order to end up with one single map [12]. The software is able to differentiate between two types of data formats: raster and vector. Raster data (also called as grid data) represents the surfaces and it is cell-based [13]. Vector formats can be split into three types: points, lines and polygon data. Vector data can be used for example to store GIS data with firm borders such as roads. There are many different software tools available, but this paper uses the free and open-source QGIS tool, which is widely used and familiar to many researchers.

Poland is the second-largest coal-mining country in Europe and the ninth-largest coal producer in the world [14]. Coal is regrettably the most important primary energy fuel in the country and plays a big role in electricity production. Throughout the 90s, it delivered annually around 95% of total electricity production. Luckily, the share of other fuels (biofuel, gas, wind and solar) grew since mid-2000s and partially replaced coal [15]. This change happened as a result of EU climate and energy policies which enforced the use of renewables [16].

Nevertheless, this rather poor energy mix influences renewable development in Poland and traditional coal use is one of the barriers for renewables [17]. Additionally, there are many various factors that have impacted on the development of renewables in Poland, such as lack of long experience in renewables utilisation, low stability and unpredictable political framework [17].

Wind, biomass and waste were the largest source of RE in Poland [18]. Solar power is still at the last place of RES in Poland, but it has observed a drastic growth in the recent years. Wind energy has been intensively growing until it was halted in 201. Undoubtedly, it is an effect of unfavourable legal solutions for wind energy, in particular the Wind Farms Investment Act of May 2016 [17]. The most important output from this act is the distance in which wind farms can be located and built and it is to be around 1,5 – 2 km from housing regardless of the opinion of local residents [17].

The rationale behind selecting QGIS as the GIS tool for this study lies in its versatility, accessibility, and compatibility with the objectives of the research. QGIS, being an open-source software, provides a cost-effective solution for data collection, analysis, and visualization, aligning well with the aim of utilizing free and open sources for gathering geodata. Its robust functionality allows for the integration of diverse data formats, including shapefiles and TIFF files, which were the primary formats used in this study. Additionally, QGIS offers a user-friendly interface and a wide range of geospatial analysis tools, making it suitable for both qualitative and quantitative analysis required for this research. Furthermore, QGIS has gained popularity among researchers and practitioners in the field of GIS, ensuring ample resources and support for troubleshooting and implementation. Hence, QGIS emerged as the preferred choice over other software options due to its compatibility with the study's methodology, cost-effectiveness, versatility, and user-friendliness.

2 Theoretical background

This section will analyse the theoretical background of current renewable energy situation in Poland, with focus on wind and solar, and the hybrid renewable energy system. Furthermore, the use of GIS will be described and analysed.

This part will focus on the theoretical knowledge about the hybrid renewable energy systems and wind-solar energy systems. In order to see the benefits of creating a hybrid energy map, the theoretical background is going to be briefly discussed. Obviously, each system can be a standalone structure. However, there are advantages of considering implementation of a hybrid solution. This section aims to describe the use of hybridization of processes.

Hybrid renewable energy system (HRES) is, according to Khare, et al. [19], a combination of renewable and conventional energy source. Nevertheless, it can also combine two or more renewable energy sources that work in standalone or grid-connected mode.

Wind and solar energy are intermittent resources and are dependent on geographical and weather conditions [20]. Although each of the systems can work independently, none of them will generate accessible energy for noticeable portion of the year. Therefore, according to Abu-Hamdeh and Alnefaie, hybridization of wind and solar energy systems for electricity are usually more reliable and less expensive compared to standalone system. An example of the hybrid system will be shown in order to get the general understanding of the concept.

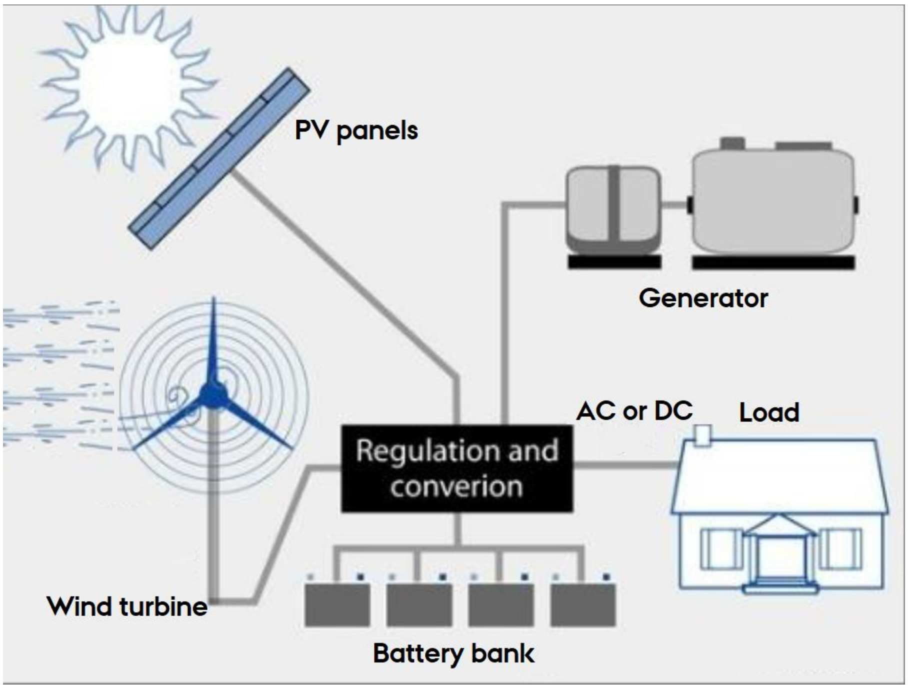

Fig. 2. A Schematic form of a hybrid power system [21]

Figure 2 shows the schematic of solar-wind hybrid system. As it can be seen the solar panels are being used to collect light and convert it to energy along with the wind turbines that collect energy from wind. In this case there is only one solar wind inverter that has inputs for two sources. It includes required AC to DC transformer to supply charge to batteries from AC generators. Eventually, the power from the solar panels and the wind turbines is filtered and stored in the battery bank [22].

The HRSE that combines both solar and wind energy key resources can operate in two modes: simultaneous and sequential. The difference between both is that the first one produces energy concurrently while the latter produces energy alternatively [19].

Taking into consideration the current situation of energy mix in Poland it is worth to notice that one of the main advantages of hybrid wind-solar system is generating approximately twice as much as solar or wind only systems.

Many different researchers have carried out on the development and assessment of the wind-solar hybrid systems. Ramli et al. [23] has presented a case study model based on the wind-solar system on the techno-economic energy analysis in Saudi Arabia. Furthermore, Khare et al. [19] presented a research study focused on different issues related to HRSE such as optimum sizing, feasibility analysis and control aspects.

There is a lot of research and studies conducted on that matter, however, this paper aims to describe the concept briefly to have the common understanding of the reader. To conclude, the solar-wind hybrid RE system is increasing day by day and has shown great development in the recent years for electricity production all over the world. Next section of the research will focus on the practical application of GIS in order to show the potential for solar-wind system implementation.

3 GIS mapping analysis

In order to answer the problem of this paper and the research questions, various data is required. The aim of this report was to utilise the free and open sources, such as Diva GIS, Geofabrik, Open Street Maps and GADM [24]. Afterwards, the acquired geodata was split based on the scope of the layers.

3.1 Data sources

The objective of this paper is to create a visualization of a hybrid energy map for Poland. In order to fulfil it and answer the research questions various data are required. Data were collected from numerous free and open sources. The base of the map was the wind and solar atlas. Wind map for Poland has been collected from Global Wind Atlas [25] and respectively, solar map for the same territory was collected from Global Solar Atlas [26]. Furthermore, other geodata required for the constraints have been collected from Diva and Geofabrik.

The infrastructural category includes layers that are the constraints such as roads, railways and waterbodies [27]. The next category includes only the land use, in this case – buildings. The last category consists of two main resources – wind speed and solar power. Table 1 summarizes all of the categories and criteria.

Diva-gis.org and Geodata.de are some of the most reliable and free geodata available in the market and thus, most of the data has been collected from there.

All the geodata gathered for this paper was collected in two formats, namely Shape files or TIFF files. These are the main formats used in this paper. Shapefiles are able to support point, line and area features. TIFF format is used for georeferenced raster imagery. It is mostly used for satellite or aerial photography [28].

Table 1. Collected geodata

Category	Criteria	Source	Requirements
Infrastructure	Roads	Diva-gis.org	
	Railways	Diva-gis.org	
	Waterways/waterbodies	Diva-gis.org	
	Borders	GADM.org	
Land use	Buildings	Geofabrik.de	
Resource Based Data	Wind speed	Global Wind Atlas	above 6m/s
	Solar speed	Global Solar Atlas	above 1,100 kWh/kW

In detail, regarding the GIS mapping process, the following steps were followed:

- Preprocessing the Data:
  - The first step involved gathering geospatial data from various sources such as the Global Wind Atlas, Global Solar Atlas, Diva-gis.org, and Geofabrik.de.
  - Data collected included wind and solar maps for Poland, as well as infrastructure data such as roads, railways, water bodies, and land use data like buildings.
  - The data collected were in different formats, including shapefiles and TIFF files, and needed to be organized and imported into QGIS.
- Spatial Analysis:
  - Once the data were imported and organized, spatial analysis was conducted to identify areas suitable for wind and solar power generation.
  - For wind power analysis, a raster function in QGIS was used to calculate areas with wind speeds greater than or equal to 6 meters per second (m/s), which is optimal for large-scale wind energy projects.
  - Similarly, for solar power analysis, areas with solar radiation exceeding 1,100 kilowatt-hours per kilowatt (kWh/kW) were identified as suitable for solar power generation.
  - Constraints such as roads, railways, water bodies, and buildings were overlaid on the wind and solar maps to identify feasible locations for hybrid energy generation.
- Visualization of Results:
  - After conducting spatial analysis, the results were visualized using QGIS to create the hybrid energy map of Poland.
  - The final map displayed areas with sufficient wind speed and solar radiation, indicating potential locations for hybrid energy generation.

- Areas that did not meet the criteria for wind and solar power generation were left out.
- The visualization provided a clear depiction of prime locations with the greatest potential for hybrid wind-solar energy generation in Poland, aiding decision-making for future renewable energy projects.

Based on the above information it is natural to conclude that the resource-based data layers are TIFF files as wind and solar data are difficult to present as point or lines. They are represented in raster format. All the other data layers for infrastructure and land use category are shape files as they are represented by point, line or polygon. Data format has a crucial impact on the reliability of the final outcome and therefore, it is significant to find the layers in the required formats.

3.2 Organising the data

Once all the required data was collected the next step of the analysis was to import it to QGIS and organise it. As a starting point, the coordinate reference system (CRS) has been set. CRS refers to the way in which spatial data that represents the earth's surface are flattened. In this project meters are used for defining the location of features instead of meridian of latitudinal or longitudinal. Therefore, Universal Transverse Mercator (UTM) zones have been selected for CRS of this papers, namely WGS 84/ UTM zone 33N. After setting the right CRS for the whole project, the same must be done for each layer in order to make sure that the features on the map are represented accurately.

3.3 Calculations

After gathering the data and setting up the CRS the calculations could be done. The process of calculating and creating the final map consists of 3 main steps with different sub-tasks and can be seen in Figure 3.

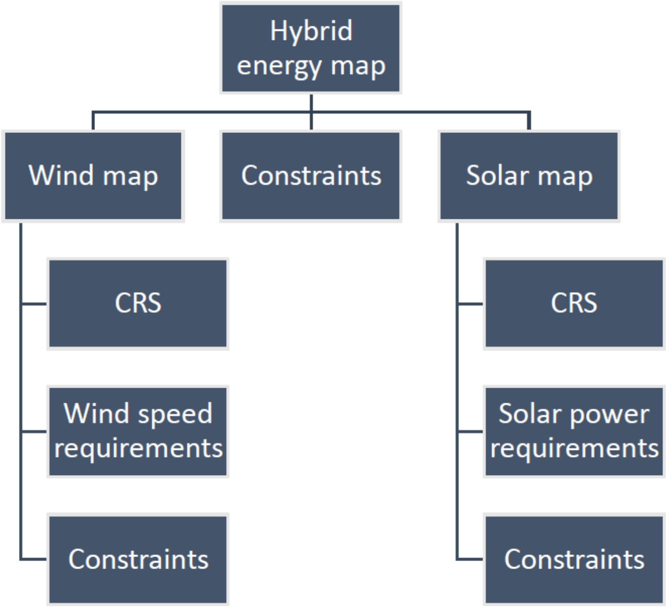

Fig. 3. Mapping Process

The wind map has been taken into consideration. The first thing was to set the correct CRS for all the layers as mentioned in the previous section.

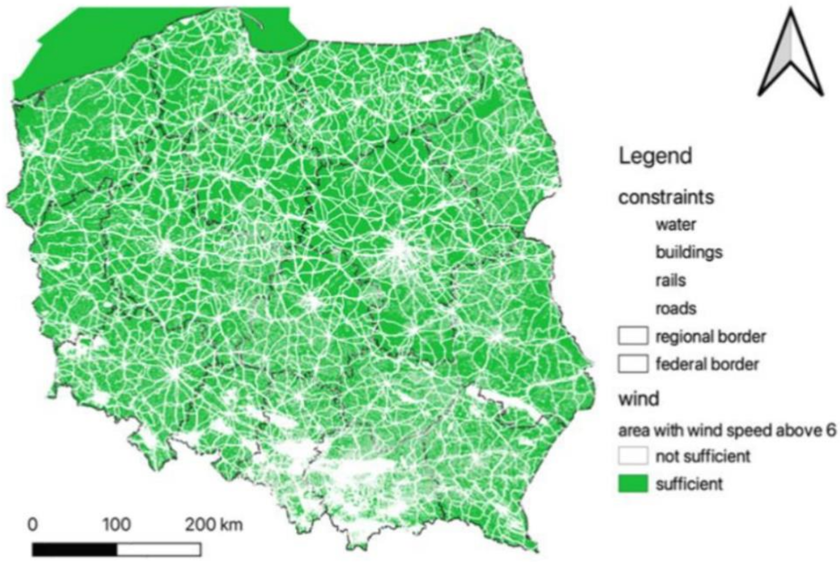

Fig. 4. Wind map with wind resource above 6m/s

As stated in Table 1, the requirement for wind speed is 6s/m in order to be optimal for large scale projects implementations. It has been done with use of raster function in QGIS, where the wind map at 100m has been calculated as >= 6, since below 6 m/s or 6.5 m/s it is very hard to find a viable approach on the long terms for any wind energy project [29]. Afterwards, the software has automatically shown the area that meets these requirements together with other constraints.

Figure 4 shows a map of Poland with available potential area (green) with wind speed equal or bigger than 6s/m. It means that theoretically the wind farms could be installed in the green points, and it would not interfere with the constraints chosen for this paper, namely: roads, railways, waterbodies and buildings. It is worth noticing that the map takes into consideration the offshore area of Poland. By clipping the area accordingly to the federal borders, the offshore space could not be clipped as the northern border of the country crosses the sea.

Afterwards, the same process has been performed for the solar map. The requirement chosen for the solar power was 1,100 kWh/kW. The purpose of choosing this value was to show the potential space available for rather big industrial PV installations. The outcome has been surprising as the potential area with solar power equal or bigger than 1,100 kWh/kW is more limited than the wind range. Figure 5 shows the final outcome of the solar map above 1,100 kWh/kW.

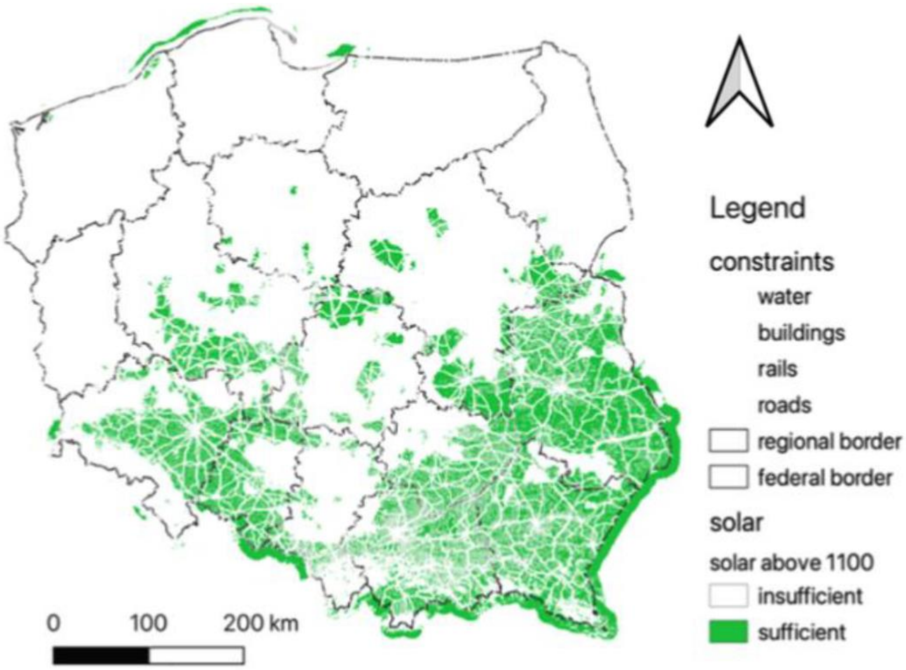

Fig. 5. Solar map with solar resource above 1,100 kWh/kW

3.4 Outcome

The outcome of the two maps has been calculated through raster function as follows: (wind map >=6) *1 AND (solar map >=1,100)*1

By using this function, QGIS tool showed only the area that was meeting the requirements of wind speed above 6s/m and solar power of 1,100 kWh/kW. It can be clearly seen that the space shrank radically from only wind potential area, then solar that was already limited to the final one.

Figure 6 shows the final visual outcome of the hybrid energy map of Poland, where green is the area with sufficient wind speed and solar power, and white is the insufficient area.

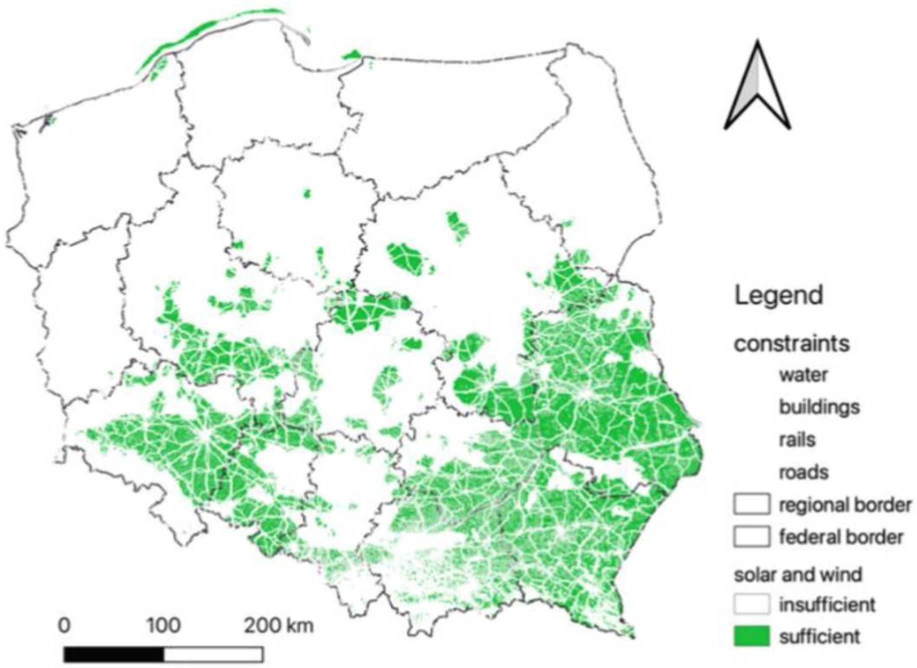

Fig. 6. Hybrid wind-solar power map of Poland

4 Discussion

The final outcome of this paper can lead to many different discussions. The current energy mix in Poland shows the need for renewable energy implementation in order to limit the use of hard coal and lignite and eventually eliminate it completely. As mentioned earlier in the paper, Poland is obliged by EU to reach 21% share of RES in gross final energy consumption by 2030. The preliminary hybrid energy map of Poland that is the outcome of this paper can serve as an aid for the companies as well as for the government to decide on the location of the future wind and solar farms. It can be seen which areas are worth to research further in order to use the hybrid renewable system.

Furthermore, the final visual outcome of this report can ease the decision on either to even consider use of hybrid renewable system or proceed with the single renewable source, e.g. wind farm. It can be clearly noticed that south-eastern part of Poland has higher potential for hybrid wind-solar use than the rest of the country.

The hybrid energy map for Poland presents policymakers with crucial insights into the distribution of renewable resources, guiding strategic decisions for sustainable energy development. By identifying regions ripe for wind-solar hybrid projects, policymakers can craft effective policies to incentivize investment and meet renewable energy targets. Investors benefit from clear guidance on optimal deployment areas, while collaboration with local communities and grid modernization efforts can address regulatory and infrastructure challenges. Overcoming barriers such as financing constraints and regulatory hurdles requires a concerted effort from stakeholders. Ultimately, leveraging the hybrid energy map's findings can drive Poland towards a greener and more resilient energy future.

The paper introduces a hybrid energy map designed specifically for Poland, focusing on the viability of wind and solar power generation. This map is crafted utilizing Geographic Information System (GIS) software along with geodata, which undergoes evaluation alongside various siting constraints. The objective of the study is to pinpoint the most promising locations for wind and solar power generation within Poland, taking into account infrastructural limitations, land usage, and the availability of renewable energy resources. Furthermore, the paper delves into an analysis of the current state of renewable energy in Poland, the benefits of employing hybrid resources, and the constraints integrated into the mapping process to identify suitable areas for hybrid energy utilization.

In contrast to prior studies, this paper adopts a comprehensive approach to identify potential sites for wind and solar power generation in Poland [31]. Leveraging GIS and geodata facilitates a meticulous examination of the country's constraints and resources [32]. Furthermore, the paper underscores the significance of renewable energy sources in fulfilling the EU's renewable energy objectives [33].

One limitation of the study lies in its exclusive focus on wind and solar power generation, potentially overlooking the broader spectrum of renewable energy sources in Poland. Moreover, the paper could enhance its impact by providing a more nuanced discussion on the policy ramifications of the hybrid energy map [34].

Future research endeavors could explore the potential of alternative renewable energy sources in Poland, such as hydropower and geothermal energy. Additionally, further scrutiny could be directed towards assessing the prospective ramifications of the hybrid energy map on the Polish energy market and the environment.

Last but not least, taking aside all the advantages of the hybrid wind-solar installations, it is worth discussing if the country has actually the prerequisites for that. The preliminary wind map shows that there is a lot of available space with sufficient wind speed in Poland, therefore, it could mean that the main focus should be on the wind farms and the hybrid installations should be implemented only if possible (in the area available in the hybrid energy map of this paper).

5 Conclusions

This section will aim to give a brief summary of the paper and answer the research questions. Next, the criticism of this report will be formulated and suggestions for further research are presented.

The research questions will be answered and finally the results to the main question will be presented. The aim of this research was to describe the current situation of renewable energy in Poland in order to give the reader a common understanding of the position the country is currently in. Briefly, Poland is still a country of coal, where the hard coal accounts for more than 50% of the total installed capacity in 2020. As Poland is a member of EU, it is obliged to develop the RES constantly. Currently, the obligation is 21% by 2030. However, the national laws and directives do not help to reach that goal [30].

Furthermore, the hybrid renewable energy system has been introduced together with its benefits. One of the main advantages of hybrid wind-solar system is generating approximately twice as much as solar or wind only systems, which in case of Poland's energy mix can be very beneficial and move things forward.

Last research question was regarding the constraints taken into consideration while mapping the available space. In this paper only the buildings, roads, railways and water have been taken into consideration. All the above helped answering the main problem of this paper, namely:

What are the prime locations in Poland with the greatest potential for wind and solar power generation?

The problem has been answered only visually in Figure 6. It shows clearly that the southern part of Poland has better potential for hybrid energy use and that is where the focus should be.

Every research or study faces difficulties and limits of certain elements and so does this one. Naturally, there are internal and external factors that limit the study. Therefore, this section aims to formulate the criticism of the report. Due to limited scope of the project, several assumptions had to be made. The wind map and solar map have been used in different units of measurement, which is a big limitation to the final outcome and requires further research. The wind speed has been indicated at 100m in m/s, whereas the solar power has been specified in kWh/kW. Moreover, the map is preliminary and thus, the buffers have not been included, since the researchers were aiming to show the big picture; after all a detailed analysis including all the buffer zones for the whole country, would have required a huge computing capacity, which was not available at the moment. Due to the above-mentioned, only the visual outcome has been delivered as the time and resource limitations did not allow the researcher to go more in depth with the further calculations.

There are many different ways to continue with this study, especially, as mentioned before, this is research for a preliminary hybrid energy map of Poland.

First of all, more detailed map in terms of constraints could be one of the topics to continue further with. This said, the constraints could include ecological constrains such as NATURA200 and other projects that limit the space available. Furthermore, as mentioned in the limitations section, the buffers could be added to the buildings, airports, etc. Once this is done, the wind map and solar map could be presented in the same units of measurements, e.g. kWh/kW. Furthermore, more detailed calculations in terms of the available space could be conducted. That would result in the percentage of the country that is available for the hybrid wind-solar system. Last but not least, once the before mentioned would be studied, there would be another very interesting topic for further study. Namely, verifying how many wind turbines and solar panels could be installed in the available space in Poland and what would be the outcome of it.

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