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Renewable Energy Policy Planning for Low-Carbon Economy

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Abstract. Climate change forces policy-makers to undertake actions to reduce human impact on socio-environmental system. One of the directions is to shift into low-carbon economy, also by increasing the role of renewable energy sources (RES) in energy sector. Therefore, there is a need to support local stakeholders with a knowledge-based approaches in order to implement RES more effectively. There are some systems assessing natural potential for RES installations, however, legal regulations are not always making it possible everywhere. The aim of this research is to expand existing functions of the decision support system for hybrid RES by the feasibility assessment of selected locations due to legal regulations. The developed tool was applied and presented on the case of a selected Polish region. The RES potential is assessed based on the universal databases (Global Wind Atlas, Global Solar Atlas, CORINE Land Cover), however, it was customized to local legal regulations, which allows the solution to be more practical and helpful for implementation in a low-carbon economy. Promotion of decision support systems for RES planning may constitute effective solution to reach goals set in the European Green Deal.

Keywords. Public policy, infrastructure planning, sustainable development

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1. Introduction

Accelerating climate change requires urgent actions at global as well as local scale in order to mitigate its' negative effects [1]. Despite many discussions considering mechanisms of climate change and identification of key driving forces, most of policies in that domain focus on minimizing emissions of greenhouse gases [2,3]. Therefore, different targets are set at different levels. For example, the concept of 2000-Watt Society which is a leading principle in Swiss municipal policy aims to consume by society as much energy as worldwide energy reserves permit without damaging the environment [4]. This concept became more popular with the time and considered as a target also in other countries worldwide [5]. Even more courageous goal was recently introduced in December 2019 by the European Union. The European Green Deal aims to no net emissions of greenhouse gases by transition into climate neutrality [6]. These targets should be obtained by both lowering energy consumption [7] as well as development of renewable energy sources (RES) in energy sector [8,9]. Energy transformation impacts many different aspects of urban and regional metabolism like housing [10], transportation [11], industry [12] and many others. Cumulative effect of all these changes can lead to the low-carbon economy which is defined as the activities which generate products or services which deliver low carbon outputs reached mainly by energy efficiency and clean technologies implementation [13].

In European conditions socio-economic transformation is strongly related to the support of European Funds [14]. One of the major aspects of this transformation is the implementation of RES and in that way shift into low-carbon economy [15]. RES development plays especially a significant role in case of areas which has low-density development. In case of rural areas energy transmission costs are higher than in case of urban areas which makes convention and centralized energy systems less effective. Specific transition zone between these two forms is a suburban area [16,17] where RES could also constitute effective solution due to rapid urbanization process [18,19]. Therefore, more efficient solution in that case could be to implement energy clusters and energy cooperatives covering independent or semi-independent dispersed installations producing energy from biomass, biogas, wind, solar radiation, and where geologically rational also geothermal sources. Such local initiatives and cooperatives have already some institutional experiences in realization of local activities [20,21], which may influence more effective RES implementation in Central and Eastern Europe and shift location of center of gravity into new areas [22]. While considering low-carbon economy it is important to highlight that besides high costs many public investments result also in additional value created [23,24]. Therefore, RES development is not only a burden for local communities but can also constitute a very important factor for further redevelopment and built environment renewal which are constantly designed [25]. However, in order to implement appropriate RES technologies in specific areas there is a need to assess potential of different sources.

In order to support renewable energy installations planning different Decision Support Systems (DSSs) are being used. The first and commonly used DSSs are these utilizing GIS to perform spatial analyses and resource assessments for potential renewable energy installations. GIS-based DSS offer invaluable tools for evaluating solar potential, wind patterns, hydrological features, and biomass availability within designated geographic regions. These systems assist in identifying optimal locations for energy infrastructure based on resource abundance and proximity to existing infrastructure [26]. The second group are Multi-Criteria Decision Analysis (MCDA) frameworks which employed to evaluate multiple, often conflicting, criteria involved in renewable energy installation planning. These criteria encompass economic factors, environmental impacts, social considerations, and technological feasibility. MCDA-based DSS enable stakeholders to assess trade-offs and arrive at informed decisions by quantifying and prioritizing these diverse criteria [27]. Another DSSs are based on machine learning techniques. They are increasingly being integrated into DSS to enhance predictive modeling and optimization processes. Predictive models utilize historical data and current conditions to forecast energy production, demand, and potential system failures. Machine learning algorithms optimize system parameters, considering variables such as weather patterns, load profiles, and equipment performance, ultimately aiding in efficient renewable energy installation planning [28]. The fourth group are Life Cycle Assessment (LCA) and Sustainability Metrics. DSSs utilizing LCA methodologies enable the evaluation of environmental and sustainability aspects throughout the lifecycle of renewable energy installations. LCA-based DSS help quantify environmental footprints, resource utilization, and emissions associated with various renewable energy technologies, facilitating environmentally conscious decision-making in the planning phase [29]. The last group integrates of real-time data and sensing technologies. Modern DSSs emphasize the integration of real-time data from sensors and Internet of Things devices to enhance the accuracy and responsiveness of decision-making processes. Real-time data on energy generation, consumption, and grid conditions enable dynamic adjustments and efficient planning for renewable energy installations, optimizing performance and reliability [30].

After revising existing DSSs it was concluded that the approaches focus on natural conditions omitting legal regulations [31]. In case of Poland, such legal burden of wind turbine implementation is the restriction of minimal distance to housing areas which used to be equal to height of the installation multiplied by 10 (10H) [32] and after recent amendment of regulations is 700 m [33]. Similar condition is applicable in case of natural protected areas, which may play a significant role in transformation of economic functions in these locations [34,35]. The regulations limiting minimal distance of wind turbines from housing areas visibly limited the development of onshore installations which is an obstacle in reaching national targets concerning the share of RES in energy sector. Therefore, in this research the DSS for hybrid renewable energy planning [36] has been expanded by the component enabling not only natural potential of RES assessment but also feasibility of selected locations due to legal framework. The developed tool was applied and presented on the case of one selected region in Poland – West Pomeranian voivodeship, which is a coastal region of the country with high wind energy potential. The development of a regional renewable energy policy planning tool is an approach which suits to the current concept of regional policy and management which implies decision-makers should consider this level of planning and development.

2. Data and Methods

The tool for renewable energy policy planning developed in this research combine wind (Global Wind Atlas) and solar (Global Solar Atlas) energy potentials together with information about the land cover (CORINE Land Cover 2018), natural protected areas and administrative division of the country. Both, Global Solar Atlas and Global Wind Atlas are opensource, web-based databases. Solar energy potential is evaluated as the amount of energy converted by a photovoltaic (PV) system into electricity according to the geographical conditions of a site and a configuration of the PV system. Spatial data on photovoltaic electricity output (PVOUT) is originally provided in kWh/kWp. PVOUT is calculated according to natural solar resources, air temperature as well as terrain elevation relative to sea level. PVOUT calculation algorithm is based on three commonly used PV systems: small residential rooftop; distributed, or medium-size commercial roof-mounted system, and large or utility-scale PV power plant [37]. Wind energy potential presents wind power density reflected in W/m2. Wind power density is estimated by downscaling from large-scale wind climate data to the microscale wind climate data. Generalization is a key methodological concept developed by the Technical University of Denmark. It incorporates data on global circulation, orography, topography, position of the coastline as well as a surface roughness [38]. According to methodological limitations both RES potentials can be used for prospection and preliminary assessments. Information about land cover comes from CORINE Land Cover 2018 (CLC2018). It demonstrates changes in land cover/land use that occurred in 2012-2018 and the construction of a uniform and opensource CLC2018 database. Additionally, High Resolution Layers have been developed including: impermeable areas, forests (crowns and forest types), permanent grasslands, water reservoirs and wetlands and local products, i.e. Urban Atlas, detailed land cover/land use along the largest rivers (Riperian zones) and selected nature protection areas NATURA2000 [39]. CLC2018 uses a minimum mapping unit of 25 hectares for areal phenomena and a minimum width of 100 m for linear phenomena. The time series are complemented by change layers, which highlight changes in land cover with a minimum mapping unit of 5 ha [40]. Four kinds of natural protected areas were used in the research: Natura 2000, national parks, landscape parks and nature reserve areas. Data was obtained from the General Directorate for Environmental Protection [41]. Administrative division of the country was obtained from the Head Office of Geodesy and Cartography. In current research three levels of the national division of the country were used: region (West Pomeranian voivodeship), counties (21 counties with average size of approx. 1090 km2) and municipalities (105 municipalities with average size of approx. 218 km2). The region has relatively favourable conditions for RES implementation, especially in terms of wind potential on the coastal area. Local climate conditions of the capital city of the region (Szczecin) based on the last two decades (2003-2022; period with full data coverage) divided into seasons of the year give detailed input about RES potential (Fig. 1).

Insolation, measured in hours per month, demonstrates variations throughout the year. The highest monthly insolation occurs in May (244.53 hours) and June (247.26 hours), indicating extended daylight exposure during these months. Conversely, the lowest insolation is observed in December, with only 30.43 hours of sunlight. The total yearly insolation is 1767.22 hours. Mean wind speed, recorded in meters per second, exhibits slight fluctuations over the months. Winds are generally moderate, with the highest average wind speed in November (4.3 m/s) and December (4.3 m/s). In contrast, the lowest average wind speed is recorded in September (3.1 m/s). Overall, the annual mean wind speed is 3.7 m/s, suggesting a relatively consistent wind pattern throughout the year.

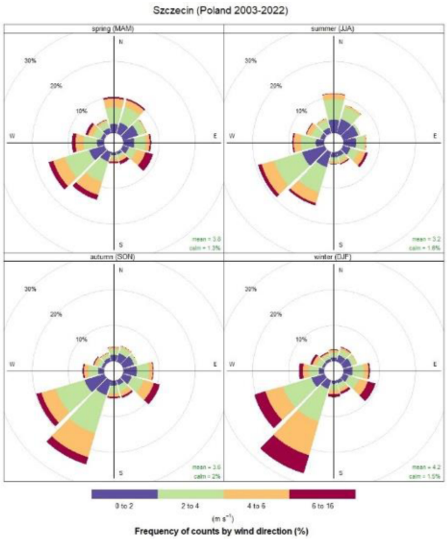

Figure 1. Local climate conditions in the capital city of the region – Szczecin.

The integration of described data was carried out with the use of Geographic Information System (GIS) and Business Intelligence (BI) analytic environment. In particular, we configured and operated ArcGIS 10.4 and Tableau 2019.4.1 in live connection mode. In that way, GIS and BI software had simultaneous access to spatial data stored in geodatabase file. The ArcGIS was used for data blending and pre-processing together with advanced geoprocessing and geostatistical operations. Tableau was applied for visual analytics and geodata-based decision-making support tool. Interactive dashboard created as final output of this research enables visual data exploration by selecting and filtering information to perform data grouping, clustering, calculating basic statistics and assessing trends and correlations between used datasets. The workflow of the designed tool is presented in the diagram (Fig. 2).

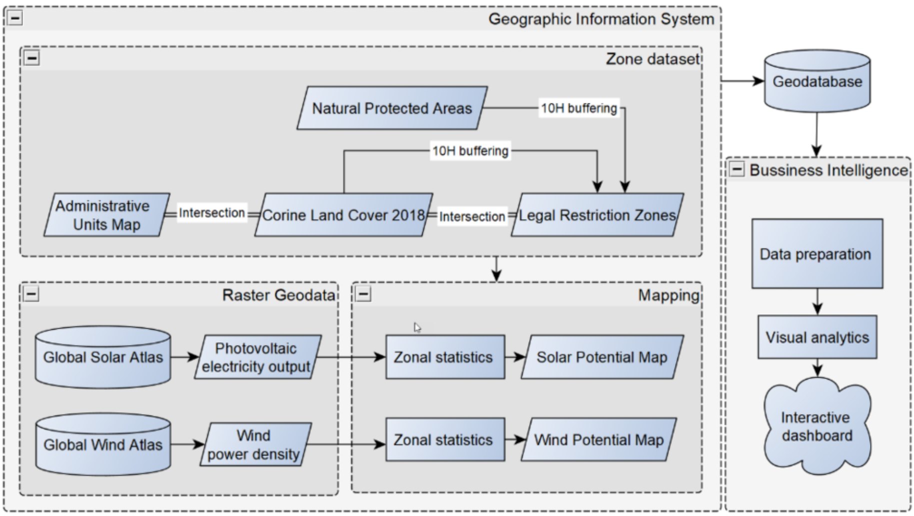

Figure 2. Research framework.

The analytical process for determining renewable energy production areas initiates with data retrieval from the "Global Solar Atlas" and the "Global Wind Atlas." These sources offer initial data, setting the stage for in-depth spatial data analysis. At the subsequent stage, data undergoes a "Zonal Statistics" procedure to understand spatial variations in energy potential. This step delineates regions with notable renewable energy potential, serving as a precursor to a detailed analysis of energy resource allocation. Further in the process, data from "Natural Protected Areas" integrates with "CLC2018" data and administrative boundaries, giving rise to a "Legal Restriction Zones" layer. This layer aids in identifying areas with potential legal and environmental constraints, facilitating strategic planning in renewable energy projects. In the penultimate stage, integration occurs between the "Legal Restriction Zones" layer and the maps generated from the previous zonal analysis, indicating solar and wind potential. This integrated data set allows for the identification of areas meeting legal and environmental criteria, alongside substantial energy potential. As the process approaches its culmination, the analyzed data finds storage in a Geodatabase, setting a robust base for future analyses. Following this, the data transitions to a BI module. In this final stage, an analytical dashboard forms, providing visual representation of the potential landscapes for renewable energy projects, assisting in data-driven decision-making. In summary, this tool can potentially steer renewable energy policy planning towards informed and judicious decisions, guided by comprehensive data analysis. It stands as a practical utility in the renewable energy landscape, helping navigate the multifaceted pathway of renewable energy policy planning with a foundation in rigorous research and data analysis.

3. Results

The comprehensive tool devised for strategic planning in renewable energy policy unfolds to decision-makers with an interface housing eight integrated elements, all seamlessly interconnected within a dynamic dashboard. Central to this interface is a geographical map illustrating the region of interest. This map is linked to a scatter plot, providing a visual depiction of RES potential distributed across counties. Additionally, a bar chart featuring a Likert scale enriches the visualization of RES potential while considering the division of legal restrictions, adding a crucial layer of insight.

A further functionality of this tool is the integration of a scatter plot illustrating the distribution of renewable energy potential units. This scatter plot offers a unique perspective by combining essential parameters such as land cover, administrative division, legal restrictions, and RES potential into a single, coherent visualization. These four primary windows within the tool interact seamlessly, forming a cohesive analytical environment.

Furthermore, the tool incorporates four dynamic legends, augmenting user experience with powerful filtering functions. These legends enable users to refine their insights by selectively displaying and filtering information based on critical aspects like legal restrictions, land cover, and administrative division. The interconnectedness of these elements within the tool enhances data exploration and facilitates informed decision-making, as illustrated in Figure 3 for a clearer representation.

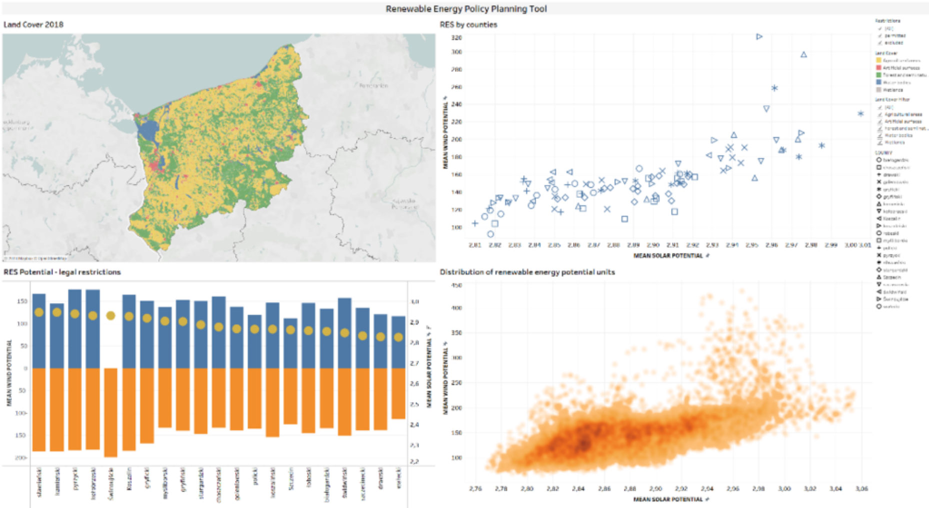

Figure 3. Interactive dashboard for renewable energy policy planning.

As previously mentioned, all elements within the interface—such as maps, charts, plots, and legends—are intricately interconnected in a dynamic manner. This interconnectedness ensures that any action on one element, be it a selection or a filter, triggers direct reactions across all other elements. For instance, a user can select individual objects or groups of objects, employing various methods to do so. When selecting objects on a map, the user can opt to choose objects within a specified distance from a point or define an irregular range of objects based on personal preferences. Similar selection mechanisms apply to scatter plots and charts. Moreover, the selection made from the legend allows for the precise highlighting of specific object classes. In the scenario where a new component is added, it becomes possible to assess the renewable energy system's potential in the analyzed objects, encompassing the overall physical potential. This potential is further divided into two categories: the potential in areas where prevailing legal conditions permit the installation of wind turbines and the potential in areas where such installation is currently prohibited in accordance with existing regulations. Through the application of this module, it becomes feasible to integrate an evaluation of physical suitability with legal feasibility. This integration provides decision-makers with a broader context for planning renewable energy policies. Upon selecting units with the highest renewable energy potential values, the map automatically zooms into the analyzed area situated along the coastline. The charts accompanying this zoomed-in view effectively condense the presentation of administrative divisions and the legal feasibility regarding wind turbine investments in the selected area.

4. Conclusions

Upcoming more commonly the era of big data challenges users from many domains to incorporate knowledge-based decision making process into their regular tasks. Despite the fact that scientists and researchers develop innovative solutions, still 92% of managers are not using decision support systems. Mostly it is cause by their high level of complexity [42]. Therefore, tools for renewable energy policy planning should be based on intuitive dashboards that are going to be understandable by layman. The interactive dashboard proposed in this research constitute a solution that recently became popular in local energy planning [43] as well as in other fields, including among others: management [44], manufacturing [45], medicine [46] or education [47,48] Visual data discovery approach, proposed in this research, suits better to human cognitive skills which may influence the use of new databases in regional planning. Presented example show that such intuitive solution was achieved. However, it has to be highlighted that proposed solution is designed for initial screening. Results from regional assessment should be always verified by local data and local stakeholders who know the context. This is to avoid the risk associated with generalization and data accuracy. Downscaling from large-scale wind climate data to the microscale wind, like it happens in case of Global Wind Atlas, may bias the results. In order to overcome this limitation it is possible for use for instance open source tools like an R package to access free in-situ meteorological and hydrological datasets for environmental assessment [49] which output is presented in Figure 1.

The proposed solution for effective renewable energy policy planning has the potential to become a pivotal instrument for local stakeholders striving to cultivate a low-carbon economy through the transformation of regional energy systems. Addressing this challenge stands at the forefront of contemporary climate policies on a global scale. In the specific example under analysis, a prominent barrier to the successful implementation of Renewable Energy Sources (RES) in the West Pomeranian voivodeship emerges from the influence of national regulations pertaining to onshore wind turbines. A discernible reduction in the number of areas deemed potentially suitable for wind turbines has been observed across all counties, with some counties experiencing a complete absence of available land for this purpose. This limitation significantly hinders advancements in sustainability within the Baltic Sea Region, a concern that holds significance in both academic discourse and political deliberations [50]. However, it's important to note that recent modifications, such as the adjustment of the 10H rule to a 700-meter distance requirement between wind turbines and residential areas, highlight the potential for conditions to evolve based on political decisions. These alterations underscore the adaptability of the regulatory landscape, showcasing that with the right political will, local stakeholders can readily be supported through an updated version of the tool. This updated tool holds the promise of expediting RES planning and facilitating the transformation of local energy systems, contributing to a sustainable and greener future.

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