Location support system for energy clusters management at regional level

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Abstract. This study provides the location support system solution for the new Polish Energy Policy to 2040. The Location support system combing geographic information system (GIS) with business intelligence (BI) analytic environment is developed. The Decision Support System in this research integrates three renewable energy sources (RES): biomass, solar and wind. The renewable energy technical potentials are analyzed in relation to the local human development index (LHDI) and the average use of low-voltage electricity [kWh per capita] in rural households. The research indicates internal diversification of the country in terms of energy consumption, level of development and potential to renewable energy production. The most developed rural areas are in the west of the country and in the vicinity of large cities. Regions suitable for biomass production are located in S-W and W part. The best conditions for solar energy sector are in the S, S-E and central regions. Good wind conditions are in central Poland and locally at the Baltic coast as well as in sub mountainous regions in the south. The newly developed analytical system can be effective instrument, which can strengthen the production and consumption of renewable energy in rural areas. As an added value, it should improve the quality of life of local communities. The results of the study support decision makers in sustainable energy cluster allocation and management.

1. Introduction

Polish government has just released the new project of Polish Energy Policy to 2040 (PEP January 26th, 2019). The Policy aims at reducing the amount of emissions produced by the energy sector and supporting diversification of energy sources. The reduction of the emissions is planned to be achieved by increasing the share of renewable energy sources (RES) up to 21% in the whole energy sector and 27% in the electro-energy sector in 2030. Significant investments are required to reach the 21% (double of the current national energy production from RES) target set in the Polish Energy Policy. The diversification of energy sources will be supported by increasing the number of new installations, including energy production from biomass, biogas, wind, solar radiation, and where geologically rational also geothermal. These new installations would play a key role especially in rural and peripheral areas, which are located far from main existing networks. Rural and peripheral areas will benefit from investments in the development of energy clusters and energy cooperatives. According to PEP, it is assumed that in 2030 there will be about 300 such forms of cooperation in Poland. The strategic question is what are the most suitable placed for locating energy clusters in rural areas of Poland. In this
contribution we aim to develop a decision support tool for locating energy clusters. The paper presents a novel location support system for effective planning and management of sub-regional energy clusters. The Decision Support System (DSS) in this research has been designed to integrate multiple renewable energy resources fulfilling the requirements set in the draft Polish Energy Policy until 2040. To the best of our knowledge, is it the only attempt for creating a DSS addressing energy policy needs in the context of the new PEP in Poland.

1.1. Energy clusters in Polish Energy Policy

Energy clusters are a new tool in Polish conditions for the development of RES. Hence, their implementation in Poland is in the initial phase and requires additional regulation and guidelines for their application. It is important to highlight that the concept of energy clusters is intended mainly for rural areas. Legislative tool of energy clusters is one of the instruments supporting the production of electricity from RES according to the act of 22nd June 2016 amending the act on renewable energy sources and some other acts, art. 2 point 15a. They constitute a separate subsystem of energy producers and recipients, connected by a formal network. They create the possibility of local energy balancing through its aggregation. They provide a platform to stimulate local stakeholders to cooperate and generate energy from RES for their own needs, in order to achieve free economic development based on local resources. Thus, an energy cluster is a marketplace stronger and more competitive.

Polish law defines an energy cluster as a civil law agreement that may include people, corporations and enterprises at any legal status, scientific units, research and development units as well as local government units. The diversity of entities will ensure greater efficiency of operations and the financial and innovative efficiency of the cluster. The agreement on energy cluster operations include generation and balancing of energy needs, distribution or trading from RES or other sources or fuels within a distribution network with a rated voltage of less than 110 kV, in the cluster area. The territorial range of the energy cluster in accordance with legal conditions should include the borders of one poviat (county) or five communes. The area of the energy cluster's operation is determined by the place of connection of generators and energy consumers according to the act of 22nd June 2016 amending the act on renewable energy sources and some other acts, art. 38a paragraph 4. The scope of the energy cluster's activities excludes activities involving connection with neighbouring countries according to the act of 22nd June 2016 amending the act on renewable energy sources and some other acts, art. 38a paragraph 5.

The implementation of energy clusters should consider impact on different groups, their needs as well as operational barriers. Clustering should be integrated with other long term social and economic goals and policies. Jaegersberg and Ure underlined the need of leveraging disparate knowledge, skills and resources more effectively for innovation. The stakeholders activation and collaborative action research should be carried out [1]. Integrating renewables into socio economic policy should be supported by innovative methods and tools, such as Decision Support Systems (DSSs).

1.2. Decision support systems

DSSs are computerized systems developed to enhance users to choose one of several variants. They allow automating part of the decision-making processes that require the analyses of large amounts of data in a relatively short period of time. These systems provide the structure which arranges such elements as models, participants, procedures, software, databases, communication and equipment. They are applicable for unstructured or semi-structured problems, and enable decision makers to compare obtained results by increasing their readability [2].

DSSs prove suitable for urban planning purposes, as well as new renewable energy sources location and optimisation of their energy supply potential. The level of complexity of problems solving in urban planning in recent years, together with the direction of creating the economy based on knowledge [3], influenced the use of DSSs in national, regional and local planning. DSS are used in many urban development domains, like water management [4,5], public transport management [6] or local climate regulation [7]. The DSS advanced solutions including spatial aspects supports also energy location
decisions for the purpose of suitable wind turbines location based on the local conditions [8,9], biomass estimation [10], solar potential assessment [11], increasing energy effectiveness [12] or building energy performance evaluation [13]. However, integrated DSSs which focus on few different energy aspects are still missing. To meet challenges of energy policy development, there is a need for cumulated evaluation of existing renewable energy potentials. It would allow decision makers to define which resources should be incorporated to local and sub-regional energy policies as complementary to the existing energy system. The newest study on geo-localized quantification of biomass residuals in Europe concludes, that the spatial models are crucial for building and monitoring of bioeconomy strategy [14].

2. Data and methods
The Decision Support System in this research integrates three renewable energy sources: biomass, solar and wind. The renewable energy technical potentials are analyzed in relation to the local human development index (LHDI) and the average use of low-voltage electricity [kWh per capita] in rural households in 2012 (figure 1). The study is performed for the second level of local administrative division - poviat (county). As the Polish government plans to localise energy clusters only in non-urbanised areas, we examine and present geographic data and indicators only for rural poviats. Socio-economic indicators are provided for 2012.

The DSS developed in this study integrates geographic information system (GIS) with business intelligence (BI) analytic environment. Namely, we use ArcGIS 10.4, Tableau Prep 2019.1 and Tableau 2018.3.2 directly connected to the spatial files stored in geodatabase [15]. The system builds on Tableau platform emphasizing the importance of data visualization in decision-making [16,17]. Data preparation and blending was performed with use of Tableau Prep – innovative ETL (Extract, Transform and Load) tool. Visual analytics, data exploration and clustering was carried out in Tableau software. In result, the system allowed to build the managerial dashboards, which would help to identify key trends in the data, drill and filter information as well as to improve geographically based decision-making.

2.1. Biomass energy source
The potential of biomass production for energy use in Poland is evaluated using geodata set and methodology delivered by BioBoost project [18]. The total biomass potential is calculated for following biomass resource types:

Figure 1. Research framework.
• agricultural (straw, hay, etc.) as well as animal residues (manure),
• forestry residues,
• nature conservation (green areas, hay),
• roadside vegetation,
• urban and industrial waste (municipal bio-wastes, selected agri-industrial wastes from food and wood processing).

The modelling of biomass potential is based on assumption that only wastes and residues can be used for energy generation. The model respects the principles of sustainability, including no conflicts with food production. Detailed methodology is provided by Hamelin et al [14].

Originally, the technical biomass potential was calculated and mapped as feature class in NUTS 3 zones. The NUTS classification (Nomenclature of Territorial Units for Statistics) is a statistical system established by Regulation (EC) No 1059/2003 of the European Parliament and of the Council of 26 May 2003. It divides the economic territory of the European Union into NUTS 1: major socio-economic regions; NUTS 2: basic regions for the application of regional policies; NUTS 3: small regions for specific diagnoses. The NUTS 3 is the lowest common European level. In Poland the NUTS 3 aggregates several poviat (county) units. In our research, the original BioBoost dataset was downscaled to the poviat level with use of the area-weighted calculation. Following the original dataset, the biomass potential is expressed as kilo tonnes per administrative unit as well as potential density [t/km²].

2.2. Solar energy source
Solar resource data are obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis. Potential of the solar energy 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 (grid format) 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. According methodological limitations solar potential can be used for prospection and preliminary assessments [19,20].

2.3. Wind energy source
Original spatial dataset on wind energy (grid format) was obtained from Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). Potential of the wind energy was expressed as wind power density [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 DTU Wind Energy. It incorporates data on global circulation, orography, topography, position of the coastline as well as a surface roughness. For additional information please consult: https://globalwindatlas.info [21].

The results on bioenergy, solar and wind potential originally are given in different units, which do not allow integrating these elements directly. Therefore, the results from all three data sources were normalized to convert values into the range of 0 to 100. As higher values of analyzed variables indicate more beneficial conditions for renewable energy investments, the normalization was based on one equation (equation (1)) [22].

\[ S_{uvw} = \frac{w_{ik} - w_{ik \min}}{w_{ik \max} - w_{ik \min}} \times 100 \]  

(1)

Where: \( w_{ik} \) – value of the \( k^{th} \) indicator for the \( i^{th} \) variable, \( w_{ik \min} \) – the minimum value of the \( k^{th} \) indicator for the \( i^{th} \) variable, \( w_{ik \max} \) – the maximum value of the \( k^{th} \) indicator for the \( i^{th} \) variable, \( S_{uvw} \) – normalized value of the \( k^{th} \) indicator for the \( i^{th} \) variable.
2.4. Local human development index

The level of local development in 2012 is evaluated with use of the Local Human Development Index (LHDI) [23]. It is based on the Human Development Index (HDI) methodology [24] and adopted to measure socio-economic progress at county level. LHDI incorporates the datasets on public health, education and welfare, in particular: the estimated life expectancy of a newborn child, aggregated death ratio caused by cancer and heart disease, percentage of children in pre-school education (3 to 4 years of age); average lower secondary school exam results (only for mathematics and natural sciences) as well as average income level per capita. The aggregated LHDI indicator is calculated as follows:

\[
LHDI_i = \sqrt{HI_i \times EI_i \times WI_i} \quad i=1,2,\ldots,n;
\]

Where: \(LHDI_i\) is the local human development value for a county \(i\); \(HI_i\) is the Health Index in the county \(i\); \(EI_i\) is the Education Index in the country \(i\); \(WI_i\) – is the Welfare Index in the county \(i\). Following original methodology LHDI is classified as follows: very high (55.1-87.6), high (43.7-55.0), medium (35.3-43.6), low (27.6-35.2) and very low (17.2-27.5).

As LHDI allows to identify subnational disparities, it could support policy and decision making at regional level. LHDI is also recognised as basic instrument for a better allocation and control of EU structural funds [23]. As LHDI does not cover the energy use, the data on the consumption of low-voltage electricity per capita in rural households in 2012 is added to analyses. Information on population and energy consumption was collected from Local Data Bank provided by the governmental body - Statistics Poland. All geographical data were stored in vector spatial files (.shp).

3. Results

The rural areas in Poland (312 679 km²) occupied 97% of the total area of the country in 2012. There were 314 rural poviats in 16 voivoidships with total population of 15.2 mln people. The average population density was 56 inhabitants per km² (figure 2). The rural poviats with the highest population density are located mainly in the southern part of Poland. Detailed examination shows that the poviats with highest rate are also located near to the biggest polish agglomerations: Warsaw, Cracow and Katowice, Gdansk, Poznan add Wroclaw. These counties are affected by rapid suburbanisation and population increase [25-31].

![Figure 2. Population density in rural areas in Poland.](image)

The highest mean values of LHDI are identify in the poviats neighbouring the capital city of the country (poviat piaseczniski 80.75) as well as other big Polish cities (figure 3). In general LHDI is higher in the western part of Poland.
Figure 3. The local human development index (LHDI) and the average use of low-voltage electricity [kWh per capita] in rural households in 2012.

The annual use of low-voltage electricity in rural households [kWh per capita] varies from 180 kWh to 1638 kWh, with the mean of 743.4 kWh. The higher electricity consumption is observed in more developed poviat (figure 4). It is quite clear that energy use has an influence on socio-economic development. Anyway presented figure should not be interpreted as causal relationship but rather as a significant covariance [32].

Figure 4. Relation between energy use in rural households in 2012 and LHDI measured at poviat and regional level.

Technical potentials of the biomass, solar and wind renewable energy sources are presented in figure 5. Technical potential of biomass production varies from 46.2 t/km² to 182.8 t/km². The most attractive regions are located in S-W and W part of the country. The regions with lowest potential are in N-E of Poland. Solar potential ranges from 993.1 kWh/kWp to 1096 kWh/kWp. The best conditions for solar energy sector are in the southern, south-eastern and central regions. Wind energy potential varied from 91.3 W/m² to 318.9 W/m². Good wind conditions are in central Poland. Locally fair wind potential is at the Baltic coast and in sub mountainous regions in the south (figure 5).
The DSS was calibrated and set up. Geographically oriented data has been linked to BI component. It allowed to provide multivariable visual analyses. The dashboard supporting the location of energy clusters contains information on the normalized potential of RES and a map illustrating the level of local development (figure 6). All panels are fully integrated. All spatial data, maps and charts are linked. Any selection made in one panel or a map works like a database filter.

We present here the results for the query aiming at selecting those counties which at the same time meet the condition of high potential for biomass energy production as well as solar energy (figure 7). Out of all powiats in Poland, only 62 of them meet the simultaneous conditions. They are located both in S-W and S-E parts of the country. The system allows to take into account the LHDI values and indicates that the average LHDI in the S-W part is 41.97 whereas in the S-E part it is 32.05. This result suggests eastern regions location as most relevant for establishing energy clusters, given the requirements from the policy act. The decision support system also identifies a small potential for wind energy production in the selected districts. This is an indication for decision-makers about the choice of technologies worth investing time and capital. This example does not exhaust the analytical capabilities of the system. The number of possible queries and defining boundary conditions is unlimited.
4. Discussion and conclusions

Visual analyses are of a slightly different nature than classical statistical procedures. They are based on data mapping, iterative extractions and feedback loops. Conclusions are drawn from the evaluation of patterns and trends [33]. The main BI tool used by the decision-maker is the dashboard, which allows to monitor conditions and facilitate understanding [34, 35]. End user can provide multidimensional data drilling and extraction. Feedback is immediate and visualizations are changing in real time.

In our research visual analytics is a key solution. The developed support tool shortens decision-making time, reduces communication uncertainties and facilitates knowledge-based planning. Data has been integrated in such a way that the end-user can carry out the analysis on his own without special technical preparation. The solution is in line with the latest technological trends in the world [36].

The newly developed analytical system can be a supportive instrument, which can strengthen the production and consumption of renewable energy in rural areas. As an added value, they should improve the quality of life of local communities and ensure sustainable living conditions. Energy clustering can improve the use of endogenous development potential and integration of local communities. Therefore this solutions favor the construction of local social capital and quality of life [37]. For example, McCauley and Stephens diagnosed such a local influence in Central Massachusetts [38], Benedek, Sebestyén and Bartók in Romania [39], Del Rio and Burguillo in Spain [40] or Klagge and Brocke in Germany [41]. A common feature of the studies cited here is the focus on the local case study, without making more complex and large-scale analyzes. Therefore, the application of BI and GIS software and multidimensional data in our research seems to partially complement this gap, supporting the development of policy at the national level. The conducted research and studies allow to formulate the following conclusions at the present level:

- designing the new Energy Policy in Poland should be based on the best available knowledge and good practices;
- the existing open spatial and socio-economic data resources allow for the development of a tool to support planning decisions at the regional level only, more detailed model requires the development of new databases and detailed studies;
- the location of energy clusters should encourage sustainable local development, so that data on energy production potential need to be compared with the data on local development.

![Location support system for energy clusters management](image)

Figure 7. Poviats with high biomass and solar potentials.
A limitation of this study is the use of data from 2012. This is, however, a conscious choice restricted by the accessibility of more up-to-date open data. We aim at providing the Decision Support System that is based on freely accessible data to ensure replicability of the model in other case studies and also for other policy driven purposes. The adopted resolution of analyses (on the poviat level) does not allow for precise assessment of some potentials. For example, very good conditions are not visible directly on the coast, the model does not include marine farms, does not include built-up areas. In the future, the decision-making model should additionally take into account infrastructural and capital potential.

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