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The spatial planning of wind energy plant location for power-to-gas integration: The geographic information systems – multi-criteria decision analysis approach in Poland

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ABSTRACT

The environmental changes resulting from the global warming have prompted the European Union to adapt an energy transition strategy known as the Green Deal. The aim of this initiative is to achieve the climate neutrality in Europe by 2050. To accelerate action, an interim target has been set to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels. The implementation of the European Green Deal requires a comprehensive approach to clean energy supply policy, covering key sectors of the economy such as industry, production and consumption, infrastructure, transport, agriculture and food, construction, as well as tax systems and social benefits. Due to the intermittent nature of renewable energy sources, they need to be managed appropriately. A key factor influencing their efficiency is the ability to store energy, which poses a major technological challenge. One promising solution is power-to-gas technology, which allows surplus electricity to be converted into hydrogen. This hydrogen can be used directly or converted into methane, which ensures the stability of energy supplies in a system based on renewable sources. The energy transition process will require significant financial and technological investments. Strategic decisions will need to be made regarding location, transport, and social aspects. Due to the scale of the undertaking, precise project planning will be crucial improperly designed initiatives can result in both high costs and low technical efficiency. This article analyses the feasibility of power-to-gas projects using the analytic hierarchy process decision-making method and geographic information systems in the planning of wind farm-based systems.

Keywords: power-to-gas, wind farm, geographic information systems, multi-criteria decision analysis, analytic hierarchy process, renewable energy integration.

INTRODUCTION

Since the beginning of the 20th century, there has been a gradual increase in the Earth's atmospheric temperature, which has accelerated rapidly as a result of the human industrial activity. Researches and analysis indicate that until then, the Earth's temperature had remained stable, and it was only the industrial era that initiated a clear upward trend [1]. The temperature rise began in 1920s. The upward trend in temperatures leading to global warming prompted the European Commission to present the European Green Deal in 2019 [2]. Its primary goal is to curb global warming and, in the long term, to chart a path toward a zero-emission economy (Figure 1).

Stable energy sources are the foundation of functioning economies. All goods and daily needs are met through the use of energy, which affects almost every area of life. Currently, most energy comes from fossil fuels, as illustrated by the structure of primary energy consumption in Poland Figure 2. Coal accounts for the largest share, representing approximately 38% (2024) of total

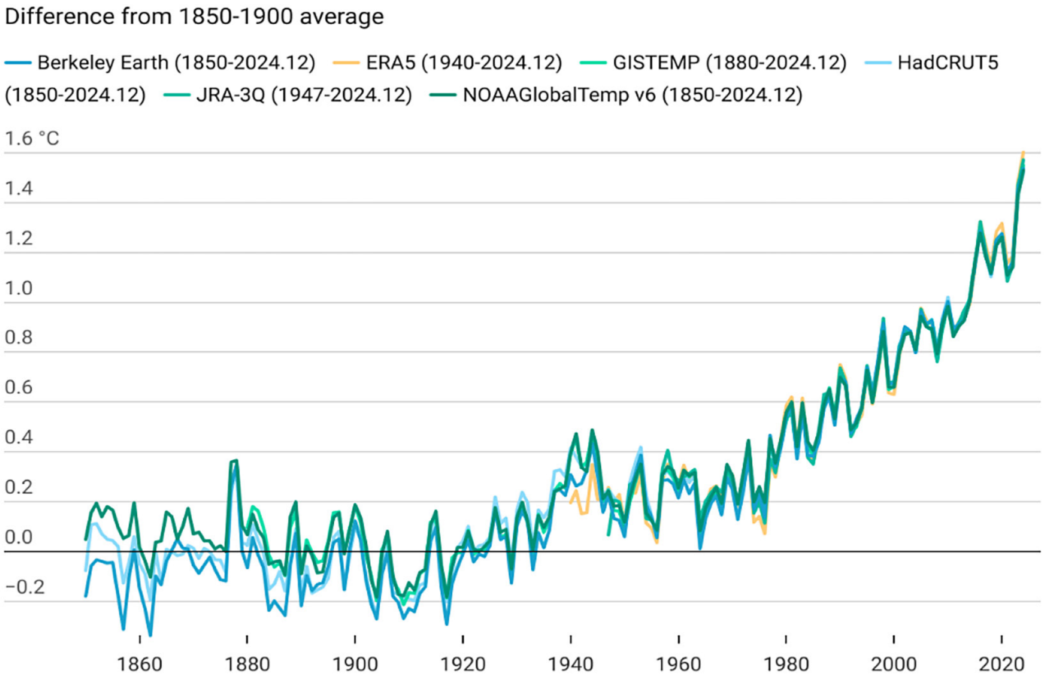

Figure 1. Mean annual temperature trend from 1850 to the present day [1]

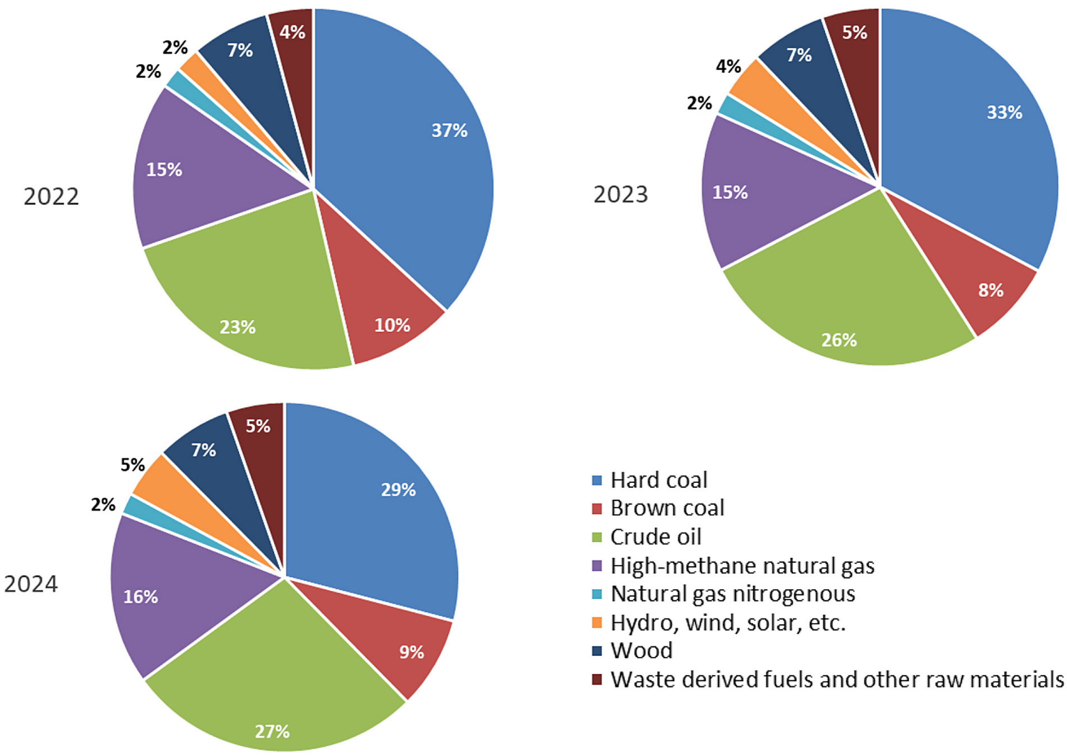

Figure 2. Structure of primary energy consumption

demands, followed by natural gas, accounting for approximately 16% (2024). The remaining energy comes from renewable sources and imports [3].

The current energy system is based on allocating resources to specific sectors and end uses. Petroleum-based fuels dominate transport, while coal and natural gas are mainly used for electricity and heat production. Electricity and gas networks operate independently, leading to limited integration between systems. This solution is inefficient in the context of a climate-neutral economy and, in the perspective of the energy transition, generates significant losses in the form of waste heat and low energy efficiency [4].

To increase efficiency, it is necessary to introduce interconnections between systems. The integration of energy systems, including gas and electricity, enables to coordinat management of them as a whole. This model takes into account the relationships between energy carriers, technical infrastructure, and areas of consumption. The energy transition will lead to changes in the way energy is obtained – ultimately, it is to come from renewable sources. This means a shift from stable, centralized sources to unstable, decentralized ones. The characteristics of renewable sources are often unpredictable and unstable. This necessitates the use of technical solutions that enable a constant flow of energy. Energy storage plays a key role in this process [5] and flexible cooperation between the electricity and gas networks [6].

In the light of it, solutions related to power-to-gas (P2G) technology are of particular importance. It allows to reduce the instability of the power system. P2G is a relatively new concept, whose development on a practical scale is just beginning. The pace of its implementation will depend on the global energy transition. Since renewable energy sources are characterized by variable production, it is necessary to develop technologies that will stabilize their operation. Possible ways of integrating energy systems are presented in Figure 3, illustrating the cooperation of the gas network with various areas of the energy sector. Due to the wide range of applications of P2G technology, this paper focuses on the cooperation of the gas network with producers of electricity from wind and solar energy. It is these sources, both during and after the energy transition, that have the potential to become the main suppliers of renewable electricity.

Renewable energy entirely depends on unpredictable weather conditions, which can lead to power outages. To ensure continuity, it is necessary to rebuild and reorganize the current energy system. P2G technology enables the integration of the electricity and gas industries and increases the efficiency of energy production from renewable sources. The gas industry, in its current form, will have to adapt to change. Currently, gas comes mainly from fossil deposits, but the gradual transition to renewable energy sources will result in a gradual reduction in its role, until it is completely replaced by renewable fuels. In the energy transition process, it is crucial to take into account the specific nature of the energy sector, and the

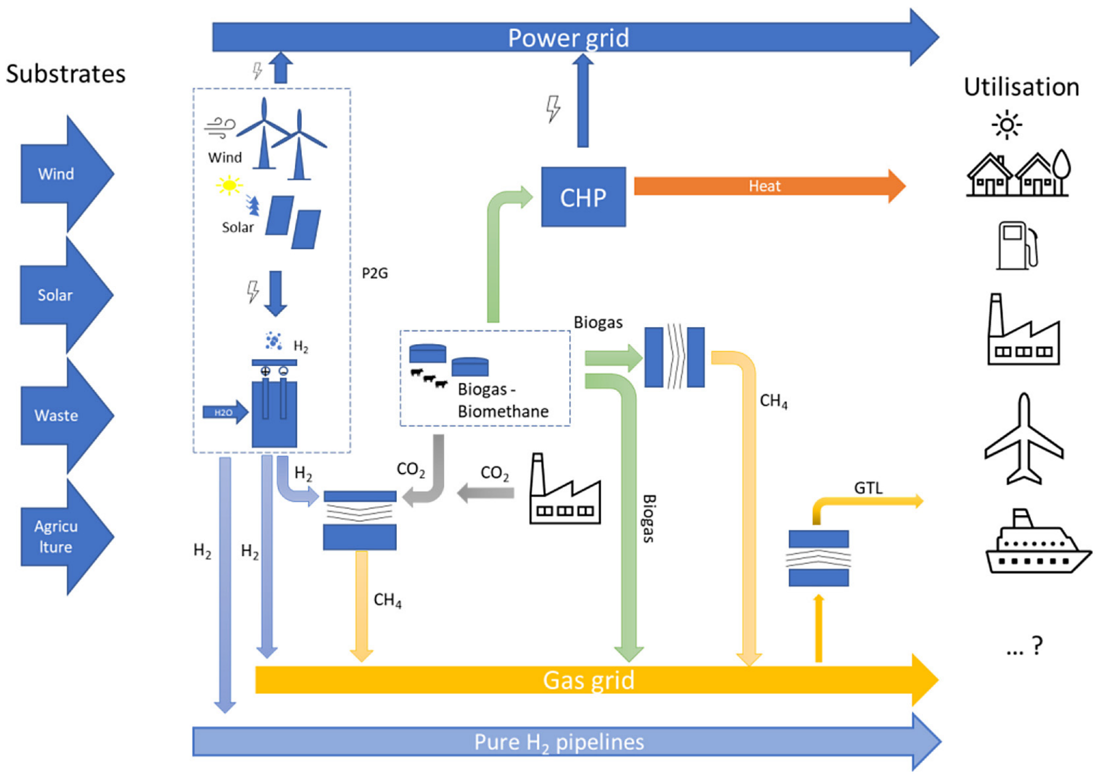

Figure 3. Schematic diagram of energy system cooperation in the P2G - P2X system

achievement of climate neutrality goals should not lead to a sharp increase in the costs of maintaining traditional energy sources (coal, natural gas, and nuclear energy). Excessive cost increases could result in higher energy prices and destabilize the economy. Therefore, the transition path must be carefully planned. The goal of achieving climate neutrality by 2050 has been set, which means that a thorough overhaul of the energy system is necessary. This is a challenge that requires quick and accurate technical, economic, and social decisions.

In P2G systems, hydrogen is the key energy carrier, enabling the integration of the electricity grid with the gas system. Its production is based on electricity from renewable sources, in particular wind and solar. However, these resources are variable and difficult to predict fully, which requires reliance on the long-term research into atmospheric conditions in a given region [7, 8] Although this allows for the selection of the best locations, it does not guarantee complete reliability of energy supply. In such cases, the storage of electricity or its derivatives is crucial, as it allows for the stabilization of the system and increases the efficiency of renewable energy sources.

P2G technology offers a flexible management of energy surpluses. In the standard mode, electricity is transmitted to end users. However, during periods of overproduction (e.g., at night), it can be used to produce hydrogen in electrolysers. The resulting hydrogen can be used on site, stored in tanks, or injected directly into the gas grid. The latter option seems to be the most effective, as it allows fuel to be transported from the place of production to the place of use. As the energy transition progresses, the share of natural gas in the gas network will decrease and be replaced by decarbonized fuels such as biomethane and synthetic methane. Not only this solution not only stabilize the operation of RES systems, but it also allows to the produce highly useful fuel.

The gas industry will have to adapt to the transport of gas mixtures containing hydrogen. The challenge is its impact on the materials used in gas infrastructure, especially in the case of steel pipelines, which are susceptible to hydrogen embrittlement. This can lead to cracks and structural weakening [9, 10]. Currently, there are no clear standards regarding the maximum hydrogen content in gas networks, but studies indicate that the safe level is from 15% to 20% by volume [10]. However, individual countries are introducing their own regulations – in Poland, in accordance with current regulations, the introduction of hydrogen into the gas network is currently limited [11–12].

Polyethylene pipelines, which are not susceptible to hydrogen embrittlement, are increasingly being used in distribution networks. As hydrogen production will mainly take place in local systems in the future, medium-pressure networks made of polyethylene will be used more often. They are more available and the costs of connection and expansion are lower. The energy value of the gas is also an important factor. The increase in the proportion of hydrogen in a methane mixture reduces the energy value of the fuel, due to the lower volume density of hydrogen and its specific transport parameters. The impact of this phenomenon depends, among other things, on the pressure in the network – the higher the pressure, the greater the decrease in energy value [10].

P2G technologies are an important element of cooperation between the gas system and other energy sectors. Their implementation enables full integration of various energy areas, which translates into increased efficiency of the entire system. The gas industry plays a key role in this process, as P2G technologies will be widely used both during and after the energy transition.

The use of P2G technologies significantly expands the capabilities of the energy sector, enabling the implementation of projects that would not be economically viable without integration with the gas industry. Any failure to utilize surplus electricity production often leads to unprofitable investments, which is why P2G is becoming a key tool in optimizing costs and resources.

At the same time, the implementation of these technologies involves numerous challenges, such as determining the acceptable proportions of hydrogen in a mixture with methane, methods of transporting fuel of varying composition, and methods of accounting for it. The author's opinion of this paper, the proper selection of P2G-based projects and their effective implementation play a key role in achieving the goals of the energy transition, leading to the development of zero-emission energy sources.

Hydrogen is seen as a key fuel for the energy transition. It is the lightest and simplest element, commonly found in the universe. It is colorless, odorless, and flammable, with an atomic mass of 1.00794 atomic mass units. However, it rarely occurs in its pure form on Earth – it is mainly found in water and organic compounds. Its extraction requires significant energy inputs and energy-intensive technologies, and in the case of using fossil fuels for hydrogen production, it also involves a high environmental burden.

Hydrogen is classified by color, which determines how it is produced: gray, blue, green, turquoise, and pink (also called purple, violet, or red) [13].

- grey hydrogen – produced in the steam reforming process of hydrocarbons (SMR – steam methane reforming), mainly methane, characterized by high greenhouse gas emissions.
- blue hydrogen – also obtained from fossil fuels, but using carbon capture and storage technology (CCS – carbon capture storage and CCU – carbon capture utilization), which reduces emissions of CO_2.
- turquoise hydrogen – obtained through methane pyrolysis, where the heat necessary for the reaction comes from renewable energy sources.
- green hydrogen – produced by electrolysis of water using electricity from renewable sources. This category sometimes also includes yellow hydrogen, which refers to electricity generated from solar energy.
- pink hydrogen (also known as violet, purple, or red) – produced through electrolysis using nuclear energy.

Each of these types of hydrogen differs in both its production method and its environmental impact, making its use an important element of decarbonization strategies.

In P2G systems, hydrogen acts as a link between the direct source of renewable electricity production (e.g., wind) and the end user.

Currently, the dominant methods of hydrogen production worldwide are methane reforming (gray hydrogen) and coal gasification (black hydrogen). Green hydrogen, i.e., hydrogen obtained exclusively from renewable sources, is the desired direction for the energy transition.

In Poland, annual hydrogen production is around 1.3 million tons, which places the country in third place in Europe, just behind Germany and the Netherlands [14]. Hydrogen is mainly produced in the steam reforming process (SMR) from fossil fuels, in chemical and fuel plants. SMR is the most common technology for large-scale hydrogen production from natural gas, which serves as both a fuel and a raw material (together with water in the form of steam). In this process, approximately 30–40% of the natural gas is burned to power the reaction, resulting in significant CO_2 emissions, while the rest of the gas is broken down into hydrogen and CO_2.

Due to its economic viability and the wide availability of existing installations, SMR is likely to remain the dominant technology for large-scale hydrogen production in the nearest future [15]. However, with the development of renewable sources, its share will gradually decrease. The use of fossil fuels in the SMR process means that this technology is not decarbonized.

Currently, hydrogen is mainly used in industry, primarily in the production of fertilizers. These technologies are not in line with the goals of achieving climate neutrality. This is why the future of hydrogen will be based mainly on electrolysis, using electricity from renewable sources. Hydrogen can also serve as an interconnector between regions rich in renewable energy sources, such as wind or solar energy.

In Poland, green hydrogen production is at a very early stage – currently, it is practically not produced on an industrial scale. However, analyses and initial pilot implementations are underway. As part of the transformation strategy, the Polish Hydrogen Strategy until 2030 was developed in 2021, which assumes the construction of 2 GW of hydrogen production capacity from low-emission or renewable sources [16]. This is an ambitious challenge, especially since global hydrogen production capacity using electrolysis amounts to about 1.4 GW Figure 4.

The increase in demand for hydrogen is shown in the forecasts presented in Figure 5. The increase in hydrogen injection into the grid and its further transport will be of a great importance. This is a consequence of the growing share of renewable sources in electricity production. Nowadays gas networks will balance the operation of renewable energy systems.

A realistic option for future hydrogen production will be a mix between blue and green hydrogen. Its use will mainly depend on local conditions, both in terms of the abundance of renewable sources and gas [19].

BACKGROUND

Modern energy system planning is complex due to the need to balance many often conflicting criteria. Energy systems must simultaneously meet economic (cost minimization), technical

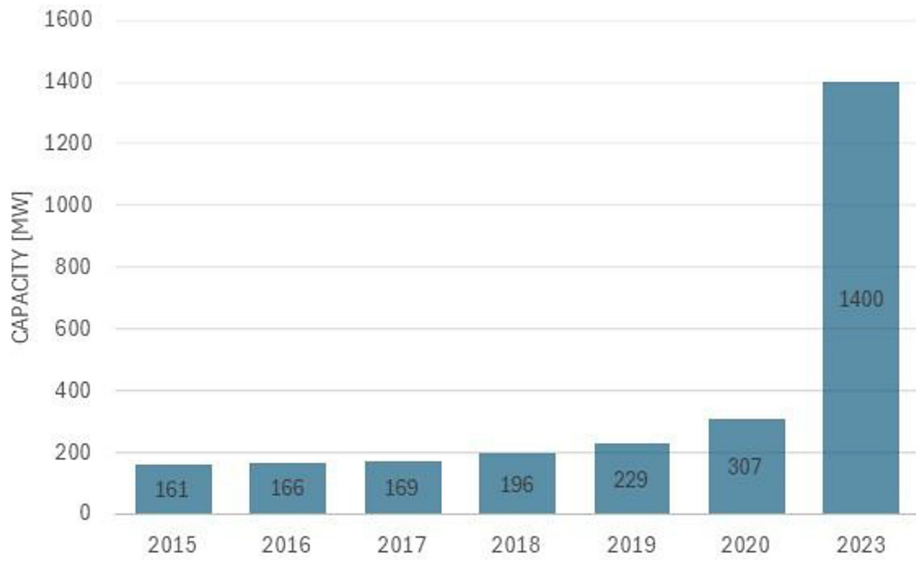

Figure 4. Installed electrolyzer capacity [17]

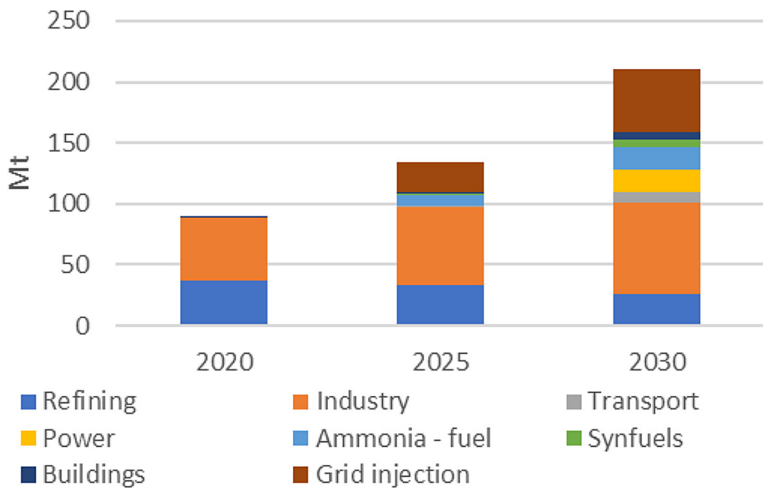

Figure 5. Global demand for hydrogen by sector [18]

(reliability and stability), environmental (emission reduction), and social (social acceptability) requirements. This multidimensionality of decision-making problems means that traditional optimization methods based on a single criterion are insufficient. In the context of this complexity, multi-criteria decision analysis (MCDA) or multi-criteria decision support MCDM become an indispensable tool for the development of energy systems. They enable the systematic consideration of various aspects of sustainable energy development and ensure a transparent decision-making process involving various stakeholders [20, 21]. In previous approaches to this problem, researchers have used a variety of MCDA/MCDM methods. For example, in the work [22]. The widely used analytical hierarchy process (AHP) method was applied to plan the location of photovoltaic farms. Several other studies have also used MCDA methods to evaluate various aspects of the energy sectors. For example, TOPSIS and AHP were used to select a relief scheme [23], and the appropriate selection of materials for the development of wind turbine blades towards sustainable energy production was carried out using methods AHP and TOPSIS [24]. There are many examples in the literature of using MCDA methods to assess the sustainability of energy sectors. For example, to assess the efficiency of energy management in Turkey compared to eight other countries, including European, North American, and Asian countries, three MCDA methods were used, namely AHP, TOPSIS, and VIKOR [25]. The result shows that Turkey's overall energy efficiency is lower than that of the countries with which it was compared. The sustainability of electricity generation technologies in Egypt was assessed using two methods MCDA – AHP and WSM [26]. The authors showed that among seven technologies (coal, natural gas, wind, concentrated solar power, photovoltaics, biomass, and nuclear energy), natural gas-fired power plants, despite being a fossil fuel-based technology, are more sustainable than others, even better than renewable energy sources. In a study conducted in Spain to evaluate the location of an onshore wind farm, both the fuzzy analytic hierarchy process (FAHP) and the fuzzy total order preference by similarity to ideal solution (FTOPSIS) technique were used [27].

In the case of geospatial analysis methods, the availability of input data for GIS is of great importance. GIS databases provide information from various areas, such as road layout, energy infrastructure, building locations, nature conservation areas, restricted areas, tree cover, etc. These databases are constantly being expanded with new data from various fields. In this way, geospatial analyses can be carried out without the need for costly field research, providing us with a range of data for evaluating project implementation. By combining multi-criteria methods with geospatial analysis, we can create a more complete picture of potential locations for Power to Gas technology [20]. Spatial decisions, such as searching for the best land for investment, identifying natural, technical, or social constraints, require information and tools to help understand the issues involved in making decisions in the search for the best solution. They also require analyses to assess and reconcile the interests of different stakeholder groups and decision-makers [20]. At work [22] a method of supporting the AHP system for planning the location of photovoltaic farms was presented. Using criteria such as distance from residential areas, solar radiation intensity, access to the site, distance from roads, and distance from power transmission lines, optimal locations for solar farms were determined. In the studies described in [28] the authors analyzed various energy storage systems for unstable renewable energy sources, such as: hydro and compressed air energy storage, hydrogen, flywheels, supercapacitors, lithium-ion battery storage, and others. A comparison of the most advantageous energy storage methods in terms of energy efficiency, flexibility, affordability, and environmental impact was analyzed in the literature [29]. The authors selected five energy storage systems: pumped storage hydroelectric power plants, conventional batteries, high-temperature batteries, flow batteries, and hydrogen. The results of the assessment indicate that technical factors have the highest impact, while social factors have a lower impact in the overall assessment of the selected energy storage technologies. Hydrogen has the highest sustainability scores compared to other energy storage systems evaluated. This demonstrates that P2G systems are extremely important for balancing the energy supply from wind and solar power plants.

Based on the literature review, the following conclusions were drawn:

- P2G technologies pose a complex decision-making challenge in which multidimensional technical, economic, environmental, and social criteria play a key role.
- implementing P2G solutions involves assessing infrastructure, regulations, market factors, proximity to transmission networks, and access to renewable energy.
- P2G project stakeholders often represent conflicting economic and environmental goals, which requires management of their preferences.
- hybrid approaches combining multicriteria decision analysis/multicriteria decision making with geospatial analysis (GIS), allowing for (1) spatial visualization of the criteria and constraints of the decisions made, (2) identification of the best locations in terms of, for example, resources and infrastructure, (3) assessment of trade-offs between different criteria in the context of area/region diversity.
- MCDA-GIS methodologies enhance the transparency of the planning process, enabling comprehensive assessment of investment scenarios and management of complex stakeholder relationships.

METODOLOGY

In the case under consideration, a model based on GIS-MCDA analysis was used, which combines geospatial data with multi-criteria decision-making methods, enabling the resolution of spatial problems. This technique is widely used, e.g., in the selection of locations for energy systems, transport route planning, land suitability assessment, and the designation of optimal areas for various sectors of the economy.

The proposed procedure suggests the use of a method that integrates multi-criteria analysis with GIS systems by combining layers using the WLC (weighted linear combination) method [30]. This technique allows the weights of individual criteria to be determined and assigned to the appropriate map layers. QGIS software was used in the process of integrating the AHP method with GIS as a spatial data processing tool. The main objective of this approach is to determine the weights for maps representing different criteria and then aggregate them to obtain a spatial analysis of decision preferences.

The GIS-MCDA approach is universal and allows for the inclusion of multiple criteria and sub-criteria in the decision-making process. Decisions in this context involve integrating the relevant map layers containing assigned attributes and decision-makers' preferences in order to identify satisfactory solutions. One of the most commonly used GIS-MCDA methods is layer overlay and the use of the WLC method [31]. The assigned weights determine the impact of individual criteria on the final result of the analysis, enabling the creation of a preference map based on specific decision-making assumptions. The steps of the procedure are presented in Figure 6.

In this article, the authors propose an approach consisting of a 6-stage procedure. The first stage involves a detailed definition of the P2G problem. In the next stage (stage II), the authors propose defining a consistent set of criteria that should be taken into account when evaluating the location of P2G systems. Based on the literature [5, 32–37] and expert consultations, five main criteria were adapted in the presented decision-making model:

- C1 – wind energy potential – (maximized environmental criterion) is defined as the average annual wind speed in the analyzed area, expressed in [m/s].
- C2 – infrastructure availability – (minimized economic and technical criterion) taking into account the availability of gas, power, and road infrastructure. In the case of gas and power infrastructure, it is crucial to ensure the possibility of transmitting the required amounts of electricity and hydrogen (and its derivatives). Road infrastructure, on the other hand, should enable the transport of wind farm components and its subsequent operation. The distance from these networks affects the investment costs associated with the construction of P2G infrastructure and wind farms.
- C3 – distance from residential buildings – (maximized legal and social criterion) – Defined as the distance from residential buildings, taking into account legal restrictions and potential nuisance to residents in the vicinity of P2G infrastructure and wind farms
- C4 – terrain slope – this is an economic and technical criterion, mainly related to difficulties in the construction and operation of facilities in areas with a steep slope. The value of this criterion is expressed as a percentage [%]. Based on a literature review, a terrain slope limit of 15% was adopted. This criterion is a subject to minimization.
- C5 – nature conservation (maximized environmental criterion) taking into account the distance from protected areas such as national parks, landscape parks, Natura 2000 areas, water reservoirs (lakes, rivers), and forests. This criterion results from both applicable legal regulations and the impact on the optimal operation of P2G infrastructure and wind farms. It is expressed as the distance of these facilities from the analyzed areas.

A group of stakeholders interested in the implementation of P2G projects was also selected. Their characteristics are presented in Table 1.

The next step is to determine the importance of each criterion using the AHP approach (30). The method is based on a comparative scale presented in Table 2.

The analytic hierarchy process is particularly well regarded in energy planning. Its popularity stems from several key factors: It is widely used and well documented in the literature [5, 38, 39]; is used in energy analyses and infrastructure investments [5, 38], enables qualitative aspects to be taken into account, which are then converted into a quantitative approach, simplifying the process of comparing criteria and variants; allows for flexible adjustment of the set of criteria by creating sub-criteria, which facilitates analysis.

The study used the AHP method to determine the weights of individual criteria. The weights obtained are the input data for the next stage of GIS analysis. As part of the AHP analysis, a group of experts compares individual pairs of criteria.

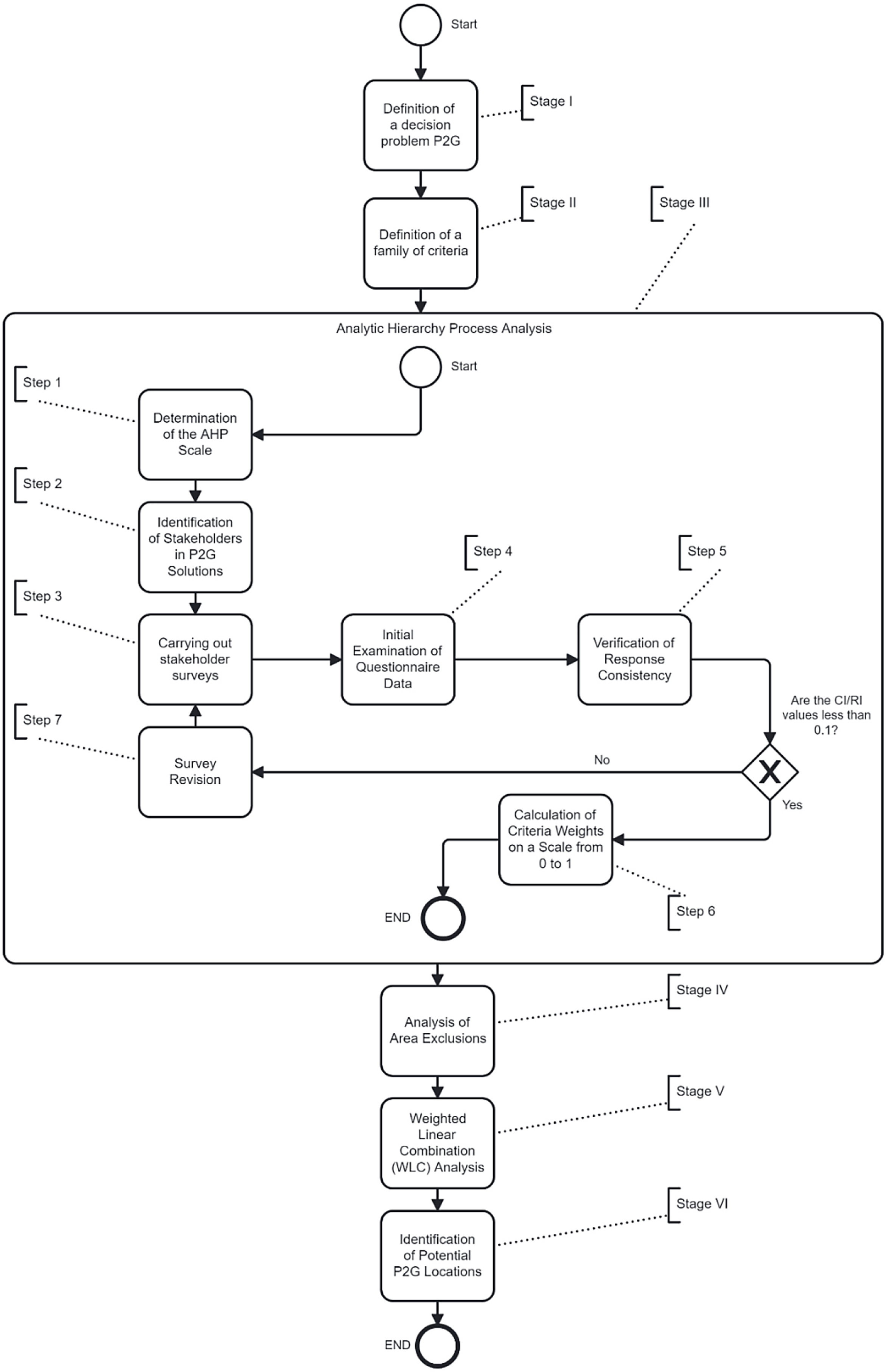

Figure 6. The P2G location assessment procedure

Table 1. Perception of criteria by stakeholders

L.p.	Interesariusz	Opis
1	Energy producers and suppliers	Companies producing electricity from renewable energy sources (wind farms, solar power plants) supply the surplus electricity needed to power electrolysers that produce hydrogen or synthetic methane.
2	Transmission and distribution network operators	• Transmission system operators (TSOs), responsible for maintaining grid balance and transporting energy to P2G installations. • Gas network operators—TSOs and DSOs—manage gas transmission and distribution infrastructure, enabling the introduction of hydrogen or methane into it.
3	Technology developers and equipment providers	Research institutes (e.g., Fraunhofer IWES, ZSW) and companies specializing in PEM electrolysers or methanation technology are developing and supplying key components for P2G plants.
4	Regulators and public authorities	State and EU organizations (e.g., dena, ACER, ENTSOG) are developing standards, definitions of "renewable gas," and regulatory frameworks that enable P2G installations to participate on an equal footing in energy and system services markets.
5	Investors and financial institutions	Venture capital funds, banks, and agencies supporting P2G projects provide financing for capital and infrastructure investments, taking into account revenue stacking models combining revenues from various services (gas production, flexibility, hydrogen sales).
6	End users	• Industries using hydrogen or H_2/CH_4 mixtures for technological processes. • Automotive and alternative fuels sector – hydrogen refueling station suppliers. • Municipal customers – district heating and households using so-called "green gas" for heating and cooking.
7	Local communities	Residents of areas where P2G installations are being built and various associations monitoring the compliance of projects with climate goals and nature conservation standards.
8	Local government	Revenue from fees and taxes, unemployment issues, environmental protection
9	Central government	National energy security, climate neutrality (climate goals), energy transition.

Table 2. Fundamental scale of absolute numbers between two parameters in AHP model [40]

Intensity of importance	Degree of preference	Explanation
1	Equally	Equal importance to objective is equal
3	Moderately	Attribute is slightly favored over another
5	Strongly	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly	Attribute is very strongly favored over another
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate values	When compromise is needed

Then, a comparison matrix C (1) of size n x n is created, where n is the number of criteria.

$$C = \begin{Bmatrix} 1 & c_{1,2} & \cdots & c_{1,n} \\ \frac{1}{c_{1,2}} & 1 & \cdots & c_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{c_{1,n}} & \frac{1}{c_{2,n}} & \cdots & 1 \end{Bmatrix} \quad (1)$$

In the case of n criteria, the number of comparisons made will be calculated according to formula (2). This means that for, e.g., five criteria, we must perform 10 comparisons.

$$Number\ of\ comparisons = \frac{n \cdot (n-1)}{2} \quad (2)$$

A characteristic feature of the matrix is the diagonal, which takes values of unity. This results from the equivalence of comparing the same criterion (e.g., C1 with C1). Determining the advantage of criterion $c_{j,i}$ in row i and column j means accepting the inverse of this criterion in row j and column i for $c_{j,i}$ (3), which is equal to:

$$c_{j,i} = \frac{1}{c_{i,j}} \quad (3)$$

In the next step, we normalize the matrix in which the elements $\bar{c}_{i,j}$ take the form of (4)

$$\bar{c}_{i,j} = \frac{c_{i,j}}{\sum_{j=1}^{n} c_{i,j}} \quad (4)$$

The priority vector for individual criteria is calculated by calculating the average of the values of individual rows of the normalized inverse matrix (5). The values obtained show the importance of a given criterion (weight).

$$w_i = \frac{\sum_{j=1}^{n} \bar{c}_{i,j}}{n} \quad (5)$$

Next, it is necessary to check the consistency of the answers provided by the expert. This is due to the fact that the expert only makes comparisons in pairs from among the group of criteria. It may happen that the answers in one pair of criteria comparisons will be inconsistent in the next comparison. AHP analysis allows for a certain degree of inconsistency at the level of 10% (40). If the value is higher, it is necessary to verify the answers provided by the expert and eliminate any inconsistencies. Consistency checks are required for all groups of criteria comparisons in the given groups. For this purpose, the consistency index CI is calculated (consistent index) according to the relationship (6).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

where: as λ_{max} is the largest eigenvalue of the matrix. This means that complete consistency occurs when the maximum eigenvalue of the matrix is equal to the order of the matrix (the number of criteria) [41, 42]. In the next step, the CR coefficient is determined. is determined (consistency ratio), which is the ratio of the consistency index to the Saaty's random index RI (random index). It is assumed that the CR ratio should not exceed 0.1 [40].

$$CR = \frac{CI}{RI} \quad (7)$$

The value of the RI coefficient was estimated by Saaty, the creator of the AHP method, and was shown in Table 3 [41].

The AHP analysis in the methodology used served to determine the importance of the selected criteria. It should be noted that the described approach (AHP) and the method of expressing the importance of criteria is one of the most common approaches in multi-criteria decision support. Nevertheless, according to the authors, it is possible to use a different method that does not involve a normalisation procedure that may distort the priorities of the criteria. The next stages are GIS analyses, which consist of the following steps: exclusion analysis (stage 4), WLC analysis (stage 5), and selection of potential areas (stage 6). A brief description is presented below.

After conducting a multi-criteria analysis and assigning weights to individual criteria, a map layer analysis is created. This process is carried out in the QGIS environment, where the following steps are performed: the weights of individual criteria and sub-criteria are mapped onto map layers (raster analysis) using standardization of individual criteria for the relevant layers. In the WLC method, each criterion is assigned a score on a scale of 1 to 10, which enables priority analysis. A diagram of the raster analysis, illustrating the overlapping of layers corresponding to individual criteria, is presented in Figure 7. Each layer contains a raster representation of criteria, standardized in a way that allows for comparison and spatial analysis. The analysis results in areas with the highest potential attractiveness. In the context of geospatial analyses, the growing availability of GIS data is of great importance. These systems provide information on road and energy infrastructure, the location of buildings, protected areas, restricted areas, tree cover, and many other aspects. The dynamic development of GIS databases enables comprehensive pre-investment analyses to be carried out without the need for costly field research. WLC analysis diagram using GIS raster analysis.

RESULTS

Characteristics of the area

In this article, the verification of the approach is presented while using the example of the Wielkopolska Province (Figure 8). The choice of location for a P2G installation depends on many factors, such as the distance of the wind farm from the gas, transport, and power grids, the development of the surrounding area, population distribution, etc. The use of multi-criteria decision-makingin a geographic information

Table 3. Coefficient values of RI

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

system (GIS) is an effective method for selecting the optimal location. The Wielkopolska Province is located in the western/western-central part of Poland and covers an area of approximately 29,826 km². The region borders seven other provinces: Pomeranian, Kuyavian-Pomeranian, Łódź, Opole, Lower Silesian, Lubusz, and West Pomeranian [44]. It ranks second in the country in terms of area and third in terms of population [45]. According to data from June 30, 2024, the Wielkopolska Province had a population of 3,484,177. The average age of inhabitants in the region is approximately 41.6 years [46]. The economy of Greater Poland is diverse and relatively strong compared to the rest of the country. The region has good industrial and transport infrastructure and a well-developed agricultural, processing, and service sector. The region is characterized by significant economic activity [47]. At the national level, in 2023, the increase in installed capacity in the wind sector reached a record level of 1.261 MW, a significant part of which came from large wind farms. The region also has good wind conditions (substrate resources), but due to the high degree of forestation and agricultural character, the availability of land is limited.

Procedure and results

In order to determine the validity of the criteria, an AHP analysis was used, the results of which were then used in a GIS analysis. The survey was conducted among experts from the energy sector, including representatives of both industry and academia. A total number of 88 people took part in the survey, with 30 questionnaires meeting the CR criterion being used for the study. The Wielkopolska Province was chosen as the research area. The choice of the area under consideration for the study can be arbitrary.

Criteria weights (Table 4) indicate that wind energy potential is a key factor, playing a dominant role in the decision-making process. Nature conservation was ranked second in terms of importance. Other factors of lesser importance were ranked in the following order: infrastructure availability, distance from residential buildings, and terrain slope. This order of priorities sets out a logical sequence of actions when selecting the optimal location. The analysis began with the preparation of exclusion areas, which, due to their nature, completely rule out the possibility of establishing wind farms. These are areas excluded in terms of nature conservation (Figure 9a), areas excluded in terms of terrain slope (Figure 9b), areas limited by distance from buildings (Figure 10).

The next step was to perform a WLC analysis using AHP analysis and GIS raster analysis. The aim was to identify areas with high potential for P2G projects. As part of these activities, a GIS analysis was performed using the weights of individual criteria obtained from the AHP analysis. The raster analysis was performed using the raster calculator in QGIS. The main objective of this approach is to determine the weights for maps representing the criteria. These weights are then

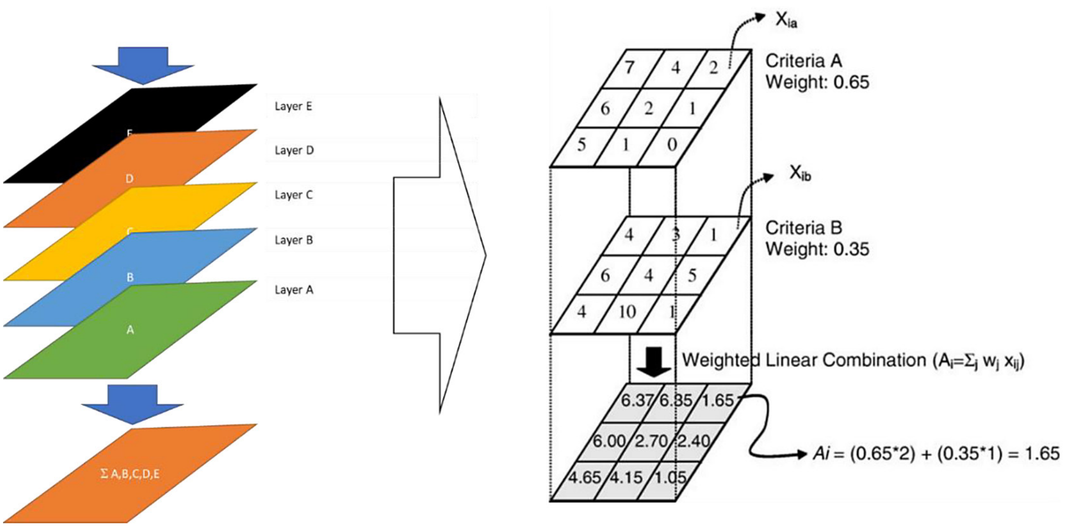

Figure 7. WLC analysis diagram using GIS raster analysis [43]

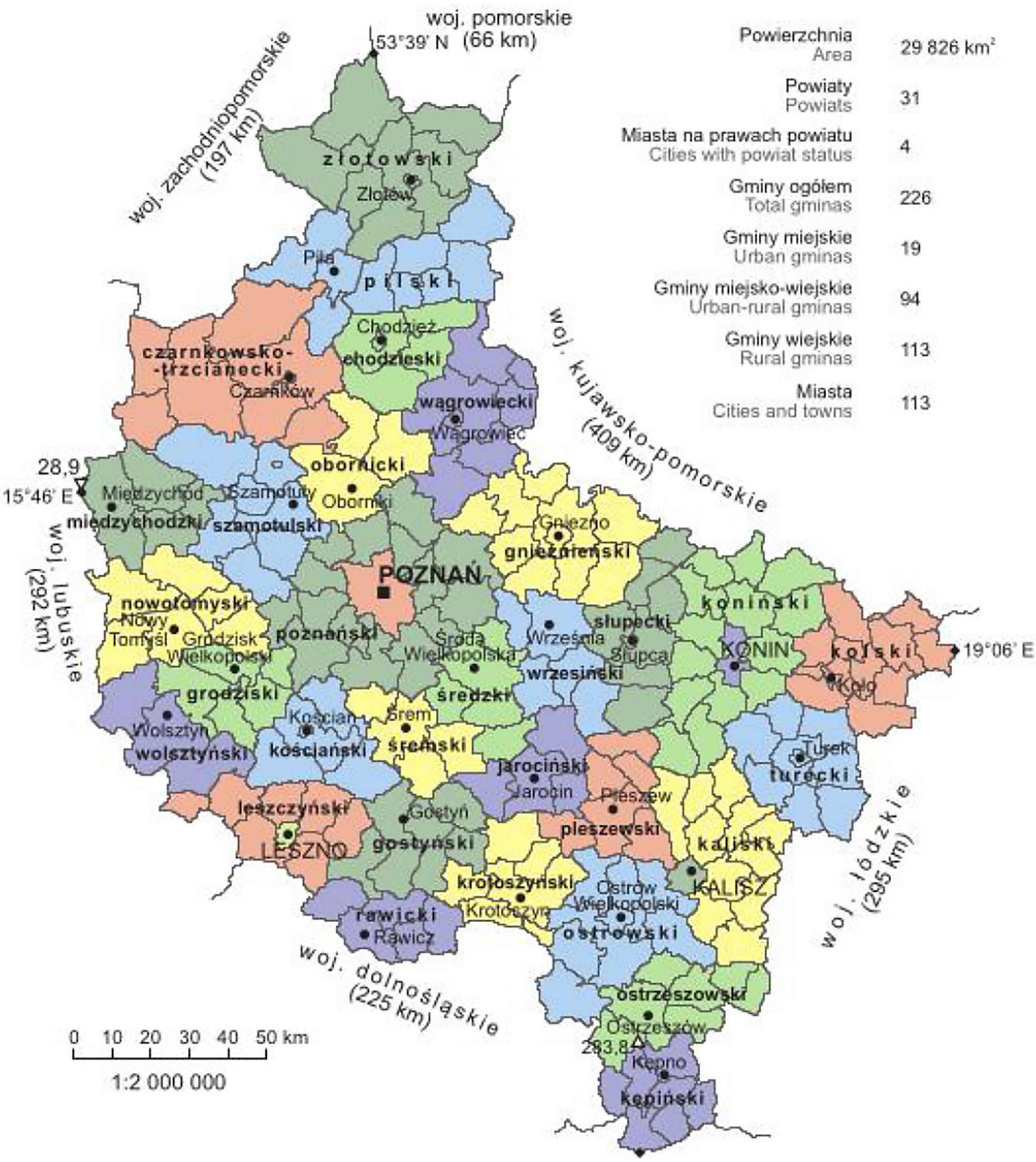

Figure 8. Map of the Wielkopolska Province – administrative division (48)

Table 4. List of criteria weights depending on the CR consistency coefficient

Scope of the cohesion factor CR	Description	C1 – Potential of the wind energy	C2 – Availability of the infrastructure	C3 – Distance from residential buildings	C4 – Slope of the terrain	C5 – Nature conserva-tion
till 10%	Ranking position	1	3	4	5	2
	Weight [%]	31.10	18.68	15.55	7.80	26.87
till 15%	Ranking position	1	3	4	5	2
	Weight [%]	30.00	18.72	15.16	7.70	28.43
till 20%	Ranking position	2	3	4	5	1
	Weight [%]	28.18	18.98	15.47	7.69	29.68

assigned to the criteria maps, which are then combined. The result of this analysis are maps showing the distribution of weights in a spatial context. The work resulted in a group of three resultant locations (three variants of distance from buildings: 500 m, 700 m, and 1000 m). These variants correspond to the legal situation in Poland [49]. The results are presented in Figure 11 while

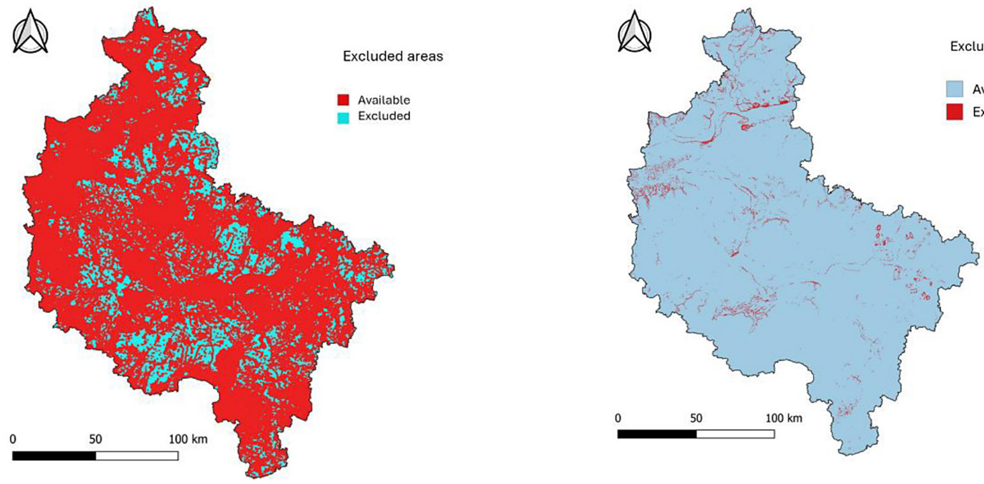

Figure 9. Excluded areas in Wielkopolska Province: (a) nature conservation zones, (b) areas excluded due to terrain slope constraints

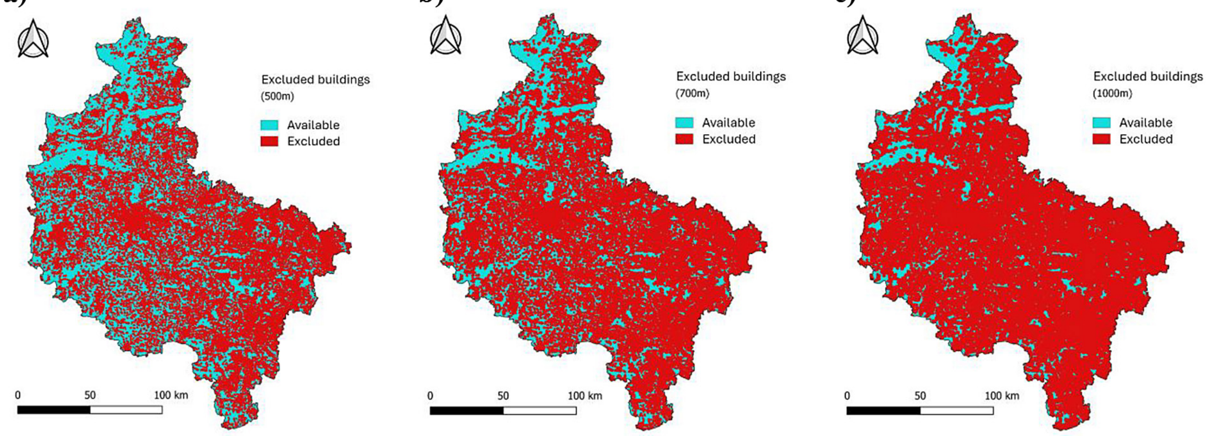

Figure 10. Exclusion zones depending on the distance from buildings: (a) 500 m, (b) 700 m, (c) 1000 m

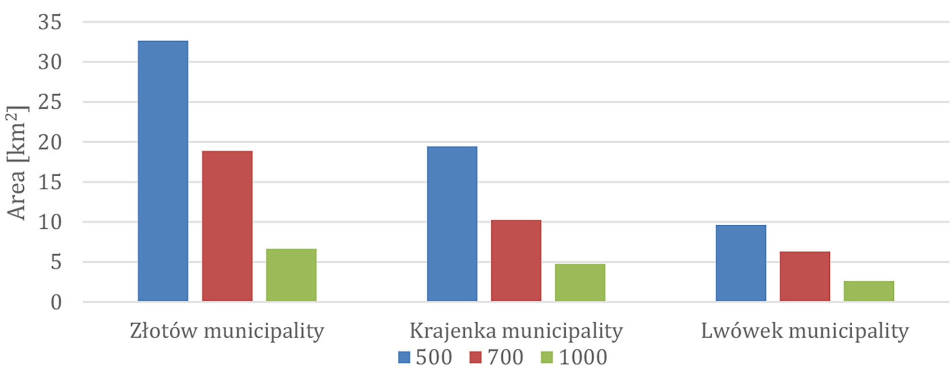

Figure 11. List of resulting locations

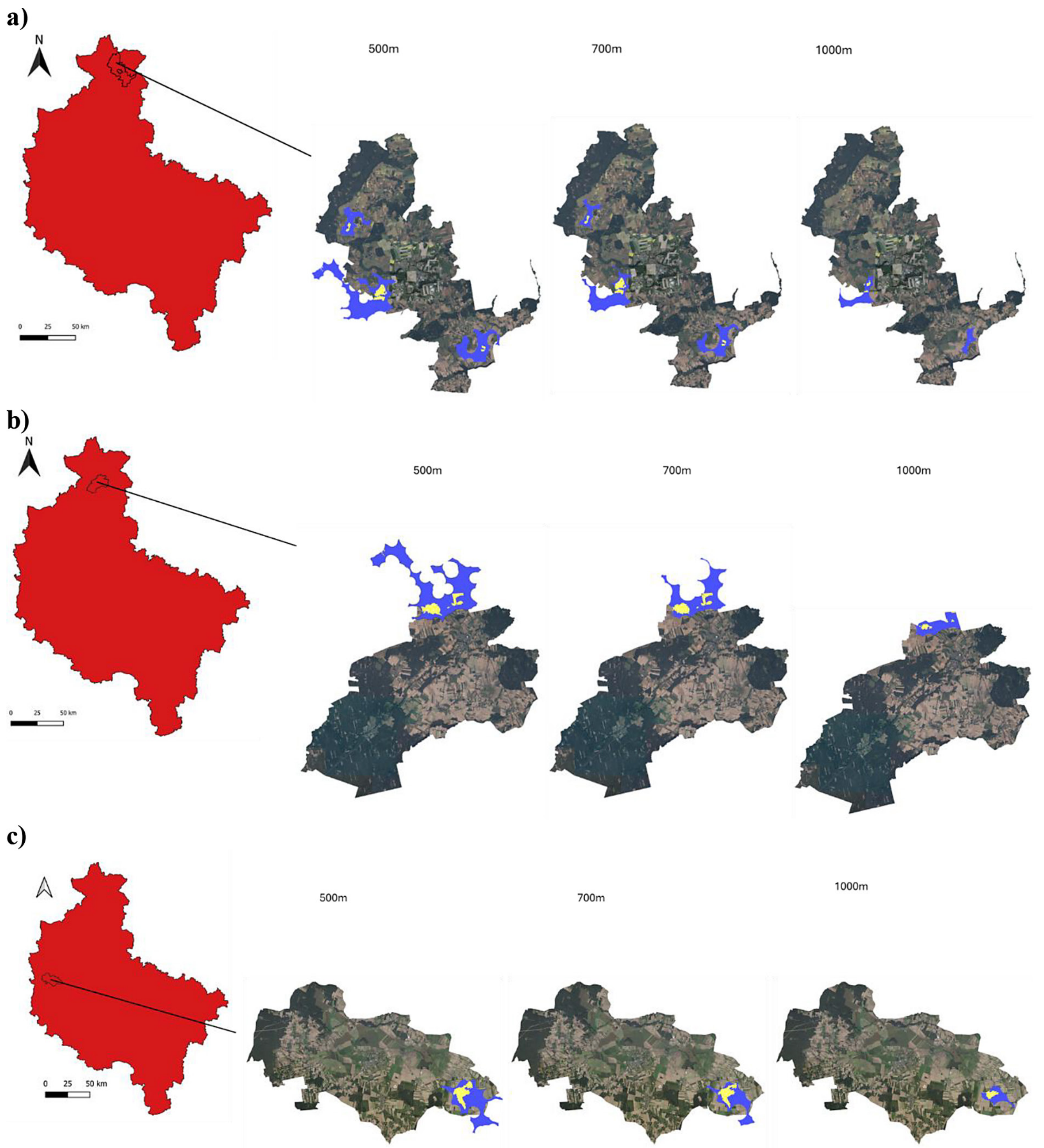

Figure 12. The resulting locations, taking into account distances of 500, 700, and 1,000 meters from buildings: (a) locations in the municipality of Złotów, (b) locations in the municipality of Krajenka, (c) locations in the municipality of Lwówek

the summary in the form of maps is presented at Figure 12 a, b, c. The locations indicated are only part of the areas in the province that can be used for P2G installations. This is important in the context of energy transition projects. P2G technologies play a key role in stabilizing the energy system. Despite the limited number of suitable sites, there are opportunities for the development of wind energy integrated with P2G technology, which opens up prospects for further expansion of this solution.

CONCLUSIONS

This article presents an example approach to evaluating P2G solutions. A multi-stage procedure based on the WLC method, which relies on multi-criteria analysis and GIS, is proposed. The AHP multi-criteria analysis method, one of the most commonly used decision-making techniques, was selected to conduct the research. The areas of restriction were defined on the basis of five key criteria reflecting the most important factors influencing the selection of wind farm locations in the context of P2G projects. Two criteria were of the greatest importance in the decision-making process: wind energy potential and nature conservation.

The AHP multi-criteria analysis was based on surveys conducted among experts. Due to the relatively young nature of the energy transition, the availability of specialists in this field is limited, which posed a challenge in conducting the research. However, as the transformation processes progress, the number of experts will increase, which will facilitate future analyses. The survey results indicate that the key factors influencing the choice of location are renewable energy resources (31.1% of responses) and environmental protection (26.9% of responses). In some cases, these criteria may conflict with each other, as areas with high wind potential often overlap with nature conservation areas. The weights of the individual criteria were taken into account in the decision-making model as part of the GIS analysis.

The functioning of the model was verified on the example of the Wielkopolska Province. The results of the study indicate that a significant part of the region is difficult to access for P2G projects. However, despite limited location options, there are areas that offer potential for the development of this technology.

Significant regulatory constraints mean that available space plays a key role in the installation of renewable energy sources. Despite the variability of operation resulting from wind conditions, wind farms provide much more stable energy production than, for example, solar installations. As a result, they can form the basis for electricity generation in the energy transition process.

The approach proposed in the article, based on GIS-MCDA methods, allows for a comprehensive (holistic) approach to the development of P2G systems. First and foremost, it is important to take into account a number of criteria that are perceived differently by stakeholders. It should be noted that the proposed approach is based on the AHP method, which is commonly used in multi-criteria infrastructure decision support. This does not mean that preferences cannot be determined using other methods. It is important that stakeholders are aware of their influence on the final P2G system solution. A holistic approach is characterised by the fact that, in addition to various stakeholders, a consistent set of criteria is taken into account in decision-making. Here, too, it is worth emphasising that their number, category (technical, environmental, social, legal, etc.) and structure depend on the specific nature of the problem and should always be adapted not only to the problem, but also to the availability of data used to calculate them. For this reason, the use of GIS tools creates opportunities for a compromise solution on the one hand, but also indicates directions for the development of decision-making in the field of energy system solutions. The suggested method is transparent and replicable, which means that it can be applied regardless of the number of criteria or variants and the area. The graphical presentation of the results, using the example of the Wielkopolska Province facilitates their interpretation, which is important for energy companies and decision-makers.

The future directions for research and analysis may include:
- the inclusion of time analyses of energy production, i.e. the uncertainty (variability) of energy production from RES,
- energy storage scenarios in dynamic models,
- scenarios related to emergency situations: natural disasters, armed conflicts,
- estimating hydrogen demand in the transport and industry sectors.

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