https://doi.org/10.7494/geom.2024.18.4.5

Marcello La Guardia[1], Filippo D'Ippolito[2]

WebGIS Open-source Platform for Localizations of New P2G Plants in Sicily

Abstract: The climatic emergency that involves the globe has led targets of greenhouse gas reduction in the EU and all over the world. In this scenario, recent advances in renewable renewable energy sources (RESs) have focused interest on the diffusion of power supplies that are produced by photovoltaic and wind plants. The non-programmable nature of these energy sources has led recent studies to consider the power-to-gas (P2G) solution as an opportunity for employing the curtailed electric energy by converting it into hydrogen. The localizations of P2G plants depend on several factors regarding power production, distances, and population distributions. The necessity of integrating these factors led this work to study the development of a cost function that is hosted by a web-based GIS (geographic information system) platform, thus allowing for the storage, elaboration, and web fruition of an entire data set that is related to the possible new localizations of P2G plants. The structure is based on open-source technology and creates a solution that is easily employable by specialists. The developed platform is composed of different remotely connected blocks that are solely based on open-source technology and is focused the interest on the territory of Sicily (Italy). GIS software, a RDBMS database, a geospatial server (Geoserver), a Python optimization module, and a WebGIS visualizer are integrated. This work represents a scientific contribution to the management of energy sources, with a particular focus on policies that are based on hydrogen technology. In fact, different data sets that contain several levels of information that are related to the management and the localization of P2G plants will be even further employed in the future.

Keywords: geospatial server, open-source, P2G, RES, WebGIS, JavaScript

Received: February 3, 2024; accepted: May 1, 2024

[1] University of Florence, Department of Civil and Environmental Engineering (DICEA), Florence, Italy, email: marcello.laguardia@unifi.it (corresponding author), https://orcid.org/0000-0003-0984-1271

[2] University of Palermo, Department of Engineering, Italy, email: filippo.dippolito@unipa.it, https://orcid.org/0000-0002-3324-4314

1. Introduction

The last decades have been characterized by research on new solutions to apply in the field of renewable energy sources (RESs) in order to solve those problems that are related to global pollution and the depletion of fossil energy sources in the world. This problem represents one of the main challenges of this century. In 2020, the Green New Deal (GND) plan was approved by the European Commission with the aim to decarbonize the European Union by 2050. In all, 143 countries outlined the target of converting the overall energy production in RES by 2050, creating the Green New Deal roadmap [1].

Recent policies have tried to exploit new RESs in the best ways, focusing their attention on photovoltaic and wind power sources in order to find possible alternative energy solutions to fossil fuels and natural gas. Unfortunately, the unpredictable nature of wind and photovoltaic energy represents a strong limitation and still remains a challenge. In fact, excesses of the daily amounts of electric energy that are produced are usually curtailed in order to prevent electrical transmission network overloads [2]. The adoption of power-to-gas (P2G) technology is a possible solution for solving this problem, converting a part of the electric energy production that comes from wind and photovoltaic plants into hydrogen [3, 4].

The conversion of electric energy into hydrogen opens new scenarios for RES energy employment; following this solution, the produced hydrogen could be injected into the natural gas network at low percentages or could be combined with CO_2 for methanation [5].

The recent diffusion of this kind of solution in Europe and Italy [4, 6–8] has led the localizations of new P2G plants to be one of the most relevant topics in the field of energy production. In the localization process, it is necessary to consider several factors that are involved in the P2G chain that are related to the definition of the mutual positions between new installations and the existing territorial assets. It is necessary to consider the proximities of new P2G installations to centers of demands, existing gas networks, the power from the associated RES plants, etc.

At the same time, the use of geographic information systems (GISs) is even more diffused in several fields of research, combining the geospatial representations (points, lines, and polygons) and semantical characterizations of territorial assets [9–13]. The possibility of integrating data set management through the use of relational database management systems (RDMBSs) and the interaction with analysis and elaboration tools makes GIS a fundamental instrument for applications in many sectors such as the economy, industry, architecture, public administration, etc. [14]. Furthermore, the technological advances on internet connections in recent years have led to the further diffusion of WebGIS applications, allowing them to be shared in web geospatial information about infrastructure, cadaster, environment, mobility, etc. [15–21]. The possibility of real-time geospatial environment fruition on PC and mobile devices and the opportunity of the real-time extraction and elaboration of complex data sets recently diffused the application of WebGIS solutions in several scientific fields, integrating multi-criteria analysis (MCA) calculations that have been applied to geospatial information [22–26].

Considering this scenario, the construction of a WebGIS open-source geospatial platform with an integrated MCA module seems to be a proper solution for the localizations of new P2G plants. Our work follows this solution, integrating an MCA module in a WebGIS structure that has been developed with open-source technologies. In particular, the heterogeneous starting data set (containing information about energy production, railway and road networks, gas pipelines, and the population of the Mediterranean island) was integrated in a WebGIS platform, where an optimization model (based on geospatial information) elaborates a specific cost function and allows users to visualize the cost for each possible P2G localization on the island via the web. The followed choice is an adoption of only open-source solution integration, which is aimed at the open diffusion and distribution of this framework without any property software limitations and without property software costs.

The open-source platform that is shown in this paper is divided into single mutual remotely connected blocks of operation that contain GIS software (QGIS), an RDBMS database (Postgres), a Python computational module (Pandas and Geopandas), a geospatial server (Geoserver), and a WebGIS JavaScript-based visualization module (Leaflet).

The work that is shown considers the case of the study of Sicily, which offers an ideal territorial asset for hosting photovoltaic and wind plants [27]. In fact, the natural meteorological condition of the island (attested to by its air temperature, solar irradiation, and wind speed) has led Sicily to be one of the best places to host new wind and photovoltaic facilities. The large diffusion of wind and photovoltaic plants in the territory led to the diffusion of P2G technology as a realistic solution for the Mediterranean island. The present study shows the construction of the WebGIS platform that allows us to calculate and visualize the best localizations of new P2G plants in the territory of Sicily. The work is the result of several steps and integrations that consider the discretization of the domain of possible P2G localizations, the construction of the cost function, and, finally, the development of the WebGIS platform that hosts the system. Previous studies that presented intermediate versions of this research have been the objects of international journal publications [28, 29]. In the following paragraphs, the state of the art in WebGIS and MCA analysis model integration in the field of energy will be presented, then the case of study will be shown; finally, the results and conclusion will be analyzed.

2. State of the Art

The development of geomatics over the last decades of the 20th century opened new scenarios on territorial analysis, allowing for the integration of

Python computational modules and geospatial processing with visualization procedures [30]. For instance, one of the main actors of the world related to the open-source geospatial software – GRASS GIS (geographical resources analysis support system), which is based on the architecture of the system on this integration – offers the possibility of making network analysis functions and SQL attribute management on vectoral and raster data sets [31, 32].

In recent times, the possibilities that are offered by GIS technologies have led scientists of several disciplines to employ geospatial data sets for data analysis and processing. Considering the world of open-source software and open data, the Open-source Geospatial Foundation (OSGeo) generated a new ecosystem where the way in which geospatial sources are employed has changed [33]. In fact, these communities developed a self-organized system of collaborative software development, where open-source software platforms such as Geoserver, QGIS, Leaflet, and Openlayers are continuously updated by the community. Recent advances in open-source WebGIS applications have allowed for the development of fully automatic processing chains for land monitoring and for sharing thematic map visualizations [34]. The last years have also been characterized by the integration of WebGIS applications and new algorithms and platforms that allow semi-automatic geoinformation data extractions; this integration is useful for implementing new editing capabilities into the WebGIS framework [35]. In recent studies, the integration of Pandas and Geopandas Python libraries into a WebGIS tool have allowed specialists to achieve such environmental management goals as the ability to analyze the impacts of anthropogenic activities into the natural environment of the marine ecosystem [36].

Considering the field of energy, the last years have been characterized by the even-more-diffused use of GIS tools and geospatial data sets for optimizing energy production. GIS tools have been fundamental for solving new biomass power plant localization problems when considering several geospatial variables that are related to forest distributions, feedstock locations, and economical and transport factors [37]. Still considering the field of bioenergy, GIS tools have been exploited in order to simulate the costs of energy supply chains based on forests and biofuel products [38]. The integration of GIS and geospatial and temporal information have been used to maximize the energy production and minimize the costs that regulate the sizes and dimensions of solar plants [39]. The possibilities that are offered by GIS allow scientists to integrate geospatial parameters that are related to the transport network, the populations of urban centers, and the environment in order to select the best sites for the localizations of solar power plants [40]. The integration of GIS tools in power-plant-localization problems is even further exploited due to the possibility of heterogeneous data management [41–47].

At the same time, the diffusion of fast internet connections around the world have given a further impulse to the implementation of WebGIS portals, allowing users real-time analyses and visualizations as well as the acquisition of geospatial information. In Denmark, for instance, the WebGIS integration helped workers exploit geothermal energy due to the acquisition of geological and geophysical data [48]. Research that was based on WebGIS technology with decision-support-system integration allowed scientists to study biomass energy production for the possible implementation of new bio-energy plants in the Lombardy region of Italy [49]. The use of the WebGIS platform allows us to study the outcomes of research on potential renewable energy production, with the possibility of analyzing hydrological maps, wind atlases, and solar irradiation maps for photovoltaic plant localizations [50].

3. Materials and Methods

3.1. Study Area

The research that was involved in this study regarded a power-plant-localization problem (considering the P2G solution) in the specific territorial asset of Sicily. The P2G solution linked the networks of two different energy sources: the power energy from wind and solar photovoltaic plants, and the gas grid. The integration of the geospatial data set into a WebGIS platform was, hence, a strategic choice. As will be shown in the following paragraphs, the WebGIS integration was not only necessary for the final fruition of the result but also for the analysis and the Python cost elaboration based on the geospatial dataset real-time acquisition.

3.2. Methodology

The workflow considered different steps, starting from the construction of the conceptual model (based on MCA analysis) and finishing with the test of the WebGIS platform. The MCA model considered several factors that involved the optimizations of new P2G plant localizations on the Mediterranean island. The optimization model was the conceptual base that was necessary to solve the localization problem. Starting from this base, a geomatics framework allowed us to transpose the conceptual model into a real-time connected WebGIS service, where the solution was elaborated by the system (considering a filtered domain of possible P2G localizations) and users could visualize and analyze the results in a real-time connected platform (Fig. 1).

The geomatics framework considered two different phases based on the conceptual model: the first regarded the definition of the domain of possible P2G localizations (this step was developed locally and consisted of the first block of this framework), while the second consisted of the construction of the WebGIS platform. The platform connected different remote operational modules that allowed us to visualize the best localizations of new P2G plants. An RDBMS database (Postgres), a Python computational module (Pandas and Geopandas), a geospatial server (Geoserver), and a WebGIS JavaScript-based visualization module (Leaflet) were connected.

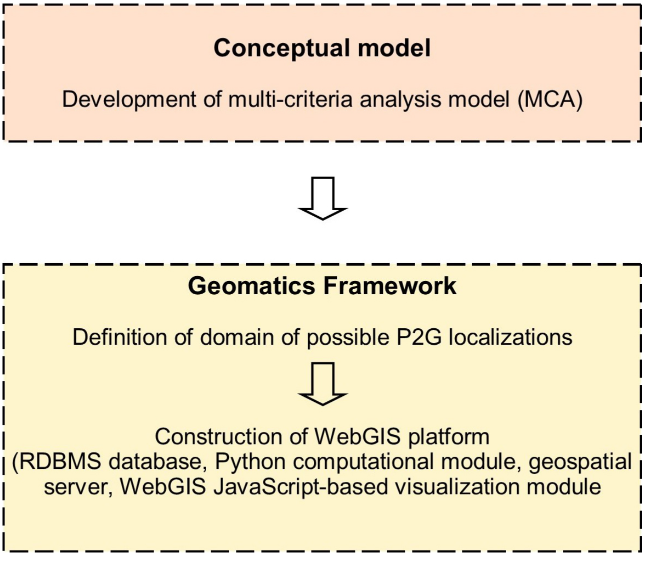

Fig. 1. Workflow followed for construction of WebGIS platform

MCA Model

The MCA model is the theorical model of the localization problem; it is based on operations research. This field of research employs mathematical optimization methods to improve decision-making problems. The developed MCA model considers a set of factors that influence the cost of possible P2G localizations.

First, the model starts with the creation of a uniform distributed grid on the terrain of Sicily that discretizes the starting territorial asset (Fig. 2). Each vertex of the regular grid of squares (1 km × 1 km) represents a possible solution of the localization problem, with a couple of associated geospatial coordinates (longitude, latitude) that defines its position inside the territorial environment of the Mediterranean island.

The domain of possible solutions is obtained by filtering the original domain of the grid. In fact, the distance constraints reduce the number of possible solutions to be inserted in the final cost function.

The optimization model can be represented in the following form:

$$\begin{cases} \min f(x) \\ x \in S \end{cases} \tag{1}$$

where f represents the cost function, and S represents the filtered domain of possible localization solutions. The best solution of the problem is those solutions inside the domain of S with minimum values of $f(x)$; this combination represents the best localizations of new P2G plants in Sicily.

The geographical distance constraints that filter the domain are listed below (Fig. 2):

– localizations near railway networks,
– localizations near road networks,
– localizations near existing wind or photovoltaic plants (excluding those that are merely associated with existing P2G plants).

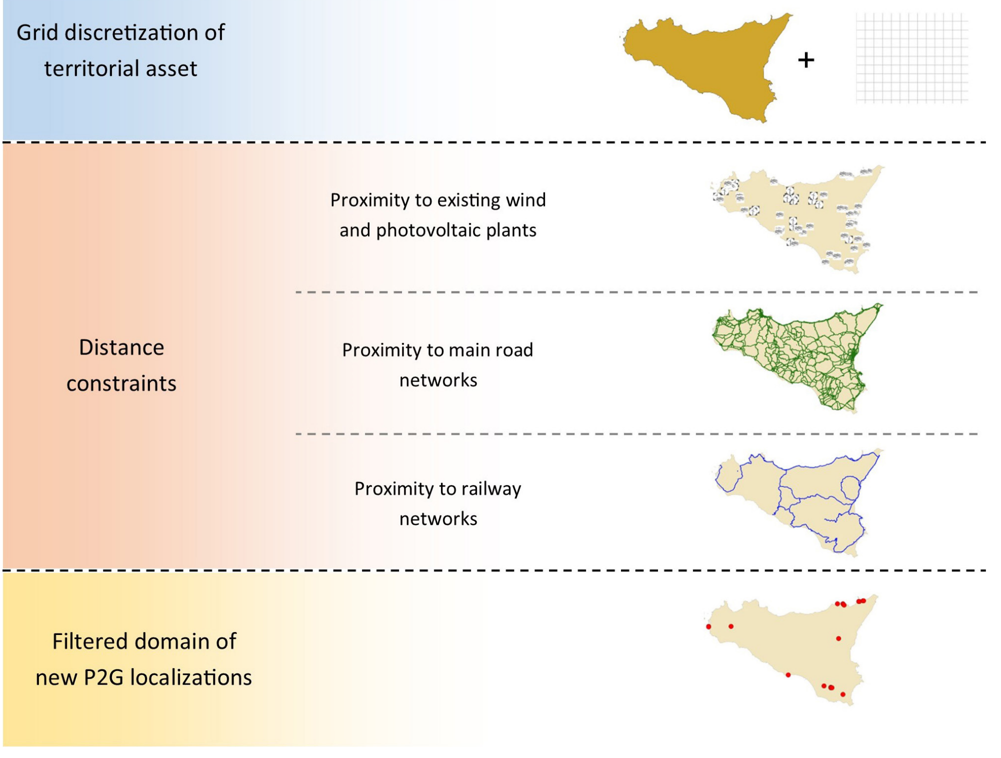

Fig. 2. Construction of domain of possible P2G localizations in Sicilian territorial asset: from grid discretization to application of distance constraints until finally achieving filtered domain of possible localization solutions

The considered constraints filter the elements of the original grid to generate the domain of possible solutions of the localization problem. The cost function is, hence, applied to this domain to find the best solution with the lowest cost (Equation (1)). The function is constituted by the sum of independent variables that consider the hydrogen demand (directly proportional with the number of inhabitants of the main urban centers), the production of energy by RES plants in Sicily (the existing photovoltaic and wind power plants are considered), and the distances between the points of production (possible localizations) and the points of demand (the main urban centers) considering three different networks (roads, railways, and gas pipelines).

Cost function $c(x)$ is calculated for each possible solution i that goes from 1 to s in the domain of possible P2G solutions:

$$c(x_i) = \frac{\sum_{j=1}^{d} \frac{RoCM_{ij}}{AN_{ij}}}{d} + \frac{\sum_{j=1}^{d} \frac{RacM_{ij}}{AN_{ij}}}{d} + DGN_i - PN_i;\ i = 1, 2, ..., s \qquad (2)$$

where:

s – number of possible P2G localizations,
d – number of main urban centers considered as points of demand;
$RoCM_{ij}$ – normalized cost of minimum distance through the road network between each possible P2G localization and each main urban center (considered to be demand node),
$RaCM_{ij}$ – normalized cost of minimum distance through road network between each possible P2G localization and each main urban center (considered to be demand node),
AN_{ij} – normalized number of inhabitants of corresponding main urban center that are considered to be demand node for related cost of minimum distance calculation,
DGN_i – normalized minimum distance between each possible P2G localization and nearest point of natural gas grid pipeline,
PN_i – normalized production of energy of RES plant associated with corresponding P2G localization.

This cost function $c(x)$ is calculated for each possible P2G localization (x_i) of the domain of possible solutions. The localization that obtains the lowest cost function value represents the best solution of a new P2G plant installation on the Mediterranean island.

Geomatics Framework:
Definition of Domain of Possible P2G Localizations

As affirmed before, the geomatics framework transposes the theorical MCA model in practice through discretizing the domain of possible P2G localizations and the development of the WebGIS platform. The discretization of the domain works locally in the first block of the chain. The system of elaborations is made by employing a semi-automated processing using QGIS open-source software. The block chain of the semi-automated processing is structured in four steps: buffering, intersection, cleaning, and cost/distance definition.

The first activity of the framework is to subdivide the territorial asset in a uniform projected square grid that divides the land into a set of possible new P2G localization solutions. This grid is overlapped with the buffered layers of the existing non-programmable RES plants (photovoltaic and wind power plants) and the main roads and railway networks. The intersection between the grid and the overlapped layers provides the domain of possible new P2G localizations. This activity discretizes all of the possible P2G localizations on the Mediterranean island; this discretization is made using QGIS open-source software creating block-chain processing.

Once defined, the domain of possible P2G localizations, the costs of the minimum distances between the possible new P2G localization solutions and the main urban centers (through the main roads and railway networks) were also defined in QGIS. In this way, the QGIS processing generated tables that regarded the costs of the distances among each solution and the main urban centers of the island. Finally, the cost of the distance between the possible new P2G localization solutions and the natural gas grid was calculated.

These operations that represent the first part of the geomatics framework were grouped in blocks on a single automated processing chain based on the Python modules of the QGIS software. The processing automatically made all of the steps of the chain – from the starting data set until the generation of the costs of the distances and the possible new P2G localizations.

Geomatics Framework: Integration of Cost Function into WebGIS Platform

The second part of the chain regarded the creation of the remote geospatial database (based on the results of the first part), the cost function operations, and the real-time visualization of the solution on a web browser. The WebGIS platform enclosed all of these blocks (Fig. 3).

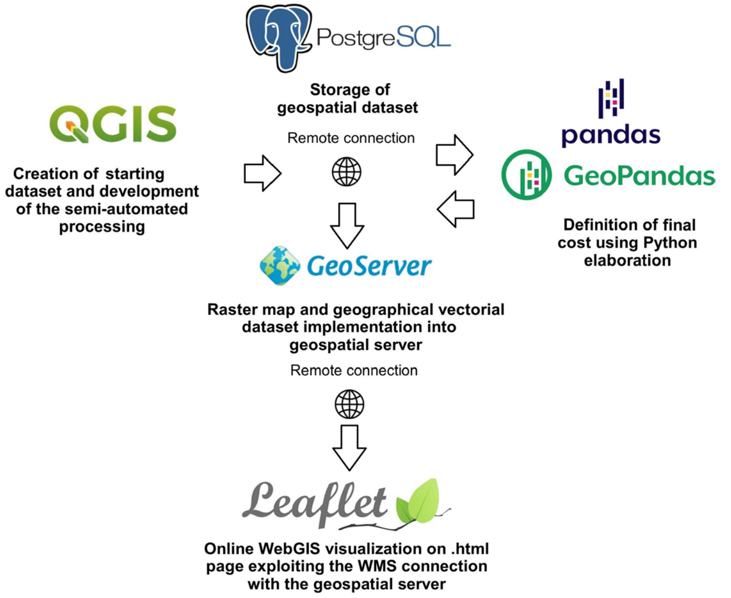

Fig. 3. Structure of WebGIS platform that integrates all blocks of chain with each other

Once the domain of possible solutions is defined, the obtained results were loaded into the Postgres RDBMS open-source database by employing a PostGIS extension; PostGIS allowed us to load geospatial data sets into Postgres. In this way, the entire data set was loaded into the relational database considering the geospatial data set and the tables of the costs. Here, the Python data-analysis open-source modules came into play; these were necessary to elaborate the cost function (Table 1). Pandas and Geopandas were the Python modules that were selected for this operation. They were remotely connected to Postgres and allowed to load the data set, elaborate the cost function in the Anaconda environment, and return the results to the database.

Table 1. Description of used Python modules and integrated modules in WebGIS platform

Type of module		Use
Python modules	Pandas	Remote data analysis and operation between columns of database tables in DOS environment
	Geopandas	Remote geospatial data analysis and operation between database tables in DOS environment
Integrated modules	Psycopg2	Shapefile remote download from Postgres database
	Sqlalchemy	Normalization of columns

The Python strings were elaborated in the DOS environment. In DOS, the tables of the costs of the distances (considering the railway networks, the main road networks, and the gas pipelines) related to each possible solution were first normalized. The next step calculated the final cost of each solution, employing Pandas, and loading the tables from Postgres through the psycopg2 plugin. Hence, the cost values of each possible solution were grouped into a table following the order of the univocal identity column as a reference. The table of the final costs was finally merged with the general geospatial data set of the possible solution by employing Geopandas and Sqlalchemy and using the univocal identity column as a join element. The Python role finished with the exportation of the geospatial data set into Postgres with the addition of the final cost column.

The final WebGIS online visualization of the geospatial data set was created, thus connecting the Postgres database with Geoserver (an open-source geospatial data server). Geoserver allowed us to store geospatial raster or vectoral data and generate WMS and WFS services for remote WebGIS online visualization. A real-time connection with the Postgres database was configured in order to load the domain of possible P2G solutions (with the final costs) and to share the results through the WMS connection.

The online visualization of the data set in the map was provided by Apache Server; thus, a customized.html page was created inside the JavaScript and CSS modules (which was necessary for creating the WebGIS navigation interface). The Leaflet open-source JavaScript module was used for the WebGIS configuration, which allowed for the real-time visualization of the geospatial data set with their features (employing the WMS service).

4. Data

The starting data set that was employed in this work was composed of several shapefiles in accordance with the standard protocol of the Open Geospatial Consortium (OGC); it was provided by ISTAT (the National Institute of Statistics of Italy), ANAS (the National Autonomous Company of Roads), and SNAM (the National Pipeline Company). The chosen reference system was UTM WGS 84 EPSG 32633. The operation that was involved in the framework used the shapefile extension (point and line shapefiles), while the results regarding the costs of the distance operations were organized in tables (Table 2).

Table 2. The input and output dataset involved in the analysis

Data	Format
INPUT DATA SET	
Square grid of possible solutions	point shapefile
Railway network	line shapefile
Main road network	line shapefile
Wind and photovoltaic power plants	point shapefile
Main urban centers	point shapefile
Gas pipeline	line shapefile
OUTPUT DATA SET	
Domain of P2G localizations	point shapefile
Cost distance (main urban centers – P2G localizations) through main road network	table
Cost distance (main urban centers – P2G localizations) through railway network	table
Minimum distance between P2G localizations and natural gas pipelines	table

In particular, the square grid that represented the base domain of possible solutions was composed of 1 km × 1 km extended squares and was represented by a point shapefile. The railway network and main road networks were represented by a linear buffer geometry with a 0.5 km thickness. The wind and photovoltaic installations were represented by a point shapefile with a diameter of 1 km. Instead, the main urban centers were represented by the centroids of the population distributions of the cities of the Mediterranean island. The minimum distance between the new localizations and the main urban centers through the railway and the road networks were obtained using a network-analysis toolbox that was developed in Python (which is available in QNEAT – QGIS's open-source software) [51].

After discretizing the domain of the possible solutions and the final cost elaboration in Python by using the Pandas and Geopandas modules, the final data set that was imported into the Postgres database indicated the cost of each considered localization of the domain (Fig. 4).

	id bigint	geom geometry	tipo text	potenza double precision	auto_x text	auto1 text	auto_y bigint	costo double precision
1	18044	0101000020797F0...	eolico	0.00375	0	0	0	7.4340246161943435
2	18045	0101000020797F0...	eolico	0.00375	1	1	1	7.385560995324925
3	31586	0101000020797F0...	fotovolt...	0.015	2	2	2	6.581797839063308
4	66070	0101000020797F0...	fotovolt...	0.207	3	3	3	4.1804379225548605
5	87682	0101000020797F0...	fotovolt...	0.0025	4	4	4	4.514760016992628
6	91710	0101000020797F0...	fotovolt...	0.009	5	5	5	4.964133185182902
7	91711	0101000020797F0...	fotovolt...	0.005	6	6	6	4.914612049209853
8	92077	0101000020797F0...	fotovolt...	1	7	7	7	4.0172392837549395
9	92443	0101000020797F0...	fotovolt...	1	8	8	8	4.1350574499230115
10	95599	0101000020797F0...	fotovolt...	0.0015	9	9	9	7.443482515178472
11	96388	0101000020797F0...	fotovolt...	0.00075	10	10	10	5.883008383299392
12	98893	0101000020797F0...	fotovolt...	0.0015	11	11	11	6.882323355455676
13	99042	0101000020797F0...	fotovolt...	0.00075	12	12	12	5.381344775844691
14	99260	0101000020797F0...	fotovolt...	0.0015	13	13	13	6.766222816465449
15	99627	0101000020797F0...	fotovolt...	0.0015	14	14	14	6.667154275816068
16	108405	0101000020797F0...	fotovolt...	0.00075	15	15	15	6.949789712852467
17	108771	0101000020797F0...	fotovolt...	0.00075	16	16	16	6.889779971354518
18	110966	0101000020797F0...	fotovolt...	0.0015	17	17	17	7.004009225609122
19	111332	0101000020797F0...	fotovolt...	0.0015	18	18	18	6.901693196604839

Fig. 4. Final data set of possible P2G localizations visualized in Postgres database: "tipo" column shows kind of associated RES plant; "potenza" column – power of associated RES plant [kW]; "costo" shows final cost of each localization

The best solution that was visualized in the Leaflet-based WebGIS environment was in the southwest position of Sicily in the middle of the triangle that is shaped by the towns of Ragusa, Vittoria, and Modica (Fig. 5).

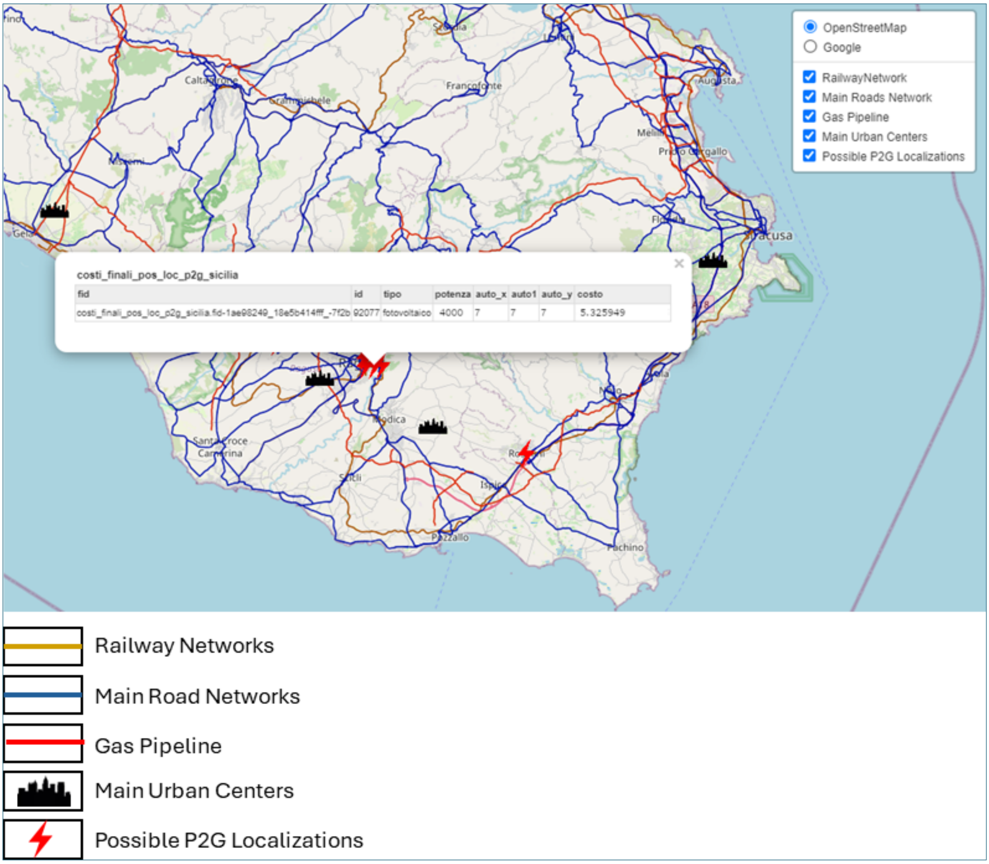

Fig. 5. Visualization of WebGIS platform of solution with lowest cost

5. Discussions and Results

The developed WebGIS platform allowed us to visualize the geospatial data set in real time through map visualization on a web browser. Users can navigate and visualize the data set using desktop or mobile devices, with the possibility to real-time analyze the cost results of the possible new P2G localizations. The QGIS software data set, the Postgres database, the Python data-analysis module, Geoserver, and the WebGIS visualizer are all remotely connected, allowing the smart management and smart fruition of the data set at the same time.

Focusing attention on the factors that were involved in the cost function, the proximity to the railway and road networks was considered to be a filtering constraint for guaranteeing the possibility of transporting the produced hydrogen in the new P2G installation in order to satisfy the energy demands of the main urban centers. In fact, this model supposed that, in the future, hydrogen will be transported in a liquid or gaseous state by using the railway and road networks. The proximity to an existing photovoltaic or wind plant was the other necessary constraint that was considered for discretizing the domain of possible P2G plant localizations. It was necessary to use the amount of energy that is not used (curtailed energy) by the wind or photovoltaic facilities (caused by the non-programmable nature of these renewable energy sources).

Considering the geomatics processing, the discretization of the possible P2G localizations was based on the MCA model. In particular, the proximity with the existing photovoltaic or wind power plants and the road and railway networks (a necessary aspect for hydrogen transportation) represented an essential requirement for the localization of a new P2G installation.

It was necessary to use both the Pandas and Geopandas modules, as each of these possesses exclusive features that were necessary. Pandas allowed us to employ specific operational modules that enabled us to make the necessary Python calculations, while Geopandas preserved the geospatial features in the Python environment. In fact, it was necessary to create a univocal identity column to join the Pandas results with the imported Geopandas data sets. The localization with the lower cost that was individuated in the analysis process was located in a very populated area and was near one of the most powerful RES plants of the region (as could be predicted).

6. Conclusions and Open Scenarios

The experimentation that was described in this work involved a multidisciplinary approach where a GIS framework was applied to the problem of positioning new P2G plants into the territory of Sicily. The application of geomatics procedures was necessary not only when building the cost function but also when growing the remote web platform; these were necessary for the acquisition, management, and final fruition of the data set on the web. This work is an example of how to integrate geomatics in a localization problem by combining different fields of research. At the same time, the integration of the Python modules was fundamental for elaborating the operations into the geospatial data set and exporting the results in the relational database-management system in real time. In the future, the same structure could be extended with the integration of real-time energy acquisition from RES plants to refine the cost-function calculation. In fact, the actual limitations of the platform are related to the absence of real-time data set acquisitions, which can be useful to improve the quality of the results in the future. This structure can also be expanded to other areas of study, creating a more complex system that can enrich the quality of the work. Furthermore, the framework that was studied in this experimentation represents a useful example considering the growing interest in hydrogen-based technology over the last years. Considering the local impact of P2G locations, the social acceptability seems to not be a relevant determining factor in the settlement of the plants due to the great understanding of the local communities regarding the diffusion of new technologies [52]. Furthermore, the employment of P2G technology that is based on electrolysis presents a lower environmental impact than other energy-production processes that are based on gas production [53]. In fact, the rapid spread of the diffusion of P2G solutions in Europe (connected with the spread of photovoltaic and wind plants) will focus attention onto these kinds of strategies to optimize the localizations of the energy sources.

In the future, the same approach could be applied to several sectors of research, and the same structure of the platform could be replicated by centers of research and municipalities to manage the localization problems of non-programmable energy sources by only employing open-source technology. Furthermore, the structure of the platform is ready to integrate IoT (Internet of Things) modules to provide the real-time acquisition of data from low-cost sensors networks, connecting the IoT modules to the relational database-management system, and providing further geospatial information that may be useful for adding new variables to the localization problem.

Funding

This research received funding from the SuperP2G (synergies utilizing renewable power regionally by means of P2G) project in the framework of the joint ERA-Net Smart Energy Systems' focus initiative, integrating regional energy systems programming initiative, with support from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 775970.

CRediT Author Contribution

M. L.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision, project administration, funding acquisition.

F. D.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision, project administration, funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data.

Use of Generative AI and AI-assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

Acknowledgements

The authors express their gratitude for the support received from the SuperP2G (synergies utilizing renewable power regionally by means of P2G) project, developed inside the ERANet Spart Energy Systems initiative.

References

[1] Jacobson M., Delucchi M.A., Cameron M.A., Coughlin S.J., Hay C.A., Manogaran I.P., Shu Y., von Krauland A.-K.: *Impacts of Green New Deal Energy plans on grid stability, costs, jobs, health, and climate in 143 countries*. One Earth, vol. 1(4), 2019, pp. 449–463. https://doi.org/10.1016/j.oneear.2019.12.003.

[2] Simonis B., Newborough M.: *Sizing and operating power-to-gas systems to absorb excess renewable electricity*. International Journal of Hydrogen Energy, vol. 42(34), 2019, pp. 21635–21647. https://doi.org/10.1016/j.ijhydene.2017.07.121.

[3] McDonagh S., O'Shea R., Wall D., Deane J., Murphy J.: *Modelling of a power-to-gas system to predict the levelised cost of energy of an advanced renewable gaseous transport fuel*. Applied Energy, vol. 215, 2018, pp.444–456. https://doi.org/10.1016/j.apenergy.2018.02.019.

[4] Thema M., Bauer F., Sterner M.: *Power-to-Gas: Electrolysis and methanation status review*. Renewable and Sustainable Energy Reviews, vol. 112, 2019, pp. 775–787. https://doi.org/10.1016/j.rser.2019.06.030.

[5] Götz M., Lefebvre J., Mörs F., McDaniel Koch A., Graf F., Bajohr S., Reimert R., Kolb T.: *Renewable Power-to-Gas: A technological and economic review*. Renewable Energy, vol. 85, 2016, pp. 1371–1390. https://doi.org/10.1016/j.renene.2015.07.066.

[6] Varone A., Ferrari M.: *Power to liquid and power to gas: An option for the German Energiewende*. Renewable and Sustainable Energy Reviews, vol. 45, 2015, pp. 207–218. https://doi.org/10.1016/j.rser.2015.01.049.

[7] Wulf C., Linßen J., Zapp P.: *Review of Power-to-Gas projects in Europe*. Energy Procedia, vol. 155, 2018, pp. 367–378. https://doi.org/10.1016/j.egypro.2018.11.041.

[8] Mazza A., Bompard E., Chicco G.: *Applications of power to gas technologies in emerging electrical systems*. Renewable and Sustainable Energy Reviews, vol. 92, 2018, pp. 794–806. https://doi.org/10.1016/j.rser.2018.04.072.

[9] Malczewski J.: *GIS-based land-use suitability analysis: A critical overview*. Progress in Planning, vol. 62(1), 2004, pp. 3–65. https://doi.org/10.1016/j.progress.2003.09.002.

[10] Bubbico R., Di Cave S., Mazzarotta B.: *Risk analysis for road and rail transport of hazardous materials: A GIS approach*. Journal of Loss Prevention in the Process Industries, vol. 17(6), 2004, pp. 483–488. https://doi.org/10.1016/j.jlp.2004.08.011.

[11] Riccioli F., El Asmar T.: *GIS Technique for Territorial Analysis*. [in:] Andreopoulou Z., Manos B., Polman N., Viaggi D. (eds.), *Agricultural and Environmental Informatics, Governance and Management: Emerging Research Applications*, IGI Global, Hershey 2011, pp. 425–445. https://doi.org/10.4018/978-1-60960-621-3.ch022.

[12] Valenti F., Porto S., Chinnici G., Cascone G., Arcidiacono C.: *A GIS-based model to estimate citrus pulp availability for biogas production: An application to a region of the Mediterranean Basin*. Biofuels, Bioproducts and Biorefining, vol. 10(6), 2016, pp. 710–727. https://doi.org/10.1002/bbb.1707.

[13] Castelluccio F., D'Orso G., Migliore M., Scianna A.: *GIS Infomobility for Travellers.* [in:] Gervasi O., Murgante B., Misra S., Rocha A.M.A.C., Torre C.M., Taniar D., Apduhan B.O., Stankova E., Wang S. (eds.), *Computational Science and Its Applications – ICCSA 2016: 16th International Conference, Beijing, China, July 4–7, 2016: Proceedings: Part III*, Lecture Notes in Computer Science, vol. 9788, Springer, Cham 2016, pp. 519–529. https://doi.org/10.1007/978-3-319-42111-7_41.

[14] Gahleitner G.: *Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications*. International Journal of Hydrogen Energy, vol. 38(5), 2013, pp. 2039–2061. https://doi.org/10.1016/j.ijhydene.2012.12.010.

[15] Balla D., Zichar M., Kiss E., Szabó G., Mester T.: *Possibilities for assessment and geovisualization of spatial and temporal water quality data using a WebGIS application*. ISPRS International Journal of Geo-Information, vol. 11(2), 2022, 108. https://doi.org/10.3390/ijgi11020108.

[16] Patera A., Pataki Z., Kitsiou D.: *Development of a WebGIS application to assess conflicting activities in the framework of marine spatial planning*. Journal of Marine Science and Engineering, vol. 10(3), 2022, 389. https://doi.org/10.3390/jmse10030389.

[17] Scianna A., Gaglio G., La Guardia M., Nuccio G.: *Development of a virtual CH path on WEB: Integration of a GIS, VR, and other multimedia data*. [in:] Ioannides M., Fink E., Cantoni L., Champion E. (eds.), *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection: 8th International Conference, EuroMed 2020, Virtual Event, November 2–5, 2020: Revised Selected Paper*, Lecture Notes in Computer Science, vol. 12642, Springer, Cham 2021, pp. 178–189. https://doi.org/10.1007/978-3-030-73043-7_15.

[18] Vacca G., Fiorino D., Pili D.: *A Spatial Information System (SIS) for the architectural and cultural heritage of Sardinia (Italy)*. ISPRS International Journal of Geo-Information, vol. 7(2), 2018, 49. https://doi.org/10.3390/ijgi7020049.

[19] Capolupo A., Monterisi C., Saponieri A., Addona F., Damiani L., Archetti R., Tarantino E.: *An interactive WebGIS framework for coastal erosion risk management*. Journal of Marine Science and Engineering, vol. 9(6), 2021, 567. https://doi.org/10.3390/jmse9060567.

[20] La Guardia M., Koeva M., D'Ippolito F., Karam S.: *3D data integration for web based open source WebGL interactive visualisation*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLVIII-4/W4-2022, 2022, pp. 89–94. https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-89-2022.

[21] Toro Herrera J.F., Carrion D., Brovelli M.A.: *A collaborative platform for water quality monitoring: Simile WebGIS*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLIII-B4-2021, 2021, pp. 201–207. https://doi.org/10.5194/isprs-archives-XLIII-B4-2021-201-2021.

[22] Suni Y.P.K., Sujono J., Istiarto: *Identifying potential sites for rainwater harvesting ponds (embung) in Indonesia's semi-arid region using GIS-based MCA techniques and satellite rainfall data*. PLOS ONE, vol. 18(6), 2023, e0286061. https://doi.org/10.1371/journal.pone.0286061.

[23] Aziz S.F., Abdulrahman K.Z., Ali S.S., Karakouzian M.: *Water harvesting in the Garmian Region (Kurdistan, Iraq) using GIS and remote sensing*. Water, vol. 15(3), 2023, 507. https://doi.org/10.3390/w15030507.

[24] Ahmed M.S., Mahmoud N., Manabu F., Chihiro Y., Mona G.I.: *Delineating suitable zones for solar-based groundwater exploitation using multi-criteria analysis: A techno-economic assessment for meeting sustainable development goals (SDGs)*. Groundwater for Sustainable Development, vol. 25, 2024, 101087. https://doi.org/10.1016/j.gsd.2024.101087.

[25] Gahalod N.S.S., Rajeev K., Pant P.K., Binjola S., Yadav R.L., Meena R.L.: *Spatial assessment of flood vulnerability and waterlogging extent in agricultural lands using RS-GIS and AHP technique – a case study of Patan district Gujarat, India*. Environmental Monitoring and Assessment, vol. 196, 2024, 338. https://doi.org/10.1007/s10661-024-12482-9.

[26] Mikias B.M.: *Potential landfill site selection for solid waste disposal using GIS-based multi-criteria decision analysis (MCDA) in Yirgalem Town, Ethiopia*. Cogent Engineering, vol. 11(1), 2024, 2297486. https://doi.org/10.1080/23311916.2023.2297486.

[27] Giallanza A., Porretto M., Puma G., Marannano G.: *A sizing approach for stand-alone hybrid photovoltaic-wind-battery systems: A Sicilian case study*. Journal of Cleaner Production, vol. 199, 2018, pp. 817–830. https://doi.org/10.1016/j.jclepro.2018.07.223.

[28] La Guardia M., D'Ippolito F., Cellura M.: *Construction of a WebGIS tool based on a GIS semiautomated processing for the localization of P2G plants in Sicily (Italy)*. ISPRS International Journal of Geo-Information, vol. 10(10), 2021, 671. https://doi.org/10.3390/ijgi10100671.

[29] La Guardia M., D'Ippolito F., Cellura M.: *A GIS-based optimization model finalized to the localization of new power-to-gas plants: The case study of Sicily (Italy)*. Renewable Energy, vol. 197, 2022, pp. 828–835. https://doi.org/10.1016/j.renene.2022.07.120

[30] Grippa T., Lennert M., Beaumont B., Vanhuysse S., Stephenne N., Wolff E.: *An open-source semi-automated processing chain for urban object-based classification*. Remote Sensing, vol. 9(4), 2017, 358. https://doi.org/10.3390/rs9040358.

[31] Neteler M., Bowman M., Landa M., Metz M.: *GRASS GIS: A multi-purpose open source GIS*. Environmental Modelling & Software, vol. 31, 2012, pp. 124–130. https://doi.org/10.1016/j.envsoft.2011.11.014.

[32] Neteler M., Beaudette D., Cavallini P., Lami L., Cepicky J.: *GRASS GIS*. [in:] Hall B.G., Leahy M.G. (eds.), *Open Source Approaches in Spatial Data Handling*, Advances in Geographic Information Science, Springer, Berlin, Heidelberg 2008, pp. 171–199. https://doi.org/10.1007/978-3-540-74831-1_9.

[33] Coetzee S., Ivánová I., Mitasova H., Brovelli M.: *Open geospatial software and data: A review of the current state and a perspective into the future*. ISPRS International Journal of Geo-Information, vol. 9(2), 2020, 90. https://doi.org/10.3390/ijgi9020090.

[34] Mishra S., Chander S., Pradhan R., Dubey A.K., Oza M.P., Sharma S.A.: *WebGIS for water level monitoring and flood forecasting using Open Source Technology*. Journal of Geomatics, vol. 14(1), 2020, pp. 49–54.

[35] Can R., Kocaman S., Ok A.: *A WebGIS framework for semi-automated geodatabase updating assisted by deep learning*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLIII-B5-2021, 2021, pp. 13–19. https://doi.org/10.5194/isprs-archives-XLIII-B5-2021-13-2021.

[36] Menegon S., Depellegrin D., Farella G., Sarretta A., Venier C., Barbanti A.: *Addressing cumulative effects, maritime conflicts and ecosystem services threats through MSP-oriented geospatial webtools*. Ocean & Coastal Management, vol. 163, 2018, pp. 417–436. https://doi.org/10.1016/j.ocecoaman.2018.07.009.

[37] Woo H., Acuna M., Moroni M., Taskhiri M., Turner P.: *Optimizing the location of biomass energy facilities by integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS)*. Forests, vol. 9(10), 2018, 585. https://doi.org/10.3390/f9100585.

[38] Tahvanainen T., Anttila P.: *Supply chain cost analysis of long-distance transportation of energy wood in Finland*. Biomass and Bioenergy, vol. 35(8), 2011, pp. 3360–3375. https://doi.org/10.1016/j.biombioe.2010.11.014.

[39] Al-Kurdi N., Pillot B., Gervet C., Linguet L.: *Towards robust scenarios of spatio-temporal renewable energy planning: A GIS-RO approach*. [in:] Schiex T., de Givry S. (eds.), *Principles and Practice of Constraint Programming: 25th International Conference, CP 2019: Stamford, CT, USA, September 30 – October 4, 2019: Proceedings*, Lecture Notes in Computer Science, vol. 11802, Springer, Cham 2019, pp. 729–747. https://doi.org/10.1007/978-3-030-30048-7_42.

[40] Al Garni H.Z., Awasthi A.: *Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia*. Applied Energy, vol. 206, 2017, pp. 1225–1240. https://doi.org/10.1016/j.apenergy.2017.10.024.

[41] Kocabaldır C., Yücel M.A.: *GIS-based multicriteria decision analysis for spatial planning of solar photovoltaic power plants in Çanakkale province, Turkey*. Renewable Energy, vol. 212, 2023, pp. 455–467. https://doi.org/10.1016/j.renene.2023.05.075.

[42] Sánchez-Lozano J.M., Henggeler Antunes C., García-Cascales M.S., Dias L.: *GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain*. Renewable Energy, vol. 66, 2014, pp. 478–494. https://doi.org/10.1016/j.renene.2013.12.038.

[43] Islam Md. R., Aziz Md. T., Alauddin M., Kader Z., Islam Md. R.: *Site suitability assessment for solar power plants in Bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach*. Renewable Energy, vol. 220, 2024, 119595. https://doi.org/10.1016/j.renene.2023.119595.

[44] Meng S., Yuanxu Z., Jinwei S., Zhixin H., Zhuxiao S.: *A decision framework for tidal current power plant site selection based on GIS-MCDM: A case study in China*. Energy, vol. 262(part B), 2023, 125476. https://doi.org/10.1016/j.energy.2022.125476.

[45] Almasad A., Pavlak G., Alquthami T., Kumara S.: *Site suitability analysis for implementing solar PV power plants using GIS and fuzzy MCDM based approach*. Solar Energy, vol. 249, 2023, pp. 642–650. https://doi.org/10.1016/j.solener.2022.11.046.

[46] Asadi M., Pourhossein K., Noorollahi Y., Marzband M., Iglesias G.: *A new decision framework for hybrid solar and wind power plant site selection using linear regression modeling based on GIS-AHP*. Sustainability, vol. 15(10), 2023, 8359. https://doi.org/10.3390/su15108359.

[47] Şahin G., Koç A., van Sark W.: *Multi-criteria decision making for solar power – Wind power plant site selection using a GIS-intuitionistic fuzzy-based approach with an application in the Netherlands*. Energy Strategy Reviews, vol. 51, 2024, 101307. https://doi.org/10.1016/j.esr.2024.101307.

[48] Vosgerau H., Mathiesen A., Sparre Andersen M., Boldreel L., Hjuler M., Kamla E., Kristensen L., Brogaard Pedersen C., Pjetursson B., Nielsen L.: *A WebGIS portal for exploration of deep geothermal energy based on geological and geophysical data*. Geological Survey of Denmark and Greenland Bulletin, vol. 35, 2016, pp. 23–26. https://doi.org/10.34194/geusb.v35.4633.

[49] Maffeis G., Roncolato D., Cherubini A., Bernardoni A., Boccardi S., Greco A., Chiesa A., Brolis M., Fasano M.: *BIOPOLE: WebGIS-based Decision Support System (DSS) in bio-energy plant localization*. [in:] Seppelt R., Voinov A.A., Lange S., Bankamp D. (eds.), *Managing Resources of a Limited Planet. Pathways and Visions under Uncertainty: 6th International Congress on Environmental Modelling and Software (iEMSs), 1 – 5 July 2012, Leipzig, Germany*, International Environmental Modelling and Software Society (iEMSs), Leipzig 2012. https://scholarsarchive.byu.edu/iemssconference/2012/Stream-B/278/ [access: 21.03.2024].

[50] Pasanisi F., Righini G., D'Isidoro M., Vitali L., Briganti G., Grauso S., Moretti L., Tebano C., Zanini G., Mahahabisa M., Letamai M., Raliselo, Seitlheko M.: *A cooperation project in Lesotho: Renewable energy potential maps embedded in a WebGIS tool*. Sustainability, vol. 13(18), 2021, 10132. https://doi.org/10.3390/su131810132.

[51] Raffler C.: *QNEAT3: QGIS Network Analysis Toolbox*. https://root676.github.io/ [access: 21.03.2024].

[52] Goraj R., Kiciński M., Ślefarski R., Duczkowska A.: V*alidity of decision criteria for selecting power-to-gas projects in Poland*. Utilities Policy, vol. 83, 2023, 101619. https://doi.org/10.1016/j.jup.2023.101619.

[53] Ozturk M., Dincer I.: *A comprehensive review on power-to-gas with hydrogen options for cleaner applications*. International Journal of Hydrogen Energy, vol. 46(62), 2021, pp. 31511–31522. https://doi.org/10.1016/j.ijhydene.2021.07.066.