Spatial Multi-criteria Analysis for Identifying Suitable Locations for Green Hydrogen Infrastructure

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Abstract. The paper proposes a Spatial Multi-Criteria Analysis for identifying suitable locations for green hydrogen infrastructure. The production and use of hydrogen as a renewable energy carrier can play a critical role in reducing carbon footprint and increasing energy security in cities worldwide. The approach considers multiple criteria, such as demand, accessibility, environmental impact, and cost, to identify optimal locations for hydrogen production, storage, and distribution facilities. The GIS component enables spatial analysis, allowing visualization and analysis of spatial relationships between potential locations and other relevant factors. The research claims that green hydrogen can significantly improve energy resilience and transform energy systems. The method is applied to a case study, an energy-intensive industry in the city of Potenza (Italy). The result is the map identifying suitable areas where hydrogen production facilities can be located. The approach suggests that urban planners, decision-makers, and stakeholders develop and use green hydrogen as a sustainable energy source.

Keywords: Green Hydrogen Infrastructure (GHI) · Analytic Hierarchy Process (AHP) · Geographic Information System (GIS)

1 Introduction

Green energy is generated by minimizing all possible negative environmental impacts. In other words, it is a renewable energy source. Green energy sources such as solar, wind, geothermal, and hydro energy are being created and promoted as alternatives with minor contributions to climate change. These energy sources are usually called "green" since they do not generate dangerous pollutants or greenhouse gases (GHGs). Switching to green energy is critical for combating climate change and lowering GHG emissions. It is also vital to realize that using green energy alone will not address the climate change problem. Additional measures, such as energy efficiency, conservation,

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and behavioral and lifestyle adjustments that lower demand for natural gas, coal, or oil-burning power plants, are required to cut emissions and address climate change issues. Rational environmental and urban planning [1, 2] based on sustainable development [3] is necessary in this respect. Hydropower and geothermal energy are clean sources with zero GHG emissions.

Furthermore, green hydrogen derived from water electrolysis (an electrolytic process in which the passage of an electric current causes the dissociation of water into oxygen and hydrogen gas) has the potential to play a significant role in the transition to a low-carbon energy system and help mitigate climate change [4]. Nevertheless, widespread acceptance will depend on cost competitiveness, technology developments, and advantageous laws and regulations. In this way, water electrolysis yields only around 5% of the hydrogen produced annually.

However, green hydrogen is now the hydrogen production system of most significant interest for two main reasons: a) the process of dissociating the water molecule into oxygen and hydrogen in the gaseous state does not result in greenhouse gas emissions; b) the electricity that is used to separate oxygen from hydrogen can be produced from renewable energy sources, and the entire process is environmentally sustainable. The first benefit is more of an environmental nature, and the second is more of a strategy in that green hydrogen production can be a tool to reduce the need to import oil, methane gas, and coal. The most significant advantage of hydrogen is that in its use the energy, it does not emit greenhouse gases and polluting factors, but the only by-product of its use is water. Thus, provided it is produced through electricity from renewable sources and is sustainable (therefore using low-impact plant and transportation solutions), green hydrogen can be considered concretely as a green fuel. The main disadvantage of hydrogen, mainly green hydrogen, has always been its cost, which is much higher than other fossil fuels. Before the start of the Ukraine War, as of early 2021, the cost alone of producing renewable hydrogen was approx. 6.5 euros/kg, while the cost of producing fossil-derived hydrogen (from the reforming of gas methane) was approx. 1.50 euros/kg, and for this reason, without an adequate incentive system, green hydrogen was not competitive against fossil alternatives. With the European energy crisis brought about by the conflict above, the scenario has changed considerably, and today hydrogen is already positioned itself as competitive with traditional fossil fuels such as gasoline, diesel, and gasoil; this is also thanks to the policy of incentives activated by the Italian government through the Plan National Restoration and Resilience plan (PNRR) [5], which provides a financial allocation of 3.2 billion euros for the "main action" called "Hydrogen." As for the 2050 horizon, on the other hand, the goal is to achieve a more robust use of hydrogen in the industries of chemicals and transportation (up to 80% of long-haul trucks) and especially in "hard-to-abate" sectors (such as energy-intensive manufacturing processes energy, aviation or the maritime sector. These emissions are in sectors and applications for which electricity is not currently the form of energy at the point of end-use and for which direct electricity-based solutions come with high costs or technical drawbacks), as well as for heating residential and commercial, with the goal of up to 20% penetration of hydrogen in final demand. This target, at least in the maximum, is more ambitious than the EU Strategy for Hydrogen (2020), which calls for a 13–14% penetration of hydrogen with low-carbon emissions.

This paper aims to investigate and identify the ideal case for establishing a green hydrogen infrastructure. We will employ a spatial multicriteria analysis technique that integrates the Analytic Hierarchy Process (AHP) method with Geographic Information Systems to accomplish this (GIS). Spatial analysis approaches have grown into a low-cost, rapid, and reliable tool for evaluating the potential of renewable energy sources. Many studies [6–12] have used spatial analytic tools to examine the possibility of renewable sources such as solar, wind, hydropower, and biomass. We will be able to consider a range of criteria and components by using these methodologies, such as the availability of renewable energy sources, present infrastructure, population density, and transportation systems. We are seeking the most feasible and desired place for creating green hydrogen infrastructure by studying and contrasting various scenarios based on these principles.

Additionally, by promoting green hydrogen as a viable alternative to traditional fossil fuels, our study will help to establish a more sustainable, low-carbon energy system. Choosing the best scenario for constructing green hydrogen infrastructure is a sophisticated and broad task that requires considering various geographical, environmental, and economic factors. We plan to build a comprehensive framework that considers these variables and helps us make informed and data-driven decisions by using the capabilities of GIS and AHP techniques. GIS allows us to see and analyze geographical data such as renewable energy potential, population density, and infrastructure. Still, AHP gives an orderly and logical way of determining the relative importance of various criteria factors and the best option. When these techniques are integrated, we will have a strong tool for analyzing and comparing alternative scenarios, such as building green hydrogen production facilities, transportation networks, and distribution systems.

The paper is divided into three sections. First, the methodology is analyzed: spatial Multi-Criteria Analysis. In the second section, these techniques are applied to identify the best site for producing green hydrogen to serve the "Siderpotenza" industry in Potenza (Basilicata, Italy). Finally, the third section discusses the study's results, outlining research perspectives.

2 Methodology

Land suitability analysis is among the main challenges for the Green Hydrogen Infrastructure (GHI) location, as multiple criteria need to be considered. Multi-Criteria Decision Making (MCDM) methods are used in several studies to solve complex decision-making problems involving both qualitative and quantitative criteria [13–15].

The literature shows that the most commonly used multi-criteria methods are [16]: Analytic Hierarchy Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR).

AHP is the most popular sustainable energy management technique [17]. The choice of using the spatial multi-criteria analysis integrating the AHP method in the Geographic Information System (GIS) environment as a methodology is legitimized by the scientific literature that connotes this tool as powerful and established [18] to assess the suitability of various sites for the installation of RES plants [19–23]. This integrated approach

makes it possible to (i) consider multiple and different criteria; (ii) assess and manage multiple spatial information; (iii) involve different stakeholders in the decision-making process. Few studies concern the GHI location [4, 24–27], highlighting that identifying the criteria necessary to evaluate the different alternatives represents a complex step in implementing the methodology. This paper aims to develop land suitability maps to determine the best site for producing green hydrogen to serve the Siderpotenza industry in Potenza (Basilicata, Italy). Figure 1 shows the methodology developed in this study for selecting suitable green hydrogen production sites.

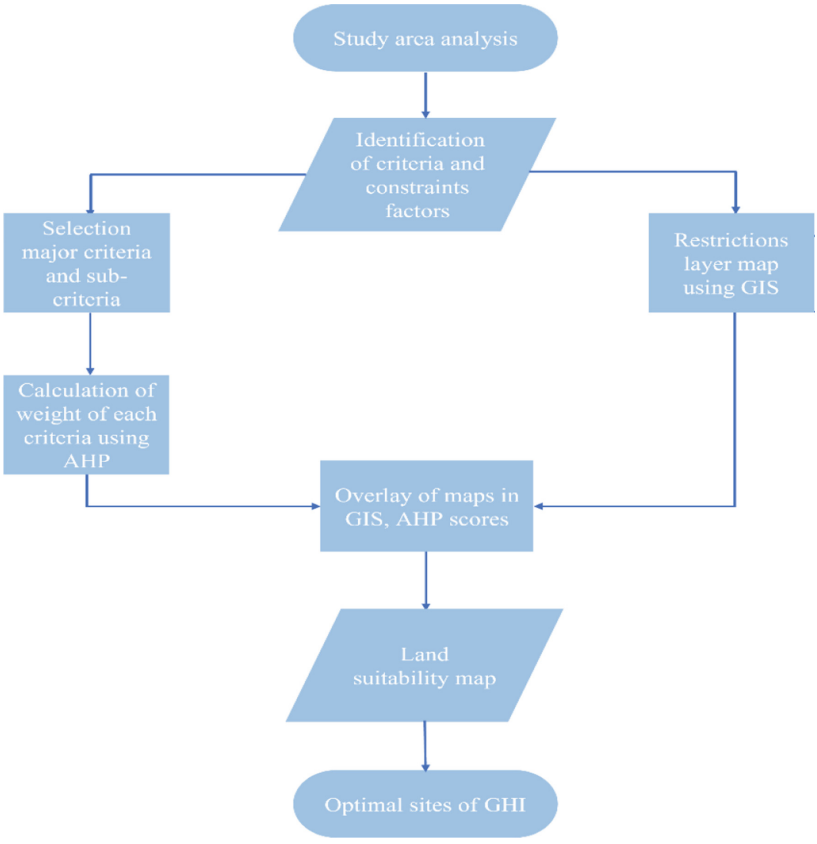


Fig. 1. Flowchart of methodology.

In the "Case Study" section, the description of the study area centered on the "Siderpotenza" industry and the surrounding area is illustrated. The first step is the identification of criteria and constraints factors. Within the GIS environment, two types of criteria are distinguished:

1) constraints criteria;
2) weighting criteria (same as those used in the AHP).

The constraints criteria were identified through a literature review [10, 24, 26, 28, 29] and an analysis of the constraints already present in the territory. The result of the analysis is the restrictions layer map. Next, the criteria and sub-criteria are identified, and for each one, a weight is calculated using AHP. After reclassifying the criteria, the individual weights are reported in the GIS environment. The Overlay tool in ArcGIS allows Map Algebra expressions to be performed in order to obtain the output of the methodological process, i.e., the land suitability map. The suitable sites for the GHI location are then identified.

3 Case Study

3.1 Study Area Analysis

The implemented case study concerns Siderpotenza, an industry belonging to the Pittini Group. The latter is configured as the first Italian producer of "long steels" intended for the construction and mechanical industry. The plant is located in the industrial area of Potenza (Basilicata, Italy). It is bordered on the northeast by a river park area and on the remaining sides by other industrial sites. Siderpotenza has been identified as three of Italy's largest energy-intensive and hard-to-abate industries and, therefore, particularly suitable for establishing a green hydrogen production plant. The study area, shown in Fig. 2, covers 728 km^2 and includes the municipality of Potenza, in which the Siderpotenza falls, and the first belt municipalities: Vaglio, Picerno, Pietragalla, Ruoti, Tito, Brindisi Montagna, Pignola, Avigliano, and Cancellara.

3.2 Identification of Criteria and Sub-criteria

The choice of criteria and sub-criteria represents a fundamental and decisive step in elaborating the final result. Also, in this case, the identification of the main criteria comes from a literature review and discussions with experts in the field. Our choice fell on three main criteria, as shown in Table 1: technical, economic, and environmental. The description of the sub-criteria is in Sect. 3.4.



Fig. 2. Study area.

Table 1. Identification of criteria and sub-criteria.

Main Criteria	Sub-Criteria
Technical	Slope
	Solar radiation
Economic	Distance of roads
	Distance of industry
	Distance of RES
	Distance of GAS pipelines
Environmental	Land use

3.3 Calculation of Criteria's Weight Using AHP

Thomas Saaty introduced AHP as a measurement method with ratio scales that allows different options to be evaluated and ranked according to specific criteria and sub-criteria [30]. AHP can reduce the complexity of decision-making problems by using a pairwise comparison technique to determine the relative importance of the criteria involved. The criteria selected depend on the research objective, which in this study is the search for a suitable area for GHI location. The first step concerns the hierarchical articulation of the decision problem's elements: goal, criteria, sub-criteria, and alternatives. It is necessary to point out that in the case of spatial AHP, the hierarchy is made up of several more or less extensive levels. Generally, [31] the alternatives are spatially characterized and

represented on each criteria map as a point, linear, or polygonal vector layer. In the case study proposed here, the alternative sites are represented as the square cells of a vector grid.

Then the AHP is, therefore, to perform a pairwise comparison of the criteria and sub-criteria. The pairwise comparison of criteria was developed using a scale defined by Saaty, shown in Table 1. This semantic scale allows qualitative judgments to be made concerning the elements compared. A value of 1 indicates that the two elements have equal weight, while a value of 9 emphasizes the extreme importance of one element over the other.

Table 2. Saaty semantic scale.

Score	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Judgment slightly favors one activity over another
5	Strong importance	Judgment strongly favors one activity over another
7	Very strong importance	An activity is favored very strongly over another
9	Extreme importance	Favoring one activity over another is of the highest affirmation
2, 4, 6, 8	Intermediate values	A compromise is needed

The comparison results in the C_x matrix are shown in Eq. 1.

$$C_x = \begin{bmatrix} C_{11} \cdots C_{1n} \\ \vdots \quad \ddots \quad \vdots \\ C_{n1} \cdots C_{nn} \end{bmatrix} \tag{1}$$

The matrix is organized into a *n* x *n*, where *n* represents the rank of the matrix, i.e. the number of elements compared. $C_x = |C_{ij}| \forall i,\ j = 1, 2, \ldots, n$ for *n* criteria that influence the ultimate objective of the study, where C_{ij} demonstrates the relative importance of the criteria C_i over C_j. The matrix is:

- square: with size equal to the number n of sub-criteria compared;
- positive: ($C_{ij} > 0 \ \forall$ i, j and with i, j = 1, 2 … n) with elements equal to 1 on the main diagonal ($C_{i\,i} = C_{jj} = 1 \ \forall$ i, j and with i, j = 1, 2 … n);
- reciprocal: ($C_{ij} = 1/C_{ji}$).

The matrix of the direct comparison of all sub-criteria is illustrated in Table 2. The second step is to calculate the vector of weights. For this purpose, its i-th element is obtained by calculating the arithmetic mean of each row of the normalized matrix C_x [32]. The normalisation is done through the ratio of each matrix element to the sum of all those in the same column. The vector of weight expressed in % is represented in Table 3.

Table 3. Pairwise comparison matrix and weights of sub-criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	w_i (%)
C_1	1,00	0,25	0,25	0,20	0,20	0,50	0,33	4
C_2	4,00	1,00	3,00	0,50	0,33	3,00	0,50	14
C_3	4,00	0,33	1,00	0,33	0,50	3,00	0,33	10
C_4	5,00	2,00	3,00	1,00	3,00	3,00	2,00	28
C_5	5,00	3,00	2,00	0,33	1,00	3,00	0,50	18
C_6	2,00	0,33	0,33	0,33	0,33	1,00	0,33	6
C_7	3,00	2,00	3,00	0,50	2,00	3,00	1,00	20

In attributing weights through pairwise comparison, i.e., through the formulation of judgments, decision makers, or the experts they use to express priorities, may unintentionally provide some degree of inconsistency. In the AHP, one must therefore verify the level of consistency concerning the priorities expressed through the Consistency Ratio (CR) calculation. The check is satisfied if: CR $<$ 5% (n $=$ 3); CR $<$ 9% (n $=$ 4); CR $<$ 10% (n $>$ 4). CR is given by the ratio between the Consistency Index (CI) and the Random Consistency Index (RCI). CI is obtained with Eq. 2:

$$CI = \frac{\lambda \max - n}{n - 1} \tag{2}$$

While RCI depends on the number n of variables according to Table 4.

Table 4. RCI values.

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,45

The consistency check is satisfied, as shown in Table 5.

Table 5. Consistency check.

λ_{max}	n	CI	RCI	CR	CR (%)
7,68	7	0,11	1,32	0,09	8,59

3.4 Elaboration of Criteria's Maps

In order to identify optimal sites for the implementation of green hydrogen infrastructure, a spatial assessment was performed. This was accomplished using GIS software to

overlay normalized data related to the project goals and criteria. Each sub-criterion was represented in a distinct map layer, resulting in nine layers of spatial data analysis. These layers included assessments of the solar radiation, slope, distance from roads, proximity to Industry (Pittini), availability of renewable energy sources (RES) in the area, distance from gas pipelines, and land usage. Table 6 shows the type of layer used with description and source for each sub-criteria.

Table 6. Data collection and their sources.

Sub-Criteria	Data	Type of layer	Source
Slope	Digital Terrain Model (DTM)	Raster	Regional Spatial Data Infrastructure of Basilicata (RSDI)
Solar radiation	Digital Terrain Model (DTM)	Raster	RSDI
Distance of roads	Road network	Vector	RSDI
Distance of industry	Industrial lots	Vector	RSDI
Distance of RES	Industrial lots	Vector	RSDI
Distance of GAS pipelines	GAS distribution network	Vector	RSDI
Land use	Corine Land Cover	Vector	European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA)

The following parts will give us more details about processing each map. Solar radiation is a key criterion in determining the suitability of a particular area for implementing green hydrogen. Green hydrogen is produced using renewable energy sources, particularly solar power, which converts sunlight into electricity through photovoltaic panels. The amount and intensity of solar radiation in a given area directly affect the efficiency and viability of solar power generation, which impacts green hydrogen production. Therefore, analyzing the solar radiation levels in a potential location can provide valuable insight into the amount of renewable energy that can be harnessed and subsequently used to produce green hydrogen. Additionally, considering solar radiation levels along with other factors such as topography, land use, and infrastructure can aid in identifying the most suitable locations for green hydrogen implementation. The ArcGIS Spatial Analyst extension's solar radiation analysis tools facilitate the cartographic and analytical assessment of the sun's impact on a specific geographical area.

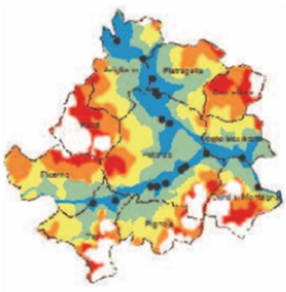
Slope assessment (Fig. 3. a) is crucial to consider in technical criteria in terms of determining the viability of implementing green hydrogen infrastructure in a particular area.



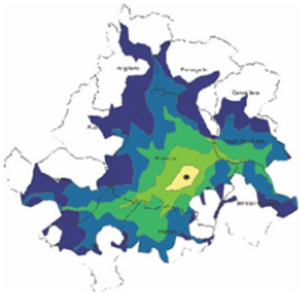
a. Slope



b. Solar radiation



c. Distance of roads



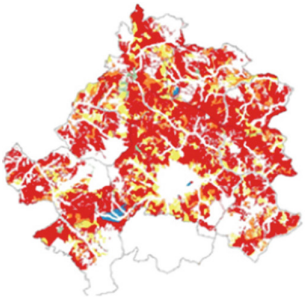
d. Distance of industry



e. Distance of RES



f. Distance of GAS pipelines



g. Land use

Fig. 3. Criteria's maps.

Regarding the study area's solar radiation map (Fig. 3. b), the region's high proportion of solar radiation is a positive characteristic. This is because most of the area receives a substantial amount of sunlight, depicted by the darker red hue on the map. The gradient and steepness of the terrain can affect the placement, orientation, and stability of solar panels used to generate renewable energy to produce green hydrogen. As shown in the map, steep slopes can pose challenges in terms of the installation and maintenance of solar panels in the study area; we can see a few sites with low slopes (dark red), which consequently can impact the efficiency of solar power systems due to shading and limited exposure to sunlight. Therefore, areas with gentle slopes are typically more favorable for installing solar arrays, as they allow for greater flexibility in the design and placement of solar panels and maximum exposure to sunlight throughout the day. Furthermore, the slope assessment is also relevant for constructing other infrastructure necessary for green hydrogen production, such as hydrogen storage facilities and transportation systems, as steep slopes may pose challenges to safe and efficient hydrogen transport.

For proximity maps, we applied two different methods. To calculate distance from roads (Fig. 3. c) and industrial sites (Fig. 3. d), we use the Isochrone tool because it calculates based on time, so we will have the fastest road to transforming the green hydrogen. On the other hand, the second tool which is used is NEAR.

There is a relevance between proximity to roads and producing green hydrogen, as the transportation of hydrogen from the point of production to its point of use can be a significant factor in the cost and efficiency of the process. Suppose a production facility for green hydrogen is located near a major road or highway. In that case, it can significantly reduce transportation costs and increase the efficiency of the process. This is because it becomes easier and cheaper to transport the hydrogen by truck to its point of use or to connect the production facility to the existing pipeline.

Here we calculate the isochrone distance, which is time dependence method to calculate proximity to intersections of main roads in the area of study by ORS tool in GIS. The distance is calculated from 5 min by heavy cars and trucks until 25 min. The map shows that heavy car reaches the vast study area in less than 30 min.

As Pittini is an end user of green hydrogen, it is essential to do it faster, so we applied the same method that we used for roads from 5 min to 25 min to have time dependence distance, which is crucial to transport hydrogen more sustainably. Regarding the map, it shows that not all the area is in the fast transport zone in Pittini destination.

Going to the second group of distance maps, the availability and reliability of RES can significantly impact the production process. For instance, fluctuations in solar or wind energy production can lead to variations in the availability of electricity for the electrolysis process. To ensure a consistent and reliable energy supply, choosing a location where renewable energy sources are abundant and where energy storage solutions can be integrated effectively is important. To measure the distance from RES (Fig. 3. e), we used the NEAR function in GIS to determine the proportion of nearest sites where intervention is possible.

We used the same method for proximity to gas pipelines (Fig. 3. f).

Furthermore, the use of the land is one of the main criteria to consider because the aim is to produce green hydrogen most sustainably, so in addition to excluding the map area that we did at the beginning, we classified the use of land into five different classes

(Fig. 3. g). The most suitable use for us is brownfield and industrial areas; on the other hand, the green areas are less important and get a five value.

3.5 Land Suitability Map

The final results of the spatial multi-criteria analysis how shown in Fig. 4, which integrated GIS and AHP methods to identify the most feasible and desirable location for establishing a green hydrogen infrastructure to serve the Siderpotenza industry, suggest that there are limited high-suitability lands for the construction of green hydrogen production facilities and distribution systems in the study area. The second level of suitable land, most of the land in the study area, falls under the medium-high suitability level, with the most favorable location near the center and close to the Pittini facility. The highest percentage of free lands is considered medium or medium-low. These findings suggest that the potential for renewable energy sources, existing infrastructure, transportation systems, and population density are significant factors in determining the suitability of a location for green hydrogen infrastructure.

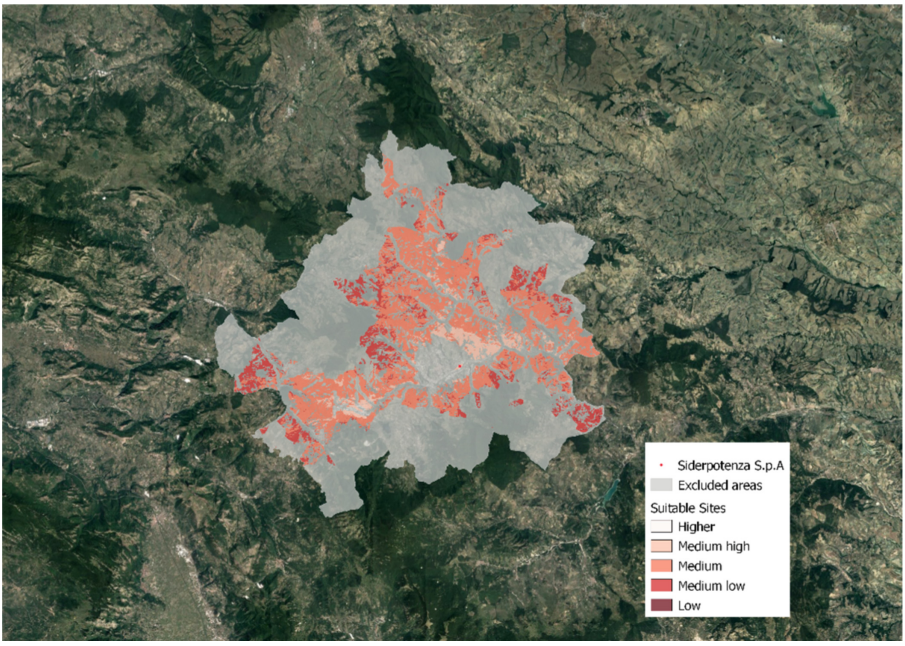


Fig. 4. Land suitability map.

4 Conclusion

In conclusion, the article aims to identify the most feasible and desirable location for establishing a green hydrogen infrastructure to promote sustainable and low-carbon energy systems. By integrating GIS and AHP techniques, the authors have developed

a comprehensive framework for spatial multi-criteria analysis that considers various geographical, environmental, and economic factors. This methodology can evaluate and compare scenarios for constructing green hydrogen production facilities, transportation networks, and distribution systems. The study's results, presented in the third section, will provide valuable insights and research perspectives for policymakers, energy companies, and stakeholders interested in promoting green hydrogen as an alternative to traditional fossil fuels. Ultimately, this research contributes to the global effort to reduce greenhouse gas emissions and combat climate change.

The methodology developed in this article for identifying the best site for establishing a green hydrogen infrastructure can be applied to other sites beyond Potenza, Italy. In particular, the goal is to identify other case studies to use different criteria to obtain different scenarios. Using the spatial multi-criteria analysis technique that integrates GIS and AHP methods, policymakers, energy companies, and stakeholders can evaluate and compare different locations based on various criteria, such as renewable energy potential, existing infrastructure, population density, and transportation systems. This approach can be adapted to various regions and industries interested in transitioning to low-carbon energy systems. It can provide valuable insights into the feasibility and effectiveness of using green hydrogen as an alternative to traditional fossil fuels.

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