Spatial Multi-criteria Analysis for the Planning of Green Hydrogen Infrastructure: The Case Study of the Industrial Area of Viggiano

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Abstract. The paper examines the criteria that help to identify the most suitable sites for the location of plants, structures, and networks needed to produce, store, and distribute green hydrogen produced through water electrolysis. To carry out this analysis, it was necessary to work through the integration of two tools: the Analytic Hierarchy Process (AHP) and the Geographic Information System (GIS). While AHP allows for the analytical analysis of criteria, GIS identifies the spatial relationships generated in identifying suitable sites for the Green Hydrogen Infrastructure (GHI) placement. The approach considers several criteria that fall into three main categories: technical, economic, and environmental. Developing the criteria results in a land suitability map as the final product. The process mentioned is evident in the case study, namely identifying suitable sites for the location of GHIs in the Viggiano industrial area in Basilicata (Italy). The paper reveals that the methodology supports urban planners, decision-makers, and stakeholders in developing and using green hydrogen as a sustainable energy source.

Keyword: Green Hydrogen Infrastructure (GHI) · Land Suitability Map · Spatial Multi-Criteria Analysis

1 Introduction

Today's society has numerous challenges and emergencies, and the climate crisis is one of them [1]. Data on environmental pollution are increasingly dramatic, and several studies [2–5] point to the well-known correlation between human health and environmental health. Greenhouse gas emissions due to the use of fossil fuels are among the main contributors to climate change [6], which is why the world's policies are moving towards clean energy sources that can overcome the limitations of fossil fuels [7]. In this scenario, green hydrogen plays a key role [8, 9]. Its versatility and diverse uses allow for easy deployment [10], although it is currently limited by investment costs in the infrastructure needed to produce, store, and distribute green hydrogen [11]. Presently, the prospects for

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the use of hydrogen are particularly favorable for the transport sector. This last is, in fact, responsible for about 65% of global Green House Gas (GHG) emissions [12]. Acting in this sector makes it possible to reduce pollution and the energy dependency of Nations [13]. Hydrogen can be used in vehicles in essentially two ways: a) in fuel cells (Fuel Cells) to produce electricity that then powers the vehicle's electric motor (FCEV - Fuel Cells Electric Vehicle) [14]; b) as fuel in an internal combustion engine (HICEV - Hydrogen Internal Combustion Engine Vehicle) [15]. Among the most promising methods for producing green hydrogen is the electrolysis of water [16]. Electrolysis is when water is split into oxygen and hydrogen gas using electricity from renewable energy sources [17]. This process makes it possible to produce hydrogen with zero carbon emissions [18]. The paper aims to investigate the criteria necessary for identifying GHIs to locate suitable sites. A spatially based analytical methodology was implemented to achieve this goal, integrating the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS). The adoption of this method is underscored in the scientific literature, highlighting its utilization in decision-making processes concerning the localization of Renewable Energy Sources [19–28]. The specificity of this approach is that it allows both qualitative and quantitative factors to be considered and their spatial dimensions to be visualized. The methodology was applied to a case study concerning the Viggiano industrial area in Basilicata, Italy, to verify its effectiveness. The final output is the land suitability map showing the suitability of the investigated study area for the placement of GHIs.

The paper is divided into three sections. The first concerns the method of analysis, in which the methodology steps are described. The second section contains the case study, and the last section regards concluding remarks.

2 Analysis Method

Assessing the sustainability of land transformation interventions is now a topic of central importance in cultural, scientific, and political debate. In this context, decision problems are typically characterized by involving a spatial component, requiring more than one evaluation criterion, and pursuing more than one objective [29]. Multicriteria assessments support decision-making processes [30, 31] that choose multiple alternative solutions. The last are analyzed against a set of criteria that can be either economic, and therefore monetizable [32], or qualitative. Multicriteria methods aim to identify the compromised solution [32–34]. The best alternative is not the one that optimizes each criterion but achieves the best compromise considering all the criteria selected for comparison. Among the most comprehensive multicriteria decision analysis methods is the Analytic Hierarchy Process (AHP) [35]. This method owes its considerable popularity in the international arena to its ease of application [36]. It also finds use in various fields [37] ranging from engineering to politics, from social issues to economics. Several simplifications have affected the AHP technique. These simplifications were introduced by its very creator, the mathematician Thomas Saaty [35, 38, 39]. The main steps are:

1) Recognize the main problem and decompose its complexity into simpler problems.
2) Identify the actors involved.
3) Represent the problem through a hierarchy consisting of the goal, criteria, sub-criteria, and alternatives.

4) Make comparisons of the elements of the same levels concerning over-ordered ones through a scale of judgments ranging from 1 to 9.
5) Identify local weights of criteria and global weights of alternatives.
6) Check the goodness-of-fit of the model by calculating the maximum eigenvalue, CI Consistency Index (CI), and Consistency Ratio (CR).

The functions of the Analytic Hierarchy Process (AHP) can be integrated [40] with the spatial functions of Geographic Information Systems (GIS). Criteria and attributes can be represented through geographic maps [41]. The hierarchy consists of levels but does not include the level of alternatives represented geographically by linear elements, polygons, or through a raster's cells if the maps' format is vector type [42]. The weights of the hierarchy elements and the spatial information of the problem under consideration can be processed in the same environment. Maps give a spatial distribution of criterion values in the study area [43–45].

The case study aims to create a land suitability map for placing GHIs (Green Hydrogen Infrastructure) in the Viggiano industrial area in Basilicata. Consequently, within the GIS environment, the following steps are followed:

1) Identifying constrained areas and making the study area map with free areas.
2) Represent the criteria and sub-criteria through maps.
3) Overlay of the maps through map-algebra tools and assignment of the weights obtained with AHP.
4) Elaborate the land suitability map.

This methodology greatly simplifies the decision-making process regarding a complex and multifaceted topic, such as choosing the most suitable site for the location of GHIs. As a result, greater stakeholder involvement promotes the development of a resilient and environmentally aware society [46–48].

3 Case Study

Hydrocarbon exploration and production in Italy using industrial techniques began in the second half of the 19th century and has developed considerably since World War II, following the discovery of significant quantities of natural gas, especially in Basilicata. In Val d'Agri, one of the most characteristic valleys in Basilicata, there is an important industrial area with the presence of the largest oil platform in continental Europe. At the Centro Oli Val d'Agri (COVA) plant, hydrocarbon processing is carried out. Crude oil fed to the plant undergoes all the treatments necessary for commercialization, which essentially consists of the separation and subsequent processing of the phases present in the extracted fluid: crude oil, gas, and water.

The water that emerges along with the crude oil and gas during extraction is called process water. These waters undergo treatment consisting of separating the associated gas, de-oiling, degassing, filtration, and storage. The treated waters can be used in electrolysis to produce green hydrogen.

3.1 Study Area

Centro Oli Val d'Agri (COVA) is located in the industrial area of Viggiano in Basilicata as show Fig. 1.

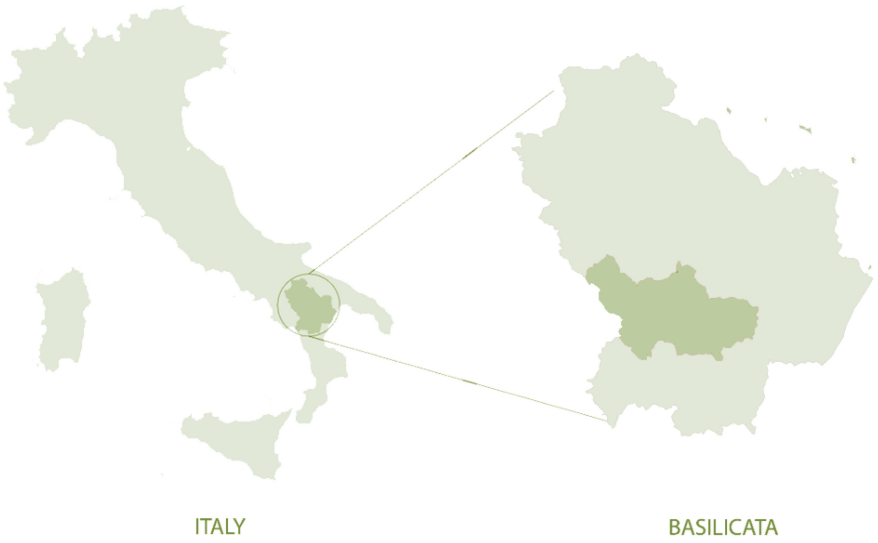

Fig. 1. Location of the study area in the Basilicata region.

The site covers an area of approximately 171,700 m^2. The southeastern perimeter of the complex runs parallel to the municipal boundary, while the surrounding areas, within a radius of 1 km, fall within the municipal territories of Viggiano and Grumento Nova. In order to carry out a more detailed analysis, for the identification of suitable sites for the installation of GHIs, it was also necessary to include neighboring municipalities, such as Armento, Aliano, Castronuovo di Sant'Andrea, Corleto Perticara, Gallicchio, Guardia Perticara, Marsico Nuovo, Marsicovetere, Missanello, Moliterno, Montemurro, Paterno, Roccanova, San Chirico Raparo, San Martino d'Agri, Sant'Arcangelo, Sarconi, Spinoso and Tramutola. The complete study area shown in Fig. 2 covers 1405 km^2.

The first operation carried out in the GIS environment involved identifying areas that are constrained and, therefore, not suitable for the installation of GHIs. The constrained areas include:

- the hazard areas of the Hydrogeological Structure Plan.
- The urban centers and rural areas are drawn from ISTAT data on national locations.
- areas protected by law concerning the regulatory framework for regional landscape planning, consisting of the European Landscape Convention (ECL).

Eliminating constrained areas resulted in the map of the vacant areas shown in Fig. 3.

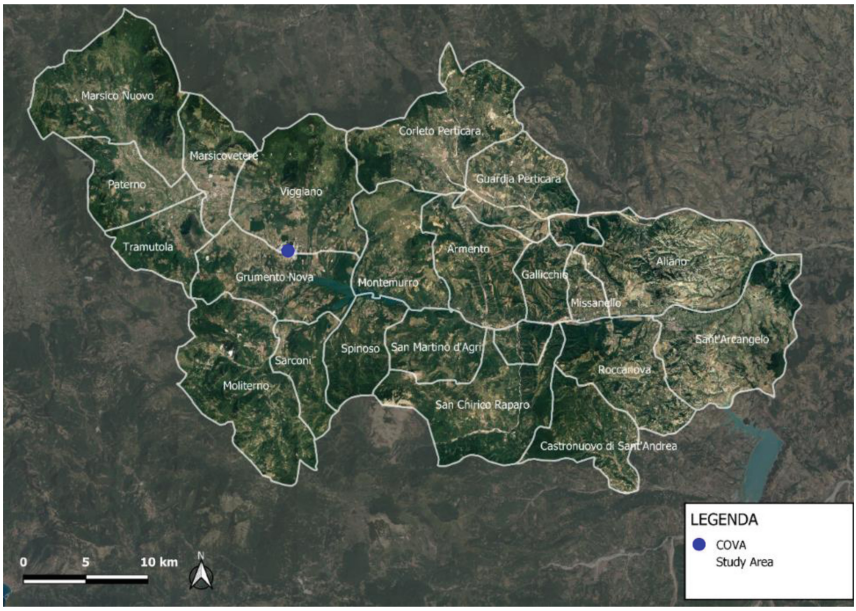

Fig. 2. Study area.

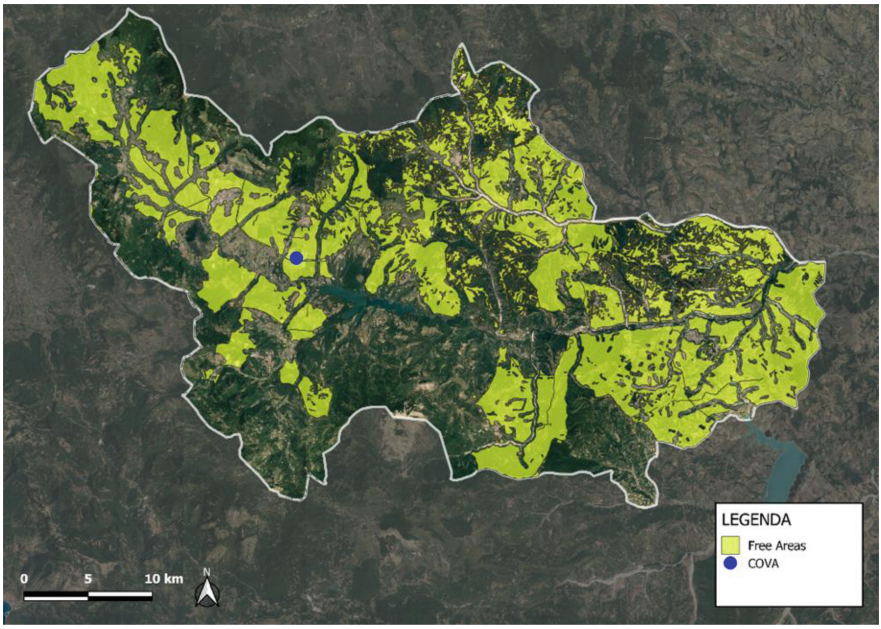

Fig. 3. Map of free areas.

3.2 Spatial Analysis of Criteria

The criteria and sub-criteria selected for the study area analysis were evaluated after careful analysis with experts in the field. The criteria pertain to three categories: technical, economic, and environmental. There are seven sub-criteria: slope, solar radiation, accessibility to roads, accessibility to the Val d'Agri Oil Center (COVA), distance to RES, and distance to the TERNA power grid. Finally, the environmental criterion has a sub-criterion as a summary indicator of three ecosystem services: habitat quality, carbon stock, and crop production. Criteria and their sub-criteria are summarized in Table 1.

Table 1. Identification of criteria and sub-criteria.

Main Criteria	Sub-Criteria
Technical	C_1: Slope
	C_2: Solar radiation
Economic	C_3: Distance of roads
	C_4: Distance of COVA
	C_5: Distance of RES
	C_6: Distance of TERNA power grid
Environmental	C_7: Ecosystem Services

Next, the steps of the AHP technique explained in Sect. 2 were applied. For each criteria, weights were calculated thanks to the pairwise comparison matrix shown in Table 2 using the semantic scale with values ranging from 1 to 9 proposed by Saaty [35]. The vector of weights is shown in the last column of the matrix.

Table 2. 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	0,17	0,17	0,20	0,20	0,25	3
C_2	4,00	1,00	0,33	0,33	0,33	0,33	0,25	6
C_3	6,00	3,00	1,00	1,00	0,50	0,50	0,25	11
C_4	6,00	3,00	1,00	1,00	0,50	0,50	0,25	11
C_5	5,00	3,00	2,00	2,00	1,00	1,00	0,25	15
C_6	5,00	3,00	2,00	2,00	1,00	1,00	0,25	15
C_7	4,00	4,00	4,00	4,00	4,00	4,00	1,00	37

The judgments' consistency was checked by calculating the maximum eigenvalue and then the Consistency Index (CI) and Consistency Ratio (CR). The consistency index

is calculated through the formula shown in Eq. 1. The term "n" represents the number of items compared; in this case, there are seven criteria.

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

The CR is provided by the ratio of the consistency index to the Random Consistency Index (RCI). The latter is a tabulated value that depends on the number of elements considered, as shown in Table 3.

Table 3. 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

As shown in Table 4, the consistency ratio is less than 10%, and the upper limit when the elements considered (n) are greater than 4. The consistency check is therefore satisfied.

Table 4. Consistency Check

λ max	n	CI	RCI	CR	CR (%)
7,730711	7	0,12	1,32	0,092262	9,23

Each criterion was then spatially analyzed in a GIS environment. A reclassification in raster format is made through ArcGIS, compared to the free areas resulting from the previous analysis. Reclassification was done using a suitability scale of 1 to 5, where:

- 1 highly suitable areas.
- 2 medium-high suitability areas.
- 3 medium suitability areas.
- 4 areas with medium-low suitability.
- 5 areas with low suitability.

3.3 Land Suitability Map

After carefully analyzing all sub-criteria, the final result of the spatial multi-criteria analysis is a Land Suitability Map shown in Fig. 4.

Through Map Algebra operations, the weights assigned to each sub-criterion, derived from the pairwise comparison table (Table 2), were entered. From the resulting map, the best sites to locate GHIs are deduced. The high suitability level presents a fair extent throughout the study area. In particular, an area of high suitability with an extent of 184,6 hectares is close to COVA. This extension appears to be largely suitable for locating facilities for producing, storing, and distributing green hydrogen. COVA falls

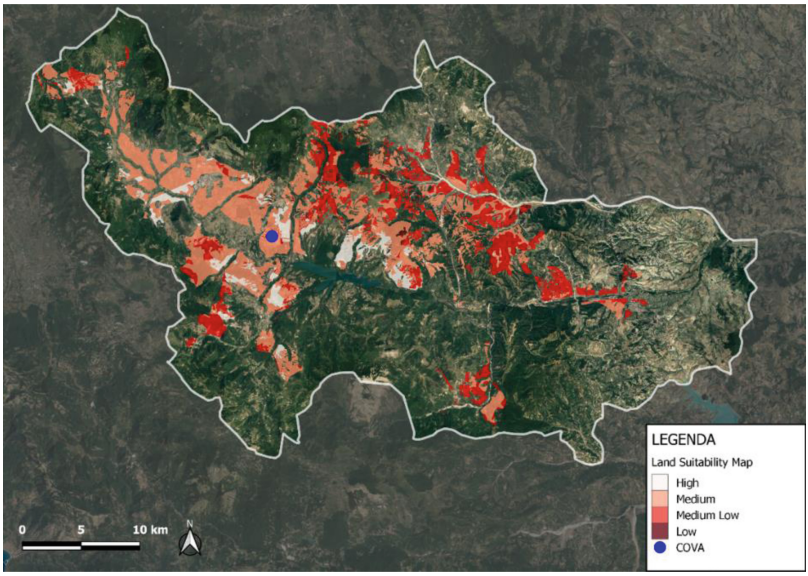

Fig. 4. Land Suitability Map.

within an area of medium suitability equal to 540 hectares. By expanding the range and considering COVA as the center of reference, the suitability decreases, with medium-low and low levels.

4 Conclusion

In conclusion, the paper's main objective is to identify the most suitable location to design and implement a green hydrogen production, storage, and distribution infrastructure to promote sustainability and low-carbon energy consumption.

The methodology used, characterized by the integration of AHP (Analytic Hierarchy Process) in a GIS (Geographic Information System) environment, sees its application to the selected case study: the identification of suitable sites for the location of Green Hydrogen Infrastructure (GHI) serving the Val d'Agri industrial area. AHP allows us to simplify a complex problem into simpler sub-problems by considering numerous quantitative and qualitative criteria. This methodology is an important support tool for planners, who play an important role in decision-making processes. Using this spatial analysis technique, stakeholders, policymakers, and companies can compare different sites and scenarios about criteria such as renewable energy, existing infrastructure, and transportation systems.

Ultimately, the elaborations show that green hydrogen represents a promising energy resource in the transition to a sustainable future, and its deployment could play a key role in powering those energy-intensive sectors.

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