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Mapping the suitability of North Africa for green hydrogen production: an application of a multi-criteria spatial decision support system combining GIS and AHP for Tunisia

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Abstract

Background In the energy transition framework towards decarbonization, green hydrogen, obtained through water electrolysis powered by renewable energy, is gaining importance. In order to pave the way to its production and trade, it is required to assess its main advantages and challenges, which are not only energy-related but involve also techno-economic, social, environmental, and geopolitical aspects. In line with this, the current article aims to provide a Multi-criteria Spatial Decision Support System to investigate the suitability of North African countries with respect to the production of solar-based hydrogen and its potential trade, and to apply it to Tunisia, as one of the most promising countries for becoming a competitive hydrogen exporting leader. Combining the Analytic Hierarchy Process and the Geographical Information System, this study focuses on evaluating the land suitability for solar hydrogen production at a country level, serving as the foundation for a methodology applicable across the entire North African region. After defining ten different criteria, these are spatially analysed and then prioritized according to different experts' preferences, so that a final suitability map is obtained. The added value of the study is the inclusion of social and geopolitical criteria in this kind of assessments, often focused on techno-economic parameters alone.

Results The suitability map allows to classify the majority of the Tunisian areas as moderately or highly suitable, even if the most favourable areas in terms of availability of resources are often negatively influenced by the geopolitical or economic assessment. The sensitivity analysis has also proved the high suitability of Tunisia, with no areas assessed as very low suitable even if the different criteria are extremized.

Conclusions Among the several influencing factors addressing the suitability for green hydrogen uptake, this article makes it possible to explore the social and geopolitical externalities, as well as the environmental and techno-economic dimensions. Even if stakeholders' preferences affect the final results, the sensitivity analysis makes it possible to test their robustness. Supporting the adoption of new clean technologies towards the carbon-neutrality target, the methodological framework could be applied for other countries and also tailored on other specific technological pathways.

Keywords Energy transition, Decarbonization, Green hydrogen, Multi-criteria spatial decision support system, Analytic hierarchy process, Spatial analysis

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Background

Concerning the increasing pace and relevance of climate change issues and pursuing the goal of carbon-neutrality set for 2050 [1], the development and the adoption of new clean technologies represent a key enabler of the current energy transition process. Among the available options for decarbonization, hydrogen represents a viable solution to fight against global warming and to address other energy-related issues involving traditional energy systems [2, 3]. Identified as one of the key drivers to reach the target of 1.5 °C as rising temperature limit [4], its adoption must evolve hand in hand with (i) the development of renewable energy; (ii) the structured implementation of energy efficiency measures; (iii) the increase in electrification; (iv) the enhancement of carbon capture processes [5]. Looking at the two major developments that the energy system is experiencing, i.e. the robust electrification of end use and the decarbonization process itself [6], hydrogen must exploit its "innovation turning point", concerning the potentiality to decarbonize those sectors that are harder to electrify [7], as well as the possibility to be used in challenging sectors (i.e. shipping, aviation, heavy industry, long-haul transport) [4]. Aiming to support emerging technologies to become competitive in the short-term and most-effective in the long-term [4], the main potentialities rely on hydrogen electrolysers; this technological option will strongly contribute to the reduction of CO_2 emissions between 2030 and 2050, as addressed by the International Energy Agency (IEA) within the "Net zero by 2050" pathway [8]. In fact, it is possible to exploit the water electrolysis process powered by renewable energy to produce clean hydrogen—the so-called green hydrogen; otherwise, if produced by fossil fuels—as it is today worldwide for about 95% of the hydrogen in the market—it will not represent a viable strategy towards decarbonization. Specifically, the majority of the hydrogen currently used is of grey type, so produced by natural gas and responsible for CO_2 emissions. According to the "Net zero" [8], 60% of the total production will rely on renewable energy (i.e. green hydrogen), while the remaining 40% will be based on the combination of steam methane reforming with carbon capture usage (CCU) and storage (CCS) technologies [8]. However, at present, the required CCS and CCU technologies to boost the blue hydrogen production are still not technologically ready and economically competitive [9]. In this framework, it is important to highlight how all the challenges and opportunities belonging to the green hydrogen development are not only technology- and economy-based, but require strong efforts concerning the broader social, environmental, and geopolitical aspects involved, as all the processes built around energy production and consumption [10]. In this regard, since hydrogen is experiencing a strong uptake, it is required to fill the gap between the technological processes and the social, technical, financial, and environmental aspects of sources and systems required for sustainable hydrogen production [11]. This article seeks to support the implementation of ad hoc decision-support systems in the framework of the potential green hydrogen production and trade, through the assessment of a broader concept of suitability, which includes not only the techno-economic feasibility, but also influenced by multi-dimensional aspects and actors. Specifically, there is strong interest in developing projects to produce and trade hydrogen from North Africa to Europe [12–14]; these assessments, even if focused on techno-economic analyses, highlight how lots of influencing factors can accelerate or slow down hydrogen adoption. The paper is novel in the application of a strategic planning process allowing a spatial characterization of both drivers and barriers related to the suitability of green hydrogen production within the broader social and geopolitical context, not only based on merely techno-economic aspects.

The paper is structured as follows: the next section addresses the role of green hydrogen in the North African energy framework, with a specific focus on the Tunisian context. It is followed by a review of the assessment framework for strategic energy planning, to detail the main methodological approaches adopted, related features and criticalities. The "Methods" section focuses on the approach and instruments exploited for the analysis, then it is introduced the application of interest, in order to show the main results and related discussion. The last section summarizes the main conclusions and future developments of the work.

The role of green hydrogen in North Africa and the Tunisian energy context

Undergoing "an unprecedented set of demographic, social, political, and economic changes that are likely to significantly modify the energy landscapes in the region" [15], North African countries, i.e. Algeria, Morocco, Tunisia, Egypt, Algeria, and Libya, will play a key role in the energy transition context in the next decades. Razi and Dicner [16] review the main operational and planned renewable energy projects in the Middle East and North Africa, stressing how the whole region is still reliant on fossils for its supply and exports. If on one side it is undoubted that North Africa has significantly high levels of solar radiation and available space for renewable infrastructure, on the other side, large renewable projects will inevitably modify the existing assets [17]. Pushing for renewables means that the cooperation between Mediterranean countries is likely to grow, but there are slowing factors to be considered that could affect the effectiveness of cross-border cooperation, i.e. technical problems and cost overruns, inflated expectations, ecological and social externalities, stakeholder fragmentation, corruption and authoritarianism [18, 19]. Energy projects accompanied by sophisticated technologies and promising affordable electricity even tend to fail many times, due to ignorance or less importance of social factors [20, 21]. In other words, it is required to fill the gap between the techno-economic viability and the externalities slowing down the achievement of ambitious development targets for renewables, targeting also effective cooperation. Specifically, influencing factors like governance quality, financial growth, cross-sectoral interactions, innovation, carbon emissions, and economic development significantly affect renewable energy development in these areas [16, 22–30]. In this regard, if strategically introduced in the local energy and economic system, hydrogen can push for many new investments, alliances, targets and strategies from the mid- to the long-term, recognized as a crucial turning point within the whole energy context [16, 27, 28]. Confirming renewable hydrogen projects and initiatives taking place in the last years [16, 28–30], there are several works dealing with the mapping of green hydrogen production potential in North Africa, studying both solar and wind power densities [27, 31–35].

In the recent mapping of [27], it is remarked that the highest annual wind-based hydrogen production density is in Morocco, i.e. 1.29 kg/m^2, followed by Egypt with 1.26 kg/m^2, while concerning solar-based hydrogen the values reach up to 5.58 kg/m^2 (in Egypt), ranging from 4.8 to 5.7 kg/m^2. There are also many studies detailing the competitiveness of green hydrogen production in terms of costs, e.g. ranging from 1.02 $/kg for wind-based hydrogen to 3.34 $/kg for solar hydrogen [27, 36] and arguing the possibility of obtaining an effective decrease of costs in the long-term, even if a series of uncertainty on the influencing parameters must be addressed, i.e. the costs of renewables, the economies of scale for electrolysers and their technological development, risks in investments and transport options deployment [37–40]. Nevertheless, while working on the potentialities and competitiveness of green hydrogen in North Africa, a crucial topic to be addressed concerns water availability for the electrolysis process, focusing on both water scarcity and water stress affecting these areas [28, 41, 42]. In fact, although water withdrawal for hydrogen is negligible compared to its use in other sectors [43], for these countries other options differently from public grid water should be considered, like seawater or wastewater treatment [28, 44, 45].

In the attempt to assess and connect all these aspects and influencing factors, the study deals with the application of a methodological procedure able to release the mapping of North Africa, with respect to the suitability for green hydrogen production; specifically, Morocco and Western Sahara, Tunisia, and Algeria, are the three countries classified among the most predisposed to green hydrogen production and trade [46]. Morocco is identified as a potential global leader in producing green hydrogen, due to its high availability of solar and wind resources [12, 47]; Algeria is defined as the most exposed country to the European energy transition, and classified as one of the "geopolitical winner" of the transition [17]; Tunisia is planning to reach the target of carbon-neutrality by 2050, aiming also to develop a competitive export-oriented hydrogen industry [48]. This last country is the one proposed as the specific application of this work. Identified among the net-oil importers—like Morocco and Egypt [20], Tunisia has signed an agreement with Germany in December 2020 towards the creation of a green hydrogen alliance and aims to develop a competitive export-oriented hydrogen industry [48]. The country had plans for publishing its hydrogen strategy in March 2023, but it was not yet available while working on this study [49, 50]; it has been just released in May 2024, confirming the ambitions declared, with a total green hydrogen production of around 8.3 Mtons by 2050—more than 75% to be exported [51]. Showing an increasing interest in energy issues in the last years, concerning the development of ad hoc decarbonization policies and strategies, Tunisia has updated its Nationally Determined Contribution (NDC) in October 2021, aiming to reduce its carbon intensity by 45% by 2030 [52], to finally reach carbon-neutrality in 2050 [53]. Looking at the recent increase in energy imports and the current limited renewable energy production, a strong changeover for Tunisia is expected; its energy transition will rely on (i) energy mix diversification with effective renewable integration; (ii) energy efficiency measures; (iii) rationalization of subsidies in the energy sector; (iv) strengthening of grid and interconnections [54]. Moreover, the significant environmental and socio-economic vulnerability of the Tunisian areas must be considered; it is one of the Mediterranean countries most exposed to climate change, with also a high degree of risk to natural hazards [55].

The role of multi-criteria and spatial analysis for strategic energy planning

In literature, several different methodological approaches are exploited or developed to address energy planning problems; nevertheless, dealing with strategic planning and assessment methods means building up a structure that (i) is strategic, (ii) is integrated, (iii) supports social learning, (iv) supports national-communicative planning, (v) provides consistent guidance [56]. Among the plurality of the policy evaluation approaches, the

Multi-criteria Decision Methods (MCDM) [57] is a valuable instrument; it consists of evaluation structures aiming to solve environmental, socio-economic, technical and institutional barriers involved in energy planning [58]. Moreover, each energy transition process is geographically constituted; in other words, energy planning processes and their structure (i.e. different methodological approaches and assessments) affect places but are at the same time strictly influenced by the special features of places, thus generating significant policy implications [59]. In line with this, the Multi-criteria Spatial Decision Support System (MC-SDSS) framework, through the combination of MCDM techniques and the Geographic Information System (GIS), allows to integrate the amount of complexities in spatial planning and decision-making, from both technical and social perspectives [60], as well as economic, environmental, political, legal and cultural viewpoints. The interest in studies and applications of GIS integrated with multi-criteria analyses (MCA) has spread exponentially in a lot of different fields [61], becoming an increasingly relevant topic for spatial complex problems in the last decades [61, 62], and being most often used for tackling land suitability problems among different applications [61, 63]. Specifically, in literature it is possible to find an increasing number of MC-SDSS applications regarding the optimal site selection for renewable projects [64–66], but there are also other case studies, ranging from landfill location [67] to healthcare facilities [62, 68] or multi-functional landscape evaluation [69]. Among the several multi-criteria techniques adopted for land suitability problems, and specifically for renewable energy site selection [64–66, 70], there are the Analytic Hierarchy Process (AHP), the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the Elimination and Choice Translating Reality (ELECTRE), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [21, 64, 70]. Being one of the most consolidated MCA approach, the AHP is a popular method in MC-SDSS applications, allowing to deal with a very large number of alternatives, to make a simple implementation within the GIS environment, and to easily involve non-technical participants [61]. As reviewed by [71], AHP is the most widely chosen—alone or in combination with other MCDM techniques—because (i) it is simple to understand and to be applied to complex problems; (ii) the procedure decomposes a large problem into smaller ones hierarchically; (iii) the comparative importance of criteria is made possible; (iv) it applies to both qualitative and quantitative datasets; (v) there is the consistency check of the decision [61, 64, 71–78].

Specifically, the crucial role of the MCA is widely recognized for selecting solar power plant locations, allowing to address techno-economic aspects, efficiency, land usage, flexibility, emissions, reliability and accuracy [65, 71, 74, 75, 77, 79–90]. Focusing on photovoltaic (PV) plants and concentrated solar power (CSP), Spyridonidou and Vagiona [65] review the exclusion selection as the most frequently applied methodological stage, with a very high relevance of GIS-based procedure for this step. Moreover, the AHP is widely used for the assessment criteria, while also the entropy method is suggested for this step as it is less subjective than AHP [65]. Looking at the specific sites of North Africa, several applications deal with the combination of GIS and AHP to assess the land suitability of these countries, concerning the installation of PV plants [32, 33, 35, 36, 71, 78–82, 85, 86]. Specifically, there are some interesting case studies related to Morocco; for large-scale solar power plants, the application of AHP and GIS allows the selection of specific criteria for suitability belonging to climate, orography, location and water resources [80–82]. Taoufik et al. [81] analyse the Moroccan suitability for solar potential distinguishing among technical, socio-economic and environmental parameters. Concerning Tunisia, a recent work exploits a GIS-based MCDM approach to study large-scale solar PV installation, using spatially measurable factors like solar radiation, slope, land use, temperature, proximity to grid, and water resources [71]. Within this work, GIS techniques are combined with the application of fuzzy logic on AHP (FAHP); it is an effective choice instead of a simple AHP for handling problems with high level of uncertainty [71, 91–93]. The authors of [71] also conduct a more detailed assessment for solar-based green hydrogen production in Tunisia [94]; different ranking methods are exploited to select the most promising sites, located in the south-eastern and southwestern area of the country. Among the aspects exploited for the land suitability assessment related to PV power plants, there are mainly global horizontal irradiation (GHI), slope, land use [77–93]; Spyridonidou and Vagiona [65] reviews also the proximity to the electricity grid among the most significant criteria selected. Looking specifically to clean hydrogen production, which requires extending the suitability concept to both the renewable and hydrogen plants, there are some specific applications involving North African countries. Messaoudi et al. [85] exploit the combination of AHP and GIS to select solar hydrogen production site in Algeria; different exclusion criteria are involved in the analysis, i.e. land use, water bodies, waterways, roads, railways, power lines, while as weighting criteria the hydrogen demand, the potential solar hydrogen production, digital elevation models (DEMs), slope, proximity to roads, railways, and power lines are assessed [85]. Concerning both solar and wind hydrogen potential, Rahmouni et al.

[86] also conduct specific spatial analyses to quantify the potentialities of the Algerian areas [86], while spatially defined criteria are also exploited by Gouareh et al. [93] to assess geothermal heat extraction processes for both electricity and hydrogen production potential in Algeria [93]. Also concerning West Africa, the work of Bhandari [95] allows a focus on Nigeria, through a detailed analysis of the potentiality of production and trade, including analyses of land use assessment, productivity and water consumption. Another interesting study is conducted by Zelt et al. [96]; using Renewable Energy Pathway Simulation System GIS and the AHP to capture stakeholders' preferences, alternative long-term electricity scenarios are developed for Jordan, Morocco, and Tunisia [96]. Involving about 25 participants for each country, among which academia members, people from the private sector and policy makers, different criteria are identified for the assessment, belonging to techno-economic dimension, the social and the environmental one, according to qualitative and quantitative information [96]. Looking not only at the national strategies but focusing on the cross-border alliances, Papapostolou et al. [97] propose a methodology to adopt the most appropriate strategic plan for the establishment of a successful cross-border cooperation, considering Europe and Morocco, and Europe and Egypt as case studies [97]. The AHP, the Strength Weakness Opportunities and Threats (SWOT) analysis and the TOPSIS are exploited, in a multi-step procedure [97]; it is of interest to note that the investment field accounts for seven criteria over the total of 12, while for the socio-environmental side, only two criteria are assessed. In the framework of potential cross-border cooperation, the non-technical aspects assume a significant role in the effective realization of projects, considering how this type of risk in North Africa is very real and likely to create considerable delays [20]. In Appendix A specific tables are added (from Tables 4, 5, 6, 7, 8), referring to the main exclusion criteria and assessment criteria belonging to the solar projects, as reviewed by [64], and confirming the strong importance given to techno-economic criteria while there is a less general interest on the social dimension.

In line with this, the paper aims to use the MC-SDSS methodological framework to address the multi-dimensional nature of the suitability concept, stressing the influence of several factors that in literature are missed in relation to the objective of assessing land suitability for strategic energy planning. Such factors concerning geopolitical stability, social health and human development are in fact strictly related to the concept of security of supply and positive energy cooperation but are missed within techno-economic analysis pretending to be exhaustive for land suitability problems. Specifically, in the energy transition context, it is recognized the need to develop a multi-layered and multi-actor assessment with respect to the production of green hydrogen in North Africa, looking at the potential cross-border cooperation in the Mediterranean area. In fact, even if well-known and applied within this context, according to the authors' knowledge the combination of AHP and GIS is not used to tackle the interplay between techno-economic suitability and socio-geopolitical stability, that as previously reviewed can strongly affect the achievement of the objective in this framework.

Methods

Among several techniques and methodological approaches available in the MCDM framework, the MC-SDSS as a combination of AHP and GIS guarantees the identification of geographical alternatives which satisfy specific criteria and the generation of user-friendly maps that clearly show the outputs of the assessment and its main results to each actor—with different backgrounds and interest—involved in the decision-making process [62, 98]. In this way, the spatial multi-criteria analysis becomes a powerful tool (i) to identify suitable areas for new infrastructure, (ii) according to which legitimize policies and actions, (iii) for the elaboration of scenarios to share among all parties [62]. Concerning the integration of the AHP with GIS analyses, Fig. 1 deepens the main steps of the AHP technique [99], while Fig. 2 details the conceptual framework involving both AHP and GIS, from the definition of the problem to the discussion of the results [100–104], in line with the work detailed in a technical report produced by the authors [34]. The AHP allows to specifically prioritize criteria and sub-criteria involved in the assessment.

As summarized by Fig. 2, the MC-SDSS procedure accounts for nine different steps, each belonging to a specific phase; four phases are identified, with three of them requiring both the MCDA and the GIS environments. Specifically, the intelligent phase consists of the first steps required by each MCA, i.e. the definition of the problem and the identification of the evaluation criteria, and the first spatial analyses by GIS, involving data acquisition, data processing and analysis. Within this step, also the exclusion criteria are identified in order to account for specific spatial constraints which do not allow to satisfy the objective of the assessment. Secondly, the design phase is devoted to the standardization of the maps and to the application of the specific multi-criteria approach guaranteeing the proper weighting procedure for criteria through the stakeholders' involvement. According to the choice phase, all the elaborated maps are aggregated to obtain the final suitability maps, while the review phase consists of a sensitivity analysis to focus on the impact of

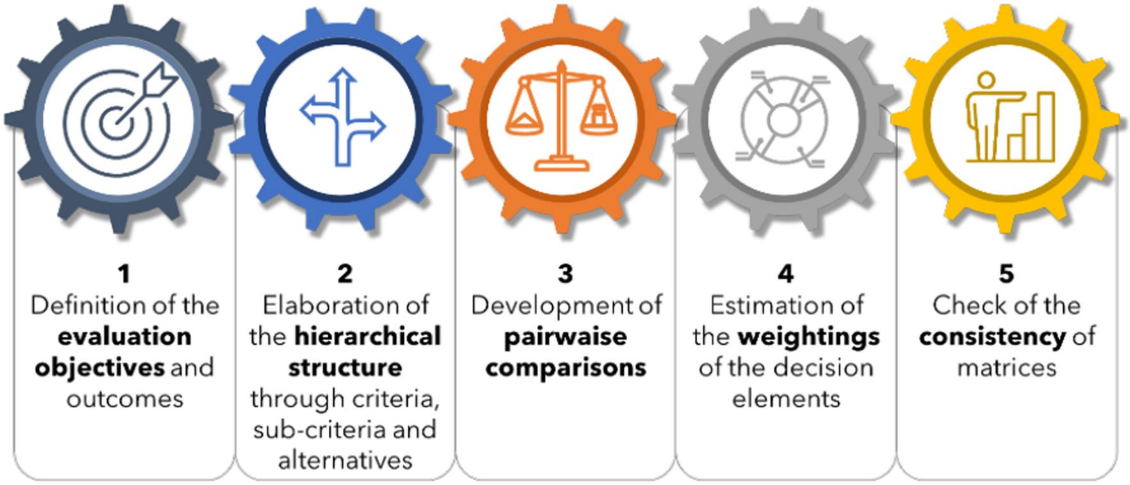

Fig. 1 The AHP technique: main steps, adapted from [99]

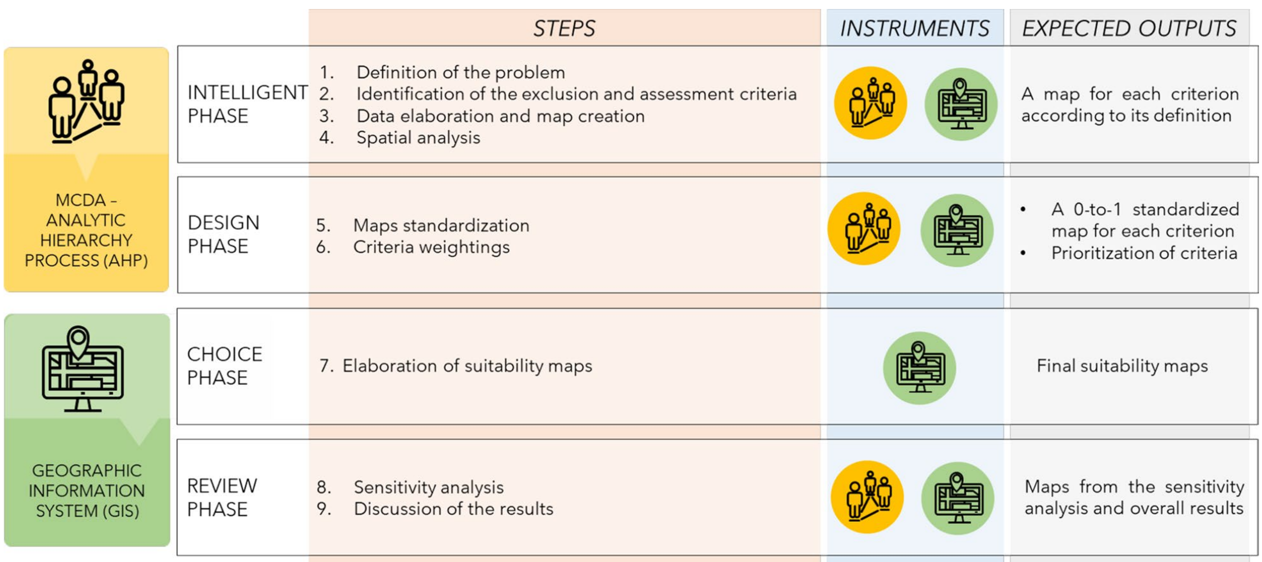

Fig. 2 The MC-SDSS methodological framework, adapted from [62, 99–103]

weightings and to discuss how the solution is affected by the prioritization of the criteria.

The intelligent phase

The application is focused on mapping the suitability for solar-based hydrogen production in Tunisia, considering the possibility of exploiting solar energy from photovoltaic panels to power the water electrolysis process. In the following, all the steps are tailored to the application of interest, starting from the problem definition, which is identified as "Which are the suitable areas to produce solar-based hydrogen (i.e. produced by water electrolysis powered by solar energy)?".

In this regard, it is needed to focus not only on the specific siting requirements to exploit solar resources (e.g. solar radiation, slope, etc.), but much effort must be put into considering the water requirement for electrolysis and the need for proper infrastructure systems. Different experts are involved through specific structured interviews; specific opinions and points of view are collected and added to the information selected from the literature. First, a group of experts from Polytechnic of Turin and stakeholders from two companies involved in renewable energy projects in Tunisia and Algeria took part in a 1-day workshop, to investigate the framework of the activities and detail the characterization of the renewable energy planning processes. After this, an expert from each group has been selected: (i) an energy engineer with 10 years of activities in Tunisia and Algeria on mostly natural gas; (ii) an environmental engineer with 15 years experience in energy planning procedures; (iii) an energy policy expert, managing collaborations with Tunisia for renewable energy development. According to them, the environmental factors must be prioritized, considering that green hydrogen is increasing its relevance because of the challenges of transition to tackle climate change. In addition to this, a second crucial factor is represented by the political and geopolitical conditions; technological readiness is not enough if there is a condition of instability. In this sense, the geopolitical criterion should be prioritized with respect to the technological one, which loses its value if peace and prosperity are not guaranteed. According to the environmental engineer, the crucial problem of water availability should be highlighted; it becomes a key factor for the assessment, both from technical and environmental points of view, also considering that North African countries are experiencing water scarcity and imbalance in water availability more than others. Moreover, dealing with desertic areas leads to the involvement of specific technical or environmental challenges, concerning sand, high temperature, and droughts. It is also important to ensure economic affordability and stability; in these areas economic and financial uncertainty can affect the needs of local and foreign investors, also impacting local development and the way of living. In the definition and elaboration of criteria, it would have been useful to involve all the multi-interest stakeholders, belonging to the political and private categories, at the national and local levels.

As shown in Fig. 3, there are exclusion criteria to be assessed before working on the assessment criteria (Table 1); these exclusion criteria are selected according also to the reviewed studies [32, 33, 64, 65, 71–92], and in line with Table 4 shown in Appendix A.

The selection of the exclusion criteria and the definition of specific threshold values are in line with the literature review already discussed; specific buffers are also introduced as reported in Table 1. Through the definition of the five assessment criteria (i.e. Society, Technology, Atmosphere and Environmental Land, Geopolitics, Economy), ten different sub-criteria are identified, to be spatially assessed for the multi-dimensional suitability maps. Specifically, as better stated in Table 2, the term "proximity" is used to define the sub-criteria that must

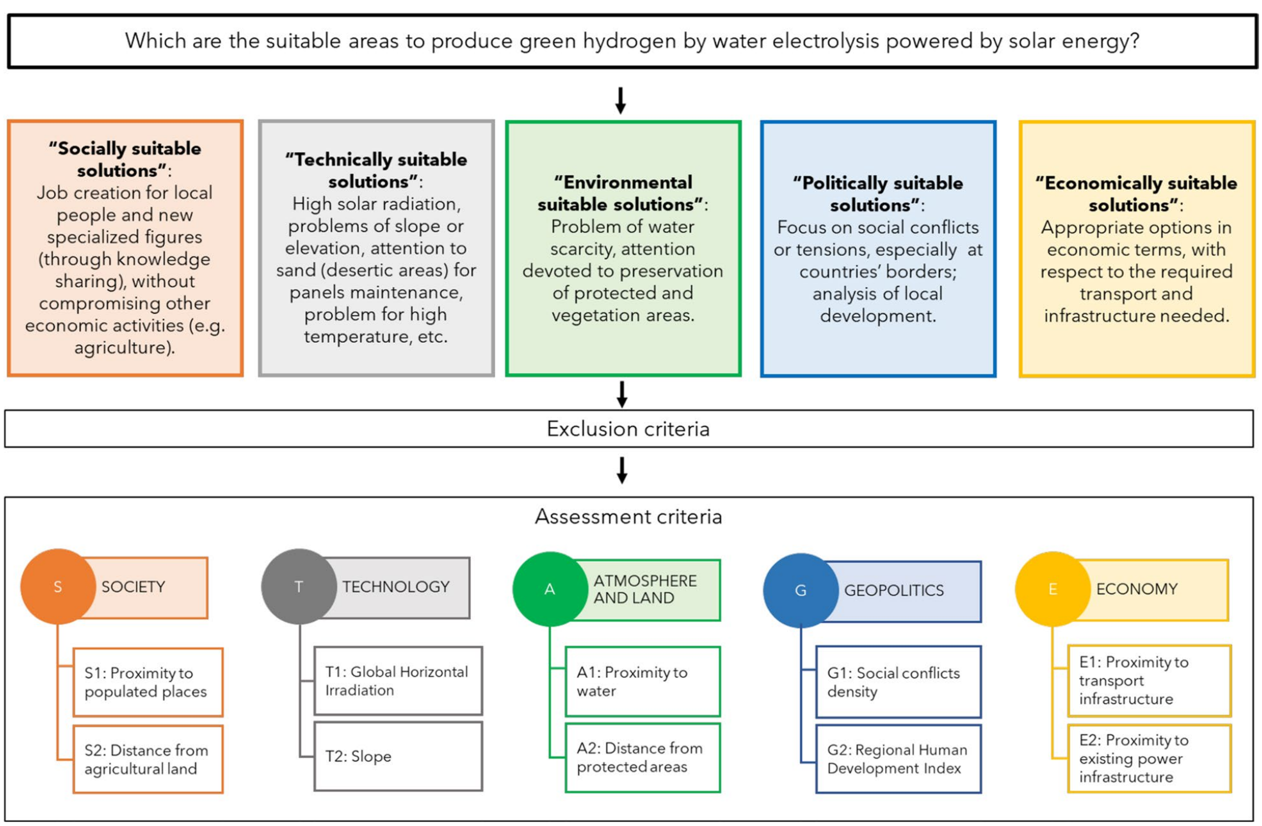

Fig. 3 From the problem statement definition to the identification of the assessment criteria

Table 1 The exclusion criteria adopted in the assessment

Exclusion criterion	Area excluded if	Source	Buffering area
GHI (Global Horizontal Irradiation)	GHI < 4.5 kWh/m^2/day	Global Solar Atlas 2.0 [105]	
Slope	Slope > 5°	DEM-SRTM NASA [106]	
Water bodies	Water areas and water lines	Open Africa dataset [107]	Buffer of 500 m
Protected areas and Other Effective Conservation Measures areas	Biologic reserves, sites of ecologic and biologic interest, protected maritime areas, natural parks, hunting reserves, UNESCO sites	World Database on Protected Areas (WDPA) [108]	Buffer of 500 m
Populated areas	Populated places points and polygons	OpenStreetMap (OSM) [109]	Villages: buffer of 1 km; towns: buffer of 2 km; cities: buffer of 4 km
Other land uses	Not bare areas neither areas with scrubs	Esri 2020 LandCover [110]	Buffer of 100 m
Transport and power infrastructure	Railroads, roads, airports, electricity infrastructure, natural gas infrastructure	OpenStreetMap (OSM) [109], WFP OSM [111],	Buffer of 100 m

Table 2 The main features of the sub-criteria defined to address the multi-dimensional suitability concept

Criterion	Code	Sub-criterion	Measure unit	Preference type	GIS data source
Society	S1	Proximity to populated places	[km]	Min	HOTOSM [109]
	S2	Distance from agricultural land	[km]	Max	ESRI [110]
Technology	T1	GHI	[kWh/m^2/day]	Max	Global Solar Atlas [105]
	T2	Slope	[°]	Min	SRTM 90 m DEM Database [106]
Atmosphere and environmental land	A1	Proximity to coastline	[km]	Min	GADM [112]
	A2	Distance from protected areas	[km]	Max	WDPA [108]
Geopolitics	G1	Social conflicts density	[%]	Min	GADM [112]; ACLED [113]
	G2	Regional HDI	[0–1]	Max	UNDP [114]
Economy	E1	Proximity to transport infrastructure	[km]	Min	HOTOSM [109]; WFP OSM [111]
	E2	Proximity to power infrastructure	[km]	Min	World Bank [115]; self-elaboration

be minimized (i.e. the lower, the better) and the term “distance” is used to address the sub-criteria to be maximized (i.e. the higher, the better).

The social criterion addresses from one side the possibility of creating job opportunities through the development of new energy projects, specifically measuring the distance from the urban areas; the higher the proximity of cities, villages and towns, the higher the possibility to be effectively involved in the energy projects as workers, without compromising quality of life and standard of living. On the other side, the sub-criterion S2 considers the significance of the agricultural activities in the North African economies, so that it is needed to not compromise this land use. Looking at the technical criterion, two main key drivers of the technical feasibility of solar PV installations are considered, i.e. the average daily GHI, defined as T1, and the land slope (T2). Within T1, which measures the total amount of shortwave radiation on a horizontal surface integrated over time, it is included the key importance of solar radiation in this kind of site selection process; the higher the solar resource potential, the higher the profitability of the project and, as expected, this measure is mentioned in all the studies related to renewable energy planning [64, 65, 79]. Concerning the selection of slope as a technical criterion, it is elaborated according to the SRTM Digital Elevation Model (DEM) dataset [106]; a larger slope makes a project less feasible and more expensive, so a more 5° slope is considered not suitable at all, i.e. to be excluded. About atmosphere and environmental land, a sub-criterion to assess the problem of water scarcity and water stress [28] is introduced; the sub-criterion A1 accounts for the proximity to seawater, i.e. the lower, the better, referring to the potential exploitation of seawater treatment through desalination. In fact, although a study comparing different water sources for electrolysis argues that the public grid water is the most suited [44], also seawater desalination can be a viable solution, with the aim to minimize the hydrogen’s water footprint [28]. To this regard, using seawater as a feed for electrolysers can be a promising option for countries experiencing water scarcity like Tunisia, exploiting also the improvements in desalination technologies using renewable energy [45], even if it is an energy-intensive process and brine as by-product represents a drawback to be managed. The second environmental sub-criterion accounts for the need to avoid potential conflicts with protected areas and energy projects, through the measurement of distance from the areas which must be preserved in terms of ecosystem. To do this, the World Database of Protected Areas (WDPA) is used, as the most comprehensive database of marine and terrestrial protected areas [108]. The geopolitical dimension is the most critical to be identified and spatially assessed, but also the added value of this analysis; the aim is to investigate the stability of the involved regions, specifically at the borders, also accounting for the stability of the internal politics, and with respect to foreign affairs. It is decided to assess a first sub-criterion related to the stability concept and a second one involving the welfare condition, respectively, calculated at the governorate and macro-region level. The (geo)political sub-criterion "Social conflicts density" (G1) is a self-elaborated indicator through the registration of social conflicts in the year 2021 by the ACLED portal (Armed Conflict Location & Event Data Project) [113] and collects battles, protests (peaceful, with interventions, with excessive force practised against protesters), riots, violence against civilians, strategic development, explosion/remote violence. Specifically, it is calculated as the total number of social conflict events registered in each governorate in 2021 divided by its population. In this way, a "social conflicts density" is elaborated, as the percentage of the number of events over people; the lower the percentage, the better the performance of the governorate under assessment. Regarding the second geopolitical sub-criterion, the Human Development Index (HDI) for each governorate is collected, being available at the macro-region level for each country [114], and so identified as Regional HDI in the sub-criterion definition (G2). It measures, in a range from 0 to 1, three basic dimensions of human development: long and healthy life, access to knowledge and a decent standard of living [114]. Along the choices of the criteria, the geopolitical dimension appears as the most critical to be assessed and within the participatory process the regional HDI is selected as it allows to measurement of the specific level of economic and social development according to a common procedure; the higher the HDI, the more predisposed for projects development and new economic activities, as an indicator of local welfare. Finally, looking at the economic criterion, it is first analysed the available transport infrastructure, addressing railway lines, main roads and seaport infrastructure, through the sub-criterion E1; the proximity to existing transport infrastructure makes projects more feasible in economic and technical terms. The second economic sub-criterion E2 assesses the potential exploitation of the existing electric power infrastructure supporting the realization of new renewable plants and the natural gas pipelines already developed; the latter can make it simpler and cheaper to develop new projects and realize interconnections.

To adequately develop the data elaboration and map creation, which represent the third step of the MC-SDSS approach (Fig. 2), ArcGIS Pro software is used, in particular the Suitability Modeler Workflow [116]. According to the different maps data types downloaded through the sources introduced in Table 2 or self-elaborated, different spatial analyses are conducted, so that a map for each sub-criterion is finally obtained. Specifically, different functionalities for map processing are exploited, e.g. merge of feature classes, mosaic to raster, conversion from vector to raster format, resample, buffer, raster calculator, Euclidean distance. Specifically, each map is converted and/or resampled in order to obtain a raster file with a spatial resolution of around 90 m × 90 m (the projected coordinate system is used as reference system). For S1, S2, A2, E1, E2, (i) specific buffers are applied to the selected areas and (ii) the Euclidean distance is calculated; for S1 a distinction between villages, towns and cities is made, so that it is applied a marge of the maps before converting to raster file. For the geopolitical datasets, the country map with sub-regional subdivision is exploited, assigning the specific index to each area before converting to a raster. Concerning the technical sub-criteria, no conversion or processing through distances is needed, just a resample to obtain the required resolution could be applied.

The design phase

For this phase, it is required to standardize the obtained maps; a 0-to-1 scale is used, according to a linear function, taking care of the fact that the specific sub-criterion must be minimized or maximized (Table 2). Appendix B reports each sub-criterion—specifically applied to Tunisia—covering the elaboration from the 3rd step, related to data elaboration and maps creation, to 5th step, consisting of standardization; each figure reports: (i) initial map; (ii) intermediate map, if present (here consisting of the application of the Euclidean distance tool); (iii) standardization function to be exploited; (iv) standardized (0-to-1) map obtained.

As following step, to deliver a final suitability map, the experts' preferences are collected to define the proper weightings, at the criteria and sub-criteria levels. Looking at the AHP procedure (Fig. 1), pairwise comparisons are required; to this end, the Saaty's fundamental scale, from

1 to 9, is exploited. Ranging from "equally preferred" to "extremely preferred" options, five experts are involved: (i) an energy engineer, as technical expert; (ii) an urban planner specialized in environmental impact assessment, as environmental expert; (iii) a policy expert involved in energy policy activities and planning to assess the geopolitical field; (iv) an engineer specialized in economic evaluation of energy projects to deal with the economic criterion; and (v) a Ph.D. student involved in sustainable development studies for developing countries, as interested expert in social externalities of new projects development. To practically elaborate the weightings, the software SuperDecisions is used (version 2.10) [117]. Table 3 summarizes the final priorities for criteria and sub-criteria, implemented to elaborate the suitability maps, which constitute the choice phase.

At the criteria level, each expert is interviewed; the final criteria weightings of this assessment reported in Table 3 are obtained through the average of the individual experts' opinions on criteria priorities. Concerning the sub-criteria level, each expert is interviewed concerning her/his domain of expertise, so that for each criterion the weightings associated to the sub-criteria are also determined. In the weighting procedure, through the software calculations, the consistency of the matrices for each expert's assessment is verified (it must be lower than 0.1).

Looking at the final priorities at the criteria level, the significance of the environmental issues to assess the suitability for solar hydrogen production is evident; specifically, for the experts the problem of water availability becomes crucial, as pointed out not only by the prioritization of the environmental criterion, but also by the influence of A1 with respect to A2 at sub-criteria level. The water problem is followed by the technological criterion, prioritizing, as expected, the solar radiation (T1), which obtains a higher weighting with respect to T2. Also, the economic criterion is prioritized through a 20.7%, to recognize the importance of the infrastructure, and it is followed by the social criterion, for which more importance is given to the proximity to urban areas in order to guarantee more opportunities for green jobs. The lowest influence in the assessment is related to the geopolitical aspects; more importance is given to political stability through the sub-criterion G1, in contraposition to the assessment of the regional welfare (G2).

Table 3 Final weightings at criteria and sub-criteria levels

Criterion	Final priorities (criteria level) (%)	Sub-criterion	Final priorities (sub-criteria level) (%)
Society	18.7	S1	75
		S2	25
Technology	22.1	T1	83.3
		T2	16.7
Atmosphere and environmental land	24.8	A1	87.5
		A2	12.5
Geopolitics	13.7	G1	75
		G2	25
Economy	20.7	E1	75
		E2	25

The choice phase

Having set the standardization function for each spatially defined sub-criterion and then properly defined the weightings at the criteria and sub-criteria levels, the choice phase consists of the elaboration of the suitability maps. Specifically, it is calculated a suitability index for each cell of the map according to Eq. (1):

$$\text{Suitability} = S_j = \sum w_i \cdot X_i. \tag{1}$$

S_j is evaluated through a weighted sum function and represents the suitability of the jth cell of the map; it relies on the weight of the ith factor and the standardized score of the ith factor.

Results

The final suitability map is obtained through the application of the weightings introduced in Table 3 on the standardization maps elaborated. Specifically, on ArcGIS is it possible to directly elaborate a suitability assessment, involving both the standardization functions and the weightings procedure, so that the map illustrated in Fig. 4 is obtained working on the suitability modeller [116].

As clarified by the grey areas in the figure, to adequately manage the sub-criteria involved, some specific sites are excluded, according to Table 1. Then, five different suitability classes are defined and associated to different ranges of the suitability index S_j (Eq. 1), from "very low suitability" to "very high suitability".

Through the aggregation at sub-criteria and then criteria levels, the final suitability map shown in Fig. 4 is obtained, with the legend that identifies the different ranges associated to each class of suitability.

As detailed in Fig. 5, the majority of the Tunisian area is assessed as suitable to produce green hydrogen based on solar-powered water electrolysis; the 35.9% is evaluated as highly suitable, while about 4% is assessed as very highly suitable. Moreover, nearly 50% of Tunisia area was excluded because of the constraints considered and only a marginal area of 0.01% of the country is considered of low suitability.

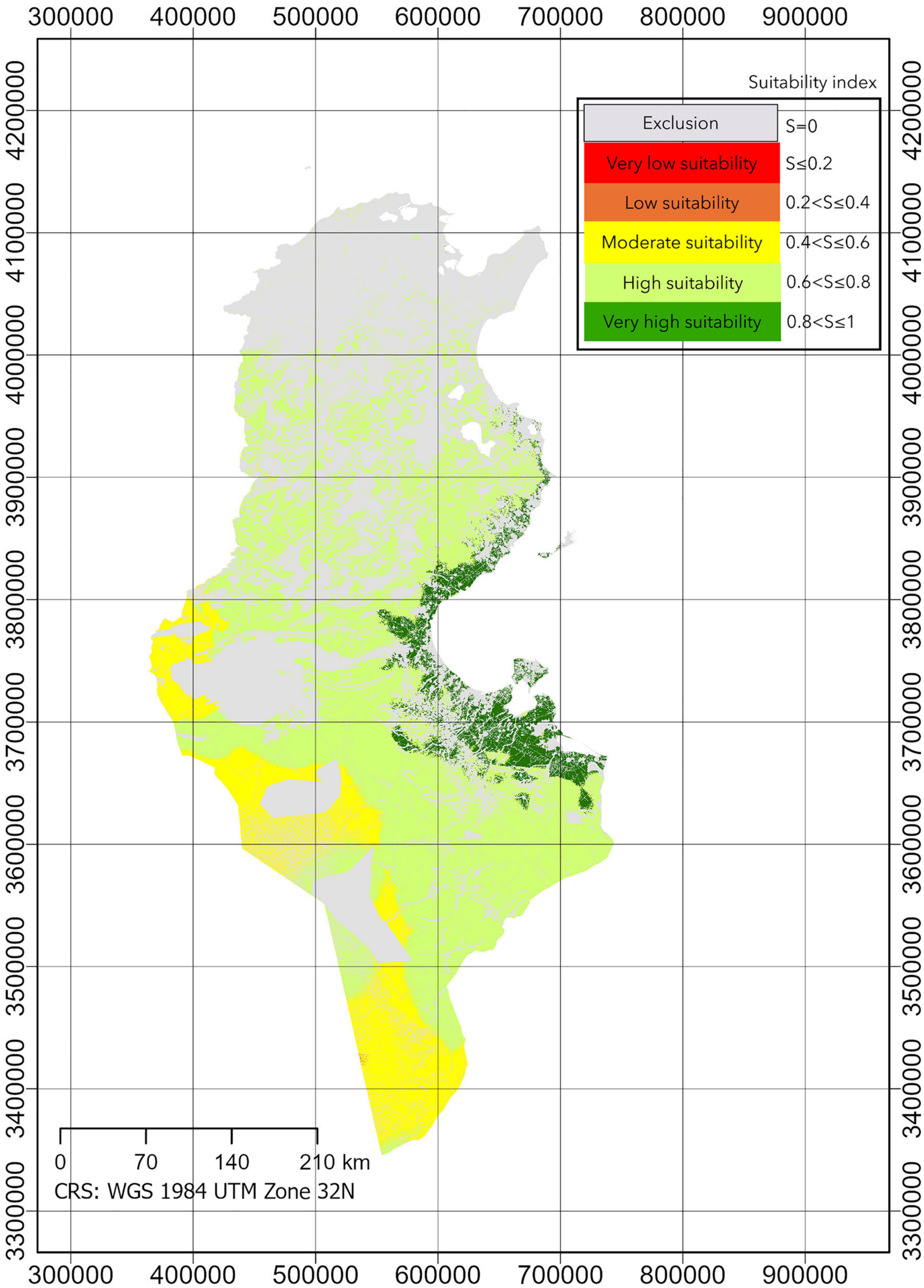

Fig. 4 Tunisia, solar hydrogen: the final suitability map, ranging from exclusion areas to very highly suitable areas

As clarified by the final suitability map (Fig. 4) the results are strongly influenced by the proximity to water (i.e. sub-criterion A1), and also the GHI (i.e. sub-criterion T1) and the proximity to transport infrastructure (i.e. sub-criterion E1). In particular, A1 and T1 perform oppositely for what concerns the South-western part of the country, making those areas moderate suitability. In fact, as expected by the prioritization given to the environmental and technical aspects, the best performing areas are the closest to the coast and with very high solar

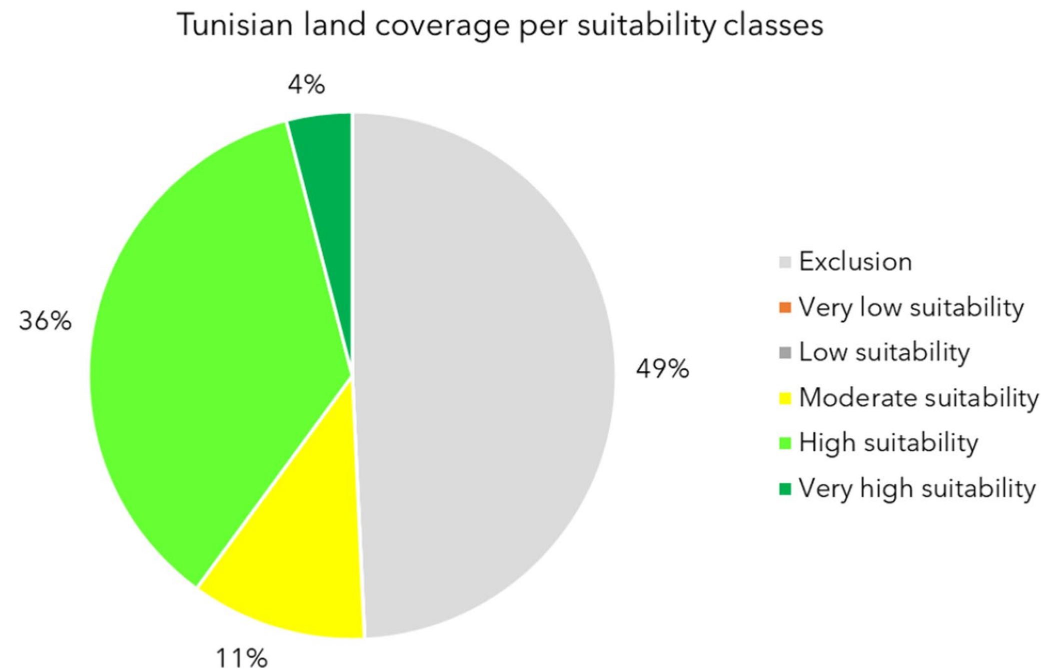

Fig. 5 Tunisia, solar hydrogen: the share of the different classes of suitability

radiation measured. In the following section, results are better investigated and discussed, supported also by a specific sensitivity analysis.

Discussion

The final results highlight the high suitability of Tunisian areas for green hydrogen projects if different multidimensional criteria are addressed. Nevertheless, it is important to consider the influence that the weightings applied to criteria and sub-criteria have on the final results. To test the robustness of the outputs and critically discuss the results, it is useful to conduct a proper sensitivity analysis, which in fact is introduced as last step of the procedure of a MC-SDSS (Fig. 2). In this case, six scenarios are defined, i.e. an equal scenario, assessing an equal weighting of 20% to each criterion, and also an "extreme" scenario for each criterion involved, assigning 60% to the criterion to be extremized (to be equally shared between the two related sub-criteria) and the remaining part to be equally divided among the other criteria and related sub-criteria. Figure 6 summarizes the six different cases introduced.

Figure 7 reports the maps elaborated through the sensitivity analysis. For the equal case, there are no areas classified with very high suitability, neither with very low suitability. The social scenario identifies the majority of the Tunisian areas as moderately suitable, while for the technological scenario the majority of the areas appears as highly suitable, as expected, because of the high availability of solar energy in the majority of the Tunisian areas, especially in the Southern part. For the environmental scenario there are no areas belonging to the moderate suitability class, with the proximity to the coastline (i.e. the sub-criterion A1) making the Eastern side very highly suitable and on the contrary the Western part as low suitable. Concerning the geopolitical case, most of the areas are included in the moderate class, while the extreme economic scenario reflects the pattern of the existing infrastructure, in line with what happens to the extreme environmental case according to the assessment of the proximity to the coastline. Focusing on the geopolitical dimension, it is important to say that the authors would have expected a higher prioritization of this aspect by the involved experts; this dimension represents a crucial novelty of the assessment, making it possible to assess externalities often not considered by renewable projects and their potential failures. If from one side it is found that there is a few awareness on the impact of these externalities on the effective realization of projects, on the other side these aspects are difficult to measure and assess through consolidated values or spatially defined indicators. It is argued the need to elaborate ad hoc indicators allowing a precise detection of political stability and local welfare, as influencing factors for renewable projects development.

As expected, the sensitivity analysis gives the possibility to study the influence of the experts' judgements and the robustness of the results according to

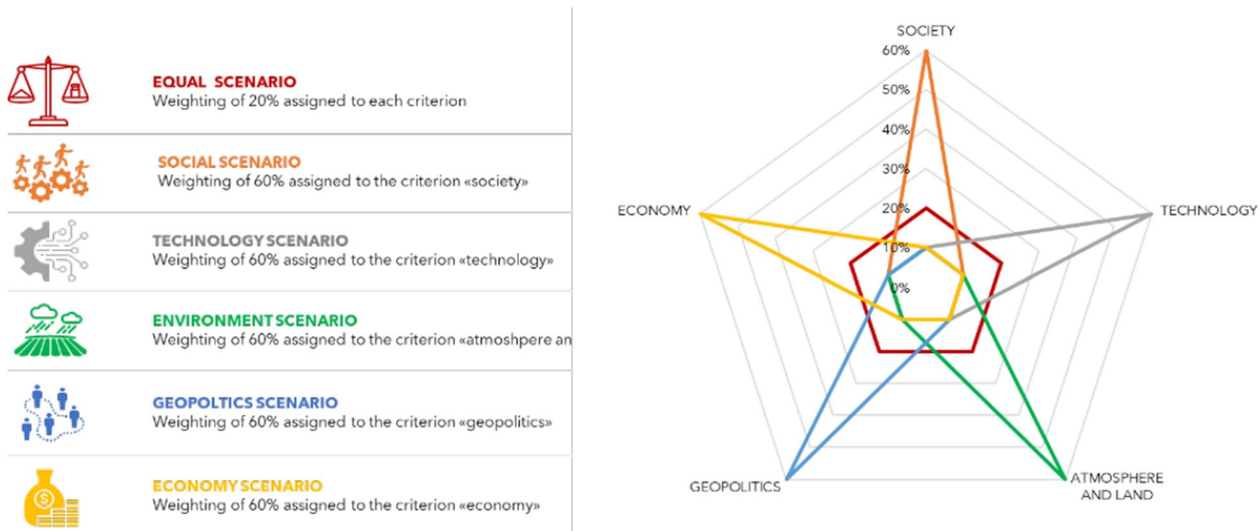

Fig. 6 The six scenarios assessed to conduct a proper sensitivity analysis

the assumptions and criteria involved; it is significant that there are no areas classified as very low suitable, and so, having set that half of the country is potentially available for the solar hydrogen production (49.25% is excluded because of constraints), there are significant portions of the land (i.e. about 40%) high suitable or very suitable for this purpose. Despite the extremization of the criteria, there is still a very high potentiality that can be exploited in Tunisia for solar hydrogen production, confirming the multi-dimensional suitability of this area with respect to the exploitation of this country, even if each specific site can be affected by proper challenges to be addressed.

Among the limitations of the work, it is worth mentioning that different stakeholders at specific levels, involving different resources and categories and supporting specific expectations, must be involved in the assessment as active part of the process, being able to reflect local opinions and addressing the social context of the analysis. By involving more stakeholders and experts, additional factors and aspects could be assessed throughout the analysis, making it possible to select more detailed criteria and impacting on the final results and evaluations. In line with this, also the update of the spatial datasets and their accuracy strongly affect the main outcomes of the study, together with the standardization process. Another important aspect concerns the introduction within the assessment of new sub-criteria; on the techno-economic side, it can be useful to introduce the topic of storage options or also account for specific hydrogen final users, and also mapping temperature or considering the problem of sand for the production plants.

Conclusions

Being aware of the innovation turning point that hydrogen is experiencing, in line with the features and objectives of the energy transition process, it is crucial to develop ad hoc strategic decision support systems able to boost its adoption in the decarbonization scenarios. The opportunities and challenges related to the production and trade of green hydrogen need to be conveniently addressed; this paper proposed a Multi-criteria Spatial Decision Support System able to tackle the multi-dimensionality of the suitability concept concerning energy planning processes. Specifically, it provides the possibility to assess North African countries for the exploitation of solar energy for hydrogen production through water electrolysis. Different experts are involved in defining and prioritizing the spatially measurable criteria and related sub-criteria for the analysis, addressing the social, technical, environmental, geopolitical, and economic aspects. As expected, concerning solar hydrogen production the most influencing factors are high GHI, water availability and proximity to existing infrastructure systems, even if it becomes necessary to consider also social and geopolitical aspects. Here, the Tunisian case is detailed; half of the country (i.e. 49.25%) is excluded according to the exclusion constraints introduced, while 35.9% of Tunisia falls in the "high suitable" range and about 4% in the "very high suitable" one, meaning that the country is very well performing with respect to the multi-dimensional suitability concept introduced for the analysis of the solar hydrogen potential. Moreover, the results of the sensitivity analysis are still in line with the outputs of the final suitability map. Nevertheless, it is important to stress the influence that the experts and stakeholders involved have

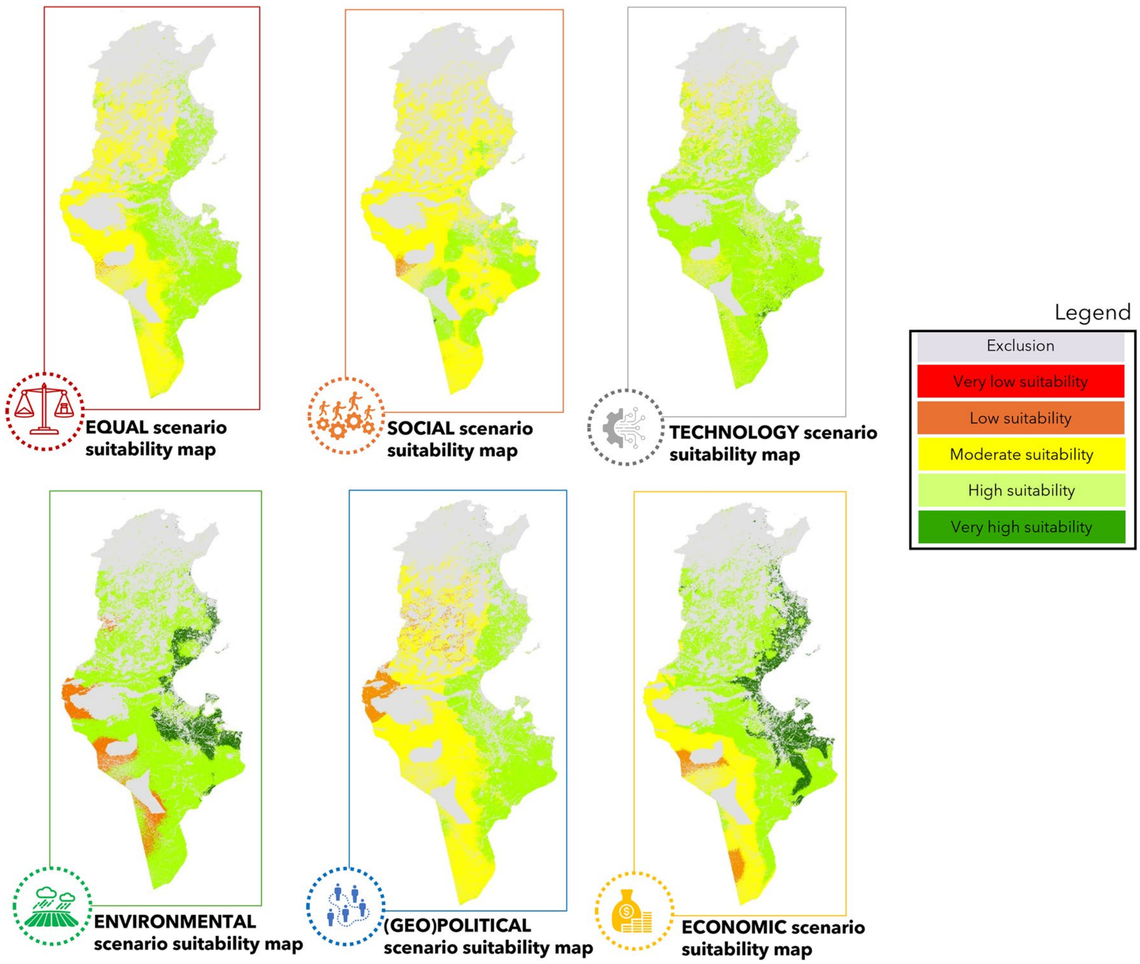

Fig. 7 Tunisia, solar hydrogen: the suitability maps referring to cases belonging to the sensitivity analysis

in the assessments and final results, together with the selection of the exclusion and evaluation criteria mapped.

All the aspects discussed as limitations can be further analysed as future development of the work, to better detail the mapping and offering specific instruments for decision-making processes. It could be of interest to select ad hoc sites which are suitable for satisfying specific hydrogen demands, in order to strategically address projects for hydrogen production and deployment. Moreover, it can be useful to test different methodological procedures (e.g. different approaches for prioritization) to analyse to what extent results are different.

Despite several limitations and the need for future investigations, as main outcome of the analysis it is important to stress that the methodological framework introduced perfectly fits the application to the other North African countries and also other areas of interest. Moreover, just looking at the technical criterion—and specifically changing the T1—it would be useful to make a valuable assessment also for wind hydrogen production, concerning the exploitation of wind resources for water electrolysis.

Being aware of the new significant outcomes that more and different stakeholders can give to this study as further development of the work, the presented article allows to preliminarily apply a Multi-criteria Decision Support System to involve geopolitical criteria, besides the typical techno-economic characterization of assessments for land suitability. If from one side it is undoubted the role of renewable sources and land availability, on the other it is also crucial to assess socio-political externalities that can influence an effective penetration of green hydrogen as crucial player to decarbonize.

Appendices

Appendix A

From Tables 4, 5, 6, 7, 8 the main (i) exclusion criteria, (ii) technical criteria, (iii) economic criteria, (iv) environmental criteria, (v) social criteria related to the multi-criteria decision-making approaches used for PV site selection are summarized, as reviewed by [64], highlighting the frequency of each criterion with respect to the assessments analysed. As already detailed in the text, the technical and economic criteria are the most used within the literature, while the social criteria reviewed are very few and no details on geopolitical aspects are introduced. More details in terms of review can be found also in [65].

Table 4 Exclusion criteria for solar farm site selection, based on [64]

Exclusion criteria
Protected areas and undeveloped areas
Water bodies
Urban areas
Roads
Slope
Solar radiation
Railroads
Vegetation
Unsuitable land uses
Cultural heritage
Forest
Water infrastructure
Community interest sites
Transmission lines
Watercourses and streams
Archeological sites
Paleontological sites
Areas for protection of birds
Rural areas
Settlements
Mediterranean coast
Mountains
Areas of high landscape value
Agricultural areas
Sand dunes
Airport
Religious sites
Touristic sites
Population density
Flood areas
Aspect

Table 5 Technical criteria for solar farm site selection, based on [64]

Technical criteria
Solar radiation
Slope
Aspect
Air temperature
Sunshine duration
Elevation
Humidity
Cloudiness
Distance from water
Distance from dams
D. underground wat.
Land surface temp.
Climatic conditions

Table 6 Economic criteria for solar farm site selection, based on [64]

Economic criteria
Distance from roads
D. from transmiss. l.
D. from resid. areas
Costs
D. from railroads
D. to elec. substations
Pop. Density
Electricity demand
Payback period

Table 7 Environmental criteria for solar farm site selection, based on [64]

Environmental criteria
Land use
Poll. emi. red. benefits
Agrological capacity
Land availability
Ecological damage
Energy saving benefit
Wildlife impact
Visual impact
Noise

Table 8 Social criteria for solar farm site selection, based on [64]

Social criteria
Public support
Impact on local econ.
Policy support
Impact on local tourism
Political risk
Effect on surroundings
Local gov. support
Regulatory boundaries
Resettlement/rehabilitat.
Population
Public security
Impact on local res. life

Appendix B

This appendix details the mapping procedure elaborated working on ArcGIS Pro [116], in order to obtain the final outputs of the intelligent phase (Fig. 2). In the following figures, for each sub-criterion it is reported (i) initial map, (ii) intermediate map, if present (here consisting of the application of the Euclidean distance tool), (iii) standardization function to be exploited, (iv) standardized (0-to-1) map obtained (see Figs. 8, 9, 10, 11, 12).

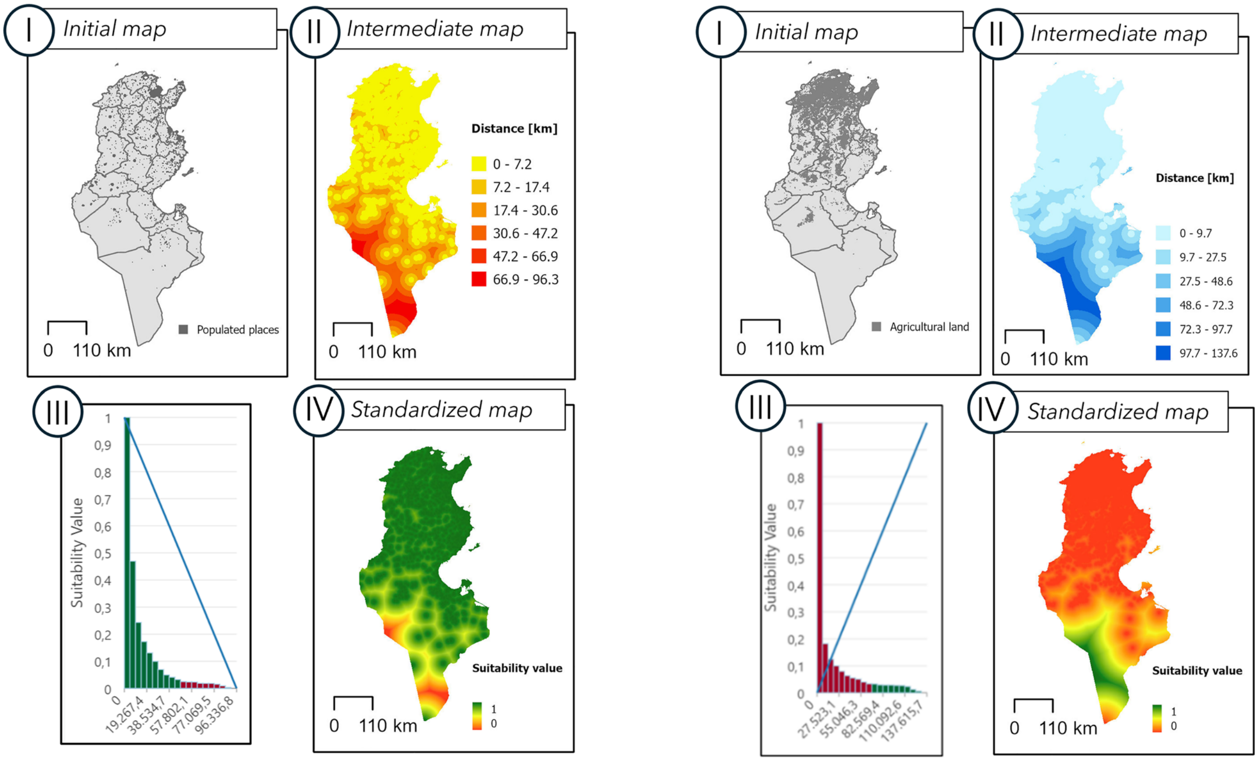

Fig. 8 The social sub-criteria from the initial map to the standardized map, S1 (left) and S2 (right)

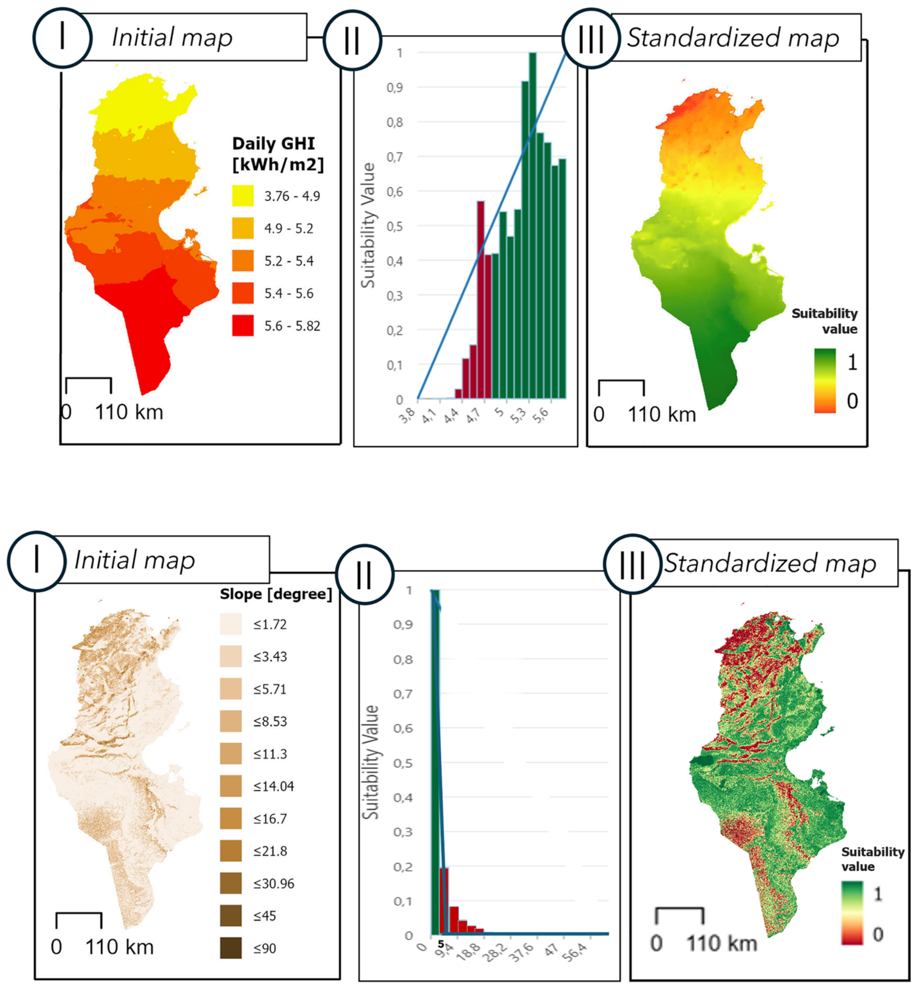

Fig. 9 The technical sub-criteria from the initial map to the standardized map, T1 (up) and T2 (down)

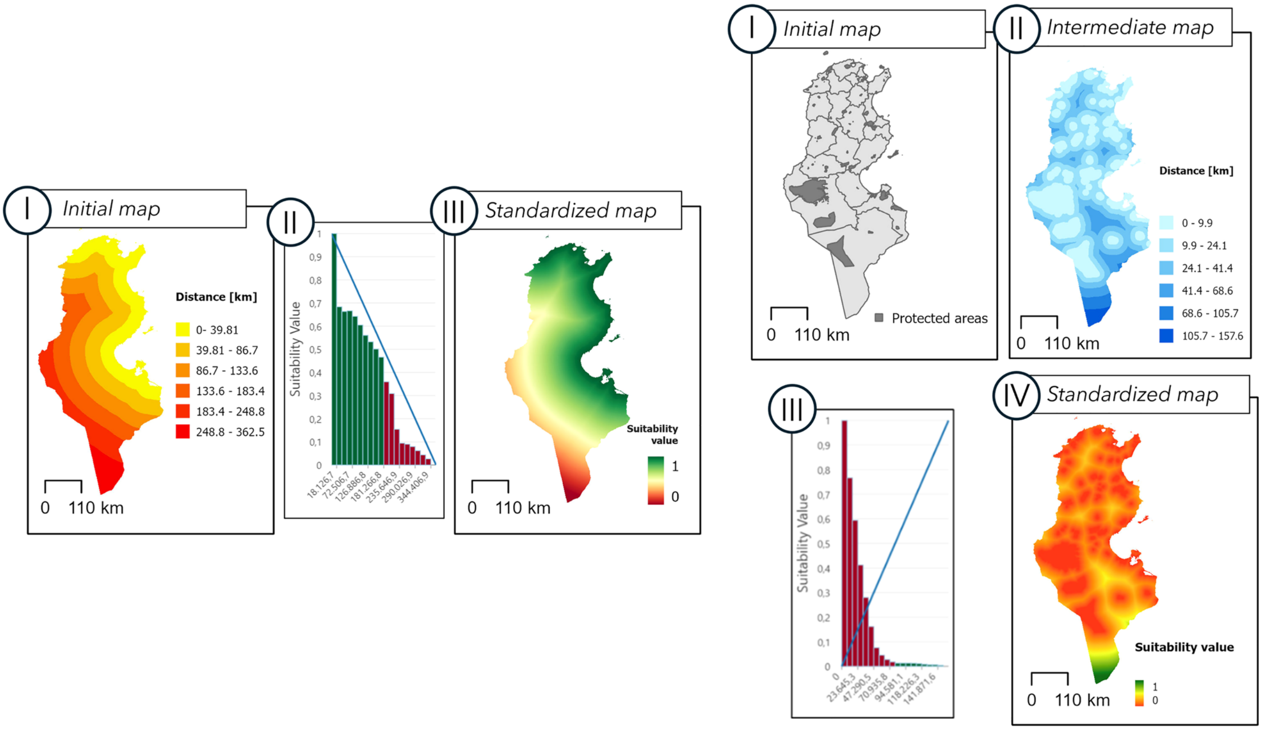

Fig. 10 The environmental sub-criteria from the initial map to the standardized map, A1 (left) and A2 (right)

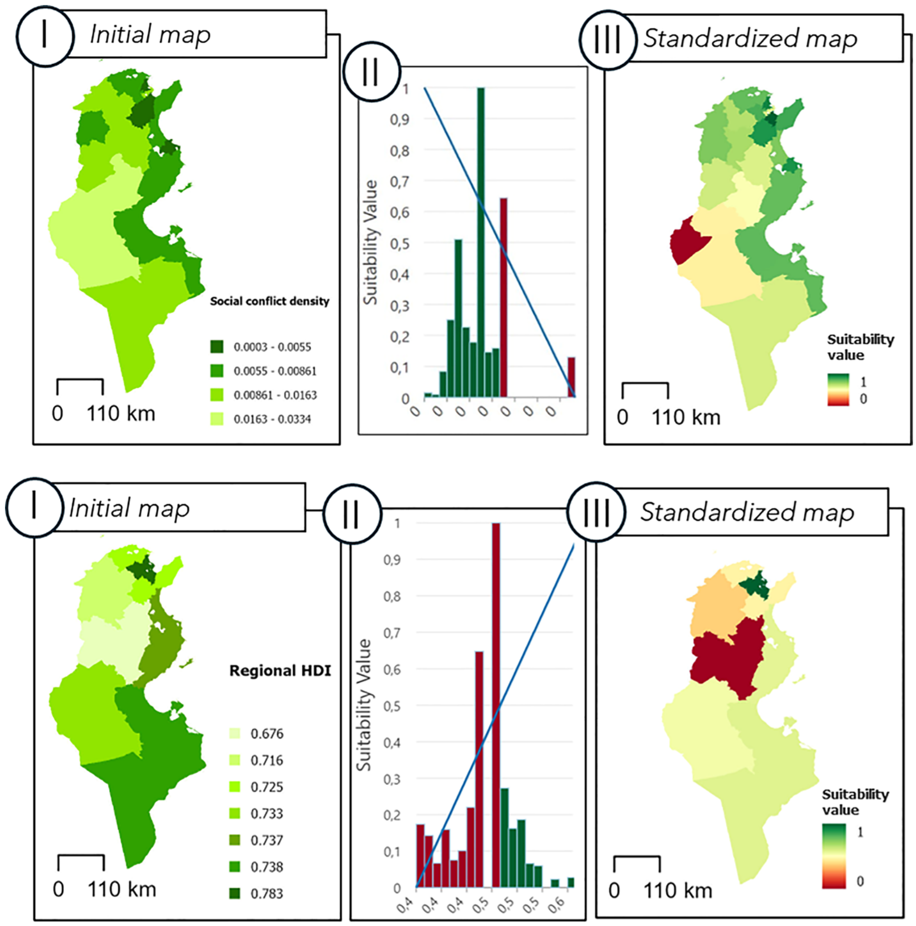

Fig. 11 The geopolitical sub-criteria from the initial map to the standardized map, G1 (left) and G2 (right)

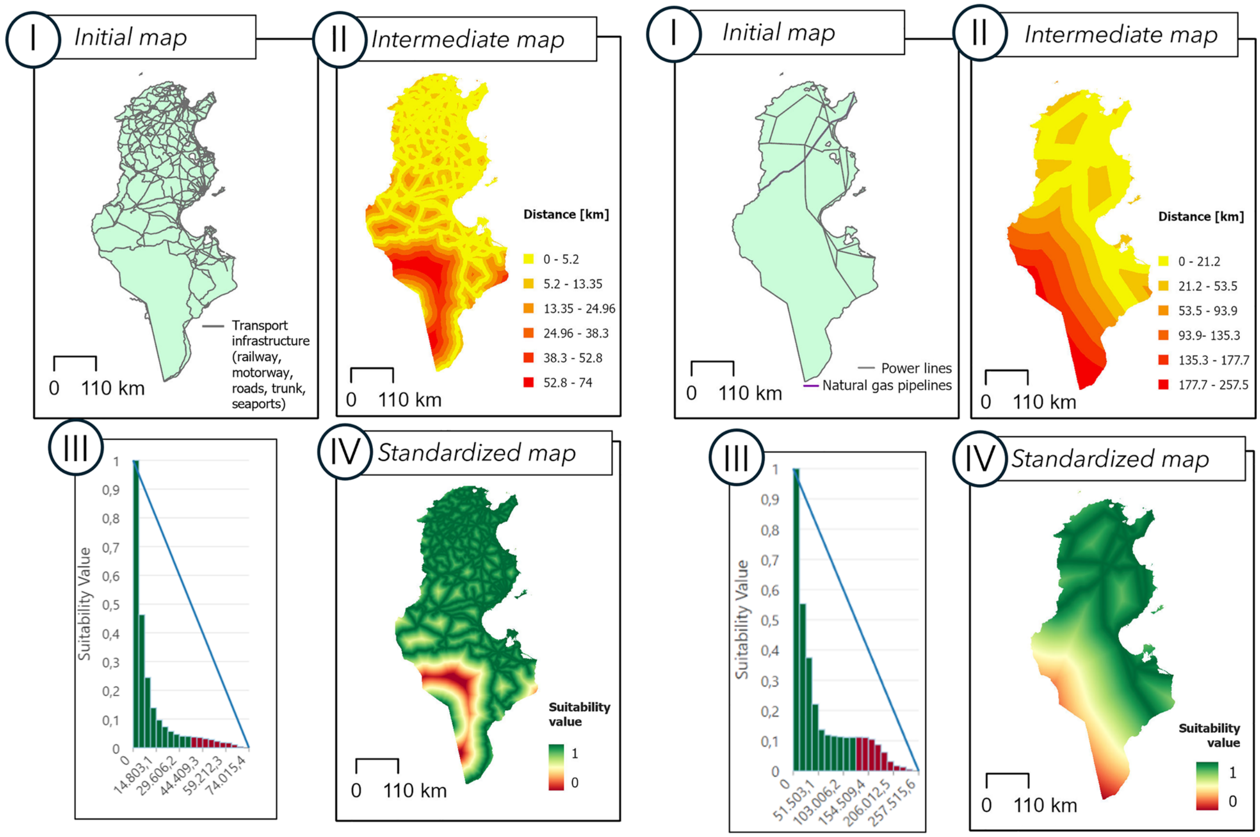

Fig. 12 The economic sub-criteria from the initial map to the standardized map, E1 (left) and E2 (right)

Abbreviations

ACLED	Armed Conflict Location & Event Data Project
AHP	Analytic hierarchy process
CCS	Carbon capture storage
CCU	Carbon capture usage
DEM	Digital elevation model
ELECTRE	Elimination and choice translating reality
ESRI	Environmental System Research Institute
GADM	Global Administrative Areas
GHI	Global horizontal irradiation
GIS	Geographic Information System
HDI	Human Development Index
HOTOSM	Humanitarian OpenStreetMap
IEA	International Energy Agency
MCA	Multi-criteria analysis
MCDM	Multi-criteria decision method
MC-SDSS	Multi-criteria Spatial Decision Support System
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
SRTM	Shuttle Radar Topography Mission
SWOT	Strength weakness opportunities and threats
TOPSIS	Technique for order of preference by similarity to ideal solution
UNDP	United Nations Development Programme
WDPA	World Database on Protected Areas
WFP OSM	World Food Programme OpenStreetMap

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Author contributions
P.M.C.: Investigation, resources, methodology, software, writing—original draft, writing—review and editing, visualization. A.E.: conceptualization, methodology, writing—review and editing, supervision. G.M., B.P., C.S.P.: conceptualization, methodology, supervision.

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Availability of data and materials
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Declarations

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Interviewees have consented to contribute to the analysis.

Consent for publications
Not applicable.

Competing interests
The authors declare no competing interests.

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