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Energy for the future: Planning and mapping renewable energy. The case of Algeria

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ABSTRACT

An open-access software and open geospatial data are used to assess, map and undertake a preliminary examination of Algeria's potential for setting individual or combined wind and photovoltaic solar farms. In order to carry out the analysis, a locational model has been built and implemented. Results indicated that 97% of the Algerian territory is found unsuitable for the location of wind and PV power plants. However, although most restrictive criteria have been applied, there are still numerous areas with high potential in Algeria (25,377 km^2 have potential for wind plants, 13,485 km^2 for the construction of solar plants, and 11,199 km^2 for both). These areas should be subject to more detailed studies in the future. The elasticity and iterative nature of the designed model allows to generate potentiality maps for various scenarios, pointing out areas where an extension of the electric grid would greatly increase the potential of the Algerian territory for the construction of RE plants.

Introduction

From the 1970s onwards, various sustainable development targets have led to the design of national and supranational strategies to achieve them. Particularly relevant strategies are: the international agreement to reduce the emission of greenhouse gasses [1], the formulation of a common environment and energy policy in the EU [2], the Paris Agreement [3] and the 2030 Agenda for Sustainable Development [4]. In all of them, renewable energy (RE) has been presented as one possible way to reduce greenhouse gas emissions while keeping up with energy demands. This commitment for RE has led to ambitious targets being set for the construction of RE plants. For instance, the EU's current target is for 32% of all energy consumed within it to come from RE sources by 2030 [5].

The importance of RE in meeting greenhouse gas reduction targets in combination with the information technology revolution in the last decade has resulted in the publication of an increasing number of works that analyse the potential of different regions for the construction of RE plants [6,7]. The majority of these works use geographical information that represents incompatibility criteria or potentiality factors, processed with Geographical Information Systems (GIS) in combination with Multi-criteria Decision-Making methods (MCDM). Other works have examined the suitability of the MCDM methods implemented by these studies. For example, in [8] 300 research articles published between 1990 and 2004 was assessed. In [6] 105 papers – in the Web of Science Core Collection – on energy sustainability issues and MCDM methods published between 2004 and 2017 were analysed. More recently, [7] based their work on a review of the existing literature concerning the application of MCDM methods in the field of sustainable engineering. According to these documents, several conclusions could be obtained from this literature review:

- The number of articles that aim to identify optimal locations for the construction of RE plants has increased substantially in recent years, encouraging researchers to improve on available knowledge to assist decision-making processes.
- Most studies use GIS software and open-access geospatial information produced by local planning and management bodies. Few use open-access software [9,10], and even fewer use spatial relational databases [11]. The use of spatial relational databases increase replicability of the analyses for experts, but it requires advanced spatial modelling and database-language knowledge, which hampers replicability and traceability for non-expert uses.

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- Concerning MCDM, the chosen method can have a significant effect on decision-making processes [12]. In general, in the field of RE, analytical hierarchy method developed by Saaty AHP [13] and the analogous Fuzzy AHP have been widely used [14–24].
- Assessments for identifying and mapping areas of high potential for RE sources are usually focused on one type of plant rather than assessing the individual or combined potential of two or more RE plants or hybrid plants (RE-Fossil fuels). In this field, the work undertaken by [25–27] can be highlighted.

From the point of view of the geographical data required to undertake these analyses, the information technology revolution has allowed for vast amounts of geographical information to be generated by planning and management bodies. Often, this information is freely available on open internet portals. For some regions, however, the information is neither available nor freely accessible. These shortcomings can often be overcome by using internet portals maintained by international bodies that distribute geographical information on a global scale. Especially outstanding among these are global GIS datasets, which include cultural and physical vectors such as Natural Earth Data [28] and OpenStreetMap [29], as well as other, more specific, tools such as Global Forest Watch [30], the UN's MapX [31] and the UN Biodiversity Laboratory [32].

More specifically, oriented towards resource assessment (wind speed, radiation maps, etc.), there are several works worldwide that provide freely accessible data for carrying out the necessary analyses, such as SOLARGIS [33], the Global Wind Atlas [34], the Global Solar Atlas [35] or other analysis carried out by researchers at the Joint Research Center [36–38]. Although the use of this information presents many opportunities, it also poses challenges [39–41]. These are principally related to the use of complex formats, different resolutions and coordinate systems. This sometimes makes the information difficult to manage, and specific knowledge of geodesy is often needed to normalise and homogenise the data. These data sets vary in resolution, quality, and usefulness, depending on the application.

Recent developments in tools have improved the way RE sources at a particular location are assessed and analysed. Some examples are: the implementation of new analytical functionalities in GIS software; the development of open-access software, which makes powerful software tools such as QGIS [42], gvSIG [43] and SAGA [44] freely accessible; and the migration of analysis to open-access relational databases, such as PostgreSQL/PostGIS [45], which have the ability to analyse and manage in detail large amounts of geographical data.

On the other hand, the Algerian economy is strongly dependent on fossil fuels and during the last decade, the market price of crude oil has fallen down drastically which have severely affected the national economy [46]. In addition, the electricity consumption has been risen in recent years in line with the growth of the population [47]. Approximately 90% of the electricity in Algeria is mainly being produced from the natural gas power plants [46,48]. The need to reduce the production of GHG, the Algerian government has been promoting RE in the country since 1998 [47].

The aim of this study is the use of open-access software and open geospatial data to assess, map and undertake a preliminary examination of Algeria's potential for setting individual or combined wind and photovoltaic solar farms. In order to carry out the analysis, a combined MCDM and GIS locational model will be built and implemented. This model is designed and developed with open source software and using free and open access data that have been standardised in terms of raster resolution and reference systems. Both points are fundamental, especially in territories where access to geospatial information is difficult and rarely available.

Although there are studies that analyse and map the existence of wind and solar resources for Algeria [49–57], the selection of suitable areas for wind or solar deployment requires taking into account other specific criteria than estimation of the resource potential, avoiding as much as possible, the potential negative impacts for the environment and population [11] . References for the entire study area that incorporate other territorial restrictions are scarce. The analyses carried out for concentrating solar power [58] and photovoltaic solar energy [59] stand out. Similarly, analysis of wind energy and PV-wind combination, has not been developed in the study area before.

This work conducts a baseline study for Algeria in order to provide needed information for future RE development. Many studies were conducted by several researchers monitoring challenges for solar and wind energy including passive air pollution [60], deposited dust [61], aeolian activities in the specific area [62], sand blasting due to loss of native vegetation [63] and radionuclide's [64], following a useful methodology to assess establishment of any future sustainable energy stations [65]. Monitoring aeolian sand and dust quatities properties are essential before establishing any future wind and/or solar energy units in desert areas [66]. Aeolian activities monthly results, show significant differences from location to location [67–68]. There is no geographic information available for the whole Algerian territory, linked to the aspects mentioned above, as well as others. This study can serve to locate specific areas where to prioritise efforts and money in a second phase, where these criteria and other methodologies must be taking into account.

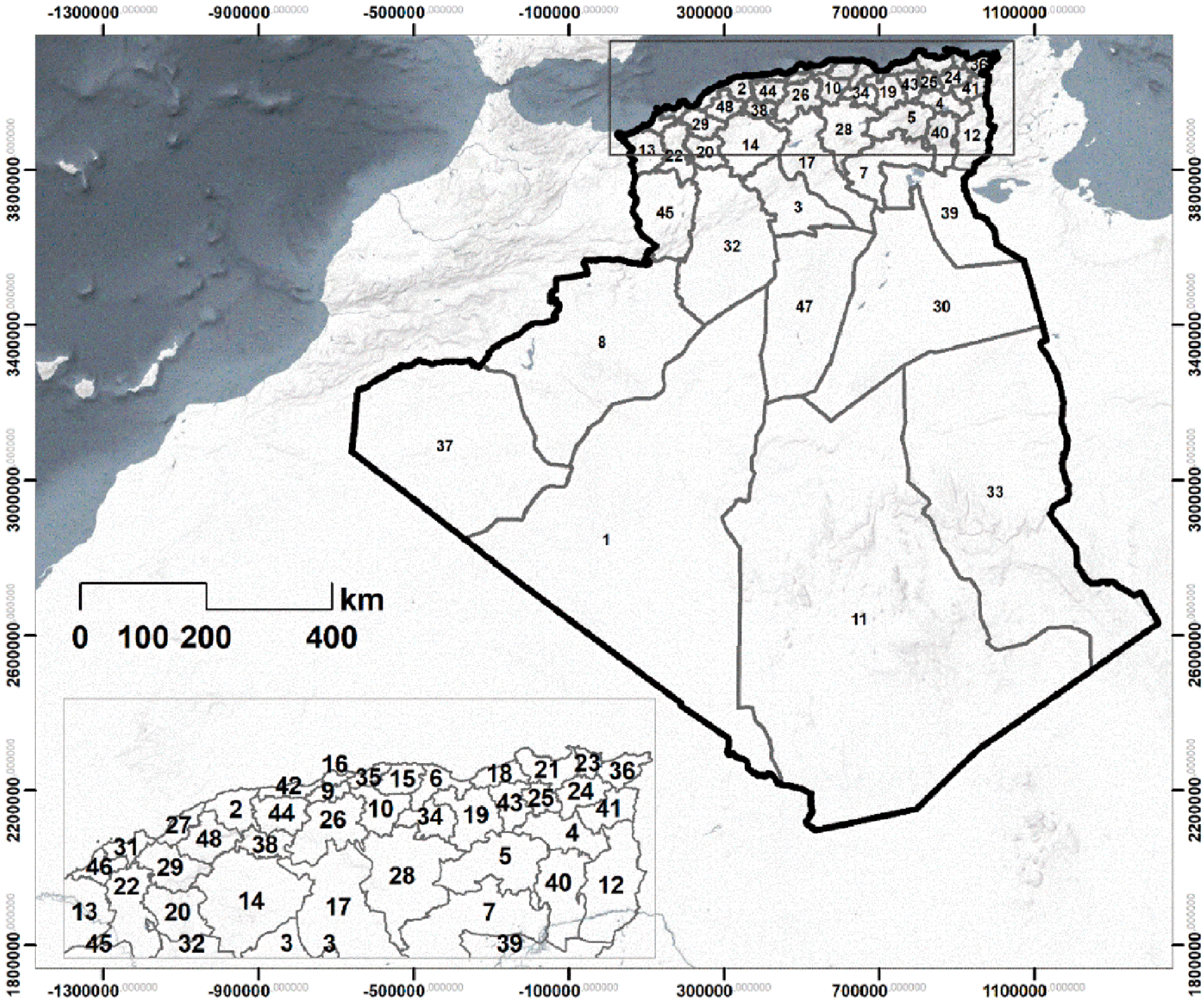
Study area

Algeria was selected as a case of study (Fig. 1), because this country is currently implementing an ambitious programme to promote RE: The National Plan for Renewable Energy 2011–2020 [69]. Initially, the objective of the plan was to reach 11.000 MW of RE by 2030 but in 2015, the Algerian government updated the 2011–2020 program, envisioning the installation of 22,000 MW of RE by 2030 [70], (see Table 1). The main aim of the RE programme is for approximately 27% of total electricity production by 2030 to have an RE source [69].

According to this programme, the main RE source rate will be photovoltaic energy, followed by wind energy. The input of both will increase substantially, especially during the second stage of the programme (2020–2030). It is planned that, by 2030, these two sources will account for 84% of all energy produced with RE sources [69]. The Algerian company SKTM is responsible for installing the RE program. In 2018, around 354 MW was installed for PV and 10.2 MW for wind energy. In five last years, only a small amount of the total program was realised [71].

The program of 22 GW was decreased to 16 GW with same objectives and extended to 2035. Recently, the government launched a big project named TAFOUK1to install 4000 MW of PV for the period 2015–2020 [72]. These ambitious targets are grounded in Algeria's well-known potential for RE, especially solar and wind energy [69]. Moreover, Haddad et al. [19] evaluated different renewable energy options for case of Algeria using MCDM, both solar and wind power were ranked as the best alternatives. For these reasons, both these options were selected to be analysed in our study.

Although these plans should be formulated on the basis of intense assessing, planning and mapping of areas with RE potential, only references to the localization of wind farms and photovoltaic solar farms in Algeria has been found in the existing literature. This could be due to two factors. First, some geographical information for the area does not exist or is difficult to access. The Algerian National Institute for Cartography and Remote Sensing was created in order to generate, compile, develop, preserve and disseminate geographical information [73] although the bulk of the data is not currently available online. Second, Algeria is a large country, which hampers detailed analysis since managing large datasets requires significant technical capabilities. Algeria is the largest country in Africa, with an area of more than 2 million km^2, divided into 48 provinces. Two-thirds of the country is covered by desert [74], and it has a population of 43 million – as of January 2019 [75] – most of whom live in the northern regions, where



N.	Province	N.	Province	N.	Province	N.	Province	N.	Province
1	Adrar	11	Tamanrasset	21	Skikda	31	Orán	41	Souk Ahras
2	Chlef	12	Tébessa	22	Sidi Bel Abbès	32	El Bayadh	42	Tipasa
3	Laghouat	13	Tlemcen	23	Annaba	33	Illizi	43	Mila
4	Oum El Bouaghi	14	Tiaret	24	Guelma	34	Bordj Bou Arréridj	44	Ain Defla
5	Batna	15	Tizi Ouzou	25	Constantina	35	Boumerdès	45	Naâma
6	Béjaia	16	Argel	26	Médéa	36	El Tarf	46	Ain Temouchent
7	Biskra	17	Djelfa	27	Mostaganem	37	Tindouf	47	Ghardaïa
8	Béchar	18	Jijel	28	Msila	38	Tissemsilt	48	Relizan
9	Blida	19	Sétif	29	Muaskar	39	El Oued		
10	Bouira	20	Saida	30	Ouargla	40	Khenchela		

Fig. 1. Study area. Source: Author's elaboration and EOX::Maps.

population density and energy demands are very high.

This study will serve as a basis for further studies, not only in Algeria but also in other countries which suffer from similar information-accessibility issues. Open data and open-access software were used in order to facilitate replicability and reliability.

Table 1
Stages and targets for RE production in Algeria.

	2015–2020 (MW)	2020–2030 (MW)	Total (MW)	Total (%)
Photovoltaic (PV)	3000	10,575	13,575	61.70
Wind power	1010	4000	5010	22.77
Concentrated solar power (CSP)		2000	2000	9.09
Biomass	360	640	1000	4.55
Cogeneration	150	250	400	1.82
Geothermal	5	10	15	0.07
Total	4525	17,475	22,000	

Source: Algeria Ministry of Energy Program.

Material and methods

The methodology followed for analyse the Algeria's potential for the installation of wind and solar farms, is divided into two stages: 1) Identification of unsuitable areas and 2) Characterisation of suitable areas.

The software QGIS [42] has been used to carry out the calculations, analysis and spatial representation of the information. QGIS allows, from its interface, to take advantage of several functionalities of other geographic information systems or libraries such as GRASS [76], SAGA [44] or GDAL [77].

Also, the use of QGIS software ensure replicability because this tool is both open access and user-friendly, and its latest versions include the necessary raster analysis tools for calculations

Identification of unsuitable areas

Establishing unfeasibility criteria

In order to map unsuitable areas, incompatible criteria were firstly established. This process involved a thorough literature review to identify a set of unsuitability criteria as presented in Table 2. However, as a result of the significant advances in the field in recent years, only those works published within the past 10 years were taken into account.

Some criteria collected in Table 2, cannot be applied owing to the lack of good-quality spatial information. This could lead to unsuitable areas (cultural-heritage concerns, the presence of inundation areas, military areas, electricity network capacity, geological characteristics as faults, plane rocky terrain, etc.) being regarded as suitable. Although other studies dealing with regions which have similar restrictions to information select specific areas for the installation of the plants, when the scale and extend of the territory under consideration are taking into account, this is not advisable and could lead to errors and problems further down the process. Similarly, as illustrated by Table 2, no consensus exists concerning the degree of restrictions to be applied to each criterion. In this study the most restrictive model is adopted, which guarantees that results will highlight the most suitable areas in the worst-case scenario but ensuring that these areas comply with the maximum restriction applied. For all these reasons, the results must be regarded as preliminary, but the suitable areas identified in this study should be given priority in future studies, where criteria that could not be taking into account at this level of analysis, must be studied in detail. This is the potential of this work, to be able to prioritize where to carry out these studies in a territory of more than 2 million square km, optimizing time and resources.

The final selection of criteria and restrictions are presented in Table 3. Table 3 shows that most suitability criteria are based on economic reasons (E). Steep areas, for instance, demand substantial initial investments and involve high maintenance costs. Other criteria aim to protect the environment (EN) and the local population or its activities (P). Some criteria, however, combine economic efficiency and environmental protection variables, for instance proximity to the electric grid (plants located more than 10 km away from the grid would lead to energy and economic loses, and the construction of new branches of the grid would lead to environmental damage).

Table 2
Unsuitability criteria for the construction of wind and solar farms.

	Wind	Solar PV
Slope	Slope >30% [78]	Areas with the most pronounced slopes [10,16,24] >3% [79] >10% [59] >25% [80]
Altitude	>1500 m [81]	–
Faults	<500 m [82] <200 m [83]	
Resource	<4.5 m/s [84] <6 m/s [85]	<1650 kWh/m^2 [86] <1700 kWh/m^2 [79]
Road network	<500 m from motorways and highways, other roads and footpaths [82,87–88]	>20 km [86] Unsuitable [27]
Electric grid	Electrical network < 100 m [27,78]; <250 m [82,88] >10 km [27,81]	>10 km [27] >20 km [86]
Protected areas	The entire surface and 2 km distance from these areas [87]	Unsuitable [79]
Rivers, bodies of water	<50 m [78]	<50 m >15 km from rivers [86] >25 km from swamps [86]
High-potential agricultural areas	<250 m from these areas [89]	Unsuitable [16,24,27]
Population centers	Cities and main population nuclei <500 m Rural villages and buildings <250 m [27] <2 km from major cities [82,87–88]	Unsuitable, except in industrial districts [16,27]
Cultural heritage	<1000 m from asset of cultural interest [88]	Unsuitable [27]
Forested areas	<250 m [90]	Unsuitable [16,27]
Fluvial inundation areas	Fluvial inundation areas to be considered unsuitable for a period of 100 years [91]	
Airports, landing strips	2.5 km from airports [92] 25 km from airports [88]	For safety reasons, areas located near airports are to be avoided [93]
Military areas	<600 m from military areas [82]	Unsuitable [16–17]

Source: Author's elaboration.

Calculating unfeasible areas

Once incompatibility criteria have been identify, they were calculated and mapped All the sources used are open access and can be downloaded for free. Following, a process of normalization have been developed. This process involves the assessing the quality of the information, transform it into the same reference system and into the same spatial resolution. This is an important step in this kind of analysis and should be clearly stated as it directly influences the results. However, the existing literature often does not even mention the reference system used, which is crucial in this type of analysis, especially when dealing with very large study areas, which may be subject to different geographical uses, given that it may affect the calculation of areas. This is the case of Algeria, where territory is included in uses 29, 30, 31 and 32. All spatial data were adjusted to UTM Z31N.

Equally important is to adjust all data to the same spatial resolution, to avoid errors in the calculation of areas. A common minimum resolution of 100 m × 100 m was adopted.

Basically, four parameters have been used in this phase:

1. *Slope, aspect, curvature* (SAGA): From the Digital Elevation Model (SRTM) it is possible to calculate the slope of a territory. This can be done with different functions. However, given that the slope in

Table 3
Selected unsuitability criteria for the installation of wind and solar farms.

	Wind	Solar PV	Reason	Source of the spatial data
Orography	Slope >30% [78] Altitude >1500 m [81]	>3% [79]	E	Digital elevation model of NASA Shuttle Radar Topographic Mission (SRTM). 90 m at the Equator Hole-filled SRTM for the globe: version 4: data grid [94].
Resource	< 6 m/s [85]	<1700 kWh/ m^2 [79]	E	Average wind speed: Global Wind Atlas (GWA 3.0) at 100-m altitude. Resolution: 0.0025 last version feb 2020 [34] Global horizontal irradiation: Global Solar Atlas 9 arcsec (nominally 250 m) last version feb 2020 [35]
Road network	< 500 m from road network [82,87,88] >20 km [86]		E, P and EN	Digital Chart of the World [95], comprehensive 1:1,000,000 scale and an extraction of roads from OpenStreetMap data made by WFPGeonode [96]
Electric grid	Electric grid < 250 m [82,88] >10 km [27]		E and EN	World Bank [97], and electricity-grid data on Algeria from the Algerian Ministry of Energy and Mining [98]. The electric grid (lines and substations) has been digitised.
Protected areas	The entire surface and 2,000 m distance from these areas [87]	Unsuitable [79]	EN	World Database Protected Area and digitisation from Google Maps [99]
Rivers, bodies of water	<50 m [78]	>15 km from rivers [86] >25 km from swamps [86]	E and EN	Global Lakes and Water Database [100]; International Steering Committee for Global Mapping [101]
Agricultural areas	<250 m from these areas [89]	Unsuitable [16,24,27]	E	Global Land Cover-SHARE database (2014) GLC-SHARE - Trees covered area GeoTIFF format in the World Geodetic System 1984 (WGS 84) coordinate system of 30 arc-seconds (~1 sq.km) [102]
Population centers	Unsuitable <2 km from villages or cities [82,87–88]	Unsuitable [16,27]	P and E	Population density for each 100 m × 100 m grid square [103–104]
Forested areas	<250 m [90]	Unsuitable [16,27,79]	E	Global Land Cover-SHARE database (2014) GLC-SHARE - Trees covered area GeoTIFF format in the World Geodetic System 1984 (WGS 84) coordinate system of 30 arc-seconds (~1 sq.km) [102]
Airport	25 km from airports [88]	For safety reasons, airport areas are avoided [93]	P	Shapefile from International Steering Committee for Global Mapping and The National Institute of Cartography and Remote Sensing, Algeria [101]

Source: Author's elaboration.

percentage is needed, this function has been used.

2. *r.grow.distance* (GRASS): By means of this function, the euclidean distance to roads, electricity network, rivers, population centers, agricultural areas, airports and protected areas has been calculated. However, any distance analysis in QGIS, needs the input layers to be raster, therefore, vector files have to be converted to raster. This is one of the disadvantages of QGIS compared to proprietary software such as ArcGIS, which allows distance calculation from vector data. To do this, the *Rasterize* function (SAGA) has been used. This function offers more analysis possibilities and allows assigning a desired cell size.

3. *r.reclass* (QGIS): This function creates a new map layer, whose category values are based on a reclassification of the categories of an existing raster layer. Thus, all pixels have been reclassified to assign values of 0 to the unsuitable and 1 to the suitable ones.

4. *Raster calculator* (QGIS): This function allows you to perform algebraic operations with the different rasters. By means of this tool, incompatibility criteria maps were combined (by multiplication with each other) to generate a map of suitable/unsuitable zones (Eq. (1)).

$$U_{(0,1)=}\left(Ui_{(0,1)}*\cdots*Un_{(0,1)}\right) \quad (1)$$

where $\boldsymbol{U}_{(0,1)}$ = final incompatible values, and Ui-n, incompatible value for each criterion.

In addition to these, the *raster layer value report* function (QGIS) has been used to calculate statistics, since this algorithm returns the total number and area of each unique value of a given raster layer

Characterisation of suitable areas

Identifying and calculating suitability criteria

In order to identify and characterise suitable areas for the construction of wind and solar farms in Algeria, that should be the focus of more detailed studies, three experts in the installation of this sort of plant and one expert in the study area were consulted.

Following Díaz et al. [27], five suitability factors were taken into consideration for both (wind and PV): distance to the electric grid, distance to population centers and to the road network, the slope, and the availability of wind and solar resources.

Concerning the electric grid, in some cases, the remoteness of wind/solar plants from the grid connection points seriously compromises the profitability of the project, making projects with good resource quality and little or no environmental problems as unfeasible. The mere presence of an electrical grid does not guarantee the possibility of implementation RE facilities, since this depends on the grid's capacity to evacuate the energy. It is often difficult to find geospatial data on the layout of these networks, due to the economic, social and environmental implications that these infrastructures have on the territory. However, the need to avoid the environmental impact of building new power lines (which could have negative environmental repercussions in the area), and to avoid transmission losses, makes the proximity to the existing electrical grid the best available factor.

Areas closest to population centers and activities related to the population (once these are protected from the possible negative impacts derived from the excessive proximity of these plants) are considered to have greater potential, due to the interest of countries in investing in distributed generation (DG). The fact that the generation areas are located close to consumption centers also reduces the size and number of power lines that must be built and maintained in good condition, as the proximity to the centers of consumption will prevent the loss of energy through transport.

Concerning the road and railroad network; the construction of new lines generates economic and environmental costs, which are to be avoided. Finally, steep slopes should be avoided in order to reduce construction costs and the geomorphological impact of construction [27].

Distances map to the electric grid, road network and population centers were measured on the last section. Also slopes and the geographical representation of wind and solar resources were calculated. Following, suitable areas were scored from 1 to 5 based on five distance intervals, calculated by quantiles. That is, areas within the top

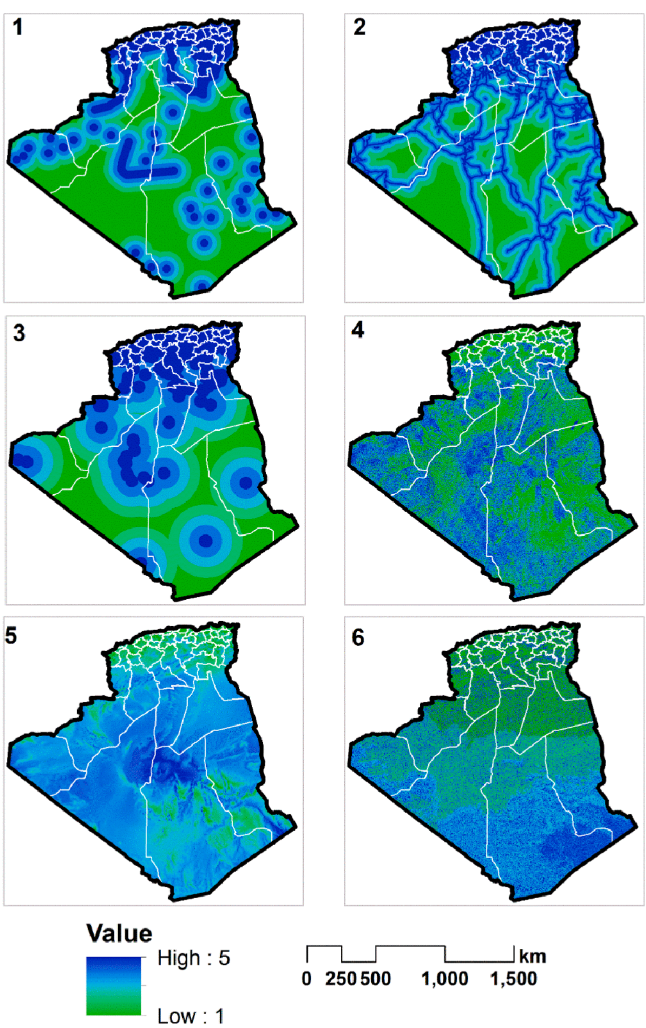


Fig. 2. Suitability factors. 1. Electric grid; 2. Road network; 3. Population centers; 4. Slope; 5. Wind resources; 6. Solar resources. Source: Author's elaboration.

20% of scores were assigned a value of 5 (see Fig. 2).

The meetings with the experts resulted in a number of interesting points:

1) Concerning solar power, south-facing areas were considered more suitable [16,27,105].

Orientation was calculated through the digital elevation model of the study area. Following orientations values were assigned a score from 1 to 5; south orientations were assigned a score of 5, some SE and SW orientations a score of 3, and the rest a score of 1. The resulting map was multiplied by the radiation map, and normalised to a scale from 1 to 5. The areas within the top 20% of scores were assigned a value of 5.

2) The experts were asked about the possibility of weighing criteria. In order to do this, Saaty's analytical hierarchy's method was used [106,107]. This method is widely used for the selection of suitable locations for the location of RE plants. It is based on the pairwise comparison of factors, each of which is associated with a value on the Saaty scale. The Saaty scale goes from 1 to 9; a value of 1 means that two factors are equally important, and a value of 9 denotes extremely important. As such, a 1/9 relationship indicates that one factor is considerably less important than the other. Finally, the comparison matrix measures robustness in expert bias in terms of the consistency ratio, Cr [107–108]. If $Cr > 0.1$, judgements are inconsistent, and the analysis must be repeated.

On three occasions, the experts made judgments on the importance of factors that proved to be inconsistent ($Cr > 0.1$), and agreement about the relative importance of one factor over another proved impossible. This is also reflected in the existing literature, where it can be observed that weights assigned to different criteria vary significantly.

While Aly et al. [79] assigned greater importance to the solar resource (irradiation) (69.6%), accessibility (22.9%) and distance to population nuclei (7.5%) for the photovoltaic plant, Al Garni and Awasthi [105] assigned the solar resource (irradiation and temperature) a weight of 0.587, the slope a rate of 0.159, accessibility a rate of 0.078 (electric grid and road network) and proximity to population nuclei a rate of 0.070. Contrary, Díaz et al. [11], based on the fact that the whole study area presents high solar-radiation values, decided not to prioritise solar potential, with proximity to the electricity grid being the weightiest factor.

For these reasons, and also considering the scale of the study area it was decided to leave the weighting of the factors to the planning and management bodies of each specific area (provinces, municipalities, etc.) and to future more detailed analyses. Based on this statement, the aim of this study was only to identify suitable areas, pointing out the zones that have more potentiality, which could later be analysed in more detail with different methodologies and criteria.

Calculating suitable areas

Finally, the classification of areas according its suitability (S) will be obtained from multiply the unfeasible areas (U), reclassified as 0 or 1 for the result of sum the five suitability factors (Sf), previously reclassified between 1 and 5 (Eq. (2)).

$$S = U(0,1)x\sum_{n=1}^{5} Sf(1-5) \qquad (2)$$

In order to provide further details to assist with decision-making, calculations were made to consider the construction of wind and solar facilities jointly. This was carried out with QGIS's SAGA *Cross-Classification and Tabulation* tool, which, like its equivalent tool in ArcGIS *Combine,*combines different rasters and provides a single exit value to each combination of data entered [27].

Results

Unsuitable areas

The unsuitable areas for wind and PV plants are shown in Fig. 3.

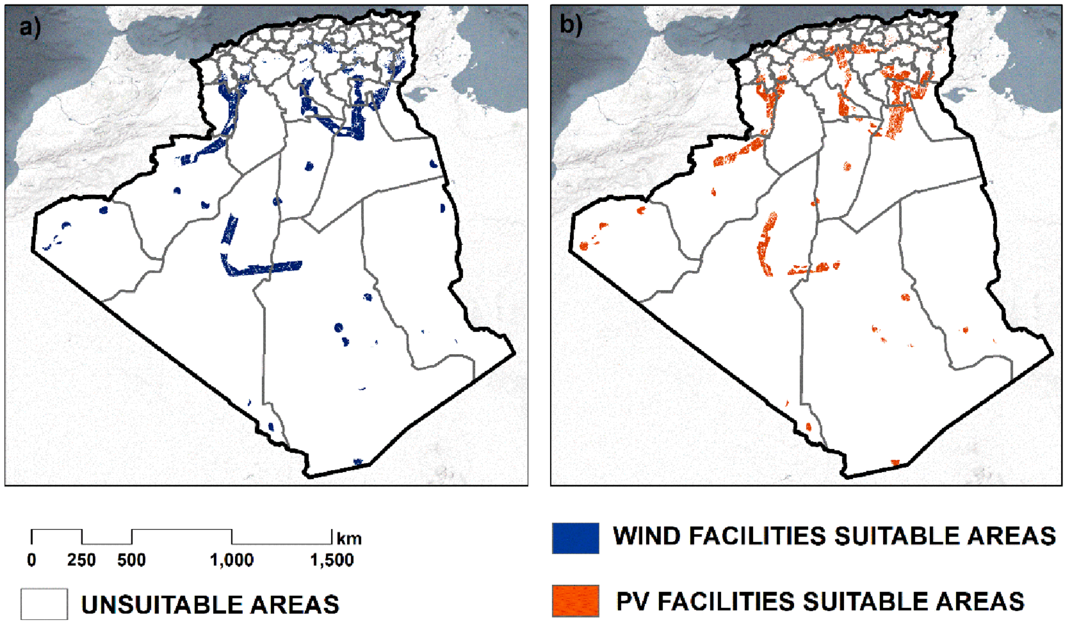


Fig. 3. Suitable and unsuitable areas for locating of wind (a) and PV (b) facilities. Source: Author's elaboration.

Approximately 97% of the Algerian territory is considered unsuitable for the location of wind plants (Fig. 3a), and 97.2% is considered unsuitable for the location of solar plants (Fig. 3b).

These high percentages are the result of the application of the most restrictive criteria found in the literature. Distance to the electric grid and the road network rules out most of the Algerian territory (90% and 63% respectively concerning wind energy, and 89% and 42% concerning solar energy).

Although they are densely populated, northern provinces present a lower percentage of compatible areas owing to the presence of wooded areas and steep slopes around the Atlas Mountains. In the southern provinces, the lack of electric infrastructure and roads in the Sahara desert rule out most areas.

High-potential areas

Approximately 3% of the Algerian territory is considered suitable for the location of wind farms (67,705 km^2), and 2.8% is considered

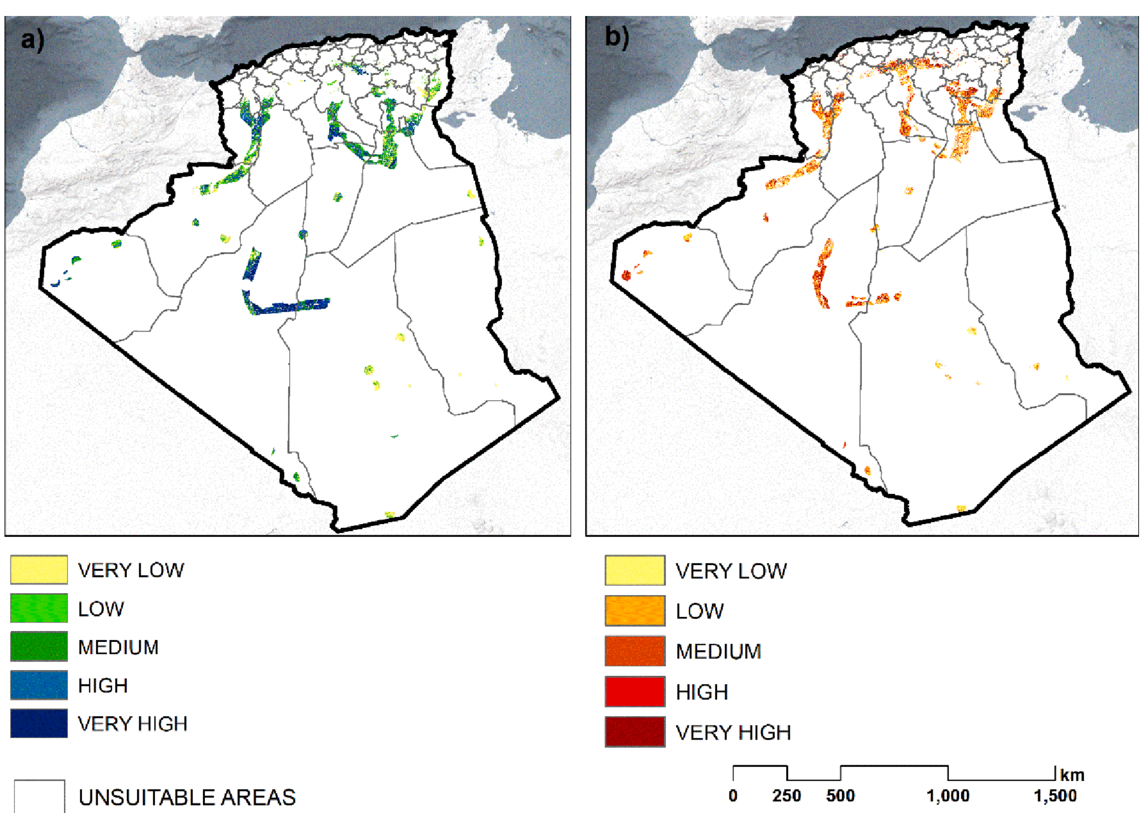


Fig. 4. Potential areas for the installation of wind (a) and solar (b) facilities. Source: Author's elaboration.

suitable for the location of solar farms (63,192 km^2).

Fig. 4 illustrates the areas with the greatest potential for the location of wind and solar facilities. This is the result of the sum of the factors under analysis (reclassified between 1 and 5), multiplied with the mapping of unsuitable areas. These areas were divided into five groups by quantiles; as such, high-potential areas are those in the top 20% overall score. Despite the major restrictions applied, 33,188 km^2 and 17,378 km^2 are regarded as having high potential for the construction of wind and solar plants respectively.

Given that the areas suitable for the construction of wind and solar plants largely overlap, and although that a simply combining the two layers does not illustrate the optimum location for both, this analysis have been carried out, in order to provide further details to assist with decision-making (Fig. 5).

For this, the QGIS's SAGA *Cross-Classification and Tabulation* tool have been used. It should be noted that, despite being easy to use and being a very valuable tool for energy planning, the authors have not found evidence for the use of this tool in any previous study. This tool is also available in ArGIS proprietary software, under the command *Combine.* This tool was used by Díaz-Cuevas et al. [27] to identify high-potential areas for the construction of single or combined wind , solar and biomass generation facilities in Andalusia (south of Spain). The results indicate that 25,377 km^2 have high or very high potential for the construction of wind farms, 13,485 km^2 have potential for the construction of solar farms, and 11,199 km^2 have potential for both.

Discussion

The present work aims to design an individual or combined wind and solar plants locational model that has been applied in Algeria. This work can be considered an example for other regions on how to deal with spatial data availability problems. In order to ensure replicability, the software and the geographical data used in this study are open access.

It should be noted that although the information technology revolution has allowed several geographical information productions, for some regions, the geographical data required to undertake these analyses, is either not available or not freely accessible. Internet geoportals maintained by international agencies that distribute geographic information on a global scale can help overcome these shortcomings although this information is often distributed in complex formats, different resolutions and coordinate systems. In this sense, an important effort of normalization and homogenization (same system of coordinates, same cell size, etc.) has been necessary.

Concerning the unfeasibility criteria and the restrictions to be applied on them, the literature review shows that no consensus exists in relation to the degree of restrictions to be applied to each criterion. In this instance, the most restrictive model has been adopted, which guarantees that results will highlight the most suitable areas in the worst-case scenario.

Regarding to the suitability criteria, the experts were asked about the possibility of weighting these. On three occasions, experts made judgments on the importance of factors, by means of AHP methodology [106–107], that proved to be inconsistent. This is also reflected in the existing literature, where it can be observed that weights assigned to different criteria vary significantly. For this reason it was decided to leave the weighting of factors to the planning and management bodies of each specific area (provinces, municipalities, etc.). These bodies are also the ones who know deeply each territory. For example, it does not make

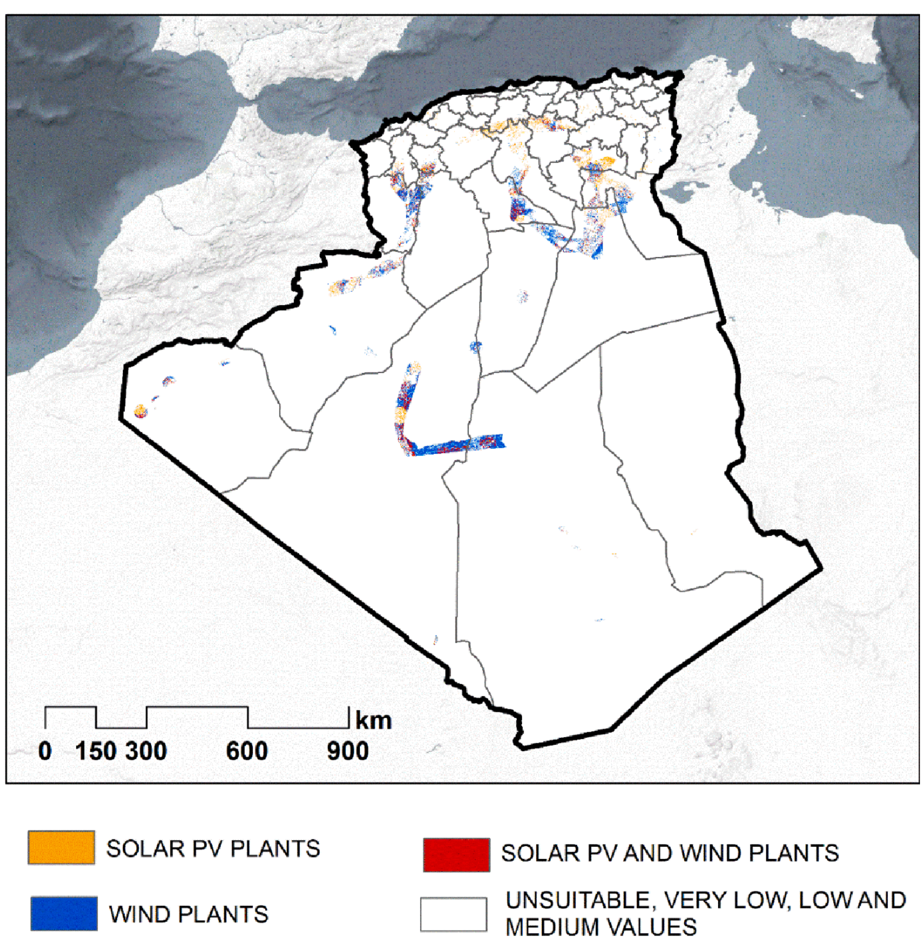


Fig. 5. Potential for the installation of wind and PV facilities, separately and combined. Source: Author's elaboration.

sense to give more weight to the lesser slope areas in the case of solar and wind energy, if the whole study area has a lower slope than the restriction used. Consequently, it could be considered that giving more weight to areas with higher radiation would not make sense either. when the whole study area is above the established optimal values. Indeed, it is important that both, experts in the RE analysed technologies and the experts in the area of study, contribute in determining the weights. Likewise, each territory must decide according to its needs and its development vision, to apply more or less weight on the analysed criteria.

The sources used for designing and creating the locational model are all "open source", and substantial work was done to standardise and integrate results. However, the lack of information about data production can lead to certain data-inherent errors in the methodology and the results. In order to ensure reliability, some criteria had to be dismissed. The geographical information concerning the electric grid is among the most difficult to obtain and is particularly sensitive to these errors. In this case the distance to electricity grid is the criterion that imposes the greatest restrictions since as much as 90% of the Algerian territory could be ruled out. Given that the elasticity and iterative nature of the build model and the analytical power of GIS allows for different scenarios to be taken into consideration, another scenario has been calculated. In this scenario, it was assumed that all areas were within 10 km of the electric grid (thus lifting the restriction that affected the previous scenario).

The Fig. 6, shows the potential of the Algerian territory for wind and PV plants, assuming that all areas were within 10 km of the electric grid . The lifting of this restriction involved a substantial increase of high- and very high-potential areas: 262,229 km^2 and 153,337 km^2 for wind and solar plants, respectively.

The comparison of the two scenarios (the original and the no electric grid restriction scenario) provides useful and critical information for planners and investors, who will be able to identify areas which, reaching high and very high potentiality values in the other factors are considered incompatible or with low levels of potentiality due to the lack of a nearby electricity grid. In these areas an improvement in the electric network would be more efficient and would increase the areas with high and very high potentiality.

Fig. 7a shows high- and very high-potential areas in the original scenario, and Fig. 7b the high- and very high-potential areas in the no electric grid restriction scenario. As a result, an improvement of the electricity network would greatly increase the potential of the Algerian territory for the construction of RE plants (Fig. 7c). However, given the vast extension of territory categorised with high potentiality for placing these infrastructures (with the current power grid), the priority here should focus on detailed assessments of high potential areas before directing any efforts towards an increase in the electricity network.

For all the aforementioned reasons, the model presented here is a powerful tool for territorial planning in the field of RE. However, more detailed analysis is needed for specific areas before making the final decision. The large size of the area under consideration has had an effect on the criteria selected. For instance, the Fig. 6 also illustrate that a large area of the Algerian territory is deemed unsuitable owing to distance to the road network, the second most limiting criterion. It should be noted that the roads used for this analysis are from the Digital Chart of the World [95] with a 1:1,000,000 scale. In order to update the information taken from the previous source, roads have been extracted from OpenStreetMap data made by WWFGeonode [96]. Primary, secondary and tertiary roads have been included in the analysis, but smaller paths were not taken in account. For future and more detailed assessments, path should also be considered as this may modified the results.

Although they are densely populated, northern provinces present a lower percentage of compatible areas owing to the presence of wooded areas and steep slopes around the Atlas Mountains. Probably rooftop PV makes a lot of sense in these areas, something that will have to be verified in future studies. In the southern provinces, the lack of electric infrastructure and roads in the Sahara Desert rule out most areas. Not only it is important the grid in the way it was considered in the study, but in which manner the grid is used. A grid that is used at 90–95% of its

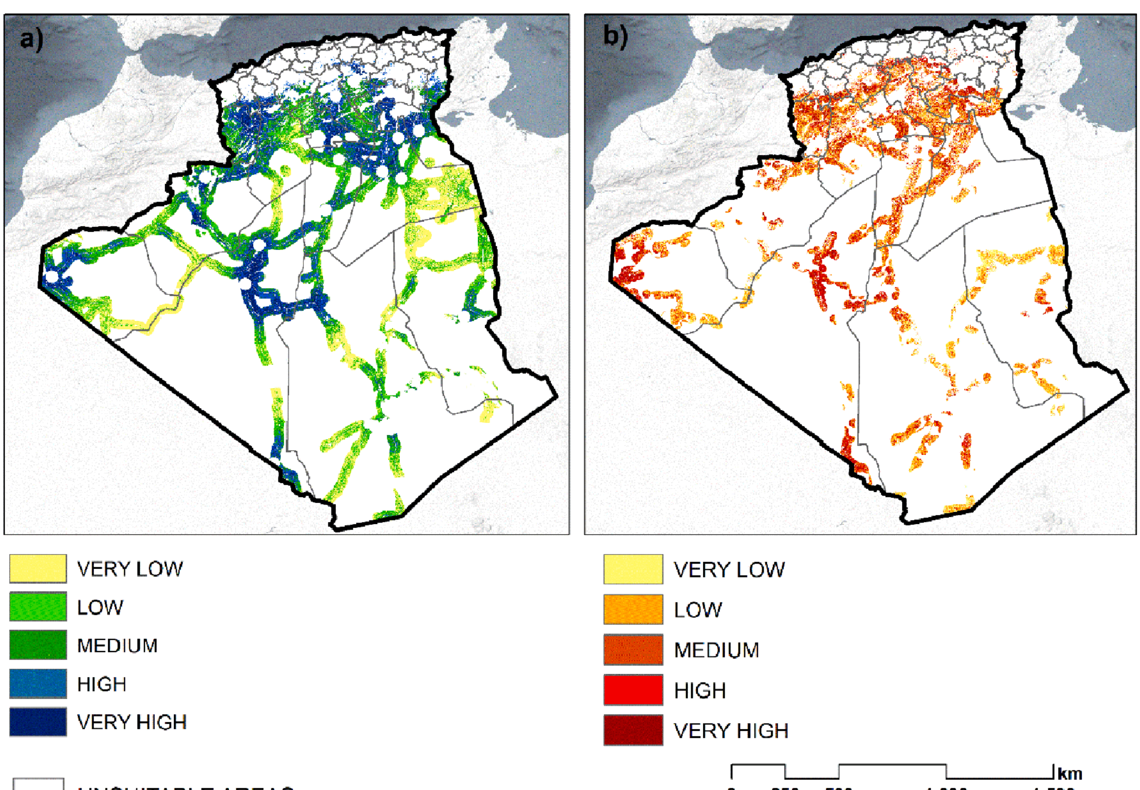


Fig. 6. Potential of the Algerian territory, for wind (a) and PV (b) assuming that all areas are within 10 km of the electric grid. Source: Author's elaboration.

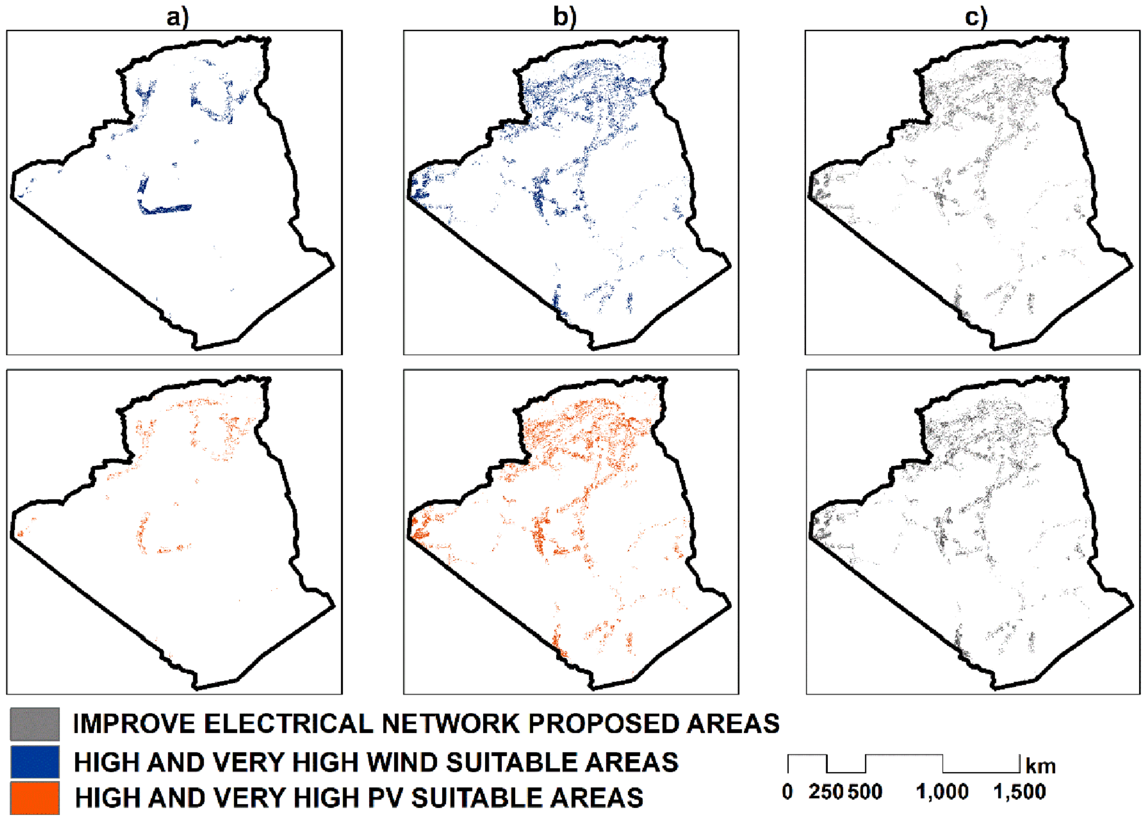


Fig. 7. High- and very high-potential areas in the original scenario (a), high- and very high-potential areas in the second scenario (b) and increase of high- and very high-potential areas due to an extension of the electric grid (c). Source: Author's elaboration.

capacity has not much room for more renewables facilities. The use of the grid should be considered in the methods as well as future plans for grid development Accessing this information for the whole Algerian territory is complicated, as it is usually not publicly available. Most authors cannot include this information and include only the network layout to select optimal areas. This is where this work makes sense because although the network layout has been used as an additional criterion, the need for more detailed studies have been identified.

In line with this, variables such as visual impact, impact on wildlife, and the opinion of the locals, which are so important for decision-making processes in this field, could not be taken into consideration owing to inability of collecting the data that this would have necessitated. Furthermore, the lack of geospatial data that would allow the analysis of other important criteria implies that these first results must be taken as provisional. These preliminary results should be considered as a scenario (the worst scenario in this case, given that it incorporates the maximum restrictions applied), which will allow us to indicate specific areas where the necessary information must be obtained, reducing costs and time. These variables should be considered in future studies that focus on smaller areas where other could be coupled with economic indicators such as Levelized Cost of Electricity (LCOE), and other specific freeware GIS tools [109], leading to select only those profitable sites.

Conclusion

Geospatial information and technologies have significant value in implementing the 2030 Agenda for Sustainable Development (SDGs) [110]. According with Arnold et al. [111]: "It has been estimated that approximately 20% of the SDG indicators can be interpreted and measured either through direct use of geospatial data itself or through integration with statistical data".

RE have a direct impact on two of the 17 SDGs (Goal number 7 "Affordable and Clean Energy" and Goal number 14 "Climate Action"), and decision-making processes linked to RE must need precise data and access to information [41,112–113]. Thus, obtaining reliable, open source and high-resolution geospatial data has become a crucial task.

This study covers a GIS- and MCDM-based assessment of Algeria's potential for the installation of individual and combined wind and PV plants. The first result indicated that 97% of the Algerian territory is found unsuitable for the location of wind and PV power plants.

Although the most restrictive restrictions have been applied a large proportion of the Algerian territory is considered suitable for the construction of wind and PV plants: 25,377 km^2 have high or very high potential for the construction of wind plants, 13,485 km^2 have potential for the construction of solar plants, and 11,199 km^2 have potential for both. If all areas were within 10 km of the electric grid it would involve a substantial increase of high- and very high-potential areas: 262,229 km^2 for wind farms, and 153,337 km^2 for solar farms.

The model presented here is useful for both planners and managers because it not only outlines suitable and unsuitable areas, allowing planners to prioritize areas for more detailed analyses, but it is also iterative and elastic, so different scenarios can be easily projected. For instance, the model suggests that an extension of the electric grid would lead to a substantial increase in suitable areas. However, the priority should focus on detailed assessments of high potential areas obtained with the current power grid

The availability and accessibility of geospatial information and open-access GIS software are key for appropriate planning. Due to the monetary limitations and institutional restrictions for getting access to proprietary GIS software and some spatial information, open-source spatial information and software have been used in order to ensure replicability. In this sense, internet geoportals that facilitate open-access spatial information are critical for those countries where this information is not freely available or difficult to get through official institutions. To guarantee an efficient use of this information, open-access data must be checked, processed, normalized, and integrated into a spatial database management system or Geographical Information System. In order to do this, users must have skills in managing and processing geographical information.

Although the quality of the spatial information taken for this work is considered the best available up to date, errors related to the generation and distribution of the spatial data out of the author's control are possible. The nature and availability of data determine the kind of analysis that can be conducted. Based on this statement, the identified site-specific areas for locating RE plants should be subject to more detailed studies where these errors must be taken in account and aided before choosing the final location. Other criteria (such as electricity network capacity, visibility, impacts on wildlife, and social opinion) also should be taken in account in detailed site-specific assessments.

Declaration of Competing Interest

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

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