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Article

Solar energy potential assessment for electricity generation on the south-eastern coast of Iran

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ABSTRACT

Among the types of renewable energy, solar energy has received more attention due to its ability to convert directly into electricity and heat, its ease of use, its possibility of storage, and its endlessness, so in recent decades, a lot of research has been done on solar energy systems in the world and in Iran. Considering Iran's potential in the field of solar energy and the country's need for this type of energy, it is necessary to locate and identify suitable sites for the use of solar energy. In this research, the potential of generating power from solar energy on the ocean coasts of south-eastern Iran has been investigated. The geographical data of the solar radiation map of Iran was used to estimate the power of electrical energy from spatial limiting criteria for the feasibility of installing photovoltaic panels at the power plant scale. Finally, the total power of electricity that can be extracted from suitable places in the region was calculated; results showed that 37.5% of the Makran area is exploitable as solar farms. With a conversion efficiency of 15% and an area factor of 70%, annual electricity production for the exploitable area is roughly 17200 GWh, which can be a driving force for the industrial, economic and social development of Makran region.

1. Introduction

Increasing The increase in the population of the planet and the process of industrialization of the countries of the world has led to the increasing use of various energy sources. The development of human societies has been directly related to increasing energy consumption. On the one hand, the need of countries around the world for sustainable, accessible, and cheap energy resources, and on the other hand, their obligation to meet international commitments that Environmental constraints have led these countries to turn their attention to renewable energy [1]. The increase in electricity consumption in the twentieth century has led governments to respond to their country's demand for this type of secondary energy by building various power plants [2]. However, the construction of these power plants, often without planning and location studies, caused serious problems for human communities in these countries. Today, due to limited fossil resources and increasing energy demand, and ultimately environmental considerations, the exploitation of renewable energy sources has become inevitable. The solar power plant is one of the new technologies in the field of electricity production or minimizing environmental pollution, and considering that Iran has good potential in the field of solar energy, the use of this clean and unlimited energy source seems necessary. A solar site selection problem motivated by a real-world case study to determine sustainable locations for establishing solar sites in the east of Iran was addressed [3]. Also, a comprehensive literature review on the photovoltaic status in Iran regarding the climate conditions, photovoltaic development potentials, energy policies within the country, and photovoltaic experiences was provided [4]. A reliable solution to replace natural gas with solar or wind energy on a national scale using a simulation approach was aimed to find. It was concluded that using solar thermal collectors decreased the average total cost by about 13% [5]. In order to solve the problem of accumulation of dust on transparent surfaces, Nanocoatings were deposited on glass samples to create a self-cleaning property. A nanospray was used to create a hydrophobic film on the surface, and TiO_2 was coated in three different thicknesses to create a hydrophilic film on sample surfaces. It seems that the south-eastern ocean coast of Iran is one of the talented and suitable areas for the deployment of solar systems at the power plant scale. Investing in solar energy can significantly contribute to the economic, industrial, and social development of this region of the country. The purpose of this study is to estimate the potential of solar energy for large-scale electrical energy generation. In the following, a number of articles and research studies conducted in Iran and the world on the issues of potential measurement and location of solar power plants are briefly reviewed. In 2014, in the article by Lozano et al. [6], location indicators were divided into two constraints and criteria categories; in the constraints section, the study area is reduced due to the presence of limiting factors. These limiting factors include protected areas, military zones, high-value lands, streams and rivers, roads and railways, urban areas, parks, and airports. In the criteria section, these indicators evaluate the available land. For this purpose, he mentioned criteria such as the amount of access to the electricity transmission network, distance from population centers, environmental criteria, and technical criteria such as air temperature and the amount of solar radiation energy. In an article published by Nazlionka et al. [7], indicators have been used to determine the appropriate location for the construction of hybrid wind and solar power plant. In this article, first, environmental, economic, and technical criteria and indicators have been determined by comprehensively reviewing previous studies, conducting interviews with the General Directorate of Resources and Electricity Development of the Republic of Turkey, and reviewing the laws and regulations of Turkey. Also, in this research, a fuzzy decision model has been used. In this way, the criteria are first fuzzy, and the evaluation of places is done on this basis. Fuzzy operations have been used to combine these criteria and identify the most appropriate locations. In this study, first, the priority locations for the wind and solar systems are determined separately in the GIS, and finally, these locations are combined with each other, and the best location for the installation of the solar-wind hybrid system is determined.

In an article by Gastley and Cherabi [8], For the first time, the effect of airborne dust on the location of a solar power plant has been investigated. In this research, the numerical model of COSMO climate forecast with high resolution to extract the annual temperature pattern of Oman and also with the help of Multi-angle Imagine Spectro-Radiometer (MISR) is used, which is usually applied to calculate the degree of contamination of mineral Aerosol in the air. The optical depth quantity of the particles (Aerosol) is measured. The results show that in the case of the effect of dust and temperature, many areas are out of the desired options due to high temperature and the amount of dust. Optimal places are reduced to 81% by considering two new factors. Polo et al. [9], in their article, the best places to install solar systems are based on technical and geographical criteria. This article presents Vietnam's solar potential maps, as well as its extractable power, based on CSP, PV grid-connected technology. Production of solar potential maps is done by performing calculations on satellite data and entering atmospheric and weather parameters, and combining it with information related to sunny hours, etc. In the research by Fountoulakis et al. [10], Geographical parameters such as the amount of water vapor, airborne particles, the amount of sunlight, and the percentage of reflection from the earth and clouds have been used to calculate the quantities of GHI and DNI. What shows the value of this article is the calculations that have been done to obtain solar radiation information. Data sources can be divided into three categories: satellite imagery, numerical climate models, and ground-based transmission and measurements of solar radiation. Yanovo et al. [11] used a new fuzzy linguistic operator to be able to bring the decision model closer to reality. This paper proposes a three-step decision-making framework: In the first step, identify areas that are potentially suitable for the construction of a solar thermal power plant in terms of energy potential, infrastructure, social and environmental factors, and land. In the second stage, criteria are weighted using a fuzzy scale, and in the third stage, linguistic variables replace the theory of fuzzy sets or numerical values that express the preferences of experts. Finally, by using a group decision method and Choquet language operator, the options are prioritized. Tercan et al. [12] used a combination of AHP, WLC, and IDW methods in a GIS environment. They considered complex and contradictory 17 evaluation criteria to find convenient PV farms locations. It was concluded that the western region of the study area had an excellent solar energy potential. Sun et al. [13] presented a GIS-based MCDM method for site selection of large-scale solar plants and assessed theoretical and technical potentials for both PV and CSP technologies. They obtained the land suitability map of Ningxia with the spatial distribution of capacity and power output. In Iran, Rezaei et al. [14] have studied the indicators and criteria that are effective in locating the solar power plant, and then determined the appropriate and desirable locations for the construction of solar power plants in Tehran province, and finally using the decision model FTOPSIS, Prioritize the desired locations. In this research, multi-criteria decision-making methods have been used to select and prioritize the proposed locations, and GIS is a powerful tool for data processing to provide useful and necessary information for optimal management of resources and facilities. Janjai et al. [15], due to the factors affecting the efficiency of the wind farm, found a suitable place to install wind turbines. In this research, the potential of wind resources with the ability to generate electricity, using the geographic information system and considering the selection criteria of wind farms, has been studied. In the discussion of calculating wind potential in this paper, the criteria are considered with equal importance, and these criteria include technical, environmental, geographical, and economic criteria. Mousavi et al. [16] analyzed the feasibility of utilizing a hybrid solar system to provide electricity, hot water, and drinking water in the parks of Tehran, Iran. The simulation and experimental results confirmed the feasibility of the system regarding the technical and economic aspects. Shorabeh et al. [17] investigated the location of solar power plants with emphasis on factors and Climatic parameters. In this study, first, the factors affecting solar energy have been studied, and by combining them in the GIS environment, more susceptible areas in Khuzestan province have been identified. This is achieved by analyzing the sundials as the most important parameter in the utilization of solar energy and the parameters affecting the sundials, including cloudiness, dusty days, relative humidity, altitude, and annual rainfall, in the GIS environment. In this study, the methodology based on the literature is developed by considering various criteria and alternatives to find the most appropriate solar farms for PV and solar power sites in the Makran region located in southeast Iran. Despite the previous studies, a novel methodology is conducted in the current research regarding theoretical and technical methods of solar power generation for PV technologies in a non-build-up area which can also be used in other locations in the world. Defined alternatives which were used in some literature reviews and this study have some differences; for example, some criteria like beach or river parameters are used in the potentiometry of solar energy for the first time. The aim of this study is to present the technical and theoretical potential of the best suitable area for solar power generation with regard to the appropriate technology in the studied area.

2. Methods

To achieve the best area for installing a solar power plant, the defined criteria in the literature are identified and categorized. After defining criteria for site selection, multi-criteria decision-making and analytical hierarchy process are used. The first step in the AHP method is to assess the criteria that enable us to make an accurate comparison and rights decisions to provide subjective judgments. In the AHP process, the decision-making procedure is broken down into a hierarchy of goals, criteria, and alternatives, respectively. In order to specify the most suitable area, a combination of defined indicators in each criterion is applied to indicate the best suitable area in the criteria. Regarding the GIS and spatial analysis tool, all the criteria final maps are classified, and by weighted overlaying them, the final suitable map for the solar power plants is acquired.

2.1 Case study

The study area is the south-eastern coast of Iran, with an area of about 79,406 square kilometers, as shown in Figure 1 [18]. This area includes parts of Sistan and Baluchestan, and Hormozgan provinces. Among the important cities in this study area, we can mention Chabahar, Nikshahr, Minab, Jask, and Sarbaz. This region is bounded on the south by the Arabian Sea, on the east by Pakistan, on the west by the Strait of Hormuz, and on the north by the cities of Saravan, Iranshahr, Kahnooj, and Bandar Abbas.

2.2 Data preparation and analysis

According to the definition of sustainable development, resource use, investment guidance, technology development orientation, and institutional change should be consistent with the current and future needs of the country. Thus, in the process of locating solar power plants, in addition to technical issues, economic and environmental issues must also be considered. The efficiency of solar power plants, unlike fossil power plants, is highly dependent on geographical and spatial factors. Among them, we can mention parameters such as the amount of radiation received from the sun, the number of hours of sunshine per year, the amount of dust in the air, etc. Solar power plants are among the infrastructure of Iran, and their construction and location should follow the pattern of sustainable development [19]. Reviewing internal and external research, it was found that various factors and parameters are influential in the location of the solar power plant. This set of factors influencing the power plant's location is usually classified into two parts: restrictions and criteria [20]. Indicators of the constraint set are used to remove inaccessible lands, and a set of criteria is used to evaluate the remaining lands. Determining the appropriate location for the construction of a solar photovoltaic power plant requires attention to various criteria and factors, most of which are the nature of the reference location. The capability of GIS in storage, retrieval, updating, processing, analysis, and display of spatial information suggests its use as a useful and efficient solution in locating the power plant. A GIS is an information system that generates, processes, analyzes, and manages geographic information. In this study, with the aim of providing the necessary support for decisions based on spatial data, the GIS is used [21]. The required information is obtained by combining different layers of data in different ways.

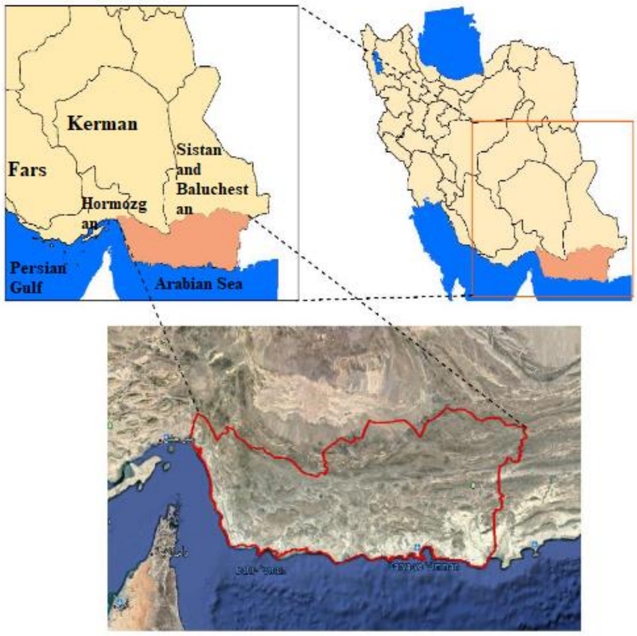

Figure 1. Case study

2.2.1 Land scope

This parameter is related to the steepness of the slope in the investigated area. The slope areas are important since the construction in these areas are more costly.

2.2.2 The main faults

This parameter is the restriction map of distance to major faults. The faults area is important because it can be one of the economic criteria [22].

2.2.3 Beach

Since the Makran region is the studied area and its proximity to the Gulf of Oman, the beach areas should be considered as a parameter.

2.2.4 Urban areas

The closeness of a solar power plant to the urban areas is one of the economic factors, in fact, proximity to the urban area reduces the cost of construction infrastructure and the environmental damage

2.2.5 Rural areas

Building solar power plants near rural areas can cause environmental problems and negative impacts on the future development of residential areas. On the other hand, the areas with a long distance to residential areas are not economically favorable because for supplying the residents' electricity needs, the proximity to residential areas could be important.

2.2.6 Permanent rivers

The distance to rivers is important because of the high river density in the study area. So, the permanent rivers should be considered as a parameter.

2.2.7 Land use (forests, green spaces, agriculture rands and wetlands)

Forests, wetlands, agricultural lands, and wildlife conservation areas are sensitive areas that must be kept away from toxic materials. On the other hand, solar modules consist of some toxic and hazardous materials that must be avoided from being released into the environment. Therefore, solar power plants should be installed at a safe distance from the scope of these sensitive areas. In this study, the criteria of Table 1 are examined to determine the extent of land suitability of the study area. Inadequate areas are areas that will have zero value in fuzzy functions.

Table 1. Solar power plant location criteria for fuzzy maps [23]

Constraint parameters	Inappropriate awed	Good areas	Very good areas	Function
Land scope	More than 10%	Between 3 and 10%	less than 3%	Fuzzy-linear
The main faults	Less than 500%	Between 500m and 1 km	More than 1 km	Fuzzy-linear
Beach	Less than 2 km	Between 2 to 5 km	More than 5km	Fuzzy-linear
Urban areas	Less than 2km and more than 45km	More than 20 km	Between 2 to 20 km	Fuzzy-Trapezoidal
Rural areas	Less than 500m and more than 10km	More than 7 km	Between 500 m to 7km	Fuzzy-Trapezoidal
Permanent rivers	Less than 500m	Between 500 to 20000m	More than 2000m	Fuzzy-linear
Land use (forests, green spaces, agricultural lands and wetlands)	Less than 500m	Between 500 to 2000m	More than 2000m	Fuzzy-linear

Good and very good areas by linear and trapezoidal functions, between zero and one, are valued. Fuzzy sets refer to sets in which the membership of the members of the canal is not known, and its elements are relatively part of that set [24]. In fuzzy sets, unlike definite sets, the membership rate of different elements varies between zero and one, and the elements are not divided into two groups of non-member members [23]. When preparing fuzzy maps, give each pixel for each distance a value commensurate with that distance relative to the function of each parameter. This evaluation is done by numerical representation in fuzzy logic [25]. In some criteria, such as the distance from the main fault, the farther we go from them, the higher the score, and vice versa; in others, such as the distance from urban areas, the value of the pixels decreases with increasing distance. The mathematical functions used in the process of fuzzy of the criteria maps are shown in Table 2 [26].

Table 2. Mathematical relations of fuzzy functions [27]

function	mathematical
Linear-Ascending	$linear(a,b)\begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a < x < b \\ 1 & x \ge b \end{cases}$
Linear-Descending	$linear(a,b)\begin{cases} 1 & x \le a \\ \frac{x-b}{a-b} & a < x < b \\ 0 & x \ge b \end{cases}$
Trapezoidal	$Trapezoidal(a,b,c,d)\begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a < x < b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c < x < d \\ 0 & x \ge d \end{cases}$

Using these mathematical relationships, the degree of membership of each of the pixels in the study area is calculated. The degree of membership determines the relative importance of each pixel based on that parameter. Invoice maps are shown in Figure 2. When the criteria were organized by the AHP method, the procedure is done with the seven mentioned indicators. As shown in Table 3, the indicator's final weights used in each criterion are obtained by the AHP method.

3. Results and discussion

After preparing the required fuzzy maps, the final integration of the maps is done using the gamma fuzzy operator, the result of which is shown in Figure 3. The mathematical relation of the gamma fuzzy operator is defined as follows [28]:

$$\mu = (\mu\ fuzzy\ sum)^{\gamma} + (\mu\ fuzzy\ product)^{1-\gamma}$$

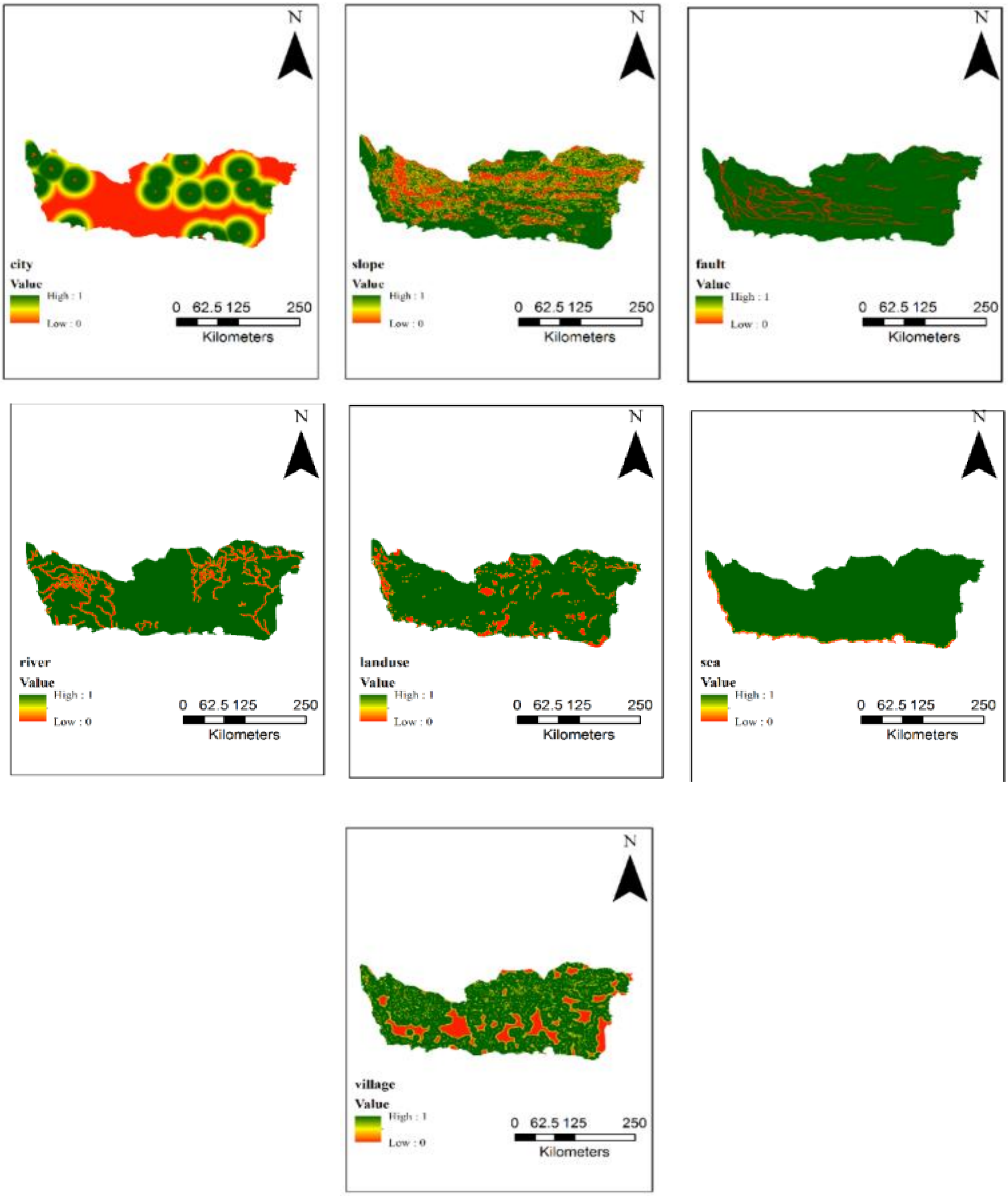

Figure 2. Fuzzy maps of the land slope, urban and rural areas, major faults, permanent rivers, coastline, and land use

Table 3. The indicator's final weights using each criterion is obtained by the AHP method

Factors	Weights (%)
Land scope	21
The main faults	12
Beach	26
Urban areas	11
Rural areas	7
Permanent rivers	10
Land use	13

The study area is divided into four areas. These four areas are: areas with very good desirability, good desirability, moderate desirability, and low desirability. The extent of each of these zones is given in Table 4.

Table 4. Extent and share of zones in the study area

Desirability	**Area (thousand hectares)**	**Share of study area (percentage)**
Vexy good	1188	15
good	1791	22.5
Medium	385	5
low	4576	57.5
Total	7940	100

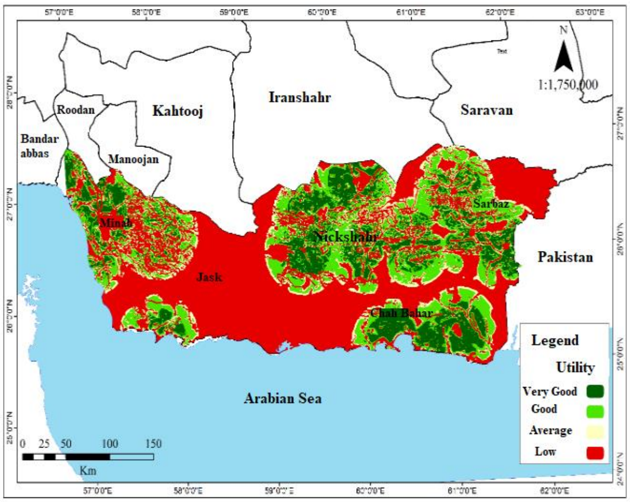

Figure 3. The final map of suitable places for the establishment of solar photovoltaic power plants

The efficiency of solar power plants, unlike fossil power plants, is strongly dependent on geographical and spatial factors, such as parameters such as the amount of radiation received from the sun, the number of hours of sunshine per year, the amount of dust in the air and etc. In order to relatively accurately estimate the potential of solar power generation based on solar photovoltaic panel technology, it is necessary to simulate the performance of a solar power plant with a capacity of one megawatt in climatic conditions of the study area to estimate the amount of electricity generated over a year. For this purpose, the RETscreen software, which is a clean energy project analysis software that can evaluate energy production and reduce greenhouse gas emissions and perform financial analysis of the project [27]. RETScreen software is provided with NASA's Satellite-derived Meteorological Data (developed by NASA' Langley Research Center in collaboration with CanmetENERGY) for any location and the NASA Prediction of Worldwide Energy Resource (POWER) project. This data set is a helpful option when there is no access to ground-based data or itemized resource maps for the project location; It is calculated from data collected for a 20-year period starting in July 1983, applying a 1-degree cell (at mid-latitudes (45°) the cell dimensions is around 80 × 110 km). Solar radiation parameters are derived using satellite data of the atmosphere and Earth's surface [29]. The other meteorological values are adapted from Goddard Earth Observing System (GEOS) meteorological analysis by the NASA's Global Modeling and Analysis Office (GMAO). The selected sites for this simulation are shown in Table 5.

Table 5. Climate conditions of the selected sites

City	Annual average Radiation (kW.h/m^2.day)	Average air Temperature (C)
Baft	5.53	16.3
Jiroft	5.46	20.5
Chah bahar	7.19	28.9
Khash	5.39	19.9
Port of Jask	6.18	27.8
Saravan	5.49	22.1
Sirjan	5.46	16.6
Minab	6.07	26.7
Sarbaz	5.61	23.2
Nickshahr	5.73	21.3

Climate data for these sites are gathered from the weather station and NASA database in RETScreen. In the simulation of this power plant, monocrystalline photovoltaic modules with a power of 250 watts and an efficiency of 15.3% were selected. Other technical specifications of photovoltaic panels are given in Table 6. This software is implemented for the climatic conditions of the two coastal cities of Chabahar and Jask. The amount of electricity produced in one year for the two cities of Chabahar and Jask was estimated at 1744 and 1945 MWh, respectively. In order to measure the electricity generation potential of the whole study area based on the technology of solar photovoltaic panels, the estimated annual generated electricity in these two cities (1844.5 MWh) is generalized to the whole area. In fact, it is assumed that the entire area of the zones will be covered with one-megawatt solar power plants to get a good estimate of the solar potential of the area. The area of land required for a photovoltaic power plant with a capacity of one megawatt is about 2 hectares [30]. The results of measuring the potential of solar power generation for zones with different utilities are shown in Table 7. Due to the high cost of establishing power plants using renewable energy technology, it is necessary to prioritize the investment and construction of solar power plants in areas with very good utility and low risk. As can be seen, the potential for renewable electricity generation in the Makran region is very high due to adequate solar radiation. However, covering such a large area with a solar power plant seems somewhat illogical. However, this research shows that investing in the Makran region for the establishment of solar power plants is recommended and necessary due to the existence of a large area with very good utility.

Table 6. Technical specifications of photovoltaic module in power plant simulation

Item	STC	NOCT
Power output	2.50	181.6
Voltage at P_{max}	30.5	27.6
Current at P_{max}	8.20	6.58
Open- circuit voltage	38.1	35.1
Short-circuit current	8.71	7.02

Table 7. Electricity generation potential using solar photovoltaic technology

Desirability of the area	Electrical energy (100 GW hour in the year)	Investment priority
Very good	250	First
Good	30.5	Second
Medium	8.20	Third
Low	38.1	Fourth
total	8.71	fourth

4. Conclusion

With the economic development and population growth of the country, the demand for widespread use of fossil fuels is increasing steeply. Attention to the use of new energy, including solar energy, to provide part of the electricity and heat needed by cities and villages to achieve the goals of sustainable development and diversification of Iran's energy basket and reduce fossil fuel consumption seems necessary. Due to Iran's high potential in the field of solar energy and the country's future need for renewable energy, it is necessary to locate andidentify suitable sites for the use of solar energy. In this study, the potential of photovoltaic power generation on the ocean coast of south-eastern Iran was investigated. To estimate the power of electrical energy, spatially limited criteria were used to evaluate the feasibility of installing photovoltaic panels at the power plant scale. The total power of electricity that can be extracted from suitable places in the region was calculated, which shows the high potential of the south-eastern coast of Iran in benefiting from renewable energy, which can be a driving force for the industrial, economic, and social development of the Makran region. Calculations show that only with the construction of photovoltaic power plants with a total capacity of 3,000 megawatts in the study area, which covers only about half a percent of very good land, the total electricity generated by the current power plants in Sistan and Baluchestan can be replaced the year 2016. This is a good indication of the high potential of solar energy in the Makran region, which has been neglected so far.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

Author Contributions

All authors contributed to the study conception and design, material preparation, data collection and analysis were performed by Rahim Zahedi. The first draft of the manuscript was written by Rahim Zahedi and Erfan Sadeghitabar and all authors commented on previous versions of the manuscript. Abolfazl Ahmadi supervised the manuscript. All authors read and approved the final manuscript.

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