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Research paper

Where to harvest solar energy in Iran? A geographic information system (GIS) analysis for supporting the siting of photovoltaic (PV) parks and concentrating solar power (CSP) plants

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ABSTRACT

Iran's electricity generation relies heavily on fossil fuels, resulting in frequent power shortages and widespread blackouts in major cities. Given the high levels of solar irradiance across the country, photovoltaic (PV) and concentrating solar power (CSP) technologies could provide a sustainable alternative. Existing studies focus on specific technologies or individual regions. Currently, there is no consistent, comprehensive mapping of the scope for political decision-making in Iran. This study aims to address this issue by providing the first nationwide assessment of solar energy potential in Iran, evaluating both PV and CSP. This GIS-based assessment uses an expanded set of environmental and technical criteria and performs sensitivity analyses to ensure robust results and identify the most effective and sustainable locations for PV and CSP plants. The model incorporates specific constraints, such as protected natural areas, to exclude unsuitable sites, and assesses suitability based on criteria such as solar irradiation levels and proximity to grid infrastructure. These factors are categorised into four suitability classes, ranging from 'high' to 'very low' for both PV and CSP installations. By synthesising the constraint and suitability maps, the model identifies feasible sites and assesses their relative desirability. A sensitivity analysis, focusing on the weighting of the suitability criteria, confirms the robustness of the results. The results highlight Iran's considerable capacity for solar power generation and suggest that the country could exceed its current electricity production by a multiple through the development of solar power plants. The model applies 14 exclusion criteria, revealing that 70% of Iran's land is unsuitable for PV and 83% for CSP. The results show that 14.5% of Iran's land is suitable for PV and 7.5% for CSP (medium and high suitable), with central and eastern regions offering the highest potential. Additionally, the study highlights the promising prospects of GIS modeling in renewable energy siting, emphasizing improved data integration, global scalability, environmental impact assessment, and policy harmonization.

1. Introduction

Iran's electricity generation is predominantly fossil fuel-based, with natural gas accounting for around 80% and oil around 15%. This has led to frequent power shortages and rolling blackouts in major cities (IRANWIRE, 2025; Low CarbonPower, 2025). These disruptions to the energy supply have had a severe impact on daily life and economic activities, highlighting the urgent need for reliable, alternative sources of electricity.

Large ground-mounted installations of photovoltaic (PV) panels, referred to as PV parks in this study, offer a viable opportunity to give up fossil fuel-based power production. The cost of PV technology has decreased dramatically over the last decades, as a result of technological learning induced by a large increase in the production of PV panels. These reductions are driven by improvements in battery storage, grid expansion, and demand-side flexibility (Luderer et al., 2021). Innovations like tandem structures and thin-film modules help lower costs, while supply chain risks drive diversification efforts in regions like China, the United States, and Europe (Haegel et al., 2023). This in turn was stimulated by economic policy instruments like the guaranteed Feed-In-Tariffs for electric power produced from renewable energy sources, introduced in Germany in 2000 and emulated by various countries around the world.

According to the Fraunhofer Institute for Solar Energy Systems (ISE),

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the generation cost of utility-scale ground-mounted PV with battery storage is now below the generation cost of fossil-fuel based electric generation (Fraunhofer ISE, 2024a; Fraunhofer, 2024b)– this in Germany, with its average solar irradiaton. For countries with high solar irradiation, large PV parks are even more economical, as is demonstrated by, for example, India, home to Bhadla Park, the world's largest PV park for several years, with a capacity twice that of a typical nuclear power plant in Germany. In recent years, China has built PV Parks a multiple of the capacity of Bhadla park.

Iran is one of the world's top ten greenhouse gas emitters, accounting for around 2% of global CO_2 emissions, totaling approximately 817 million tonnes annually as of 2023 (Hanna et al., 2024a). The country aims to cut emissions by 4% unconditionally or 12% conditionally, with the higher goal depending on international support and lifted sanctions (ACT A, 2023). To address these challenges, the government has promoted PV systems, including rooftop and large-scale installations. However, it has struggled to meet goals like the 2016–2021 plan for 5000 MW of renewable capacity. By 2020, renewables accounted for only 5% of electricity generation, with PV contributing a small share. Still, the solar market is projected to grow 5% annually until 2028 (Luderer et al., 2021), and the Ministry of Energy plans to add 10, 000 MW of renewable capacity by August 2025 (Tehran Times, 2023). As of 2022, Iran had invested in 135 MW of renewable energy, with another 3625 MW in the pipeline (Tehran Times, 2023). Continued solar investment is vital for achieving clean energy goals and reducing fossil fuel reliance.

Iran has strong solar energy potential due to its abundant resources, environmental benefits, and ability to enhance energy security (Mandal et al., 2024; Hanna et al., 2024b; Attanayake et al., 2024). Solar power reduces emissions, creates jobs, and is harnessed through two main technologies: CSP, which uses mirrors to produce steam and drive turbines, and PV, which directly converts sunlight into electricity. CSP allows energy storage but needs more land, while PV is more flexible and widely used.

CSP and PV parks differ in terms of land use and energy efficiency (Kennedy et al., 2022).CSP requires 4–16 ha/MWp due to thermal systems, while PV requires 2.5–10 ha/MWp. PV achieves 20–30% efficiency and 10–25% capacity factors; CSP achieves ~50% Carnot efficiency and 30–50% capacity factors with thermal storage. CSP can deliver up to 350 MWh/ha/year, slightly more than PV (263−350), although PV's smaller footprint allows flexible deployment. PV systems are scalable, from rooftops to large parks, and help reduce blackouts, contributing to energy reliability during recent electricity shortages (DW, 2023; Somerville, 2022).

Iran's adoption of renewable energy is challenged by international sanctions, which limit local manufacturing and increase reliance on costly imported materials - undermining self-sufficiency. Low fossil fuel prices further reduce incentives for stakeholders to switch to renewables (Lauren and Karlsson, 2022).However, with over 1900 kWh/m^2 of annual solar irradiation (SOLARGIS, 2020), Iran has strong potential for CSP and PV. Although PV plants contribute to climate change mitigation, they also affect land cover (Xia et al., 2022). Xia et al. (2022) note their role in combating desertification and supporting sustainable growth. Effective deployment requires detailed site analysis across Iran's diverse landscape.

Geographic Information Systems (GIS) play a vital role in renewable energy planning by streamlining the site selection process, significantly reducing the time and cost of identifying optimal sites (Barzehkar et al., 2021). In this study, a GIS model is developed to evaluate site suitability for PV parks and CSP installations in Iran. It integrates land use constraints, such as protected areas, and suitability criteria like proximity to power lines, which impact the economic feasibility of PV parks. The methodology developed by Fakharizadehshirazi and Rösch (2024) served as a framework for this study. It was further modified and adapted to the specific conditions and requirements of the case study to ensure its applicability to the given context. The model provides a comprehensive evaluation framework by categorizing sites into high, medium, low, and very low suitability and conducting sensitivity analyses. Unlike previous studies, which focused on single technologies or limited regions. Rather than employing complex decision-support frameworks such as the Analytical Hierarchy Process (AHP), it uses scenario-based sensitivity analyses to rigorously test the robustness of the suitability results. The study's main objective is to support the strategic planning and decision-making processes associated with expanding solar energy in Iran. This is achieved through a GIS-based evaluation which identifies and analyses the most suitable and sustainable sites for developing PV and CSP plants. By integrating spatial data, environmental considerations and technical criteria, the research aims to provide decision-makers with a framework for optimising the deployment of solar energy technology nationwide.

2. Literature review

This section reviews previous GIS-based and multi-criteria approaches to locating solar PV and CSP projects. The review article by Spyridonidou & Vagiona (2023) (Spyridonidou and Vagiona, 2023) was the starting point for the research. These authors reviewed 152 publications on the siting of solar projects worldwide using multiple criteria. Of these 152 studies, 33 were examined in more detail. Several recent studies have investigated the optimal siting of large-scale photovoltaic (PV) projects using advanced methods such as GIS and multi-criteria decision-making (MCDM).

A large number of studies focus specifically on the siting of PV projects using GIS and MCDM methods. These studies primarily aim to maximise electricity generation and minimise costs by integrating technical, economic, and environmental criteria. For example Al Garni and Awasthi (2017) (Al Garni and Awasthi, 2017) focused on Saudi Arabia and aimed to maximise electricity generation while minimising project costs by using GIS and MCDM to account for additional criteria. Bandira et al. (2022) demonstrated the effectiveness of NASA-POWER data in locating potential PV parks in Malaysia, confirming that a GIS-based MCDM approach can accurately identify areas with high solar energy potential. In southern central Vietnam, (Nguyen et al. (2022) developed a GIS-based simulation to select optimal PV park locations, highlighting the importance of effective planning. Palmer et al. (2019) studied the UK and identified suitable locations for large-scale PV parks, highlighting the need to consider planning permissions and grid constraints. On the island of Ulleung in Korea, Suh and Brownson (2016) used a GIS multi-criteria assessment to identify particularly suitable areas for installing PV parks. In southern Morocco, Tahri et al. (2015) assessed criteria for PV park suitability and found climate to be the most important factor. Uyan and Dogmus (2023) studied the Cumra region in Turkey, combining the Analytical Network Process (ANP) and GIS to identify suitable locations for solar power plants. Collectively, these studies illustrate the use of GIS and MCDM techniques to identify suitable locations for large-scale PV projects under different geographic contexts.

In parallel, several studies have investigated the siting of concentrating solar power CSP) plants using similar spatial decision-support methods. In eastern Morocco, Alami et al. (2023) evaluated cooling technologies for CSP plants using AHP methodology. In the United Arab Emirates, Alqaderi and Emar (2018) used GIS data and MCDM methods to evaluate site selection criteria for large-scale CSP plants. In Tanzania, Aly et al. (2017) identified CSP and PV hotspots using AHP methodology, while Dawson and Schlyter (2012) developed a GIS-based CSP site suitability methodology in Western Australia. Gouareh et al. (2021) conducted a detailed multi-criteria assessment in Algeria, identifying critical factors such as direct normal irradiance DNI). In the Philippines, Levosada et al. (2022) attempted to identify the most suitable CSP sites using AHP, while Tlhalerwa and Mulalu (2019) assessed the CSP potential of Botswana using a bottom-up approach. Yushchenko et al. (2018) explored the solar energy generation potential of West Africa using GIS and MCDM techniques. These studies demonstrate that spatial multi-criteria methods are also widely applied in CSP siting analyses across diverse regions.

Iran represents a well-studied case in the solar siting literature, largely due to its high solar potential, there extensive efforts have been made to harness solar energy. Asakereh et al. (2014) started their investigation in Khuzestan using Fuzzy AHP and GIS, and found that 18.25% of the region was ideal for PV parks. Their follow-up studies extended the focus to the entire province and showed that the potential for solar energy could exceed Iran's total electricity generation. Barzehkar et al. (2021) optimised wind and solar sites in Isfahan, while Firozjaei et al. (2019) provided a comprehensive overview of the solar energy potential in several provinces. Hafeznia et al. (2017) focused on spatial planning in Birjand and Mokarram et al. (2020) maximised solar potential in Fars province. Other studies, such as those by Noorollahi et al. (2016) and Sadeghi and Karimi (2017), looked at different provinces and the potential of renewable energy to stabilise the electricity grid. Ghasemi et al. (2019) investigated the potential of PV and solar thermal power plants in Sistan and Baluchistan, and Mohammadi and Khorasanizadeh (2019) the feasibility of solar thermal power plants across Iran. The studies show varying degrees of specificity in geographical focus but emphasise the assessment of solar radiation as the main criteria to identify suitable sites for PV parks and CSP plants (Table S1 in the Supplementary). Other aspects considered in the studies are the proximity to power lines, climate, land use and effective planning. The challenges faced by Iranian studies, such as sanctions and fluctuating oil and gas prices, are closely linked to Iran's geopolitical and economic context, which illustrates the limited research on solar thermal power plants in the country.

More recent research has begun to address these limitations by integrating socio-technical and environmental dimensions into spatial solar assessments. Fakharizadehshirazi and Rösch (2024) developed a socio-techno-environmental GIS model to assess GM-PV in Germany, integrating socio-technical, environmental, and climate criteria like soil erosion and CO_2 release. They also assessed the socio-technical spatial potential of agrivoltaics in Germany to address the challenges of

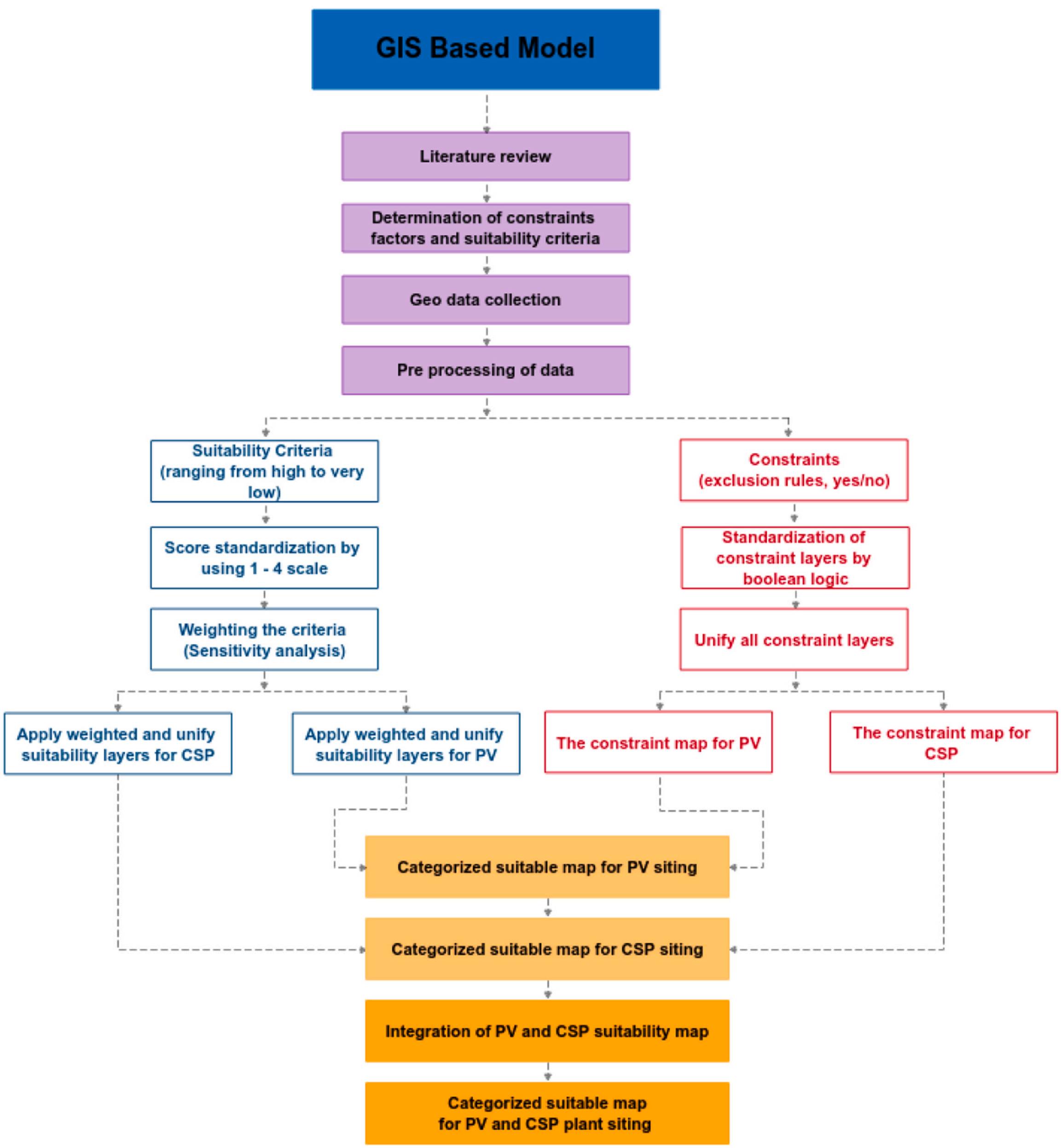

Fig. 1. Work flowchart of the socio-technical GIS model for PV and CSP plant site identification.

increased land-use competition while supporting renewable energy goals. Rösch and Fakharizadehshirazi (2024)'s GIS-based model evaluated the integration of small-scale agrivoltaic systems over permanent and shade-tolerant crops.

3. Methodology

The development of a GIS-based model for the site selection of PV parks and CSP plants for Iran, which is fundamentally based on the GM-PV GIS-Model by Fakharizadehshirazi and Rösch (2024), involves several steps to ensure accurate decision-making, as illustrated in Fig. 1. A topographic overview of Iran is presented in Supplementary Figure S1.

ArcGIS Pro v2.7.2 was the primary platform used for data processing and spatial analysis. This enabled diverse datasets, such as those relating to solar radiation, topography and land use, to be integrated for PV and CSP site selection. Python 3.1 and the ArcPy libraries were used to automate geoprocessing tasks and support the advanced spatial analyses required by the modelling framework.

Data availability, a critical component of the methodology, for the case study in Iran is limited compared to more developed regions. To overcome this, a strategic decision was made to utilise open data repositories and use proprietary datasets, including information from organisations such as the Academy of Geospatial Sciences (AGSI, 2021) of Iran and widely used Open Street Map data, which provides a wide range of relevant datasets. Table 1 shows the geodata and sources used.

The analysis was carried out in two main stages. Restriction and suitability analysis. **Restriction analysis:** A GIS-based restriction model was used to exclude areas unsuitable for PV and CSP due to legal, environmental, and social constraints. Restriction layers (14 layers) included protected areas, water protection zones, agricultural lands, significant landscapes, forests, settlements, transport infrastructure, airports, waterways, and military zones. Buffer distances were applied according to the literature review. Each constraint is modelled in a single layer, and the combination of these layers provides a map of available areas for solar plant siting. The analysis excludes constraint areas, including buffer zones around sensitive land categories as defined by previous studies and national regulations (Supplementary Tables S2 and S3). A binary map (0 = excluded, 1 = eligible) was created by overlaying all exclusion layers to identify suitable land for solar development. The exclusion layers and their buffer distances are detailed in Table 2.

Suitability analysis: Non-constrained areas were assessed against nine suitability criteria, with each site receiving a score from 1 (high suitability) to 4 (very low suitability). The criteria are aggregated using a weighted arithmetic mean at a spatial resolution of 100 × 100-meter grid cells. The development of suitability criteria for the selection of PV and CSP sites is based on previous studies (Supplementary Tables S4 and S5) using nine criteria covering location (distance from roads, power lines, and residential areas), climate (solar radiation, maximum temperature, optical depth of dust aerosol and total cloud cover), and topographical factors (slope and orientation). Tables S6 in the supplementary document shows the suitability criteria considered in the current and previous studies. These nine criteria were used to evaluate sites for PV and CSP.

To optimise the evaluation process, the identified criteria were grouped into four categories: high, medium, low, and very low suitability. This classification is essential for evaluating different sites in Iran's diverse climatic and geographical regions. The suitability criteria and their classifications for PV and CSP are presented in Figs. 2 and 3 in the supplementary document, respectively.

The classes for PV and CSP for the locations were defined in the same way. The main difference is the slope, with the slope limitation for CSP being more restrictive than for PV. CSP can only be deployed in areas with a gentler slope.

Criteria weighting was evaluated through scenario-based sensitivity analyses to test the robustness of the suitability results. Sensitivity analysis was conducted to evaluate the robustness of the suitability results to changes in criteria weights. Four scenarios were analysed by varying individual criterion weights.

The classification of the suitability criteria allows a systematic grouping. The weighting of these criteria according to their importance is essential for the evaluation. According to the literature review, solar radiation is the most influential factor (Supplementary Table S7). Different scenarios (Scenario 1–4) were tested to analyse the effect of different weightings, including with and without proximity to power plants, and variations based on location, climate and topography. In scenario 4 weights for the suitability criteria were derived from a normalised average of values reported in the literature, with adjustments made to reflect local conditions in Iran. In particular, the weight for 'distance to transmission lines' was increased due to economic and grid limitations, whereas the weight for solar radiation was slightly reduced

Table 1
Used geodata and sources.

Category	Layers	Sources	Description	Resolution
Infra-structure	Road, railroads, waterways, powerlines	OSM (OSM, 2023)	Polyline	Unknown
	Power stations	(Transformator, 2023)	Point	Unknown
Land use	Settlement	(GHSL, 2023)	Raster	100 m
	Forest Agricultural land, wetland, airport	Academy of Geospatial Sciences of Iran (AGSI, 2021)	Polygon Polygon	Unknown Unknown
Topography	Slope, aspect	Earthdata-Nasa (2023)-Aster 30 m DEM (Nasa, 2023)	Raster	30 m
Climate	Maximum and average air temperature	Worldclim (2020)-(1970–2000) (WorldcClim, 2015)	Raster	1 km
	Cloud cover	ECMWF. ERA5 - (2003–2024) (ERA5)	Raster	~24 km
	Dusty days	Synoptic stations	In situ	-
	Direct Normal and Global Horizontal Irradiance	Global Solar Atlas-(1999–2018) (GLSA, 2023)	Raster	~300 m
Natural hazard	Iran Remote Sensing Academy	Iran Remote Sensing Academy (IRSA, 2019)	Polyline	Unknown
Protected area	Protected area	WDPA (2023) (WDPA, 2023)	Polygon	Unknown
	Military zone	OSM (OSM, 2023)	Polygon	Unknown

Table 2
Constraint layers for PV and CSP plants with the corresponding buffer zone.

Constraint Layers	Considered Buffer zone (m)	Considered Buffer zone (m) in National studies
Forests	200	100–1000
Agricultural land	500	100–400
Good pastures	200	-
Protected areas	1000	100–2000
Settlements	1000	500–10000
Railroad	1000	100–4000
Road	500	100–5000
Waterways	200	100–500
Wetland	100	100–500
Airport	3000	3000
Military zone	0	1000
Fault	500	200–1000
Floodplain	500	100–400
Slope > 15% (PV)	0	-
Slope > 3% (CSP)	0	-

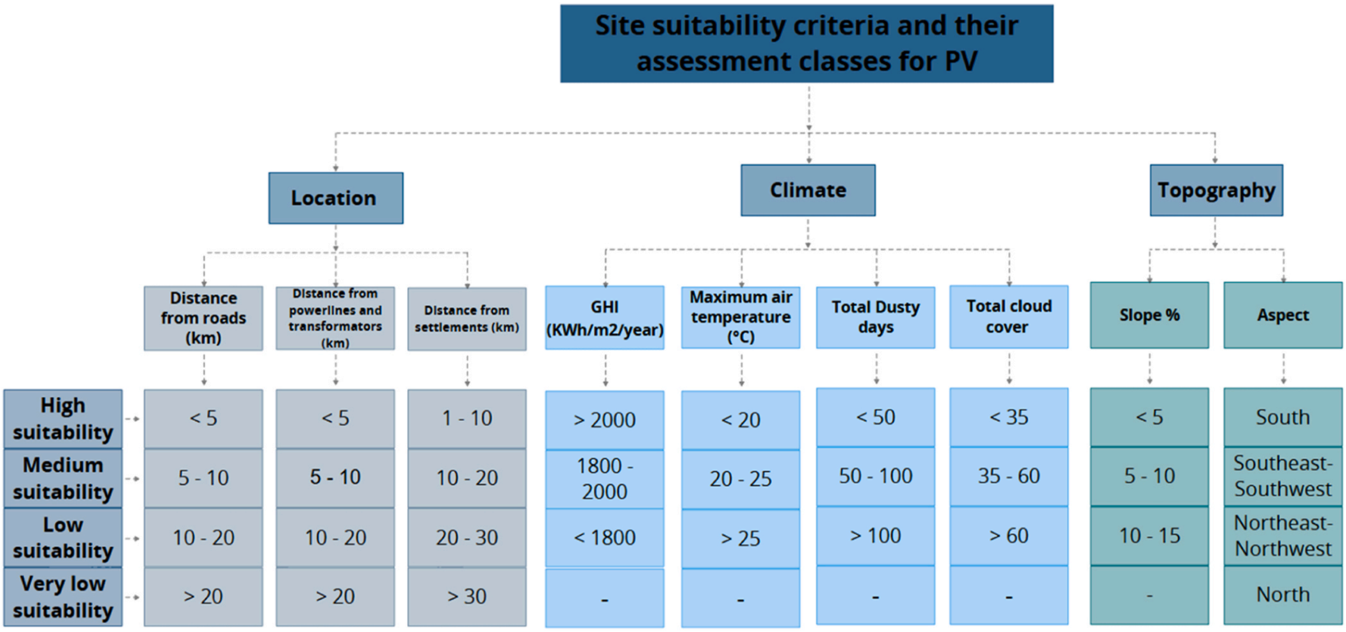

Fig. 2. Site suitability criteria and their assessment classes for PV parks.

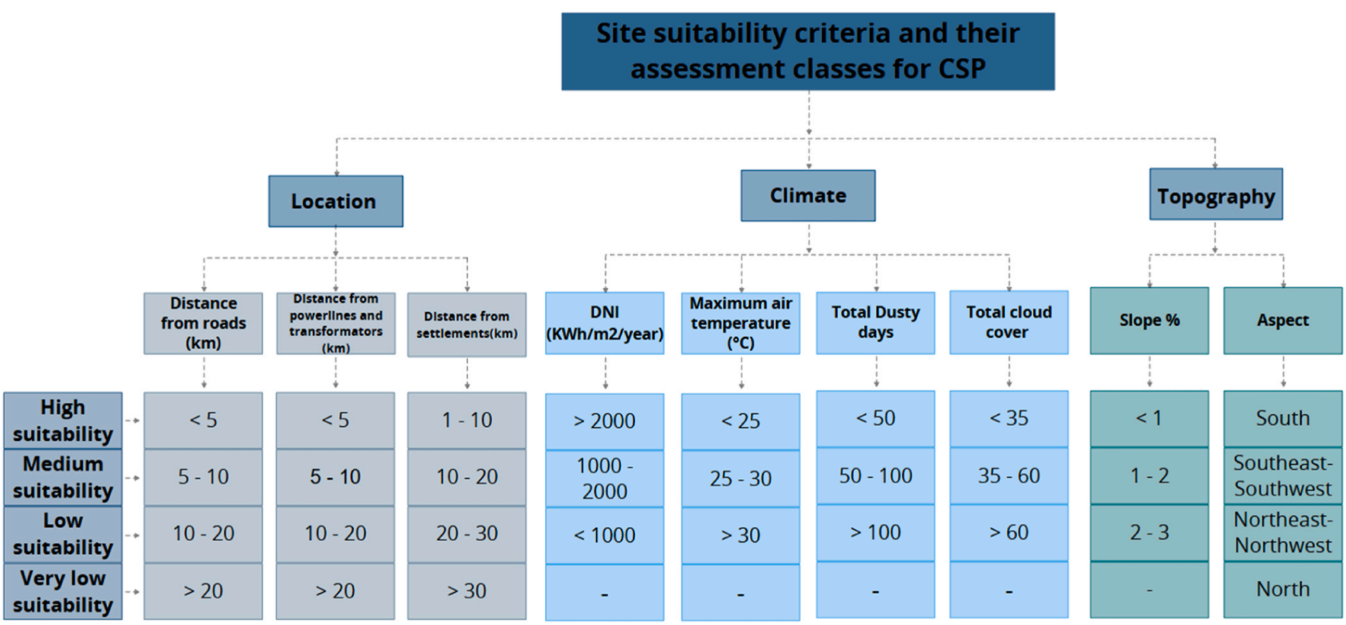

Fig. 3. Site suitability criteria and their assessment classes for CSP.

because of the high solar availability across Iran, which minimises its limiting effect. The remaining criteria largely follow the literature review, with minor differences arising from variations in the number and type of criteria used in previous studies. The suitability assessment criteria for PV and CSP were used to generate two separate maps, each showing four suitability levels. These were then integrated with the results of the constraint model.

For PV projects, land requirements typically range from 5 to 10 acres per megawatt of capacity, or 2–4 ha per MW, with 5 ha being a reasonable estimate for small projects (Solar Authority, 2024). CSP plants generally require more land. A significant CSP plant could require around 50 ha (Atomic Insights, 2010). Therefore, sites smaller than 5 ha were excluded from the PV map and sites smaller than 50 ha were excluded from the CSP map. They are divided into high, medium, low and very low suitability classes.

4. Results

4.1. Land constraints for PV and CSP

The constraint model developed in this study produces binary maps represented by 0 s and 1 s for PV and CSP installations, where 0 represents constrained areas and 1 represents open, unconstrained areas. Table 3 documents the number of constrained areas assigned to each factor. The percentage of restriction factors varies between 0.1% and 25.6%. The sum of the areas in Table 3 is greater than 100% due to overlapping restrictions caused by the different geological layers. The integration of these limiting factors results in the creation of the

Table 3
Percentage of excluded area in the constraint criteria for PV and CSP plants in the total area of Iran.

Constraints	Area excluded (%)
Infrastructure (Roads, Railroads)	22.1
River and Waterbody	25.5
Protected areas	9.4
Settlements	23.3
Agricultural areas	25.6
Good pastures	2.4
Forests	11.1
Wetlands	0.5
Natural hazards	13.1
Military zones	0.1
Airports	0.2
Slope > 15% (PV)	14.1
Slope > 3% (CSP)	51.6
Aspect (North direction)	12.9

constraint area map for installing PV and CSP (Supplementary Figures S2 and S3). These maps show that about 70% of Iran's land area is classified as unsuitable (excluded) for the construction of PV plants due to various constraints, while about 83% of the land area is similarly unsuitable (excluded) for the development of CSP plants. The main differentiator between these constraints for PV and CSP is the slope criterion, with PV land considered not feasible if the slope exceeds 15%, and CSP land considered not feasible if the slope exceeds 3%.

A suitability model for evaluating PV and CSP plants in Iran has been developed based on nine criteria that classify areas into four suitability categories. The model considers factors such as Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), air temperature, cloud cover, dust indices and slope, with weighted criteria derived from a literature review (Table S9). Four scenarios were considered for weighting the criteria (Table 4).

In Scenario 1, where equal weighting was applied to the "power station" and power lines criteria. For Scenarios 2–4, the evaluation model was executed without considering the distance to power stations. Scenario 1 results in a significant portion of the areas being considered to be very suitable due to their distance from power plants. It should be noted that the available power station data show 234 power stations in Iran (Transformator, 2023), which contradicts the information published by the Ministry of Energy (2023). According to this report, the number of power stations from 725 to 821 power stations within five years. This indicates that the map of existing power stations is underestimated. Therefore, the "distance to power station" criterion was removed from the evaluation criteria, and the focus was shifted to "distance to power lines." Power line data were extracted from OpenStreetMap OSM), which is considered a relatively reliable source of information on linear features such as power lines. Risch et al. (2022), found that OSM and Basis-DLM provide largely comparable information for several categories in Germany, particularly for line-like features such as power lines and railways. Basis-DLM, Germany's official vector-based digital landscape model, offers high positional accuracy: ±3 m for critical features such as roads, railways and watercourses, and ±10–15 m for other landscape objects. This makes it a precise and standardised GIS foundation for spatial analyses and planning.

Areas more than 20 km away from power lines classified as very low suitability. While longer distances were considered in some previous studies (Gouareh et al., 2021; Tlhalerwa and Mulalu, 2019; Ghasemi et al., 2019; Ziuku et al., 2014), the 20 km threshold was retained due to the economic importance of proximity to power lines and roads in Iran. The suitability model for both PV and CSP revealed minimal differences in the suitable areas between the two, as shown in Table 5. The final results of CSP interestingly did not contain any location in the „low suitability „category. As a result, the "very low suitability" areas accounted for a large percentage of Iran, reaching 54% in Scenarios 2 through 4.

Scenario 1 yielded significantly different results than the other scenarios, primarily due to the extensive areas classified as "very low suitability" caused by their distance from power stations. As a result, Scenario 1 was excluded from further consideration. Meanwhile, Scenarios 2 and 4 produced almost identical results. Scenario 3 was not far from scenarios 2 and 4. It was found that changes in weight distribution had little effect on the results. Therefore, Scenario 4 was selected for further analysis as it seemed consistent with the literature review results and the authors' comments.

4.2. Integration of constraint layer and classified suitability map

For further analysis, Scenario 4's results identifying suitable areas for PV and CSP construction were integrated with the results of the constraint model. The integrated results show the imposition of overlapping constraints and suitable areas in Figure S4 for PV and Figure S5 for CSP in the supplementary document. These maps visually represent areas that meet both the suitability and constraint criteria.

Fig. 4 provides an overview of the results by showing the percentage of suitable areas from the whole of Iran for PV and CSP in each suitability category. In summary, the analysis shows that about 14.5% of the total land area in Iran is suitable for PV park siting in high and medium suitability, while about 7.5% of the land area is suitable for CSP plant

Table 4
Assign weighting to criteria in four scenarios.

Category	Assessment criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Climate	GHI, DNI	12.0	12.0	25.0	40.0
	Average maximum air temperature	11.0	11.0	5.0	6.0
	Dust optical depth	11.0	11.0	2.0	2.0
	Total cloud fraction	11.0	11.0	2.0	2.0
Location	Distance to power lines	5.5	11.0	18.0	20.0
	Distance to power stations	5.5	-	-	-
	Distance to roads	11.0	11.0	9.0	8.0
	Distance to settlements	11.0	11.0	6.0	8.0
Topography	Slope	11.0	11.0	20.0	9.0
	Aspect	11.0	11.0	13.0	5.0

Table 5
Resulting shares of land area in the four scenarios and four suitability classes for PV parks and CSP.

Scenario	High suitability	Medium suitability	Low suitability	Very low suitability
		PV		
Scenario 1	3.8	8.8	0.0	87.4
Scenario 2	12.1	34.1	0.0	53.8
Scenario 3	13.4	32.6	0.2	53.8
Scenario 4	15.3	30.5	0.3	53.8
		CSP		
Scenario 1	0.0	8.5	0.0	87.4
Scenario 2	10.5	14.6	0.0	74.9
Scenario 3	9.0	16.1	0.0	74.9
Scenario 4	0.1	1.4	0.0	74.9

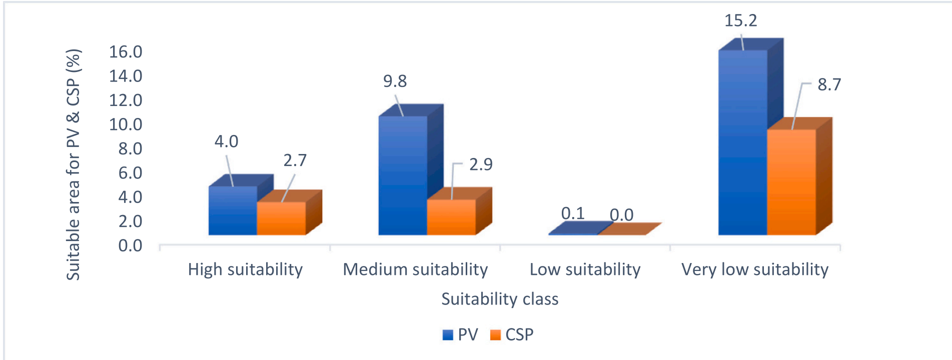

Fig. 4. Percentage of suitable area for constructing PV and CSP in Iran.

siting in two classes of high and medium suitability.

4.3. Integration of PV and CSP suitability map

By combining two suitable areas, one for PV and one for CSP, a final suitability map was created that incorporates both technologies (Fig. 5). This map offers a comprehensive view of the potential deployment locations for these solar energy systems. It reveals that areas rated as "high suitability" for both PV and CSP are predominantly found in Iran's central and eastern parts. However, a distinction becomes apparent in the western part of the country, where the suitability for PV and CSP diverges. The western regions are more suitable for PV, primarily due to the uneven terrain and steep ground conditions, making CSP plants less viable.

Figure S6 illustrates the suitability of the areas for PV and CSP plants. It shows the areas where these solar technologies can be practically deployed, considering their specific suitability criteria and constraints. Fig. 6 complements the analysis by showing the percentage of land suitable for PV and CSP installations throughout Iran. This figure helps renewable energy decision-makers and stakeholders make informed decisions about siting and resource allocation by providing valuable insight into the distribution and availability of suitable land for solar energy projects in the country.

4.4. Electricity generation potential in suitable PV and CSP areas

Scientists typically use PV power potential calculations to estimate the efficiency potential of PV systems. While these calculations are approximate, an estimation is provided by Aguilar et al. (2016). It is generally estimated that two hectares of PV parks are required to

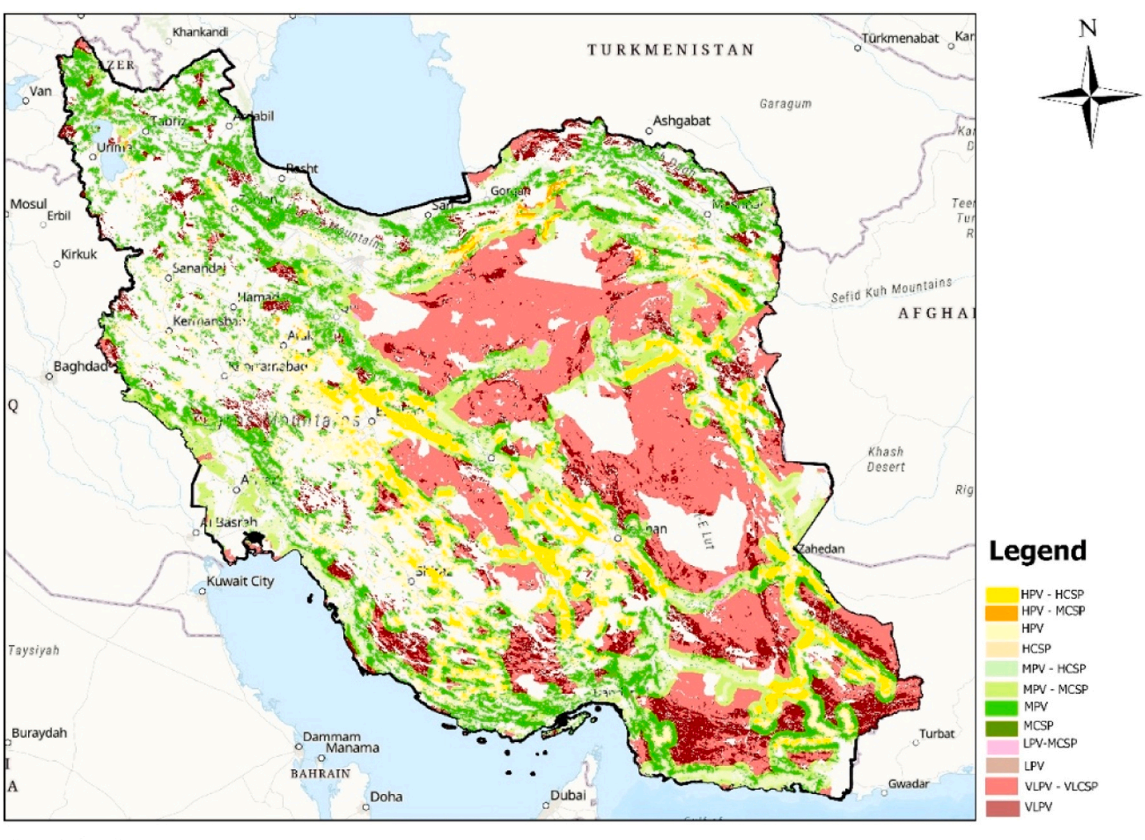

Fig. 5. Categorized suitable area for PV and CSP plant siting in Iran. Legend: VLPV: Very low suitability for PV, LPV: Low suitability for PV, MPV: Medium suitability for PV, HPV: High suitability for PV, VLCSP: Very low suitability for CSP, MCSP: Medium suitability for CSP, HCSP: High suitability for CSP.

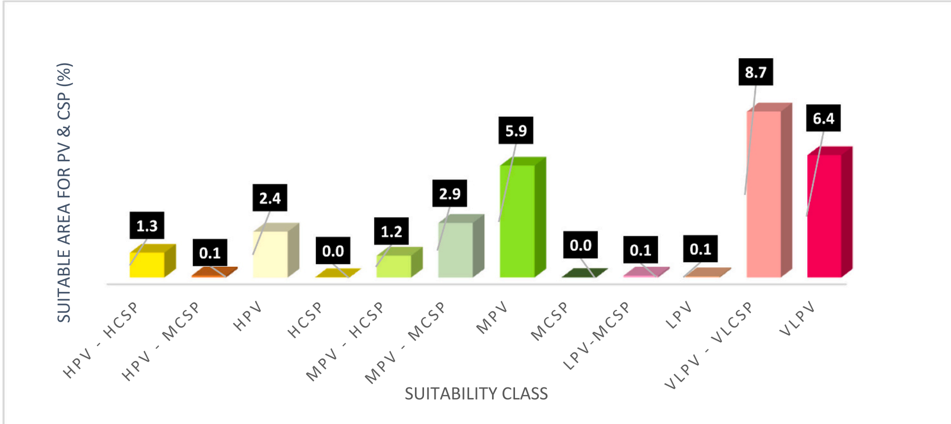

Fig. 6. Percentage of suitable area for installing PV and CSP plants in Iran. Legend: VLPV: Very low suitability for PV, LPV: Low suitability for PV, MPV: Medium suitability for PV, HPV: High suitability for PV, VLCSP: Very low suitability for CSP, MCSP: Medium suitability for CSP, HCSP: High suitability for CSP.

generate 1 MWp (megawatt peak) of electricity (Aguilar et al., 2016). Based on this assumption, and considering that 1 MWp is equivalent to 1000 kWh kilowatt-hours), an estimate of the electric generation potential of PV parks can be derived. Data from Ong et al. (2013) were used to determine the potential electricity generation from concentrated solar power (CSP). It was found that approximately 1.6 ha of land are needed to generate 1 MWp of electricity using CSP technology. Detailed estimates of electricity generation from CSP are presented in Table 6. Certain regions are suitable for both PV and CSP installations.

According to the IEA, (2020), Iran's total electricity consumption is approximately 325 terawatt hours (TWh). Solar energy's potential to generate electricity exceeds current generation. With the strategic installation of PV parks, Iran has the potential to meet its electricity needs on a significant scale effectively.

5. Discussion

Iran is promoting solar energy to reduce pollution and power shortages but is falling short of its targets. By 2023, 484 MW of the planned 933 MW of PV capacity had been achieved, with a target of 10,000 MW by 2025 (Tehran Times, 2023). Investment stands at 135 MW, with 3625 MW planned, highlighting the need for further development (Ministry of Energy, 2023). The results of this study demonstrate the potential of using GIS in the site selection process for PV and CSP plants in Iran. The binary constraint model shows that a significant portion of Iran's land area, about 70% for PV and 83% for CSP, is considered unsuitable for solar energy projects due to various geographical and environmental constraints. These constraints include steep slopes, which differ significantly in their suitability for PV and CSP. More than 15% slope makes land unsuitable for PV, while CSP requires an even stricter maximum slope of 3%. Notably, the percentage of very low suitability land for CSP is about two times higher than for PV. This difference is mainly due to the inherent restriction of CSP plant construction to areas with slopes higher than 3%.

Table 6
Estimation of electricity generation in potential areas PV and CSP plants.

Suitability classes	Electricity Generation Potential (TWh) - PV	Electricity Generation Potential (TWh) - CSP
LPV-MCSP	79	98
MPV - MCSP	2283	2853
MPV - HCSP	915	1144
HPV - MCSP	81	102
HPV - HCSP	1037	1297
VLPV	5120	6400
VLPV - VLCSP	6941	8676
LPV	46	-
MPV	4682	-
HPV	1917	-
MCSP	-	19
HCSP	-	11

Legend: VLPV: Very low suitability for PV, LPV: Low suitability for PV, MPV: Medium suitability for PV, HPV: High suitability for PV, VLCSP: Very low suitability for CSP, MCSP: Medium suitability for CSP, HCSP: High suitability for CSP.

This distinction highlights the need to tailor site selection criteria to the specific requirements of each technology. In the analysis of the impact of slope on the viability of CSP plants, substantial areas in western and northern Iran are deemed poorly suitable or unsuitable for CSP development due to their topographic features. It is worth noting that even in regions with lower levels of DNI and GHI, higher maximum air temperature, higher levels of dust, and higher levels of cloud cover, there are still opportunities for constructing solar power plants. Although these conditions may slightly reduce the efficiency of solar power plants, their overall effectiveness is significant.

CSP plants use wet, dry or hybrid cooling systems to reject heat. While wet cooling is efficient, it requires large volumes of water, which is impractical in arid regions. In contrast, dry cooling can reduce water use by 80–90%, making CSP a feasible option even in arid areas. Hybrid systems strike a balance between water savings and efficiency (Alami Merrouni et al., 2018). Thanks to dry-cooling technology, CSP plants in Iran can operate efficiently in arid and water-scarce regions without the need for large amounts of water.

Determining the socio-technical potential of installing solar power plants in certain areas requires careful evaluation, especially in developing countries such as Iran, which are facing economic problems. In particular, areas with steep terrain and remote locations away from roads and power lines do not offer economically viable options. The maps illustrate this problem, as two major regions in Iran, the Lut desert and the Kavir desert (in the centre of the country, see Supplementary Figure S1), are considered very low suitable because of their distance from infrastructure and human settlements.

The analysis of proximity to power stations showed a major challenge to installing solar power plants in many areas of Iran due to the long distance between these potential sites and the nearest power plant. This distance factor plays a significant role in determining the economic feasibility of solar power plant projects. Areas that are located far away from power plants may have higher infrastructure costs, mainly due to the need for extending and constructing new transmission lines and substations. In developing countries, such as Iran, where economic considerations are paramount, these additional costs can make solar power projects financially unviable.

Numerous studies have investigated the potential for photovoltaic (PV) in Iran, while concentrating solar power (CSP) has received much less attention. However, interest in CSP is growing as its potential is increasingly recognised. However, most of these studies focus on specific regions rather than providing a comprehensive nationwide assessment. Of the 15 studies reviewed in the literature, 13 were limited to analysing specific regions within Iran, while only three studies examined the potential for the entire country. In addition, 13 studies focused exclusively on PV park potential, one study analysed CSP potential, and only one addressed both PV and CSP technologies. Therefore, this study is the first comprehensive analysis of the potential for both PV parks and CSP plants across Iran, using a comprehensive set of constraints and suitability criteria.

The study by Ghasemi et al. (2019) distinguishes site selection criteria for PV plants and CSP based on global horizontal irradiation (GHI) for PV and direct normal irradiation (DNI) for CSP. In comparison, this study introduces additional criteria, including distinct slope thresholds and minimum size requirements, for PV and CSP applied at a nationwide scale and integrated with constraints and suitability maps for a more realistic site selection. Noorollahi et al. (2016) presented a detailed assessment of the potential of PV parks across the country. A comparison between the current study and Noorollahi's findings reveals significant differences in the results. For example, Noorollahi et al. (2016), Ghasemi et al. (2019) identified 14.7% of Iran's land area as highly suitable for PV parks, while the current study identified only 4% as highly suitable. In addition, restricted areas accounted for 35.8% of the total area in Noorollahi et al. (2019), (Noorollahi et al., 2016)'s study, compared to approximately 70% in the current study.

The discrepancies between the present study and that of Noorollahi et al. (2016) arise from substantial differences in the number of restriction layers used, the buffer criteria employed, the suitability thresholds applied, and the sources of the input data. Noorollahi et al. (2016) applied six restriction layers, whereas the present study used fourteen, many of which incorporated buffer zones that increased the extent of excluded land. For instance, Noorollahi et al. did not apply buffer zones around forests or agricultural areas, whereas the present study incorporated 200–500 m buffers around these areas. Additionally, 'good pasture' land, which is critical for Iran’s livestock economy, was classified as restricted in the present study, but not excluded in Noorollahi et al., 2016's analysis.

Differences in suitability criteria also had a significant impact on the results. In Noorollahi et al. (2016), land located less than 50 km from transmission lines was considered suitable; however, the present study applied a stricter condition, considering only land within 20 km as suitable. Furthermore, highly suitable areas in the present study were required to be within 5 km of transmission lines. These tighter thresholds significantly altered the spatial distribution of the suitability outcomes, demonstrating the strong impact that methodological decisions can have on final classifications. As suitability results are highly sensitive to such choices of criteria, it is essential to engage stakeholders, including planners, energy authorities and environmental agencies, to ensure that threshold values reflect practical, economic and environmental priorities.

Variation in data sources also contributed to the observed differences. The present study relied exclusively on freely available datasets, which have inherent limitations. Some power station data in Iran is outdated; national infrastructure datasets contain gaps and inconsistencies; the cloud cover used is at a coarse spatial resolution; and dusty day information from synoptic stations has not been updated recently. These inconsistencies in data quality and temporal coverage also influenced the variation in suitability outcomes between the two studies.

6. Conclusion

This study emphasises the vital role of geographic information systems (GIS) in integrating multiple criteria, conducting sensitivity analyses, and evaluating potential cost and time savings. GIS studies are also crucial for identifying the most suitable locations for photovoltaic (PV) and concentrated solar power (CSP) installations. The study demonstrates that solar energy has the potential to surpass current electricity generation levels, address environmental concerns, fulfil domestic energy needs and enable Iran to export energy, thereby establishing itself as a regional electricity exporter. The results demonstrate that solar power can play a pivotal role in combatting climate change by providing sustainable and resilient energy, while reducing dependence on fossil fuels and imports. This will facilitate the transition to sustainable, resilient and affordable energy systems. It should be noted that the results of the GIS study depend on the technologies being investigated, land availability and the structural and environmental constraints of solar power generation, particularly with regard to solar radiation, climatic conditions and topography. This study does not explore the integration of concentrated solar power (CSP) with photovoltaics (PV) or other power generation technologies. Future studies should therefore consider the technical potential of hybrid systems, which could further enhance efficiency and energy reliability. The study is limited by the availability of freely accessible data from multiple sources, which vary in spatial resolution and temporal coverage. This could affect the accuracy and comparability of the results.

Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

Irene Peters: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Christine Rösch:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Reza Rezagholi:** Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elham Fakharizadehshirazi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2026.109170.

Data availability

Data will be made available on request.

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