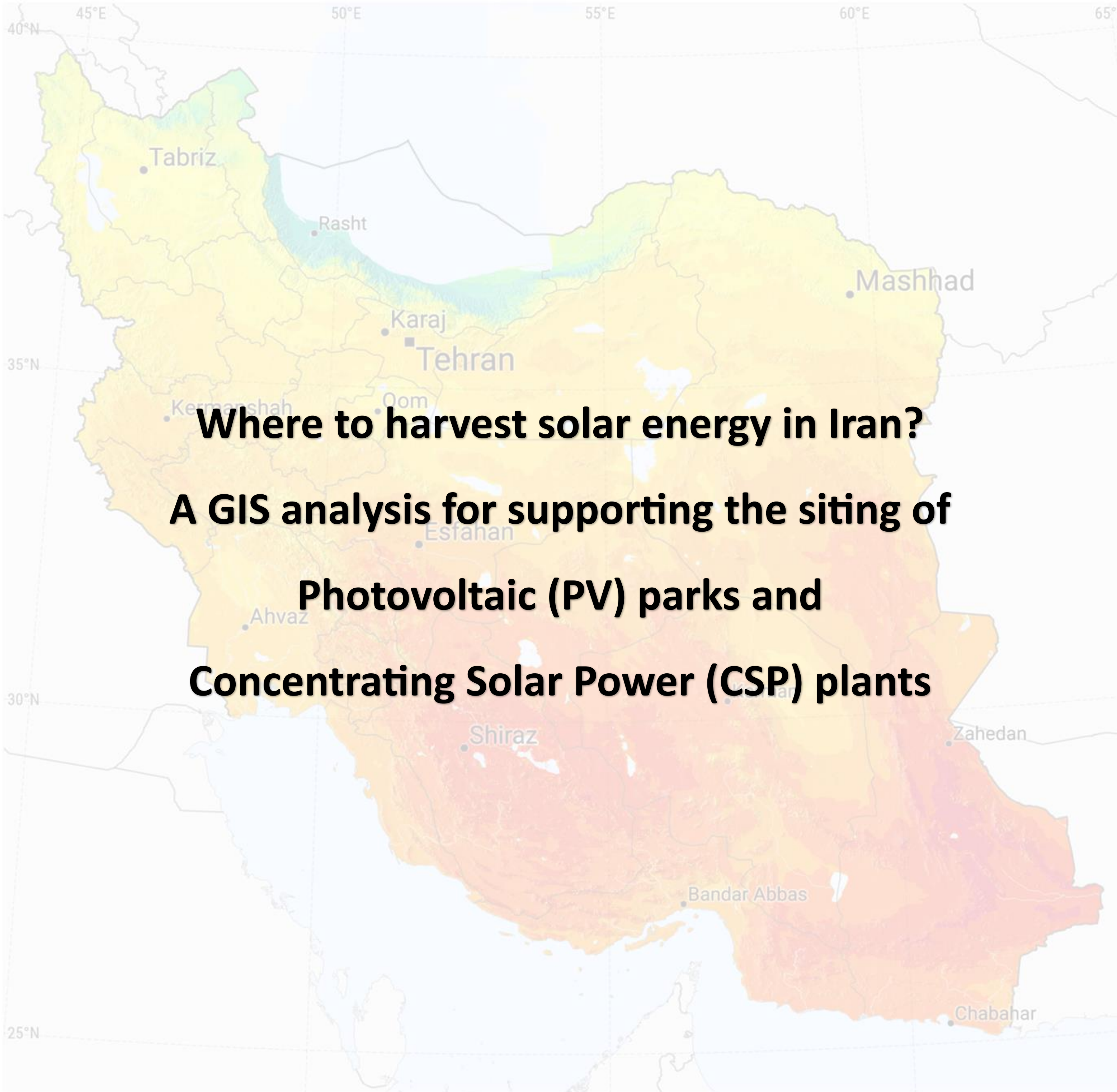
Where to harvest solar energy in Iran?

A GIS analysis for supporting the siting of Photovoltaic (PV) parks and Concentrating Solar Power (CSP) plants



Where to harvest solar energy in Iran?
A GIS analysis for supporting the siting of Photovoltaic (PV) parks and Concentrating Solar Power (CSP) plants

By: **Reza Rezagholi**

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HafenCity University Hamburg

Supervisor: **Prof. Irene Peters, Ph.D.**

HafenCity University Hamburg (HCU)

Co-supervisor: **Dr. Elham Fakharizadehshirazi**

Karlsruher Institut für Technologie (KIT)

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Abstract

Iran is a country with a large potential for harvesting solar energy which is barely tapped yet. This study presents a Geographical Information System (GIS) model for siting solar energy plants in Iran. There is enough space for Photovoltaics (PV) as well as Concentrating Solar Power (CSP), the latter being a technology that has not received the attention it deserves as a viable renewable energy technology with many advantages.

The GIS model developed in this study uses constraints that rule out a solar plant siting and suitability criteria that indicate four suitability classes ranging from “high” to “very low” for both PV and CSP. The chosen constraints (f. ex. nature preserves) and suitability criteria (f. ex. solar irradiation and proximity to power grid lines) are based on the literature.

The synthesis of the constraint and suitability maps results in feasible sites and their preferability. A sensitivity analysis with respect to weighting the suitability criteria shows the robustness of these results.

The analysis underlines Iran's substantial potential for solar energy generation. The country could meet its current power generation multiple times with solar plants. In addition, the analysis shows the promising prospects of GIS modeling in renewable energy siting, highlighting the prospects for improved data integration, global scalability, comprehensive environmental impact assessment, and harmonization of policy considerations.

Kurzzusammenfassung

Der Iran ist ein Land mit großem Potenzial für die Nutzung von Solarenergie, das noch kaum erschlossen ist. In dieser Studie wird ein Geografisches Informationssystem (GIS) für die Standortwahl von Solarenergieanlagen im Iran vorgestellt. Das Land bietet viel Raum für Freiflächen-Photovoltaik (PV) und solarthermische Kraftwerke (Concentrating Solar Power, CSP), wobei letztere Technologie noch nicht die Aufmerksamkeit erhalten hat, die sie als Erneuerbare-Energien-Technologie mit verschiedenen Vorteilen verdient.

Das in dieser Studie entwickelte GIS-Modell verwendet sowohl für PV als auch für CSP sog. Constraints (Einschränkungen), die prinzipell mögliche Standorte für Solarkraftwerke ermitteln, indem sie unmögliche Standorte ausschließen, sowie Eignungskriterien, die in vier Eignungsklassen von "hoch" bis "sehr niedrig" gefasst werden. Die verwendeten Constraints (bpsw. Naturschutzgebiete) und Eignungskriterien ((bpsw. die Nähe zu Stromtrassen für die Aufnahme des erzeugten Stroms) basieren auf der Fachliteratur.

Die Synthese der Constraints- und Eignungskarten ergibt mögliche Standorte und deren Eignung. Eine Sensitivitätsanalyse variiert die Gewichtung der Eignungskriterien und zeigt die Robustheit dieser Ergebnisse.

Die Studie zeigt das erhebliche Potenzial Irans für die Stromerzeugung aus Sonnenenergie. Mit Ausbau der PV und CSP allein schon an den Standorten mit „hoher“ Eignung könnte das Land seine derzeitige Stromproduktion um ein Vielfaches übertreffen. Zudem demonstriert die Studie die vielversprechenden Möglichkeiten der GIS-Modellierung für die Standortwahl erneuerbarer-Energien-Anlagen. Diese liegen in einer verbesserten Datenintegration, globalen Skalierbarkeit, raumbezogenen Abschätzung von Umweltauswirkungen und einer Harmonisierung energiepolitischer Maßnahmen.

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List of Abbreviations

A-Si Amorphous silicon

ANP Analytical Network Process

BWM Best-Worst Method

CAMS Copernicus Atmosphere Monitoring Service

CdTe Cadmium Telluride

c-Si Crystalline Silicon

CIGS Copper Indium Gallium Selenide

CIS Copper Indium Sulfide

CSP Concentrating Solar Power

CSPP Concentrating Solar Power Plant

DEM Digital Elevation Mode

DHI Diffuse Horizontal Irradiance

DNI Direct Normal Irradiance

DSSCs Dye-Sensitized Solar Cells

EQW Equally Weighted

GaAs Gallium Arsenide

GHSL Global Human Settlement Layer

GHI Global Horizontal Irradiance

GIS Geographical Information System

HTF Heat Transfer Fluid

kWh Kilowatt-hours

kWh/m2 Kilowatt-hours per square meter

LFR Linear Fresnel Reflector

mc-Si Multi-Crystalline Silicon

MCE Multi-Criteria Evaluation

MSDM Multi-Criteria Decision Making

MW Megawatt

MWp Megawatt peak

OPVs Organic Photovoltaics

OSM OpenStreetMap

OWA Ordered Weighted Averaging

PSCs Perovskite Solar Cells

PTC Parabolic Trough Collector

PV Photovoltaic

PVP Photovoltaic Park

QDs Quantum Dot Solar Cells

Sc-Si Single-crystal Silicon

SPT Solar Power Tower

TES Thermal Energy Storage

TWh Terawatt-hours

UN United Nation

WDPA World Database on Protected Areas

WLC Weighted Linear Combination

Chapter 1 Introduction

1.1 Iran's solar energy potential

Humankind's heavy reliance on fossil energy sources such as coal, gas, and oil have severe consequences, particularly in terms of air pollution and the emission of greenhouse gases, of which carbon dioxide is a major contributor. These energy carriers, in their mining and transport, also pose a significant threat to critical natural ecosystems by releasing harmful compounds and disrupting essential ecosystem services (Barzehkar et al., 2021). In response to these threats, countries around the globe look to renewable energy sources. Solar farms are a renewable energy source, offering viable opportunities for present and future generations, and this is not only in ecological terms. Already the cost of solar energy technology has decreased so dramatically that it is cheaper than fossil fuel technology in many places, even if that is subsidized. Solar energy technologies are well on their way to being very competitive in economic terms.(Dhunny et al., 2019).

Solar energy is increasingly attracting attention in Iran as an abundant and renewable resource with several environmental benefits. As a clean and environmentally friendly source of electricity, solar power can significantly reduce greenhouse gas emissions and air pollution, improving energy security and creating local employment opportunities. Despite relatively high up-front investment cost, there has been significant progress in establishing solar farms that use Photovoltaic (PV) panels or Concentrated Solar Power (CSP) plants. Furthermore, PV has the valuable ability to generate electricity during peak demand periods, especially on hot summer days. This feature relieves pressure on the grid and reduces the risk of power outages, and it is an essential benefit as Iran has recently experienced blackouts challenging its energy infrastructure. Frequent power shortages and blackouts have not only been an inconvenience to the population but have also impacted various industries and businesses, resulting in economic disruption. Iran can significantly improve its energy resilience and reliability by harnessing the potential of solar power to generate electricity during peak demand periods. (DW, 2023; Somerville, 2022).

Moreover, the negative impact of sanctions on the environment of Iran extends beyond CO_2 emissions. The imposition of sanctions has also impacted the adoption of renewable energy sources. The fact that Iran relies on imported materials for renewable energy projects because of limited local manufacturing capabilities raises concerns about the quality, cost, and overall effectiveness of such materials. Relying on imported resources hinders the country's self-sufficiency in implementing renewable energy and creates barriers to widespread adoption. The high cost and dependency on imported systems are the main reasons why politicians and the population view renewables negatively. These challenges underscore the significant role of sanctions in impeding environmental progress in Iran and contributing to the country's overall environmental degradation (Fotourehchi, 2020).

The country's low price of fossil fuel contributes to the fact that renewable energy is less attractive to managers, civil servants, and consumers, as economic factors significantly impact attitudes and behavior toward energy sources. Governmental policies and the lack of a clear roadmap for developing renewable energy pose significant barriers. Stakeholders face uncertainty and hesitation, and potential investors and developers are discouraged from pursuing renewable energy projects without supportive policies and a well-defined strategy. A clear policy framework with incentives to help transition to renewable energy is essential to help build social acceptance and promote renewable energy adoption (Solaymani, 2021).

Achieving a sustainable future depends to a large extend on harnessing the potential of renewable energy. Iran is rich in solar irradiation which can be utilized with PV and CSP. These technologies can play an essential role in the common efforts to combat climate change, reduce dependence on fossil fuels and help countries move towards sustainable, low-carbon energy systems. Countries with favorable solar conditions, such as Iran, whose high annual irradiation exceeds 1900 kWh/m2 (*SOLARGIS*, 2020) , stand out as promising regions for implementing Concentrated Solar Power plants. Iran has an excellent opportunity to effectively produce solar energy with the CSP technology. The country can significantly contribute to the fight against climate change by using its renewable resources.

1.2 Research task and method

Geographical Information Systems (GIS) are an efficient decision-supporting tool for siting renewable energy plants. GIS can significantly reduce the time and cost of the site selection process by utilizing and combining various databases on geographical locations. Geography is of the essence in site selection for both PV and CSP (Barzehkar et al., 2021).

In this section, I will highlight the objectives, approach, and innovative aspects of my work by describing the research problem and method of this study.

My main objective is to evaluate and compare the suitability of photovoltaic (PV) and concentrated solar power (CSP) sites under different conditions in Iran.

I develop a GIS model with constraints (conditions that rule out locations for solar plants siting, like the presence of a nature preservation area) and criteria for assessing the suitability of sites for solar plant location (an example for such a suitability criterion is proximity to power lines, which affects the economics of a plant).

These suitability criteria can take on the values „high“, „medium“, „low“ and „very low“ suitability for hosting a solar energy plant. I then apply weights to the suitability criteria which I vary for the purpose of sensitivity analysis. The result is a classification of sites regarding their suitability for PV and CSP. My choice of constraints, suitability criteria, and their weighting is based on the literature.

What makes my study different from previous studies is

— I look at both PV and CSP sites simultaneously

— I apply more comprehensive constraints and assessment criteria than in previous studies

— I deliberately do not use one of the more elaborate decision support techniques like the Analytical Hierarchy Process (AHP) for the sake of greater transparency. Instead, I rely on a simpler sensitivity analysis in applying the suitability criteria to show the robustness of my results.

1.3 How this thesis is organized

As the reader can expect in the following chapters, I provide an overview of the organization and structure of this paper.

Chapter 1 introduces the context of Iran's solar energy efforts and provides insights into the country's renewable energy goals and the need for efficient siting methods.

Chapter 2 provides a brief overview of Iran, describes the country's geographic location and energy situation, and lays the foundation for the discussions in the following chapters.

Chapter 3 covers the basics of photovoltaic (PV) and concentrating solar power (CSP). By explaining these renewable energy systems, the foundation is laid for the analysis that follows.

Chapter 4 begins with a comprehensive literature review, examining the existing research on PV and CSP siting both internationally and in Iran, and identifying the gaps and needs for my study.

Chapter 5 outlines my methodology. It explains the tools, datasets, and procedures used for site selection, including the innovative aspects of my approach such as sensitivity analysis.

Chapter 6 presents and discusses the results of my analysis in detail to shed light on the suitability of PV and CSP plants in different regions of Iran.

Chapter 7 summarizes the main findings, discusses their implications, and provides an outlook on the future of renewable energy siting in Iran.

Chapter 2 Short Portrait of Iran

2.1 Physical and human geography of Iran

Iran, which occupies an area of 1,640,195 square kilometers, is located primarily on the Iranian plateau in the southern half of the northern temperate zone, which includes geographic coordinates between 25°, 03′ and 39°, 47′ north latitude and 44°, 05′ and 63°, 18′ east longitude. Iran, 18th largest country in the world by area, has a unique and diverse climate that sets it apart from its neighboring countries. The annual temperature range is approximately 40 to 50 °C between its hottest and coldest regions. For example, while Shahrekord can record temperatures as low as 30 °C on a winter night, Ahvaz can experience scorching temperatures of 50 °C in the summer (Alamdari et al., 2013).

The landscape of Iran is characterized by the Elburz Mountains (Figure 1), which extend for more than 1000 km from the west to the east, serving as the northern boundary of the Iranian plateau and running along the southern coast of the Caspian Sea. These mountains vary in width from 30 km to 130 km and are adorned with Hyrcanian forests on their northern slopes. In the northeast, the Kopet Dagh Mountains stretch 650 km between Iran and Turkmenistan, while the Zagros Mountains run along the western and southwestern borders of the Iranian Plateau, stretching 1500 km from Turkish Kurdistan to southeastern Iran. In addition, Iran is home to two well-known deserts, the Kavir Desert and the Lut Desert[1], both of which are located in the central plateau and are known for their extreme heat (Kehl, 2009).

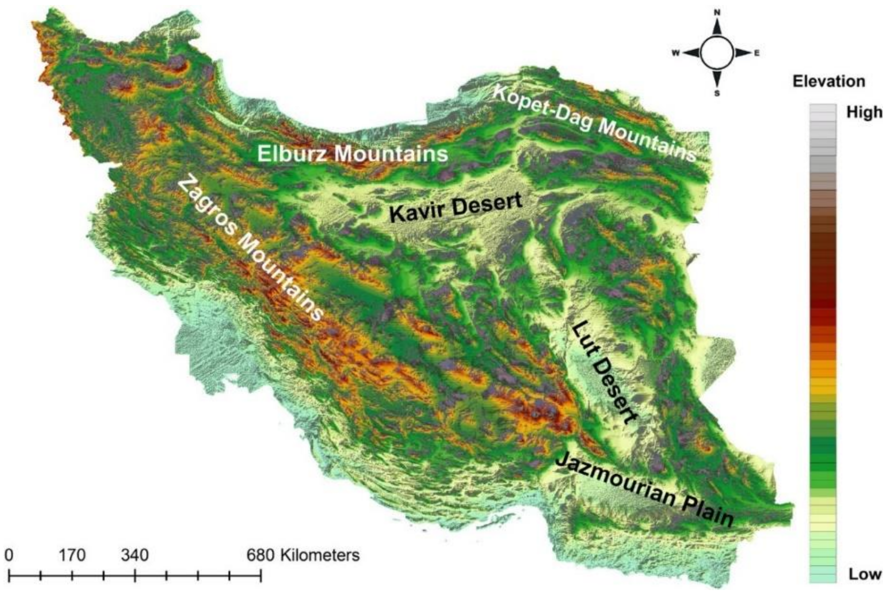


Figure 1 Topographic overview of Iran (Kafash et al., 2020)

[11] The hottest place in the world between 2004 and 2007, and 2009
https://earthobservatory.nasa.gov/features/HottestSpot/page2.php

The latest population statistics in Iran indicate that it has a considerable population of around 87 million people. Tehran, the capital city, is the largest urban center in the country, with a significantly high population of nearly 8 million residents. Additionally, there are several other major cities in Iran, including Mashhad, Isfahan, Karaj, Shiraz, and Tabriz which also have substantial populations.

Iran is geographically divided into five regions comprising 31 provinces (Figure 2), each further divided into counties, districts, and sub-districts. The country has witnessed significant urbanization, with the urban population growing from 27% to 60% between 1950 and 2002. The highest levels of socioeconomic development are observed in provinces like Tehran, Isfahan, and Semnan, with a more urbanized population. Conversely, provinces such as Sistan and Baluchistan, Golestan, Hormozgan, Kohgiluyeh and Boyer-Ahmad, and North Khorasan have higher percentages of rural inhabitants. Iran experiences moderate internal migration, with around 12% of its population changing residences every five years. This migration rate is similar to countries like Indonesia, Vietnam, and Thailand, but below the global and Asian averages of 21% and 17%, respectively (Bell, 2020).

Figure 2 Provinces of Iran (Ghahari et al., 2017)

Figure 3 displays a visual representation of renewable power plant projects that were implemented until early 2022 in Iran. The provinces of Ghazvin, Yazd, Kerman, and Fars are highlighted as progressive regions in terms of renewable energy development. These provinces have seen substantial progress in adopting and implementing renewable power projects.

In Ghazvin, there is a total renewable power plant capacity of 169 MW, indicating significant strides in clean energy adoption. Similarly, Yazd has made considerable progress with a renewable energy capacity of 98 MW. Kerman and Fars provinces have also shown strong commitment to renewable energy, each with a capacity of 98 MW and 93 MW, respectively.

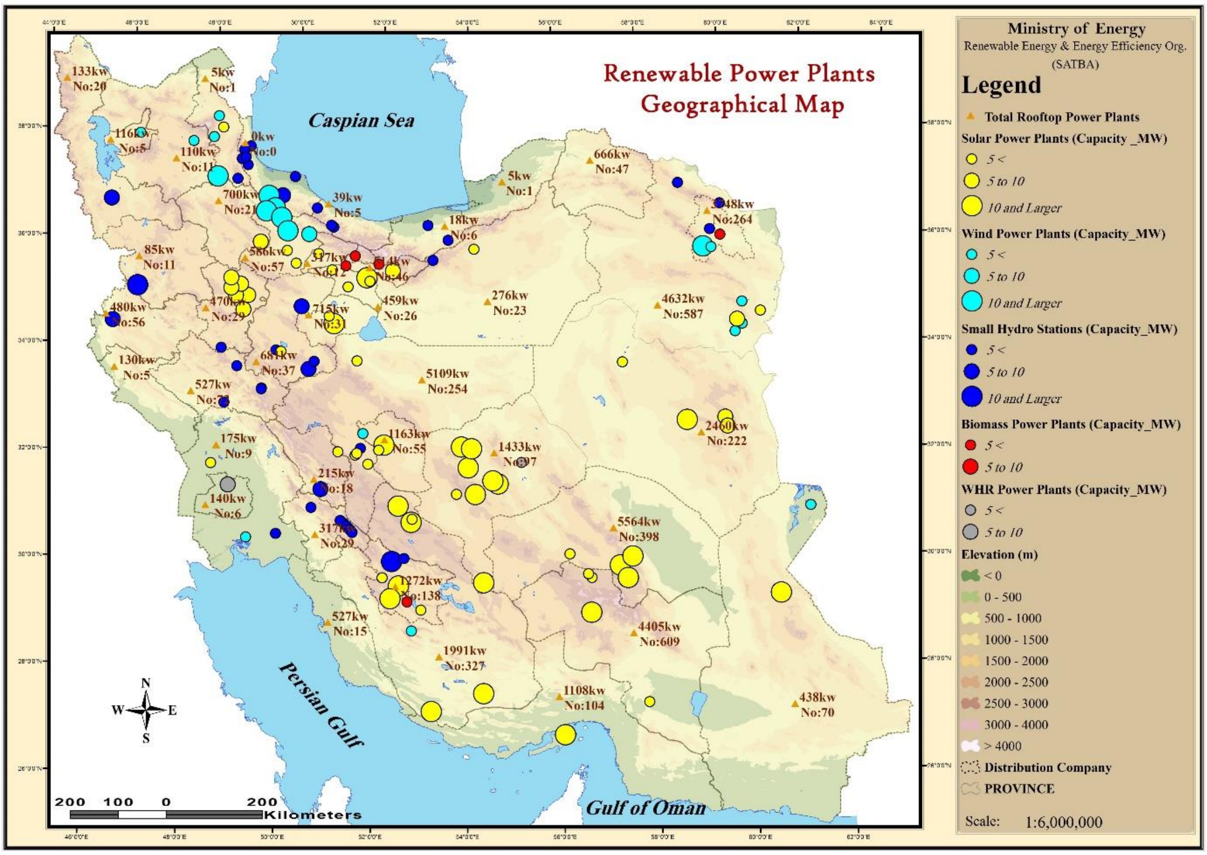


Figure 3 Renewable power plants (SATBA, 2022)

In term of potential photovoltaic (PV) (Figure 4), Iran reveals promising opportunities across different regions of the country. Iran's vast and diverse landscapes offer varying levels of solar irradiance, making it well-suited for solar energy generation. In the southern provinces, such as Yazd, Hormozgan and Kerman, where the sun shines intensely, the solar potential is exceptionally high, making them prime locations for large-scale PV installations. These regions could host solar parks with capacities to rival conventional power plants. Northern provinces, such as Gilan and Mazandaran, receive less sunlight but still have enough solar potential to contribute to Iran's renewable energy goals. The central and western provinces, including Tehran, Isfahan, Yazd and Alborz, offer excellent opportunities. By harnessing the solar potential of these diverse regions, Iran can pave the way for a sustainable and clean energy future, while reducing its dependence on fossil fuels and mitigating environmental challenges.

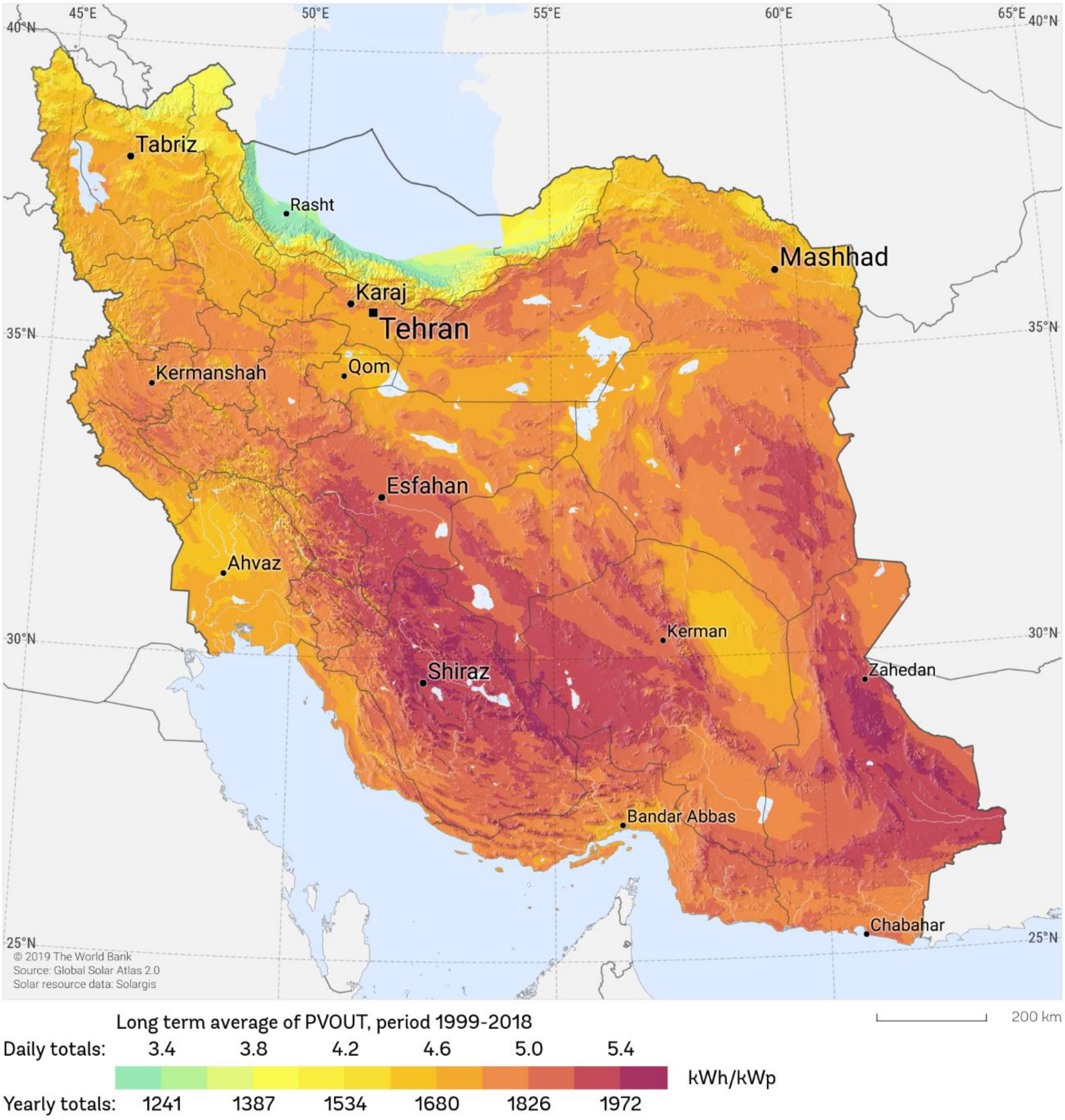


Figure 4 Photovoltaic (PV) power potential (*SOLARGIS*, 2020)

2.2 Iran's energy system and goals for an energy transition

Iran, a nation blessed with abundant hydrocarbon resources, has long relied on fossil fuels, primarily oil and gas, to fuel its energy system. This dependence, while economically significant, has come at a heavy environmental cost. The country's major cities grapple with severe pollution, largely attributed to the emissions from these conventional energy sources. Additionally, during the sweltering summer months, Iran experiences power shortages due to the surging demand for electricity, driven by the expansion of its industrial and agricultural sectors.

The Iranian government has actively promoted the establishment of photovoltaics (PV) to provide clean energy to villages and cities. PV can be applied to buildings and in urban space and can also be mounted on large structures in the open land, in so-called „parks ". These PV parks are a particularly low-cost option to utilize PV, where there is sufficient land. Many countries with large stretches of uninhabited land and deserts have constructed such PV parks, often with a capacity of several hundred MW, even thousands MW per park, nearing the capacity of a conventional coal-fired or nuclear power plant.

Despite commendable efforts, the previous development plan (2016-2021), which aimed to install 5,000 MW of renewable energy capacity, fell short of the target. As Iran looks ahead to the next development plan[2], there is an urgent need for substantial investment to bridge the gaping power generation deficit and accelerate the transition to renewable energy sources. This underscores the critical importance of a well-coordinated effort to achieve these energy-related goals.

As per the most recent report from the International Energy Agency in 2020, the total electricity generation amounted to around 325 TWh, accounting for only 5 percent of the total energy production from renewable sources. Specifically, photovoltaic (PV) technology accounted for approximately 5 percent of the entire renewable energy output. In other words, while renewable energy is a small portion of the overall energy production, PV technology contributes a small fraction of that renewable energy production (*Figure 5*).

[2] 7th Five-Year Development Plan (2023-2027): This policy document shapes Iran's economy-wide development program, aligned with the nation's ongoing commitment to five-year plans and associated initiatives.

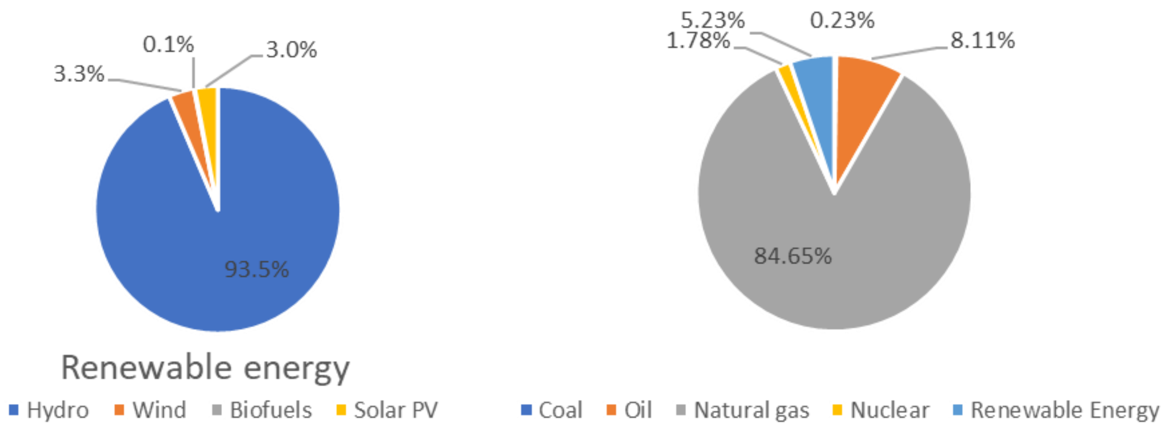


Figure 5 Electricity generation by source, Iran

Despite the dramatic decline in the solar energy market due to the COVID-19 pandemic, Statista's forecast predicts that the solar energy market in Iran will grow by nearly 5% per year until 2028 (Statista, 2023). On the other hand, the Iranian Ministry of Energy has made it a priority to increase the country's renewable power plant capacity by 10,000 MW by the end of the current government's term in August 2025 (tehrantimes, 2023).

By 2022, investment in renewable power plants have reached an impressive milestone, totaling around 135 megawatts. However, the future looks even brighter with ambitious plans on the horizon. A substantial 3625 megawatts of additional renewable energy capacity are currently in the planning stages (Ministry of Energy, 2023). This initiative underscores the importance of continued investment and advancement in solar energy infrastructure as a means of advancing Iran's clean energy goals and reducing its dependence on non-renewable energy sources.

Chapter 3 Basics on the Photovoltaics (PV) and Concentrating Solar Power (CSP) Technologies

3.1 Concentrating Solar Power (CSP) systems: From the beginnings to next generation technology

CSP is a clean technology. It harnesses the sun's energy by focusing its rays onto a receiver containing a fluid, such as thermal oil or molten salts, to transfer heat. This fluid, called a Heat Transfer Fluid (HTF), HTF generates electricity through a steam turbine generator, like conventional thermal power plants. There are four main CSP technologies on the market: parabolic trough, solar tower, linear Fresnel, and parabolic dish (Figure 6). Parabolic trough is the dominant technology in CSP installations to date, with a market share of 81 percent. Fresnel and parabolic dish systems account for a very small fraction of the current installed capacity, with most of the remaining installations being solar towers (worldbank, 2021).

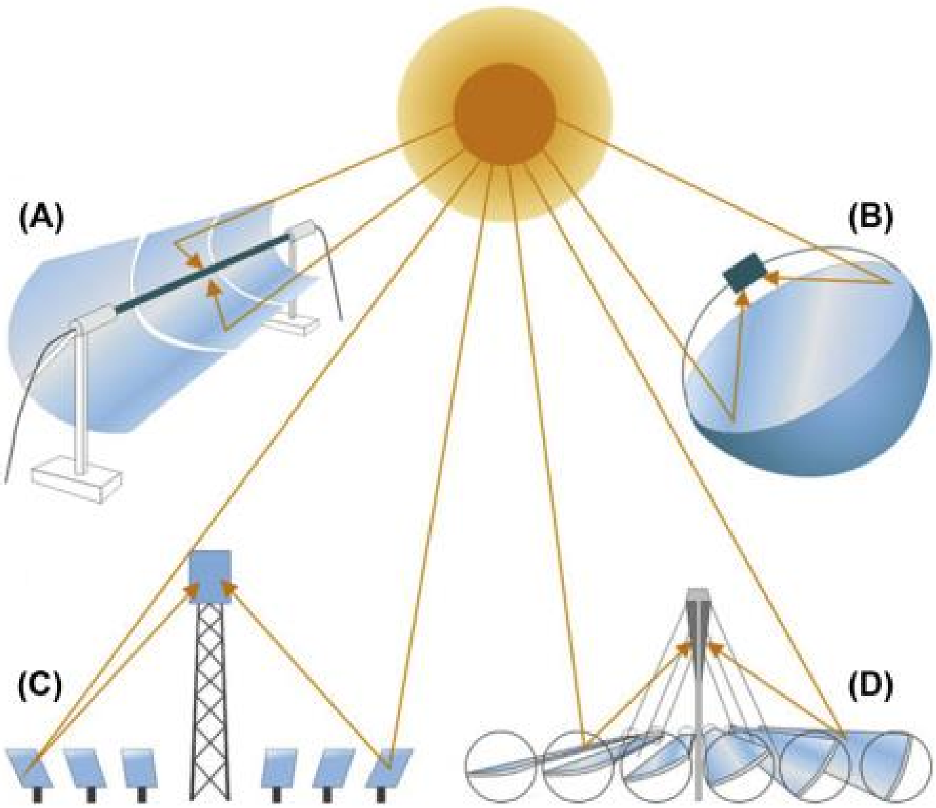


Figure 6 (A) Solar collectors; (B) Parabolic dishes, (C) Tower, (D) Linear Fresnel reflectors (*Advances in Renewable Energies and Power Technologies*, 2018)

CSP has a long history, beginning with the first solar steam generator in the late 1800s. Although modern commercial CSP systems were not available initially, a parabolic trough system was used in the Middle East and North Africa as early as 1912 in Cairo, Egypt. This early method was an influential producer of steam for irrigation pumps. After the 1973 oil crisis, the US federal research budget for CSP tripled. This, together with incentives from Californian politicians, led to the construction of the first commercial CSP plant (worldbank, 2021).

Typical efficiencies of 28% to 38% have been achieved by the first generation of CSPPs using the Rankine cycle with peak cycle temperatures in the range of 240°C to 440°C. The Parabolic Trough Collector (PTC), Solar Power Tower (SPT), and Linear Fresnel Reflector (LFR) technologies are commonly used in this generation. However, most first-generation CSPPs were limited by the lack of thermal storage, which limited them to operating only on sunny days. Despite this, the first generation of CSPPs still dominates the installed CSP capacity, with PTC systems accounting for 64% of the total number of projects (He et al., 2020).

A second generation of commercial CSPPs did not emerge until the early 2000s in the United States and Spain. In the U.S., the combination of the ''investment tax credit'', ''Public Utility Regulatory Policies Act reforms'', and ''renewable portfolio standards'' reignited interest, while Spain's government-backed feed-in tariff made it a world leader in installed CSP capacity. However, Spain's CSP installations were later in decline with the reduction of the feed-in tariff (worldbank, 2021).

Most second-generation CSPPs consist of PTC, SPT and LFR systems with Rankine cycle efficiencies between 38 and 45% and maximum cycle temperatures of 565°C. All new second generation CSP systems are equipped with thermal storage. Because of their high cycle efficiencies, these second-generation CSPPs can achieve annual solar electric efficiencies of about 10 to 20 percent, compared to 9 to 16 percent for first-generation CSPPs (He et al., 2020).

(NREL, 2022) is leading efforts to define the next generation of CSP systems. This will be achieved by seamlessly integrating thermal energy storage technologies that will increase system capacity, reliability, efficiency, and grid stability. A primary goal of the Gen3 CSP initiative is to reduce the cost of CSP systems to approximately $0.05 per kilowatt-hour. This will make solar baseload configurations highly competitive with other dispatchable power generators in the sun-rich southern half of the United States. Among the most advanced CSP systems are power tower systems with integrated two-tank molten salt thermal energy storage. These provide thermal energy at 565°C and integrate seamlessly with conventional steam ranking cycle power plants. A key focus is to increase plant efficiency by increasing the temperature of the delivered heat to over 700°C to achieve Gen3 CSP goals and cost reductions. In Figure 7 is showed comparison between various CSP generation.

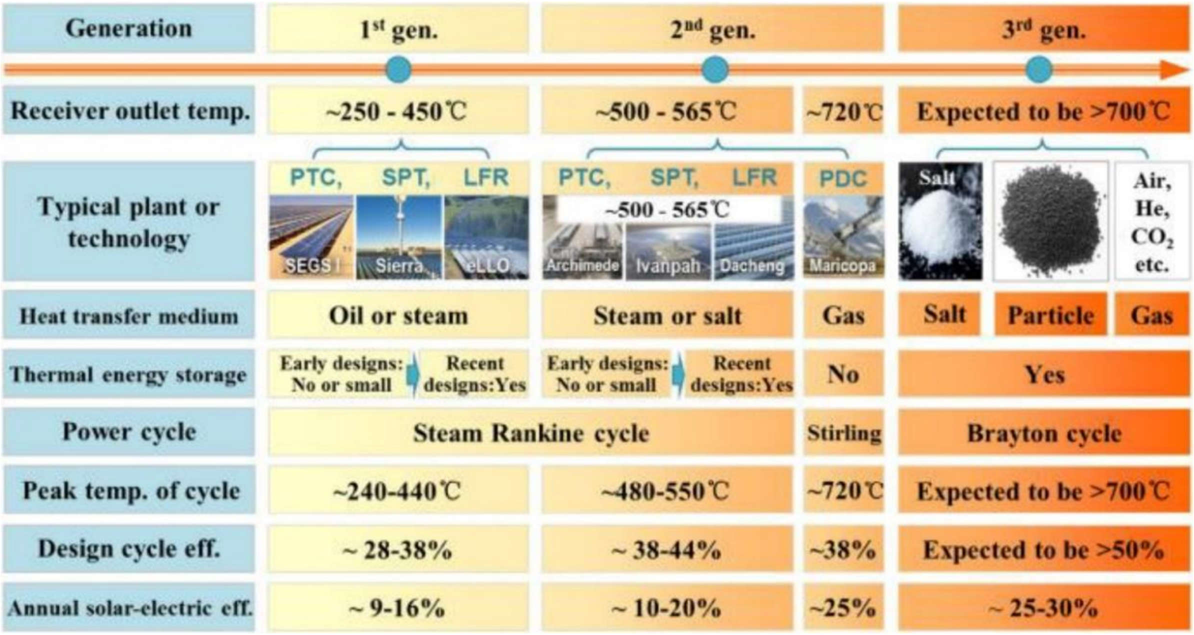


Figure 7 Comparison of various CSP generations (He et al., 2020)

HTFs are critical to the efficient collection of solar field heat in CSP systems. Performance and economics are significantly affected by the choice of HTF. Molten salts are widely preferred for their thermal stability, while water/steam systems offer a lower-cost alternative. Other fluids are used for specific temperature ranges, such as glycol-based and synthetic oils. Biphenyl/diphenyl oxide fluids are commonly used in commercial CSP systems. Air is rarely used as the HTF in large CSPPs. A 1.5 MWe pre-commercial solar tower at Jülich, Germany, is a notable example. Compared to liquid HTFs such as molten salts or liquid metals, air has been shown to have superior flow properties in CSP tubes. However, efficient heat transfer must be ensured since air has a lower thermal conductivity. Water/steam solar thermal offers cost advantages over oil-based technologies but challenges in arid regions. Molten salt is the preferred HTF used in CSP systems due to its thermal stability, while other oils are limited and costly. The selection of the most suitable HTF is a balance between temperature requirements and economic considerations (Alami et al., 2023).

3.2 Photovoltaic (PV) technology

PV cells generate electricity in various sizes, shapes, and semiconductor materials. When several solar cells are electrically connected and mounted on a support frame, they form a PV module. Wiring together numerous modules creates an array capable of producing direct current electricity. Other components include an inverter, a storage device, and mounting structures. There are three generations of PV systems, each with significant differences in energy efficiency, material costs, manufacturing processes, technology life cycle, and embedded emissions.

The evolution of photovoltaic (PV) technology has been examined over three generations in a comprehensive study by Muteri et al., 2020. Based on this study, different phases have seen the introduction of new materials and processes. They have resulted in different levels of efficiency, with a range of advantages and disadvantages. As PV technology continues to evolve, the lessons learned from each generation contribute to the ongoing development of renewable energy solutions.

Traditional crystalline Silicon (c-Si) panels with single and multi-crystalline silicon (mc-Si) cells are the first generation of panels. Due to its excellent electronic, chemical, and mechanical properties, silicon remains the most widely used material in PV modules. Solar technologies using this semiconductor are considered the best developed in the industry. Single-crystal Silicon (Sc-Si) is the most efficient compared to other solar technologies, with 25-27% laboratory efficiencies. On a commercial scale, Sc-Si has an efficiency of 16-22%. Mc-Si is a viable alternative to reduce PV module costs, although it is slightly less efficient at 15-18%. However, the process used to manufacture silicon wafers, particularly the Czochralski process[3], is both material and energy intensive, which poses certain challenges.

The second generation of PV cells uses thin-film technology, where the layers are a few nanometers to tens of micrometers thick. Because of the limited amount of semiconductor material required for each cell, this generation has the advantage of lower manufacturing and material costs.

Thinfilm solar cells are flexible, lightweight, and drag less than first-generation PV cells. Amorphous silicon (A-Si), Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Copper Indium Sulfide (CIS) are the different types of thin-film solar cells. A-Si solar cells are the cheapest on the market but have lower efficiency than crystalline silicon cells due to thinner layers and less material to absorb solar radiation. GaAs offer a high level of efficiency but come at a higher cost. CdTe cells can exploit a broader wavelength spectrum than silicon cells.

However, they raise environmental concerns due to the toxicity of cadmium. CIGS cells are expensive to produce because they are less efficient than Si solar cells and use toxic chemicals. CIS is relatively expensive due to the materials used but has good heat resistance compared to silicon-based modules.

A few innovative technologies, still in the research and development phase, comprise the third generation of PV cells. These cells aim to generate electricity using organic, semi-organic, or inorganic materials, hybrid systems, or new technology processes based on nanometer and molecular scale components. Some examples include Perovskite Solar Cells (PSCs), Organic Photovoltaics (OPVs) and polymer solar cells, Dye-Sensitized Solar Cells (DSSCs), and Quantum Dot solar cells (QDs).

[3] The Czochralski technique is a method of crystal growth used to obtain single crystals of semiconductors, The challenges of the Czochralski technique include potential contamination, crystal defects, precise growth control, dopant incorporation, large crystal size requirements, high costs, and long growth times.

PSC has cost advantages over silicon and shows promise with efficiencies in the 19-22% range. However, it is faced with challenges related to degradation and concerns about toxicity due to the presence of lead. OPV and polymer solar cells are light, flexible, and suitable for large-scale roll-to-roll production. However, they have lower efficiency, durability, and stability. DSSCs offer flexibility, low cost, and high efficiency, even in low-light conditions, but their electrolyte can freeze at low temperatures, reducing the amount of power they can produce. QDs offer easy to synthesize and prepare but currently exhibit low efficiency.

3.3 Hybrid CSP-PV plants

Hybrid systems that combine Concentrating Solar Power (CSP) with Photovoltaic (PV) technology offer a compelling solution for renewable energy generation. CSP plants provide dispatchable power, even after sunset, with up to 15 hours of cost-competitive electricity production.

The thermal storage in CSP enhances nighttime energy availability, a crucial factor for a renewable-based power grid. Simultaneously, the decreasing cost of electricity from PV plants makes combining CSP and PV an attractive approach. This integration not only reduces CSP production costs but also boosts the capacity factor of PV plants, optimizing renewable energy generation (Figure 9). One example is Fraunhofer ISE, which aims to enhance Integrated CSP and PV Hybrid Plant technology. They are focusing on developing a cost-effective electric heater for large-scale CSP-PV hybrid plants (Fraunhofer ISE, 2023).

In hybrid systems, a combination of wind turbines and PV panels store their energy in the thermal energy storage (TES) of the CSPP using an electric heater or in separate energy storage systems such as batteries, as shown in Figure 8.

This approach eliminates the need for curtailment and allows for the flexible dispatch of electricity as needed. In some cases, other technologies, such as geothermal power plants, can supplement CSP plants to improve overall performance when renewable energy resources are limited.

The electricity generated by the PV and wind systems is used to heat the solar salt in the TES by means of an electrical heating mechanism. The TES stores both the thermal energy from the CSP system and the power from the electrical heater. The capacity of the TES can be expanded to store additional thermal energy during harsh weather conditions, providing a flexible and dispatchable source of power to help meet varying load demands and to help balance the energy supply (Alami et al., 2023).

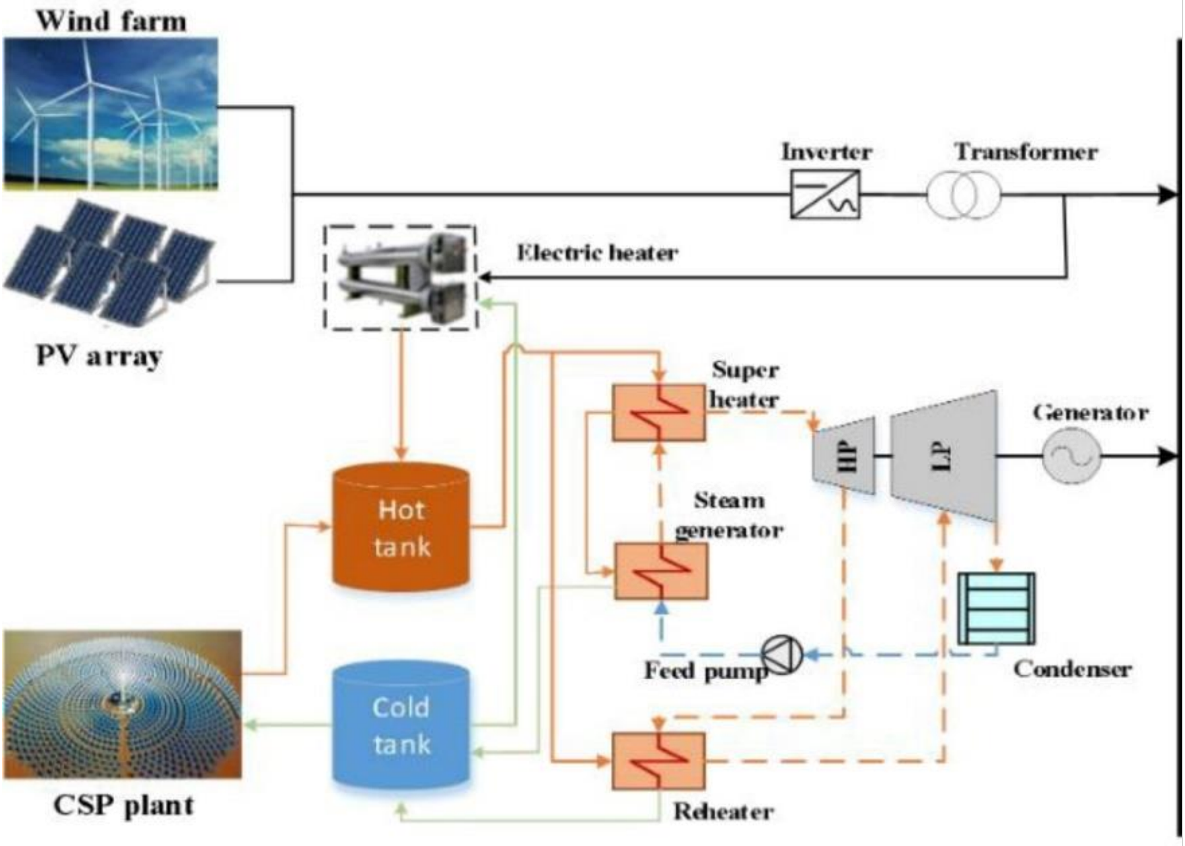


Figure 8 Schematic of the PV/Wind/CSP hybrid system (Alami et al., 2023)

Figure 9 The Hybrid CSP/PV plant Cerro Dominador in Chile (Fraunhofer ISE, 2023)

Chapter 4 Literature Review

In this chapter, I present a number of studies on solar energy projects siting around the world. The review article by Spyridonidou & Vagiona, 2023 served as a very helpful starting point for my thesis. These authors review 152 publications on solar projects siting around the world according to a number of criteria. From these 152 studies, I took a closer look at 33 studies, summarized in the following tables. Table 1 and Table 2 below present studies on solar plant siting around the world (Table 1 on seven PV plant siting studies and Table 2 on eleven CSP plant siting studies), Table 3 and Table 4 present studies on Iran (thirteen on PV plant siting and two on CSP plant siting).

These studies have commonalities and differences. They all apply GIS to identify optimal locations and they differ in methods most use a decision-support technique like Analytical Hierarchy Process (AHP). These methods have been instrumental in the identification of suitable locations for consideration of technical, environmental, economic, and geographical factors.

To the best of my knowledge should be noted that, in some studies, different criteria have been chosen, and based on scope of study and author's opinion some criteria is considered in range of constraint criteria or in other case the same criteria considered as suitability criteria which at the next chapter (Chapter 5) they have been examined.

Table 1 PV literature review international studies

Author (References)	Country	Type	summary
Al Garni & Awasthi, 2017	Saudi Arabia	PV	The study attempts to analyses and select the best sites for utility scale solar PV projects in Saudi Arabia using GIS and Multi-Criteria Decision Making[4] (MCDM) approaches. Economic and technological considerations are examined to increase power output while minimizing project costs. The combination of GIS and MCDM is advantageous for the processing of geographical data and the determination of the relevance of the criteria. The research provides insights into possible PV project sites by integrating solar irradiance and air temperature data with real atmospheric characteristics. This allows informed decisions to be made for sustainable energy development in Saudi Arabia.
Bandira et al., 2022	Malaysia	PV	The study found that the performance of the NASA POWER data was satisfactory for identifying solar farms and that the GIS-based MCDM method effectively identified potential areas for solar farms. The model output can effectively target locations with the highest potential for solar power generation. The study suggests that in order to generate more accurate climate information for solar projects, future research should integrate NASA-POWER and weather station data.
Nguyen et al., 2022	south-central Vietnam	PV	This study developed a GIS-based simulation for selecting the optimal location for a solar farm in Binh Thuan province, south-central Vietnam. It used the AHP to assess site suitability and emphasized the importance of effective planning to ensure successful solar farm establishment and address end-of-life solar panel disposal concerns.
Palmer et al., 2019	UK	PV	identify suitable locations for large-scale solar farms in the UK. It found that considering planning permission and grid constraints is vital to avoid overestimating potential areas by up to 97%. Solar energy resources were identified as the main obstacle to utility-scale solar expansion. Government policies and grid connections also play significant roles in determining solar farm locations.

[4] MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. below compare different MCDMs: https://cord.cranfield.ac.uk/articles/dataset/A_Comprehensive_Collection_of_Multiple_Criteria_Decision_Analysis_MCDA_Methods/13420022/1

Table 1 (continued)

Author (References)	Country	Type	summary
Suh & Brownson, 2016	Ulleung Island, Korea	PV	The results showed three areas on the island that were highly suitable for the installation of solar farms. It suggests that GIS- Multi-Criteria Evaluation (MCE) can be used for further projects in the field of solar farm siting. Future enhancements could include improved irradiance statistics, field surveys and the incorporation of changing economic considerations to be more accurate. The versatility of the model makes it relevant to a wide range of sites with limited access to the grid.
Tahri et al., 2015	southern Morocco	PV	AHP was used to calculate the weights of the four criteria: location, orography, land use, and climate. The climate was found to be the most important criterion, followed by the orography and then the location. The study shows that the overlay layer analysis revealed that the majority of the Ouarzazate area is highly suitable for installing photovoltaic farms due to favorable factors such as solar radiation and southern exposure. The selected areas could significantly contribute to reducing Morocco's energy dependency while benefiting populated areas with direct access.
Uyan & Dogmus, 2023	Cumra Region, Turkey	PV	the study uses a combination of the Analytical Network Process (ANP) and GIS to determine suitable locations for solar power plants in the Cumra Region, Konya, Turkey. Six main criteria were considered, and their weight values were determined using ANP. The study highlights the importance of considering various criteria to minimize negative environmental, economic, and social impacts and increase the efficiency of solar farms in the region. The region's high solar radiation and suitable lands make it a promising area for solar energy investments.

Table 2 CSP literature review international studies

Author (References)	Country	Type	summary
Alami Merrouni et al., 2018	Eastern Morocco	CSP	The study evaluated two cooling technologies (dry and wet) with AHP methods and found that the eastern part of Morocco is a very good location for the installation of CSPPs, with 11.7% of the total area being suitable for wet cooling systems and 5.5% for dry cooling systems. The study encourages investment in solar energy and promotes sustainable development in the region and the country as a whole, providing valuable information for policymakers and investors.
Alqaderi et al., 2018	UAE	CSP	This study aims to identify suitable locations for large-scale CSPPs in UAE using GIS data and MCDM. The study uses the AHP to determine the weights of the ranking criteria and highlights the most suitable locations for CSP projects in the UAE, helping policy and decision makers to make informed investments in renewable energy.
Aly et al., 2017	Tanzania	CSP	The study highlights the limited amount of research and information on renewable energy in Tanzania, which has led to a heavy reliance on fossil fuels. Using AHP methodology, the study identifies CSP and PV hotspots. With potential for broader application to other regions and renewable energy technologies, the study aims to help decision makers and developers assess suitable areas for large-scale solar power projects.
Dawson & Schlyter, 2012	Western Australia	CSP	The objective of this paper is the development of a GIS-based methodology with a revised Simos procedure for the identification of suitable sites for CSP on a continental scale. The study tests the methodology in Western Australia and finds a significant reduction in the number of technically suitable areas to areas of medium to very high suitability. The remaining suitable areas are still sufficient to motivate and support utility-scale CSP production, although current global estimates of CSP potential are likely overestimated.

Table 2 (continued)

Author (References)	Country	Type	summary
Gouareh et al., 2021	Algeria	CSP	The study used multiple criteria decision-making and GIS to identify seven evaluation criteria and three scenarios AHP, Equally Weighted (EQW), and Best-Worst Method (BWM) to weight the criteria. The findings showed that DNI, proximity to grid electricity and sunshine duration were the most important factors. Approximately 11% of the studied area was considered suitable for generating electricity using CSP. The BWM method was found to be more robust and more efficient than the AHP method.
Haddad et al., 2021	Algeria	CSP	The study aims to identify suitable locations for CSPPs in Algeria using a hybrid methodology combining MCDM and GIS. The study highlights the need to consider multiple criteria beyond Direct Normal Irradiance values for effective energy planning and offers confidence to investors for installing solar power plants in suitable regions.
Levosada et al., 2022	Philippines	CSP	To identify the most suitable sites, the study used the AHP method with exclusion and ranking factors. These factors included protected areas, slope, DNI, water bodies, and land cover type. Further research can be conducted to provide a more comprehensive view of the potential for CSP plants in the country, including additional parameters and economic assessments.
Sun et al., 2021	Ningxia, China	PV-CSP	The study aims to use AHP method to evaluate suitable locations and technical potentials for large-scale PV and CSP plant in Ningxia, China. Findings indicate that Ningxia's central area is recommended for the deployment of solar power plants, and PV technology is more suitable because of limited water resources. The study emphasizes the need for careful consideration of various factors and uncertainties in the decision-making process.

Table 2 (continued)

Author (References)	Country	Type	summary
Levosada et al., 2022	Philippines	CSP	To identify the most suitable sites, the study used the AHP method with exclusion and ranking factors. These factors included protected areas, slope, DNI, water bodies, and land cover type. Further research can be conducted to provide a more comprehensive view of the potential for CSP plants in the country, including additional parameters and economic assessments.
Tlhalerwa & Mulalu, 2019	Botswana	CSP	The study is an assessment of Botswana's CSP potential through a bottom-up approach and analysis of land exclusion criteria by feasibility analysis direct normal irradiation. It identifies significant available CSP land, particularly in the Central and Kgalagadi districts, but emphasizes the need to consider economic factors such as the levelized cost of electricity and implement supportive renewable energy and climate change policies for successful implementation.
Yushchenko et al., 2018	West Africa	PV-CSP	The study is an assessment of the geographic and technical potential for solar power generation in rural areas of West Africa through the use of GIS and MCDM techniques. Results indicate significant potential for large-scale grid-connected (CSP and PV) and off-grid PV in the region, with potential applications for governments, investors, and energy planning and electrification stakeholders. However, the study suggests further research into the economic potential and energy supply needs, while acknowledging the need for detailed local data for actual project implementation.
Ziuku et al., 2014	Zimbabwe	CSP	Study mapped solar radiation distribution in Zimbabwe using data from 26 meteorological stations and feasibility analysis direct normal irradiation. CSP technologies, particularly in northwest and southwest regions with good solar irradiation and proximity to grid power and water, offer clean energy opportunities. However, in Zimbabwe and other developing countries, technology and capital costs remain significant barriers to CSP development.

Table 3 PV literature review Iran case studies

Author (References)	Country	Type	Summary
Asakereh et al., 2014	Khuzestan (Shodirwan region), Iran	PV	In this study, suitable locations for solar energy farms in Shodirwan region of Iran were identified using Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and GIS. The GIS interpolation showed that the annual amount of solar radiation in the area is favorable for the potential locations of solar energy farms. The findings showed that about 18.25% of the area of Shodirwan is suitable for solar farms.
Asakereh et al., 2017	Khuzestan, Iran	PV	The objective of this study is to prioritize suitable sites for solar photovoltaic (PV) farms from a techno-economic and environmental point of view. In order to assess the suitability of land, fuzzy logic, fuzzy membership functions, and AHP were used. The results showed that Khuzestan Province has significant potential for solar power generation. In the worst-case scenario, the potential exceeds the gross electricity produced in Iran. In addition, the installation of solar farms in the vulnerable desert and semi-desert areas of the province could contribute to the fight against desertification, while at the same time reducing the overall cost of solar power generation.
Barzehkar et al., 2021	Isfahan, Iran	PV, Wind	The purpose of this study is to optimize the location of wind and photovoltaic solar power plants using a hybrid decision support system that incorporates a MCE based on AHP, fuzzy logic, weighted linear combination (WLC) approach, and GIS models. The results indicated that about 26% of the land area was highly suitable for solar farms, and 18% was highly suitable for wind farms. The use of these decision support tools can lead to more effective and flexible environmental planning for renewable energy systems, promoting sustainable electricity generation.
Firozjaei et al., 2019	Iran	PV	The purpose of this study was to investigate the feasibility of solar energy in Iran using a GIS-based analysis and to integrate the concept of risk using the Ordered Weighted Averaging (OWA) approach. The results identified optimal areas for solar power plant installations based on different risk strategies, with provinces such as Kerman, Yazd, Fars, Khuzestan, Sistan and Baluchistan, South Khorasan, and Isfahan showing good potential for investment in solar energy projects.

Table 3 (continued)

Author (References)	Country	Type	Summary
Hafeznia et al., 2017	Birjand, Iran	PV	The study assessed the potential of photovoltaic solar energy by using a framework that incorporated spatial planning and performance simulation of photovoltaic power systems. The results identified optimal sites covering 0.5% of the country's territory, with estimated electricity generation capacity sufficient to meet the demand of Southern Khorasan Province and the possibility of exporting excess electricity to neighboring regions.
Mokarram et al., 2020	Fars, Iran	PV	The purpose of this paper is to determine the optimal location for solar farms in order to maximize solar energy potential. It employs GIS-MCDA techniques, fuzzy AHP and fuzzy ANP, and a feature selection algorithm. Compared to using AHP and ANP independently, combining fuzzy ANP with the algorithm resulted in a more accurate approach. According to the report, the northern and northeastern areas have the most potential for hosting solar farms.
Noorollahi et al., 2016	Iran	PV	The study evaluated the suitability of regions in Iran for solar photovoltaic (PV) power plants based on technical, environmental, geographic, and economic criteria. Provinces such as Kerman, Yazd, Fars, Sistan and Baluchestan, South Khorasan, and Isfahan were identified as highly suitable for solar energy utilization, providing valuable insights for energy planners and investors to strategically develop solar energy projects in Iran.
Sadeghi & Karimi, 2017	Tehran, Iran	PV, wind	The study identified suitable locations for solar and wind farms in Tehran, Iran using GIS and AHP. The results show the potential of renewable energy for the improvement of the stability of the electricity grid and the reduction of the environmental impact.

Table 3 (continued)

Author (References)	Country	Type	Summary
Safarianzengir et al., 2022	East Azerbaijan Province, Iran	PV	The purpose of this research is to assess the feasibility of the establishment of solar thermal power plants in northwestern Iran by means of fuzzy logic and eight climatic parameters. The results indicate that certain areas such as Bonab and Miyaneh stations are suitable for the establishment of solar power plants. The study highlights the potential of solar energy as a clean and accessible resource for sustainable development. It encourages attention to sectors that use sustainable energy.
Shorabeh et al., 2019	Mazandaran, Kermanshah, Razavi Khorasan, and Yazd, Iran	PV	The studies aim to use GIS-based analysis and the OWA model to incorporate risk in order to identify potential locations for solar power plants in different provinces of Iran. Weather conditions play an important role in determining the optimal locations, and provinces with arid climates, such as Yazd, are found to have more suitable areas for solar power plants. The results highlight the importance of considering climate impacts in site selection and are valuable for regional investors.
Tavana et al., 2017	Kerman and Yazd, Iran	PV	The articles propose a three-step fuzzy evaluation framework using ANFIS, fuzzy AHP and FIS methods to identify suitable locations for the construction of solar power plants in Iran's regions. The approach takes into account the imprecision of the evaluations while considering different criteria and factors.
Yousefi et al., 2018	Markazi, Iran	PV	The article presents a study on site selection for solar power plants in Markazi Province, Iran, using fuzzy logic along with a Boolean logic model and GIS. Suitable areas were identified near Mahalat and Zarandineh cities, validating the combined method for future site selection of renewable energy plants in diverse climates.

Table 3 (continued)

Author (References)	Country	Type	Summary
Zoghi et al., 2017	Isfahan, Iran	PV	This paper optimizes the siting of solar power plants in Isfahan Province, Iran using fuzzy logic, weighted linear combination (WLC), and multiple criteria decision-making methods. The study identifies certain regions with high potential for solar energy utilization, particularly the cities of Isfahan, Borkhar, Nain, Shahin Shahr, and Meimeh. The overall conclusion is that Isfahan Province offers significant opportunities for installing solar power plants, with the eastern and southern parts being particularly suitable.

Table 4 CSP literature review Iran case studies

Author (References)	Country	Type	summary
Ghasemi et al., 2019	Sistan Balochistan, Iran	PV-CSP	The study assessed the potential of solar power plants in the province of Sistan and Baluchistan, southeastern Iran, using a multi-criteria decision-making approach coupled with GIS and AHP methods. The study identifies the most suitable areas for PV and CSP plants. The technical potential is estimated to be 8,758 TWh/year for PV and 7,419 TWh/year for CSP in the selected region. The results show that PV solar power plants offer a higher potential for electricity supply as compared to CSP solar power plants.
Mohammadi & Khorasanizadeh, 2019	Iran	CSP	This study assesses the feasibility analysis of direct normal irradiation of CSP in Iran. It identifies suitable regions with abundant DNI for CSP development. The possibility of hybridizing CSP with other energy sources is explored. In spite of incentives such as feed-in tariffs, barriers such as financing and policy gaps need to be addressed in order to promote CSP projects in the country.

The studies demonstrate varying degrees of specificity in their geographical focus. However, they all emphasize the importance of assessing solar radiation and suitability. The role of solar irradiance is evident in studies between different climatic regions, for example in the Sistan and Baluchistan region of Iran compared with the Ningxia region of China, both located in arid regions, the south-eastern region of Iran has high potential for the best suitable area both for PV (14%) and CSP (12%), but in Ningxia represents 3.73% and 2.46% of the local land area, The solar irradiance, climatic conditions, land availability and other variables are key factors that determine the distinction between these two studies. Some studies focus on specific regions, such as Vietnam and Morocco, while others, such as those in Saudi Arabia and Malaysia, take a broader national perspective.

Proximity to power lines or grid connections emerges as a key consideration in most studies, along with factors such as climate, land use and effective planning. Solar irradiation consistently emerges as a key criterion for site selection, recognized in both international and Iranian studies.

Iranian studies often focus on specific provinces or localized areas within the country. They often address unique challenges, such as the impact of sanctions and fluctuations in oil and gas prices, which have a significant impact on photovoltaic (PV) projects in Iran. These challenges are closely linked to Iran's geopolitical and economic context. It's important to note that there is limited research on solar concentrated power plants in Iran.

Chapter 5 Methodology

5.1 Developing of GIS-based model for Photovoltaics (PV) parks and Concentrating Solar Power (CSP) plants site selection

Geographical Information Systems (GIS) are an efficient decision-supporting tool, facilitating accurate siting in the renewable energy sector. GIS can significantly reduce the time and cost of the process by utilizing a database of information on the most favorable sites (Barzehkar et al. 2021).

The GIS analysis in this study proceeds in two major stages. In the first stage, I performed a land availability analysis using a constraint model. I applied fourteen constraints like „Plant cannot be located on a road“ or „on top of a settlement“ or „in a nature protected area“ , modelling each constraint in one layer. Combining fourteen layers, each representing one constraint, produced a map of principally available areas for solar plant siting (more detail in section 5.4).

I then analyzed these areas by nine suitability criteria, assessing each potential site on the nine criteria, where each criterion could take on a value from 1 to 4, representing: 1: high suitability 2. medium suitability 3. low suitability 4. very low suitability. I combined the criteria through forming a weighted arithmetic average (details in section 5.5) The spatial resolution of the analysis is raster cells of 100 x 100 meters (more detail in section 5.3) the subchapter on data and their characteristics the workflow diagram is shown in Figure 10.

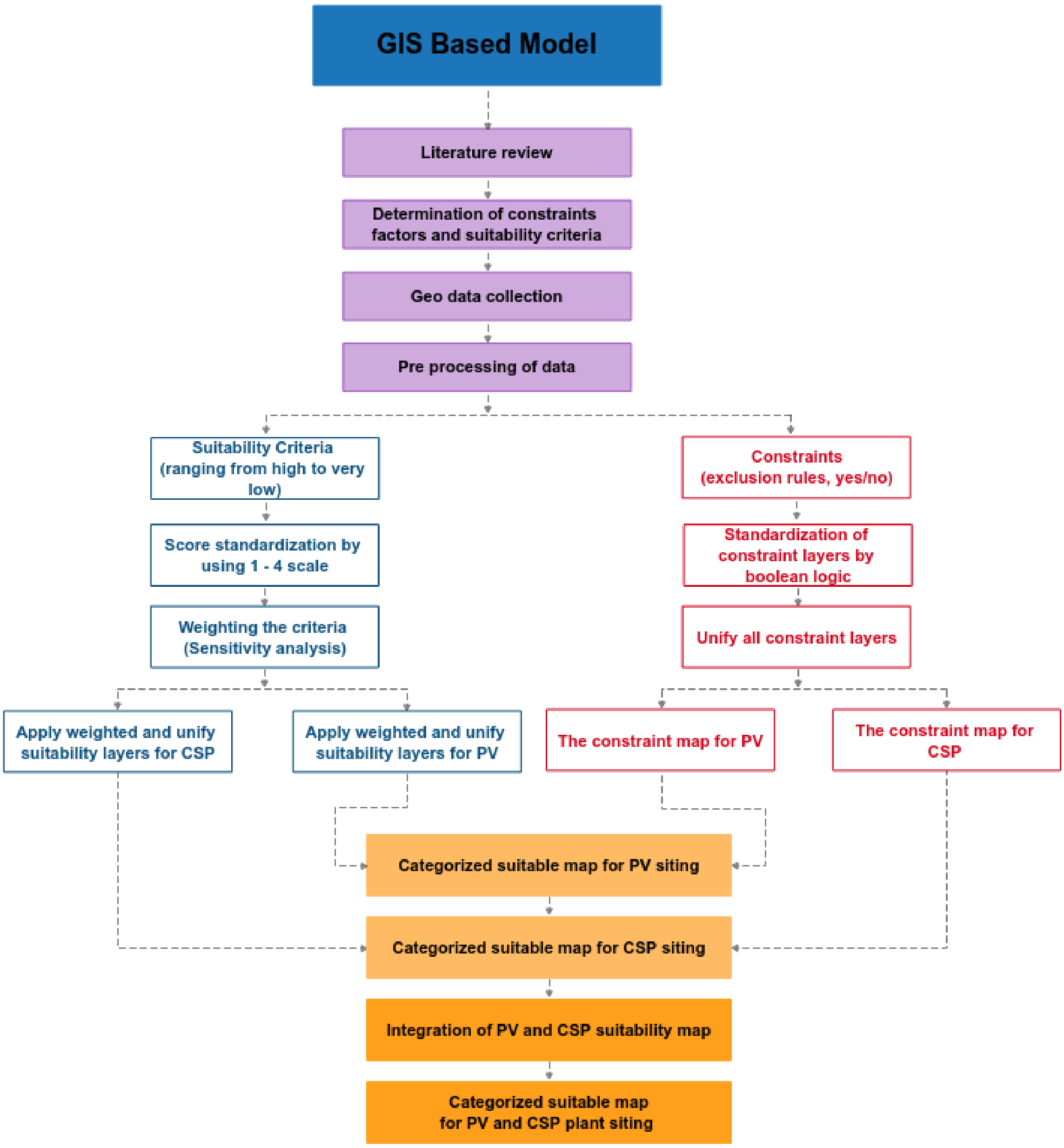


Figure 10 Work flowchart (by author)

5.2 Used software

The ArcGIS Pro v2.72 license by HafenCity Universität, which provides robust GIS analysis capabilities, was an essential tool in my research. This software facilitates the integration of various spatial datasets, such as solar radiation, topography, and land use, into models for PV and CSP site selection.

Python 3.1, combined with the Arcpy Libraries for ArcGIS Pro, greatly enhanced the ability to conduct the required research. This advanced spatial analysis enabled geoprocessing and supported PV and CSP site selection. Furthermore, the Python package esy-osmfilter extracted the OpenStreetMap layers from a pbf file.

5.3 Data collection and sources

The data collection approach for obtaining constraint and assessment geospatial data is a fundamental and integral part of the overall research methodology. It provides essential geospatial information to guide project planning, implementation, and sustainability, forming the basis for the decision-making process.

In this research, open-source data played a decisive role in completing the research. Using freely available data sources, extensive information was collected and used to evaluate the criteria of PV and CSP. The criteria selection process has been carefully tailored based on insights from an extensive literature review that analyzes available studies and academic articles from Iran and the international level and provides valuable insights into the factors affecting performance and profitability.

Data availability for the Iran case study is significantly limited compared to more developed regions, especially for spatially detailed grid data. Given this constraint, I made a strategic decision to use open data repositories. In order to broaden the scope of our analysis, I have also integrated data from a variety of sources, including some proprietary data sets, such as protected areas and climate data, which have a global scope.

Used geodata and sources are presented in Table 5 The following databases are used and briefly explained.

Table 5 Used geodata and sources

Category	Layers	Sources	Description	Resolution/ Accuracy
Infrastructure	Road	(*OpenStreetMap*, 2023)	Polyline	Unknown
	Railroad	(*OpenStreetMap*, 2023)	Polyline	Unknown
	Waterway	(*OpenStreetMap*, 2023)	Polyline	Unknown
	Powerlines	(*OpenStreetMap*, 2023)	Polyline	Unknown
	Power stations	(*Transformator*, 2023)	Point	Unknown
Land use	Settlement	(*GHSL - Global Human Settlement Layer*, 2023)	Raster	100 m
	Forest	(*Academy of Geospatial Sciences of Iran*, 2021)	Polygon	Unknown
	Agricultural land	(*Academy of Geospatial Sciences of Iran*, 2021)	Polygon	Unknown
	Wetland	(*Academy of Geospatial Sciences of Iran*, 2021)	Polygon	Unknown
	Airport	(*Academy of Geospatial Sciences of Iran*, 2021)	Polygon	Unknown
Topography	Slope	(*Earthdata-Nasa*, 2023)-Aster 30m DEM	Raster	30 m
	Aspect	(*Earthdata-Nasa*, 2023)-Aster 30m DEM	Raster	30 m
Climate	Maximum air temperature	(*Worldclim*, 2020) (1970-2000)	Raster	1 km
	Average air temperature	(*Worldclim*, 2020) (1970-2000)	Raster	1 km
	Cloud cover fraction	(*CAMS*, 2021) (2016-2022)	Raster	~44 km
	Dust aerosol optical depth at 550 nm	(*CAMS*, 2021)(2016-2022)	Raster	~83 km
	Direct Normal Irradiance	(*Global Solar Atlas*)- (1999-2018)	Raster	~300m
	Global Horizontal Irradiance	(*Global Solar Atlas*) (1999-2018)	Raster	~300m
Natural hazard	Floodplain	(*Iran Remote Sensing Academy Company*, 2019)	Polyline	Unknown
	Fault	(*Iran Remote Sensing Academy Company*, 2019)	Polyline	Unknown
Protected area	Protected area	(*Protected Areas (WDPA)*, 2023)	Polygon	Unknown
	Military zone	(*OpenStreetMap*, 2023)	Polygon	Unknown

Along with other data, some of the data sourced from NGOs and companies such as the Academy of Geospatial Sciences of Iran is a critical asset that is driving progress and development in the country with a wide range of data sets covering different domains. More details on additional databases are provided below.

5.3.1 Open Street Map (OSM) data

I extracted information, including features such as roads, railways, water bodies, rivers, power lines and Military zone, from OpenStreetMap (OSM) data. To do this, I used a method called "esy-osmfilter".

The esy-osmfilter method is a useful tool which allows researchers and developers to extract specific geographic details from the massive OpenStreetMap data set. In this way, I can obtain important information such as road networks, railway lines and waterways that are suitable for the analysis or application I worked on (esy-osmfilter 1.0.11 2020).

A detailed guide on how to use esy-osmfilter can be found in Appendix 1, which explains how to customize the data extraction on the basis of different criteria, such as specific areas, tags or attributes. The guide also covers the settings and options available to fine-tune the extraction process.

5.3.2 Global solar atlas data

Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) are the important data that complement the understanding of solar resources. This data is derived from the Global Solar Atlas, a platform that provides access to information on solar resources around the world. The Global Solar Atlas provides GHI and DNI data in GeoTIFF and AAIGRID format, providing valuable insights into solar energy resources worldwide at long-term yearly/monthly average of daily total and long-term average of yearly/monthly totals (*Global Solar Atlas Iran*, 2019).

5.3.3 WorldClim data

Air temperature data were extracted from *Worldclim*, 2020 database**,** WorldClim provides valuable insight into global weather and climate patterns by providing air temperature data, including maximum and average air temperatures. This database is precious for understanding various climate factors, such as air temperature, in different regions worldwide. Researchers use World Clim extensively for mapping, spatial modeling, and addressing climate-related issues.(EEA, 2015).

5.3.4 Copernicus Atmosphere Monitoring Service (CAMS) data

Dust aerosol optical depth and total cloud cover fraction are extracted from Copernicus Atmosphere Monitoring Service (CAMS) to produce global forecasts for atmospheric composition. CAMS provides two global atmospheric forecasts each day. These forecasts include more than 50 chemicals and seven aerosol types, while also incorporating meteorological factors. For initial conditions, the forecasts are combined with real-time satellite data through data assimilation.

The forecast then uses a physics-based model to predict concentrations of each species over five days. It undergoes annual upgrades to adjust resolution, add new species, and improve accuracy. For long-term data, the CAMS Global Reanalysis is available through the Atmosphere Data Store, which extends back to 2003. The horizontal resolution of the prediction grid is 0.4°x0.4° (*CAMS*, 2021).

5.3.5 World Database on Protected Areas (WDPA) data

The World Database on Protected Areas is a global database of marine and terrestrial protected areas that is updated monthly. The WDPA plays a critical role in improving the understanding of the distribution and effectiveness of protected areas and assists in the evaluation of global conservation efforts. The organization is a collaboration between the United Nations (UN) Environment Programme and the International Union for Conservation of Nature, in partnership with governments, NGOs, academia and industry (*Protected Areas (WDPA)*, 2023).

5.3.6 The Global Human Settlement Layer (GHSL) data

GHSL database is provided by the Joint Research Center of the European Commission. This database provides high-resolution data on urban areas, rural settlements and population distribution as a result of remote sensing and geospatial analysis (*GHSL - Global Human Settlement Layer*, 2023).

5.3.7 NASA's ASTER satellite data

Slope and aspect are key terrain features extracted from high-resolution elevation data, the 30-metre DEM provided by NASA's ASTER satellite (*Earthdata-Nasa*, 2023) is used to drive slope and aspect. Slope measures how steep or gentle the land is at different points. Steep areas have higher slope values, while flatter areas have lower values. By assessing changes in elevation over short distances, the 30-metre DEM data can be used to calculate slope.

Aspect is the direction in which a slope faces, like a compass reading for the orientation of the slope. For example, a slope facing north would have an aspect of approximately 0°, while slopes facing south would have an aspect of approximately 180°. By determining the direction of the steepest slope at each point, ASTER DEM data helps to determine aspect.

5.4 Constraints for PV park and CSP plant siting

I collected and processed the data, an analysis of available land took place, excluding land that was not available.

In addition, to constrain the layers, I have considered the buffer zone around some layers where the construction of PV and CSP plants is limited. The size of the buffer zone varies in the previous studies, which may be related to the region's conditions and different legal regulations. Land availability also plays a vital role in determining the buffer zone. Table 6 and Table 7 lists the restricted layer and buffer zone considered in national and international studies for constructing PV and CSP. In this study, the determination of the buffer zone is based on a national literature review.

In this step, a binary map is created based on individual constraints, where a value of 0 indicates areas that are not permitted, and a value of 1 indicates locations that are suitable for solar power generation. An overall map was created to identify ideal sites that meet the requirements for PV and CSP by combining all the maps and overlaying the individual constraint maps.

In Figure 11 the constraint layer is shown with the corresponding buffer zone. The assessments for both the PV parks and the CSP sites are subject to identical constraints.

Table 6 Constraint considered in previous studies (PV)

Constraints PV	Authors					
	1*	2*	3*	4*	5*	6*
	Locations					
	Iran, Markazi	Iran, Khuzestan	Iran, Isfahan	Iran	Iran, Isfahan	Iran (Kerman and Yazd)
Roads	1 km	100-400 m	2 km	100 m	250 m	Y/NB
Railroads	N	100-400 m	N	N	N	N
Airports (flight security)	N***	N	N	N	N	N
Natural disaster (flood Area etc)	N	100-400 m	Y/NB**	N	N	N
Faults	1km	N	500 m	500 m	N	N
Settlement	2 km	1-5 km	500 m	2 km	500 m	500 m
Rural area	500 m	300-700 m	N	500 m	N	N
Industrial area	N	N	N	N	N	N
Fish farming ponds	N	N	N	N	N	N
Protected area	300 m	100-400 m	500 m	2 km	500 m	N
Natural parks	N	N	N	N	N	N
landfill sites	N	N	N	N	N	N
Vegetation coverage	N	100-400 m	N	N	N	N
Agricultural land	N	100-400 m	N	N	N	N
Land use	N	N	Y/NB	Y/NB	N	N
Water, river, lake	500 m	100-500 m	500 m	1 km	Y/NB	N
Wetland	N	100-500 m	N	N	500 m	N
Forest area and wetland	1 km	100-500 m	N	N	Y/NB	N
Military zones	N	N	N	N	N	N
Warehouse	N	N	N	N	N	N
Fuel storage tanks	N	N	N	N	N	N
Cultural heritage site	N	N	N	N	N	N
Religious places	N	N	N	N	N	N
Archaeological site	1 km	N	N	N	N	N
Remarks (sources)	**PV**	**PV**	**PV, wind**	**PV**	**PV**	**PV**

*1- (Yousefi et al., 2018), 2- (Asakereh et al., 2017), 3- (Barzehkar et al., 2021), 4- (Noorollahi et al., 2016), 5- (Zoghi et al., 2017), 6- (Tavana et al., 2017)

**Y/NB= considered without buffer zone, ***N= not considered

Table 6 (continued)

Constraints PV	Authors					
	7*	8*	9*	10*	11*	12*
	Locations					
	Iran (Mazandaran, Kermanshah,Razavi Khorasan, and Yazd)	Iran, Tehran	Iran, Fars	Iran, Birjand	Iran, Khuzestan	Korea, Ulleung Island
Roads	500 m	100	5 km	300 m	Y/NB	N
Railroads	N***	N	N	N	N	N
Airports (flight security)	N	N	N	3 km	N	N
Natural disaster (flood area etc)	N	N	N	N	N	N
Faults	N	N	N	200 m	N	N
Settlement	500 m	500 m	10 km	1 km	Y/NB	Y/NB
Rural area	N	N	N	500 m	Y/NB	N
Industrial area	N	N	N	500 m	Y/NB	N
Fish farming ponds	N	N	N	100 m	N	N
Protected area	N	500 m	N	N	Y/NB	Y/NB
Natural parks	N	N	N	200 m	N	N
landfill sites	N	N	N	200 m	N	N
Vegetation coverage	N	N	N	500 m	Y/NB	N
Agricultural land	N	N	N	100 m	Y/NB	N
Land use	N	Y/NB**	Y/NB	Y/NB	Y/NB	Y/NB
Water, river, lake	N	N	N	200 m	Y/NB	Y/NB
Wetland	N	500 m	N	N	N	N
Forest area and wetland	N	500 m	N	N	N	N
Military zones	N	N	N	1 km	N	N
Warehouse	N	N	N	500 m	N	N
Fuel storage tanks	N	N	N	500 m	N	N
Cultural heritage site	N	N	N	1 km	N	Y/NB
Religious places	N	N	N	100 m	N	Y/NB
Archaeological site	N	N	N	N	N	Y/NB
Remarks (sources)	**PV**	**PV, wind**	**PV**	**PV**	**PV**	**PV**

*7- (Shorabeh et al., 2019), 8- (Sadeghi & Karimi, 2017), 9- (Mokarram et al., 2020), 10- (Hafeznia et al., 2017), 11- (Asakereh et al., 2014), 12- (Suh & Brownson, 2016)

**Y/NB= considered without buffer zone,

***N= not considered

Table 6 (continued)

Constraints PV	Authors					
	13*	14*	15*	16*	17*	18*
	Locations					
	Turkey ,Cumra	Malaysia	south-central Vietnam	Saudi Arabia	southern Morocco	UK
Roads	100 m	5 km	100 m	1.5 km	1.4 km	N
Railroads	100 m	N	N	N	N	N
Airports (flight security)	N	N	N	N	N	N
Natural disaster (flood area etc)	N	N	N	N	N	Y/NB
Faults	N	N	N	N	N	N
Settlement	1 km	5 km	1 km	1.5 km	Y/NB	Y/NB
Rural area	N	N	N	N	N	N
Industrial area	N	N	N	N	N	N
Fish farming ponds	N	N	N	N	N	N
Protected area	1 km	N	N	N	N	Y/NB
Natural parks	N	N	N	N	N	Y/NB
landfill sites	N	N	N	N	N	N
Vegetation coverage	N	N	N	N	N	N
Agricultural land	Y/NB	N	N	N	N	Y/NB
Land use	N	Y/NB	Y/NB	N	Y/NB	2.5 km
Water, river, lake	500 m	N	N	N	N	Y/NB
Wetland	N	N	N	N	N	Y/NB
Forest area and wetland	N	N	N	N	N	N
Military zones	N	N	N	N	N	N
Warehouse	N	N	N	N	N	N
Fuel Storage Tanks	N	N	N	N	N	N
Cultural heritage site	N	N	500 m	N	N	N
Religious places	N	N	N	N	N	N
Archaeological site	N	N	N	N	N	N
Remarks (sources)	**PV**	**PV**	**PV**	**PV**	**PV**	**PV**

*13- (Uyan & Dogmus, 2023) , 14- (Bandira et al., 2022), 15- (Nguyen et al., 2022), 16- (Al Garni & Awasthi, 2017), 17- (Tahri et al., 2015), 18- (Palmer et al., 2019)

Table 7 Constraint considered in previous studies (CSP)

Constraints CSP	Authors										
	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*
	Locations										
	Iran, Sistan Balochistan	Algeria	China, Ningxia	Zimbabwe	Philippines	UAE	west Australia	Eastern Morocco	Algeria	Tanzania	Botswana
Roads	1.5 km	500 m	500 m	N	N	N	N	1.5 km	100 m	N	Y/NB
Railroads	N	N	500 m	N	N	N	N	1.5 km	100 m	N	N
Airports (flight security)	3 km	N	3 km	N	N	N	N	N	Y/NB	N	N
Natural disaster (flood area etc)	N	N	N	N	N	N	N	N	N	N	Y/NB
Urban area	N	2 km	N	Y/NB	Y/NB	N	Y/NB	N	N	Y/NB	N
Rural area	N	N	N	Y/NB	N	N	N	N	N	N	N
Residential area	2 km	N	1 km	N	N	Y/NB	N	1 km	N	N	Y/NB
Fish farming ponds	N	N	Y/NB**	N	N	N	N	N	N	N	N
Protected area	500 m	2 km	Y/NB	N	Y/NB	Y/NB	N	Y/NB	N	Y/NB	Y/NB
Natural parks	N	N	500 m	Y/NB	N	N	N	Y/NB	N	N	Y/NB
Biosphere	N	N	500 m	N	N	N	N	N	N	N	N
Vegetation coverage	N	N	N	N	N	N	N	Y/NB	N	N	N
Agricultural land	N	N	500 m	Y/NB	Y/NB	N	N	N	N	N	Y/NB
Land use	Y/NB	Y/NB	N	Y/NB	Y/NB	Y/NB	Y/NB	N	N	Y/NB	Y/NB
Dams	N	N	N	N	N	N	N	10 km	Y/NB	N	N
Underground water	N	N	N	N	N	N	N	2.5 km	N	N	N
Water, river, lakes	1 km	N	500 m	Y/NB	Y/NB	Y/NB	Y/NB	5 km	N	Y/NB	N
Wetland	N	N	N	N	N	N	N	N	N	Y/NB	N
Forest area	N	N	1 km	Y/NB	N	N	N	N	N	N	Y/NB
Cultural heritage site	N	N	500 m	N	N	N	N	N	N	N	N
Remarks (sources)	PV vs CSP	CSP	PV vs CSP	CSP	CSP	CSP	CSP	CSP	CSP	CSP	CSP

*1- (Ghasemi et al., 2019), 2- (Gouareh et al., 2021), 3- (Sun et al., 2021), 4- (Ziuku et al., 2014), 5-(Levosada et al., 2022), 6- (Alqaderi et al., 2018), 7- (Dawson & Schlyter, 2012), 8- (Alami Merrouni et al., 2018), 9- (Haddad et al., 2021), 10- (Aly et al., 2017), 11- (Tlhalerwa & Mulalu, 2019)

**Y= with considering buffer zone, NB without considering buffer zone

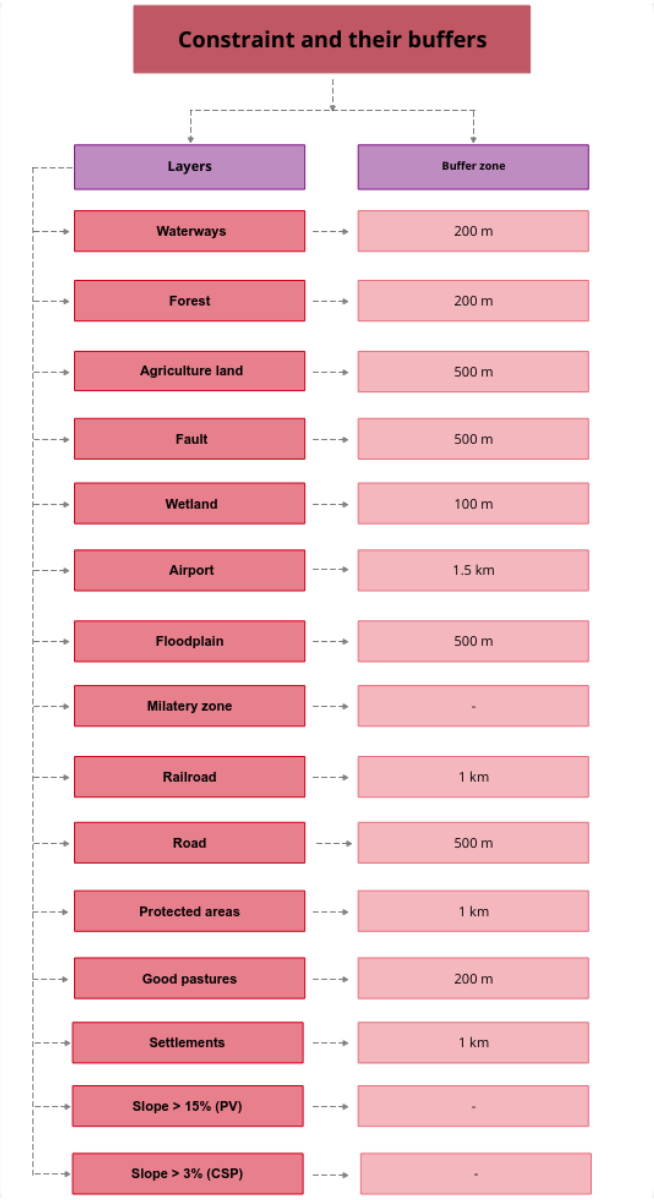


Figure 11 Constraint for PV and CSP plants with the corresponding buffer (by author).

5.5 Development of suitability criteria for Photovoltaics (PV) parks and Concentrating Solar Power (CSP) plant site selection

Previous studies (Table 9 and Table 10) used nine criteria to assess the land for PV and CSP construction. The criteria include three location criteria (distance from road, distance from power lines and transformers, and distance from housing), four climate criteria (solar insolation, maximum temperature, optical depth of dust aerosol, and total cloud fraction), and two topographic criteria (slope and aspect). The criteria are as follows.

5.5.1 Distance from settlements

This criterion concerns the distance between the potential location of a solar installation and nearby human settlements or densely populated areas. Excessive proximity to residential areas can raise issues of visual impact, land use conflict, and possible disruption to the community. Maintaining an appropriate distance from settlements will help to minimize these concerns and ensure the compatibility of the solar project with the surroundings.

This criterion refers to the proximity of the potential site to a road or transport network. Access to the site is critical for construction and maintenance. In general, sites near roads are easier to access and develop.

5.5.2 Distance from power lines and transformers

This measure considers the distance between the potential site and existing power lines and transformers. More excellent proximity to electricity infrastructure can reduce the cost and complexity of connecting solar installations to the grid and ensure efficient power transmission.

Transformers refers to the availability of transformers in the vicinity of the site. Transformers are required to convert the electricity generated to a level compatible with the grid. Having a transformer nearby reduces losses and transmission costs.

5.5.3 Solar irradiance

Solar irradiance is the sunlight received at a given location. High solar irradiance is desirable for both PV and CSP systems as it directly impacts the power generation potential. More sunlight leads to more power generation. This study uses two different measures of solar irradiance to assess PV and CSP: GHI for PV and DNI for CSP.

The Global Horizontal Irradiation (GHI) measures the total solar irradiance on a horizontal surface. This includes direct sunlight and sunlight scattered by the atmosphere. As photovoltaic systems are usually installed horizontally or at a fixed tilt angle, the GHI is a suitable measure for assessing the power production potential, or electric generation potential of photovoltaic systems. The GHI represents the total solar energy available to convert the photovoltaic modules into electricity.

Direct Normal Irradiation measures the amount of solar radiation a surface receives in direct sunlight. It indicates the proportion of solar radiation not scattered by the atmosphere. CSP systems, which focus sunlight using mirrors or lenses to generate heat, require robust and direct sunlight. The DNI is very important for assessing the potential of CSP plants as it directly impacts the efficiency of the concentration process. CSP plants are designed to follow the path of the sun in order to capture the maximum amount of direct sunlight, which makes the DNI a more relevant parameter than the GHI.

Each criterion is selected based on its relevance to the operational requirements of the technology in order to ensure an accurate assessment of the power generation potential of each one. „That is, for the assessment of site suitability for PV I use the GHI criterion, and for the assessment of site suitability for CSP, I use the DNI criterion. “

5.5.4 Maximum air temperature

The maximum air temperature refers to the highest temperature reached at a site. Extreme temperatures can affect solar modules and CSP systems efficiency and lifetime. To ensure optimum performance, sites with moderate maximum temperatures are preferred.

5.5.5 Optical depth of dust aerosols

The optical depth of dust aerosol indicates the amount of dust or particles in the atmosphere capable of reducing solar radiation. Higher dust concentrations can reduce the amount of sunlight reaching the solar cells and mirrors in CSP systems and affect energy production. Low levels of dust are desirable.

5.5.6 Total cloud cover fraction

Total cloud cover measures the percentage of the sky covered by clouds. Cloud cover can significantly reduce solar output and affect PV and CSP systems. Sites with low cloud cover are more suitable for solar energy production.

5.5.7 Slope

Slope refers to the slope of the land at the location being considered. Steep slopes can make building and maintaining PV and CSP systems difficult. Sites with moderate slopes are preferred for ease of installation and access.

5.5.8 Aspect

Orientation refers to the direction in which the earth is facing. This is particularly important in the case of solar orientation. Optimal solar energy production occurs when the solar modules or mirrors directly face the sun. A favorable orientation ensures maximum solar radiation.

Taken together, these nine criteria provide a comprehensive framework for assessing potential sites for PV and CSP installations. The aim is to identify sites that offer the best combination of access, solar resource potential, weather conditions, and topographical features to ensure efficient and cost-effective solar energy production.

Table 8 Assessment criteria considered in previous studies (PV)

Suitability Criteria PV	Authors									
	1*	2*	3*	4*	5*	6*	7*	8*	9*	10*
	Locations									
	Iran, Markazi	Iran, Khuzestan	Iran, Isfahan	Iran	Iran, Isfahan	Iran (Kerman and Yazd)	Iran (Mazandaran, Kermanshah, Razavi Khorasan, and Yazd)	Iran, Tehran	Iran, Fars Province	Iran, Birjand (South Khorasan)
Distance to road	Y	N	Y	Y	N	Y	Y	Y	Y	Y
Distance to settlement	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
Slope	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Aspect	N	N	N	N	N	N	N	Y	N	Y
Elevation	Y	N	N	Y	Y	N	N	Y	Y	N
Solar radiation (GHI)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
Wind speed	N	N	Y	N	Y	N	N	N	N	N
Air temperature	N	N	N	Y	N	N	N	N	Y	Y
Precipitation	N	N	N	N	N	N	Y	N	N	Y
Rainy and snowy days	N	N	N	N	Y	N	N	N	N	N
Humidity	N	N	N	Y	Y	N	N	Y	Y	N
Distance to power lines	N	N	Y	Y	Y	Y	N	Y	Y	Y
sunny hours	N	N	N	N	Y	N	N	N	N	N
Sunshine hours	N	N	N	N	N	N	Y	Y	N	N
Cloudy days	N	N	N	Y	Y	N	N	N	Y	N
Dusty days	N	N	N	Y	Y	N	Y	N	Y	N
Mining activities	N	N	N	N	N	N	N	N	N	Y
NVDI	N	N	N	N	N	N	Y	N	N	N
LST	N	N	N	N	N	N	Y	N	N	N
Remarks (sources)	PV	PV	PV, wind	PV	PV	PV	PV	PV, wind	PV	PV

*1- (Yousefi et al., 2018), 2- (Asakereh et al., 2017), 3- (Barzehkar et al., 2021), 4- (Noorollahi et al., 2016), 5- (Zoghi et al., 2017), 6- (Tavana et al., 2017), 7- (Shorabeh et al., 2019), 8- (Sadeghi & Karimi, 2017), 9- (Mokarram et al., 2020), 10- (Hafeznia et al., 2017)

Table 8 (continued)

Suitability Criteria PV	Authors								
	11*	12*	13*	14*	15*	16*	17*	18*	19*
	Locations								
	Iran	Iran, Khuzestan (Shodirwan)	Korea, Ulleung Island	Turkey, Cumra	Malaysia	South-central Vietnam	Saudi Arabia	Southern Morocco	UK
Distance to road	Y	Y	Y	Y	Y	Y	Y	Y	Y
Distance to settlement	Y	N	N	Y	Y	Y	Y	Y	N
Slope	Y	Y	Y	Y	Y	Y	Y	Y	Y
Aspect	N	Y	N	N	N	N	Y	Y	N
Elevation	N	Y	Y	N	Y	N	N	N	N
Solar radiation	Y	Y	Y	N	Y	Y	Y	Y	Y
Wind speed	N	N	N	N	Y	N	N	N	N
Air temperature	N	N	Y	N	Y	Y	Y	Y	N
Precipitation	N	N	N	N	Y	N	N	N	N
Rainy and snowy days	N	N	N	N	N	N	N	N	N
Humidity	N	N	N	N	Y	N	N	N	N
Distance to power lines	N	Y	Y	Y	Y	Y	Y	N	Y
Sunny hours	N	N	N	N	N	N	N	N	N
Sunshine hours	N	N	Y	N	Y	N	N	N	N
Cloudy days	N	N	N	N	N	N	N	N	N
Dusty days	N	N	N	N	N	N	N	N	N
Mining activities	N	N	N	N	N	N	N	N	N
NVDI	Y	N	N	N	N	N	N	N	N
LST	N	N	N	N	N	N	N	N	N
Remarks (sources)	**PV**	**PV**	**PV**	**PV**	**PV**	**PV**	**PV**	**PV**	**PV**

*11- (Firozjaei et al., 2019), 12- (Asakereh et al., 2014), 13- (Suh & Brownson, 2016), 14- (Uyan & Dogmus, 2023), 15- (Bandira et al., 2022), 16- (Nguyen et al., 2022), 17- (Al Garni & Awasthi, 2017), 18- (Tahri et al., 2015), 19- (Palmer et al., 2019)

Table 9 Assessment criteria considered in previous studies (CSP)

Suitability Criteria CSP	Authors					
	1*	2*	3*	4*	5*	6*
	Locations					
Location	Iran	Iran, Sistan Balochistan	Algeria	China, Ningxia	Zimbabwe	Philippines
Distance to road	N	Y	Y	Y	N	Y
Distance to settlement	N	Y	Y	Y	N	N
Slope	Y	Y	Y	Y	Y	Y
Aspect	N	Y	N	N	N	N
Elevation	N	N	Y	N	N	N
Solar radiation	Y	Y	Y	Y	Y	Y
Wind speed	N	N	N	N	N	N
Air temperature (Annual)	N	Y	N	N	N	N
Fuel supply	N	N	N	N	N	N
Voltage rating nearest grid line	N	N	N	N	N	Y
Distance to power lines	Y	Y	Y	Y	Y	N
Distance to Water, river …	Y	N	N	N	Y	Y
sunny hours	N	N	Y	N	N	N
Sunshine hours	N	N	N	Y	N	N
Cloudy days	N	N	N	N	N	N
Remarks (sources)	CSP	PV vs CSP	CSP	PV vs CSP	CSP	CSP

*1- (Mohammadi & Khorasanizadeh, 2019), 2- (Ghasemi et al., 2019), 3- (Gouareh et al., 2021), 4- (Sun et al., 2021), 5- (Ziuku et al., 2014), 6- (Levosada et al., 2022)

Table 9 (continued)

Suitability Criteria CSP	Authors						
	7*	8*	9*	10*	11*	12*	13*
	Locations						
	UAE	Western Australia	Eastern Morocco	Algeria	Tanzania	Botswana	West Africa
Distance to road	Y	Y	Y	Y	Y	N	Y
Distance to settlement	N	N	Y	Y	Y	N	Y
Slope	Y	Y	Y	Y	Y	Y	Y
Aspect	N	N	N	Y	N	N	N
Elevation	Y	N	Y	N	N	N	N
Solar radiation	Y	Y	Y	Y	Y	Y	Y
Wind speed	N	Y	N	N	N	Y	N
Air temperature (Annual)	N	N	N	N	N	Y	N
Fuel supply	N	Y	N	N	N	N	N
Voltage rating nearest grid line	N	N	N	N	Y	N	N
Distance to power lines	Y	Y	Y	Y	Y	Y	Y
Distance to Water, river	Y	Y	Y	Y	Y	Y	N
sunny hours	N	N	N	N	N	N	N
Sunshine hours	N	N	N	N	N	N	N
Cloudy days	N	Y	N	N	N	N	N
Remarks (sources)	**CSP**	**CSP**	**CSP**	**CSP**	**CSP**	**CSP**	**PV vs CSP**

*7- (Alqaderi et al., 2018), 8- (Dawson & Schlyter, 2012), 9- (Alami Merrouni et al., 2018), 10- (Haddad et al., 2021), 11- (Aly et al., 2017), 12- (Tlhalerwa & Mulalu, 2019), 13- (Yushchenko et al., 2018)

5.6 Score standardization of suitability criteria

Potential CSP and PV sites were assessed based on the literature and the spatial distribution of these criteria across the country.

To simplify the suitability process, I have systematically grouped the identified criteria into appropriate classes, namely 'high suitability,' 'medium suitability,' 'low suitability,' and 'very low suitability.' This classification framework helped assess the suitability of different sites for solar energy installations, as it considers the subtle variations common in Iran's different climatic and geographical regions.

Classification methods for CSP and PV showed similarities but significant differences, particularly in slope. For PV, a slope of up to 15% was considered compatible with operational requirements. In contrast, the strict operational considerations for CSP require a more precise tilt threshold of 3%.

Furthermore, unlike previous studies that primarily consider mean air temperature, my approach considers mean maximum air temperature. This decision was influenced by Iran's climate, where average temperature alone may not accurately reflect warmer environmental conditions.

By focusing on mean maximum temperature, I ensure a better indicator of the heat stress that both CSP and PV systems may experience in different regions of the country.

Figure 12 and Figure 13 show the suitability criteria for PV and CSP plant siting for for classification and assessment class.

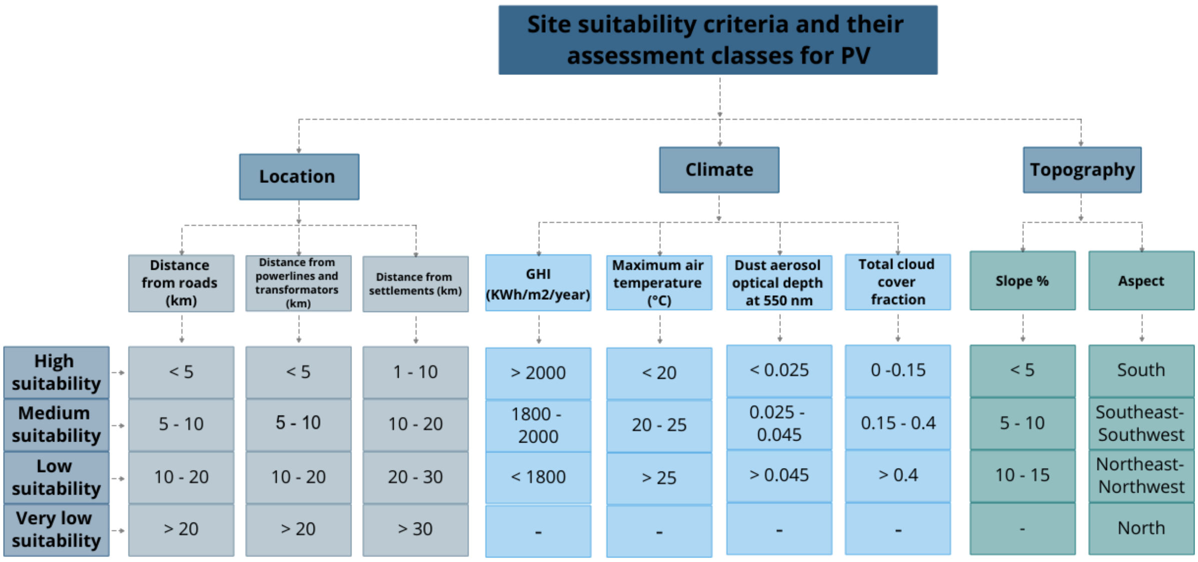


Figure 12 Criteria and associated scoring for the assessment of site suitability for PV plants (by author)

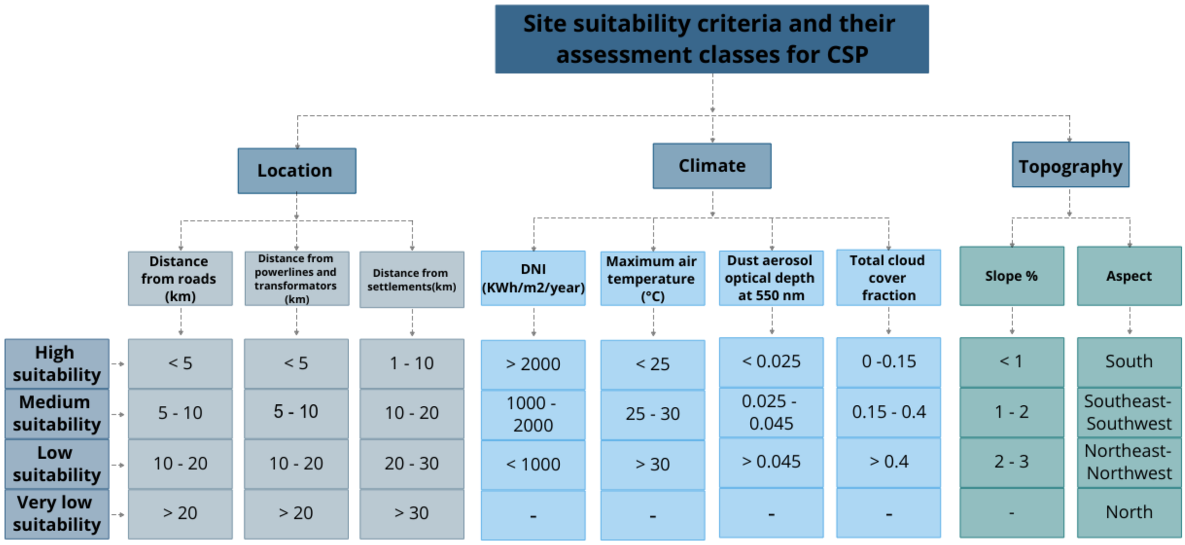


Figure 13 Criteria and associated scoring for the assessment of site suitability for CSP plants (by author)

5.7 Weighting the criteria and sensitivity analysis

From literature review, I have learned that an essential part of my evaluation is deciding which criteria are the most important to us. I do this by giving each criterion specific importance, called 'weighting.' I have found that one criterion stands out in previous studies: solar radiation. It is the most essential factor in my evaluation, as shown in Table 8.

Therefore, I wanted to see what would happen if I changed the weighting of the criteria. I ran several tests, or 'scenarios,' to see how each change would affect the results. Here are the scenarios:

Scenario 0: Equal weighting considering the criterion "proximity to power stations".

Scenario 1: Equal weighting without the "proximity to power stations " criterion.

Scenario 2: Equal weighting of the criteria "Location" (33 %), "Climate" (34 %), and "Topography" (33 %), followed by a further breakdown of the weighting of the individual sub-criteria according to their importance The importance of each criterion was determined based on the authors' opinions and the results of the literature review.

Scenario 3: Equal weighting of direct PV performance criteria (DNI, GHI, and aspect, 45%) and economic criteria (distance to infrastructure, location, and slope, 45%) with lower weighting of efficiency criteria. Efficiency (temperature, optical dust depth, and cloud fraction, 10%). The sub-criteria were also weighted according to their importance, the authors' opinion, and the literature review results.

In order to see the effect of the different weightings on the results, we used a unique tool in ArcGIS, the overlay tool. This tool allows us to combine the weighted measures and create maps showing how sites in different locations are ranked.

5.8 Integration of constraint layers and assessment maps

The suitability assessment criteria for both PV and CSP technologies were integrated, resulting in two separate assessment maps: one for PV and one for CSP. These separate maps assign geographic regions to four different levels of suitability, ranging from high suitability to very low suitability.

In the next phase, these two maps will be integrated with the results of the availability model. Building PV and CSP plants on a small scale proves to be economically impractical. To ensure the efficiency of solar plants, certain size limits were set. In my investigation into land requirements for solar energy projects, I discovered that the minimum land area needed for an economically feasible PV solar project typically falls within the range of approximately 5 hectares (*List of Photovoltaic Power Stations*, 2023). Conversely, CSP plants generally necessitate a larger allocation, typically around 50 hectares (*List of Solar Thermal Power Stations*, 2023). It is worth highlighting that these measurements may vary depending on the distinctive characteristics inherent to specific solar projects. Therefore, depending on the specific circumstances of each project, 5 hectares for PV and 50 hectares for CSP may be a rough estimate, but actual land requirements may be more or less. (National Renewable Energy Laboratory, 2013). Areas smaller than 5 hectares were excluded from the PV map, and areas smaller than 50 hectares were excluded from the CSP map. In this way, two unrestricted classified suitability maps were created for PV and CSP technologies.

5.9 Integration of Photovoltaics (PV) and Concentrating Solar Power (CSP) suitability maps

The final step in developing feasible suitability maps for PV and CSP plants is to combine the two separate maps. One of these maps identifies unrestricted areas suitable for PV plant construction, while the other map identifies unrestricted areas suitable for CSP plant construction. The resulting map provides a comprehensive assessment of land suitability for both PV and CSP plants, effectively showing the appropriateness of land for these installations. This composite map is divided into four classes: "high suitability," "medium suitability," "low suitability," and "very low suitability," providing a clear assessment of the suitability of each area for PV and CSP projects.

Chapter 6 Results and Discussion

6.1 Constraint model

The result is two map of the binary constraining model represented as a number consisting of 0s and 1s for PV and CSP. This map is carefully constructed by integrating different geographic layers representing different constraining factors. In this framework, zero represents constrained areas, while one represents open areas for unconstrained PV and CSP. The number of constrained areas assigned to each factor is documented detail in Table 10.

The percentage of restriction factors varies between 0.1 and 25.6 percent. The sum of the areas in Table 10 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 constraint area map for installing PV and CSP (Figure 14 and Figure 15). 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 infeasible if the slope exceeds 15%, and CSP land considered infeasible if the slope exceeds 3%.

Figure 16 to Figure 30 depicts the various constraint.

Table 10 Percentage of excluded area in the constraint criteria for PV and CSP plants in the total area of Iran (by author)

Constraint	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	0.1
Slope > 15 % (PV)	14.1
Slope > 3 % (CSP)	51.6
Aspect (North direction)	12.9

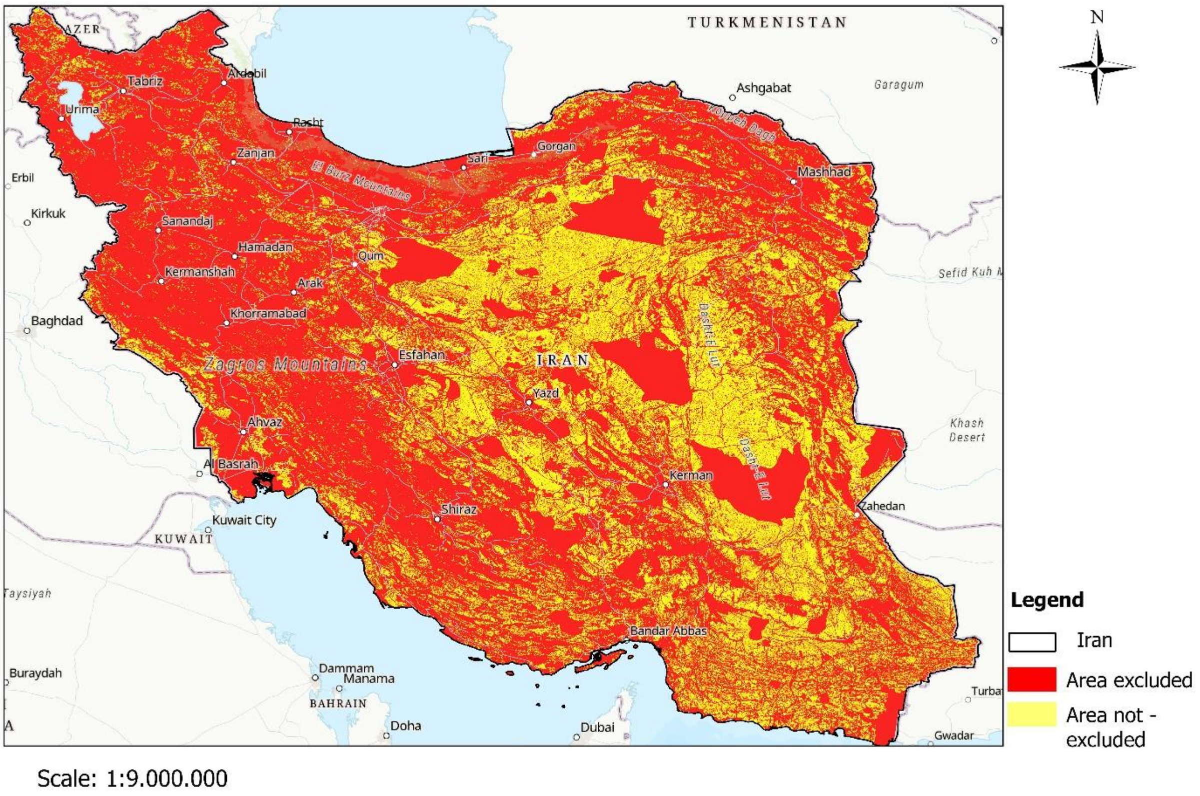


Figure 14 Constraint areas for PV siting (by author)

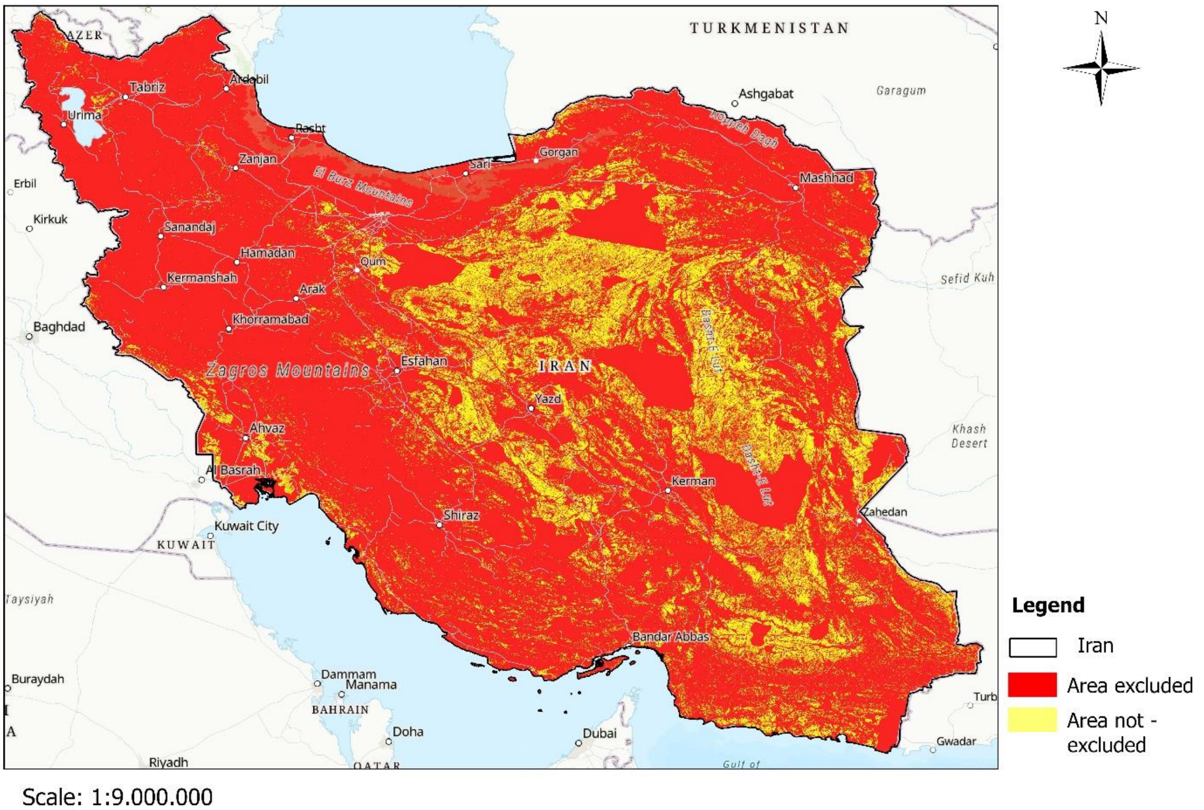
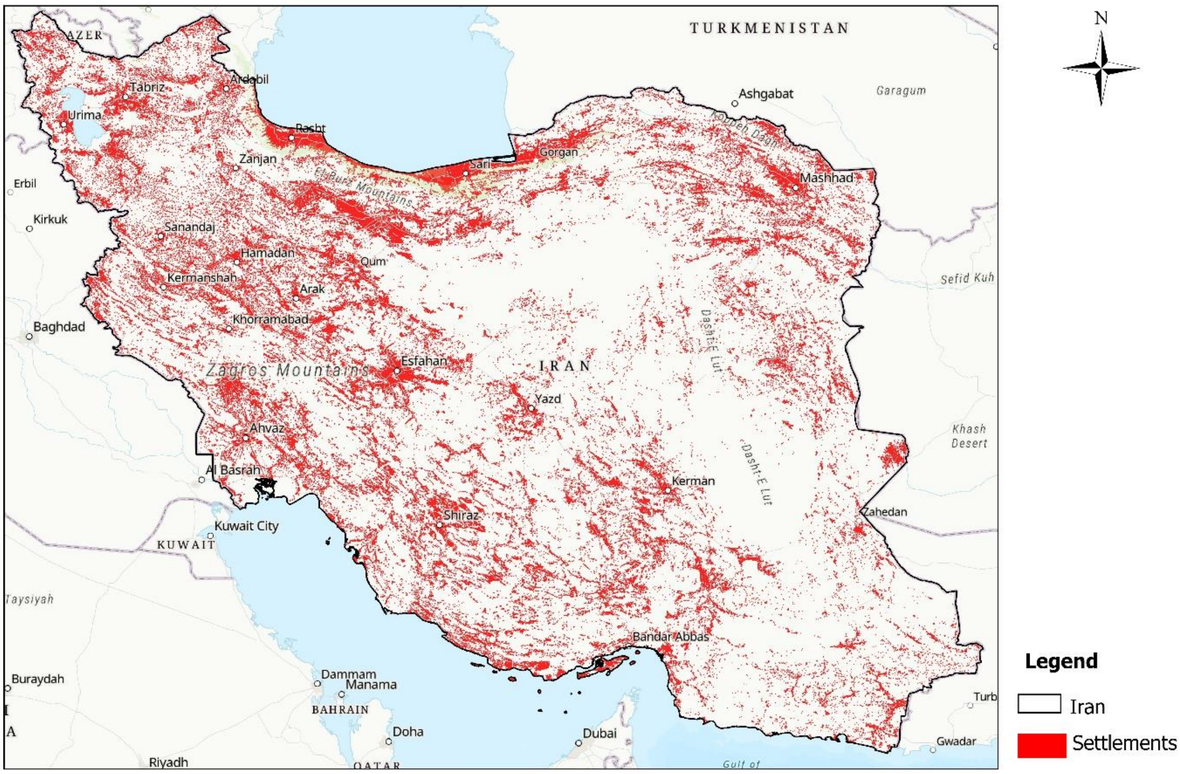
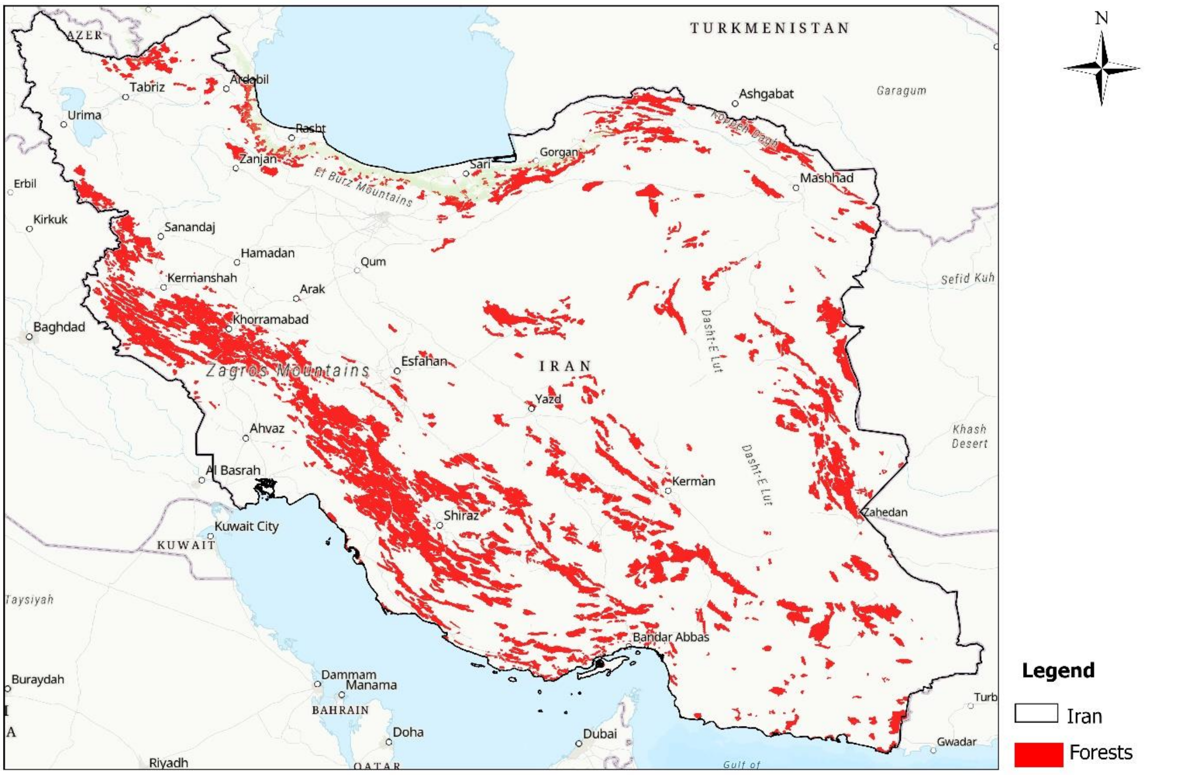


Figure 15 Constraint areas for CSP siting (by author)



Scale: 1:9.000.000

Figure 16 Settlements (by author extracted from (*GHSL - Global Human Settlement Layer*, 2023))



Scale: 1:9.000.000

Figure 17 Forest (by author extracted from (*Academy of Geospatial Sciences of Iran*, 2021))

Scale: 1:9.000.000

Figure 18 Railroads (by author extracted from (*OpenStreetMap*, 2023))

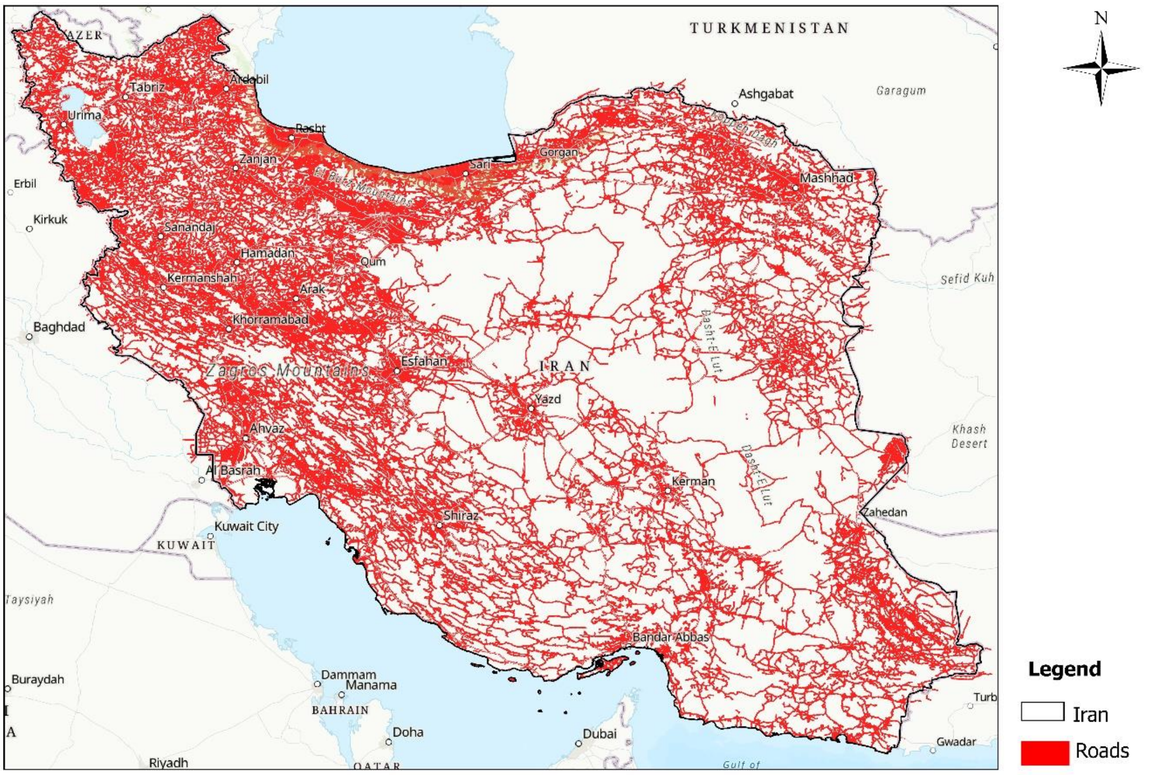


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Figure 19 Roads (by author extracted from (*OpenStreetMap*, 2023))

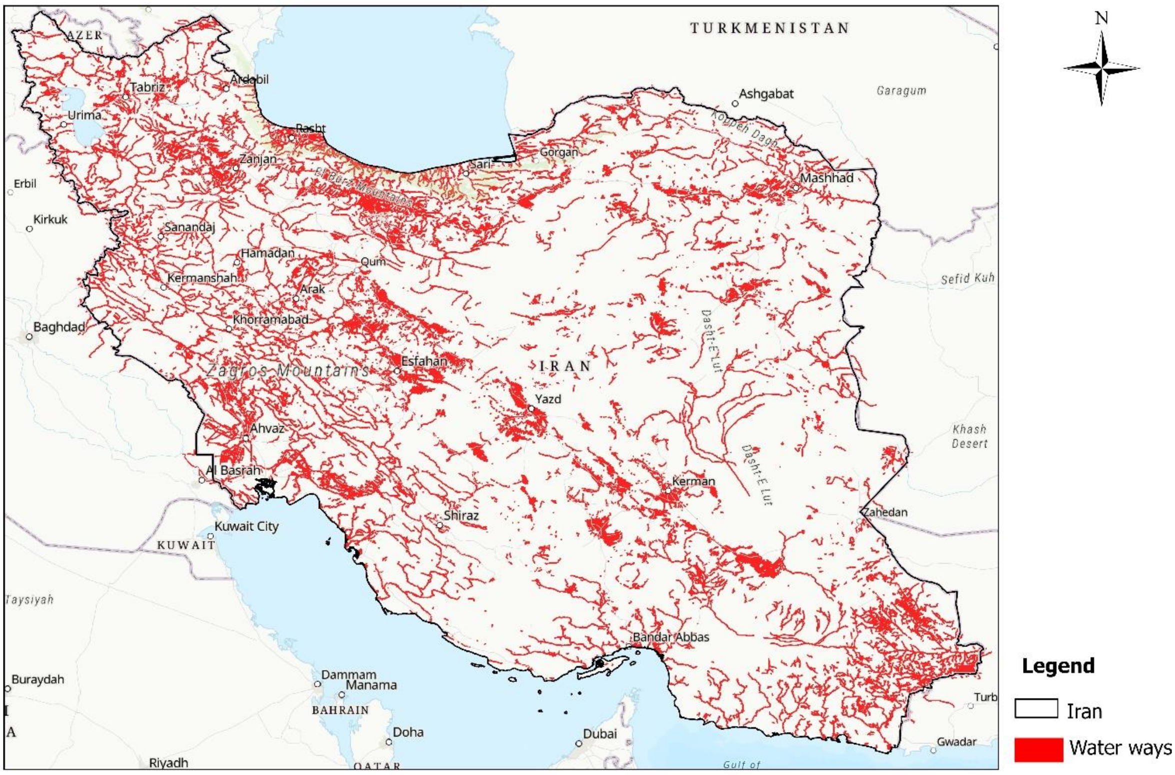

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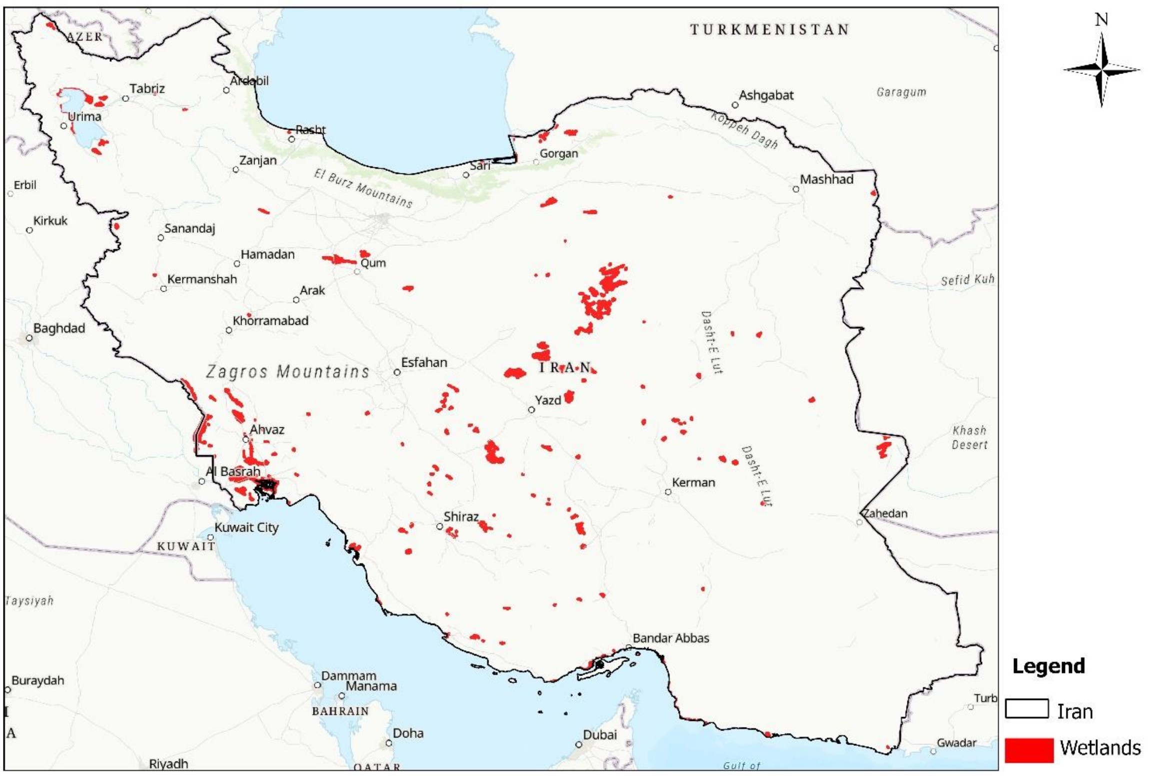
Figure 20 waterways (by author extracted from (*OpenStreetMap*, 2023))



Scale: 1:9.000.000

Figure 21 Wetlands (by author extracted from (*Academy of Geospatial Sciences of Iran*, 2021))

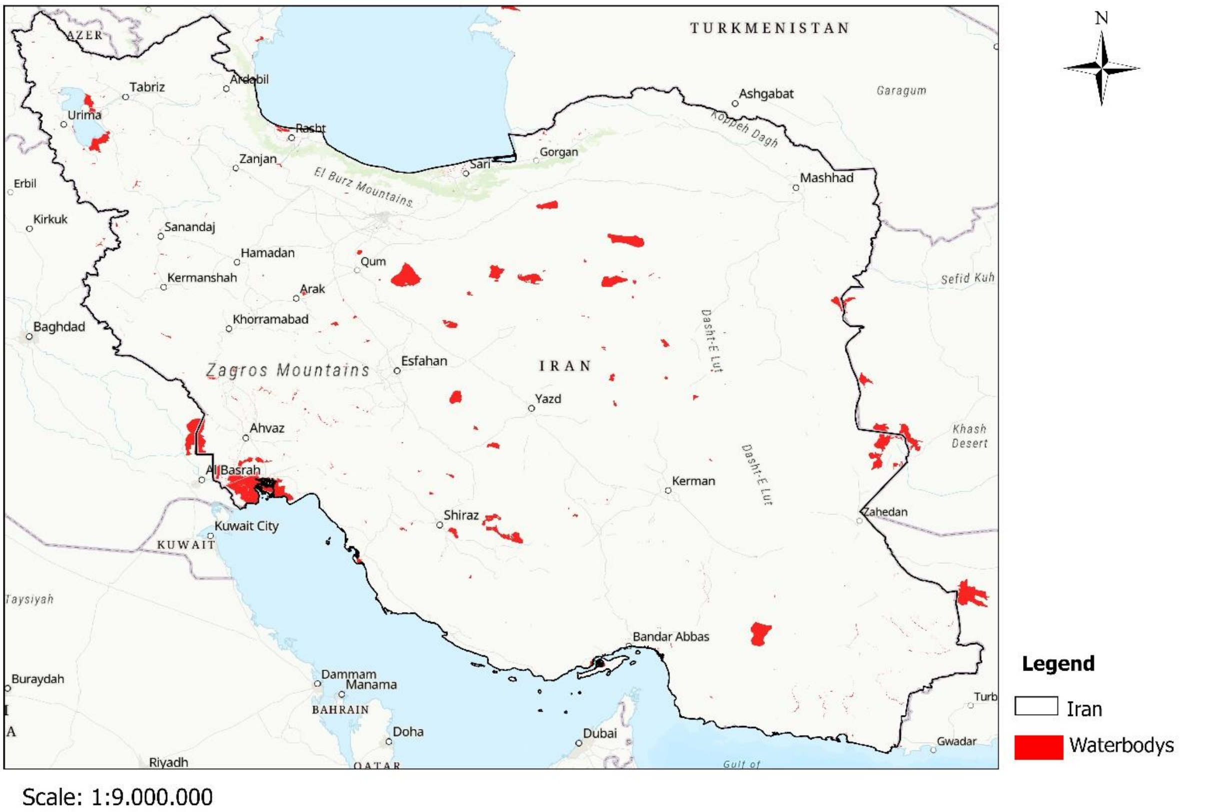


Figure 22 Waterbody (by author extracted from (*OpenStreetMap*, 2023))

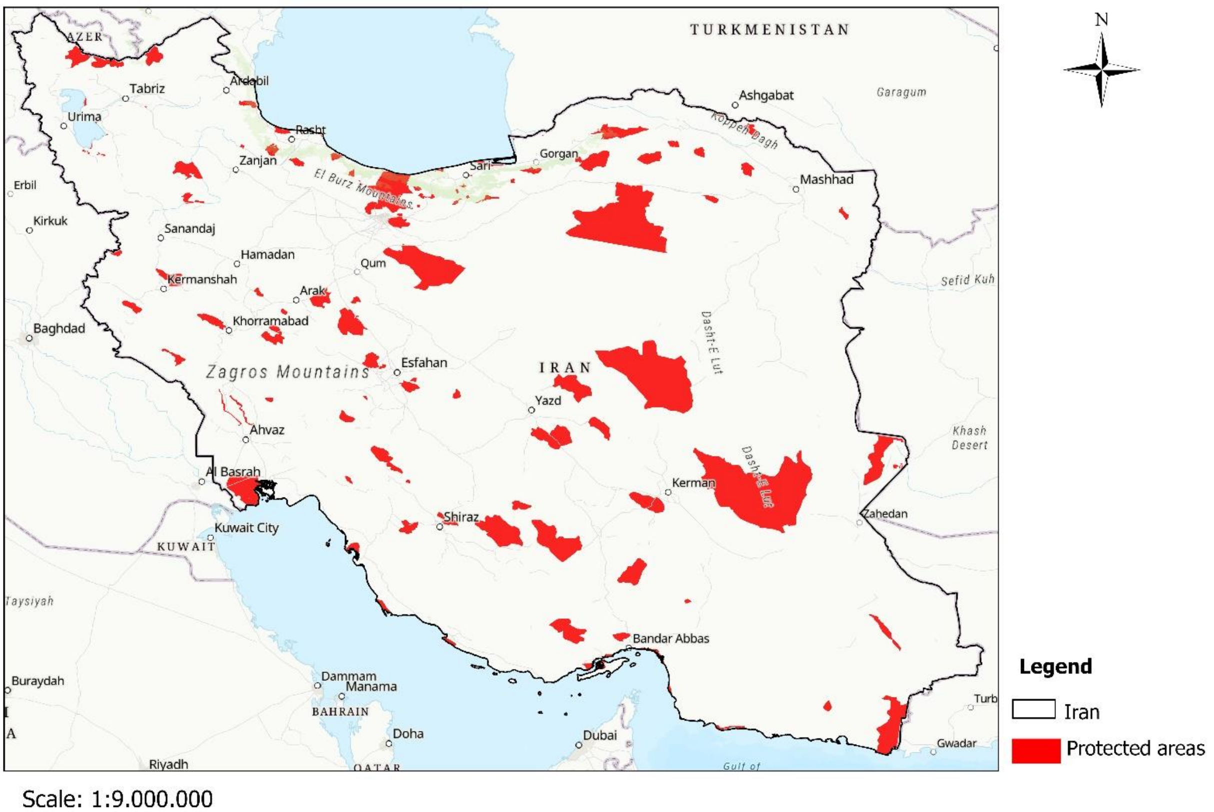


Figure 23 Protected areas (by author extracted from (*Protected Areas (WDPA)*, 2023))

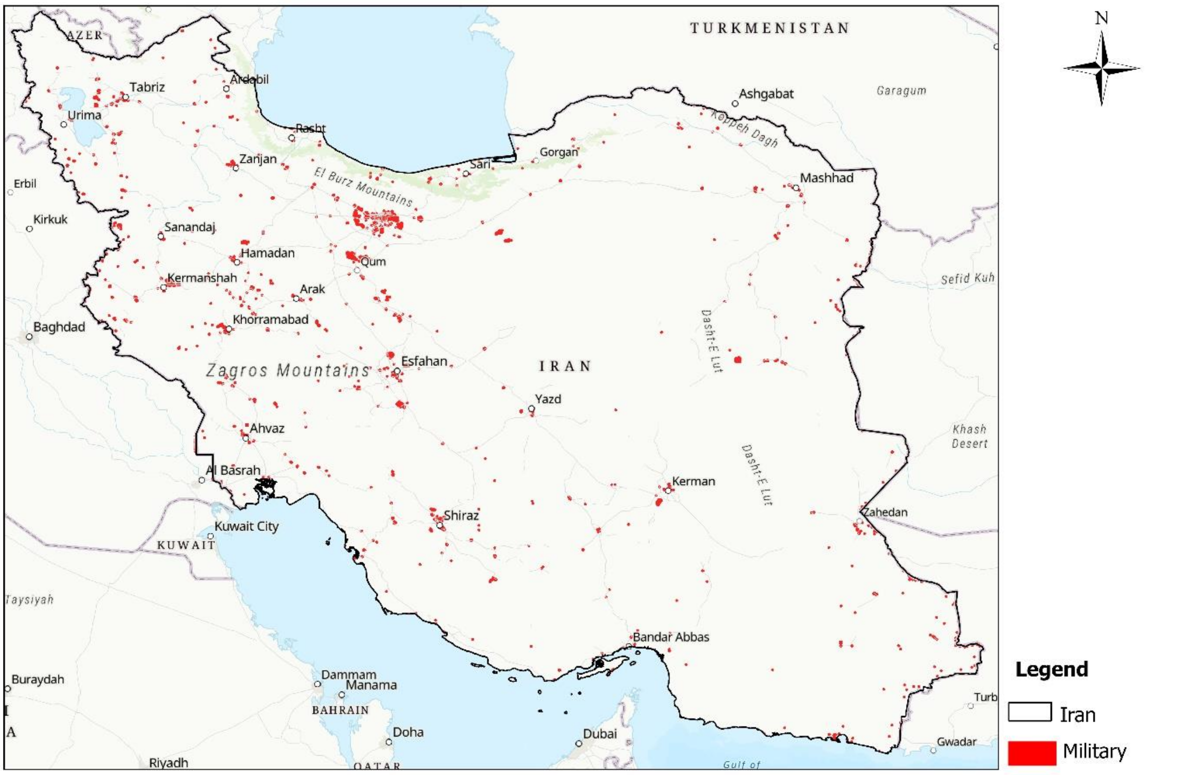


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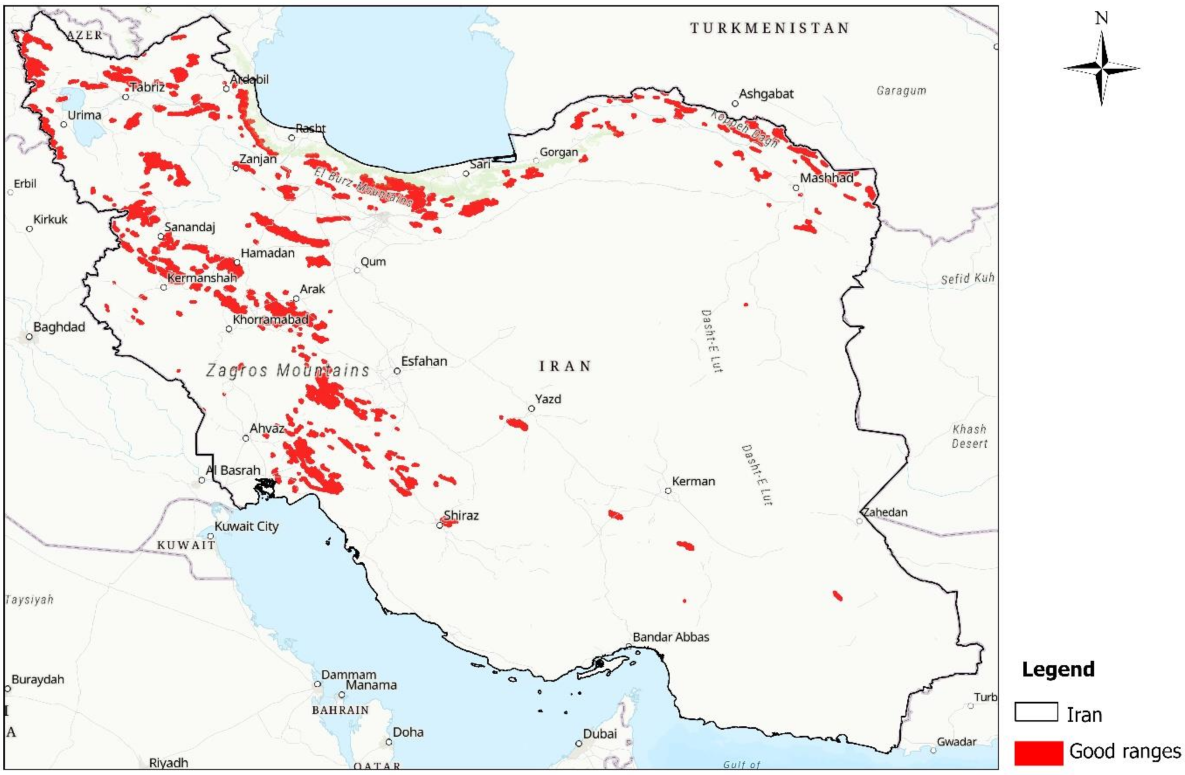
Figure 24 Military zones (by author extracted from (*OpenStreetMap*, 2023))



Scale: 1:9.000.000

Figure 25 Good ranges (by author extracted from (*Academy of Geospatial Sciences of Iran*, 2021))

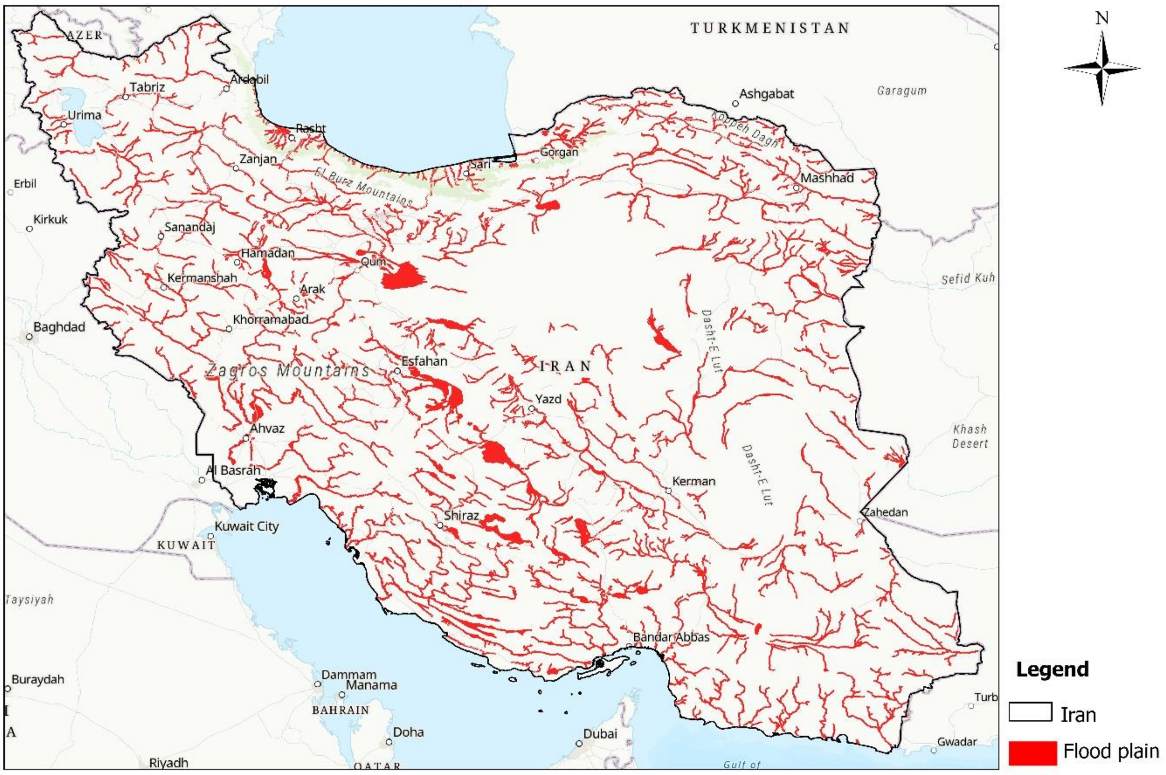


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Figure 26 Floodplain (by author extracted from (*Iran Remote Sensing Academy Company*, 2019))

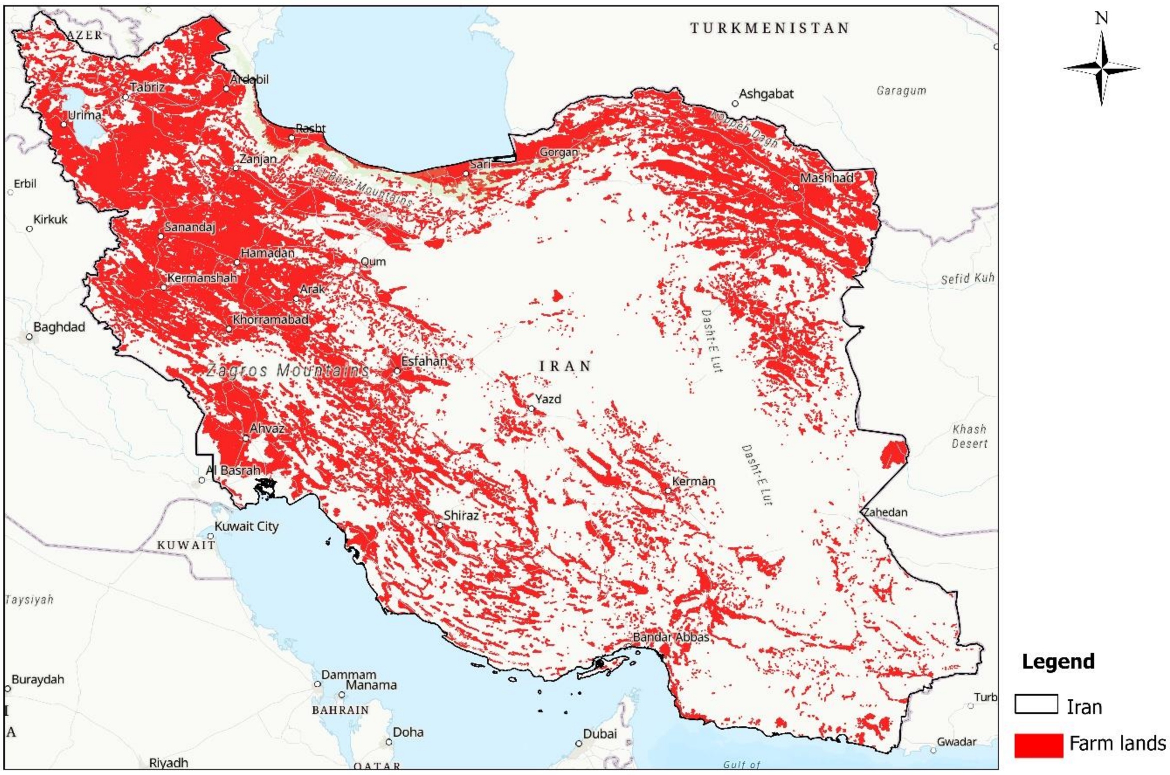

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Figure 27 Farm land (by author extracted from (*Academy of Geospatial Sciences of Iran*, 2021))

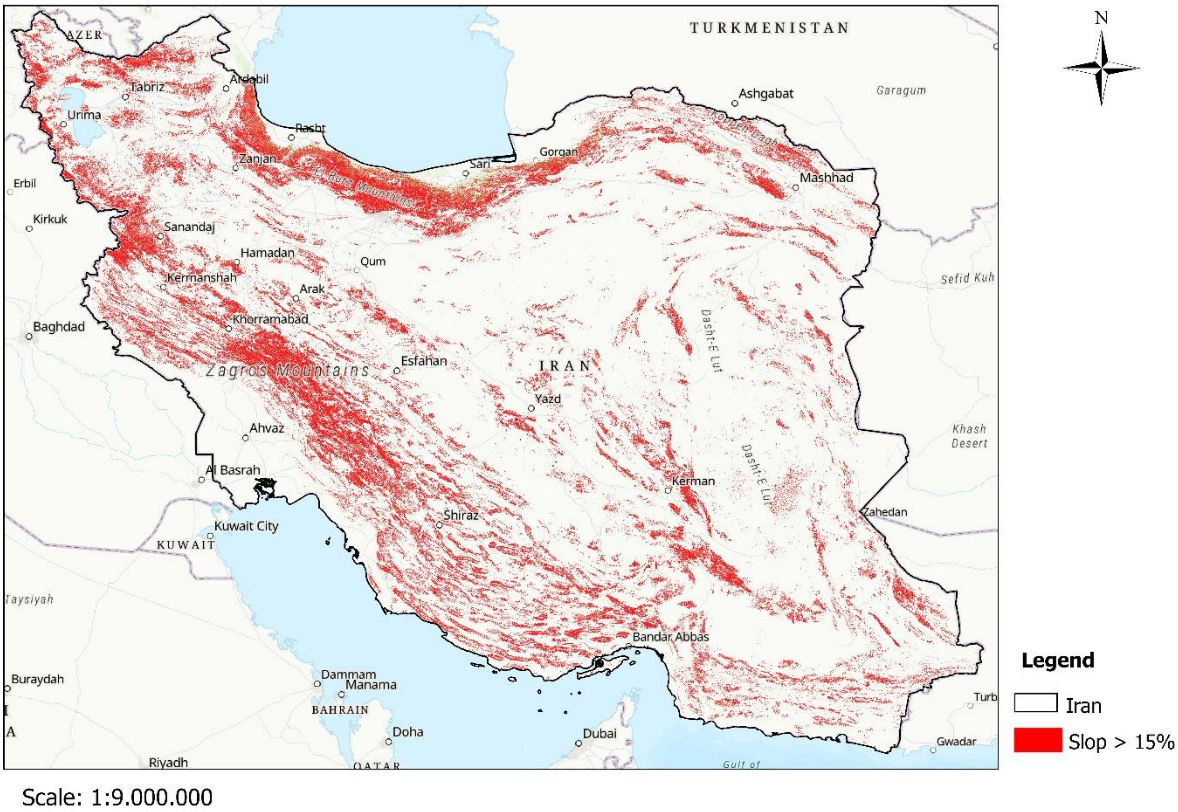

Figure 28 Slope greater than 15 % (Constraint for PV) (by author)

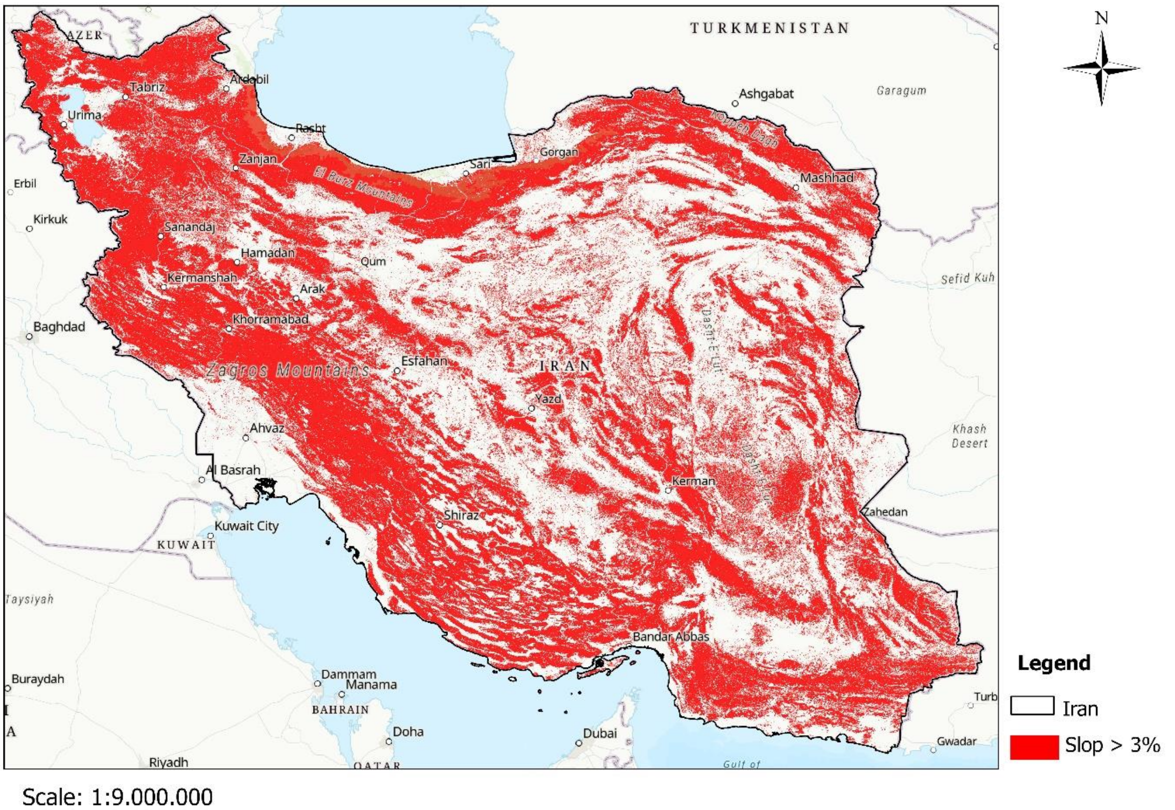

Figure 29 Slope greater than 3 % (Constraint for CSP) (by author)

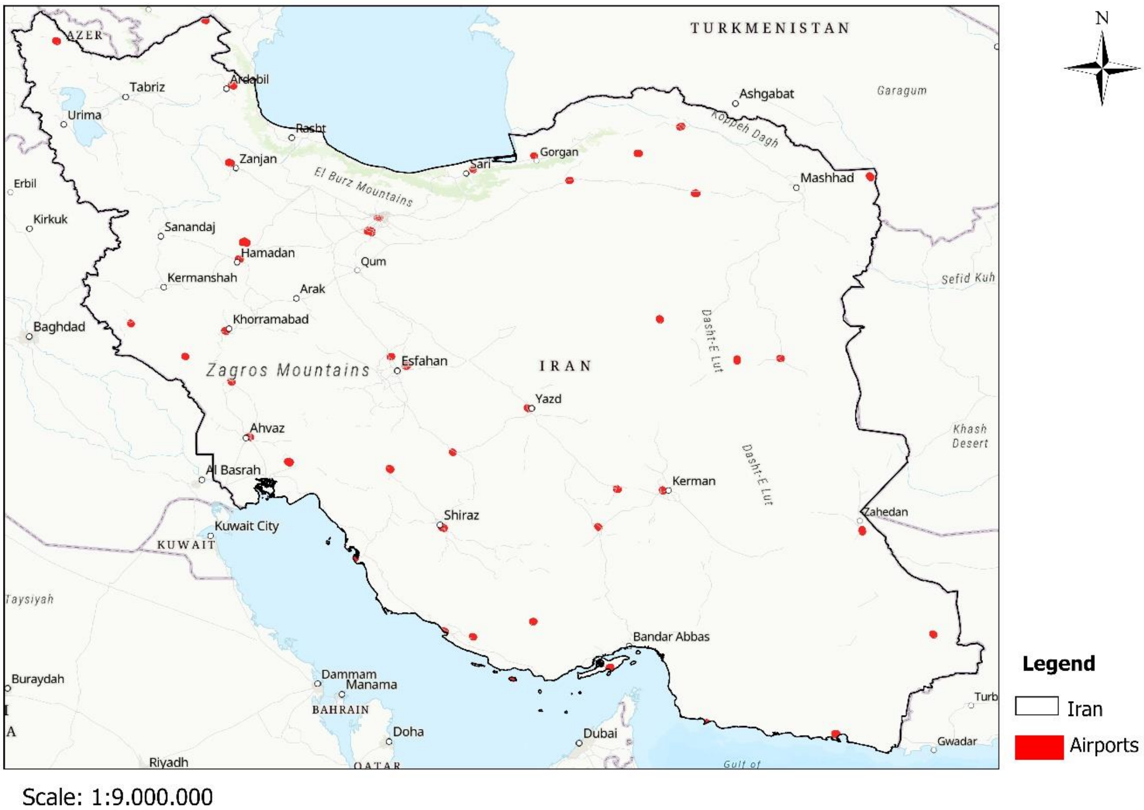

Figure 30 Airports (by author extracted from (*Academy of Geospatial Sciences of Iran*, 2021))

6.2 Suitability assessment

I have developed a suitability model for evaluating PV and CSP plants. The model is based on a set of nine evaluation criteria that allow us to classify these plants into four different classes: " high suitability," " medium suitability," " low suitability," and " very low suitability" (as shown in Figure 12 and Figure 13).

The suitability criteria consider the wide range of factors and ensure thorough suitability assessment of PV parks and CSP plants. This allows stakeholders and policymakers to decide when to choose the right locations for these renewable energy projects.

6.3 Score standardization of suitability criteria

Figure 31 to Figure 43 provide an overview of the categorical evaluation criteria. Consideration of various influencing factors, including DNI for CSP applications and GHI for PV installations (Figure 31 and Figure 32), maximum air temperature, cloud cover, and dust indices, are essential in evaluating potential sites for solar power installations.

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 the construction of solar power plants. Although these conditions may slightly reduce the efficiency of solar power plants, their overall effectiveness is significant.

However, determining the economic feasibility of installing solar power plants in certain areas requires careful evaluation, especially in developing countries such as Iran that 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, Lut desert and Kavir desert (in the center of the country, see Figure 1), are considered very low suitable because of their distance from infrastructure and human settlements (Figure 33 and Figure 36).

Figure 34 shows the proximity to power stations. The analysis of this map shows that there is a major challenge to the installation of solar power plants in many areas of Iran - 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 extensive transmission lines and substations. In developing countries, such as Iran, where economic considerations are of paramount importance, these additional costs can make solar power projects financially unviable.

Note that the data presented in Figure 35 may not be completely current. In Iran, there are data gaps and inconsistencies in several areas, including energy infrastructure. Ministry of Energy, 2023 indicates that Iran has over 800 power stations, while the data in the map indicate about 230 power stations. This disparity raises questions about the accuracy and value of the information provided by the *Transformator*, 2023.

In the study of the effect of slope on the viability of CSP plants, large parts of western and northern Iran are very low suitable or unsuitable for CSP projects due to their topographic characteristics (Figure 38). In Section 4.6.2, I presented a classification system specifically designed to evaluate two critical parameters: Slope and Average Maximum Air Temperature, which are applicable to both PV and CSP with different classification applications. Why it matters. It is important to note that all other criteria for PV and CSP have the same classification (Figure 39 and Figure 40).

It should be noted that the cloud cover is more pronounced in the north-western regions of Iran (Figure 42), while the south-eastern regions have the highest levels of dust (Figure 43). However, there are problems with data accuracy in measuring the optical depth of clouds and dust content in Iran. The measurement scale is large, and it is difficult to detect changes between different regions. As a result, much of Iran appears to have similar dust and cloudiness values despite significant differences.

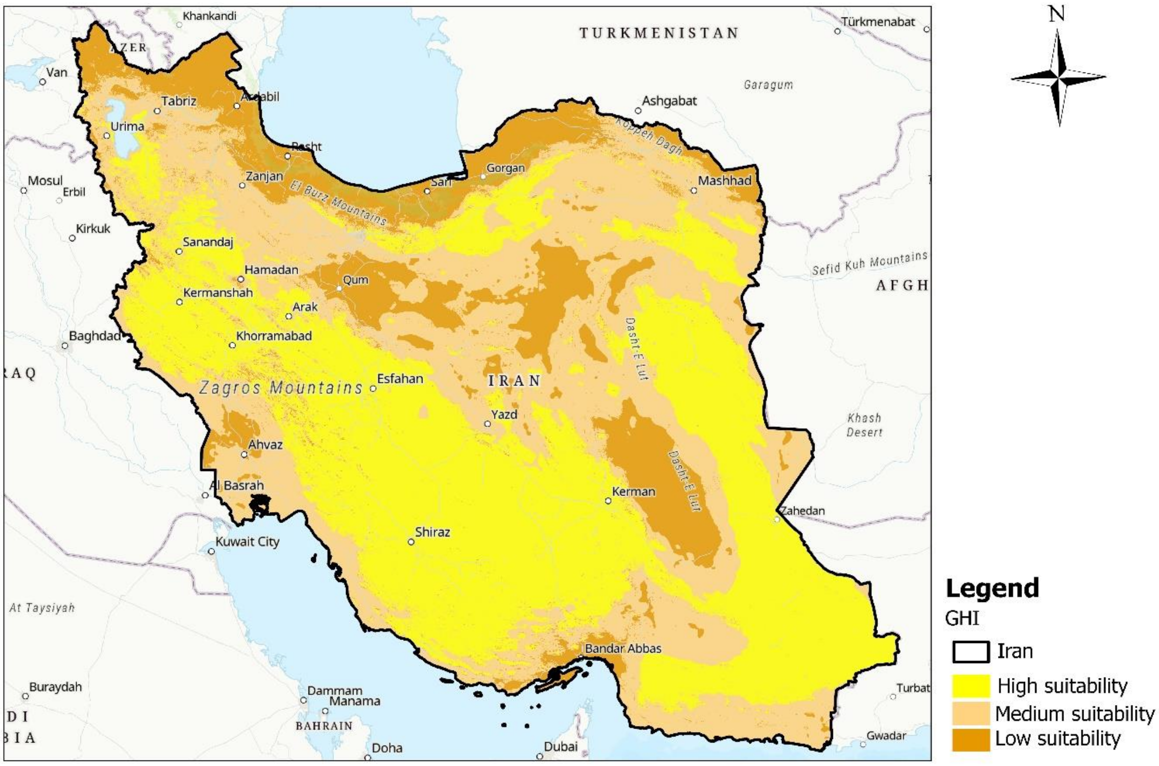

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Figure 31 Assessment of land suitability for PV based on GHI Criterion (by Author)

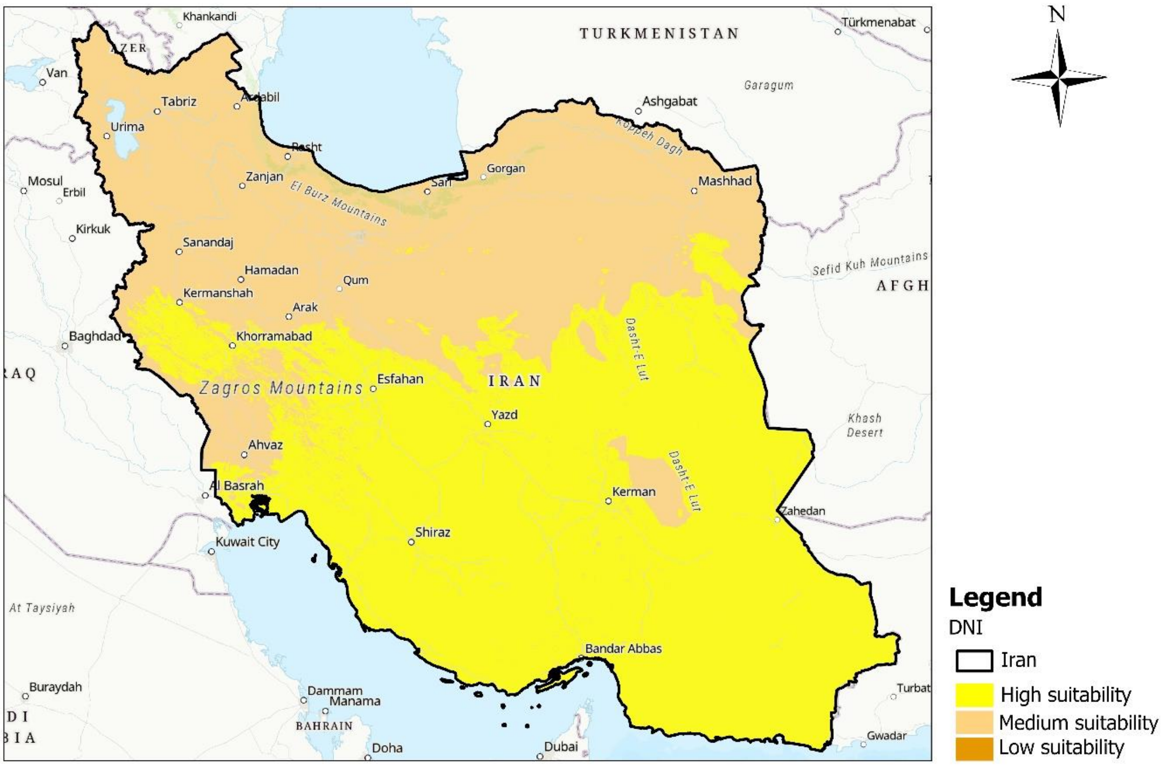

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Figure 32 Assessment of land suitability for CSP based on DNI Criterion (by Author)

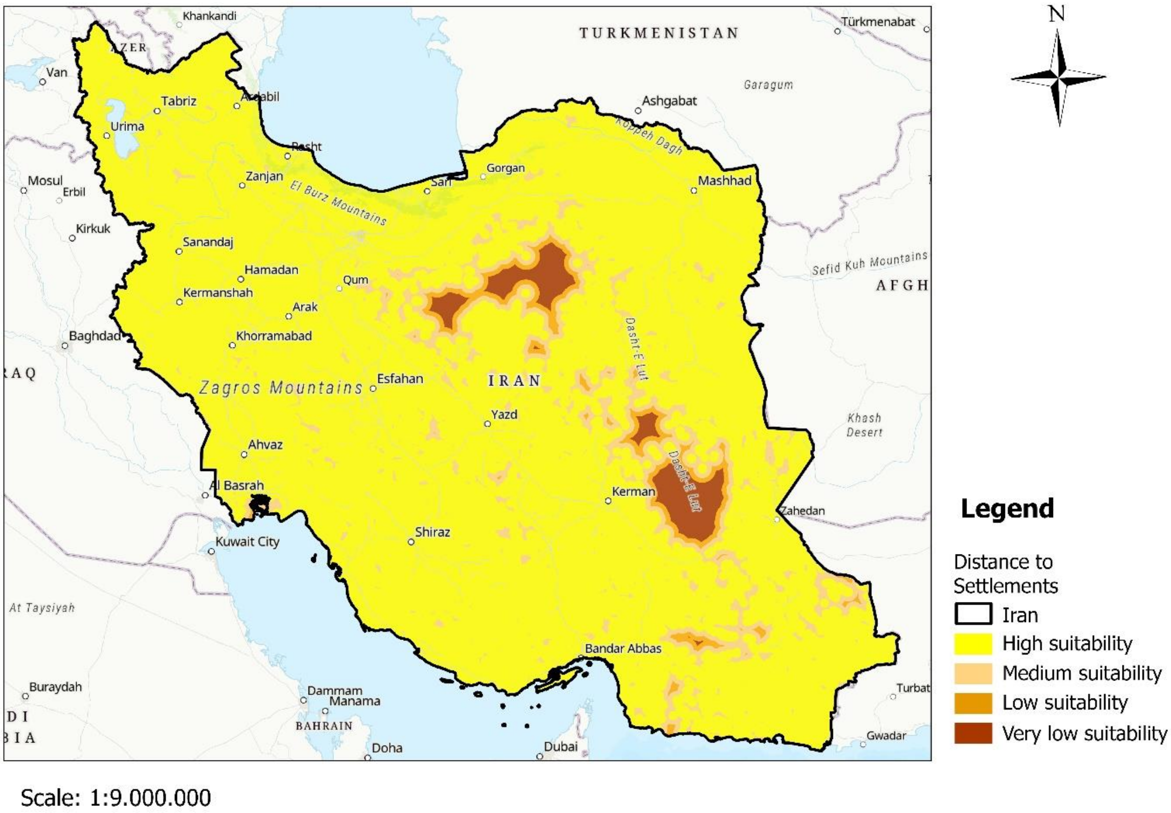

Figure 33 Assessment of land suitability for PV & CSP based on distance to settlements criterion (by Author)

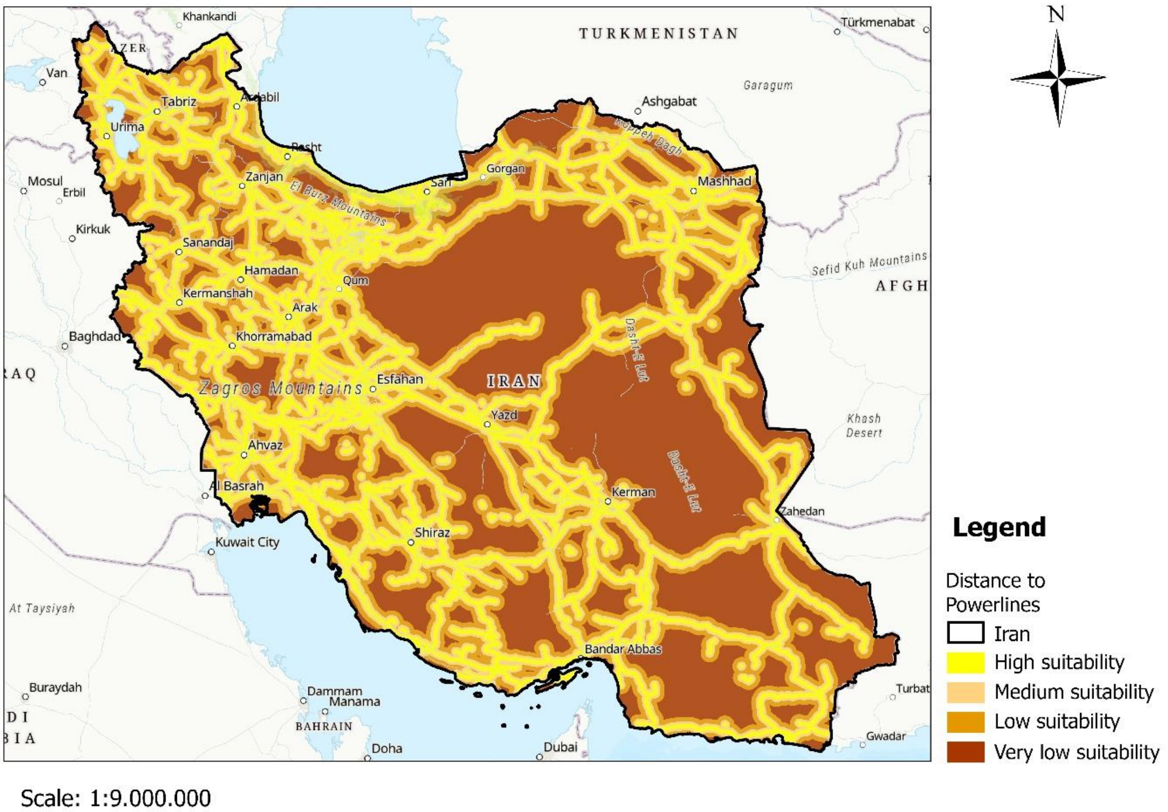

Figure 34 Assessment of land suitability for PV & CSP based on distance to powerlines criterion (by Author)

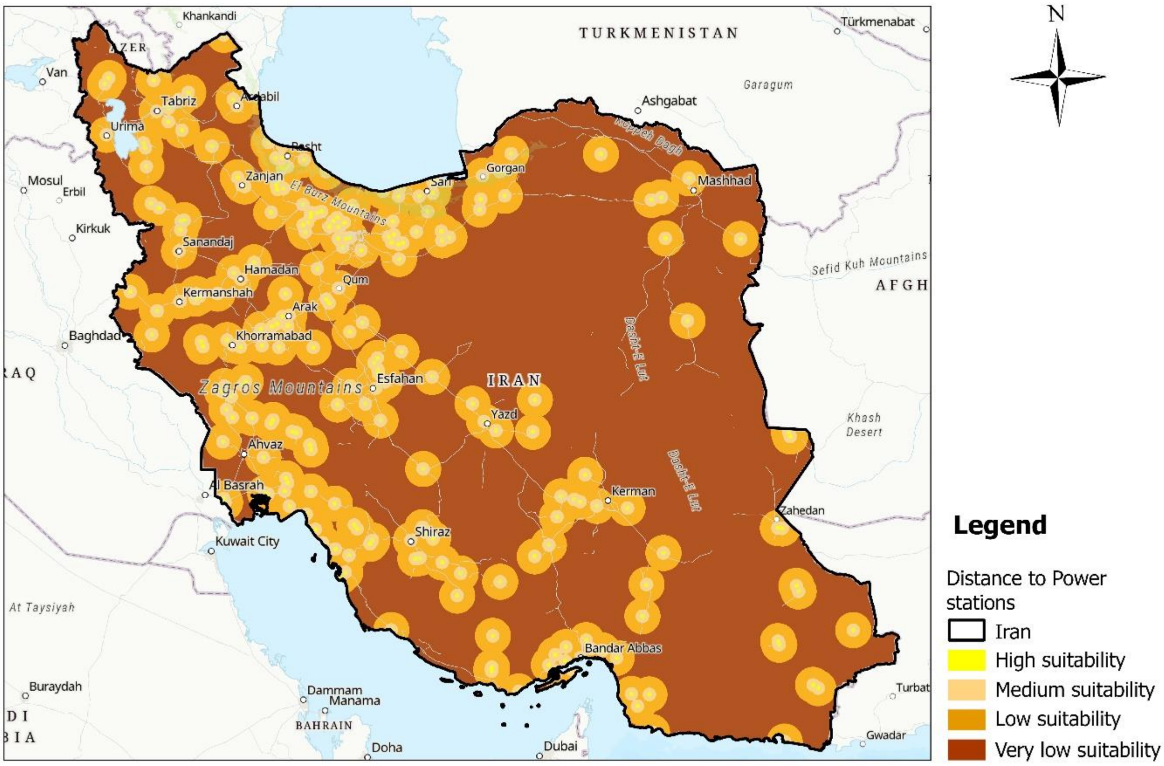

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Figure 35 Assessment of land suitability for PV & CSP based on distance to power stations criterion (by Author)

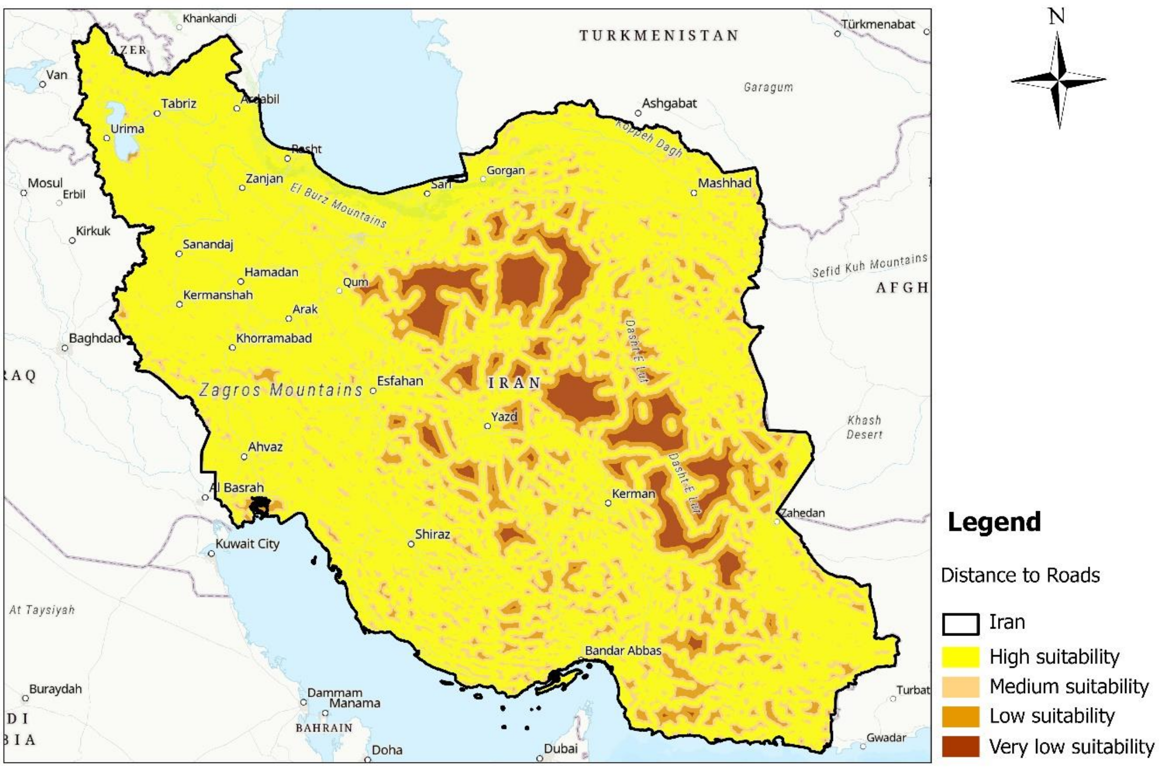

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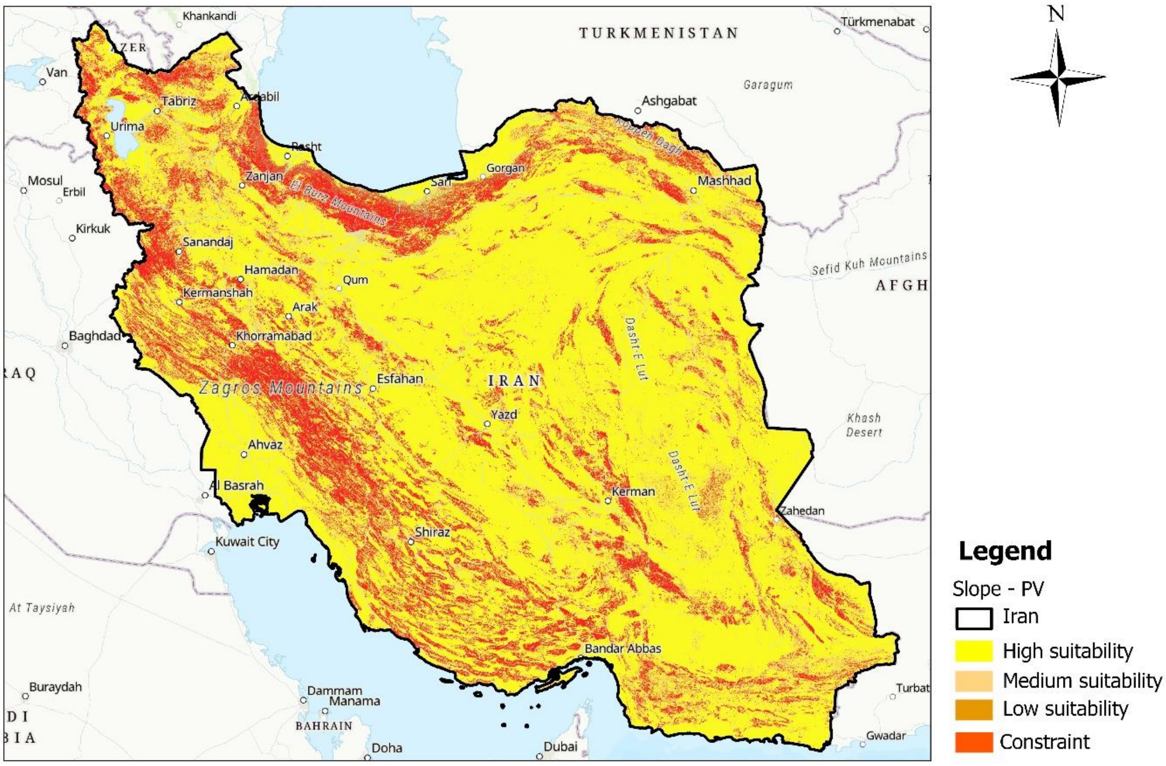
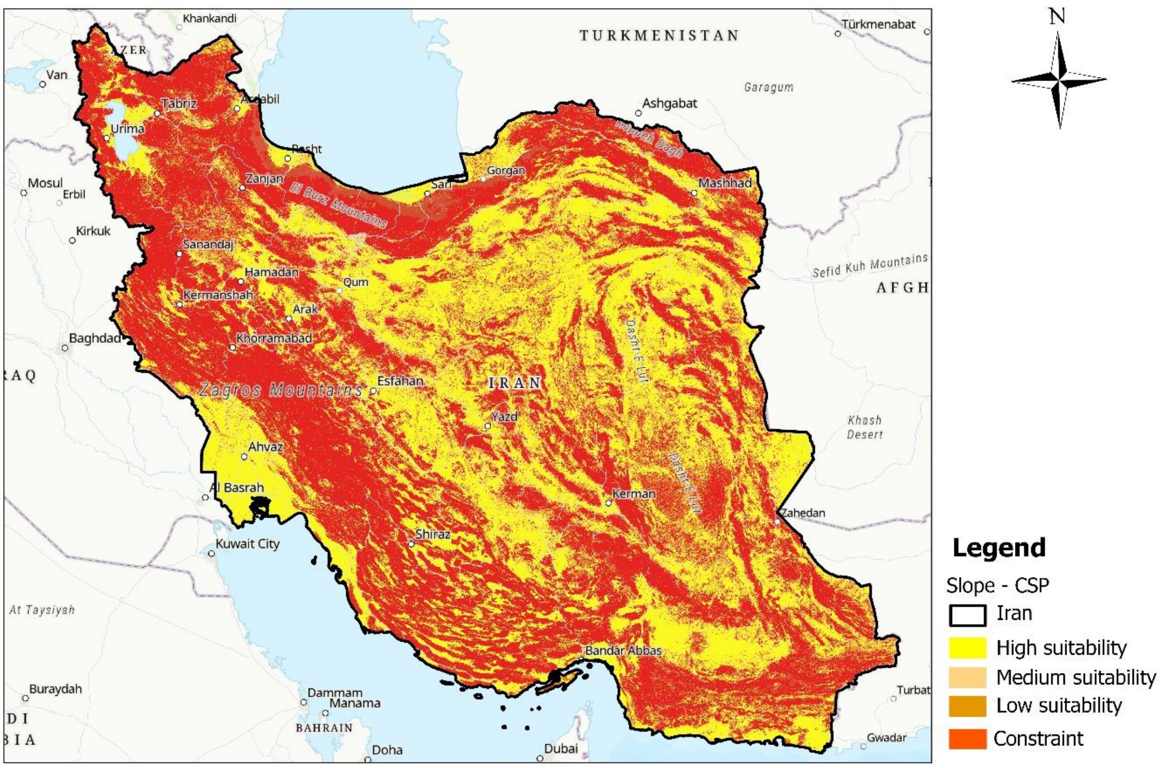
Figure 36 Assessment of land suitability for PV & CSP based on distance to roads criterion (by Author)



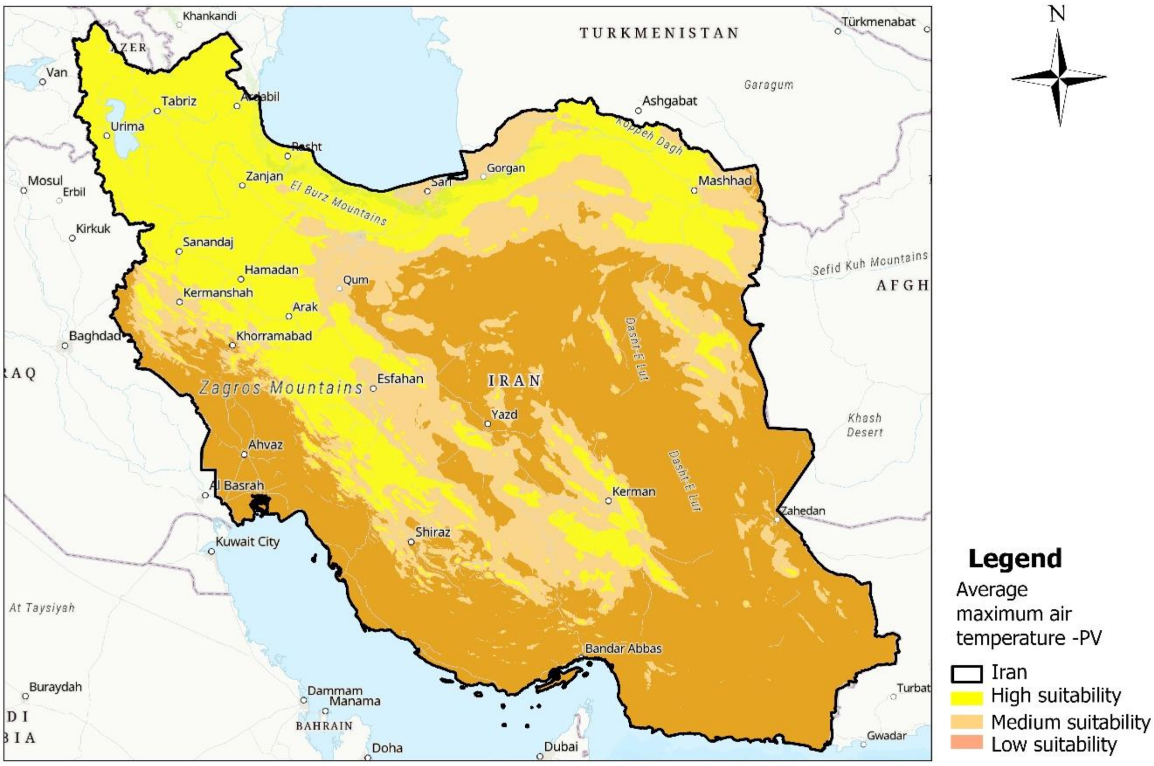
Scale: 1:9.000.000

Figure 37 Assessment of land suitability for PV based on slope criterion (by Author)



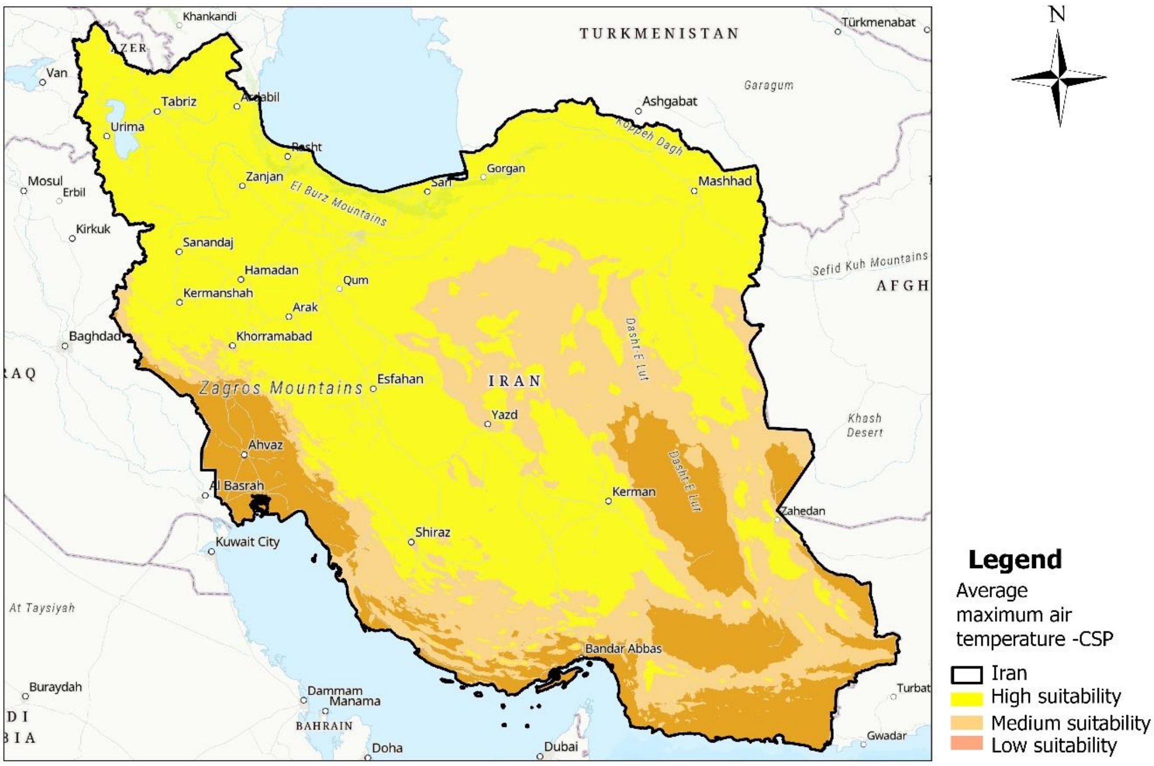
Scale: 1:9.000.000

Figure 38 Assessment of land suitability for CSP based on slope criterion (by Author)



Scale: 1:9.000.000

Figure 39 Assessment of land suitability for PV based on average maximum air temperature criterion (by Author)

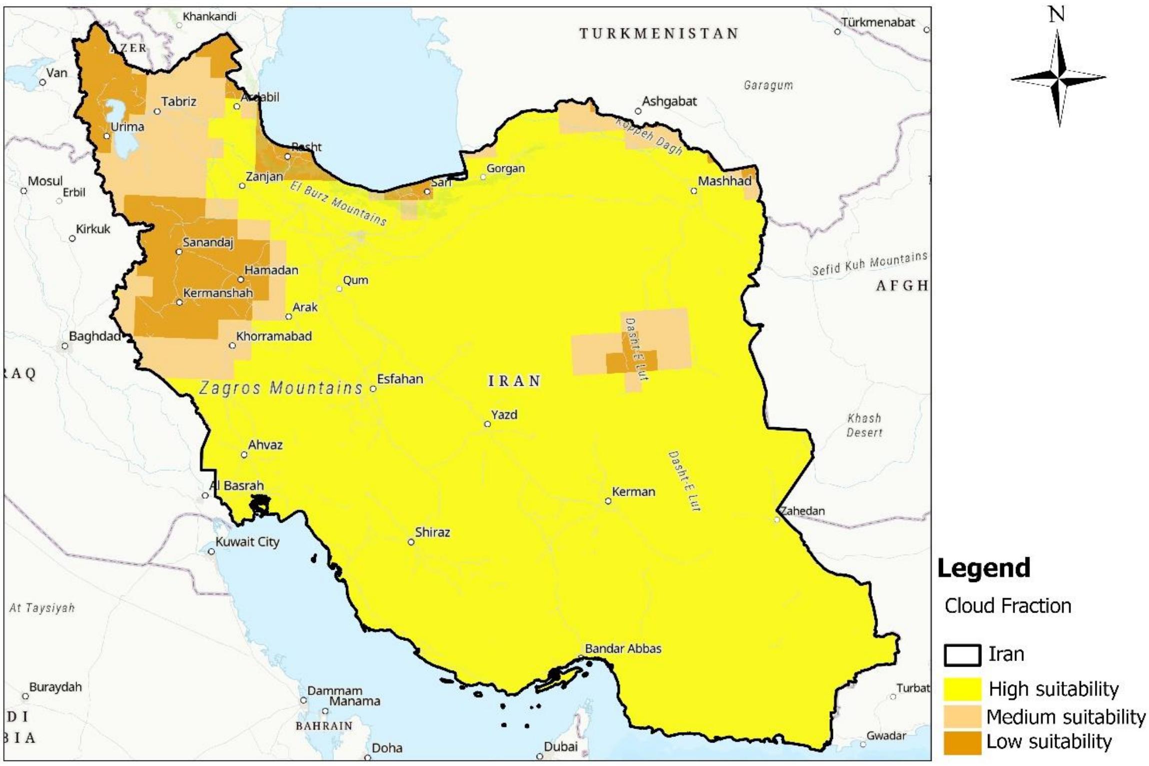


Scale: 1:9.000.000

Figure 40 Assessment of land suitability for CSP based on average maximum air temperature criterion (by Author)

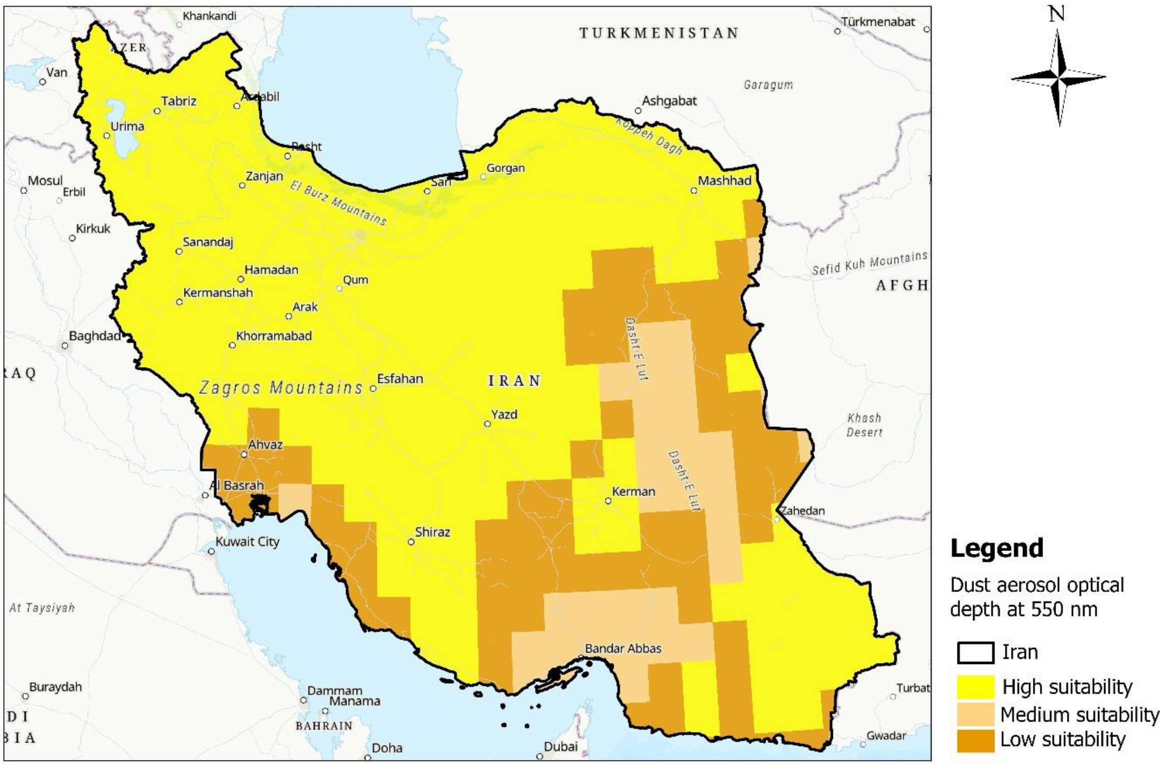
Scale: 1:9.000.000

Figure 41 Assessment of land suitability for PV & CSP based on aspect criterion (by Author)



Scale: 1:9.000.000

Figure 42 Assessment of land suitability for PV & CSP based on total cloud cover fraction criterion (by Author)



Scale: 1:9.000.000

Figure 43 Assessment of land suitability for PV & CSP based on dust aerosol optical depth criterion (by Author)

6.4 Weighting the criteria and sensitivity analysis

After classifying the evaluation criteria, an essential step in the current study was to assign weight to each criterion. To begin this process, I conducted a thorough literature review that culminated in the creation of Table 11. In this table, I listed the general evaluation criteria from the existing research and labeled the rest of the criteria as "other criteria," with a specific number of criteria considered in each study.

The first assumption for weighting the evaluation criteria was to normalize the weights. This was done by dividing by the number of criteria. I then multiplied the average weights from all studies by the number of criteria in the current study, which consisted of nine criteria (as described in Table 11).

Table 11 Weighting of Suitability Criteria in Previous Studies

Source	Distance to roads	Distance to powerlines	Distance to settlements	Solar radiation	Air temperatur	Dusty days	Cloud cover fraction	Slope	Aspect	others*	Number of Criteria	Type
(Asakereh et al., 2017)	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.46	3	PV
(Barzehkar et al., 2021)	0.08	0.14	0.13	0.31	0.00	0.00	0.00	0.02	0.00	0.32	12	PV
(Firozjaei et al., 2019)	0.08	0.00	0.10	0.50	0.00	0.00	0.00	0.14	0.00	0.18	5	PV
(Mokarram et al., 2020)	0.11	0.15	0.09	0.25	0.20	0.02	0.03	0.05	0.00	0.12	11	PV
(Noorollahi et al., 2016)	0.09	0.11	0.08	0.28	0.07	0.05	0.06	0.08	0.00	0.19	11	PV
(Sadeghi & Karimi, 2017)	0.00	0.00	0.00	0.64	0.00	0.00	0.00	0.00	0.00	0.36	5	PV
(Shorabeh et al., 2019)	0.07	0.00	0.09	0.18	0.00	0.10	0.00	0.09	0.00	0.47	10	PV
(Tavana et al., 2017)	0.08	0.11	0.19	0.32	0.00	0.00	0.00	0.00	0.00	0.31	5	PV
(Zoghi et al., 2017)	0.03	0.05	0.01	0.25	0.00	0.05	0.11	0.04	0.07	0.38	12	PV
(Al Garni & Awasthi, 2017)	0.05	0.07	0.03	0.35	0.24	0.00	0.00	0.16	0.11	0.00	7	PV
(Suh & Brownson, 2016)	0.06	0.12	0.00	0.39	0.08	0.00	0.00	0.08	0.00	0.27	6	PV
(Uyan & Dogmus, 2023)	0.09	0.16	0.03	0.00	0.00	0.00	0.00	0.00	0.16	0.56	6	PV
(Ghasemi et al., 2019)	0.02	0.04	0.02	0.31	0.26	0.00	0.00	0.16	0.12	0.07	8	CSP
(Alami Merrouni et al., 2018)	0.02	0.03	0.05	0.59	0.00	0.00	0.00	0.26	0.00	0.05	8	CSP

Table 11 (continued)

Source	Distance to roads	Distance to powerlines	Distance to settlements, urban area	Solar radiation	Air temperature	Dusty days	Cloud cover fraction	Slope	Aspect	others*	Number of Criteria	Type
(Aly et al., 2017)	0.02	0.03	0.15	0.59	0.00	0.00	0.00	0.00	0.00	0.21	5	CSP
(Aly et al., 2017)	0.03	0.05	0.02	0.70	0.00	0.00	0.00	0.00	0.00	0.21	5	PV
(Haddad et al., 2021)	0.05	0.23	0.23	0.27	0.00	0.00	0.00	0.05	0.04	0.13	7	CSP
(Sun et al., 2021)	0.08	0.15	0.05	0.28	0.09	0.00	0.00	0.12	0.00	0.23	7	CSP
(Sun et al., 2021)	0.08	0.15	0.05	0.35	0.12	0.00	0.00	0.18	0.00	0.09	7	PV
(Ziuku et al., 2014)	0.00	0.04	0.00	0.50	0.00	0.00	0.00	0.20	0.00	0.26	5	CSP
(Yushchenko et al., 2018)	0.14	0.25	0.14	0.47	0.00	0.00	0.00	0.00	0.00	0.00	4	CSP
(Tahri et al., 2015)	0.06	0.00	0.07	0.42	0.22	0.00	0.00	0.11	0.07	0.05	7	PV
Average normalization	0.08	0.12	0.10	0.60	0.07	0.01	0.01	0.10	0.03	0.33	-	-
Divided by 9 criteria	0.05	0.08	0.07	0.42	0.05	0.01	0.00	0.07	0.02	0.23	-	-

*Other criteria: Distance to wetland and protected area, Land use, Flooding, Distance from rivers, Soil texture, Fault, Humidity, Sunshine hours, Rainfall, Distance to water, Distance from transformer center, Wind speed, Geological formations, Access to Land, Normalized Difference Vegetation Index, LST, Environmental constraints, Availability of transport links,

I then ran the scoring models for four different scenarios (section 6.3)

The weights assigned to each scenario are summarized in Table 12.

Table 12 Assign weighting to criteria in 4 scenarios (by author)

Effect	Category	Assessment criteria	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Electricity harvest from PV	Climate	GHI, DNI	12,0	12,0	25,0	40,0
Efficiency		Average maximum air temperature	11,0	11,0	5,0	6,0
Efficiency		Dust optical depth	11,0	11,0	2,0	2,0
Efficiency		Total cloud fraction	11,0	11,0	2,0	2,0
Economic	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
Electricity harvest from PV		Aspect	11,0	11,0	13,0	5,0
Sum			100,0	100,0	100,0	100,0

For scenario 0, where the weighting was the same considering the "power station" criterion, the results are shown in Figure 44, which shows the suitability for PV and CSP, respectively (Figure 44, a and b) The evaluation model was run without considering the distance to power stations for scenarios 1 to 3 (Figure 45 to Figure 47).

Figure 44, a and b show that a significant portion of the areas are considered very low 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 Ministry of Energy, 2023 (Table 5). According to this report, the number of power stations and power generation increased from 725 to 821 power stations within five years. This indicates that the map of existing power stations is underestimated. Therefore, I removed the "distance to power station" criterion from the evaluation criteria, instead focused on "distance to power lines" and considered areas with distances greater than 20 km from power lines as very low suitability class. While some previous studies considered longer distances (Ghasemi et al., 2019; Gouareh et al., 2021; Tlhalerwa & Mulalu, 2019; Ziuku et al., 2014), I retained the 20 km threshold because proximity to power lines and roads is critical for economic reasons in Iran.

I ran the suitability model for both PV and CSP and found that the differences in suitable areas between the two were minimal, as shown in Figure 44 to Figure 47 and Table 13 and Table 14.

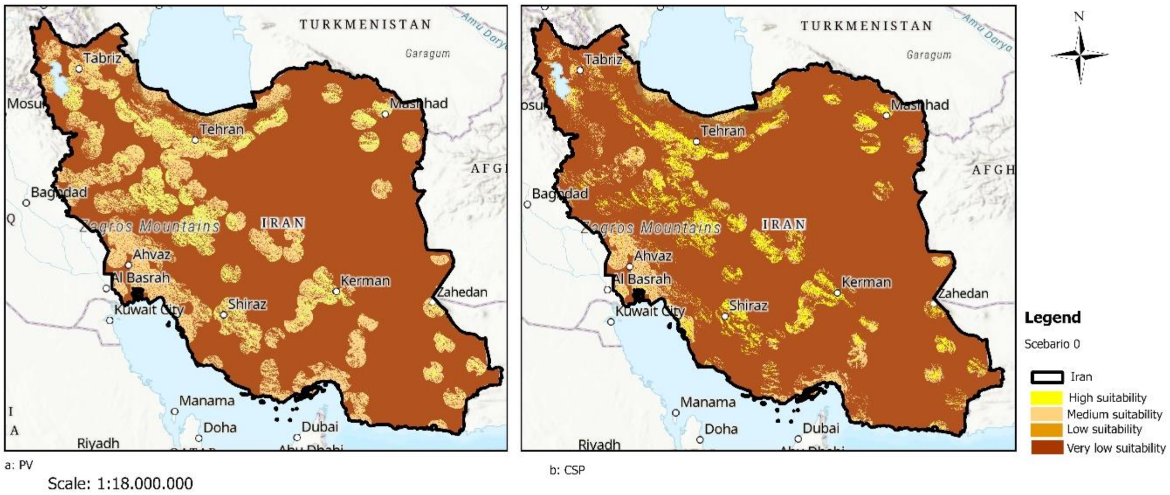


Figure 44 Assessment of suitability of PV (a) and CSP (b) plant siting in Iran - Scenario 0 (by author)

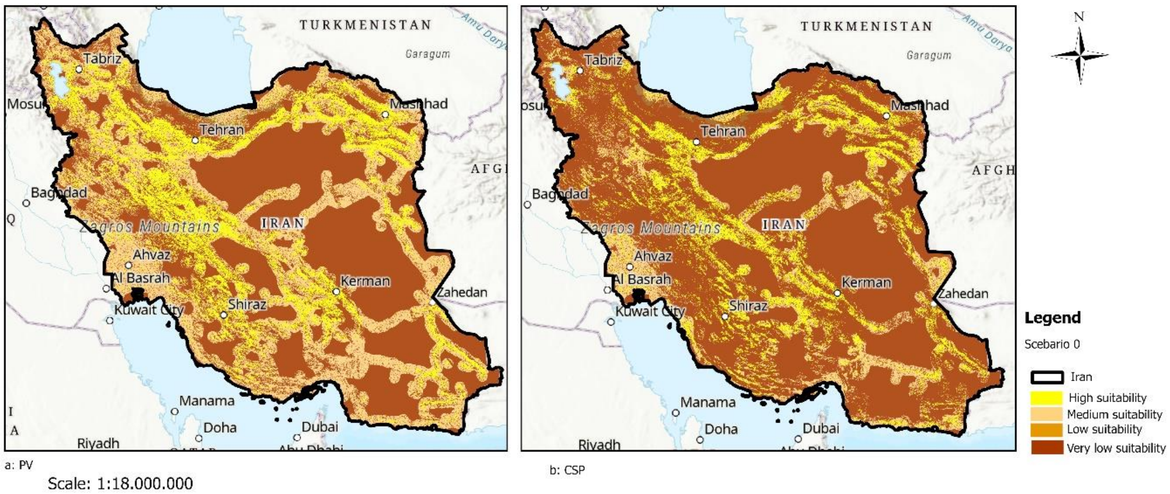


Figure 45 Assessment of suitability of PV (a) and CSP (b) plant siting in Iran - Scenario 1 (by author)

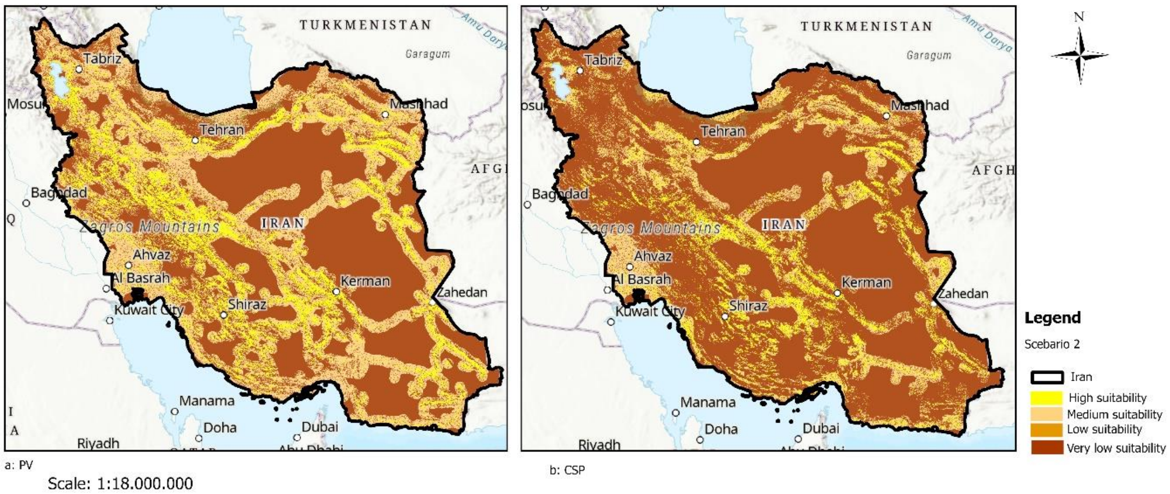


Figure 46 Assessment of suitability of PV (a) and CSP (b) plant siting in Iran - Scenario 2 (by author)

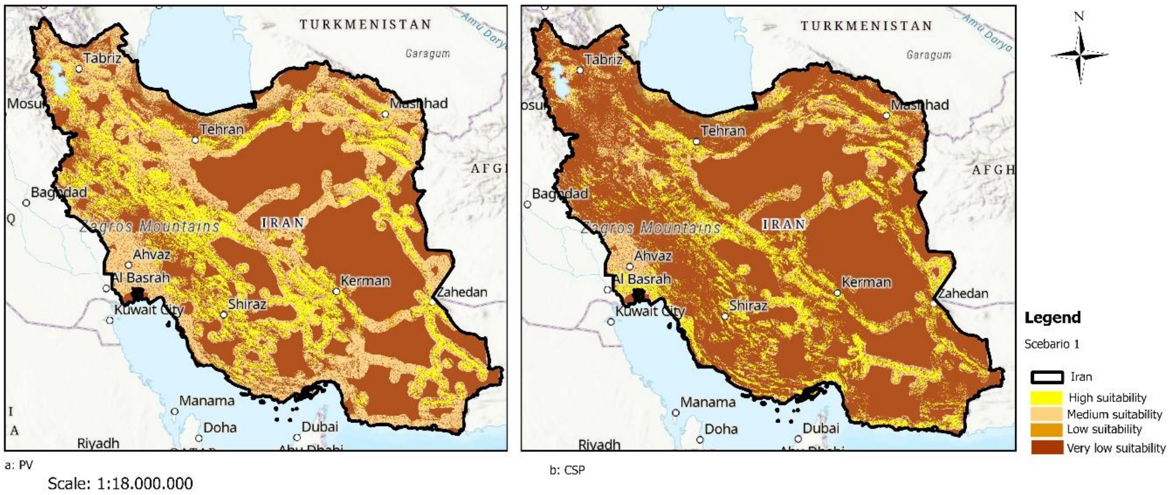


Figure 47 Assessment of suitability of PV (a) and CSP (b) plant siting in Iran - Scenario 3 (by author)

Table 13 Resulting shares of land area in the four scenarios and four suitability classes (for PV) (by author)

PV	High suitability	Medium suitability	Low suitability	Very low suitability
Scenario 0	7,4	15,9	0,0	76,7
Scenario 1	16,9	29,4	0,0	53,8
Scenario 2	14,0	32,0	0,2	53,8
Scenario 3	16,1	29,9	0,3	53,8

Table 14 Resulting shares of land area in the four scenarios and four suitability classes (for CSP) (by author)

CSP	High suitability	Medium suitability	Low suitability	Very low suitability
Scenario 0	6,0	6,7	0,0	87,3
Scenario 1	13,1	12,1	0,0	74,8
Scenario 2	9,3	15,8	0,0	74,8
Scenario 3	13,0	12,1	0,0	74,8

Of note, the "low suitability" class did not appear in the final results for CSP because it was grouped with other suitability classes in another criterion. As a result, the "very low suitability" areas accounted for a large percentage of Iran, reaching 54% in Scenarios 1 through 3.

Scenario 0 had significantly different results than the other scenarios due to the large number of "very low suitability" areas due to distance from power stations. Scenario 0 was therefore discarded. Scenarios 1 and 3 produced almost identical results. Scenario 2 was not far from scenarios 1 and 3. It was found that changes in weight distribution had little effect on the results. Therefore, Scenario 3 was selected for further analysis as it seemed consistent with the literature review results and the authors' comments.

6.5 Integration of constraint layer and classified suitability map

After evaluating the results of scenarios 0 to 3, I concluded that scenario 3 was the most promising for further analysis and investigation. In scenario 3, the weighting scheme was consistent with the research objectives and the literature review results.

To further analysis, I integrated the results of Scenario 3, which identifies suitable areas for PV and CSP plant construction (Figure 47, a and b) with the results of the constraint model (Figure 14 and Figure 15). This integration allowed to make a more refined selection of potential sites.

The integrated results show the imposition of overlapping constraints and suitable areas in Figure 48 for PV and Figure 49 for CSP. These maps visually represent areas that meet the suitability and constraint criteria.

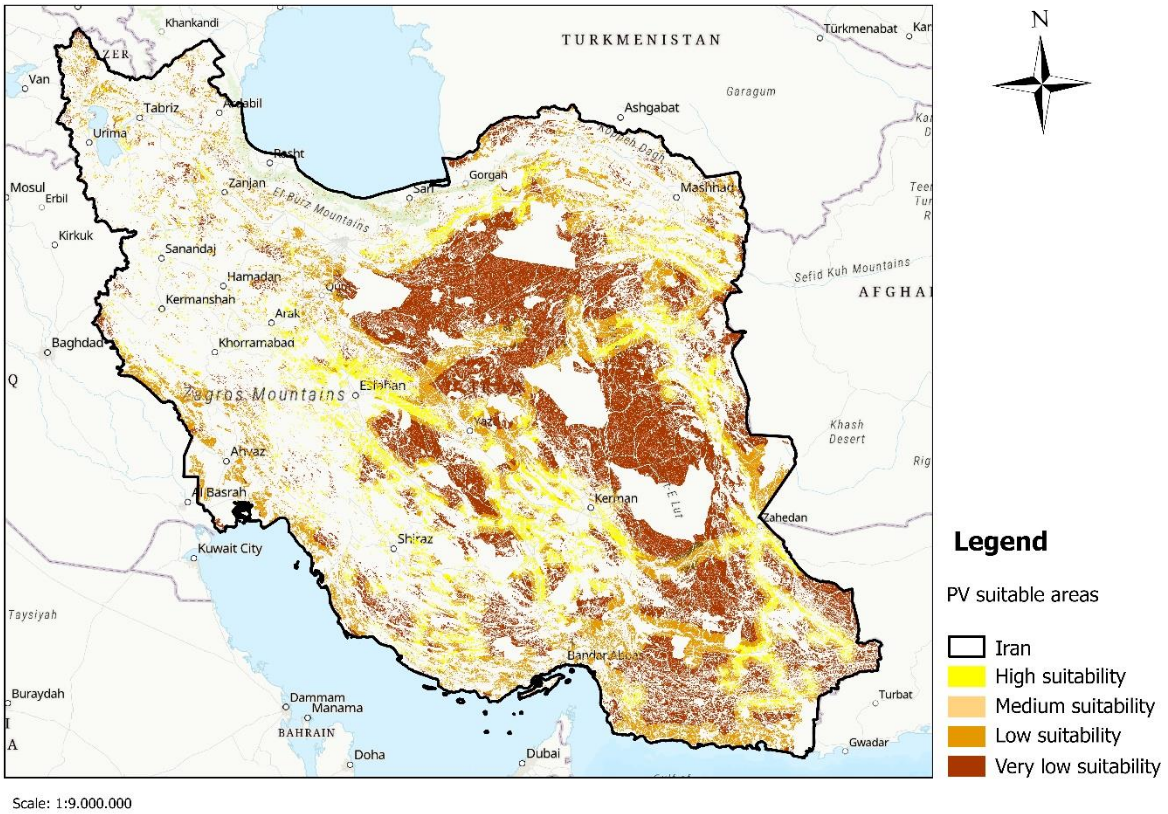


Figure 48 Resulting suitable areas for PV park siting in Iran (Scenario 3) (by author)

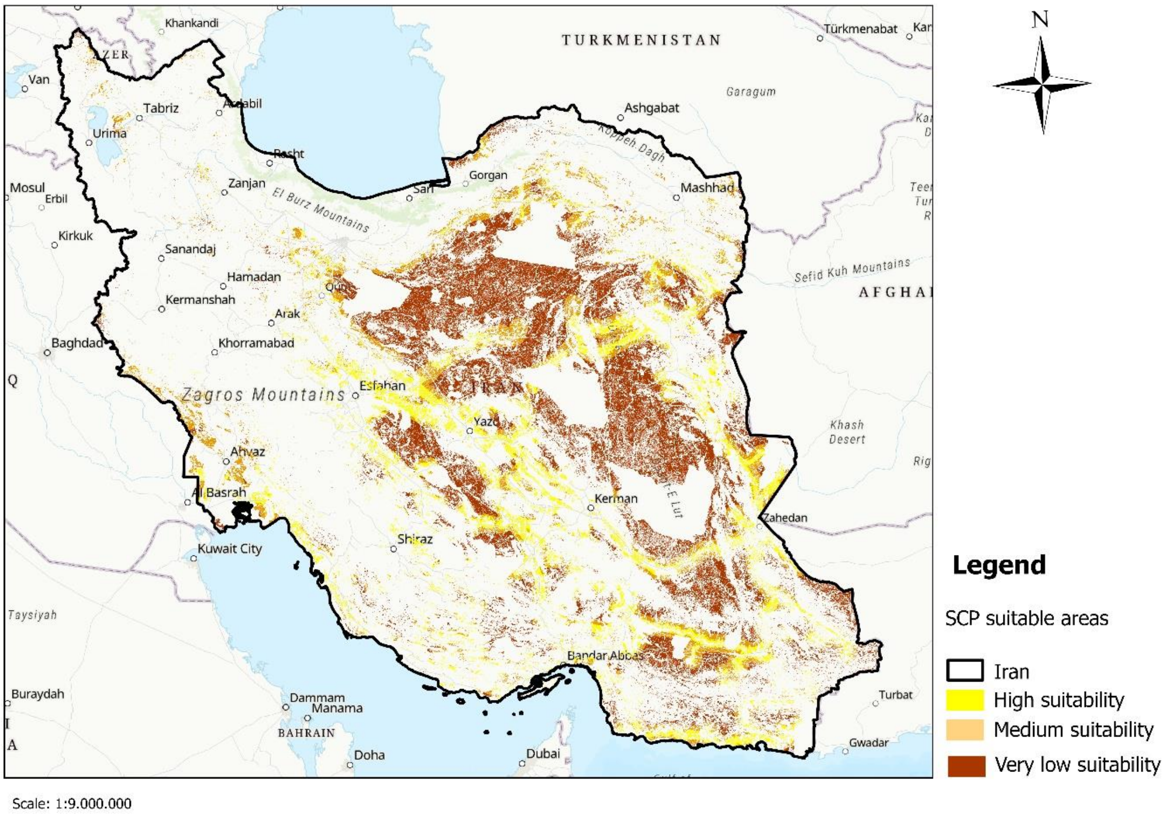


Figure 49 Resulting suitable areas for CSP plant siting in Iran (Scenario 3) (by author)

Figure 50 provides an overview of the results by showing the percentage of suitable areas from whole Iran for PV and CSP in each suitability category. It is noteworthy that the percentage of very low suitability land for CSP is about 2 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%.

In summary, the analysis shows that about 14.0% of the total Iran is high and medium suitability for PV park siting, while about 5.6% of the land area is suitable for CSP plant siting in two classes of high suitability and medium suitability.

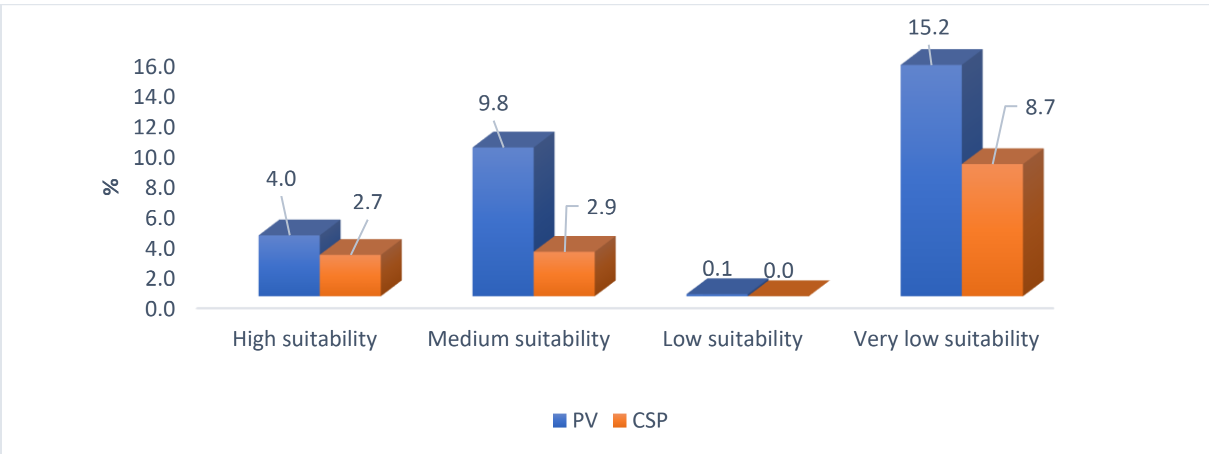


Figure 50 Percentage of suitable area for constructing PV and CSP in Iran (by author)

6.6 Integration of PV and CSP suitability map

By combining two suitable areas, one for PV and one for CSP, I was able to create a final suitability map that includes both technologies (Figure 51). This final map provides a comprehensive view of where these solar energy systems can be effectively deployed.

An analysis of the final map shows that the areas rated as " high suitability" for both PV and CSP are mainly located in the central and eastern parts of Iran. However, a difference emerges when I look at the western part of the country. There, the match between PV and CSP is different, with the western regions being more suitable for PV. The main reason for this difference is that CSP plants are less suitable in western Iran due to the uneven terrain and steep ground conditions.

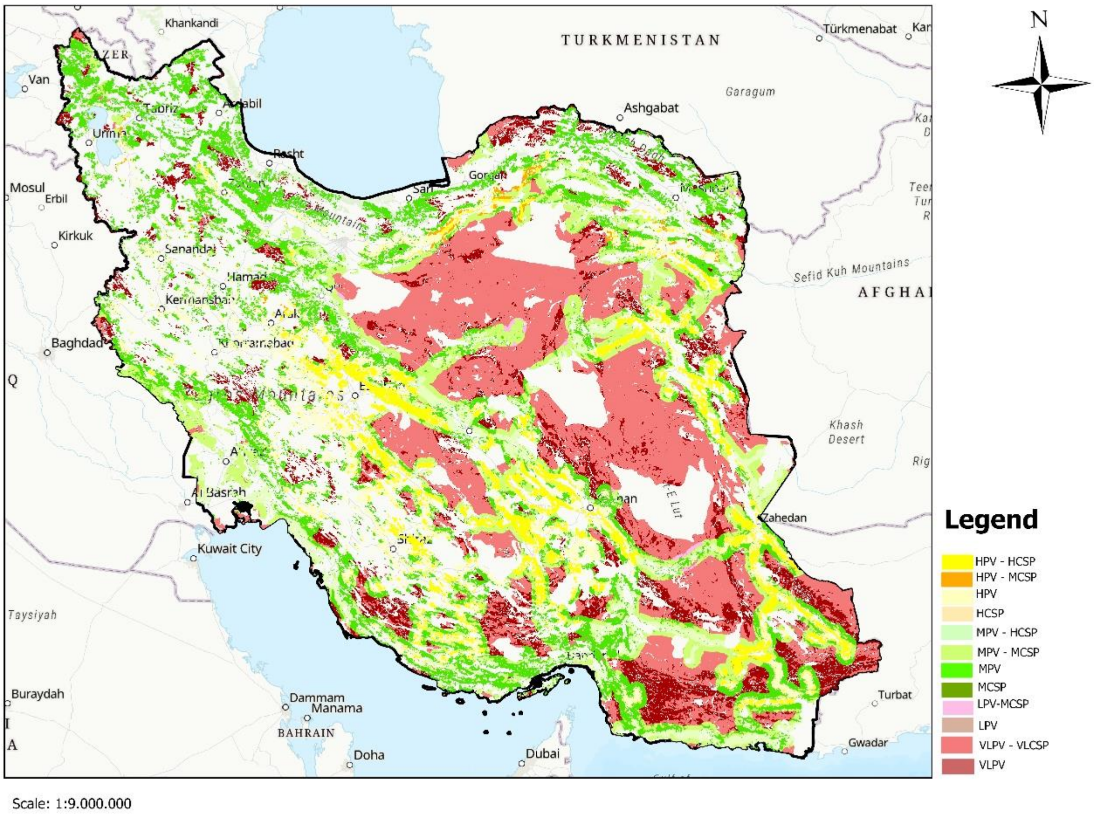


Figure 51 Categorized suitable area for PV and CSP plant siting in Iran (by author)

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.

To get a better picture of the suitability of the areas for PV and CSP plants, Figure 52 provides an illustration. It shows the areas where these solar technologies can be practically deployed considering their specific suitability criteria and constraints.

In addition, Figure 53 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.

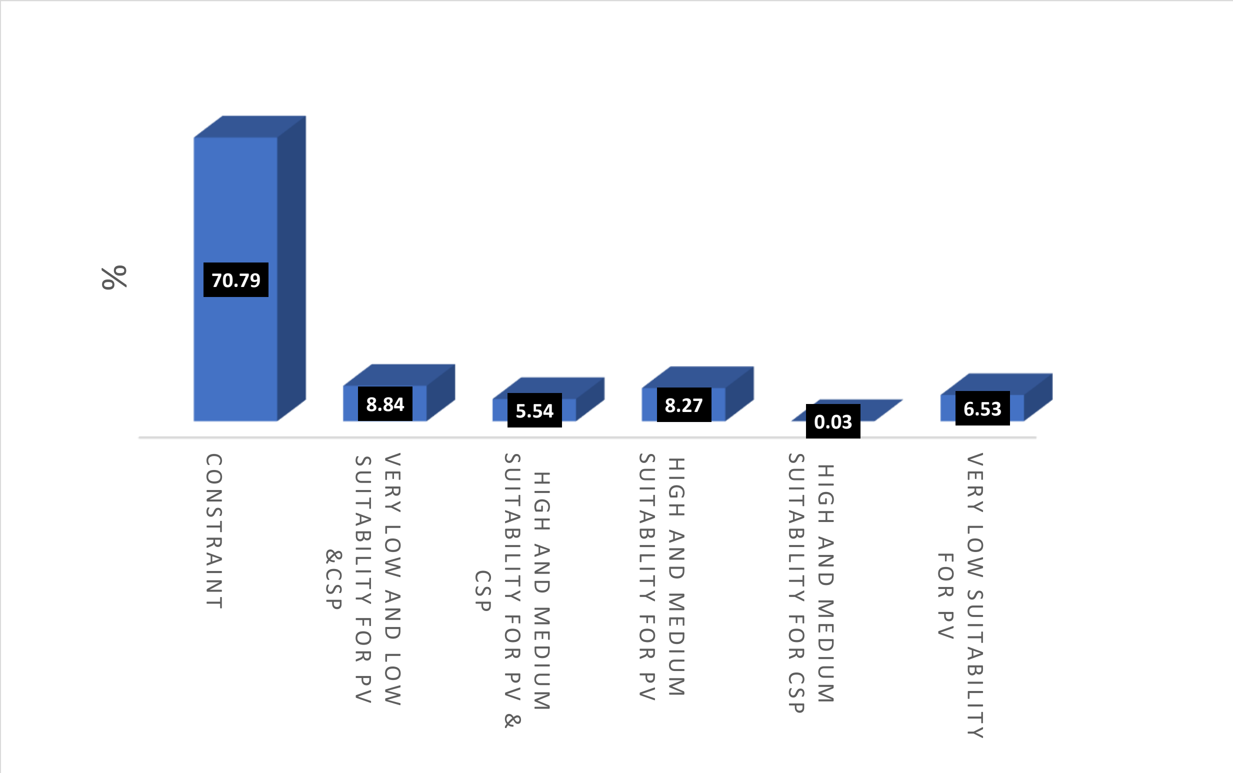


Figure 52 Land eligibility analysis for installing PV and CSP plant in Iran (by author)

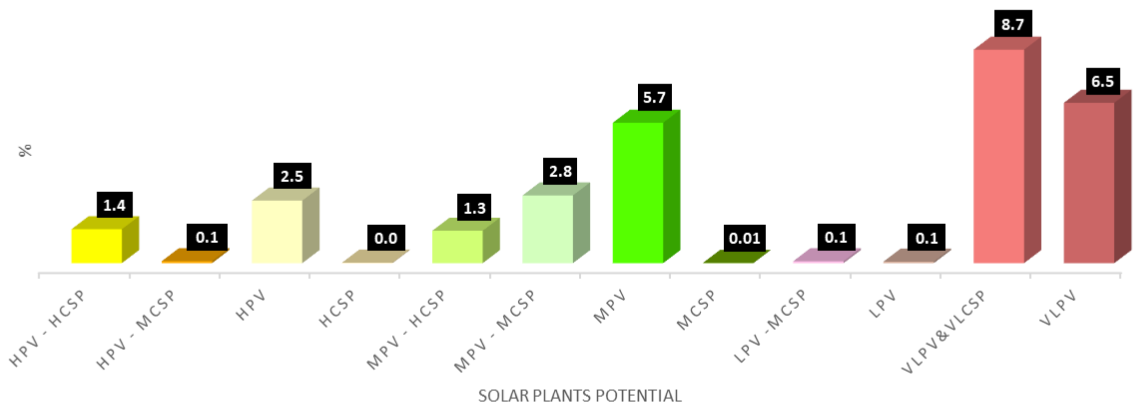


Figure 53 Percentage of suitable area for installing PV and CSP plants in Iran (by author)

6.7 Electricity generation potential in suitable PV and CSP areas

Usually, scientists rely on PV power potential calculations to estimate the efficiency potential of PV systems. While these calculations are not exact, Bundesverband Solarwirtschaft, 2015 gives us an approximation.

On average, it is estimated that 2 hectares of PV parks are needed to generate 1 MWp (megawatt peak) of electricity (Bundesverband Solarwirtschaft, 2015). On this basis, and assuming that 1 MWp is equivalent to 1000 kWh (kilowatt-hours), I can derive an estimate of the electric generation potential of PV parks, shown in Table 15.

To determine the potential electricity generation from concentrated solar power (CSP), I rely on data from (National Renewable Energy Laboratory, 2013). It was found that approximately 1.6 hectares of land is needed to generate 1 megawatt peak (MWp) of electricity using CSP technology. Detailed estimates of electricity generation from CSP are provided in Table 15. Some regions are suitable for both solar photovoltaic (PV) and CSP installations, and Table 15 provides estimates of potential electricity generation for both technologies, PV and CSP.

Table 15 Estimation of electricity generation in potential areas PV and CSP plants (by author)

Suitability classes	Electricity Generation Potential (TWh) - PV	Electricity Generation Potential (TWh) - CSP
HPV - HCSP	1126	1408
HPV - MCSP	64	79
HPV	2077	-
HCSP	-	21
MPV - HCSP	1076	1345
MPV - MCSP	2249	2812
MPV	4664	-
MCSP	-	12
LPV -MCSP	63	78
LPV	49	-
VLPV&VLCSP	7094	8867
VLPV	5327	-

The total electricity generation in Iran is approximately 325 terawatt hours (TWh) according to the (IEA, 2020). The electric power generation potential from solar energy exceeds current generation. With the strategic installation of solar farms, Iran has the potential to effectively meet its electricity needs on a significant scale.

Chapter 7 Conclusions

Countries around the world are turning to renewable energy sources in response to the severe environmental impacts caused by reliance on fossil fuels. Solar parks are a renewable energy source, providing viable economic opportunities for current and future generations (Dhunny et al. 2019). In Iran, solar energy is gaining attention as an abundant and renewable resource with numerous environmental benefits.

Iran, which is rich in hydrocarbon resources, has relied on fossil fuels for a long time, which has resulted in severe pollution in major cities and electricity shortages during the summer months. The government has been a proponent of solar photovoltaics (PV) as a source of clean energy. Iran is falling short of its renewable energy targets and urgently needs investment to close its electricity gap. Ministry of Energy, 2023 report shows headway: 484 MW of the total 933 MW of PV capacity. Iran's solar market is expected to grow, with the government targeting 10,000 MW of renewable energy capacity by 2025, despite challenges such as COVID-19 (tehrantimes, 2023). Investment has reached 135 MW, with a further 3,625 MW planned, highlighting the need for further development of solar energy (Ministry of Energy, 2023).

This research highlights the crucial significance of Geographic Information Systems (GIS) in the efficient identification of ideal locations for both photovoltaic (PV) and concentrated solar power (CSP) installations. The utilization of GIS tools and methodologies has considerably streamlined the decision-making process for renewable energy initiatives, yielding noteworthy reductions in both costs and time expenditures.

This research was carried out in two main stages. First, I conducted a comprehensive analysis of land availability, considering fourteen different constraints, including proximity to infrastructure and environmental considerations. Combining these constraints resulted in a map of feasible areas for solar installations. Then I evaluated these areas based on nine suitability criteria, including solar irradiation, climatic conditions, and topography. This assessment provided more understanding of locations for PV and CSP plants.

The achievement of a sustainable future depends to a large extent on harnessing the potential of renewable energy sources. Iran, rich in solar radiation that can be harnessed with PV and CSP, can play an important role in the world's collective efforts to combat climate change, reduce dependence on fossil fuels, and help countries transition to sustainable, low-carbon energy systems. This research illustrates that the adoption of PV and CSP plants could be a vital step toward attaining energy self-sufficiency addressing environmental concerns and capitalizing on the chance to not only fulfill domestic energy for Iran and also enable it to become a regional electricity exporter.

The future of GIS modeling for renewable energy siting holds great promise. As technology advances and data becomes more readily available, several opportunities for further research and development are emerging:

Better Data Integration: To improve the accuracy and precision of site selection, future studies can explore more sophisticated methods for integrating different data sets, including real-time data streams and high-resolution satellite imagery.

Machine learning and artificial intelligence: Integrating machine learning and artificial intelligence techniques into GIS models can improve predictive capabilities, enabling more proactive and adaptive site selection strategies.

Global application: Expanding the application of GIS-based models beyond specific regions can facilitate comprehensive global energy planning that considers the unique challenges and opportunities that arise in different geographic locations.

Environmental impact assessment: Incorporating more detailed environmental impact assessments into GIS models can further refine site selection by considering ecological factors and minimizing the environmental footprint of renewable energy projects.

Integration of policy and regulation: Future research can explore ways in which policy and regulatory factors can be integrated into GIS models to allow for a more holistic assessment that takes into account both technical feasibility and compliance with regulatory frameworks.

Hybrid system: Future research endeavors can delve into the integration of hybrid systems, combining PV and CSP plants, and possibly even including wind power or other technologies, to conduct comprehensive analyses of their potential synergies and benefits.

In summary, GIS-based renewable energy siting models, as demonstrated in my research, continue to evolve and provide invaluable insight and efficiency in finding sustainable energy solutions. The integration of GIS into renewable energy planning promises to play an increasingly important role in shaping a clean and sustainable energy future as technology and data evolve.

This thesis has not looked at sites for the integration of CSP with PV and other electric generation technology. This is a promising technical opportunity (Fraunhofer ISE, 2023). The constraint and suitability criteria would have to be moderately adjusted for this type of analysis, there is a large overlap of constraints and suitability classes for the two technologies.

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Appendices

Extraction of geodata from OpenStreetMap

esy-osmfilter serves as a Python library intended for the reading and filtration of OpenStreetMap data, focusing on optimizing disk space utilization and computational efficiency. This library employs parallelized prefiltering techniques for OSM pbf files data, swiftly reducing the size of the initial dataset. The prefiltered data can be conveniently stored on the hard drive. These prefiltered datasets can be iteratively employed during the primary filtering procedure to identify distinct elements using dedicated specialized filters. Ultimately, the resulting output can be exported in the GeoJSON format (Pluta & Lünsdorf, 2020).

The Python 3.1 environment was utilized with the assistance of the Python library. The coding process occurred within Visual Studio Code, a cost-free integrated development environment, where the program code was written and executed. OSM mappers utilize keys and values for tagging objects that contribute to the project. The approach to this tagging is expounded upon in the OSM Wiki, as outlined in the *OpenStreetMap Wiki*, 2023.

The Figure 54 shows the process of esy-osmfilter acquires data from a pbf file, accomplished through a dual-phase approach. The initial step involves a prefilter mechanism, characterized by predefined key-value pairs, which sifts through the complete file and subsequently records it within the 'Data' repository. A JSON file, later designated as the output file, is generated at this juncture. Subsequently, the second phase entails filtering the 'Data' repository using a black-and-white filter. The black filter encompasses key-value pairs representing data to be excluded, whereas the white filter identifies key-value pairs of data that must be retained. The outcome of this process is then documented within the 'Elements' file. Notably, both steps can be executed within a singular function. Furthermore, the data about the 'Element' entity can be exported into a geojson file through an alternative function.

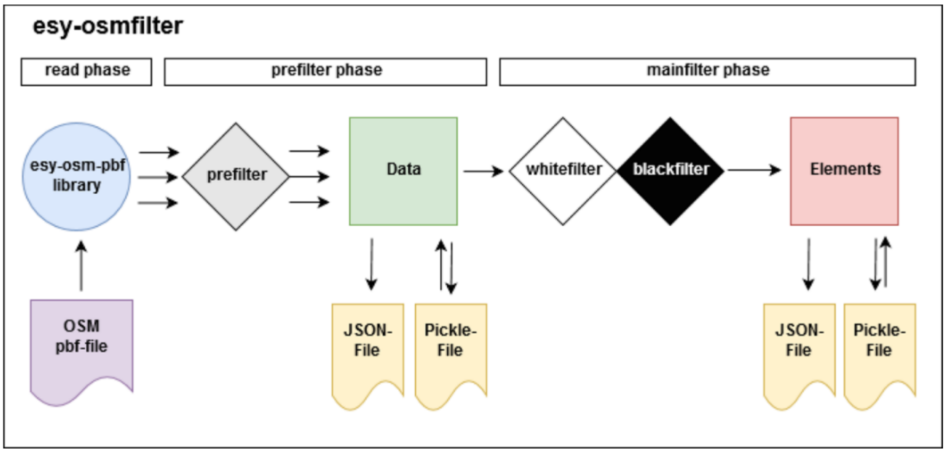

Figure 54 Diagram of the esy-osmfilter architecture (Pluta & Lünsdorf, 2020).