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RESEARCH ARTICLE

# Potential of Concentrated Solar Power in the Western Region of Saudi Arabia: A GIS-Based Land Suitability Analysis and Techno-Economic Feasibility Assessment

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**ABSTRACT** Saudi Arabia (SA) currently relies on fossil fuels to address its escalating electricity demand and rapid industrialization, a practice that significantly contributes to climate change. This study underscores the potential of solar energy as a key renewable energy source (RES) for SA, with a specific focus on Concentrated Solar Power (CSP). CSP stands out due to its capacity to provide dispatchable electricity coupled with thermal energy storage (TES). This research introduces an integrated energy model encompassing both site suitability and techno-economic analyses tailored for utility-scale CSP technology. The investigation unfolds in two phases: site suitability analysis and techno-economic assessment, each designed to scrutinize the viability and applicability of CSP technology for power generation in SA's western region. In the initial phase, an innovative approach, leveraging Fuzzy-Boolean Logic and Analytical Hierarchy Process (AHP) through GIS tools, is employed to identify optimal CSP plant locations. This method offers a more comprehensive and robust analysis by accounting for uncertainty and ambiguity in decision-making. Criteria are prioritized based on relative importance, contributing a novel dimension to the field. The analysis reveals that 70% of the province's land is suitable for CSP deployment, with Makkah, Taif, Al-Khumra, and Turbah identified as the most favorable locations. In the second phase, two established CSP plants, Shams-1 and Noor III, are utilized to evaluate the technical and economic feasibility of CSP in five selected sites within the most suitable areas. The analysis unveils the lowest levelized cost of electricity (LCOE) for utility-scale CSP plants in Makkah province, standing at 9.58 ¢/kWh for parabolic trough (PT) technology and 9.17 ¢/kWh for solar power tower (SPT) technology. Sensitivity analysis of TES indicates that CSP plants with 8 hours of storage exhibit the optimal configuration, producing electricity with the lowest LCOE and the highest capacity factor (CF). This comprehensive study establishes CSP as a viable and promising renewable energy (RE) technology for SA. The proposed site selection methodology facilitates the identification of suitable locations for CSP plants, while the techno-economic analysis demonstrates that CSP plants equipped with TES are both cost-effective and reliable.

**INDEX TERMS** Analytical hierarchy process, concentrated solar power, geographic information system, multi-criteria decision-making, site suitability analysis, techno-economic analysis.

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## NOMENCLATURE

*Abbreviations*

| | |
|---|---|
| AHP | Analytical Hierarchy Process. |
| CF | Capacity Factor. |
| CI | Consistency Index. |
| CR | Consistency Ratio. |
| CSP | Concentrated Solar Power. |
| DEM | Digital Elevation Model. |
| DNI | Diffused Normal Irradiation. |
| FL | Fuzzy Logic. |
| GHG | Greenhouse Gas. |
| NPV | Net Present Value. |
| GHI | Global Horizontal Irradiation. |
| GIS | Geographical Information System. |
| HTF | Heat Transfer Fluid. |
| IEA | International Energy Agency. |
| UAE | United Arab Emirates. |
| IRENA | International Renewable Energy Agency. |
| ISCC | Integrated Solar Combined Cycle. |
| LCOE | Levelized Cost of Energy. |
| LFR | Linear Fresnel Reflector. |
| MCDM | Multi-Criteria Decision-Making. |
| MENA | Middle East and North Africa. |
| NASA | National Aeronautics and Space Administration. |
| NREL | National Renewable Energy Laboratory. |
| PD | Parabolic Dish. |
| POWER | Prediction Of Worldwide Energy Resources. |
| PT | Parabolic Trough. |
| PV | Photovoltaic. |
| RE | Renewable Energy. |
| SA | Saudi Arabia. |
| SWOT | Strengths, Weaknesses, Opportunities, and Threats. |
| RH | Relative Humidity. |
| RI | Random Index. |
| SAM | System Advisor Model. |
| SPT | Solar Power Tower. |
| SEC | Saudi Electricity Company. |
| O&M | Operation and Maintenance. |
| TES | Thermal Energy Storage. |
| WLC | Weighted Linear Combination. |

## I. INTRODUCTION

Energy plays a pivotal role as a driving force for economic and social development, and the significance of renewable energy (RE) has escalated within the power industry [1]. While historical concerns centered on oil prices, contemporary global attention is directed toward navigating intricate challenges, such as greenhouse gas (GHG) emissions and the overarching issue of global warming [2]. Simultaneously, the world grapples with the dual challenge of meeting escalating energy demands while mitigating environmental threats associated with the combustion of fossil fuels. According to projections by the International Energy Agency (IEA), global energy demand is anticipated to rise by 1% annually until 2030, doubling by 2050, with a particularly accelerated growth in electricity demand outpacing primary energy supply [3]. Consequently, there is a pressing need for a sustained focus on energy efficiency, necessitating a comprehensive and enduring financing strategy. In this context, renewable energy emerges as a pragmatic and viable alternative to effectively address the mounting energy demand while concurrently curbing GHG emissions [4].

Saudi Arabia (SA) holds the distinction of being the world's largest oil producer and exporter, with oil constituting a substantial 90% of exports and contributing 75% of revenues [5]. The nation's burgeoning population necessitates a dependable electricity supply to keep pace with the escalating demand, which is surging by 8% annually, reaching 289,333 GWh in 2020. The western region emerged as the highest consumer of electric energy (30.97%), followed by the central (29.87%), eastern (28.69%), and southern (10.47%) regions. Sector-specifically, the residential sector accounted for 47.58% of electrical energy consumption, followed by the industrial sector at 20%, and the commercial sector at 14.21%. Governmental and other sectors consumed 12.51% and 5.7% of the total energy consumption, respectively. This heightened demand is propelled by factors such as population growth, desalinization, air conditioning needs, affordability considerations, and infrastructural expansion. Concurrently, the electrical energy generated in 2020 experienced a modest increase of 0.77%, reaching 338,031 GWh compared to the 335,445 GWh produced in 2019. The Saudi Electricity Company (SEC) spearheaded the electricity production, contributing 54.24% to the total, with steam turbines, combined-cycle units, and gas units contributing 45.41%, 31.68%, and 22%, respectively. Notably, water desalination plants contributed 40.59% to the overall electricity production [6], [7]. While SA has successfully powered the entire nation, its prolonged dependence on fossil fuels has positioned it among the countries with the highest greenhouse gas (GHG) emissions [8]. In light of this, there is an escalating imperative to explore alternative energy sources. The significance of investigating alternative energy sources is beyond dispute, and it is evident that solar energy resources present a viable avenue for delivering a reliable, efficient, and environmentally clean power supply in the Gulf region [9], [10].

Solar energy has great potential in the country due to its abundant sunlight and high solar irradiation levels, with an average daily total global horizontal irradiation (GHI) of 6 kWh/m$^2$/day [11]. Through harnessing solar energy and substituting it for conventional energy, SA can reduce its reliance on fossil fuels, decrease GHG emissions, and create a more sustainable and environmentally friendly energy infrastructure. In addition to being environmentally friendly, solar energy is also a cost-effective and sustainable solution for meeting energy demands in SA [12]. Moreover,

**TABLE 1. Status of CSP plants in MENA region [24].**

| Powe Station | STARTED YEAR | Country | Technology | Capacity (MW) | Status |
|---|---|---|---|---|---|
| ISCC Hassi R'mel | 2011 | Algeria | PT | 20 | Operation |
| ISCC Kuraymat | 2011 | Egypt | PT | 20 | Operation |
| Ashalim Plot A / Negev Energy | 2019 | Israel | PT | 110 | Operation |
| Ashalim Plot B / Megalim | 2019 | Israel | SPT | 121 | Operation |
| SEDC | 2008 | Israel | SPT | 6 | Operation |
| Shagaya | 2019 | Kuwait | PT | 50 | Operation |
| Airlight Energy Ait-Baha Pilot Plant | 2014 | Morocco | PT | 3 | Operation |
| ISCC Ain Beni Mathar | 2011 | Morocco | PT | 20 | Operation |
| NOOR I | 2015 | Morocco | PT | 160 | Operation |
| NOOR II | 2018 | Morocco | PT | 200 | Operation |
| NOOR III | 2018 | Morocco | PT | 150 | Operation |
| ISCC Duba 1 | 2023 | Saudi Arabia | PT | 43 | Under construction |
| ISCC Waad Al Shamal | 2018 | Saudi Arabia | PT | 50 | Operation |
| Bokpoort | 2016 | South Africa | PT | 50 | Operation |
| Ilanga I | 2018 | South Africa | PT | 100 | Operation |
| Kathu Solar Park | 2019 | South Africa | PT | 100 | Operation |
| KaXu Solar One | 2015 | South Africa | PT | 100 | Operation |
| Khi Solar One | 2016 | South Africa | SPT | 50 | Operation |
| Redstone | 2018 | South Africa | SPT | 100 | Under construction |
| Xina Solar One | 2018 | South Africa | PT | 100 | Operation |
| Noor Energy 1 / DEWA IV | 2022 | UAE | SPT | 100 | Under construction |
| Noor Energy 1 / DEWA IV trough segment | 2022 | UAE | PT | 600 | Under construction |
| Shams-1 | 2013 | UAE | PT | 100 | Operation |

SA's geographical location allows it to transmit electricity to Europe, Asia, and other Middle East countries, making it a suitable region for the utilization of solar energy [13]. The Saudi government has accordingly made a strong commitment to the development of renewable energy sources (RES), including solar energy, and has set ambitious targets for the expansion of the RE sector [14], [15]. The first two large-scale RE projects, the Sakaka solar project and the Dumat Al-Jandal wind farm, are in the northern region of Al-Jawf and have a combined capacity of 700 MW. These projects can supply electricity to over 100,000 households, reduce $CO_2$ emissions by one million tons per year, and save the equivalent of over 1.2 million barrels of oil per year [16]. Despite the goal of Vision 2030 to increase the use of RES for electricity generation, the current proportion of renewables in total electricity generation remains small [15]. However, the country's recent announcement of a new RE target of achieving net-zero emissions by 2060 is a positive step towards further development of RES [17], [18].

Concentrated Solar Power (CSP) emerges as a highly promising solar thermal energy technology for electricity generation, particularly in the sun-rich and resource-abundant Middle East and North Africa (MENA) region. Recognizing the considerable solar and wind potential capable of meeting the European Union's electricity demand, there is a discernible surge in interest toward transitioning to Renewable Energy Sources (RES) to mitigate emissions [19]. The DESERTEC Foundation aligns with this momentum, actively championing CSP projects in the MENA region to foster decarbonization and diversify the energy mix [20]. Globally, the installed capacity of CSP has demonstrated a noteworthy growth trajectory, escalating from 4.75 GW in 2015 to 6.4 GW in 2020 [21]. Within the MENA region, several noteworthy electricity generation projects featuring CSP plants are currently in progress. Notable examples include the Redstone CSP project in South Africa, heralded as the country's largest Renewable Energy (RE) investment, and it is anticipated to become operational by 2023. In the United Arab Emirates (UAE), the Noor Energy-1 project boasts a planned capacity of 350 GW for solar generation, incorporating 100 MW of solar power tower (SPT), with completion expected in 2023. Demonstrating a commitment to sustainable energy practices, Saudi Arabia has set a target to install 23 GW of CSP technologies by 2032. In pursuit of this goal, the Saudi Electricity Company (SEC) has initiated the operational phase of the Waad Al-Shamal Integrated Solar Combined Cycle (ISCC) plant, boasting a total capacity of 1.39 GW, including 50 GW of CSP based on Parabolic Trough (PT) technology [22]. Another significant venture in Saudi Arabia is the Duba-1 ISCC project, a 600 MW hybrid power plant that includes a 43 MW Parabolic Trough (PT) CSP plant [23]. To provide a comprehensive overview, the status of CSP plants across the MENA region is detailed in Table 1, highlighting the dynamic landscape of renewable energy initiatives in the region.

**TABLE 2. Literature review on CSP potential in Saudi Arabia.**

| Reference | Year | Objectives | Major Findings |
|---|---|---|---|
| [8] | 2017 | Investigate strengths, weaknesses, opportunities, and threats of CSP technology in Saudi Arabia. | • PT is the most mature CSP technology.<br>• SPT is suitable for large TES capacities.<br>• FT has the lowest LCOE compared to other technologies. |
| [13] | 2021 | Optimize PT-based CSP plant for electricity export to Europe and Asia. | • Plants in the west region are more economically viable.<br>• Energy exports to Pakistan have the highest LCOE compared to other countries. |
| [25] | 2016 | Assess environmental impact of HYSOL CSP plants in Saudi Arabia and other locations. | • Solar irradiance, energy mix, and transportation cost have major impact on the performance. |
| [26] | 2021 | Demonstrate performance of prototype CSP plant and forecast solar flux using ANN model. | • A 13-kW prototype achieved 12.52 kW of thermal energy.<br>Gaussian2D and Lorentz2D models have high $R^2$ values. |
| [27] | 2021 | Perform techno-economic analysis of 548.3 MW ISCC plant with 50 MW of SPT-based CSP. | • CSP plant produces a significant amount of energy relative to its capacity.<br>• The hybridized power plant achieves efficiency between 53% and 59%, while the CF is 49.9%.<br>Economic analysis shows CSP plant has an LCOE of 12.7 ¢/kWh and NPV of $10.2 million. |
| [28] | 2022 | Evaluate economic feasibility of 16-hour molten salt TES-based SPT CSP plant for NEOM city. | The plant achieved 95% CF and 7.84 ¢/kWh LCOE. |
| [29] | 2022 | Investigate techno-economic feasibility of PT-based CSP and PV plants at 40 locations in Saudi Arabia. | • LCOE for CSP plants with 9-hour TES ranges from 9.3 to 13.2%.<br>PV farms with BES achieve LCOE between 12.1 and 15.6%. |

## II. REVIEW, CSP OVERVIEW, MOTIVATION, SCOPE, AND CONTRIBUTION

### A. LITERATURE REVIEW

Extensive research has been conducted worldwide to assess the potential of Concentrated Solar Power (CSP). Researchers investigating CSP's potential employ a diverse range of studies to explore its applicability. One focus area involves component design, where scientists investigate how various CSP components, such as mirrors, receivers, and thermal storages, function under varying conditions. Additionally, studies are dedicated to solar resource assessment, aiming to identify suitable CSP installation locations based on solar irradiance, weather patterns, and geographical factors. Advanced geospatial analysis tools are utilized in these studies to assess the long-term feasibility of CSP projects in specific regions. Furthermore, researchers conduct optimization studies to enhance the overall efficiency of CSP systems. These optimization studies often use specialized software tools that facilitate complex calculations and simulations, such as System Advisor Model (SAM) and Hybrid Optimization of Multiple Energy Resources (HOMER). These tools enable researchers to evaluate various CSP configurations and accurately predict their technical and economic performance. In a study [30], the authors explored the potential of CSP technologies for powering vertical farming in Iraq's arid regions. A techno-economic assessment was conducted by relocating an existing CSP plant in Seville, Spain, to six locations in Iraq. The study found that five of the six locations had higher annual energy output, capacity factor, and lower Levelized Cost of Energy (LCOE) compared to the reference plant. Chen et al. [31] assessed CSP generation potential in China using a Geographical Information System (GIS) framework. Exclusion criteria were applied to determine suitable land, identifying 1.02 million km$^2$ available. The technical potential of CSP in China was found to be $2.45 \times 10^7$–$5.40 \times 10^7$ MW, with an annual energy generation potential of $6.46 \times 10^{13}$–$1.85 \times 10^{14}$ kWh, concentrated significantly in western provinces. Authors in [32] evaluated CSP development trends and status in China through a strengths, weaknesses, opportunities, and threats (SWOT) analysis, finding that the technology has opportunities for growth if proper timely policies are instituted by stakeholders. In [33], a multistage stochastic programming model was developed to demonstrate the economic value of CSP integration by reducing power system volatility, especially with high variable renewable shares. An extensive review of 143 global CSP projects was conducted in [34], comparing aspects such as technologies, efficiencies, locations, and challenges such as heat transfer fluid (HTF) and storage options. A hybrid GIS-MCDA approach in [35] mapped suitable CSP sites in Algeria, finding that over 51% of the land is unsuitable due to constraints beyond direct normal irradiation (DNI), emphasizing the importance of considering multiple factors when siting CSP plants. He et al. [36] analyzed pathways to improve CSP operational temperatures above 700 °C, identifying a lack of high-temperature heliostat, receiver, and storage designs as barriers requiring novel approaches. In [21], two mature CSP technologies were hypothetically relocated to Sudan using SAM. Several zones in the northern region outperformed reference plants from Spain, suggesting that Sudan has significant potential for CSP development. The authors proposed a 5 MWe pilot SPT plant to demonstrate the feasibility of CSP in Sudan. In [1], a hybrid power network (PV/Battery/Grid) was developed and analyzed for King Abdullah Campus, The University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan. The results showed that the proposed system was more efficient, stable, cost-effective, and environmentally friendly than the existing system.

In [8], the authors explored six CSP technology scenarios for Saudi Arabia (SA) through a techno-economic analysis and SWOT evaluation. Parabolic Trough (PT) collectors were identified as the most mature, while Solar Power Tower (SPT) technology enabled higher storage integration. Simulation results favored tower designs with significant capacity factors per initial cost. Zubair et al. [13] optimized a PT CSP plant for solar energy export from SA to Europe and Asia based on peak load hours. Analysis of a 2 GW plant transmitting to Karachi, Pakistan through High Voltage Direct Current (HVDC) lines yielded the highest Net Present Value (NPV) of 1,866 million USD and Levelized Cost of Energy (LCOE) of 10.76 ¢/kWh. Corona et al. [25] utilized SimPro software to conduct a lifecycle assessment of typical hybrid solar-CSP plants installed in different countries, including SA. The results indicated that the environmental impact of CSP plants varies significantly (up to 43%) depending on local resources and energy mixes. Hybridizing CSP plants with biomethane rather than natural gas also resulted in significant reductions in environmental impact, particularly in terms of climate change impacts. The structure and design of a short scope CSP prototype developed at King Abdul-Aziz University in Jeddah were investigated in [26], demonstrating the applicability of CSP systems in SA [24]. In [27], a techno-economic assessment of a 548.4 MW Integrated Solar Combined Cycle (ISCC) plant with 50 MW SPT in SA was conducted. The hybridization improved annual generation, lowered costs, and facilitated standalone CSP transitions, contributing to building operating expertise. Boretti and Castelletto [28] studied an SPT-type CSP plant with molten salt Thermal Energy Storage (TES) in NEOM City and found that a 16-hour TES can achieve a capacity factor of 95% and provide electricity at a rate of 7.84 ¢/kWh. While a combination of solar PV and wind turbines can provide a lower LCOE of Renewable Energy (RE)-based electricity, the suggested CSP system achieves reliability. Shakeel and Mokheimer [29] determined CSP and PV feasibility across 40 Saudi cities through System Advisor Model (SAM) modeling. Western province locations produced lower LCOEs ranging from 9.3–13.2 ¢/kWh for CSP plants equipped with 9-hour TES. Table 2 summarizes the studies that have investigated the potential of CSP in SA.

### B. CONCENTRATED SOLAR POWER (CSP) OVERVIEW

Concentrated Solar Power (CSP) technology distinguishes itself from photovoltaic (PV) technology by utilizing angles and directed mirrors to concentrate Direct Normal Irradiance (DNI). This concentrated solar energy is employed to heat up a Heat Transfer Fluid (HTF), which, in turn, produces steam. The steam is then used to spin turbines, generating electricity. Notably, CSP possesses a key advantage over PV in its capacity to economically store heat in a Thermal Energy Storage (TES) system before converting it into electricity [37], [38]. The process of steam generation in CSP mirrors that of conventional power plants, with the notable advantage of being 100% clean, free from Greenhouse Gas (GHG) emissions or waste. Moreover, CSP systems extend their utility beyond electricity generation, serving as heating sources for diverse industrial applications. These applications include desalination, enhanced oil recovery, food processing, petrochemical plants, and metal processing. CSP plants, illustrated in Fig. 1, are categorized into four types based on their approach to capturing solar thermal energy: Parabolic Trough (PT), Solar Power Tower (SPT), Linear Fresnel Reflector (LFR), and Parabolic Dish (PD) systems. Table 3 presents a comprehensive comparison of the main technical and financial characteristics of these four CSP technologies [31].

### C. GIS-BASED SUITABILITY ANALYSIS

A thorough site suitability analysis is imperative for evaluating the viability of utility-scale Concentrated Solar Power (CSP) projects, optimizing land utilization, and ensuring alignment with environmental conditions. Geographic Information System (GIS) tools prove instrumental in this assessment, capable of integrating and analyzing various spatial and temporal data. This includes parameters such as solar irradiance, land use, slope, aspect, distance to roads and transmission lines, and environmental constraints, which are weighted using Multi-Criteria Decision-Making (MCDM) algorithms. This information aids in identifying areas most suitable for CSP development, taking into account diverse criteria. The utilization of GIS for CSP site suitability analysis offers several key advantages, allowing for the consideration of a broad spectrum of factors impacting the performance and cost-effectiveness of a CSP plant. For instance, GIS enables:

- **Identification of Areas with High Solar Irradiance:** Pinpointing areas with optimal solar irradiance, crucial for the efficient operation of CSP plants.
- **Identification of Areas with Suitable Land Use:** Locating areas with open or degraded land, unsuitable for alternative purposes, ensuring optimal land use.
- **Consideration of Favorable Slope and Aspect:** Identifying areas with favorable slope and aspect, minimizing land clearing and grading requirements.
- **Recognition of Environmental Constraints:** Identifying environmental constraints, including protected areas, wetlands, and regions with elevated air or water pollution levels. These constraints assist in excluding areas from CSP development consideration or pinpointing locations necessitating special mitigation measures.

Once a set of criteria is established, GIS facilitates the generation of suitability maps depicting the relative suitability of different areas for CSP development. These maps, in turn, aid in identifying specific sites for CSP development and support decision-making processes related to CSP development. Researchers globally have leveraged GIS to assess the potential of CSP projects, constructing comprehensive GIS-based frameworks for CSP site suitability analysis. These frameworks encompass a diverse array of

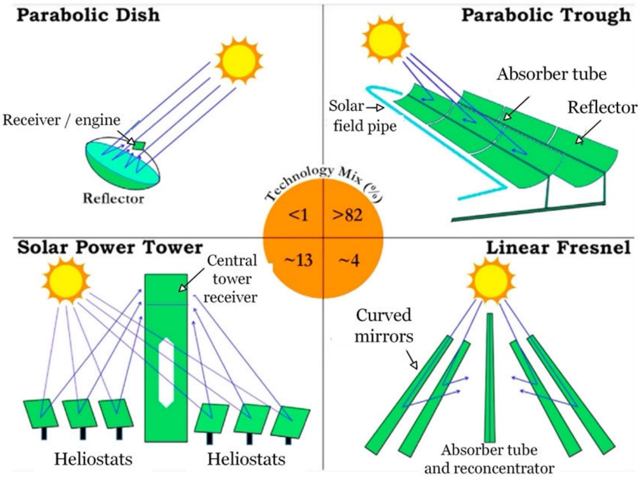



**FIGURE 1.** Types of CSP technology. Source: Adapted from Ref. [22].

factors, including solar irradiance, land use, slope, aspect, distance to infrastructure, environmental constraints, and economic considerations. Table 4 provides a compilation of the literature on GIS-based suitability analysis for CSP projects.

### D. MOTIVATION, SCOPE, AND CONTRIBUTION

The imperative shift towards sustainable and Renewable Energy Sources (RES) plays a critical role in mitigating climate change and ensuring energy security. Within the Saudi Arabian (SA) context, exploring the potential of Concentrated Solar Power (CSP) becomes a necessity, particularly in the promising western region abundant with solar resources. By harnessing concentrated sunlight in this region, CSP projects have the potential to significantly contribute to SA's renewable energy goals, diminish reliance on fossil fuels, and establish a cleaner and more sustainable energy future. Despite the abundant solar potential, a literature survey revealed a limited number of studies exploring CSP potential in SA. Notably, no comprehensive energy planning incorporating techno-economic analysis and Multi-Criteria Decision-Making (MCDM) methodology for selecting optimal CSP project locations has been identified. Therefore, this article proposes an energy plan encompassing data collection, site assessment, weather data review, cost estimates, energy performance evaluation, and Thermal Energy Storage (TES) optimization. The scope extends to a detailed techno-economic feasibility assessment, evaluating the costs, benefits, and overall viability of implementing CSP projects in identified suitable locations. By amalgamating economic aspects with geographical factors, the research aims to provide a holistic perspective on the feasibility of CSP in the western region, addressing this gap through the development of a systematic energy plan. The specific Objectives are as follows:

1) Conduct a GIS-based multi-criteria analysis to identify optimal CSP project locations considering technical restrictions.
2) Model existing Shams-1 and Noor III CSP plants to evaluate annual generation, capacity factors, and levelized costs of Parabolic Trough (PT) and Solar Power Tower (SPT) technologies at shortlisted sites.
3) Optimize CSP plants' performance through electrical energy storage sensitivity analyses.

This research contributes significantly to the field of Renewable Energy and sustainable development in SA. Firstly, it uncovers the untapped potential of CSP in the western region by offering valuable insights into viable project locations. The GIS-based analysis ensures a data-driven approach, enhancing the precision of site selection. Secondly, the study conducts a thorough techno-economic feasibility assessment, considering not only technical but also economic viability. This research will enhance the country's expertise in Renewable Energy, offering a replicable plan for other RES and adaptable at various regional levels. The plan provides valuable data for public officials and decision-makers, aiding strategic resource planning at the local level. These contributions collectively offer a roadmap for policymakers, investors, and researchers, guiding strategic decisions towards a greener and more sustainable energy landscape in SA. The study commenced by systematizing a database of GIS layers and shapefiles obtained through public access portals. Restriction factors and criteria were identified and processed using the Analytical Hierarchy Process (AHP) methodology. GIS tools and hierarchical criteria were employed to create the final suitability map, categorizing the Makkah Province area into suitability levels. A techno-economic investigation of two proposed CSP technologies in Makkah Province was performed, referencing two existing plants in the MENA region.

**TABLE 3.** Comparison of CSP technologies [21], [22], [39], [40].

| CSP technology | PT | SPT | LFR | PD |
|---|---|---|---|---|
| Typical capacity (MW) | 10-300 | 10-200 | 10-200 | 0.01-0.025 |
| Focusing type | Linear | Point | Linear | Point |
| Tracking type | Single axis | Dual axis | Dual axis | Single axis |
| Receiver type | Mobile | Stationary | Stationary | Mobile |
| Cost relative | Low | High | Very low | Very high |
| Operating temperature range (°C) | 350-400 | 250-565 | 250-350 | 550-750 |
| Average CF (%) | • 25-28 (without TES)<br>29-43 (7 h TES) | 25-28 (10 h TES) | 22-24 | 25-28 |
| Land occupation ($m^2$/MWe) | 0.025 | 0.036 | 0.008 | 0.011 |
| Cooling type | Wet or dry | Wet or dry | Wet or dry | None |
| Suitability for dry cooling | Low to good | Good | Low | High |
| Cooling water (L/MWh) for wet cooling | 3000 | 1500 | 3000 | None |
| Thermodynamic efficiency | Low | High | Low | High |
| Annual peak efficiency (%) | 23-27 | 23-35 | 18-22 | 29-32 |
| Annual average efficiency (%) | 11-16 | 20-35 | 8-13 | 16-29 |
| Solar concentration factor | 10-80 | > 1000 | > 60 | Up to 10,000 |
| TES | • Indirect two-tank molten salt at 380 °C (ΔT = 100 °C)<br>Direct two-tank molten salt at 550 °C (ΔT = 300 °C) | Direct two-tank molten salt at 550 °C (ΔT = 300 °C) | Short-term pressurized steam storage (<10 min) | None |
| Hybridization | Yes | Yes | Yes | Limited |
| Grid stability | • Medium (without TES)<br>High (with TES or hybridized) | High (large TES) | Medium (back-up firing possible) | Low |
| Cycle | Superheated Rankine steam cycle | Superheated Rankine steam cycle | Saturated Rankine steam cycle | Stirling |
| Steam conditions (°C/bar) | 380–540/100 | 540/100–160 | 260/50 | n.a. |
| Maximum slope of solar field (%) | <1-3 | <2-4 | <4 | 10 or more |
| TES with molten salt | Commercially available | Commercially available | Possible, but not proven | Possible, but not proven |
| Application type | Grid-tied | Grid-tied | Grid-tied | Grid-tied and off-grid |
| Total installed cost ($/kW) in 2021 | 4,449 | 5938 | - | - |

## III. RESEARCH OUTLINES

The analysis employed in this research, as outlined in Fig. 2, involves a systematic and comprehensive approach, integrating geospatial analysis, technical modeling, and economic evaluations to assess the potential and viability of CSP installations in the western region of SA. The research comprises two main investigations: a geospatial analysis to identify suitable CSP locations and a techno-economic analysis comparing CSP technologies with a focus on PT and SPT configurations.

### *A. SITE SUITABILITY ANALYSIS*

#### 1) DATA COLLECTION AND PROCESSING

Geospatial analysis begins with the collection of relevant data, including solar irradiance, weather patterns, topography, and land use data. High-resolution satellite imagery and climatic databases are utilized to acquire precise geographical information for the western province of SA.

#### 2) GIS-BASED MULTI-CRITERIA ANALYSIS

GIS analysis is utilized to execute a multi-criteria analysis aimed at identifying optimal CSP project locations. This involves the integration of various factors, including DNI, land suitability, proximity to existing infrastructure, and environmental constraints, into the GIS framework. Advanced GIS algorithms and spatial analysis techniques are deployed to assess and determine suitable land areas for the installation of CSP facilities. This approach ensures a comprehensive and data-driven evaluation, allowing for the precise identification of areas conducive to effective CSP implementation.

#### 3) NOMINATING SUITABLE SITES

Based on the results of the GIS analysis, potential sites for CSP installations are shortlisted. The shortlisting process involves rigorous evaluation of technical restrictions and geographical constraints, ensuring the selection of sites conducive to efficient CSP operations.

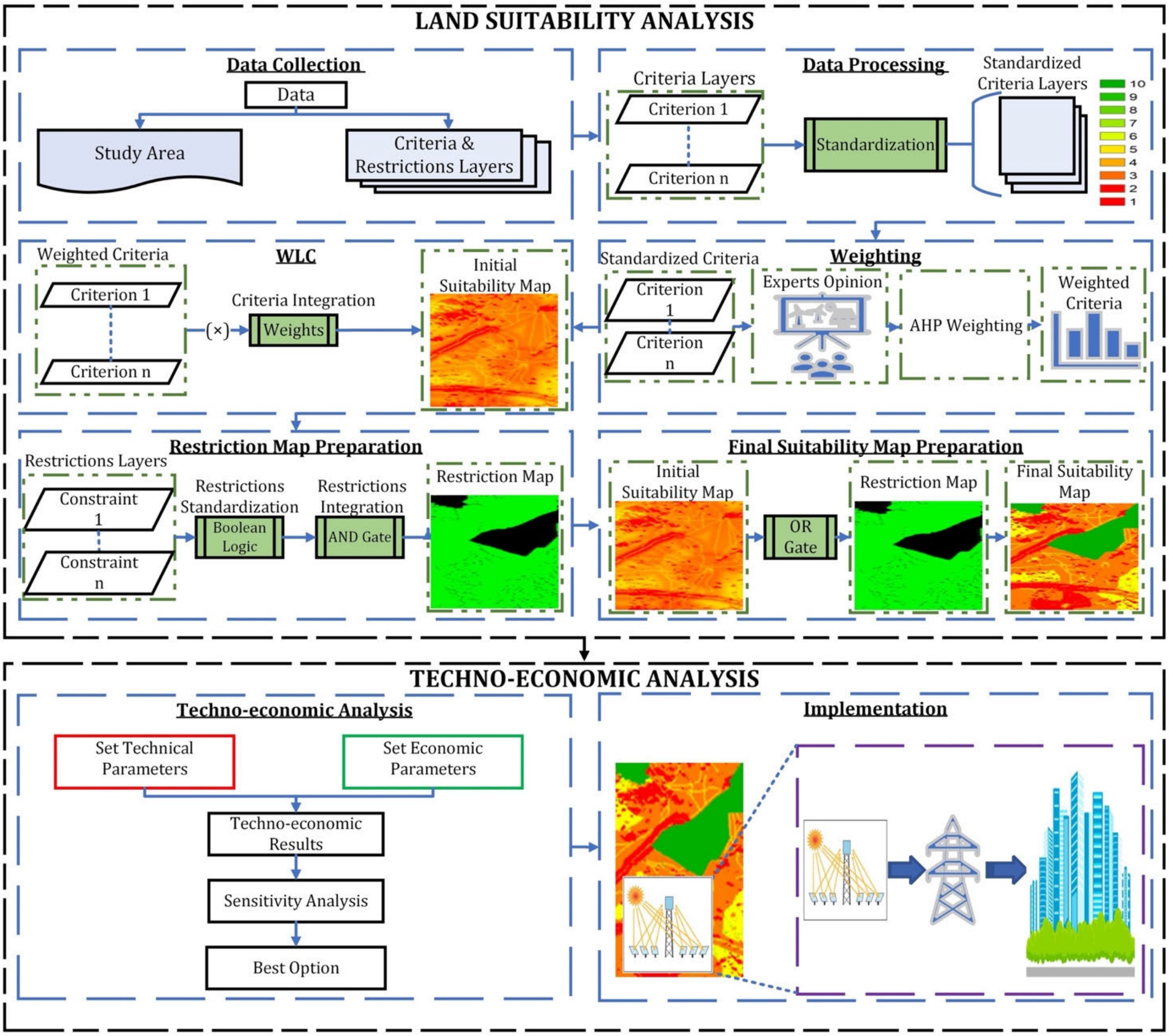



**FIGURE 2.** Flowchart of site the suitability analysis.

## *B. TECHNO-ECONOMIC ANALYSIS*

### 1) MODELING EXISTING CSP PLANTS

Two existing CSP plants, namely Shams-1 and Noor III, serve as reference models. The technical parameters, configurations, and performance data of these plants are meticulously modeled using specialized software tools. Detailed simulations are conducted to evaluate annual generation, Capacity Factor (CF), and efficiency metrics for PT and SPT technologies at the shortlisted sites.

### 2) TECHNICAL AND ECONOMIC ASSESSMENT

The techno-economic feasibility analysis is performed using the SAM modeling tool. Evaluation metrics, such as annual energy generation, CF, and LCOE are calculated for PT and SPT configurations at the selected sites is calculated. Further, a sensitivity study on TES size is performed to optimize plant performance.

### 3) TES SENSITIVITY ANALYSIS

The simulation model can be used to evaluate the performance of the CSP plant with different TES sizes. Therefore, sensitivity analysis in this study is performed to evaluate how the performance and economics of the CSP plants change when the electric storage size is varied.

The combination of rigorous geospatial analysis detailed technical modeling, economic evaluations, and sensitivity analyses forms the foundation of this research. By systematically evaluating both the geographical suitability and economic viability of CSP technologies, this study provides valuable insights into the untapped potential of CSP in the western region of SA.

## *C. ASSUMPTIONS AND LIMITATIONS*

### 1) ASSUMPTIONS

To adequately model and assess the technical and economic feasibility of CSP installations in Makkah province,

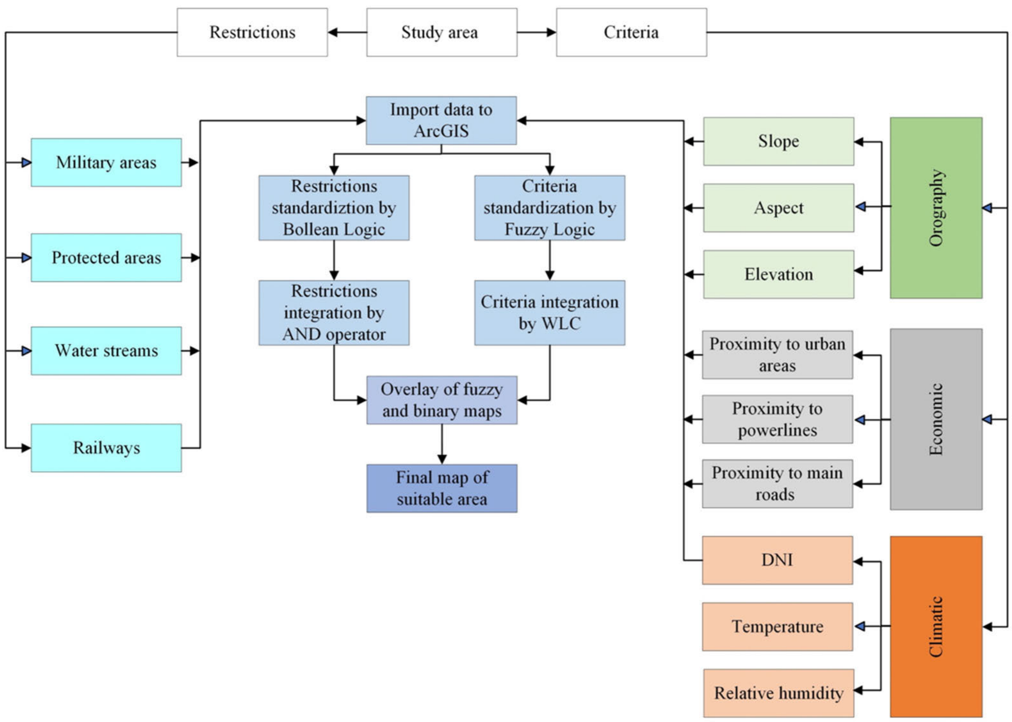



**FIGURE 3. Flowchart of site suitability analysis.**

several assumptions were necessary to simulate and analyze system performance over their lifetimes. While aiming to reflect realistic on-site conditions, inherent uncertainties remain given the complexity of the technology, location specifics, and future uncertainties. The following key assumptions were made as part of the feasibility analysis methodology:

- Land identified as suitable through the GIS analysis will be available for utility-scale CSP development and protected land restrictions will not change.
- Climate and weather patterns in the study area will remain relatively consistent over the lifespan of the proposed CSP projects. Long-term solar irradiation and temperature data are representative of conditions.
- Technical specifications and performance of the modeled Shams-1 and Noor III plants used as base cases accurately reflect actual operations of these reference facilities.
- Modeled locations have proper connectivity to the existing electricity grid and transmission infrastructure without requirement of grid extension.
- CSP technology costs from sources like IRENA for capital, operation and maintenance (O&M) cost, and country-specific financial parameters are used in SAM financial model.
- Simulated single-year performance of plants based on typical meteorological year appropriately represents long-term output without need for multi-year simulations.
- Modeled plants achieve steady operations throughout their lifetime with an annual degradation rate of 1% for components, which impacts generation output and efficiency over the project lifetime.

#### 2) LIMITATIONS

- Geographic scope is limited to Makkah province in the western region of SA.
- Only two existing CSP plant designs, Shams-1 (PT) and Noor III (SPT), are modelled as base cases for evaluation at nominated sites.
- Technical parameters of the models are kept identical to base cases except climatic data specific to Saudi locations.
- Financial data used is limited to reported costs instead of actual costs from Saudi market.
- Sensitivity analysis is limited to varying the TES capacity only.

## IV. CSP SITE SUITABILITY ANALYSIS OF MAKKAH PROVINCE

The study assessed the suitability of the province's land for deploying Concentrated Solar Power (CSP) systems. A total of nine criteria, influencing the performance of CSP plants, were identified from existing literature and further validated through interviews with expert professors in the Renewable Energy field at King Abdulaziz University. These criteria were categorized as economic, climatic, environmental, and topographic factors. The flowchart depicted in Fig. 3

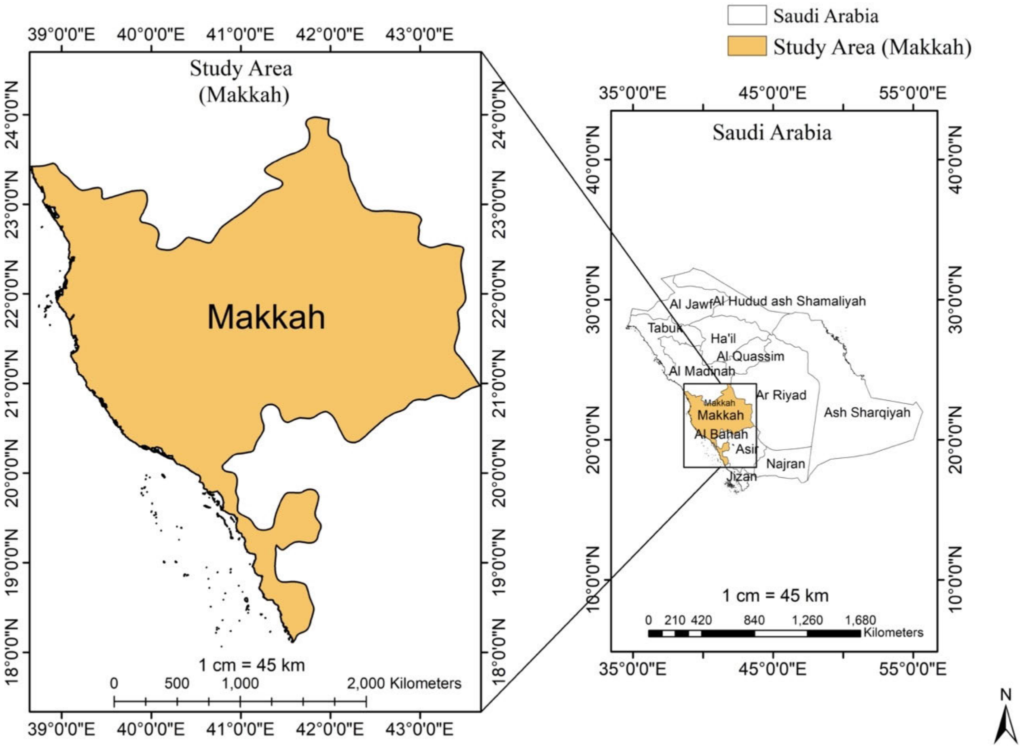



**FIGURE 4.** The study area.

illustrates the process of site suitability analysis, incorporating the AHP method to assign weights to criteria, which were standardized using fuzzy logic (FL). Subsequently, the analysis of criteria within a GIS environment is presented, highlighting the contribution of each criterion to the suitability model. This comprehensive approach ensures a thorough and systematic evaluation of the land's suitability for the deployment of CSP systems.

### A. STUDY AREA

Makkah Province (Fig. 4) is in the western region of SA and lies between latitudes of 21° 29' 59.99'' N and longitudes of 41° 00' 0.00'' E. It covers an area of 153,128 km$^2$ and has a population of 9,033.491 people, which is equivalent to 26.5% of the total population of SA in 2019. Makkah is one of the provinces with the highest average temperatures (37 °C) in SA, and the sunniest month is May, with 13 hours of daily sunshine [41]. The climate varies between the Mediterranean and monsoonal systems, with an average daily DNI of 5667.8 Wh/m$^2$/day. Fig. 5 is a DNI satellite map of SA that was retrieved from the Global Solar Atlas 2.0 developed by SOLARGIS [42].

### B. GEOSPATIAL DATA ANALYSIS

Geospatial data, encompassing information on the locations and configurations of geographical features along with their interaction patterns, is pivotal and often represented as maps. Location information plays a crucial role in decision-making, especially in the initiation of a power plant. In the analysis of CSP land suitability, various GIS data, such as climatic data, orographic data, road networks, and topographic data (including digital elevation, slope, and aspect), are gathered to evaluate the suitability of a given location. Subsequently, the analysis process is streamlined by breaking down the real data into layers, where each layer represents point locations, areas, or networks of lines. These layers of spatial data can be combined, interpreted, analyzed, or visualized to generate geographic information aiding decision-making related to location selection based on specific criteria [43].

In this study, the land suitability analysis for the proposed CSP systems was conducted using ArcGIS version 10.8 software and a free web-based AHP calculator. The framework for the CSP system site suitability optimization is illustrated in Fig. 6. This approach ensures a systematic and efficient evaluation of potential sites, leveraging geospatial data to inform decision-making processes related to CSP system deployment.

### C. FEATURES LAYERS PREPARATION AND FUZZY STANDARDIZATION

A feature layer comprises properties with similar characteristics and their associated attributes. In this study, ArcGIS was employed to represent data acquired in the form of point, multipoint, polyline, polygon, or vector as feature classes. The criteria and restriction data considered in this study encompass aspect, elevation, slope (extracted from the

**TABLE 4. Existing literature of GIS-based optimum site selection.**

| Reference | Case study | Method | Optimization | Criteria and weight (%) |
|---|---|---|---|---|
| [35] | Algeria | AHP | CSP | • DNI (27.05)<br>• Distance to roads and railways (5.31)<br>• Distance to high population densities (22.95)<br>• Distance to electricity grid (23)<br>• Distance to waterways and dams (12.51)<br>• Slope (5.48)<br>Slope orientation (3.7) |
| [44] | Brazil | AHP<br>WLC | CSP | • DNI (43.1)<br>• Slope (15)<br>• Proximity to transmission lines (8.49)<br>• Proximity to substations (11.96)<br>• Proximity to urban areas (1.93)<br>• Water availability (4)<br>• Proximity to highways (4.17)<br>• Proximity to railways (0.87)<br>• Proximity to cargo airports (0.43)<br>• Proximity to waterways (1.42)<br>• Open areas (4.02)<br>• Pasture (2.34)<br>• Agricultural areas (1.04)<br>• Sparse vegetation (0.91)<br>Forest vegetation (0.28) |
| [45] | China | AHP | CSP+PV | • Solar irradiation (27.5)<br>• Average temperature (9.1)<br>• Slope (12.4)<br>• Proximity to rivers (23.3)<br>• Proximity to roads and railways (8.3)<br>• Proximity to powerlines (15)<br>Proximity to load demand (4.5) |
| [46] | Ghana | AHP | CSP+PV | • DNI (37.99)<br>• Population density (24.25)<br>• Distance to powerlines (19.08)<br>• Distance to rivers (11.26)<br>Slope (7.42) |
| [47] | Greece | AHP | CSP+PV | • Distance from the coastline (16)<br>• Distance from water bodies (12)<br>• Distance from transmission lines (7)<br>• Distance from roads (8)<br>• Slope direction (10)<br>• Land cover (12)<br>• Slope (8)<br>• Elevation (9)<br>• Visibility from most-visited sites (9)<br>Solar potential (7) |
| [38] | Morocco | AHP | CSP+PV | • DNI (32.6)<br>• GHI (21.5)<br>• Temperature (4.7)<br>• Slope (25.5)<br>• Distance from cities (4.8)<br>• Distance from grid (3.3)<br>• Distance to roads and railways (2.3)<br>• Distance from waterways (1.5)<br>• Distance from dams (0.6)<br>WRI (3.2) |
| [48] | Morocco | AHP | CSP | • DNI (58.8)<br>• Slope (25.5)<br>• Distance to residential (4.8)<br>• Distance to electricity grid (3.3)<br>• Distance to road and railway networks (2.3)<br>• Distance to waterway (3.3)<br>• Distance to dams (1.5)<br>Distance to ground water (0.5) |
| [49] | Tanzania | AHP | CSP+PV | • DNI (61.8)<br>• Water availability (20.3)<br>• Proximity to roads (4.5) |

**TABLE 4.** ***(Continued.)*** **Existing literature of GIS-based optimum site selection.**

| | | | | |
|---|---|---|---|---|
| [50] | West Africa | AHP | CSP+PV | • Proximity to utility grid (8.9)<br>• Proximity to cities with over 250,000 inhabitants (3.4)<br>Proximity to cities with 100,000 to 250,000 inhabitants (1.1)<br>• Solar irradiance (46.9)<br>• Distance to electricity grid lines (24.9)<br>• Distance to roads (14)<br>• Population density (9.5)<br>Distance from settlements (4.7) |
| [51] | Zimbabwe | AHP | CSP | • Solar radiation (50)<br>• Land use (6)<br>• Water bodies (20)<br>• Powerlines (4)<br>Slope (20) |
| This study | Saudi Arabia | FL<br>Boolean logic<br>AHP<br>WLC | CSP | • DNI<br>• Average temperature<br>• RH<br>• Slope<br>• Aspect<br>• Elevation<br>• Distance to roads<br>• Distance to cities<br>Distance to powerlines |

location Digital Elevation Model (DEM) file), as well as Direct Normal Irradiance (DNI), temperature, relative humidity (RH), powerlines, main roads, land use, water streams, and urban areas. These criteria and their respective layers are detailed in Table 5, including their source databases, and the corresponding layers mapped in ArcGIS are presented in Fig. 7. This structured approach ensures a comprehensive consideration of key factors influencing the suitability of locations for CSP systems.

Several restrictions are often implemented in identical CSP land suitability analyses. This investigation considers protected areas, military areas, railroads, and water streams as restricted zones to ensure compliance with environmental regulations and land-use restrictions. The protected area in SA constitutes around 10.42% of the country's total area [52], [53]. To create the final restriction map, the province's restriction layers were extracted from spatial data using a masking tool. Then, the individual restriction layers were combined using the Boolean logic method, where input values were assigned 0 or 1 to represent pixels of areas to be eliminated or permitted zones, respectively. The final restriction map was developed by combining the individual restriction layers using the AND logic operator available in the raster calculator tool of ArcGIS 10.8.

Standardizing the layers is an essential step because the data comprising the features often have different scales and units of measurement. This process ensures that the layers are compatible and can be combined to produce accurate and reliable site suitability maps. FL is used to standardize feature layers by converting the data layers into fuzzy values using membership functions. This process enables the transformation of layers into comparable fuzzy values, facilitating their integration and analysis. In FL, a fuzzy membership function can represent multiple values based on the degree of truth or falsity. A zero-degree membership indicates that the data point does not belong to the fuzzy set defined by the membership function, while a one-degree membership indicates that the data point entirely represents the fuzzy set [54]. Table 6 provides the appropriate membership functions used to reclassify the input data of each feature, while their corresponding fuzzy membership values, which were obtained from the literature and are presented in Table 7. Buffers for distance from cities, distance from roads, and distance from powerlines are automatically added to the restriction area. The individual restriction maps are presented in Fig. 8 and combined to develop the final restriction map, illustrated in Fig. 9.

### D. CRITERIA WEIGHTING

The weighting process for the identified criteria was conducted through the AHP, employing pairwise comparisons. AHP is a widely used MCDM approach that formulates a square matrix through these comparisons. In this method, decision-makers or experts assess the importance of one criterion relative to another. The main eigenvector derived from this matrix establishes the weights (wi), offering a quantitative measure of the consistency of value judgments between pairs of criteria. Unlike assigning ordinal rankings of importance, the AHP method generates ratios, revealing how important one criterion is relative to another [58]. It also has the capability to adjust for inconsistency in experts' judgments. However, it may become challenging when dealing with a large number of criteria [59]. This approach ensures a rigorous and systematic determination of the relative importance of each criterion in the site suitability analysis for CSP systems.

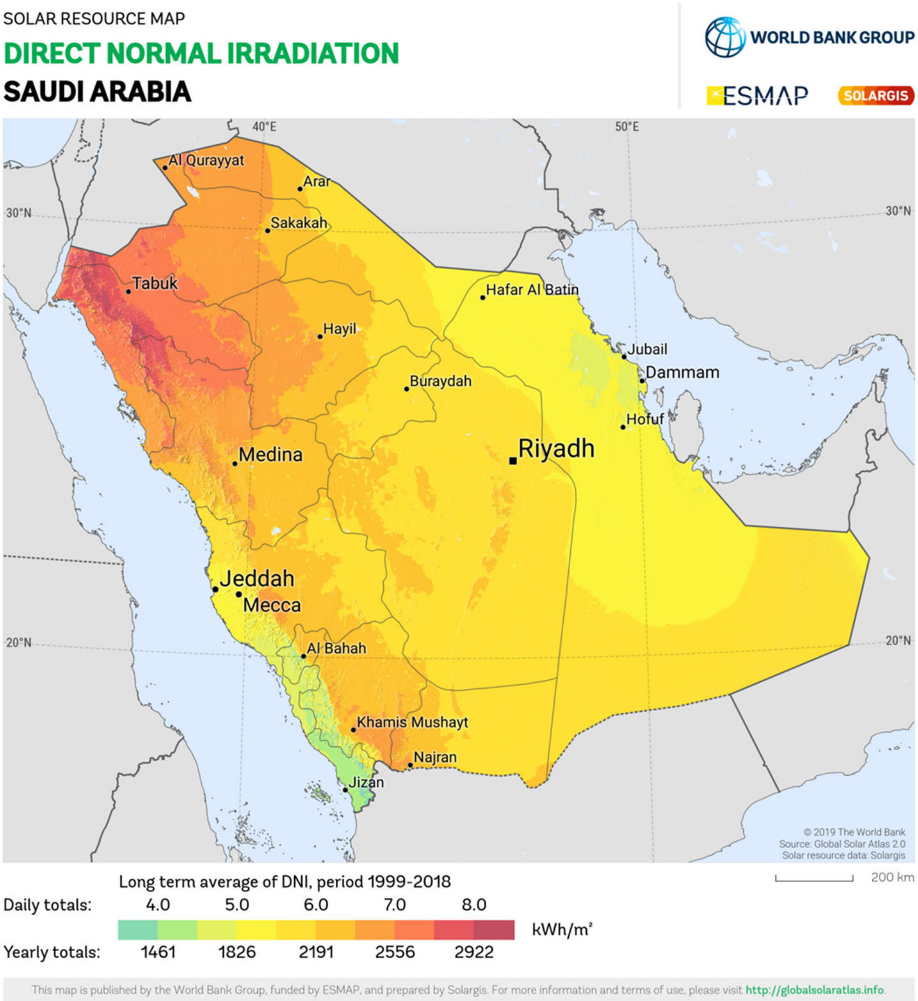



**FIGURE 5.** Average direct normal irradiation (DNI) of Saudi Arabia [42].

**TABLE 5.** Datasets and corresponding sources.

| Data | Type | Source | Reference |
|---|---|---|---|
| DEM | Raster | DIVA-GIS | [55] |
| DNI | Points | POWER data access viewer | [56] |
| Temperature | Points | POWER data access viewer | [56] |
| RH | Points | POWER data access viewer | [56] |
| Powerlines | Polyline | NEXT-GIS | [57] |
| Main Roads | Polyline | DIVA-GIS | [55] |
| Land Use | Polygon | DIVA-GIS | [55] |
| Water Streams | Polyline | DIVA-GIS | [55] |
| Urban Areas | Polygon | DIVA-GIS | [55] |

The AHP algorithm is executed following these steps [60]:

- Identify the criteria.
- Formulate the pairwise comparison matrix (m = n×n): To formulate the pairwise comparison matrix for the criteria, a scoring approach is used. The intensity value $P_{ij}$ compares the priority of the criterion in the i-th row with the criterion in the j-th column. To determine the value of the priority intensity $P_{ij}$, the scaling table suggested by Saaty (Table 8) is used. The criteria with the intensity values $P_{ij}$ and $P_{ij}$ must comply with the condition in (1). The resulting pairwise comparison matrix and criteria correlation are shown in Fig. 10.

$$P_{ij} \times P_{ji} = 1 \tag{1}$$

- Formulate the normalized pairwise comparison matrix ($\bar{m}$): the normalization of each score in the pairwise

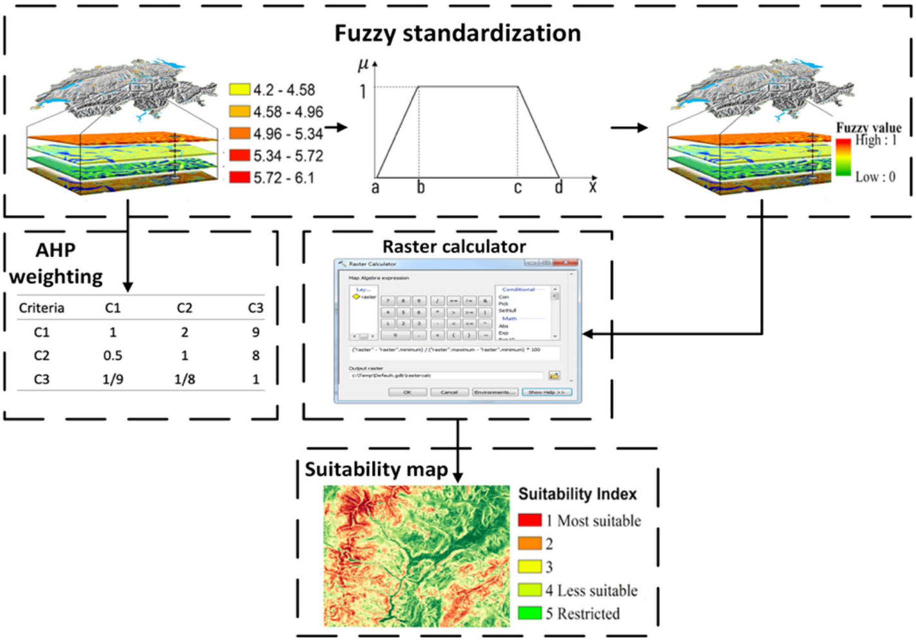



**FIGURE 6.** Framework of the suitability analysis.

matrix is attained by dividing the score by the sum of scores in its respective column. Thus, a normalized score $\bar{P}_{ij}$ is defined by (2).

$$\bar{P}_{ij} = \frac{P_{ij}}{\sum_{i=1}^{n} P_{ij}} \tag{2}$$

- Calculate the relative weight of each criterion ($w_i$): as shown in (3), the average weight of each criterion is calculated by dividing the sum of each row by the number of the priority intensity in the row (n).

$$w_i = \frac{\sum_{j=1}^{n} P_{ij}}{n} \tag{3}$$

- Determine the Consistency Ratio (CR): the consistency ratio, as presented in (4), is the ratio of the pairwise comparison matrix consistency index (CI) to the random consistency index (RI). It is the most important indicator of experts' judgement on criteria ranking. If the CR is greater than 0.10, then there is inconsistency in the pairwise comparison matrix. Therefore, the AHP process will not establish for an accurate decision-making process, hence, the ranking must be reevaluated. The CI is determined by (5), where $\lambda_{max}$ is the principal eigenvalue which is maximum pairwise comparison matrix eigenvalue. For each number of criteria (n), there is a corresponding RI as shown in Table 9. the eigenvalues obtained in this study are listed in Table 10.

$$CR = \frac{CI}{RI} \tag{4}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

The number of criteria (n) in this study was nine, resulting in an RI of 1.45. The calculated CR was 0.09, indicating acceptable consistency of the matrix. Table 11 presents the criteria relative weights obtained from the AHP method, which describe the levels of criteria importance for the study. These weights are also graphically represented in Fig. 11.

The results indicate that DNI and temperature had the highest weights, with figures of 30.3% and 21.7%, respectively, followed by the indicator slope at 13.50%. In contrast, RH had the lowest weight among the criteria, with a figure of 2.4%.

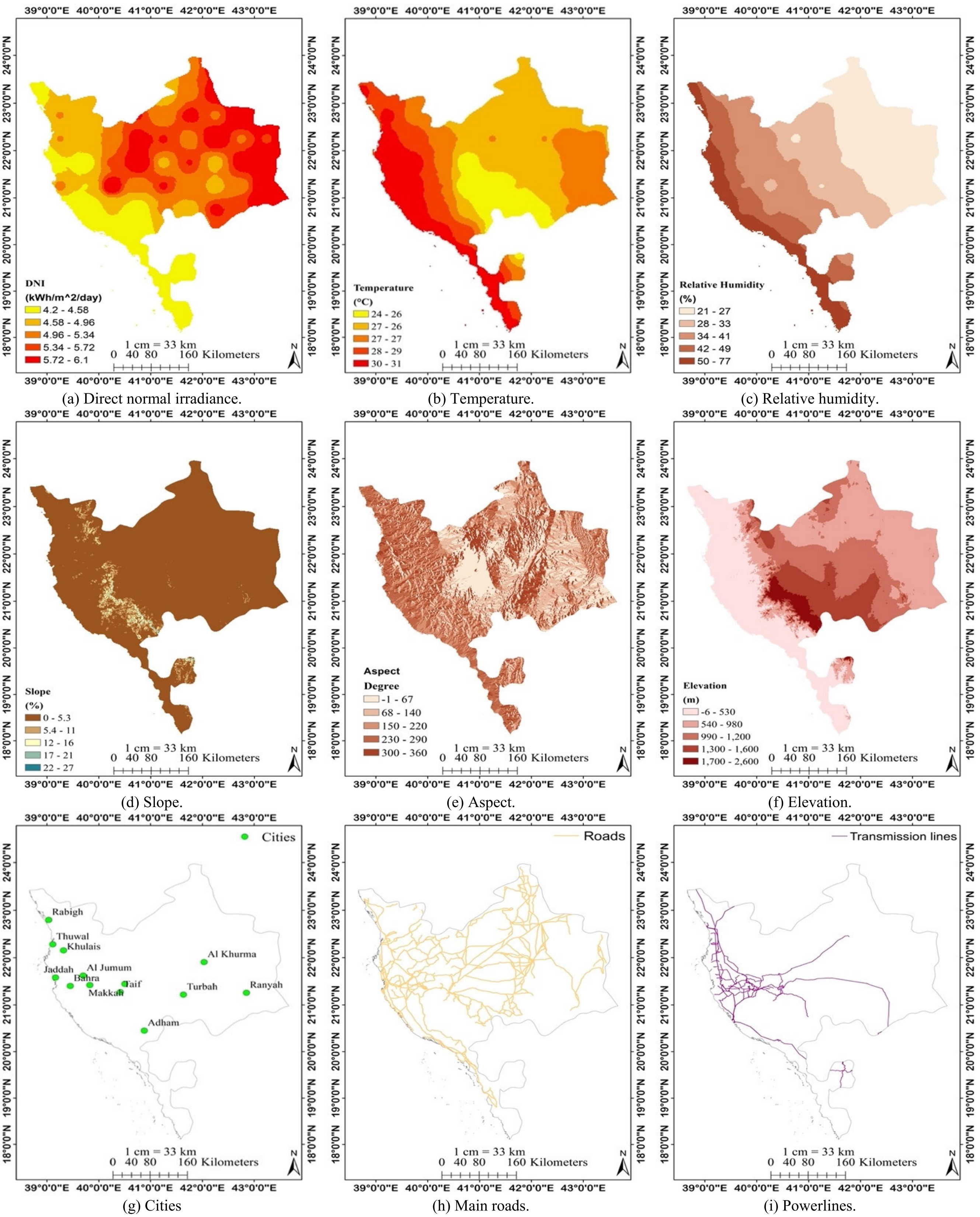
### E. WEIGHTED LINEAR COMBINATION

The Weighted Linear Combination (WLC) is one of the most used techniques for integrating raster layers of the criteria [54]. In this method, the suitable area (SA) for each fuzzy standardized criterion raster layer is defined by (6) [60]. Each pixel ($x_i$) in the fuzzy standardized layers is multiplied by the respected criteria weight ($w$) and linearly summed to the other identical pixels on the other criteria layers. If a pixel on any layer falls within a predefined restricted area, the restriction (r) is set to zero and one otherwise.

$$SA = x_i \cdot w_i \cdot r \text{ where } r \in \{1, 0\} \tag{6}$$

### F. CSP POTENTIAL SUITABILITY MAP

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray:




(a) Direct normal irradiance. (b) Temperature. (c) Relative humidity. (d) Slope. (e) Aspect. (f) Elevation. (g) Cities (h) Main roads. (i) Powerlines.

**FIGURE 7.** Criteria maps.

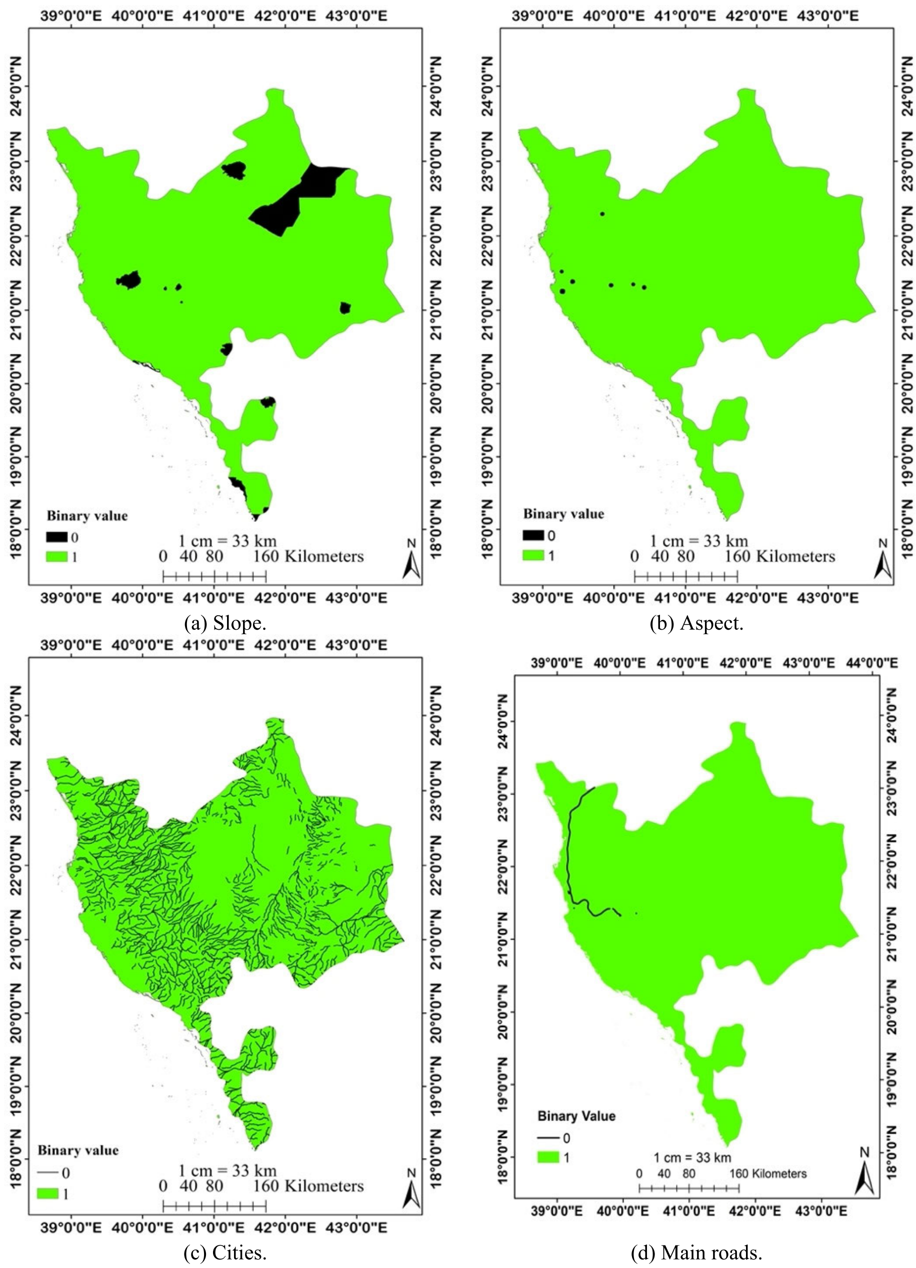



**FIGURE 8.** Individual restriction maps.

### 1) RASTER LAYERS OVERLAYING

The initial suitability map for the installation of CSP systems in Makkah province was created using the fuzzy overlay tool in ArcGIS 10.8 software. This was achieved by combining the criteria fuzzy standardized suitability maps shown in Fig. 12, with respective weights assigned to each criterion. The resulting initial suitability map, shown in Fig. 13, was obtained by overlaying the nine criteria (C1-C9) with their corresponding weights ranging from 2.4% to 30.3%.

### 2) CSP PLANT SITE NOMINATION

According to the literature, a feasible CSP plant that can operate efficiently and provide an optimum LCOE requires a minimum DNI between 1800 kWh/m$^2$/year and 2400 kWh/m$^2$/year. As a result, the final suitability map (Fig. 14) highlights five zones within the most suitable areas. These sites possess an average DNI ranging from 5.54 kWh/m$^2$/year to 6.08 kWh/m$^2$/year, while satisfying the restriction constraints and achieving a higher potential based on the criteria considered. Table 12 provides details on the climatic conditions and features of the prospective locations chosen for the techno-economic study of CSP plants in the province of Makkah.

## V. CSP TECHNO-ECONOMIC FEASIBILITY ANALYSIS

One of the goals of this research is to investigate the technical and economic feasibility of CSP plants in Makkah's province

**TABLE 6.** Fuzzy membership functions for criteria reclassification.

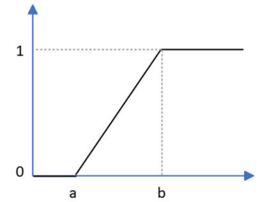
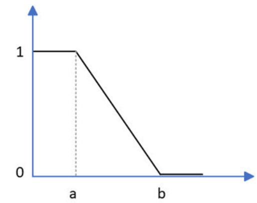
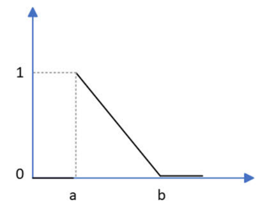
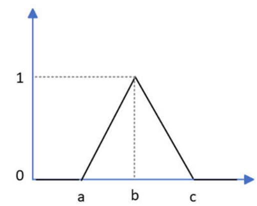
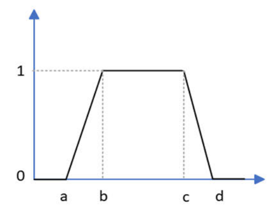
| Type | Mathematical expression | Membership function |
|---|---|---|
| Linear/ monotonically increasing | $f(x)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a<x<b\\ 1, & x\ge b\end{cases}$ |  |
| Linear/ monotonically decreasing 1 | $f(x)=\begin{cases}1, & x\le a\\ \frac{x-b}{a-b}, & a<x<b\\ 0, & x\ge b\end{cases}$ |  |
| Linear/ monotonically decreasing 2 | $f(x)=\begin{cases}0, & x\le a\\ \frac{x-b}{a-b}, & a<x<b\\ 0, & x\ge b\end{cases}$ |  |
| Triangular | $f(x)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a<x<b\\ \frac{c-x}{c-d}, & b\le x\le c\\ 0, & x\ge c\end{cases}$ |  |
| Trapezoidal | $f(x)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a<x<b\\ 1, & b\le x\le c\\ \frac{d-x}{d-d}, & c<x<d\\ 0, & x\ge b\end{cases}$ |  |

**TABLE 7.** Membership functions parameters.

| Criteria | Abbreviations | Unit | Type of membership function | a | b | c | d |
|---|---|---|---|---|---|---|---|
| DNI | C1 | kWh/m$^2$/year | Linear/ monotonically increasing | 1800 | maximum | - | - |
| Temperature | C2 | °C | Linear/ monotonically decreasing 1 | 18 | 37 | - | - |
| RH | C3 | % | Linear/ monotonically decreasing 2 | minimum | maximum | - | - |
| Slope | C4 | % | Trapezoidal | 0 | 10 | 50 | 60 |
| Aspect | C5 | Degree | Trapezoidal | 0 | 157.5 | 202.5 | 360 |
| Elevation | C6 | m | Trapezoidal | 300 | 1100 | 1800 | 2600 |
| Proximity to cities | C7 | km | Trapezoidal | 1000 | 1500 | 7000 | 15000 |
| Proximity to main roads | C8 | m | Trapezoidal | 300 | 1000 | 5000 | 15000 |
| Proximity to powerlines | C9 | m | Trapezoidal | 50 | 400 | 1000 | 5000 |

and evaluate their performance to establish a solid energy framework for planners and decision-makers for planning optimal future implementation of CSP systems with minimal uncertainty. The techno-economic investigation is an important factor in understanding how that electricity generation technology could be commercialized, as it allows for the

**TABLE 8.** Score of relative importance according to Saaty's scale [61].

| Intensity of importance | Definition |
|---|---|
| 1 | Equal Importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very strong importance |
| 9 | Extreme importance |
| 2, 4, 6, 8 | Intermediate values |
| 1/3, 1/5, 1/7 ... | Values for inverse comparison |

**TABLE 9.** Random index for n criteria [60].

| n | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 |

**TABLE 10.** Consistency matrix eigenvalues.

| $\lambda_i$ | Value |
|---|---|
| 1 | -0.094 |
| 2 | 0.037 |
| 3 | 0.037 |
| 4 | 0.002+0.462j |
| 5 | 0.002−0.462j |
| 6 | 0.072+2.090j |
| 7 | 0.072−2.090j |
| 8 | −0.575+2.445j |
| 9 | −0.575−2.445j |

**TABLE 11.** Criteria relative weights.

| Criteria | Weight (%) | Rank |
|---|---|---|
| C1 | 30.30 | 1 |
| C2 | 21.70 | 2 |
| C3 | 2.40 | 9 |
| C4 | 13.50 | 3 |
| C5 | 8.60 | 5 |
| C6 | 6.70 | 6 |
| C7 | 3.30 | 8 |
| C8 | 4.60 | 7 |
| C9 | 8.90 | 4 |
| | Total = 1.00 | |

identification of the critical technical and economic factors associated with that technology at an early stage of the project development.

This study evaluated three crucial performance indicators to investigate the performance of the proposed CSP technologies as discussed in the following points.

- Annual electricity output: the annual electricity output is the total annual electrical energy generated by the CSP plant over a year [21].
- Capacity Factor (CF): The capacity factor (CF) is the ratio between the energy generated by the plant during a given period and the energy that could have been generated during that same period if the plant worked at its rated power, therefore this parameter allows evaluating the ability of a given plant to work at its rated power. The capacity factor of a CSP plant over a year is given by (7) [62].

$$CF = \frac{Actual\ energy\ generated\ by\ CSP\ plant\ (MWh)}{CSP\ plant\ capacity\ (MW) \times 8760} \quad (7)$$

- Levelized Cost of Energy (LCOE): The LCOE is a ratio of a plant's total capital and operating costs to the present value of the electricity that plant will produce over the course of its lifetime. It is used to compare the cost of energy between different electricity generation technologies and can be estimated in either real or nominal terms. Real LCOE provides a more accurate representation of the true cost of electricity production because it considers the inflation rate. In this study, real LCOE was considered because the analysis was for a long-term projection. Equation (8) and Equation (9) present the

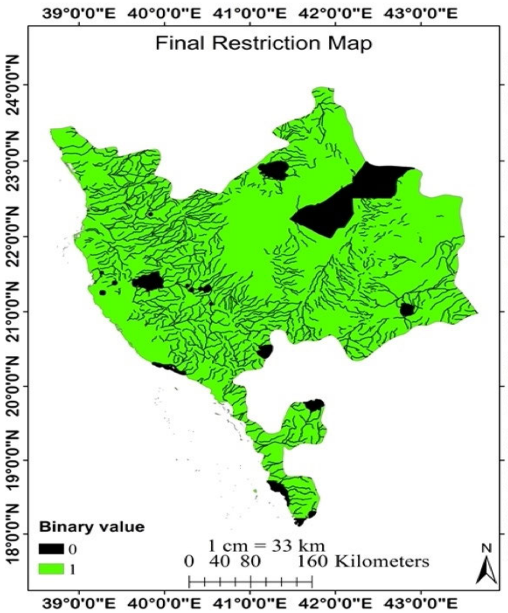



**FIGURE 9.** Final restriction map.

real and nominal LCOEs respectively [63].

$$LCOE\ (real) = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{real})^n}} \tag{8}$$

$$LCOE\ (nominal) = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{nominal})^n}} \tag{9}$$

where, $Q_n$ is the total electric energy delivered by the plant in year n, $C_0$ refers to the project's equity, $C_n$ represents the project's annual cost in year n, $N$ referes to the total years of the analysis, $d_{nominal}$ is nominal discount rate, $d_{real}$ is the real discount rate.

### A. BASE CASE VALIDATION

Utilizing appropriate simulation tools is crucial to accurately predict the technical and financial outcomes of a CSP system. Accurate performance estimates can reduce industrial risk and optimize system design and operation. SAM, a free software developed by the National Renewable Energy Laboratory (NREL), is a popular option for modelling CSP plants. SAM allows users to input technical and financial data and model the system's performance on an hourly basis for a typical year. The model can then generate charts, graphs, and tables to indicate expected electrical and financial performance [64].

This study selects two already-operational CSP plants in the MENA region as base cases. The first plant is Shams-1, a PT CSP plant located in the UAE [65]. The second plant is Noor-III, a SPT CSP plant located in Morocco [66]. These plants were chosen based on their geographical location and data availability, making them suitable base cases for the investigation.

Shams-1 and Noor III are two large concentrated solar thermal power plants, located in Abu Dhabi and Morocco, respectively. Shams-1 uses cylindro-parabolic mirrors and has a capacity of 100 MW, while Noor III has a capacity of 150 MW and uses SPT technology. Both plants have been operational since 2013 and 2018, respectively, and serve as examples of RES in arid regions.

To validate the climatic data and software sensitivity used in this investigation, both power plants have been modeled in SAM using their original location and the technical data presented in Table 13 for Shams-1 and Table 14 for Noor III. Despite the limited availability of data, the Shams-1 model achieved an annual electricity production of 209.34 GWhe, with an accuracy of 99.68%, compared to the reported value of 210 GWhe in [65]. Similarly, the Noor III model produced 524 GWhe, while the reported annual electric energy output was 500 GWhe [66]. The results of the validation models are presented in Table 15.

The outcomes of this study underscore the efficacy of the SAM tool in precisely modeling the performance of CSP systems, even in arid regions with constrained available data. The validation models not only instill confidence in the accuracy of the technical and financial estimates presented in this investigation but also affirm SAM's reliability as a tool for designing and assessing the viability of CSP systems. This validation contributes to the credibility and robustness of the study's findings, reinforcing the utility of SAM in the evaluation and planning of CSP projects.

### B. SYSTEM MODELING

The base case models are implemented across the designated locations, maintaining uniform design parameters for the entire power system, including solar fields, collectors and receivers, HTFs, power towers, thermal storages, and power blocks. These design parameters, assumed to be identical for all nominated zones, serve as the foundation for the models, with climatic data being the only variable depending on the specific locations.

The financial model in SAM relies on current CSP technology costs, encompassing capital costs, Operation and Maintenance (O&M) expenses, and financial parameters specific to the country of interest. This includes factors such as the inflation rate, discount rate, and taxes. The assessment draws on renewable power generation cost estimates for 2020 provided by the IRENA, a trusted source for collecting, analyzing, and publishing costs and performance data related to Renewable Energy (RE) sources. According to the IRENA auction and PPA database, the global weighted-average total installation costs, capacity factors, and LCOE for CSP plants commissioned in 2020 were 4,581 \$/kW, 42%, and 0.11 \$/kWh, respectively. The distribution of each component of the total installation cost for both Parabolic Trough (PT) and

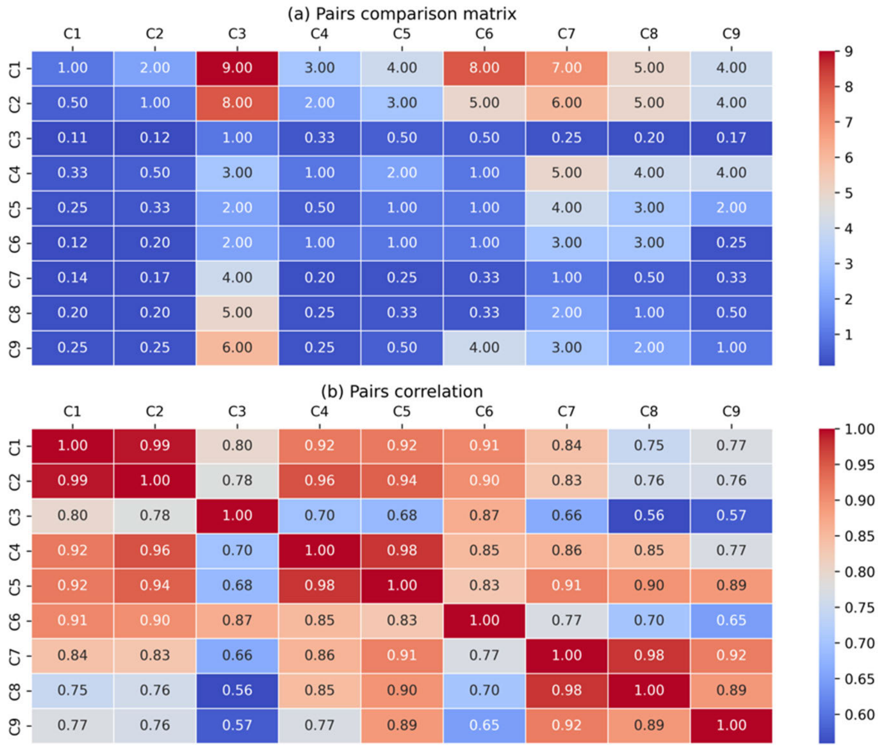



**FIGURE 10.** Criteria (a) comparison matrix; (b) pair correlation.

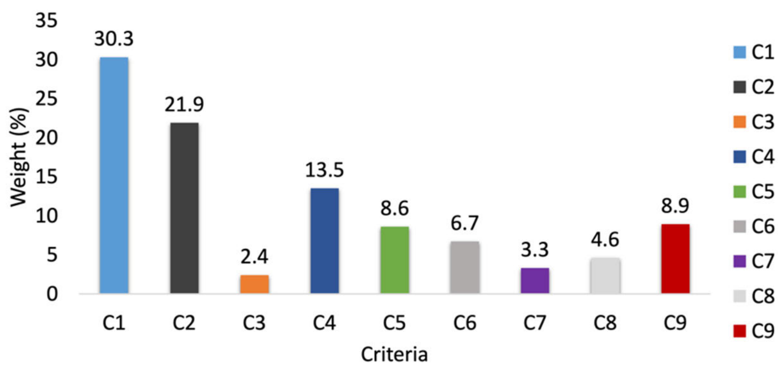
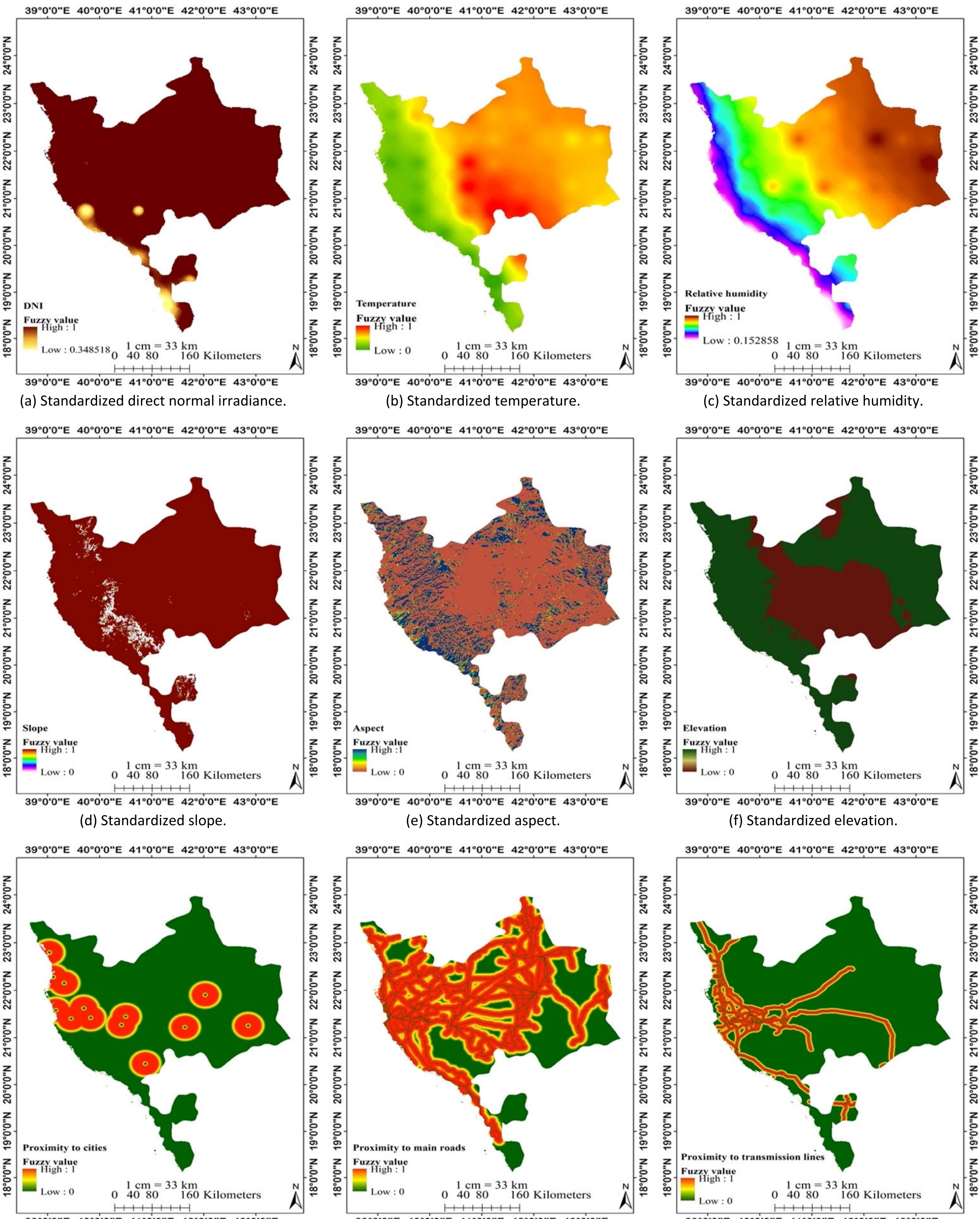



**FIGURE 11.** Infographic representation of the criteria weights.

**TABLE 12.** Annual average climatic data and features of the nominated locations.

| Location | City | Lat. (°N) | Long. (°E) | Elevation (m) | DNI (kWh/m$^2$/day) | Temperature at 2 m (°C) | Wind Speed (m/s) | RH (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | Turabah | 20.97 | 41.62 | 1252 | 5.76 | 25.9 | 3.6 | 33.47 |
| 2 | Taif | 23.26 | 41.86 | 941 | 5.77 | 26.7 | 3.6 | 26.67 |
| 3 | Taif | 21.49 | 40.50 | 1500 | 6.08 | 23.4 | 3.1 | 39.78 |
| 4 | Rabigh | 23.25 | 38.82 | 12 | 5.55 | 29.5 | 3.2 | 49.65 |
| 5 | Ranyah | 21.53 | 43.10 | 866 | 5.73 | 27.7 | 3.5 | 50.50 |

Solar Power Tower (SPT) technologies is outlined in Table 16 [67]. Additionally, the annual and monthly average climatic data profiles were obtained from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resource (POWER) database through the power data access viewer [56]. This comprehensive approach ensures the accuracy and reliability of the financial assessments and modeling outcomes.




(a) Standardized direct normal irradiance.

(b) Standardized temperature.

(c) Standardized relative humidity.

(d) Standardized slope.

(e) Standardized aspect.

(f) Standardized elevation.

(g) Standardized proximity to cities.

(h) Standardized proximity to main roads.

(i) Standardized proximity to transmission lines.

**FIGURE 12.** **Fuzzy standardized criteria maps.**

**TABLE 13.** **Shams-1 technical data.**

| Specification | Variable | | SAM Simulation | [65] |
|---|---|---|---|---|
| CSP project | Type | | PT | PT |
| Climate | Location | | Lat./Long.: 23.57, 57.71 | Lat./Long.: 23.57, 57.71 |
| | Weather File Source | | NSRDB | - |
| | Annual Averages Weather Data | GHI ($kWh/m^2/day$) | 5.89 | - |
| | | DNI ($kWh/m^2/day$) | 4.99 | - |
| | | Average Temperature (°C) | 29.1 | - |
| Solar Field | Solar Field Aperture Area (m²) | | 817,000 | 627,840 |
| | No. of Solar Collector Assemblies (SCAs) | | 768 | 768 |
| | No. of Loops | | 192 | 192 |
| | No. of SCAs per Loop | | 4 | 4 |
| | No. of Modules per SCA | | 12 | 12 |
| | SCA Length (m) | | 150 | 150 |
| Receiver | Receiver Working Fluid | | Therminol VP-1 | Therminol VP-1 |
| | Receiver Inlet Temperature (°C) | | 300 | 300 |
| | Receiver Outlet Temperature (°C) | | 400 | 400 |
| Power Block | Nominal Turbine or Power Cycle Capacity (MW) | | 100 | 100 |
| | Power Cycle | | Steam Rankine | Steam Rankine |
| | Cooling Type | | Dry | Dry |

**TABLE 14.** **Noor III technical data.**

| Specification | Variable | | SAM Simulation | [65] |
|---|---|---|---|---|
| CSP project | Type | | PT | PT |
| Climate | Location | | Lat./Long.: 31.05, -06.86 | Lat./Long.: 31.05, -06.86 |
| | Weather File Source | | NSRDB | - |
| | Annual Averages Weather Data | GHI ($kWh/m^2/day$) | 5.95 | - |
| | | DNI ($kWh/m^2/day$) | 7.34 | - |
| | | Average Temperature (°C) | 17.8 | - |
| Solar Field | Solar Field Aperture Area (m²) | | 1,312,000 | 1,312,000 |
| | No. of Heliostats | | 9339 (Calculated) | - |
| | Heliostat Width | | 12 (Default) | - |
| | Heliostat Hight | | 12 (Default) | - |
| | Ratio of Reflective Area to Profile | | 0.95 (Default) | - |
| | Solar Field Aperture Area (m²) | | 150 | 150 |
| Receiver | Receiver Working Fluid | | Molten salt | Molten salt |
| | Receiver Inlet Temperature (°C) | | 574 (Default) | - |
| | Receiver Outlet Temperature (°C) | | 290 (Default) | - |
| | Tower Hight (m) | | 247 | 247 |
| Power Block | Nominal Turbine or Power Cycle Capacity (MW) | | 150 | 150 |
| | Power Cycle | | Steam Rankine | Steam Rankine |
| | Cooling Type | | Dry | Dry |
| Thermal Storage | Hours of Storage at Design Point (hr) | | 7 | 7 |
| | TES thermal capacity (MWt-hr) | | 2,548.5 (Calculated) | - |
| | Tank height (m) | | 12 (Default) | - |
| | Storage HTF Fluid | | Molten salt | Molten salt |

**TABLE 15.** **Base cases validation results.**

| Metric | Shams-1 | | | NOOR III | | |
|---|---|---|---|---|---|---|
| | [65] | SAM value | Simulation Accuracy (%) | [66] | SAM value | Simulation Accuracy (%) |
| Annual AC Energy Output ($GWh_e$/year) | 210 | 209.34 | 99.68 | 500 | 524 | 95.42 |
| Power cycle gross Energy Output ($GWh_e$/year) | - | 236.63 | - | - | - | - |
| CF (%) | 25 | 26.6 | 93.98 | 45 | 47 | 95.74 |

### *C. SAM SIMULATION RESULTS AND DISCUSSION*

This subsection presents an in-depth analysis of the performance and economic viability of the proposed CSP systems across potential sites. To evaluate the technical feasibility of the systems, two key performance metrics are considered: annual energy production and capacity factor. The economic feasibility of the systems is assessed using the LCOE. The software tool SAM is used to calculate the net electricity generation and capacity factor in the first year of operation while taking into account various optical and parasitic thermal losses.

Figure 15 depicts the net electricity generation of both PT and SPT technologies at the selected sites and their original locations. For PT technology, location 4 exhibits the highest

**TABLE 16. Components share of the total installation cost [67].**

| Component | PT | SPT |
|---|---|---|
| Owner's cost | 8% | 9% |
| Indirect EPC cost | 12% | 15% |
| Thermal storage | 17% | 12% |
| Power block | 18% | 16% |
| Tower | 0% | 2% |
| Receiver | 6% | 18% |
| Solar field | 39% | 28% |

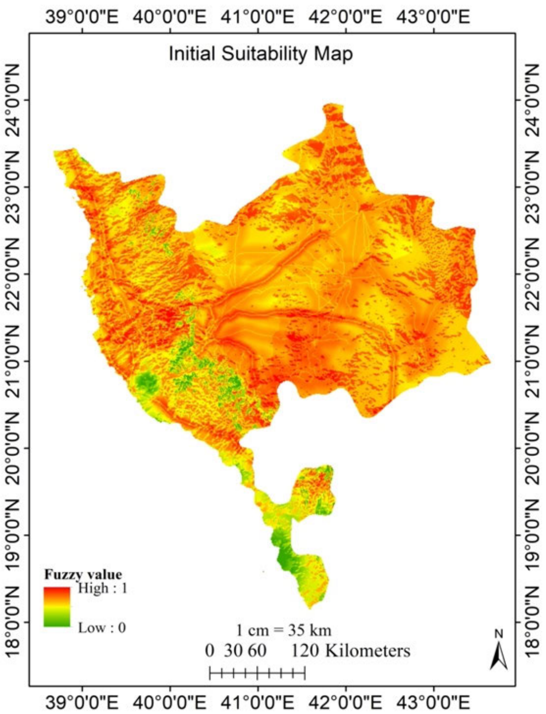



**FIGURE 13. Initial suitability map.**

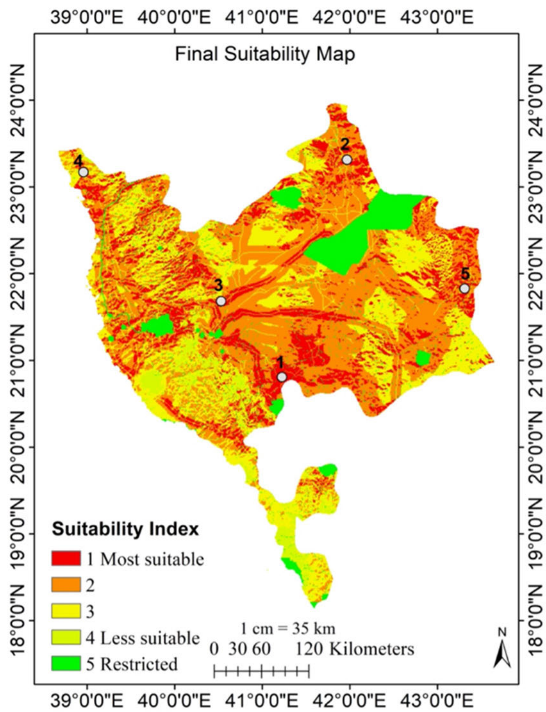


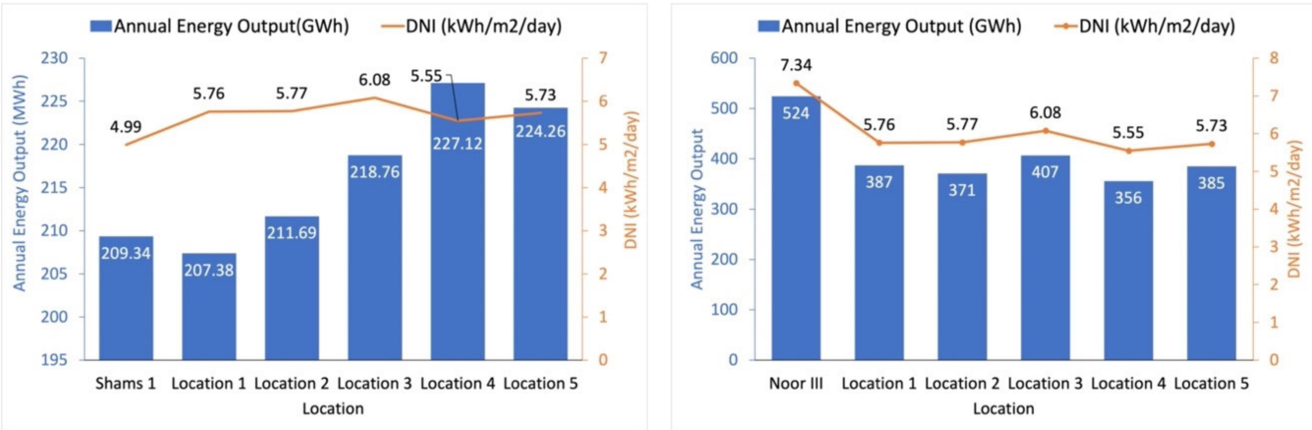

**FIGURE 14. Final suitability map.**

annual electricity output with 227.12 $GWh_e$/year, closely followed by location 5 with 224.26 $GWh_e$/year. Notably, all locations, except location 1, demonstrate higher energy production than the UAE, where the PT technology was originally located. However, it should be noted that higher DNI values do not always translate into greater energy production.

In contrast, there is a linear relationship between the average daily DNI and the annual average electricity output for SPT technology. The original SPT system in Morocco, with an average daily DNI of 7.34 $kWh/m^2$/day, generates 524 $GWh_e$/year. The highest annual electric energy output of SPT systems in Makkah province is achieved by location 3 with 407 $GWh_e$/year, followed by location 1 with 387 $GWh_e$/year. These findings suggest that the selected sites have the potential to significantly improve energy production for both PT and SPT systems, making them economically attractive options for large-scale CSP deployment.

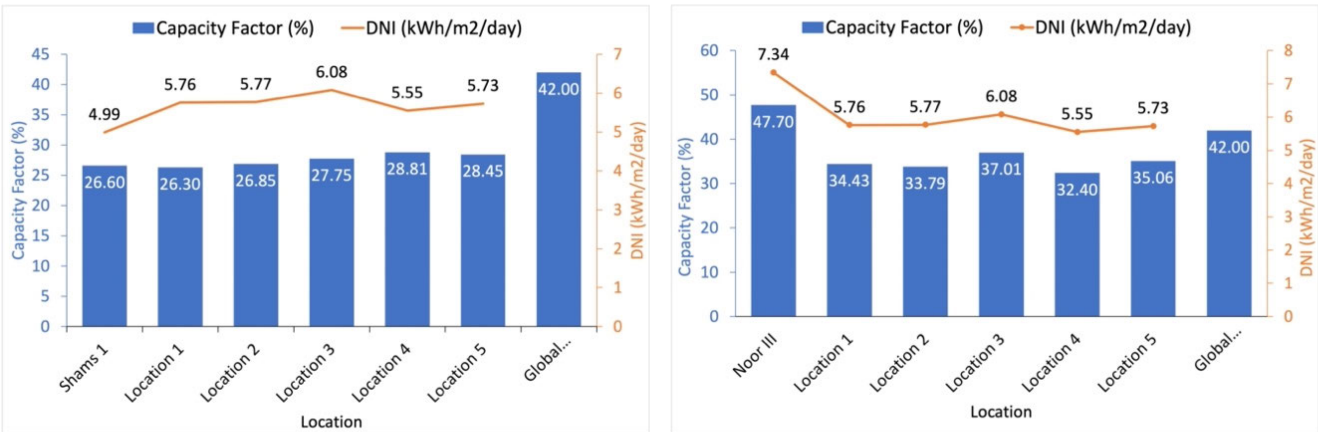
Figure 16 shows the capacity factors for both PT and SPT technologies at the candidate locations in Makkah province. It is observed that all the candidate locations have lower capacity factors than the global average weighted CSP plants commissioned in 2020. In the case of the PT scenario, the capacity factors of the different locations, including the original plant in UAE, achieved convergent and relatively low values. This is primarily due to the absence of TES, which makes CSP plants dispatchable and allows them to generate electricity during the night-time and cloudy days.

The data presented in Fig. 17 shows that the real LCOE values of the Shams-1 and Noor III scenarios at the potential locations are lower than the global weighted average LCOE in 2020. The analysis also reveals that the most competitive LCOE of electricity produced by utility-scale CSP plants in Makkah province is 9.58 ¢/kWh for PT technology at location 4 and 9.17 ¢/kWh for SPT at location 3. These findings indicate that both PT and SPT technologies are economically



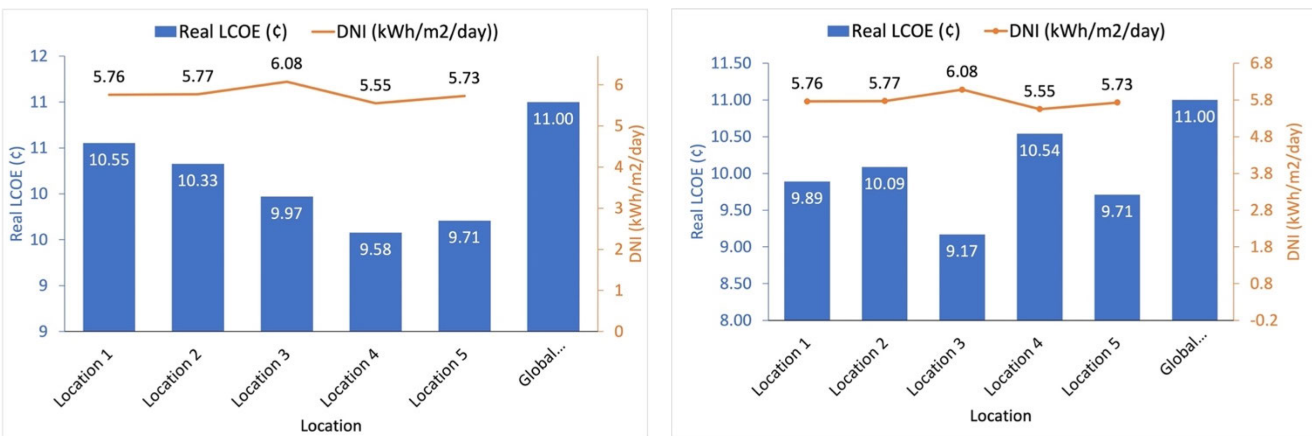

(a) PT technology annual energy output. (b) SPT technology annual energy output.

**FIGURE 15.** Annual energy generation of PT and SPT technologies.




(a) PT capacity factors. (b) SPT capacity factors.

**FIGURE 16.** Capacity factors of PT and SPT technologies.

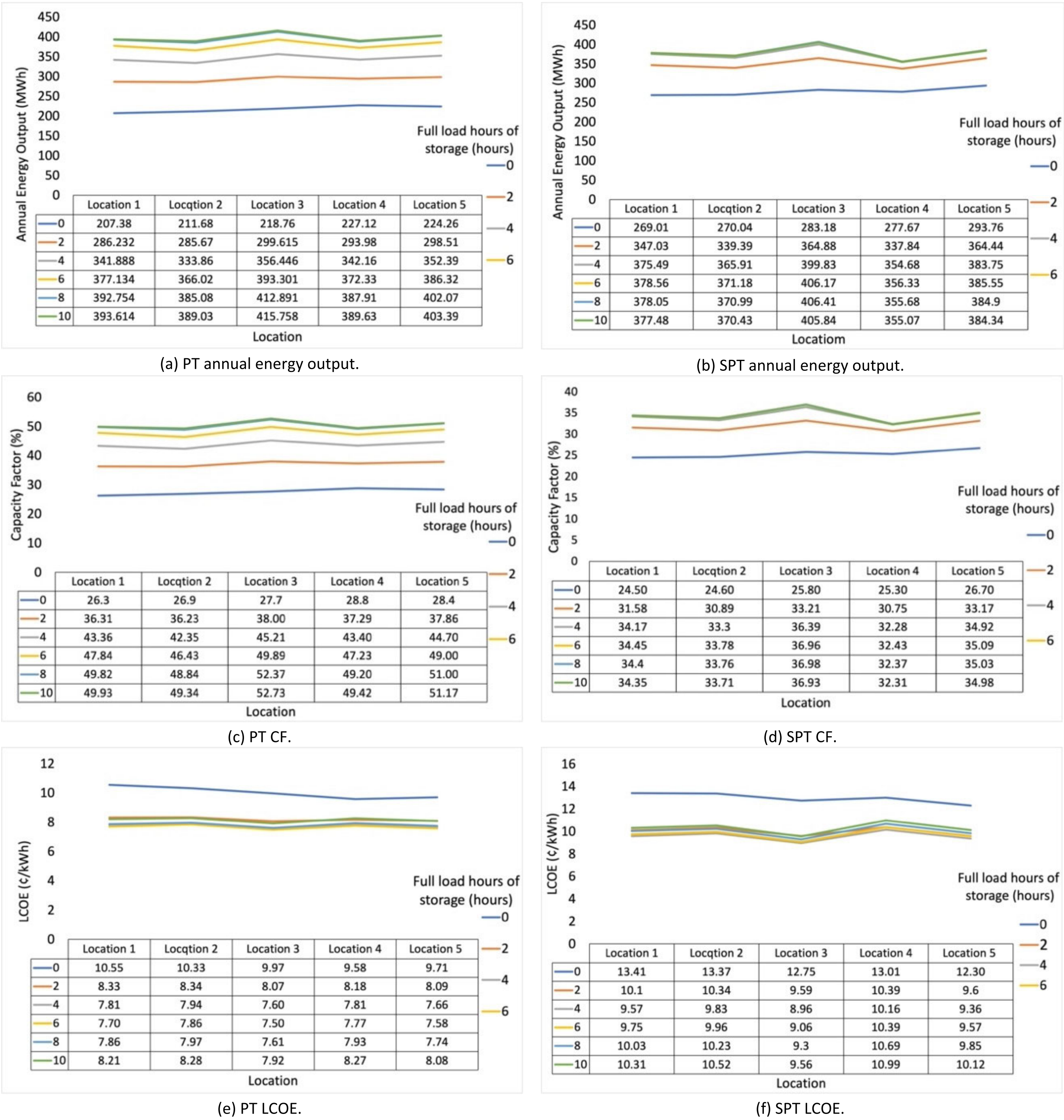



(a) PT levelized costs of energy. (b) SPT levelized costs of energy.

**FIGURE 17.** Real LCOE of PT and SPT technologies.

feasible options for large-scale CSP deployment in the region, with SPT plants generally having lower LCOE than PT.

One of the greatest challenges of electricity generation using RE sources is the availability of electricity when it is




(a) PT annual energy output. (b) SPT annual energy output.
(c) PT CF. (d) SPT CF.
(e) PT LCOE. (f) SPT LCOE.

**FIGURE 18. Sensitivity analysis of the TES capacity.**

needed, which is highly dependent on climatic conditions. This challenge can be addressed by implementing energy storage systems that can store excess energy during times of high production and release it during times of low production or high demand. However, large-scale electrical energy storage systems require further development. Currently, the best solution is to store energy in other forms and convert it to electricity when demanded. In CSP plants, TES can result in higher energy output and a higher capacity factor by storing the heat collected from the sun and allowing the plant to operate when the solar resource is not available [68]. The annual energy delivered by a CSP plant, and the capacity factor are greatly dependent on the capacity of the TES [69]. Therefore, in this analysis, different configurations with varying TES capacities have been evaluated based on three performance indicators: annual energy output, CF, and LCOE.

The sensitivity analysis results are presented in Fig. 18. It was found that the annual energy delivered, CF, and LCOE were optimized as the TES capacity increased up to a certain breakpoint, beyond which further storage capacity was no longer feasible and resulted in an increase in LCOE. For all selected locations and both PT and SPT technologies, a TES capacity greater than eight hours had no significant influence on the performance indicators. The superiority of plants with larger TES capacity is due to their availability throughout the year, except during intended shutdown periods. However, at the breakpoint, the solar multiple was not large enough to fully supply the oversized storage, resulting in higher thermal losses. In other words, the thermal energy collected by the solar field was not always sufficient to run the turbine and meet the nominal capacity of the TES.

## VI. CONCLUSION

The global shift towards adopting Renewable Energy Sources (RES) is increasingly prominent, driven by factors like declining costs of RES technologies, the imperative to address climate change, and supportive government incentives. Saudi Arabia, despite its abundant solar energy resources, heavily relies on fossil fuels for over 99% of its electricity generation. Concentrated Solar Power (CSP) emerges as a promising solar energy technology with substantial potential in the country, offering a means to diversify the energy mix. However, the adoption of CSP in Saudi Arabia encounters challenges, including limited information, cost concerns, technology maturity, grid integration issues, policy and regulatory complexities, and public awareness. This study is strategically positioned to contribute to overcoming these challenges by delving into the potential of CSP technologies to enhance cost-efficiency and performance. Focused on the western region of Saudi Arabia, which represents the largest consumer of electricity in the country, the study unfolds in two phases. Initially, optimal CSP plant locations are identified through a Multicriteria Decision-Making (MCDM) technique in ArcGIS. This phase employs fuzzy-Boolean logic to standardize criteria and utilizes the Analytical Hierarchy Process (AHP) algorithm for weighting. A comprehensive range of climatic, economic, orographic, topographical, legal, and environmental criteria is considered, treating them as evaluative and restrictive factors impacting CSP plant installations. The subsequent analysis, grounded in location characteristics like Direct Normal Irradiance (DNI) influencing plant productivity and proximity to powerlines, roads, and urban areas, pinpoints five locations suitable for adopting a 50 MW Parabolic Trough (PT)-based CSP plant (Shams-1) and the Noor III Solar Power Tower (SPT)-based CSP plant with a 150 MW capacity, originally operated in the UAE and Morocco, respectively. This strategic selection ensures optimal energy yields, efficient power evacuation, and seamless integration into the existing grid. By addressing these critical aspects, the study paves the way for increased understanding and efficient implementation of CSP-based electricity generation in Saudi Arabia's western region, contributing to the broader RES transition and energy sustainability goals.

The nominated locations are:

- Location1 near Turabah city.
- Location2 and Location3 near Taif city.
- Location4 near Rabigh city.
- Location5 near Ranyah city.

The SAM software was then employed to estimate the annual energy production, Levelized Cost of Electricity (LCOE), and Capacity Factor (CF) for both Parabolic Trough (PT) and Solar Power Tower (SPT) technologies installed at the designated locations. The higher Direct Normal Irradiance (DNI) levels in Makkah province, in comparison to the UAE location, led to increased solar irradiation available for PT plants, thereby enhancing their energy production capacity. This performance enhancement is evident in all locations except Location1, which exhibits relatively lower DNI values. Moreover, the exceptional DNI levels characteristic of North African locations, particularly in Morocco, contributed to the superior production of the Noor III plant compared to the modeled SPT plants in Makkah province. The lowest LCOE for Shams-1 and Noor III power plants, modeled in Makkah province, are 9.58 ¢/kWh at Location4 and 9.17 ¢/kWh at Location3, respectively. Subsequently, to analyze the effect of Thermal Energy Storage (TES) volume on performance indicators, analyses were conducted with a 2-hour time step from 0 to 10 hours (0:2:10) of TES capacity. For the selected multiple solar plants, PT power plants with 10-hour TES and SPT power plants with 6-hour TES achieved the optimum annual energy production and CF. Finally, the Shams-1 and Noor III scenarios obtained the most cost-effective energy production when designed with 6-hour and 4-hour TES, respectively.

In conclusion, with an annual average DNI that exceeds 2000 kWh/m$^2$/year and an average daily sunshine duration of 10 hours, the study emphasized that SA has significant potential for CSP. The study has investigated the potential and feasibility of CSP in the western region of SA using a novel and comprehensive approach that combines fuzzy-Boolean logic for criteria standardization and AHP method for criteria weighting. It has made a significant contribution to the literature on CSP in SA. The proposed site selection methodology and techno-economic assessment provide valuable insights into the potential and feasibility of CSP deployment in the country. The findings of this study can help policymakers and developers to make informed decisions about the deployment of CSP plants in SA. The key findings of this study can be described as follows:

- It developed a geographical suitability map for CSP power plants in Makkah province, SA.
- It identified the geographical suitability map for CSP power plants adoption in Makkah province.
- It found that CSP plants with PT technology and 6-hour TES can achieve the lowest LCOE in SA.

- It demonstrated that CSP plants with TES can provide dispatchable and cost-effective electricity.
- It concluded that CSP plants can help SA to reduce its reliance on fossil fuels and achieve its RE goals.

Although the research was directed towards the western region of SA, the methodology can be generalized to the entire country and other parts of the world by considering location's criteria and climatic data. Nonetheless, the study has identified several areas where further research is needed to advance the deployment of CSP technology in SA. These areas include:

1) Hybrid systems: Investigating the potential of hybrid systems comprised of CSP, PV, and wind energy could lead to more cost-effective and reliable RE systems.
2) Techno-economic assessment: Conducting a more detailed techno-economic assessment of CSP plants in SA, considering factors such as local market costs and government incentives, could provide more accurate information about the economic feasibility of CSP technology in the country.
3) Deployment roadmap: Developing a roadmap for the deployment of CSP technology in SA could help policymakers and developers to coordinate their efforts and achieve the country's RE goals.
4) The study was limited to the western region of SA. Future work can generalize the methodology to other regions of the country.

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