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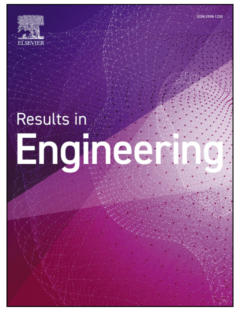


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# Potentials and Opportunities of Solar PV and Wind Energy Sources in Saudi Arabia: Land Suitability, Techno-socio-economic Feasibility, and Future Variability

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**Abstract**

Solar and wind energy sources hold significant potential to meet the escalating energy demand in Saudi Arabia sustainably. This research aims to assess the feasibility and prospects of deploying solar photovoltaic (PV) and wind energy systems in Saudi Arabia (SA). The study adopts a comprehensive approach, encompassing spatial analysis of land suitability, techno-economic feasibility studies, and prediction of renewable energy (RE) resource variability and trends using machine learning techniques. Geographical Information System (GIS) spatial analysis is employed to identify suitable areas for establishing solar PV and wind farms based on multi-criteria evaluation methods. Techno-socioeconomic feasibility analysis of solar PV and wind energy systems, under various configurations and scenarios, is conducted using the System Advisor Model (SAM) tool. Furthermore, a Support Vector Machine (SVM) machine learning algorithm is developed and deployed to forecast Global Horizontal Irradiation (GHI), wind speed, and influential weather parameters at different locations in SA. The projections of these variables derived from global climate models are utilized to analyze prospects and variabilities. The land suitability analysis identified four optimal locations for large-scale solar PV fields in Tabuk, Al Madinah, Makkah, and Riyadh provinces. Additionally, four promising wind farms were found in Al Madinah, Makkah, Riyadh, and Eastern provinces. The analysis also identified one location in Al Jouf province suitable for hybrid systems combining solar PV and wind energy. The techno-economic assessment revealed that wind farms performed best overall, achieving a capacity factor of 42.6% in Al Madinah province. Although current tariffs render projects economically unviable, solar PV, wind energy, and hybrid solar PV-wind technologies are economically feasible in SA at Power Purchase Agreement (PPA) rates above $32.8/MWh, $26.1/MWh, and $50.6/MWh, respectively. The social development analysis estimated potential job creation from solar PV and wind energy deployment under different scenarios from 2020 to 2060, indicating that more ambitious climate targets could translate to millions of renewable energy jobs. The SVM model predicted solar irradiance with an R-squared value of 0.893. The CMIP6 model was then used to project the GHI for SA in 2049, suggesting an increase of approximately 19%. Wind speed is also expected to rise roughly 5% over the same period. The integration of GIS spatial analysis, techno-economic modeling, and machine learning-based forecasting provides comprehensive insights into harnessing solar and wind energy in SA. This study facilitates evidence-based planning and risk assessment, crucial for a sustainable energy transition. The insights and roadmap derived from this research can inform policy frameworks, support the United Nations Sustainable Development Goals (UNSDGs), and attract private investments for RE development in SA. Consequently, this study establishes solar and wind energy as viable and promising solutions for meeting SA's growing energy demands sustainably, while minimizing the associated environmental impact.

*Keywords: Saudi Arabia energy transition; solar and wind energy potentials; solar and wind site suitability analysis; job creation potential; multi-criteria decision-making; techno-economic analysis; global horizontal irradiation forecast*

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## 1. Introduction

Energy plays a pivotal role in propelling the economic growth and social development of any nation [1]. Consequently, the demand for energy has experienced rapid growth across various countries in recent decades, fueled by population expansion, urbanization, and industrialization. In 2020, global power generation demand stood at 8.35 TW, with projections indicating a rise to 13.7 TW by 2050 [2]. The International Energy Agency (IEA) forecasts a nearly 50% increase in global electric energy demand over the next three decades, driven primarily by population and economic growth, particularly in developing Asian nations [3]. This escalating energy demand entails adverse consequences such as environmental pollution and the risk of energy shortages. The combustion of fossil fuels for electricity generation, in particular, significantly contributes to air pollution [4]. Furthermore, the reliance on fossil fuel-derived electricity is unsustainable due to the finite nature of these resources. Hence, there exists a pressing need for environmentally sustainable RE sources, such as solar and wind power, to address these challenges effectively [5,6].

| **Nomenclature** | | | |
|---|---|---|---|
| *Abbreviations* | | Mf | Manufacturing |
| | | NASA | National Aeronautics and Space Administration |
| AHP | Analytical Hierarchy Process | NDCs | Nationally Determined Contributions |
| C&I | Construction and installation | NPV | Net Present Value |
| Capex | capital expenditure | NREP | National Renewable Energy Program |
| CC | Cumulative Capacity | NZ | Net-Zero |
| CF | Capacity Factor | O&M | Operation and Maintenance |
| CMIP6 | Sixth Coupled Model Intercomparison Project | POWER | Prediction Of Worldwide Energy Resources |
| CRs | Consistency Ratios | PPA | Power Purchase Agreement |
| CSP | Concentrating Solar Power | PR | Performance Ratio |
| DC | Decommissioning | PV | Photovoltaic |
| EF | Employment Factor | PVOUT | Solar PV Energy Output |
| EY | Energy Yield | RE | Renewable Energy |
| GHI | Global Horizontal Irradiation | RH | Relative Humidity |
| GIS | Geographical Information System | SA | Saudi Arabia |
| IC | Installed Capacity | SAM | System Advisor Model |
| IRR | Internal Rate of Return | SVM | Support Vector Machine |
| LCOE | Levelized Cost of Energy | SVR | Support Vector Regression |
| MCDM | Multi-Criteria Decision-Making | UNFCCC | United Nations Framework Convention on Climate Change |
| MENA | Middle East and North Africa | UNSDGs | United Nations Sustainable Development Goals |
| MF | Manufacturing Factor | WLC | Weighted Linear Combination |

The adoption of renewable energy (RE) sources has witnessed significant momentum in recent years, driven by the increasing global energy demand and heightened awareness of climate change [7]. Solar power has experienced substantial growth worldwide, particularly in countries situated within the solar belt, such as India and China, over the past two decades. Concentrated solar power (CSP) and photovoltaic (PV) systems have emerged as the primary solar technologies. Solar PV, in particular, has gained prominence due to its capacity to harness both direct normal irradiance and diffuse horizontal irradiance, as well as its relatively lower cost of energy production [8]. Additionally, wind energy has emerged as the second most widely adopted form of RE, accounting for 4% of global electricity generation and contributing 7% to the electricity supply in the United States [9–11]. Solar and wind energies, being clean and abundant, constitute crucial components of the transition to RE sources. With the declining costs of solar and wind energy technologies, they have become increasingly viable options for meeting energy requirements [12,13].

### *1.1. Literature Review*

Saudi Arabia (SA), being the world's largest oil producer and exporter, has traditionally relied on oil and gas for electricity generation due to abundant reserves and a significant role in global oil markets [14]. However, the environmental impacts of fossil fuel usage, such as air pollution, greenhouse gas emissions, and climate change, have prompted the need for a shift to more sustainable energy sources [15]. SA, like many other nations, faces a growing energy demand driven by population growth and industrialization [16]. Recent data indicates a 4.23% increase in available electrical power plant capacity in SA in 2021 compared to 2020, reaching 83.036 GW. Additionally, overall electrical energy production saw a significant 49.39% increase, reaching 358.637 TWh in 2021, up from 240.068 TWh in 2010. The Saudi Electricity Company (SEC) contributed 52.5% of the total generated electric energy in 2021, utilizing various technologies, including steam units, composite cycle units, gas units, diesel units, and RE units, generating 82.911 TWh, 58.571 TWh, 45.268 TWh, 1.579 TWh, and 0.13 TWh of electric energy, respectively. Desalination plants also played a significant role, producing 119.772 TWh, with the remaining energy generated by other plants. In terms of energy consumption, the residential sector accounted for the highest share at 47.25% in 2021, followed by the industrial sector at 19.47%, the commercial sector at 15.09%, the government sector at 12.64%, the agricultural sector at 1.88%, and other sectors at 3.67%. The western region of SA recorded the highest electric energy consumption in 2021, with 93.92 TWh, representing 31.14% of the total consumption. The central region followed closely with 91.47 TWh (30.33%), and the eastern region recorded 83.28 TWh (27.62%). The southern region had the lowest consumption with 32.89 TWh, accounting for 10.91% of the total consumption. These variations in energy consumption across sectors and regions underscore the need for targeted strategies to promote energy efficiency and sustainability in SA [17]. Recognizing the global shift towards RE sources, SA acknowledges the importance of transitioning its energy mix to more sustainable alternatives. In 2015, SA submitted its Intended Nationally Determined Contributions (INDCs) report to the United Nations Framework Convention on Climate Change (UNFCCC) ahead of COP21 in Paris, committing to reducing greenhouse gas (GHG) emissions by 130 Mt of $CO_2$eq annually by 2030 [18]. In the updated 2021 report, SA increased its commitment to reducing GHG emissions by 278 Mt of $CO_2$eq annually by 2030 [19,20]. The report outlines measures such as increasing RE, reducing energy consumption, improving energy efficiency, and promoting the use of natural gas and other clean energy sources. Although specific targets in terms of RE capacities are not provided, the Vision 2030 plan aims for a 50% share of RE in the energy mix by 2030. Initiatives like the National Renewable Energy Program (NREP) target the installation of 27.3 GW of RE capacity by 2024 and 58.7 GW by 2030 [7,15]. The Middle East and North Africa (MENA) countries, with abundant sunshine and strong winds, are strategically positioned for harnessing renewable energy. MENA governments have initiated programs to diversify energy sources, enhance energy security, and promote a cleaner, more sustainable future [21]. SA, with one of the highest solar irradiation potentials globally, presents an ideal location for deploying solar energy technologies, particularly solar PV systems. The country's strategic geographical location at the intersection of three continents offers opportunities for solar energy trade and export [22]. SA also holds substantial wind energy potential, especially along its long coastline and vast deserts. The western region, known for consistently high wind speeds, is attractive for wind farms. SA has set an ambitious target of achieving 9 GW of installed wind power capacity by 2040, projected to constitute around 6.3% of the total installed generation capacity at that time [23]. Notable strides have been made in implementing the RE agenda through projects launched under the NREP in 2018. Examples include the Sakaka PV solar plant and Dumat Al-Jandal wind farm in Al Jouf. The Sakaka solar PV project, with a capacity of 300 MW, is one of the largest solar energy developments in the Middle East, aiming to reduce carbon emissions by approximately 0.74 Mt/year [24]. The Dumat Al-Jandal wind energy project involves a 400 MW onshore wind farm capable of offsetting over 0.98 Mt of $CO_2$eq annually. The King Abdullah City for Atomic and Renewable Energy (K.A.CARE) has also launched initiatives to promote RE development [25]. While the installed capacity of RE sources in SA is modest, these pioneering projects highlight the country's commitment to increasing the share of RE sources in its energy mix. However, further efforts, including research and development, are essential to achieve the ambitious goal of a sustainable energy future in SA [26,27]. RE potential assessment studies play a crucial role in determining the feasibility of RE projects, encompassing geospatial analysis, techno-economic viability evaluation, and socio-environmental impact analysis. Numerous global studies have assessed the potential of solar thermal, solar PV, and wind energy sources, as referenced in [1,8,12,13,28–37]. These studies cover diverse aspects, including geospatial analysis for land suitability and techno-economic feasibility of solar and wind farms. The ArcGIS software platform is widely used for applying Multi-Criteria Decision-Making (MCDM) algorithms to conduct geospatial evaluations and suitability mappings of solar and wind power systems. Techno-socio-economic studies in Table 1 utilized tools such as the System Advisor Model (SAM) and the Hybrid Optimization of Multiple Energy Resources (HOMER) to evaluate the feasibility of solar and wind technologies in SA and the MENA region. This research introduces a novel and comprehensive framework for assessing the feasibility and potential of solar PV and wind energy in SA. It integrates GIS spatial analysis, techno-economic modeling, and machine learning-based resource forecasting to provide valuable insights beyond the current state of knowledge. The study identifies promising locations for solar PV, wind, and hybrid systems, analyzes their techno-economic feasibility, and predicts future resource variability using a robust Support Vector Machine (SVM) model and CMIP6 projections. This integrated approach offers a roadmap for the development of policies and strategies promoting the adoption and integration of solar PV and wind energy technologies in SA. The insights align with the United Nations Sustainable Development Goals (UNSDGs), contributing to targets related to clean and affordable energy, climate action, and sustainable economic growth. By providing a robust analysis of the potential, feasibility, and risks associated with solar and wind energy in SA, this study supports evidence-based decision-making and facilitates the transition towards a more sustainable and renewable energy future in the country. The next section will outline the key steps and methodology undertaken in this research. It will begin by describing the overall goal and objectives of assessing the geographical potential and technical feasibility of solar and wind energy projects in SA. An overview of the analytical framework and integrated approach combining GIS spatial analysis, resource assessment, techno-economic modeling, and machine learning techniques will be provided. Next, Section Three will be devoted to investigating the geographical potential and presenting the results of the and site suitability analysis. This section will discuss the outcome of applying the multi-criteria analysis in GIS to identify optimal locations for solar PV, wind, and hybrid solar-wind power projects across SA. The key factors influencing siting decisions such as solar irradiation levels, wind speeds, land use constraints, and proximity to infrastructure will also be discussed. The following section will provide the findings of the techno-economic analysis conducted using SAM. This will include simulation results for different project configurations and comparison of technical and economic metrics. The sensitivity of project viability to tariff rates will also be examined in this section. Following this, Section Five will conclude the research by summarizing the main insights and providing recommendations for the sustainable deployment of renewable energy in SA.

Table 1. Literature review on solar and wind technologies in MENA region.

| Ref. | Country | Technology | Objectives | Key Findings |
|---|---|---|---|---|
| [38] | Saudi Arabia | Solar PV | To assess the technical and economic feasibility of grid-connected photovoltaic (PV) systems for residential buildings in Saudi Arabia. | • Grid-connected PV systems are a feasible and economic option for residential buildings in Saudi Arabia.<br>• A typical 12.25 kW PV system can generate 87% of the electricity needs of an apartment, with a levelized cost of energy of \$0.0382/kWh. |
| [39] | Saudi Arabia | Hybrid solar PV/wind/battery | To analyze the economic feasibility of wind/battery, PV/battery, and PV/wind/battery systems for off-grid renewable energy projects in Saudi Arabia. | • Solar PV/battery and wind/battery systems are the most economic renewable energy options for Saudi Arabia, with levelized costs of electricity ranging from \$0.07 to \$0.12/kWh.<br>• Optimal mix of renewable energy technologies depends on the location and the specific needs of the load. |
| [40] | Saudi Arabia | Solar PV | To identify the best site for the installation of a 10 MW grid-connected photovoltaic power plant in Saudi Arabia. | • Bisha is the best site for the installation of a 10 MW grid-connected photovoltaic power plant due to its high solar radiation intensity and longer sunshine duration.<br>• The study recommends that the Saudi government provide a 70% grant for the construction of large grid-connected photovoltaic plants. |
| [41] | Saudi Arabia | Solar PV | To determine the optimal size of a grid-connected PV system for a large commercial load in Saudi Arabia. | • The optimal size of a grid-connected PV system for a large commercial load in SA is 1.60 MW, with a levelized cost of energy of \$0.11/kWh.<br>• The use of a battery energy storage system can further reduce the cost of energy. |
| [42] | Saudi Arabia | Wind | To investigate the economic feasibility of developing wind farms in the western province of Saudi Arabia. | • The western province of SA has the potential to develop wind farms with a total capacity of 15 MW.<br>• The cost of generating electricity from wind farms in SA is \$0.0576/kWh. |
| [43] | Saudi Arabia | Wind | To assess the economic feasibility of developing wind farms in the coastal | • The coastal locations of SA have the potential to develop wind farms with a total capacity of 75 MW. |

| | | | | |
|---|---|---|---|---|
| | | | locations of Saudi Arabia. | • The cost of generating electricity from wind farms in SA ranges from \$0.0423 to \$0.0711/kWh. |
| [44] | Saudi Arabia | Solar PV/CSP | To compare the technical and economic feasibility of solar PV and concentrated solar power (CSP) systems for utility-scale solar energy conversion in Saudi Arabia. | • Solar PV and parabolic trough are the preferred solar energy conversion technologies for SA due to their low levelized cost of electricity.<br>• The minimum cost of electricity from solar PV in SA is \$0.06/kWh. |
| [45] | Saudi Arabia | CSP | To investigates the potential and applicability of CSP technology for power generation in the western region of SA | • The analysis showed that 70 % of the province land is suitable for CSP deployment, with Makkah, Taif, Al-Khumra, and Turbah having the most suitable locations.<br>• The lowest LCOE for utility-scale CSP plants in Makkah province is 9.58 ¢/kWh for parabolic trough (PT) technology and 9.17 ¢/kWh for solar power tower (SPT) technology.<br>• CSP plants with 8 hours of thermal energy storage have the optimal configuration that produces electricity with lowest LCOE and highest CF |
| [46] | Egypt | Solar PV | To propose and analyze the economic and technical feasibility of a rooftop PV system for Assuit University in Egypt. | • Rooftop PV systems are a feasible and economic option for Assuit University in Egypt.<br>• Particle swarm optimization is an effective algorithm for sizing rooftop PV systems. |
| [47] | Palestine | Hybrid solar PV/wind/biomass | To design an optimal hybrid renewable energy system for Jenin Governorate in Palestine. | • Renewable hybrid energy system consisting of an 80 MW PV solar field, 66 MW wind farm, and 50 MW biomass system is a feasible and economic option for Jenin Governorate in Palestine.<br>• The proposed system can generate 389 GWh/year of electricity, which is enough to meet 100% of the electrical demand of Jenin Governorate. |
| [48] | Jordan | RE | To evaluate the potential benefits and challenges of renewable energy adoption in Maan, Jordan. | • Renewable energy adoption and implementation can offer feasible energy security solutions and sustainable development on the long-term for Maan, Jordan.<br>• The study developed a framework for high officials to resolve Maan's energy situation |
| [49] | Iraq | Solar collectors | To compare the technical and economic feasibility of evacuated tube solar collectors and flat-plate solar collectors for solar water heating systems in Kirkuk, Iraq. | • Evacuated tube solar collectors are the most cost-effective and energy-efficient option for solar water heating systems in Kirkuk, Iraq.<br>• Domestic solar heating systems can offer substantial energy savings and eliminate the need for an electrical water heater |
| [50] | Palestine | Solar PV/CSP | To assess the solar energy potential of the Gaza Strip and suggest scenarios for achieving energy independence. | • Solar energy has the potential to provide the energy needs of the Gaza Strip.<br>• The study suggested two scenarios for achieving this goal: (1) installing rooftop PV systems on all residential and commercial buildings, and (2) constructing large-scale solar farms in the south of the Gaza Strip. |
| [51] | Libya | Wind | To assess the potential of wind energy in Libya | • Wind energy has great potential in Libya. |

| | | | | |
|---|---|---|---|---|
| | | | applying LCA methodology. | • Gamesa turbine offers the best economic and environmental performance.<br>• GHG emissions range from 32 to 70 GHG/kWh.<br>• Carbon payback durations are between 4.5 and 12.3 months.<br>• Energy payback periods vary from 13 to 22 months.<br>• Life Cycle Levelized Cost of Energy (LCLCOE) ranges from ¢4.8 to 8.4/kWh. |
| [52] | Oman | Solar/wind/tidal | To assess the potential for solar, wind, and tidal energy resources in Oman. | • Both solar and wind energy have significant potential in Oman.<br>• 3.2% of Oman is suitable for wind energy production.<br>• 4.4% of Oman is suitable for solar energy production. |
| [53] | MENA region | RE | To assess the job creation impact of an accelerated uptake of renewable electricity generation. | • The total number of direct energy jobs will increase from 590 thousand in 2015 to 1.7 million by 2050.<br>• Solar PV is the prime job creator, followed by wind power and storage technologies. |

## 2. Methodology

### *2.1. Research context*

SA, with its extensive land area and abundant solar and wind resources, has the potential to emerge as a major player in the RE sector. The country has set ambitious targets for RE deployment, including 40 GW of solar PV, 16 GW of wind power, and 2.7 GW of CSP by 2030 [50], as part of its Vision 2030 initiative. This study aims to provide a comprehensive framework for assessing the potentials of solar PV and wind energy in SA, considering geographical, technical, economic, and environmental factors.

### *2.2. Materials and methods*

The methodology employed in this study, as illustrated in Figure 1, integrates GIS spatial analysis, techno-economic modeling, and machine learning-based projections to evaluate the potential and future variability of solar and wind energy in SA. The methodology is divided into six primary stages:

#### *2.2.1. Stage 1: GIS spatial analysis*

A GIS-based multi-criteria evaluation approach will be utilized to identify suitable areas for the installation of solar and wind farms across SA. Factors such as land use, topography, proximity to existing infrastructure, and environmental constraints will be considered in the analysis. The ArcGIS software will be employed to perform this analysis, and the outcomes will be utilized to generate land suitability maps for solar PV and wind energy resources.

#### *2.2.2. Stage 2: Techno-economic feasibility analysis*

The techno-economic feasibility analysis of solar PV and wind energy systems under various configurations and scenarios will be conducted using the SAM software. This analysis takes into account several factors, including capital costs, operation and maintenance (O&M) costs, energy production potential, grid integration considerations, and tilt angle optimization. By considering these factors, the techno-economic analysis aims to provide insights into the economic viability and practicality of different solar and wind energy system configurations, as well as the potential benefits and challenges associated with their integration into the Saudi Arabian energy landscape.

*2.2.3. Stage 3: Social development*

A holistic picture of the potential benefits of solar and wind energy deployment in Saudi Arabia, encompassing social and economic development, will be studied by estimating job creation opportunities across multiple scenarios. The analysis will integrate relevant data on job creation potential within the solar and wind energy value chains, including manufacturing, construction, operations and maintenance, as well as decommissioning. Sources of data will include industry reports on employment in renewable energy projects, inputs and outputs from economic models simulating energy transitions, and case studies of solar and wind deployment programs and their measured social impacts in other countries with similar economic and resource conditions as Saudi Arabia. It is expected that quantifying employment across the renewable energy sectors can provide useful insights into how scaling up clean energy production can help SA diversify its economy and work towards its long-term vision of social and economic reform, in addition to environmental goals.

*2.2.4. Stage 4: Machine learning-based forecasting*

An SVM (Support Vector Machine) machine learning algorithm has been developed specifically for predicting solar irradiance, wind speed, and their correlation with other weather parameters in SA. This forecasting model considers historical climate data and satellite-derived solar and wind resource data. To ensure accuracy and reliability, the data used in the model is validated against ground-based measurements. This validation process helps to verify the accuracy of the predictions and ensures that the model can provide reliable forecasts for solar irradiance and wind speed in SA. By leveraging machine learning techniques and incorporating validated data, this forecasting model enhances our understanding of solar and wind energy resources in the region and enables more accurate planning and decision-making for RE projects.

*2.2.5. Stage 5: Prospects and variability analysis*

Projections of solar irradiance, wind speed, and climate parameters that are highly correlated with solar and wind resources are obtained from the Sixth Coupled Model Intercomparison Project (CMIP6) global climate models. These projections are then utilized to analyze the prospects and variability of solar and wind resources in SA. The analysis aims to identify potential risks and uncertainties associated with future RE deployment in the country. By examining the climate model projections, this analysis can provide insights into the potential changes and variations in solar and wind resources in SA over time. Understanding these variations and associated uncertainties is crucial for effective planning, risk assessment, and decision-making in the context of RE projects. It allows stakeholders to anticipate and mitigate potential challenges and adapt their strategies accordingly to ensure the successful and sustainable deployment of solar and wind energy in SA.

*2.2.6. Stage 6: Integration and policy implications*

The results obtained from the GIS spatial analysis, techno-economic feasibility analysis, and machine learning-based forecasting are integrated to offer comprehensive insights into the potential of solar and wind energy in SA. This integrated framework provides valuable information for evidence-based planning and risk assessment, which are crucial elements of a sustainable energy transition. By considering factors such as land suitability, economic viability, and future variability of RE sources, the study helps policymakers, energy planners, and stakeholders make informed decisions regarding the deployment of solar and wind energy in the country.

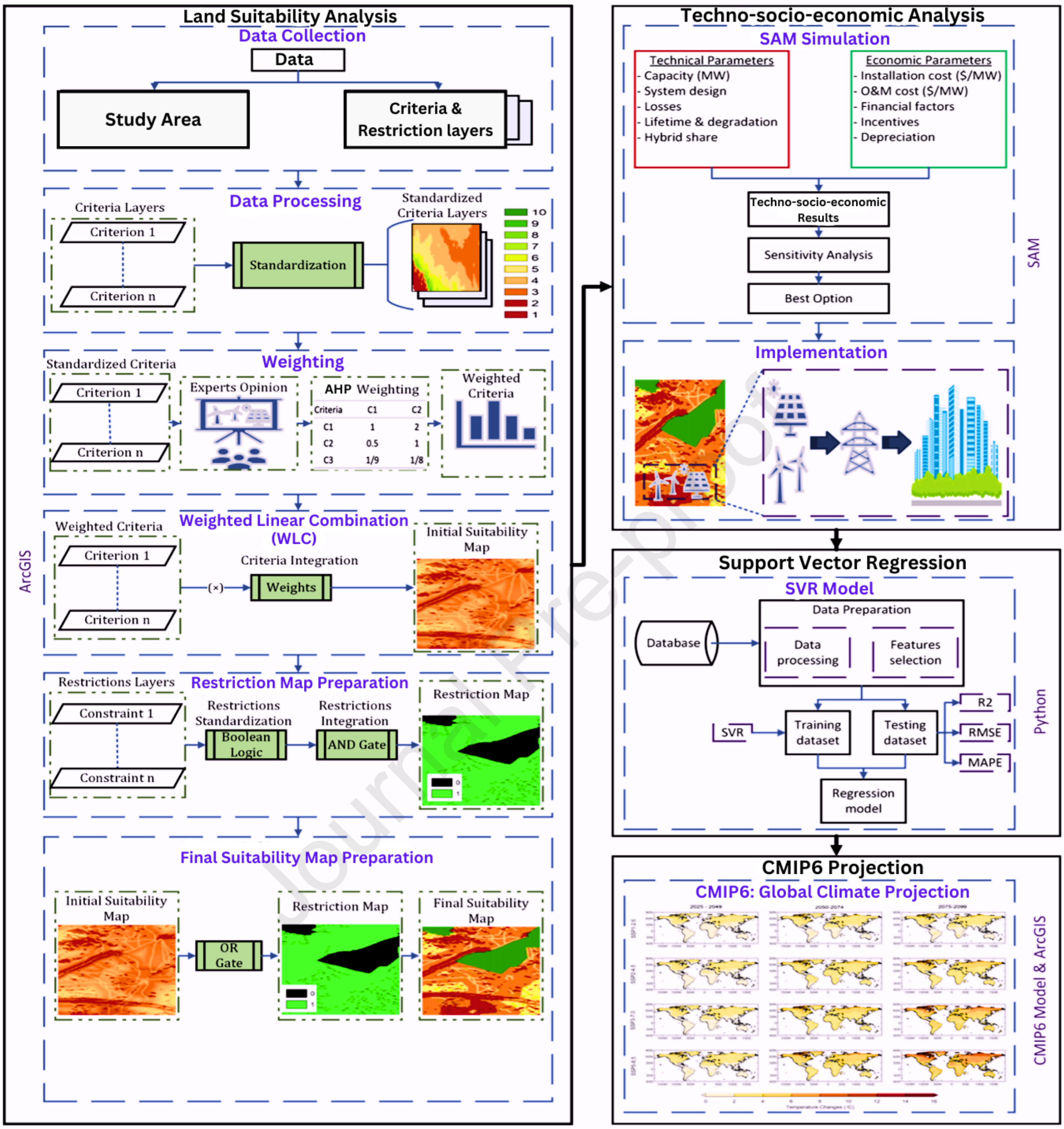



Figure 1. Framework of the proposed methodology.

*2.3. Assumptions, limitations, and uncertainties*

In assessing the potential and deployment of renewable energy (RE), certain assumptions are necessary to accurately simulate system performance over time. While we aim to reflect realistic on-site conditions, inherent uncertainties remain due to the complexity of the technologies and systems being evaluated, as well as future uncertainties. The following key assumptions, limitations, and uncertainties were considered as part of our feasibility analysis methodology:

*2.3.1. Assumptions*

- The identified suitable land is assumed to remain available and free from future restrictions.
- Constant climate conditions are assumed for the 25-year analysis period, without significant long-term variations.
- Base-case plant specifications represent actual performance, but specific details are proprietary.
- Performance is based on a single representative year, not accounting for inter-annual variations.
- Uninterrupted operation with predicted financial outputs is assumed for the entire 25 years.
- The future climate predictions are based on models, which are inherently uncertain. The actual climate may be different from what is predicted.
- Grid infrastructure is assumed to be sufficient at selected locations without additional upgrades.

*2.3.2. Limitations*

- This study focuses on evaluating the potential of two existing RE projects—Sakaka solar PV and Dumat Al Jandal wind—at nominated sites in SA.
- The study does not consider the social and environmental impacts of RE development. This is an important topic that should be addressed in future research.
- The technical parameters of the models are identical to the base cases, except for climatic data specific to the nominated Saudi locations. This approach ensures consistency while incorporating the unique environmental conditions of each potential project site.
- The financial data used in the analysis is limited to reported costs, as opposed to actual costs from the Saudi market.
- The study is limited to the Saudi Arabian context. Although the results may not be directly applicable to other contexts, the underlying approach offers valuable insights for broader analysis.
- The future climate predictions are based on models, which are inherently uncertain. The actual climate may be different from what is predicted.

*2.3.3. Uncertainties*

- The future demand for electricity in SA is shrouded in uncertainty, leading to fluctuating electricity tariffs. This volatility directly impacts the economic feasibility of RE projects.
- The future costs of fossil fuels remain unknown, creating uncertainty around the price at which RE can compete in the energy market.
- The future of RE development in SA is subject to potential changes in policies and regulations, influencing the attractiveness of investing in RE projects.

## 3. Geographical Potential and Site Suitability Analysis

Site suitability analysis plays a crucial role in identifying optimal locations for RE systems. One of the main challenges in this process is determining the most appropriate criteria that significantly impact the performance of these systems. Table 2 provides an overview of various studies that have conducted site suitability analysis for solar PV and wind projects using GIS-based methods. The literature review shows that common criteria used in solar site suitability analyses include solar irradiance, land use/land cover, slope, aspect, proximity to roads and transmission lines. For wind projects, criteria such as annual mean wind speed, land use, distance to roads and transmission lines are typically considered. By examining these previous studies, appropriate resources, orographic, socio-economic, and environmental criteria can be identified to effectively inform the siting of utility-scale solar PV and wind projects in SA. However, twelve criteria were selected from existing literature. These criteria were further confirmed for their relevance through expert interviews. The selected criteria were then categorized into climatic, orographic, economic, and environmental factors.

The process of site suitability analysis is illustrated in Figure 2, where the Analytical Hierarchical Process (AHP) algorithm is applied to assign weights to the standardized criteria. This algorithm helps in determining the relative importance of each criterion in the site suitability analysis. By employing this method, the analysis ensures a systematic and objective approach to prioritize the criteria and evaluate potential locations for solar and wind energy projects.

Table 2. Literature review on GIS-based optimum solar and wind farms site selection.

| Ref. | Optimization | Method | Criteria | Unit | Preference | Weight (%) |
|---|---|---|---|---|---|---|
| [8] | PV | Fuzzy-AHP | GHI | kWh/m$^2$/day | Max | 19.28 |
| | | | Average temperature | °C | Min | 15.06 |
| | | | Precipitation | mm/day | Min | 1.9 |
| | | | Air pressure | kPa | Max | 9.76 |
| | | | Surface Albedo | Dimensionless | Max | 8.31 |
| | | | Relative humidity (RH) | % | Min | 1.9 |
| | | | Slope | ° | <5 | 13.77 |
| | | | Aspect | - | South | 10.96 |
| | | | Distance from transmission grids | km | <10 | 10.96 |
| | | | Distance from power lines | km | <20 | 2.71 |
| | | | Distance from highways | km | <60 | 2.71 |
| | | | Distance from major cities | km | <50 | 2.71 |
| [28] | PV/Wind | AHP | GHI | kWh/m$^2$/day | >5 | 35.78 |
| | | | Slope | % | 0–1 | 5.32 |
| | | | Elevation | m | 0–50 | 0.76 |
| | | | Land use | - | Barren grassland | 11.63 |
| | | | Distance to urban area | km | >1.5 | 2.01 |
| | | | Distance to rural area | km | >1.5 | 1 |
| | | | Distance to wetland | km | >1 | 4.23 |
| | | | Distance to forest | km | >1.5 | 0.6 |
| | | | Distance to airports | km | >2 | 4.23 |
| | | | Proximity to main roads | km | 0.5-2 | 2.86 |
| | | | Proximity to transmission line | km | 0–2 | 8.59 |
| | | | Farm required area | m$^2$ | >1.5 | 22.93 |
| [13] | PV | AHP | Energy output | kWh/kWp | 1810–1850 | 22.5 |
| | | | Slope | ° | 0–2 | 5.3 |
| | | | Aspect | - | South | 4.8 |
| | | | Proximity to electrical gris | m | 0–400 | 8.8 |
| | | | Proximity to roads | m | 50–500 | 1.2 |
| | | | Total suitable areas | km$^2$ | >4 | 5 |
| | | | Number of faults | - | 0–5 | 1.1 |
| | | | Proximity to built-up areas | m | 100-1000 | 5.2 |
| | | | Proximity to protected areas | m | >2000 | 2.6 |
| | | | Power reserve-feeder | MW | 12–14.4 | 12.5 |
| | | | Power reserve-substation | MW | >140 | 17 |
| | | | Distance from substations | km | 0–7 | 8.7 |
| | | | DER number | - | 0 | 2.3 |
| | | | Feeder installed power | kVa | >40000 | 3 |
| [1] | PV | AHP | Aspect | ° | 220 | 11.9 |
| | | | Slope | ° | 0–2 | 3.15 |
| | | | Land use/cover | - | ID: 332, 333 | 7.5 |
| | | | GHI | kWh/m$^2$/year | 1775–1886 | 37.44 |
| | | | Precipitation | mm | 43-–550 | 7.99 |
| | | | Temperature | °C | 9.7–10.7 | 14.43 |
| | | | Humidity | % | 53–55 | 7.53 |
| | | | Distance from settlements | km | 0.5–2 | 1.71 |
| | | | Distance from roads | km | 0.1–2 | 1.47 |
| | | | Distance from railways | km | 0.1–2 | 0.5 |
| | | | Distance from lakes and dams | km | 0.1–4 | 0.6 |
| | | | Distance from fault lines | km | >10 | 1.02 |
| | | | Distance from rivers | km | 0.1-4 | 0.6 |
| | | | Distance from power lines | km | 0–1 | 4.17 |
| [29] | PV | Fuzzy logic | GHI | kWh/m$^2$/year | Max | 39.17 |
| | | Boolean logic | Sunshine duration | h/day | Max | 11.45 |
| | | AHP | Temperature | °C | Min | 8.7 |
| | | | RH | % | Min | 3.47 |
| | | | Wind speed | m/s | Max | 2.62 |
| | | | Distance to power lines | m | 150 | 3.81 |
| | | | Distance to roads | m | 500 | 1.45 |
| | | | Distance to substations | m | 150 | 7.71 |
| | | | Distance to urban areas | km | 2 | 0.93 |
| | | | Distance to rural areas | m | 500 | 0.7 |
| | | | Slope | % | 2 | 3.23 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Aspect | - | - | 1.87 |
| | | | Elevation | km | 1 | 0.7 |
| | | | Land use | - | - | 14.2 |
| **[30][30]** | PV/CSP | AHP | Solar irradiance | kWh/m²/year | 1678–1721 | 34.7 |
| | | | Average temperature | °C | 10.7–11.8 | 11.5 |
| | | | Slope | % | <0.3 | 17.8 |
| | | | Proximity to river | km | <0.6 | 8.6 |
| | | | Proximity to road and railway networks | km | <1.26 | 8.1 |
| | | | Proximity to power lines | km | <3.0 | 14.8 |
| | | | Proximity to load demand | km | <0.36 | 4.5 |
| [31] | PV | AHP | Solar radiation | kWh/m²/year | >2100 | 27 |
| | | | Annual average temperature | °C | 24–25 | 14.9 |
| | | | Distance from transmission lines | km | 0–5 | 10.8 |
| | | | Distance from urban | km | 3–10 | 10.1 |
| | | | Average annual cloudy days | - | 12–30 | 10.4 |
| | | | Elevation | m | 0–200 | 5.1 |
| | | | Slope | % | 1–2 | 6.5 |
| | | | Soil texture | - | <1 | 3.5 |
| | | | Distance from major roads | km | 0–5 | 4.4 |
| | | | Lighting strike flash rate | fl/km²/year | 0.625–2.5 | 7.3 |
| [32] | PV | AHP | Solar energy potential | kWh/m²/year | >4875 | 22 |
| | | | Aspect | ° | South | 14 |
| | | | Roads | km | 0.1–2 | 6 |
| | | | Residential areas | km | 0–0.5 | 7 |
| | | | Energy transmission lines | km | 0–5 | 10 |
| | | | Fault lines | km | >20 | 3 |
| | | | Lakes and dams | km | 0.1–4 | 5 |
| | | | Transformer centers | km | 0–10 | 10 |
| | | | Natural gas lines | km | >2 | 3 |
| | | | Land cover | - | Grassland | 20 |
| [33] | PV/CSP | AHP | Solar irradiance | kWh/m²/day | 5.70–6.30 | 32.68 |
| | | | Average temperature | °C | <23 | 22.73 |
| | | | Land cover | - | 200,150 | 7.34 |
| | | | Slope | % | 0–0.5 | 15.69 |
| | | | Aspect | - | South | 10.77 |
| | | | Proximity to cities | km | <5 | 2.42 |
| | | | Proximity to roads | km | <1 | 3.40 |
| | | | Proximity to power lines | km | <2 | 4.98 |
| [12] | PV/CSP | AHP | GHI | kWh/m²/year | >2100 | 34.8 |
| | | | Temperature | °C | <20 | 5.3 |
| | | | Slope | % | 0–2 | 18.1 |
| | | | Land use | - | Bare land | 12.3 |
| | | | Aspect | - | South | 4.7 |
| | | | Distance to transport links | km | 0.5–1 | 12.4 |
| | | | Distance to grid network | km | 0.3–1 | 9.4 |
| | | | Distance to urban areas | km | 2–5 | 3.0 |

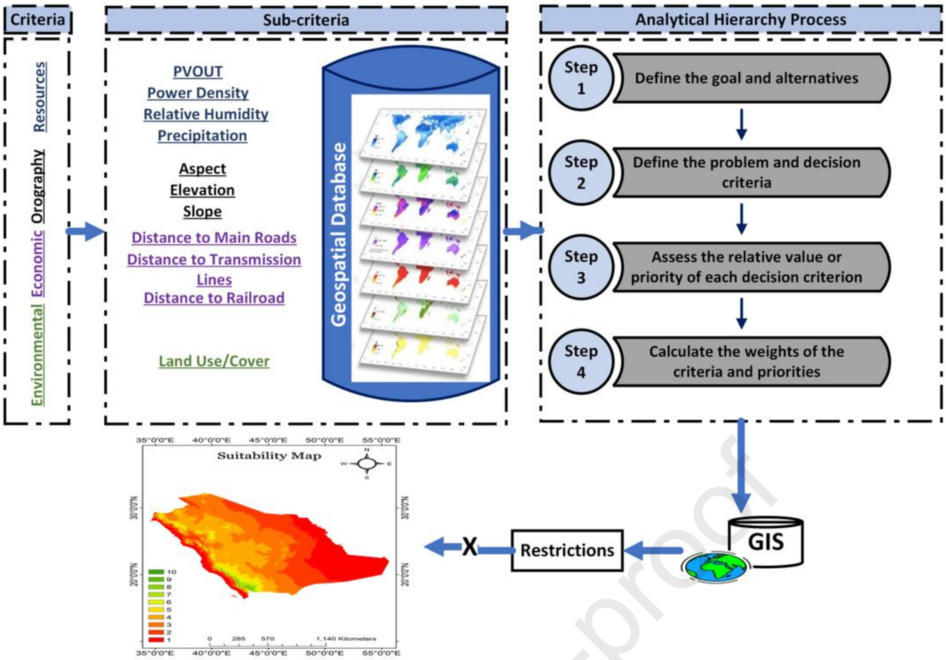



Figure 2. Site suitability analysis framework.

*3.1. Study area*

SA (Figure 3) is a vast and diverse country, encompassing an area of approximately 2.15 million km$^2$, with a population exceeding 34.2 million people. The country exhibits a wide range of climates, ranging from arid desert regions in the north and south to more temperate coastal areas in the west and east [8,54]. SA benefits from an average annual solar radiation of 6.5 kWh/m$^2$/day, which is among the highest in the world [55]. Moreover, the country possesses significant wind energy potential, with average wind speeds ranging from 0.3 to 14.9 m/s at a height of 100 m above ground level [56]. These favorable conditions position SA as an attractive and promising location for the development of solar and wind energy projects.

*3.2. Evaluation criteria*

The site suitability analysis for RE development incorporates a range of evaluation criteria to identify the most promising locations for RE projects. In this study, the criteria are classified into four main categories: climatic factors, location attributes, orographic features, and environmental considerations, comprising a total of thirteen sub-criteria. The climatic factors encompass potential solar PV energy output (PVOUT), wind power density, average temperature, RH, precipitation, and surface albedo. Location attributes include the proximity to transmission lines, main roads, and railroads to ensure accessibility and integration with existing infrastructure. Orographic features, such as aspect, elevation, and slope, account for the terrain's influence on energy production. Lastly, environmental considerations involve land cover and land use, ensuring compatibility with the surrounding environment. Table 3 provides a summary of the evaluation criteria considered in this study, along with their corresponding references. The criteria were carefully selected based on their relevance and importance to the evaluation process. While most criteria were derived from previous studies in the literature, PVOUT and wind power density were introduced in this study to directly relate to the energy production of solar PV and wind systems, respectively. The inclusion of PVOUT and wind power density allows for a more accurate assessment of solar PV and wind energy resources. It is worth noting that detailed explanations and definitions of the selected criteria, excluding PVOUT and wind power density, can be found in the references listed in Table 3. The incorporation of these criteria in the site suitability analysis enhances the assessment of solar and wind energy resources, facilitating informed decision-making for RE projects.

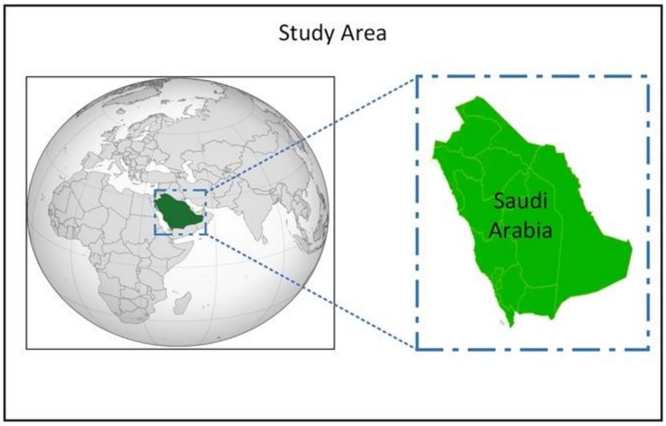


Figure 3. The study area.

*3.3. Criteria layers preparation*

ArcGIS-based site suitability analysis plays a critical role in determining optimal locations for the installation of RE power plants, enabling the efficient allocation of generation units. One essential step in this process is the preparation of criteria layers that are used to evaluate potential sites based on a variety of factors. To create these layers, data from various sources such as satellite imagery, topographic maps, and land-use databases are collected and processed. Additionally, it is crucial to standardize the evaluation criteria to ensure consistency and reliability in the analysis. This involves unifying measurement values and scales across the criteria layers. In this study, the reclassification tool available in the ArcGIS toolbox was employed to standardize the criteria layers to a common scale ranging from one to ten. In this scale, a value of one represents the lowest priority or suitability, while a value of ten represents the highest priority or suitability. Table 4 provides an overview of the geospatial datasets used in this study and their corresponding source databases. These datasets include information on factors such as solar potential, wind potential, topography, land use, and infrastructure. Figure 4 and Figure 5 visually illustrate the criteria layers and the standardized criteria, respectively, showing how the data is processed and transformed into a unified scale for site suitability analysis. By collecting and processing data from various sources and standardizing the evaluation criteria, the ArcGIS-based analysis enables a comprehensive assessment of potential sites for RE power plants. This approach facilitates informed decision-making and helps optimize the allocation of generation units based on site suitability and suitability priorities.

*3.4. Criteria weighting*

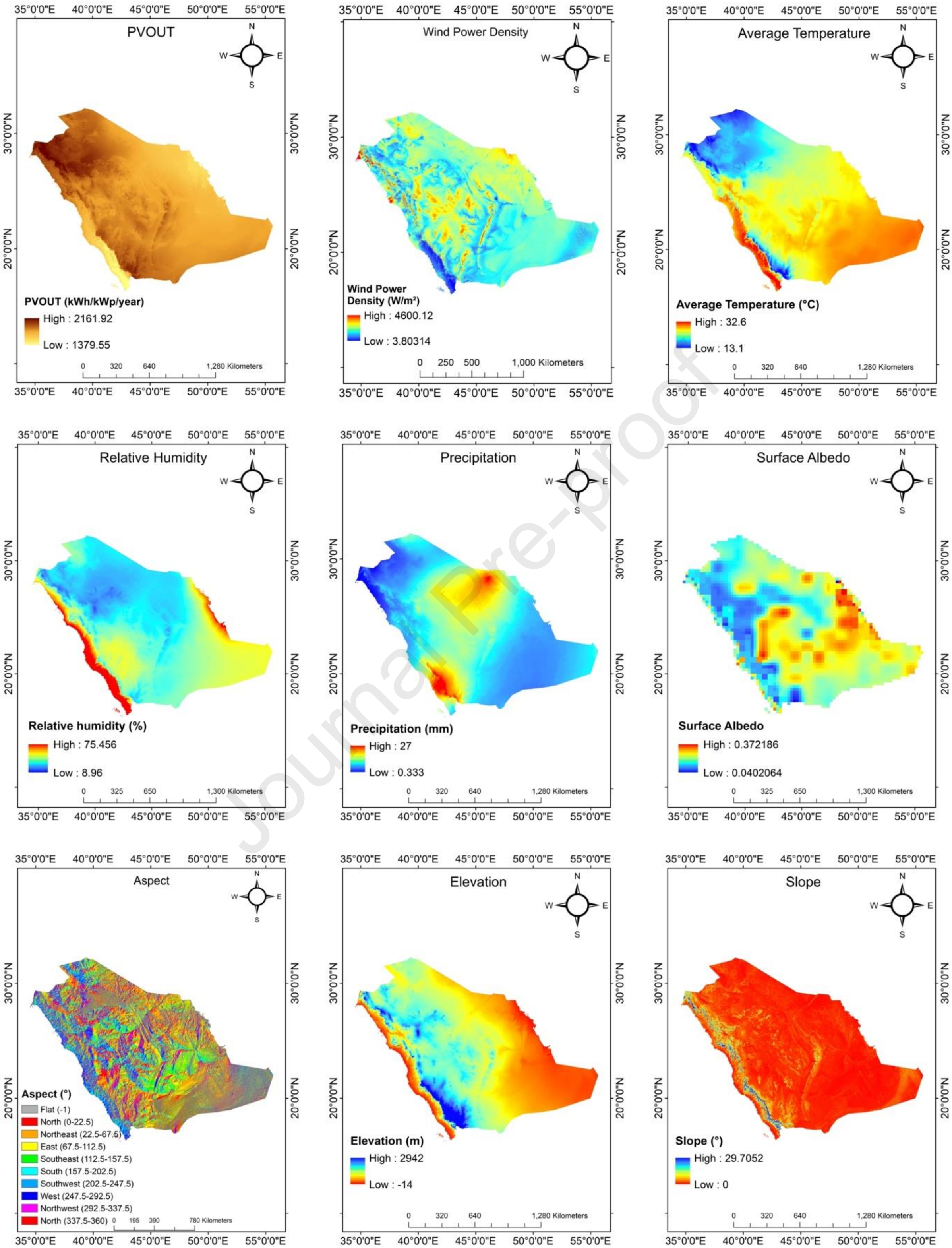
Criteria weighting is a crucial step in site suitability analysis for RE projects, ensuring that the site selection process is comprehensive and systematic. This step involves determining the relative importance of each criterion based on the project's objectives and assigning appropriate weights accordingly. The weighting procedure is subjective and relies on the expertise of domain experts, technical requirements, and project goals. Various MCDM methods can be employed to assign weights to the criteria, such as the AHP and Best-Worst Method. In this study, the AHP technique was utilized due to its capability to handle complex decision-making problems with multiple criteria. The AHP provides a structured approach to decision-making by breaking down the problem into a hierarchy of criteria and sub-criteria and then evaluating them pairwise to determine their relative importance. Once the weights are determined, they are applied to the corresponding criteria layers in the ArcGIS analysis. This allows for the aggregation of multiple criteria into a composite suitability map, which provides a holistic representation of the overall suitability of different sites for RE projects. By incorporating criteria weighting into the site suitability analysis, the study ensures that the selection process considers the relative importance of each criterion, providing a more robust and informed basis for decision-making.

Table 3. Considered evaluation criteria for solar PV and wind energy deployment in SA.

| Criteria | Sub-criteria | Reference |
|---|---|---|
| Climatic | PVOUT | - |
| | Wind power density | [33] |
| | Average temperature | [12,13,29,33,35,57–61] |
| | RH | [1,61–69][1,59–67] |
| | Precipitation | [1,8,59,61,62,66,70–72] |
| | Surface Albedo | [8] |
| Orography | Aspect | [1,13,32,35,70,73–77] |
| | Elevation | [8,13,28,29,59,61,63,68,76,78,79] |
| | Slope | [1,8,12,13,28–31,59,66] |
| Location | Distance to transmission lines | [8,12,28–31,59,61,66,80] |
| | Distance to main roads | [8,13,29–31,66,81–84] |
| | Distance to railroad | [1,8,12,30,59,66,75,81,83,85] |
| Environmental | Land use/cover | [13,29,31,66,82,83,86–88] |

Table 4. Criteria datasets and corresponding databases.

| Dataset | Database | Reference |
|---|---|---|
| PVOUT | Global Solar Atlas | [89] |
| Wind power density | Global Wind Atlas | [90] |
| Average temperature | POWER Data Access Viewer | [91] |
| RH | POWER Data Access Viewer | [91] |
| Precipitation | POWER Data Access Viewer | [91] |
| Surface Albedo | POWER Data Access Viewer | [91] |
| Aspect | POWER Data Access Viewer | [91] |
| Elevation | POWER Data Access Viewer | [91] |
| Slope | POWER Data Access Viewer | [91] |
| Powerlines | NEXT-GIS | [92] |
| Main roads | DIVA-GIS | [93] |
| Railroad | DIVA-GIS | [93] |
| Land use | DIVA-GIS | [93] |


PVOUT
PVOUT (kWh/kWp/year)
High : 2161.92
Low : 1379.55
Wind Power Density
Wind Power Density (W/m²)
High : 4600.12
Low : 3.80314
Average Temperature
Average Temperature (°C)
High : 32.6
Low : 13.1
Relative Humidity
Relative humidity (%)
High : 75.456
Low : 8.96
Precipitation
Precipitation (mm)
High : 27
Low : 0.333
Surface Albedo
Surface Albedo
High : 0.372186
Low : 0.0402064
Aspect
Aspect (°)
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)
Elevation
Elevation (m)
High : 2942
Low : -14
Slope
Slope (°)
High : 29.7052
Low : 0
N
S
E
W
35°0'0"E
40°0'0"E
45°0'0"E
50°0'0"E
55°0'0"E
20°0'0"N
30°0'0"N
0 320 640 1,280 Kilometers
0 250 500 1,000 Kilometers
0 325 650 1,300 Kilometers
0 195 390 780 Kilometers

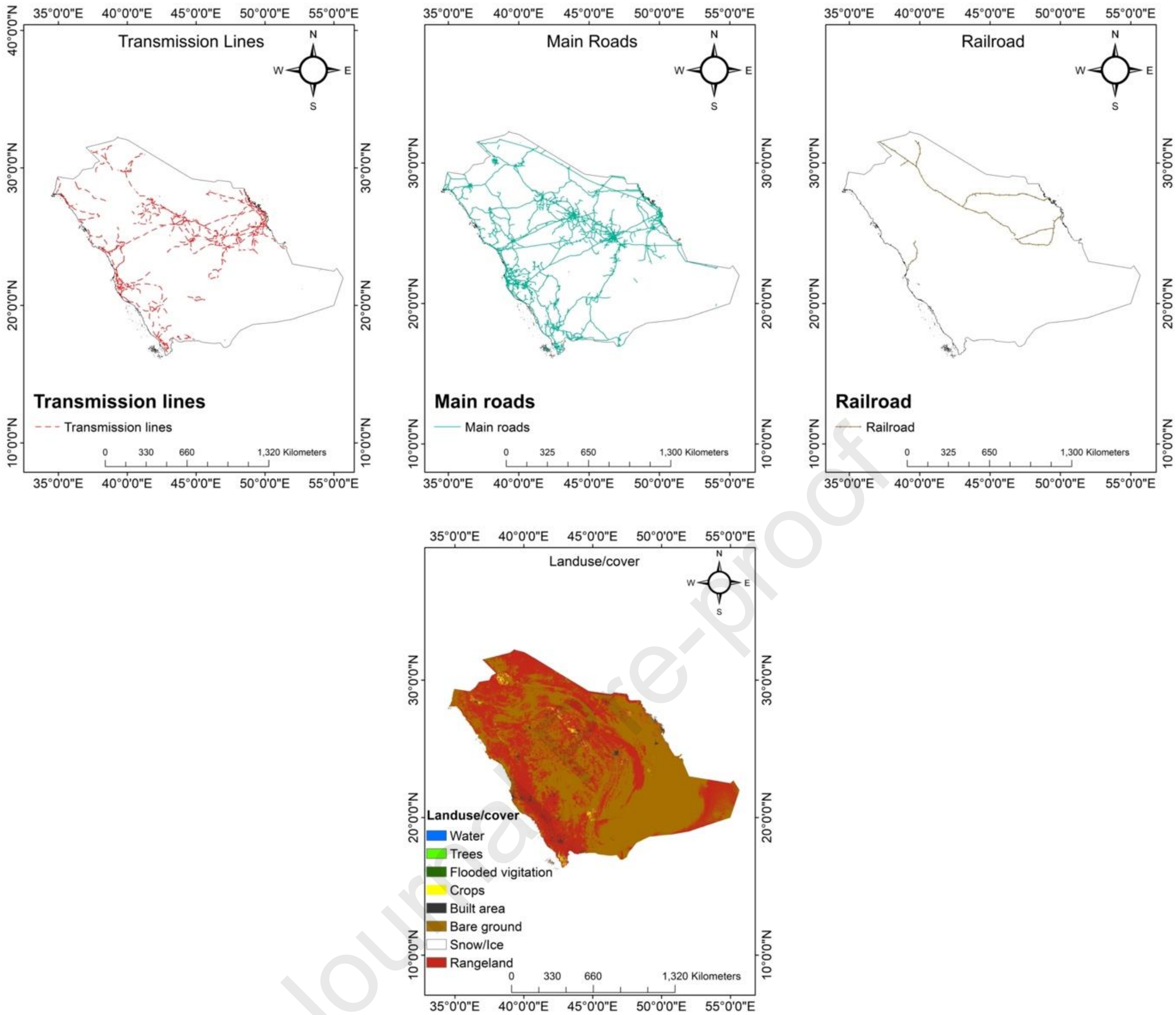
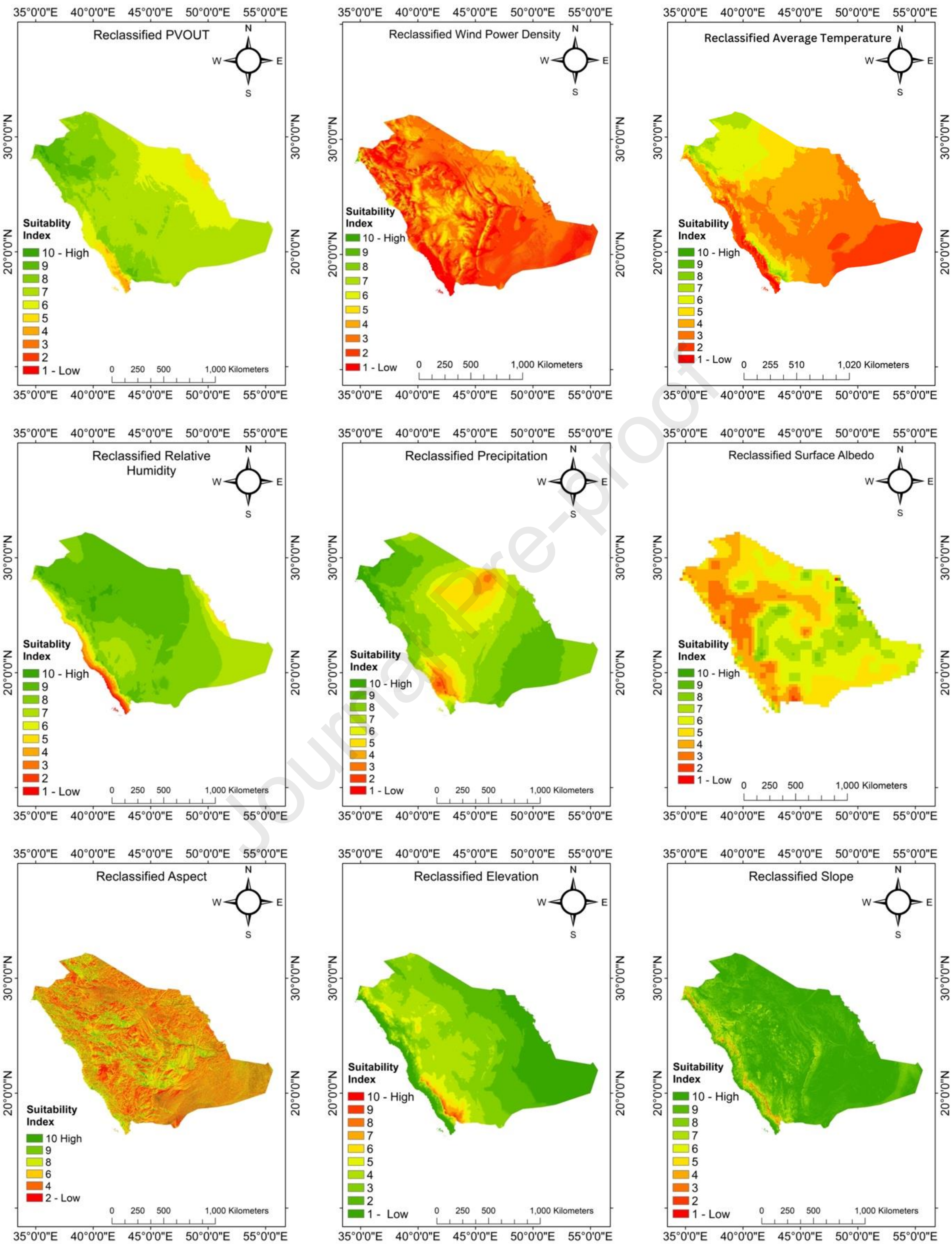



Figure 4. Study criteria.



Reclassified PVOUT
Reclassified Wind Power Density
Reclassified Average Temperature
Reclassified Relative Humidity
Reclassified Precipitation
Reclassified Surface Albedo
Reclassified Aspect
Reclassified Elevation
Reclassified Slope
Suitablity Index
Suitability Index
10 - High
9
8
7
6
5
4
3
2
1 - Low
10 High
2 - Low
N
S
W
E
35°0'0"E
40°0'0"E
45°0'0"E
50°0'0"E
55°0'0"E
30°0'0"N
20°0'0"N
0 250 500 1,000 Kilometers
0 255 510 1,020 Kilometers

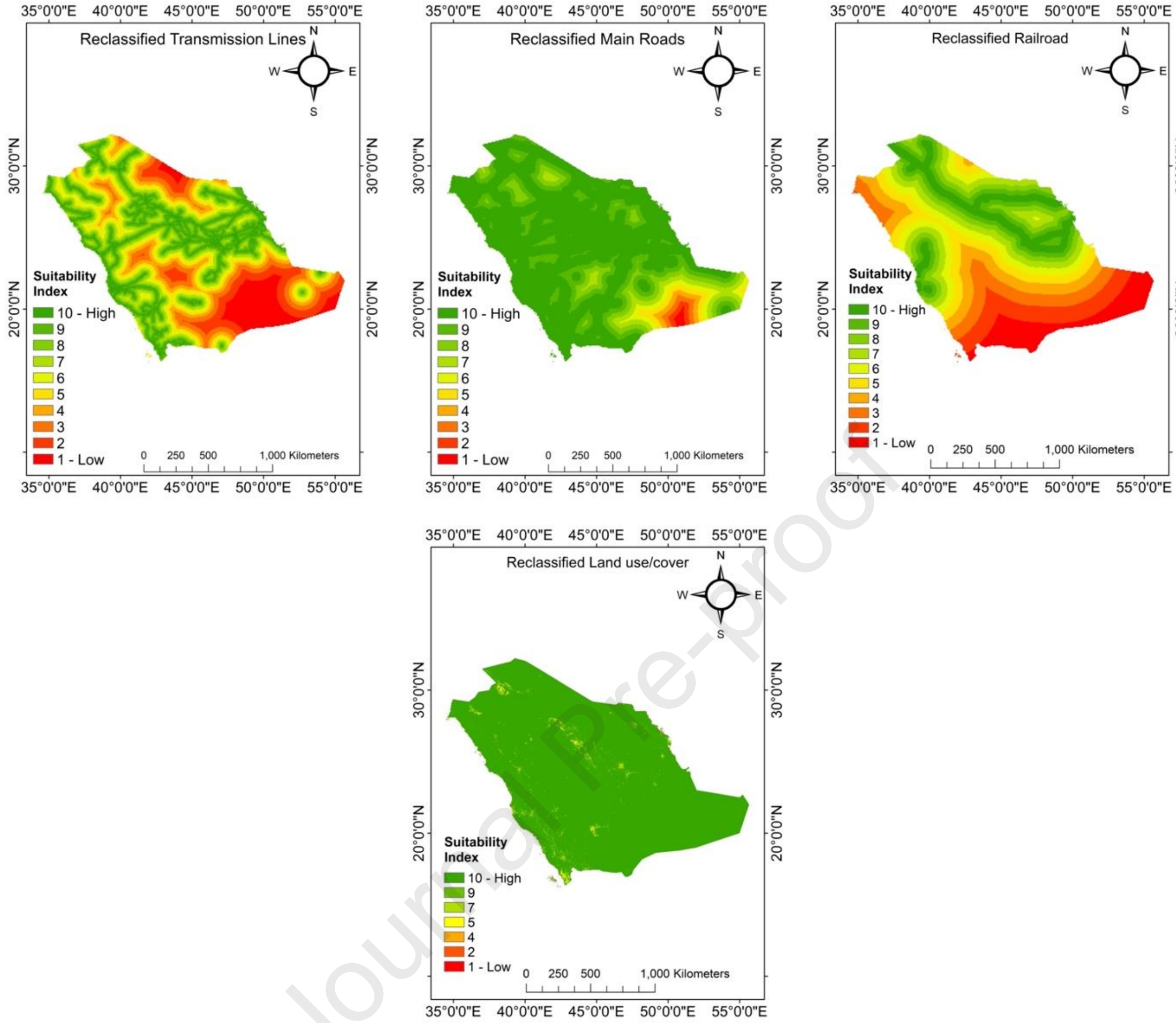



Figure 5. Standardized criteria.

*3.4.1. Analytical Hierarchy Process (AHP) weighting*

The proposed site suitability methodology requires a crucial step of criteria weighting, which was accomplished using the AHP method. AHP is a widely recognized tool for decision-making and prioritization processes in various fields, including RE. The method breaks down complex problems into smaller, more manageable components, making it easier to compare and prioritize different options. This is particularly helpful when dealing with the multifaceted nature of RE projects, which often involve considerations like environmental impact, cost, technical feasibility, and social acceptance [94]. To determine the relative importance of the main and sub-criteria, a group of five RE experts completed pairwise comparison matrices using a 1-9 scale. The resulting data was input into an online HP tool, which was used to extract weights and consistency ratios (CRs) for the main and sub-criteria. To ensure a comprehensive and balanced assessment of the factors involved in solar PV and wind energy site election, the experts' weighting results were averaged to drive the final evaluation criteria weights. Table 5 and Table 6 present the results of the AHP analysis for the solar PV and wind energy sites suitability analysis, respectively. The experts are unanimously agreed that the climatic criterion is the most important factor for solar PV and wind energy site selection, although there were varying degrees of CR values.

Table 5. Main and sub-criteria weights and CRs for solar PV suitability map.

| Criteria | Weight | Sub-criteria | Weight | Normalized weight | Rank | CR |
|---|---|---|---|---|---|---|
| **Expert 1 weighting results** | | | | | | |
| Climatic | 0.695 | PVOUT | 0.358 | 0.249 | 1 | 0.850 |
| | | Average temperature | 0.312 | 0.217 | 2 | |
| | | RH | 0.036 | 0.025 | 9 | |
| | | Precipitation | 0.137 | 0.095 | 5 | |
| | | Surface Albedo | 0.157 | 0.109 | 4 | |
| Orography | 0.132 | Aspect | 0.250 | 0.033 | 8 | |
| | | Elevation | 0.470 | 0.062 | 6 | |
| | | Slope | 0.280 | 0.037 | 7 | |
| Location | 0.149 | Distance to transmission lines | 0.792 | 0.118 | 3 | |
| | | Distance to main roads | 0.128 | 0.019 | 11 | |
| | | Distance to railroad | 0.081 | 0.012 | 12 | |
| Environmental | 0.024 | Land use/cover | 1.000 | 0.024 | 10 | |
| **Total** | | | | **1.000** | | |
| **Expert 2 weighting results** | | | | | | |
| Climatic | 0.624 | PVOUT | 0.346 | 0.216 | 1 | 0.670 |
| | | Average temperature | 0.229 | 0.143 | 3 | |
| | | RH | 0.061 | 0.038 | 8 | |
| | | Precipitation | 0.136 | 0.085 | 5 | |
| | | Surface Albedo | 0.228 | 0.142 | 4 | |
| Orography | 0.091 | Aspect | 0.363 | 0.033 | 10 | |
| | | Elevation | 0.264 | 0.024 | 11 | |
| | | Slope | 0.374 | 0.034 | 9 | |
| Location | 0.241 | Distance to transmission lines | 0.631 | 0.152 | 2 | |
| | | Distance to main roads | 0.311 | 0.075 | 6 | |
| | | Distance to railroad | 0.058 | 0.014 | 12 | |
| Environmental | 0.045 | Land use/cover | 1.000 | 0.045 | 7 | |
| **Total** | | | | **1.000** | | |
| **Expert 3 weighting results** | | | | | | |
| Climatic | 0.721 | PVOUT | 0.422 | 0.304 | 1 | 0.960 |
| | | Average temperature | 0.216 | 0.156 | 2 | |
| | | RH | 0.186 | 0.134 | 3 | |
| | | Precipitation | 0.071 | 0.051 | 7 | |
| | | Surface Albedo | 0.105 | 0.076 | 5 | |
| Orography | 0.189 | Aspect | 0.212 | 0.040 | 8 | |
| | | Elevation | 0.466 | 0.088 | 4 | |
| | | Slope | 0.323 | 0.061 | 6 | |
| Location | 0.066 | Distance to transmission lines | 0.273 | 0.018 | 11 | |
| | | Distance to main roads | 0.470 | 0.031 | 9 | |
| | | Distance to railroad | 0.258 | 0.017 | 12 | |
| Environmental | 0.025 | Land use/cover | 1.000 | 0.025 | 10 | |
| **Total** | | | | **1.000** | | |
| **Expert 4 weighting results** | | | | | | |
| Climatic | 0.729 | PVOUT | 0.377 | 0.275 | 1 | 0.770 |
| | | Average temperature | 0.180 | 0.131 | 2 | |
| | | RH | 0.136 | 0.099 | 6 | |
| | | Precipitation | 0.165 | 0.120 | 4 | |
| | | Surface Albedo | 0.143 | 0.104 | 5 | |
| Orography | 0.091 | Aspect | 0.220 | 0.020 | 11 | |
| | | Elevation | 0.374 | 0.034 | 8 | |
| | | Slope | 0.407 | 0.037 | 7 | |
| Location | 0.158 | Distance to transmission lines | 0.766 | 0.121 | 3 | |
| | | Distance to main roads | 0.152 | 0.024 | 9 | |
| | | Distance to railroad | 0.082 | 0.013 | 12 | |
| Environmental | 0.022 | Land use/cover | 1.000 | 0.022 | 10 | |
| **Total** | | | | **1.000** | | |
| **Expert 5 weighting results** | | | | | | |
| Climatic | 0.594 | PVOUT | 0.374 | 0.222 | 1 | 0.560 |
| | | Average temperature | 0.106 | 0.063 | 7 | |
| | | RH | 0.089 | 0.053 | 9 | |
| | | Precipitation | 0.199 | 0.118 | 3 | |
| | | Surface Albedo | 0.232 | 0.138 | 2 | |
| | | Aspect | 0.401 | 0.085 | 6 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Orography | 0.212 | Elevation | 0.175 | 0.037 | 10 | |
| | | Slope | 0.425 | 0.090 | 5 | |
| Location | 0.102 | Distance to transmission lines | 0.539 | 0.055 | 8 | |
| | | Distance to main roads | 0.284 | 0.029 | 11 | |
| | | Distance to railroad | 0.176 | 0.018 | 12 | |
| Environmental | 0.093 | Land use/cover | 1.000 | 0.093 | 4 | |
| **Total** | | | | **1.000** | | |
| **Averaged weights and CRs** | | | | | | |
| Climatic | 0.673 | PVOUT | 0.375 | 0.253 | 1 | 0.762 |
| | | Average temperature | 0.209 | 0.142 | 2 | |
| | | RH | 0.102 | 0.070 | 6 | |
| | | Precipitation | 0.142 | 0.094 | 4 | |
| | | Surface Albedo | 0.173 | 0.114 | 3 | |
| Orography | 0.143 | Aspect | 0.289 | 0.042 | 9 | |
| | | Elevation | 0.350 | 0.049 | 8 | |
| | | Slope | 0.362 | 0.052 | 7 | |
| Location | 0.143 | Distance to transmission lines | 0.600 | 0.093 | 5 | |
| | | Distance to main roads | 0.269 | 0.036 | 11 | |
| | | Distance to railroad | 0.131 | 0.015 | 12 | |
| Environmental | 0.042 | Land use/cover | 1.000 | 0.042 | 9 | |
| **Total** | | | | **1.000** | | |

Table 6. Main and sub-criteria weights and CRs for wind suitability map.

| Criteria | Weight | Sub-criteria | Weight | Normalized weight | Rank | CR |
|---|---|---|---|---|---|---|
| **Expert 1 weighting results** | | | | | | |
| Climatic | 0.577 | Wind power density | 0.586 | 0.338 | 1 | 0.700 |
| | | Average Temperature | 0.414 | 0.239 | 2 | |
| Orography | 0.263 | Elevation | 0.450 | 0.118 | 4 | |
| | | Slope | 0.550 | 0.145 | 3 | |
| Location | 0.141 | Distance to transmission lines | 0.539 | 0.076 | 5 | |
| | | Distance to main roads | 0.241 | 0.034 | 6 | |
| | | Distance to railroad | 0.220 | 0.031 | 7 | |
| Environmental | 0.019 | Land use/cover | 1.000 | 0.019 | 8 | |
| **Total** | | | | **1.000** | | |
| **Expert 2 weighting results** | | | | | | |
| Climatic | 0.584 | Wind power density | 0.740 | 0.432 | 1 | 0.600 |
| | | Average Temperature | 0.260 | 0.152 | 3 | |
| Orography | 0.275 | Elevation | 0.709 | 0.195 | 2 | |
| | | Slope | 0.291 | 0.080 | 4 | |
| Location | 0.120 | Distance to transmission lines | 0.458 | 0.055 | 5 | |
| | | Distance to main roads | 0.325 | 0.039 | 6 | |
| | | Distance to railroad | 0.216 | 0.026 | 7 | |
| Environmental | 0.020 | Land use/cover | 1.000 | 0.020 | 8 | |
| **Total** | | | | **1.000** | | |
| **Expert 3 weighting results** | | | | | | |
| Climatic | 0.477 | Wind power density | 0.753 | 0.359 | 1 | 0.860 |
| | | Average Temperature | 0.247 | 0.118 | 4 | |
| Orography | 0.058 | Elevation | 0.448 | 0.026 | 8 | |
| | | Slope | 0.552 | 0.032 | 7 | |
| Location | 0.343 | Distance to transmission lines | 0.534 | 0.183 | 2 | |
| | | Distance to main roads | 0.256 | 0.088 | 5 | |
| | | Distance to railroad | 0.210 | 0.072 | 6 | |
| Environmental | 0.121 | Land use/cover | 1.000 | 0.121 | 3 | |
| **Total** | | | | **1.000** | | |
| **Expert 4 weighting results** | | | | | | |
| Climatic | 0.405 | Wind power density | 0.929 | 0.376 | 1 | 0.550 |
| | | Average Temperature | 0.071 | 0.029 | 7 | |
| Orography | 0.357 | Elevation | 0.636 | 0.227 | 2 | |
| | | Slope | 0.364 | 0.130 | 3 | |
| Location | 0.196 | Distance to transmission lines | 0.597 | 0.117 | 4 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Distance to main roads | 0.306 | 0.060 | 5 | |
| | | Distance to railroad | 0.097 | 0.019 | 8 | |
| Environmental | 0.041 | Land use/cover | 1.000 | 0.041 | 6 | |
| **Total** | | | | **1.000** | | |
| **Expert 5 weighting results** | | | | | | |
| Climatic | 0.376 | Wind power density | 0.949 | 0.357 | 1 | 0.900 |
| | | Average Temperature | 0.051 | 0.019 | 8 | |
| Orography | 0.059 | Elevation | 0.576 | 0.034 | 6 | |
| | | Slope | 0.424 | 0.025 | 7 | |
| Location | 0.444 | Distance to transmission lines | 0.581 | 0.258 | 2 | |
| | | Distance to main roads | 0.259 | 0.115 | 4 | |
| | | Distance to railroad | 0.160 | 0.071 | 5 | |
| Environmental | 0.122 | Land use/cover | 1.000 | 0.122 | 3 | |
| **Total** | | | | **1.000** | | |
| **Averaged weights and CRs** | | | | | | |
| Climatic | 0.484 | Wind power density | 0.791 | 0.372 | 1 | 0.722 |
| | | Average Temperature | 0.209 | 0.111 | 4 | |
| Orography | 0.202 | Elevation | 0.564 | 0.120 | 3 | |
| | | Slope | 0.436 | 0.082 | 5 | |
| Location | 0.249 | Distance to transmission lines | 0.542 | 0.138 | 2 | |
| | | Distance to main roads | 0.277 | 0.067 | 6 | |
| | | Distance to railroad | 0.181 | 0.044 | 8 | |
| Environmental | 0.065 | Land use/cover | 1.000 | 0.065 | 7 | |
| **Total** | | | | **1.000** | | |

### *3.4.2. Weighted Linear Combination (WLC)*

In this subsection, the initial suitability maps for solar PV field, wind farm, and hybrid solar PV-wind farm in SA are prepared using Weighted Linear Combination (WLC) method. The WLC method was applied to generate suitability maps for each RE system by integrating the individual criterion and their corresponding weights using Equation (1) [95]:

$$S = \sum_{i=1}^{i=N} W_i \cdot X_i \qquad (1)$$

where S represents the calculated suitability value for each pixel, Wi is the weight of criterion i, and $X_i$ is the criterion score of factor i.

The initial suitability maps for solar PV and wind systems were then scaled into four distinct suitability levels, where the highest pixel value represented highly suitable areas and the lowest pixel value indicated the least suitable areas. For the hybrid solar PV-wind system, the initial suitability map was scaled into ten suitability levels, considering the increased complexity and variability resulting from the combination of two distinct resources. This finer resolution enabled a more precise identification of suitable sites for the hybrid systems. The scaling process facilitated the interpretation of the results and allowed for easier comparison between different systems.

Final suitability maps for solar PV (Figure 6-a), wind (Figure 6-b), and hybrid solar PV-wind (Figure 6-c) systems were obtained by applying Boolean logic to the initial suitability maps. This involved multiplying the initial suitability maps by the restriction map, which identified areas unsuitable for development based on factors such as environmental and land use/cover constraints. Notably, the analysis reveals that the two utility-scale RE installation, Sakaka solar PV plant and Dumat Al Jandal wind farm, are located within the areas identified as highly suitable. This finding highlights the precision and reliability of the methodology in determining optimal locations for Solar PV and wind energy systems. Further, nominated locations for RE systems, including the original sites of Sakaka solar PV plant and Dumat Al Jandal wind farm, were identified in the highest suitable areas of the final suitability maps. These locations were selected to perform a techno-economic analysis that aims to evaluate the feasibility and potential benefits of installing utility-scale solar PV, wind, and hybrid solar PV-wind systems in most promising areas.

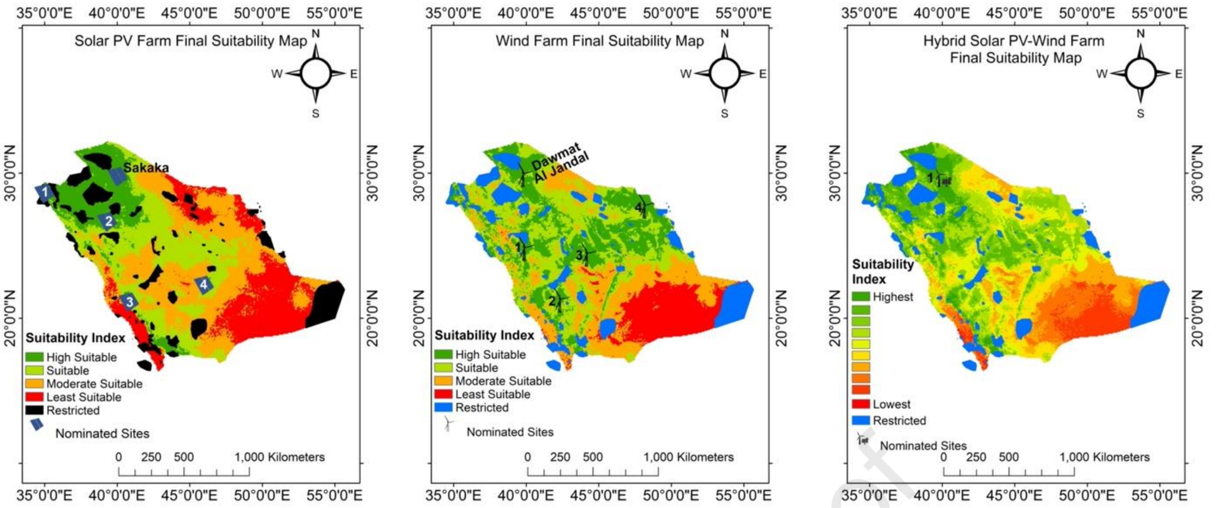



Figure 6. Final suitability maps.

## 4. Techno-economic Analysis

The techno-economic analysis aims to assess the practicality and feasibility of proposed solar PV, wind, and hybrid solar PV-wind systems at the nominated locations, including the original sites of Sakaka solar PV plant and Dumat Al Jandal wind farm. The analysis evaluates the technical and economic metrics of each system to determine the feasibility and potential benefits of installing utility-scale solar PV and wind systems in the most promising areas identified through the GIS-based site suitability analysis. This analysis provides policy and decision makers with a comprehensive understanding of the limitations and potentials of these energy sources, enabling them to meticulously plan for the implementation and development with minimal risks. Seven evaluation metrics were considered in this analysis to assess the feasibility of the systems, as elaborated in the following points.

The technical performance metrices evaluated in the analysis include:

- Annual Energy Output: the total amount of electricity generated by the RE system in one year. It is expressed in megawatt-hour (MWh) or gigawatt-hour (GWh) [2].
- Capacity Factor (CF): the ratio of actual energy output of the RE system to the maximum possible output under ideal conditions. It is expressed as percentage and calculated using Equation (2) [96]:

$$CF\ (\%) = \frac{annual\ Energy\ Output\ (MWh)}{plant\ capacity\ (MW) \times 8760} \quad (2)$$

- Energy Yield (EY): the amount of energy produced per unit of installed capacity over a year. It is expressed in megawatt-hour per megawatt (MWh/MW) and calculated using Equation (3) [38].

$$EY = \frac{annual\ Energy\ Output\ (MWh)}{plant\ capacity\ (MW)} \quad (3)$$

- Performance Ratio (PR): The PR of a solar PV system is a metric that indicates the system's overall efficiency in converting sunlight into electricity. It is defined as the ratio of the actual energy output of a PV system to the theoretical energy output that would occur under standard test conditions (STC). It is calculated using Equation (4) [38].

$$PR\ (\%) = EY \times \frac{G_{STC}}{\sum G_t} \quad (4)$$

where $G_{STC}$ represents the amount of GHI at STC and $G_t$ is the accumulative GHI in a PV array plane within a specific period.

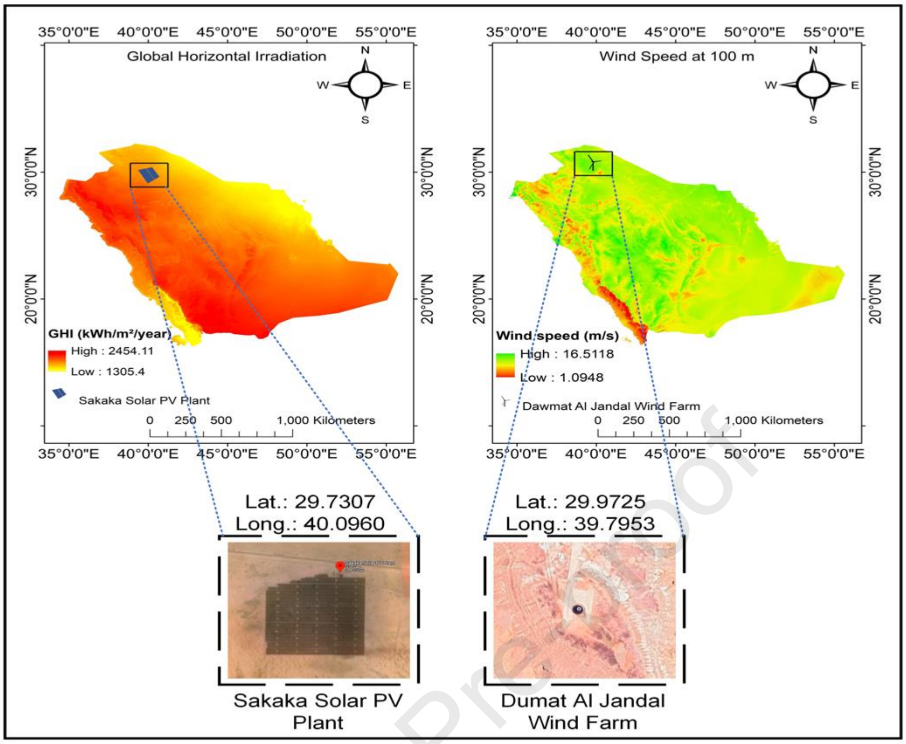



Figure 7. SA solar and wind energy potential.

The economic metrics evaluated in the techno-economic analysis include:

- Levelized Cost of Energy (LCOE): the LCOE is the average cost per unit of electricity generated by the RE system, considering the capital and operating costs over the system's lifetime. It is used to compare the cost of producing electricity from different sources and can be estimated in either nominal or real LCOE. Real LCOE represents the actual cost of electricity production in a given year, adjusted for inflation. In contrast, nominated LCOE represents the estimated cost of production at a specific point in time, without adjusting for inflation. Therefore, real LCOE provides a more accurate picture of the actual cost of electricity production over time, while nominated LCOE is a useful tool for comparing the relative costs of different energy sources at a specific point in time. Real LCOE and nominated LCOE can be estimated using Equation (5) and Equation (6), respectively [97].

$$LCOE\ (real) = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{real})^n}} \quad (5)$$

$$LCOE\ (nominal) = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{nominal})^n}} \quad (6)$$

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 refers to the total years of the analysis, $d_{nominal}$ is nominal discount rate, $d_{real}$ is the real discount rate.

- Net Present Value (NPV): The difference between the present value of cash inflows and the present value of cash outflows over the system's lifetime, considering a specific discount rate. A positive NPV indicates a profitable investment. The NPV value can be estimated using Equation (7) [38].

$$NPV = \sum_{t=0}^{N} \frac{Reveneue_t - Cost_t}{(1+d)^t} \quad (7)$$

where N represents the total years of the analysis, t is the variable to represent each year in the calculation, d is the discount rate, $Revenue_t$ is the revenue in year t, and $Cost_t$ refers to the system cost in year t.

- Internal Rate of Return (IRR): The discount rate at which the NPV of the RE system becomes zero. A higher IRR indicates a more profitable investment [38].

*4.1. Resources assessment*

The resource assessment is a critical step in the techno-economic feasibility assessment of solar and wind energy generation as it helps to optimize the energy system design. Further, the adequate availability of solar and wind energy resources at the project sites determines the energy production potential, which is a crucial factor to determine the economic viability. However, SA is characterized by its significant potential for solar and wind energy potential. Figure 7 shows the GHI and wind speed potential maps for SA, highlighting the Sakaka solar PV plant and Dumat Al Jandal wind farm on the map. The solar irradiation and other weather data used in the simulation are retrieved from the national solar radiation database (NSRDB), using SAM software. For wind speed and direction, SAM can retrieve data only for the continental United States and parts of Central America and the Caribbean. However, for SA, wind data obtained from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER) database via the Data Access Viewer web tool. While NASA database provides wind data at a height of 50 m, the elevation was not adequate for the wind turbines' hub height used in the analysis. Therefore, the wind speed at 100 m was estimated using the wind profile power low described by Equation (8) and Equation (9) [98].

$$V_2 = V_1 \times (\frac{H_2}{H_1})^{\alpha} \quad (8)$$

where $V_1$ is the wind speed at the initial height ($H_1$), $V_2$ represents the wind speed at the new height ($H_2$), $H_1$ is the initial height (50 m in this case), $H_2$ is the new height (100 m in this case), and α is the wind shear exponent.

$$\alpha = \frac{0.37 - 0.088\, ln(V_{ref})}{1 - 0.088\, ln\left(\frac{H_{ref}}{10}\right)} \quad (9)$$

where $V_{ref}$ is the average wind speed at the initial height ($H_1$) and $H_{ref}$ is reference height ($H_1$ in this case).

*4.2. Systems modeling*

The techno-economic analysis was conducted using SAM tool to simulate the capacities of the Sakaka solar PV plant and Dumat Al Jandal wind farm, both at their original sites and at nominated sites. SAM is a software tool widely used for modeling and optimizing RE systems. It enables the calculation of economic metrics and hourly energy production for RE systems. SAM was first developed in 2004 and has since undergone continuous improvement by the National Renewable Energy Laboratory (NREL), Sandia National Laboratory, and the U.S. Department of Energy (DOE) [2]. The Sakaka solar PV plant, commissioned in 2019, is SA's first RE project. It has a capacity of 300 MW and is expected to generate 800 GWh of electricity annually. The solar PV field spans an area of 4.5 $km^2$ and consists of 1.4 million PV panels [99]. Similarly, the Dumat Al Jandal wind farm is the country's first utility-scale wind farm, with a capacity of 400 MW and an expected annual electricity generation of 1.4 TWh. The wind farm covers an area of 125 $km^2$ and comprises 99 wind turbines with a hub height of 130 meters and a rotor diameter of 150 meters [100,101]. The Sakaka solar PV plant operates under a 25-year Power Purchase Agreement (PPA) with an electricity price of $23.4/MWh [102], while the Dumat Al Jandal wind farm has a 20-year PPA with an electricity price of $21.3/MWh [100]. As detailed technical and financial data for both plants are not fully available, global weighted average costs [103] and financial data published by the Saudi Central Bank [104] were used in the analysis. Table 7 presents the solar PV and wind resources at the different nominated sites, while Table 8 provides cost estimates and financial parameters of the components considered in the design of the solar PV and wind farms. The hybrid system comprises 300 MW of solar PV and 400 MW of wind turbines, and an arbitrary PPA price of $20/MWh was selected.

The cost and financial data associated with the system design and model are based on available data for solar PV and wind technologies.

Table 7. Average Solar GHI and wind speed of the sites.

| Solar PV fields | Annual average GHI (kWh/m$^2$/year) | Wind farms | Wind speed at 100 m (m/s) |
|---|---|---|---|
| Sakaka | 2231.32 | Dumat Al Jandal | 6.94 |
| Location1 | 2235.97 | Location1 | 7.72 |
| Location2 | 2315.63 | Location2 | 7.56 |
| Location3 | 2211.27 | Location3 | 7.41 |
| Location4 | 2286.17 | Location4 | 7.22 |

Table 8. Costs and financial inputs.

| Financial data | Solar PV | Onshore Wind Turbine |
|---|---|---|
| PPA ($/MWh) | 23.4 | 21.3 |
| Installation cost in 2019 ($/kW) | 1,009 | 1,491 |
| O&M cost in 2019 ($/kW/year) | 10 | 43 |
| Inflation rate (%) | 2.5 | 2.5 |
| Discount rate (%) | 5 | 5 |
| Sales tax (%) | 15 | 15 |

### *4.3. Mathematical Modeling*

#### *4.3.1. PV System with Temperature Modeling*

The output power from the PV module depends on factors such as solar irradiance, module temperature and other operating conditions. The PV module temperature is influenced by the ambient temperature and solar irradiance. A linear temperature model is used to characterize the effect of cell temperature on power output. Equation 10 demonstrates the relationship between the PV cell and ambient temperature [44]:

$$T_c = T_a + 0.07 \times H_t \qquad (10)$$

where $T_c$ is the cell temperature in °C, $T_a$ is the ambient temperature in °C, and $H_t$ is the solar irradiance in W/m$^2$.

The power output from the PV module is then given by Equation 11 [44]:

$$P_{PV} = P_{STC}\left[1 + \beta_p (T_c - T_{STC})\right] \frac{H_t}{H_{STC}} \qquad (11)$$

Where $P_{STC}$ is the maximum power output (W) at the standard test conditions (STC), $\beta_p$ is the power temperature coefficient at STC, $T_{STC}$ is the reference temperature at STC, $H_{STC}$ is the solar irradiance in W/m$^2$ at STC (usually 25°C).

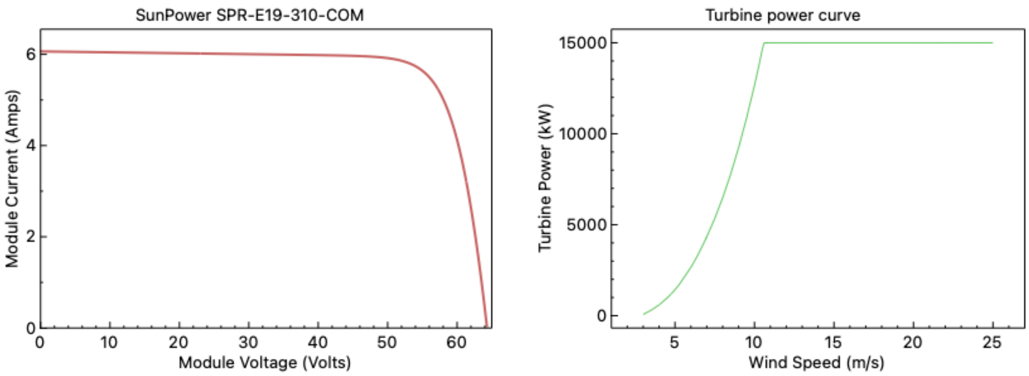
#### *4.3.2. Wind Turbine modeling*

The power output of a wind turbine is determined by the wind speed and the characteristics of the turbine. The power output is modeled using Equation 12 [105]:

$$P_e = \frac{1}{2} \times C_p(\lambda, \beta) \times \rho \times A \times V^3 \qquad (12)$$

where $C_p$ is the performance coefficient which is a function of tip-speed ratio (λ) and pitch angle (β), ρ is the air density in kg/m$^3$, A is the rotor swept area in m$^2$, V is the wind speed in m/s.

Solar PV modules and wind turbines are the key components used to harness energy from the sun and wind respectively in renewable energy systems. Both solar modules and wind turbines have specific technical specifications that influence their energy generation capabilities under different climatic conditions. Proper component sizing and selection is important for optimizing renewable energy project designs. Figure 8 shows the electrical characteristics of PV modules and the power curve of the wind turbine used in this study.




(a) Module electrical characteristics at STC (b) Turbine power curve

Figure 8. Electrical characteristics of the PV module and the power curve of wind turbine.

*4.4. Tilt angle optimization*

Tilt angle of solar panels significantly impacts the amount of electricity they generate. Choosing the optimal tilt angle is crucial for maximizing energy production. A fixed tilt angle near the local latitude is generally ideal, facing north in the Southern Hemisphere and south in the Northern Hemisphere. In this study, the optimum tilt angle for fixed PV arrays was determined through simulation of various tilt angles between latitude 0° to 90° using SAM. The tilt that resulted in capturing the highest irradiance incident on the plane of array (POA) was selected as the optimum tilt angle for each location (Figure 9).

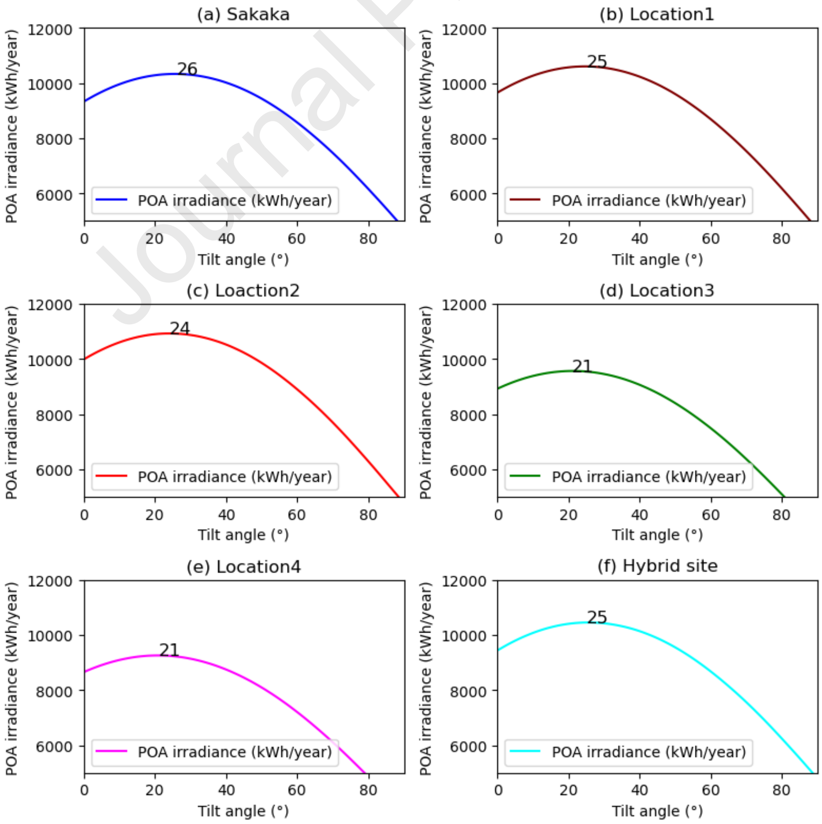



Figure 9. Solar arrays optimum tilt angles.

Table 9. Techno-economic simulation results.

| Renewable Type | Location | Metric | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Technical | | | | Economic | | | |
| | | Annual AC energy (GWh) | CF (%) | EY (MWh/kW) | PR | Nominal LCOE ($/MWh) | Real LCOE ($/MWh) | NPV ($) | IRR (%) |
| Solar PV | Sakaka | 705.288 | 26.8 | 2.351 | 0.77 | 35.4 | 27.8 | -74,876,400 | 1.87 |
| | 1 | 705.139 | 26.8 | 2.350 | 0.77 | 35.6 | 28.0 | -75,742,392 | 1.81 |
| | 2 | 726.638 | 27.6 | 2.422 | 0.76 | 34.1 | 26.8 | -67,303,392 | 2.37 |
| | 3 | 675.470 | 25.7 | 2.252 | 0.78 | 37.2 | 29.2 | -84,292,720 | 1.28 |
| | 4 | 687.897 | 26.2 | 2.293 | 0.77 | 36.6 | 28.8 | -81,496,888 | 1.44 |
| Wind Farm | Dumat Al Jandal | 1,274 | 36.3 | 3.183 | - | 34.9 | 27.3 | -164,837,312 | 0.30 |
| | 1 | 1,494 | 42.6 | 3.734 | - | 26.6 | 20.8 | -55,663,024 | 5.14 |
| | 2 | 1,415 | 40.4 | 3.535 | - | 29.3 | 22.9 | -95,078,648 | 3.41 |
| | 3 | 1,371 | 39.1 | 3.427 | - | 30.9 | 24.2 | -116,585,424 | 2.47 |
| | 4 | 1,385 | 39.5 | 3.461 | - | 30.4 | 23.8 | -109,740,480 | 2.77 |
| Hybrid PV-Wind | 1 | 2,191 | 35.6 | 3.120 | - | 60.9 | 47.6 | -941,005,568 | NaN |

### *4.5. Simulation results and discussions*

The techno-economic viability of electric power generation relying on solar PV and wind energy sources in SA was investigated using a combination of ArcGIS, SAM software tools, and an SVR prediction model. The analysis began by optimizing the RE sites using the AHP within the ArcGIS environment. The data of RE sources, systems configurations and characteristics, and cost details were then input into the SAM software to evaluate the techno-economic performance of the RE systems deployed in the highly suitable sites. The Sakaka solar PV plant and Dumat Al Jandal wind farm were simulated for different locations in SA, which were identified through GIS-based land suitability analysis. The simulation results presented in Table 9 provide valuable insights into the technical and economic feasibility of the proposed systems. The solar PV plant simulation showed that Location2 exhibited the highest performance, with an annual energy output of 726.638 GWh, surpassing the output of the Sakaka plant simulated at its original site. However, none of the simulated sites achieved the expected annual energy generation for the Sakaka solar PV plant. Similarly, the wind farm simulation revealed that Location1 had the highest energy output of 1.494 TWh/year, followed closely by Location2 with 1.415 TWh/year, which is in line with the reported annual energy generation estimate for the Dumat Al Jandal wind farm of 1.4 TWh. The actual Dumat Al Jandal site exhibited the lowest annual energy production. Furthermore, the hybrid Solar PV-wind system, which consisted of 300 MW solar PV and 400 MW wind turbines, demonstrated higher technical performance than the solar PV system, with a CF of 35.6%. This suggests that the hybrid system can generate electricity more consistently throughout the year, maximizing its potential output. On the economic front, the simulation results for the solar PV, wind turbine, and hybrid solar PV-wind projects in SA indicated negative NPVs at the respective PPA prices of $23.4/MWh, $21.3/MWh, and $20/MWh. The negative NPV results indicate that the projects are not economically viable at the current PPA prices. Increasing the PPA price could potentially enhance the profitability of these projects. Overall, the techno-economic analysis provides valuable insights into the technical and economic feasibility of solar PV, wind turbine, and hybrid solar PV-wind projects in SA. The results highlight the need for careful consideration of location-specific factors, PPA prices, and other financial considerations to ensure the long-term economic viability of RE projects in the country.

Despite the unavailability of actual cost and incentives data for the Sakaka and Dumat Al Jandal plants, the techno-economic analysis suggests that alternative sites may offer technical advantages for utility-scale solar PV and wind energy power plants. However, the current PPA rates in SA are insufficient to make these technologies economically viable when considering the global weighted average costs. Significant reductions in installation costs and higher PPA tariffs would be necessary to achieve grid parity in SA, based on the simulation assumptions and sites. Therefore, conducting a sensitivity analysis can provide insights into viable pathways for cost reduction and policy mechanisms needed to promote RE deployment in SA. This section presents a sensitivity analysis in which the PPA rates for both the Sakaka and Dumat Al Jandal plants will vary to estimate the appropriate PPA rates that result in economically feasible plants. By examining the sensitivity of the techno-economic analysis to different PPA rates, policymakers and stakeholders can gain a better understanding of the required adjustments and potential policy interventions to support the economic viability of RE projects in SA.

*4.6. Sensitivity analysis*

Sensitivity analysis is a crucial process for determining the impact of changes in variables on the technical performance and economic viability of RE power plants. In this study, sensitivity analysis was conducted to identify the appropriate PPA rates that would make solar and wind power plants economically feasible in SA. As shown in Figure 10 and Figure 11, PPA rates below the break-even figures result in negative NPV, indicating the lack of economic viability. On the other hand, PPA prices above the break-even values lead to positive NPV, indicating profitable projects. Figure 10 the utility-scale solar PV technology at the original site of the Sakaka power plant, the PPA rate needs to increase to $33.8/MWh in order to achieve a zero NPV. The alternative solar PV sites identified in this study require PPA rates ranging from $32.8/MWh to $35.4/MWh to achieve zero NPV values.. In the case of the wind energy farm, the PPA rate must increase to $33.2/MWh for the actual Dumat Al Jandal site to achieve break-even. For the alternative locations, the required PPA rates are $26.1/MWh, $28.4/MWh, $29.8/MWh, and $29.3/MWh for Location1, Location2, Location3, and Location4, respectively. Figure 11 illustrates that PPA rates below these levels result in negative NPV, while higher PPA rates yield positive NPV, indicating economic feasibility of the wind farm. Furthermore, Figure 12 demonstrates that the break-even PPA for the hybrid solar PV-wind plant is $50.6/MWh. Any PPA rate above this threshold will result in an economically viable hybrid system.

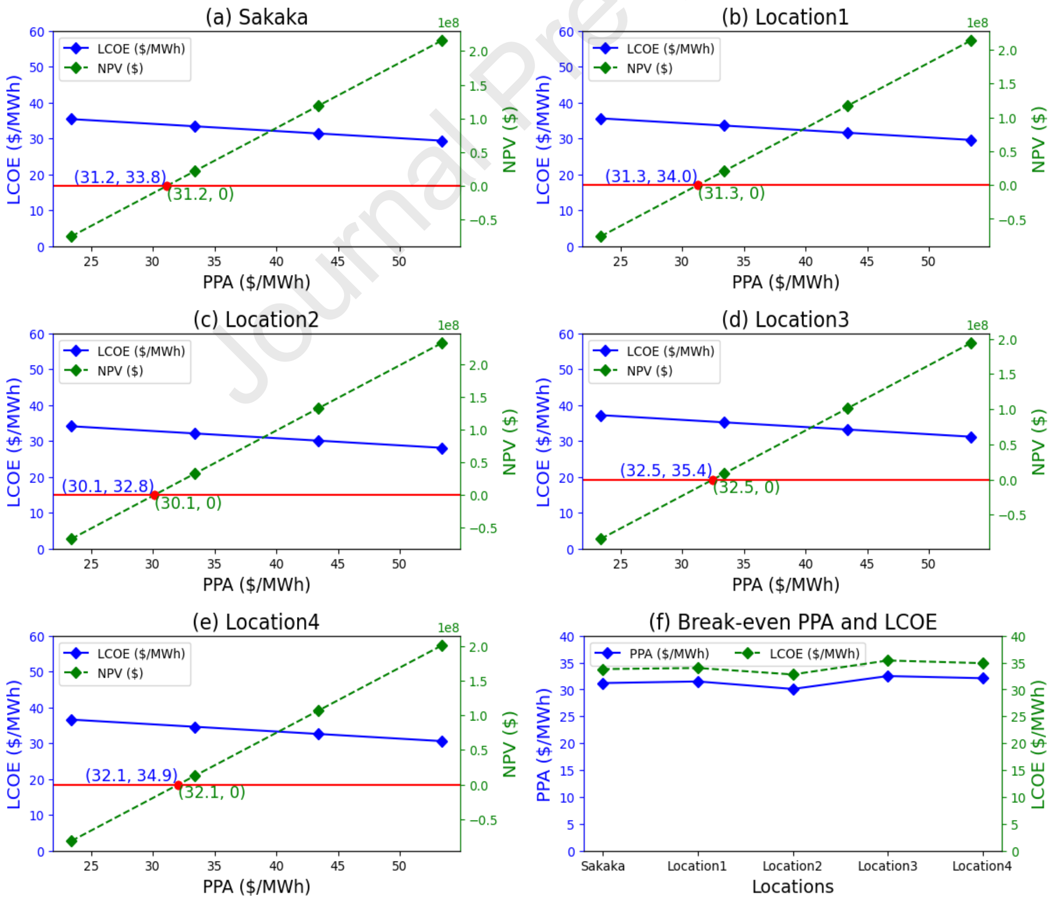



Figure 10. Solar PV fields PPA sensitivity analysis.

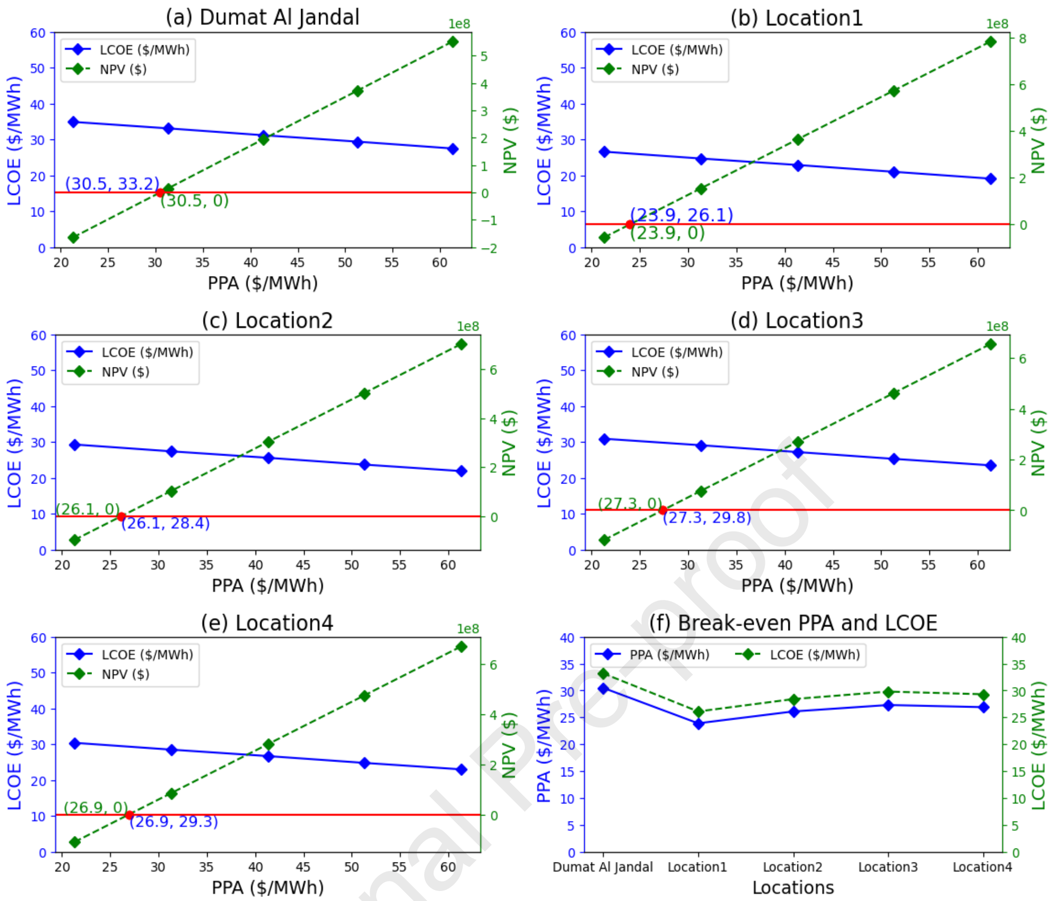



Figure 11. Wind farms PPA sensitivity analysis.

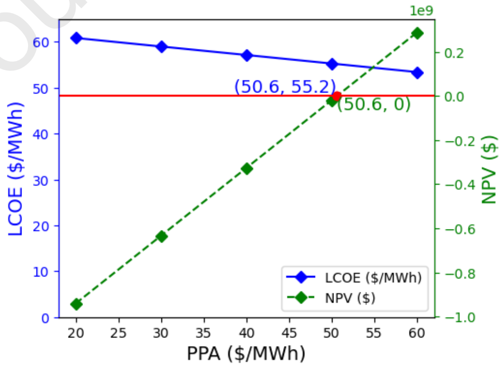



Figure 12. Hybrid farm PPA sensitivity analysis.

In this study, the impact of varying the capacities of the solar PV and wind turbines on the technical and economic performance of the hybrid solar PV-wind plant was investigated. Table 10 provides an overview of the different configurations of the hybrid system, with varying capacities of the solar PV field and wind farm. It should be noted that the total capacity of the hybrid system is kept constant at 700 MW. The results, as shown in Figure 13 and Figure 14, indicate that increasing the capacity of the wind turbines leads to improvements in both the technical and economic performance of the hybrid system. This is because wind turbines provide a more consistent and reliable source of energy compared to solar PV, which is subject to variations in solar radiation. By increasing the wind turbines' capacity, the overall output of the hybrid system becomes more stable and less dependent on solar fluctuations. However, even with the highest capacity of wind turbines (600 MW), the economic viability of the hybrid system is not achieved at a PPA rate of $20/MWh. This suggests that, under the simulation assumptions and conditions, a higher PPA rate would be necessary to make the hybrid system economically feasible. The results highlight the importance of considering the appropriate balance between solar and wind capacities and setting realistic PPA rates to ensure the financial viability of hybrid RE systems. These findings provide insights into the optimal configuration and economic considerations for hybrid solar PV-wind systems in SA. Policymakers and stakeholders can utilize this information to inform their decisions regarding capacity planning, tariff structures, and financial mechanisms to promote the deployment of economically viable hybrid RE projects.

Table 10. Hybrid system configuration.

| Configuration | Hybrid solar PV-wind configuration | |
|---|---|---|
| | Solar PV field Capacity (MW) | Wind farm capacity (MW) |
| 1 | 500 | 200 |
| 2 | 450 | 250 |
| 3 | 400 | 300 |
| 4 | 350 | 350 |
| 5 | 300 | 400 |
| 6 | 250 | 450 |
| 7 | 200 | 500 |
| 8 | 150 | 550 |
| 9 | 100 | 600 |

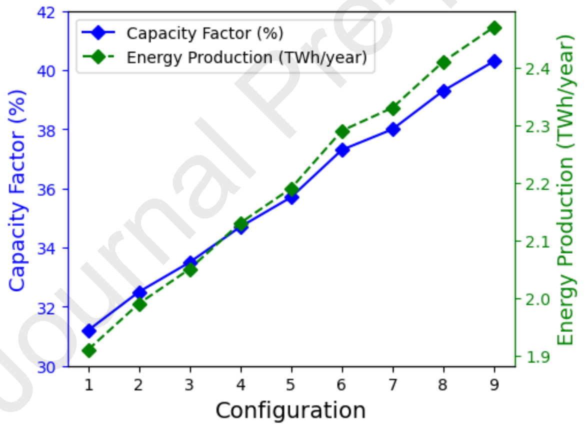



Figure 13. Technical performance of the hybrid system configurations.

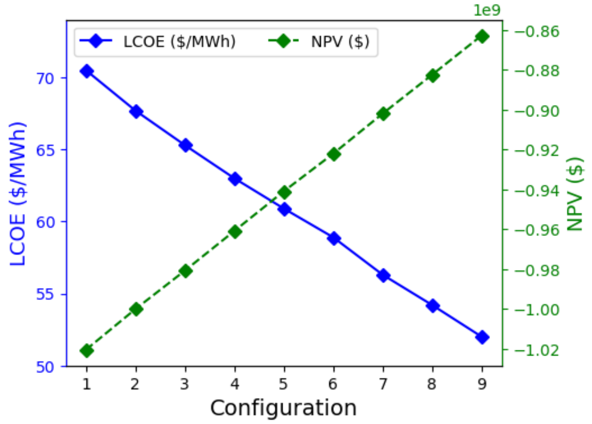



Figure 14. Economic performance of the hybrid system configurations.

The results of the sensitivity analysis highlight the importance of exploring various measures to increase the profitability and economic feasibility of RE projects in SA. Relying solely on increasing the PPA rates may not be a viable solution due to competition from cheaper fossil fuels and the potential impact on electricity prices. Therefore, alternative approaches should be considered to address the challenges and enhance the financial viability of these projects. One important measure is to focus on reducing the costs associated with the installation, operation, and maintenance of RE systems. This can be achieved through advancements in materials technologies, such as the use of more efficient solar panels and innovative wind turbine designs, which can improve the overall system performance and reduce costs. Additionally, optimizing the design and operation of these systems, such as optimizing the layout of solar PV arrays or wind turbines, can further enhance their efficiency and cost-effectiveness. Exploring alternative financial models, such as public-private partnerships (PPPs), can also play a significant role in attracting private investments and reducing the risks associated with RE projects. PPPs can provide access to additional funding sources, expertise, and resources, while also sharing the risks and responsibilities between the public and private sectors. Furthermore, the implementation of supportive policies and regulations can create a more favorable market environment for RE development. This includes introducing subsidies, feed-in tariffs, or tax incentives to incentivize investments in RE projects. These measures can help reduce the financial burden on project developers and make RE more competitive in the energy market. In conclusion, a combination of measures, including technological advancements, alternative financial models, and supportive policies, is needed to increase the profitability and economic feasibility of RE projects in SA. By adopting these strategies, the country can accelerate its transition towards a sustainable energy future, reduce dependence on fossil fuels, and contribute to global efforts in combating climate change.

## 5. Social Development

SA has ambitious long-term goals for social development and economic diversification outlined in its Vision 2030 plan. Transitioning to renewable energy sources such as solar and wind can help advance social development in several ways. Large-scale jobs in manufacturing, construction and operation of utility-scale solar and wind farms provide opportunities for workforce training and career development. Employment in the clean energy sector offers stable, skilled jobs that can help address unemployment challenges, particularly among the growing youth population. This study applies the employment factor (EF) approach to quantify potential job creation from four scenarios of solar and wind energy deployment from 2020 to 2060. Quantifying potential job creation from solar and wind energy deployment can provide insights into how the energy transition supports SA's goals for a thriving and diversified economy with an empowered population.

### *5.1. The employment factor method*

The employment factor (EF) approach used in [53] is adopted to estimate jobs from each scenario. EFs represent the number of jobs (job-years or jobs/MW) created per unit of installed capacity or investment. EFs are applied for four job categories: manufacturing, construction and installation, operations and maintenance, and decommissioning.

- Manufacturing (Mf) jobs: These are jobs required to manufacture the various components and equipment needed for solar and wind energy projects. As manufacturing may take weeks to years to complete, these jobs are expressed as job-years or total number of jobs over the lifetime of the project. Mf jobs are estimated using Equation (13) [53]:

$$Mf\ jobs = IC_i \times EF_M \times DF_{Capex} \times MF \times REM \quad (13)$$

where $IC_i$ is the installed capacity per year at year i in MW, $EF_M$ represents the manufacturing employment factor, $DF_{Capex}$ is the decline factor based on the capital expenditure (Capex), MF refers to manufacturing factor, and REM is regional employment multiplier.

- Construction and installation (C&I) jobs: These include all jobs needed for building out solar and wind farms as well as erecting the solar panels and wind turbines on site. Construction takes place over months to a few years, so these jobs are also quantified as job-years. Equation (14) is used to calculate the C&I jobs [53]:

$$C\&I\ jobs = IC_i \times EF_{C\&I} \times DF_{Capex} \times REM \tag{14}$$

where $EF_{C\&I}$ is the construction and installation employment factor.

- Operations and maintenance (O&M) jobs: These long-term jobs are needed for operating and maintaining solar and wind farms throughout their lifetime of 25-30 years. As the projects operate for decades, O&M jobs are expressed as ongoing jobs per megawatt of capacity. Equation (15) is used to calculate the O&M jobs [53]:

$$O\&M\ jobs = CC_i \times EF_{O\&M} \times DF_{Capex} \times REM \tag{15}$$

where $CC_i$ represents the cumulative capacity at year i in MW, $EF_{O\&M}$ is the operations and maintenance employment factor.

- Decommissioning (DC) jobs: At the end of their usable lifespan, solar panels and wind turbines need to be dismantled and disposed of. These jobs are similar to construction but occur once at the end of the project lifespan and are also measured in job-years. Equation (16) is used to calculate the DC jobs [53]:

$$DC\ jobs = DC_i \times EF_{DC} \times REM \tag{16}$$

where $DC_i$ refers to the decommissioned capacity at year i in MW, $EF_{DC}$ is the decommissioning employment factor.

The employment factors, decline factors, regional employment multipliers, and local manufacturing factors used in this study are taken from the reference [53] for the MENA region, which best represents the current economic and manufacturing context in Saudi Arabia.

The employment factors reflect the number of jobs created per unit of installed capacity or investment for different components of solar and wind projects. Decline factors account for expected productivity improvements over time by correlating employment factors with reductions in capital expenditure (Capex) and operating costs. Regional employment multipliers are used to adjust for Saudi Arabia's current economic conditions and labor market. And local manufacturing factors represent the percentage of domestic sourcing versus imports for project components, which may change with time as local supply chains develop. Together these parameters provide inputs to estimate jobs in SA while considering technology learning, comparative labor markets, and domestic economic participation over the deployment periods covered in the four scenarios.

### *5.2. The scenarios*

This study estimates the potential jobs created from solar PV and wind power deployment in SA under four different scenarios in reference [106] from 2020 to 2060. The scenarios are:

1. Current Policy Scenario: This scenario includes energy efficiency measures and price reforms implemented to date. It also includes a target of 50% renewable energy in electricity generation by 2030. No new policies are added post-2030.
2. Nationally Determined Contributions (NDCs) Continued Scenario: This scenario aims to meet Saudi Arabia's updated NDC target of reducing 278 $MtCO_2eq$ emissions by 2030 compared to the no policy scenario. Beyond 2030, the same annual emissions reduction rate is maintained to reach the 2030 target.
3. No Policy Scenario: This scenario assumes no climate policies or targets. Energy demand is met through continued reliance on fossil fuels with no support for renewable energy or energy efficiency.
4. Net-Zero (NZ) 2060 Scenario: In addition to meeting the 2030 NDC target, this scenario assumes net zero greenhouse gas emissions will be achieved in SA by 2060 through a linear reduction in emissions from 2030 onwards.

Table 11 from the reference study presents the modeled electricity generation in TWh by technology across the four scenarios examined. This allows to estimate the installed capacities of solar PV and wind technologies in each scenario using capacity factors for both technologies. The estimated installed capacities of solar PV and wind technologies are presented in Table 12.

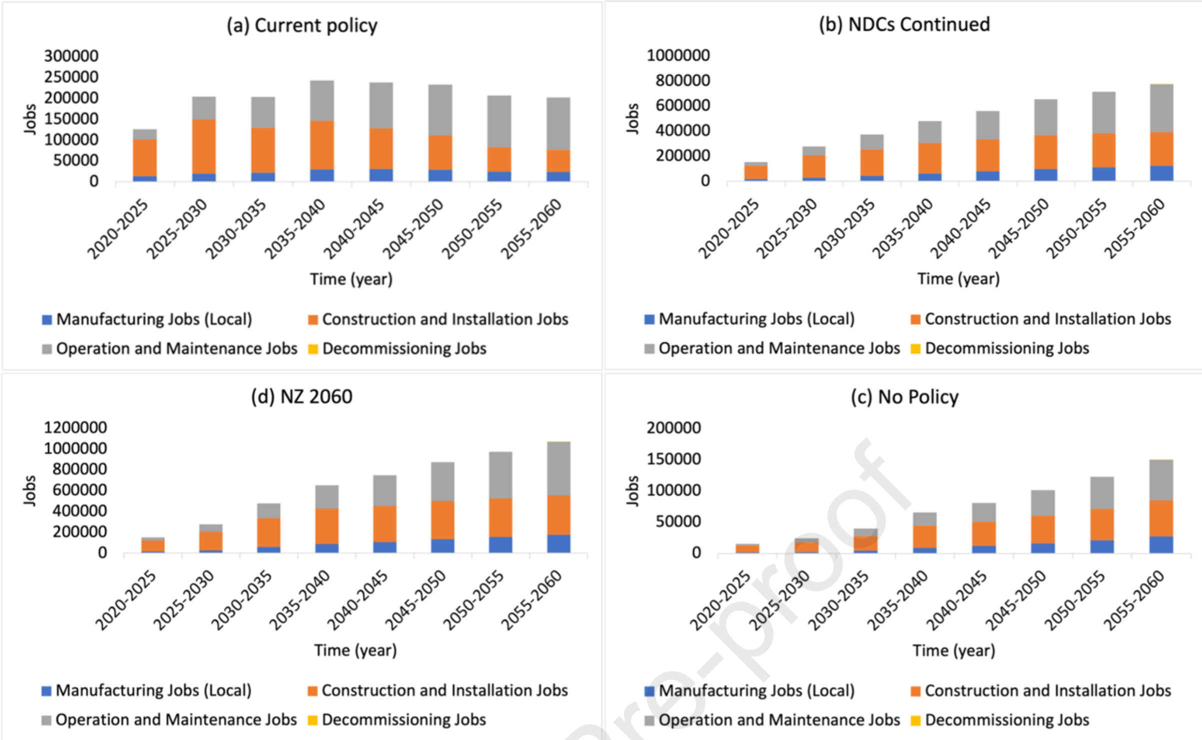



Figure 15. Solar PV Jobs based on different scenarios.

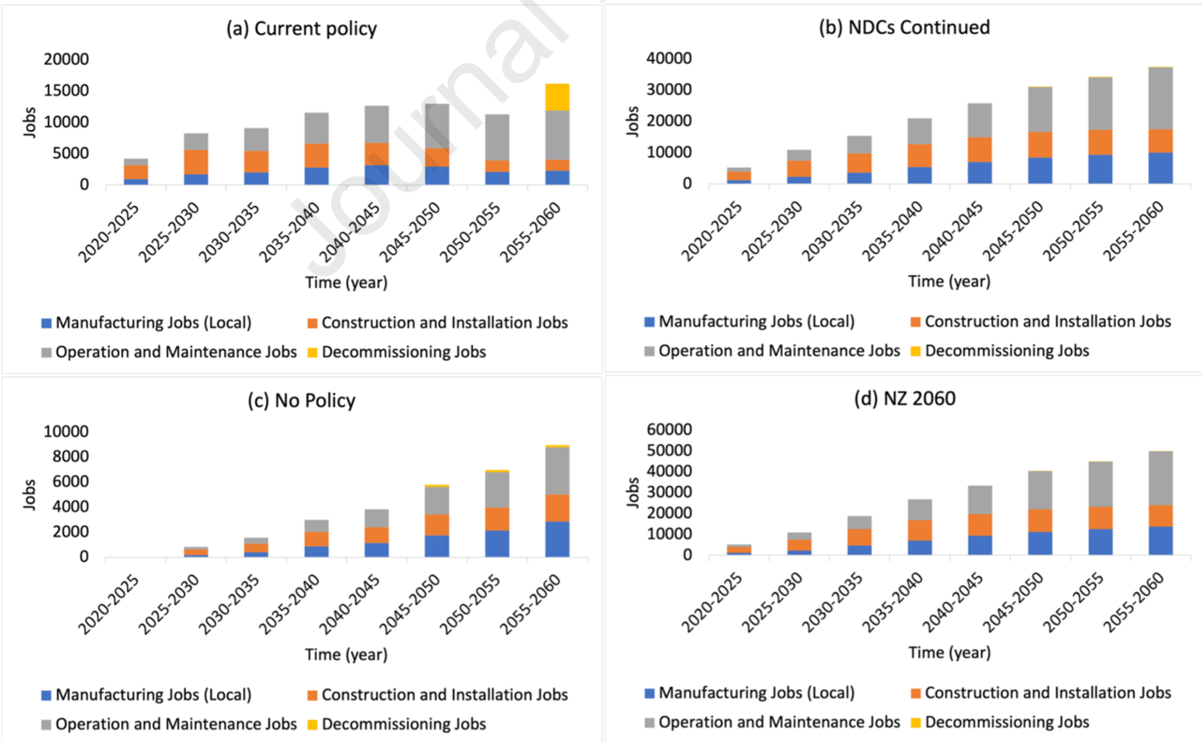



Figure 16. Wind energy Jobs based on different scenarios.

Table 11. Different scenarios solar PV and wind generation in TWh [106].

| Scenario | Technology | Generation (TWh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2020-2025 | 2025-2030 | 2030-2035 | 2035-2040 | 2040-2045 | 2045-2050 | 2050-2055 | 2055-2060 |
| Current Policy | Solar PV | 33 | 102 | 123 | 175 | 188 | 182 | 151 | 152 |
| | Wind | 4 | 9 | 10 | 13 | 14 | 12 | 8 | 8 |
| NDCs | Solar PV | 40 | 140 | 240 | 365 | 489 | 604 | 691 | 779 |
| | Wind | 5 | 12 | 18 | 25 | 31 | 34 | 35 | 35 |
| No Policy | Solar PV | 4 | 12 | 26 | 53 | 74 | 99 | 129 | 169 |
| | Wind | 0 | 1 | 2 | 4 | 5 | 7 | 8 | 10 |
| NZ 2060 | Solar PV | 40 | 139 | 318 | 510 | 661 | 815 | 952 | 1096 |
| | Wind | 5 | 12 | 23 | 33 | 41 | 45 | 47 | 48 |

Table 12. Different scenarios solar PV and wind estimated installed capacities (GW).

| Scenario | Technology | Capacity (GWh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2020-2025 | 2025-2030 | 2030-2035 | 2035-2040 | 2040-2045 | 2045-2050 | 2050-2055 | 2055-2060 |
| Current Policy | Solar PV | 15.07 | 46.58 | 56.16 | 79.91 | 85.84 | 83.11 | 68.95 | 69.41 |
| | Wind | 1.52 | 3.42 | 3.81 | 4.95 | 5.33 | 4.57 | 3.04 | 3.04 |
| NDCs | Solar PV | 18.26 | 63.93 | 109.59 | 166.67 | 223.29 | 275.80 | 315.53 | 355.71 |
| | Wind | 1.90 | 4.57 | 6.85 | 9.51 | 11.80 | 12.94 | 13.32 | 13.32 |
| No Policy | Solar PV | 1.83 | 5.48 | 11.87 | 24.20 | 33.79 | 45.21 | 58.90 | 77.17 |
| | Wind | 0.00 | 0.38 | 0.76 | 1.52 | 1.90 | 2.66 | 3.04 | 3.81 |
| NZ 2060 | Solar PV | 18.26 | 63.47 | 145.21 | 232.88 | 301.83 | 372.15 | 434.70 | 500.46 |
| | Wind | 1.90 | 4.57 | 8.75 | 12.56 | 15.60 | 17.12 | 17.88 | 18.26 |

The results of the social development analysis provide useful insights into the job creation potential associated with the increasing deployment of solar PV and wind energy under the different decarbonization pathways examined. They indicate that more ambitious climate targets correlating with higher renewable capacity additions, such as in the NDCs Continued and NZ 2060 scenarios, can translate to significant solar and wind employment opportunities.

As shown in Figure 15, the NDCs Continued and NZ 2060 scenarios project significant solar PV job creation. This corresponds with the substantial solar PV capacity scale-up indicated in these scenarios according to the electricity generation modeling. The NZ 2060 scenario, featuring the most ambitious renewables role, shows the highest number of solar PV jobs at approximately 5.22 million jobs. These jobs would result from the massive solar capacity build-out required to achieve net zero emissions by 2060.

A similar trend is observed for wind energy jobs creation as presented in Figure 16. The NDCs Continued and NZ 2060 scenarios demonstrate much higher employment opportunities in the wind sector compared to the No Policy and Current Policy scenarios. This job creation potential reflects the growing share of wind power projected to meet electricity needs as the decarbonization of the power sector deepens in the medium- to long-term time frame.

Construction and installation jobs constitute the highest share of employment across scenarios and technologies, contributing over 50% of total jobs in most cases. This indicates the significant labor required to physically build out the solar and wind projects. Operation and maintenance jobs are also a major component, ranging from 20-30% typically. This reflects the long-term employment sustained over the lifetime of the projects to carry out operations and repairs. Decommissioning jobs remain negligible given the models focus on timeframe up to 2060, before end-of-life is reached for many early projects. Over time, this job category can be expected to grow.

## 6. Resources Forecast

Solar resource forecast facilitates in incorporation of renewable-based power generation and contributes to reduction of uncertainty in electricity generation. In fact, the optimum configuration of a RE-based power generation unit is determined by the degree to which the RE source is available. The RE sources forecasting assists to reduce utilities maldistribution and ambiguity while making utility budgetary allocations. Therefore, a prediction model based on SVM is built in this study.

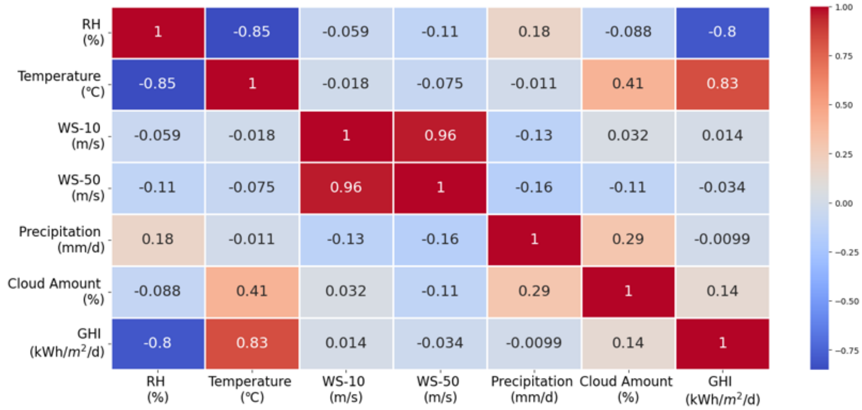



Figure 17. Features correlation with the GHI.

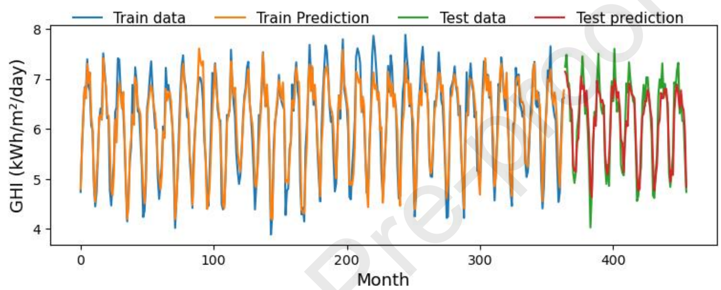



Figure 18. Forecasted GHI.

Table 13. Performance measures of the SVR model.

| Evaluation measure | Training dataset | Testing dataset |
|---|---|---|
| $R^2$ | 0.893 | 0.834 |
| MSE | 0.093 | 0.121 |
| RMSE | 0.006 | 0.022 |
| MAPE | 0.038 | 0.044 |

*6.1. Support vector machine model*

The support vector regression (SVR) establishes a relationship between the input data (independent variables) and the value of the features (dependent variables), based on structural risk minimization. In regression problems, the input vectors of multi-dimensional space are mapped; then a hyperplane is created that separates the input vectors from each other with the greatest possible distance. Further, kernel function is used to solve the problem of performing operations in a high-dimensional space. In fact, by using the kernel function, the problem of multidimensionality and non-linearity of the mapping is raised. The optimization process should be accompanied by a modified drop function, to include the distance measurement d. In fact, the goal of SVR is to estimate the parameters of the weights and the skewness of the function that best fits the data. The SVR, as presented in [107], finds the function f(x) which has at most one deviation ε with respect to the training samples ($x_i$, $y_i$), for *i* = 1, . . ., N, and which is as flat as possible. The function is given in Equation (17).

$$f(x) = w^T x_i + b \tag{17}$$

where $x \in \mathbb{R}^p$ is the input vector, $w \in \mathbb{R}^p$ is the vector of the parameters (or weights) and b is a constant to be determined.

To ensure the flatness of the function f(x), the norm of the weights $\|w\|$ is minimized (constraint on the derivative of the function f(x)). The problem therefore comes down to minimizing this norm by guaranteeing that the errors are less than ε and can be written as in Equation (18).

$$\begin{aligned} &\min_{w,b} \frac{1}{2}\|w\|^2 \\ s.c. \quad & y_i - (w^T x_i + b) \le \varepsilon, \quad i = 1, \dots, N \\ & (w^T x_i + b) - y_i \le \varepsilon, \end{aligned} \tag{18}$$

The objective of this problem formulation is not to minimize the learning error as in neural networks or most regression algorithms, as all the data exist within the boundary defined by ε. In practice, this is not always the case. In the presence of outliers, it is also important to allow some errors. The concept of soft margin is used in this case, which consists of introducing slack variables that represent positive and negative errors, and thus the formulation of the optimization problem becomes Equation (19).

$$\begin{aligned} &\min_{w,b} \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N}(\xi_i + \xi_i^*) \\ & y_i - (w^T x_i + b) \le \varepsilon, \\ s.c. \quad & (w^T x_i + b) - y_i \le \varepsilon, \quad i = 1, \dots, N \\ & \xi_i, \xi_i^* \ge 0, \end{aligned} \tag{19}$$

where, $\xi_i$ and $\xi_i^*$ are the slack variables, the constant C > 0 is a hyperparameter to adjust the trade-off between the allowable error the flatness of the function f.

This formulation of the problem amounts to using an error function $|\xi|_\varepsilon$ called ε-insensitive loss function illustrated in Equation (20). The optimization problem is then solved by Lagrangian (L) in Equation (21).

$$|\xi|_\varepsilon := \begin{cases} 0, & |\xi| \le \varepsilon \\ |\xi| - \varepsilon, & otherwise \end{cases} \tag{20}$$

$$L = \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N}(\xi_i + \xi_i^*) - \sum_{i=1}^{N}(\eta_i\xi_i + \eta_i^*\xi_i^*) - \sum_{i=1}^{N}\alpha_i\big(\varepsilon + \xi_i - y_i + (w^T x_i + b)\big) - \sum_{i=1}^{N}\alpha_i^*\big(\varepsilon + \xi_i^* + y_i - (w^T x_i + b)\big) \tag{21}$$

where $\eta_i$, $\eta_i^*$, $\alpha_i$, and $\alpha_i^*$represents the Lagrange multipliers, whereas w, b, $\xi_i$, and $\xi_i^*$ are the primal variables.

In this study, the historical daily average data over 21 years from 2000 to 2021, including temperature, RH, wind speed at 10 meters, wind speed at 50 meters, precipitation, and cloud amount, are retrieved from the NASA POWER database and utilized as features to build the SVR prediction model for the GHI prediction. Moreover, the data considered in the analysis pertains to Location2, which possesses the highest amount of GHI. The dependent and independent variables are divided into a training set (75% of the dataset) and a testing set (25%). The k-fold validation method, presented in [108], is applied to optimize the parameters of the SVR model.

The heat map presented in Figure 17 shows the highest positive correlation between GHI and temperature, while the relative humidity (RH) has the highest negative correlation with GHI. The SVR prediction model result is presented in Figure 18, and the evaluation measures, including $R^2$, mean squared error (MSE), root mean squared error (RMSE), and mean absolute percentage error (MAPE), are presented in Table 13.

## 7. Prospects and variability analysis

### *7.1. Sixth Coupled Model Intercomparison Project (CMIP6) projection*

CMIP6 is a set of high-quality climate model simulations that can be used to study the Earth's climate system and to assess the impact of climate change. One of the model goals is to produce projections of climate parameters such as solar irradiation, humidity, temperature, and wind speed [109]. Based on the results of the SVR prediction model, the most influential weather variables for solar and wind resources in SA were identified. However, this section focuses on utilizing the global projection of CMIP6 to forecast future climate scenario (2049 scenario) and their impacts on the solar and wind resources in SA. The projection of GHI, wind speed, and other influential weather parameters obtained from the CMIP6 model [110], and visualized in maps (Figure 19) using ArcGIS software will provide insights into the long-term sustainability of RE in SA.

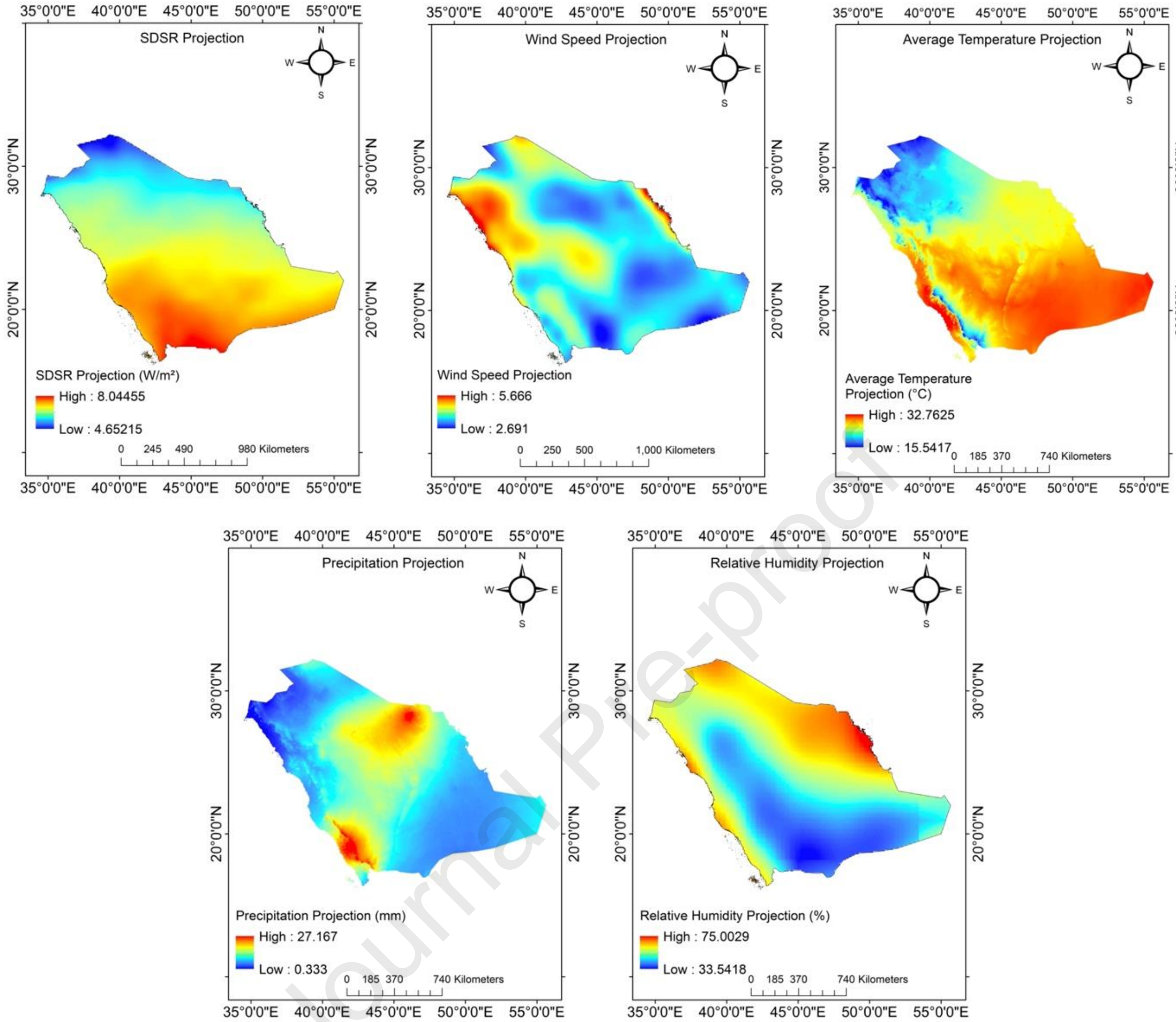


Figure 19. Climate parameters CMIP6 forecast.



The CMIP6 projections show that the GHI in SA is expected to increase by approximately 19% by 2049. The wind speed is also expected to increase by roughly 5% over the same period. This comparison is between the obtained solar irradiation and near-surface wind speed projections and the data retrieved from NASA POWER for the same location. However, the CMIP6 projections emphasizes that the GHI and wind speed are expected to increase in the future, which will further increase the potential for solar and wind energy generation in SA.

## 8. Conclusion

The demand for energy in SA is increasing rapidly and there is a need to find sustainable solutions to meet this demand. Solar and wind energy sources offer significant potential to address this issue while minimizing the environmental impact. In this study, an evaluation was conducted to assess the viability and prospects of solar PV and wind energy deployment in SA using GIS spatial analysis, techno-economic feasibility analysis, and machine learning-based resource forecasting. The approach provided comprehensive insights into the potential of solar and wind energy in the country, enabling evidence-based planning and risk assessment required for sustainable energy transition announced by SA government. To help achieve integrating RE in the country's energy mix, the study first identified the most promising sites using ArcGIS software considering various evaluation criteria. The sites suitability evaluation has identified four locations for solar PV, four locations for wind turbines, and one location for solar PV-wind hybrid systems in Al Jouf province. The solar PV locations are:

- Location1 (near Al Bida) in Tabuk province.
- Location2 (north of the city of Madinah) in Al Madinah province.
- Location3 (south of Shoqsan village) in Makkah province.
- Location4 (near Layla town) in Riyadh province.

The wind turbine locations are:

- Location1 (north of the city of Al Suwaidra) in Al Madinah province.
- Location2 (near the city of Ranyah) in Makkah province.
- Location3 (Dawadimi city) in Riyadh province.
- Location4 (Al Niqirah city) in Eastern province.

The land suitability assessment revealed that the above locations have the highest potentials for developing utility-scale solar PV, wind, and solar PV-wind hybrid power plants due to their abundant solar and wind energy sources, proximity to roads and grid networks, suitability of the land orography, and remoteness from the restricted areas. Investing in solar and wind energy in these nominated locations will have a positive impact on both sustainability and development. Beside clean production, the large capital investment required will also contribute to the socio-economic development and help to reduce greenhouse gas emissions. This is critical for achieving the UNSDGs related to affordable and clean energy, climate action, and sustainable cities and communities.

The techno-economic analysis proved that solar and wind energy are promising solutions to meet SA's increasing energy demands sustainably with minimal environmental footprint. The simulation results showed that the solar PV plant had the highest performance at Location2, while the wind farm performed best at Location1. However, all sites had negative NPV at the current PPA rates. Sensitivity analysis of PPA rates indicated that solar PV, wind energy, and hybrid solar PV-wind technologies are economically feasible in SA at PPA rates above $32.8/MWh, $26.1/MWh, and $50.6/MWh, respectively. Increasing the PPA price could increase the profitability of these projects, but other measures such as reducing installation and maintenance costs and exploring alternative financial models and policies should also be considered to create a more favorable market environment. The technical analysis also evaluated the optimal tilt angle for solar PV panels installed in the identified locations through simulation modeling. Optimizing the tilt angle is important for maximizing solar irradiance and energy generation from PV systems. The results showed that tilt angles close to the local latitude performed best, providing guidance on system design to capture highest sun exposure. The significant results are:

- Solar PV plant performed best at Location2, with an annual energy output of 726.638 GWh.
- Wind farm performed best at Location1, with an annual energy output of 1.494 TWh/year.
- Hybrid solar PV-wind technology exhibited a higher technical performance than the solar PV system, with a CF of 35.6%.
- All sites had negative NPV at the current PPA rates of $23.4/MWh for solar PV, $21.3/MWh for wind energy, and $20/MWh for hybrid solar PV-wind technology.
- Solar PV, wind energy, and hybrid solar PV-wind technologies are economically feasible in SA at PPA rates above $32.8/MWh, $26.1/MWh, and $50.6/MWh, respectively.

Additionally, the social development analysis provided valuable insights into the employment opportunities associated with increasing deployment of solar and wind energy under different decarbonization pathways. More ambitious climate targets correlated with higher renewable capacity additions, translating to substantial solar and wind job creation potential. Large-scale jobs in manufacturing, construction and long-term operation of utility-scale projects provide opportunities for workforce training and development. This supports Saudi Arabia's long-term goals for economic diversification and social reform outlined in its Vision 2030 plan. The findings indicate that scaling up clean energy production through solar and wind can help address unemployment challenges while contributing to a thriving low-carbon economy.

SVM model was developed in this study to forecast the GHI in SA. The SVM model was trained on historical data from 2000 to 2021, and the results showed that the model was able to accurately predict the GHI with an R-squared value of 0.893. The CMIP6 model was then used to project the GHI in SA for the year 2049. The results of the CMIP6 model showed that the GHI is expected to increase by approximately 19% by 2049. The wind speed is also expected to increase by roughly 5% over the same period. These results suggest that the potential for solar and wind energy generation in SA is expected to increase in the future. These findings have several implications for the development of RE in SA. First, the results of the SVM model suggest that the GHI in SA is relatively stable and can be accurately predicted. This means that solar and wind energy can be reliable sources of power generation in SA. Second, the results of the CMIP6 model suggest that the GHI and wind potentials are expected to increase in the future. However, the results of this phase suggest that SA has a significant potential for RE generation. The SVM model developed in this study can be used to accurately predict the GHI in SA, and the CMIP6 model can be used to project the GHI in SA for future years. These models can be used to help decision-makers make informed decisions regarding the deployment of solar and wind farms in SA.

The strength of this study lies in its methodology and the potential for its application beyond the Saudi Arabian case study. Moreover, the study highlights the importance of considering a site's geographical features and meteorological data to optimize the design and operation of RE systems. Therefore, the insights and roadmap developed in this study can be applied to other parts of the world by adapting the methodology to the specific location's characteristics. This approach can contribute to the successful deployment of RE systems worldwide, providing a valuable tool for decision-makers and stakeholders in the RE sector, and support the UNSDGs.

This study sheds significant light on the potential of solar and wind energy in SA, paving the way for a sustainable and secure energy future. However, it's crucial to acknowledge that certain limitations, including reliance on typical cost assumptions and lack of consideration for energy storage and grid integration issues. Further research is crucial to address remaining uncertainties and opens the door for a deeper exploration of various aspects related to RE integration in the country. Therefore, the study recommends the following:

- Considering location-specific capital and operating costs based on the Saudi Arabian market.
- Optimizing hybrid RE system design through integration of energy storage.
- There is a need for continued research and development to improve the efficiency and reduce the costs of RE technologies. This will make RE more competitive with fossil fuels and make it more affordable for consumers. Future endeavors should identify the key areas where research and development are needed to improve the performance of RE technologies.
- Identifying policies and regulations required to incentivize private sector investments in RE development.
- Study the potential for integrating RE with other energy sources, such as fossil fuels and nuclear power.
- Address the environmental impacts of RE development.

A significant conclusion of this research is that solar and wind energy represent viable and promising solutions for sustainably meeting SA's growing energy demands. However, higher PPA rates, reduced costs, alternative financing models, and supportive policies are needed to make large-scale RE projects economically feasible and accelerate the energy transition in the country.

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**Highlights**

- Utilized GIS & machine learning for RE planning.
- Developed novel SVM model for RE forecasting.
- Conducted techno-economic feasibility of PV & wind.
- Identified suitable locations for RE in Saudi Arabia.
- Provided roadmap for sustainable energy transition.

**Declaration of Interest Statement**

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article. We also declare that we have no conflicts of interest to disclose.

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