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By

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# *Opportunities and challenges of Promoting Renewable Energy in Tunisia*

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# Abstract

The global shift towards renewable energy sources is gradually phasing out traditional energy sources, leading to increased measures for mitigating climate change and reducing carbon footprints by leveraging wind and solar resources for power generation. This transition is reflected in the widespread establishment of wind and solar farms for large-scale energy production across various countries. Prior to harnessing these resources, a meticulous site suitability process is critical to determining the optimal locations for their facilities. In this regard, by blending policymakers' views with experts' opinions, GIS and MCDM models are valuable tools for spatial analysis. As a result, they have become increasingly popular for land suitability and siting applications, including planning for large-scale solar and wind power plants.

Due to its favorable geographical and climatic conditions, Tunisia offers vast potential for solar energy, presenting a promising opportunity for the development of solar and wind power projects. However, maximizing efficiency and return on investment requires careful consideration of the most optimal locations for these costly renewable energy projects. This involves navigating complex parameters such as technical requirements, economic viability, and environmental impact. In order to effectively address these challenges, this thesis delves into four intertwined problems associated with Tunisian renewable energy planning using a GIS-based MCDM approach. The first problem (Chapter 3) examined the viability of implementing large-scale solar power facilities in Tunisia, with particular emphasis on the Kasserine and Tataouine regions. In a similar vein, the second problem (Chapter 4) pertained to the evaluation of the appropriateness of locations for utility-scale onshore wind systems at the regional and national scales. Next, the third problem (Chapter 5) conducts a comprehensive investigation into the installation of PV-CSP, PV-Wind, and CSP-Wind hybrid renewable energy systems in Kasserine and Tataouine. Lastly, the fourth problem (Chapter 6) focused on the prioritization of the most feasible renewable energy technologies and the identification of the primary obstacles that hindered their implementation in Tunisia.

The study revealed that around 17.6% of Tunisia's total land offers favorable conditions for solar photovoltaic projects, with Kasserine and Tataouine emerging as particularly promising

regions for sustainable solar infrastructure. Furthermore, it indicated that the identified optimal sites have the potential to generate an estimated annual energy yield of 1059.7 TWh. Detailed projections show that the output power from PV and CSP in Kasserine could reach 130 TWh/yr and 138 TWh/yr, respectively, while even higher values were predicted in Tataouine at 260 TWh/yr and an impressive 752 TWh/yr, respectively.

As for onshore wind, it was found that around 6912 $km^2$ (4.39% of Tunisia's territory) was highly suitable. Kasserine and Tataouine stood out with significant potential, boasting the best-suited areas covering 612 $km^2$ and 500 $km^2$, respectively. It is estimated that the national wind technical power could reach a remarkable 72282 GWh per year, while specific sites in Kasserine and Tataouine are predicted to generate between 6127 and 7511 GWh annually.

Furthermore, concerning hybrid systems, including PV-CSP, PV-Wind, and CSP-Wind, the findings revealed promising sites covering an area between 50 and 189 $km^2$ in Kasserine as well as a range of 74.5 to 192 $km^2$ in Tataouine. Interestingly, it was noted that Tataouine is particularly conducive to CSP-Wind with a potential annual energy output of 76415 GWh, while Kasserine emerged as an ideal location for PV-CSP with an impressive annual energy yield of 58008 GWh.

Finally, the results indicated that solar PV emerged as the most viable option, followed closely by onshore wind. In addition, limited access to finance, high initial costs, political instability, and a lack of institutional coordination were recognized as significant barriers to the widespread adoption of these technologies in Tunisia.

By taking into consideration these results, policymakers can take the initiative to rapidly deploy these facilities to help achieve the country's 2030 goals.

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***I dedicate this thesis:***

***To my beloved son Mohammed***

***To the soul of my beloved mother***

***To the memory of my father***

***To my wife***

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## Abbreviations

| | |
|---|---|
| *AHP* | Analytical hierarchy process |
| *ANP* | Analytic network process |
| *CAPEX* | Capital expenditures |
| *CI* | Consistency's value Index |
| *COPRAS* | Complex Proportional Assessment of alternatives |
| *CR* | The Consistency Ratio |
| *CRITIC* | CRiteria Importance Through Inter-Criteria Correlation |
| *DEA* | Data envelopment analysis |
| *DEMATEL* | Decision-Making Trial and Evaluation Laboratory |
| *EDAS* | The evaluation based on distance from average solution |
| *ELECTRE* | ELimination Et Choix Traduisant la REalité |
| *FAHP* | Fuzzy analytical hierarchy process |
| *GIS* | Geographical information system |
| *IRR* | Internal rate of return |
| *MABAC* | Multi-attributive border approximation area comparison |
| *MAUT* | Multi-Attribute utility Theory |
| *MCDM* | Multi-criteria decision making |
| *Mtep* | Million-Ton Equivalent of Petroleum |
| *LCOE* | Levelized cost of energy |
| *OPEX* | Operating expenditures |
| *OWA* | Ordered weighted averaging |
| *PROMETHEE* | Preference Ranking Organization Method for Enrichment Evaluations |
| *RES* | Renewable energy sources |
| *RETs* | Renewable energy technologies |
| *RI* | Random Consistency Index |
| *SAW* | Simple Additive Weighting |
| *SWARA* | Step-wise Weight Assessment Ratio Analysis |
| *TOPSIS* | Technique for Order preference by similarity to ideal solution |
| *VIKOR* | VIseKriterijumska Optimizacija I Kompromisno Resenje |
| *WASPAS* | Weighted Aggregated Sum Product Assessment |
| $n$ | Number of criteria |
| $\lambda_{max}$ | Maximum eigenvalue |

# General Introduction

With the exponential growth of the world population and ongoing economic expansion, there has been a significant increase in energy consumption. This surge has had severe implications for the planet's climate system due to the extensive use of fossil fuels, which form the core of contemporary energy infrastructure (IPCC, 2018). This reliance on fossil fuels has led to a climate emergency that poses a threat to global ecosystems and socio-economic stability. Global primary energy consumption is a reflection of humanity's choices on energy sources, including fossil fuels (coal, oil, and natural gas), nuclear power, and renewable sources such as biomass, hydro, wind, solar. It acts as a barometer for economic progress and societal well-being while also reflecting environmental stewardship. The intricate relationship between these factors requires close examination of current trends and potential trajectories in global primary energy usage (Smil, 2017). Even today, fossil fuels continue to be the main source of global energy supply with approximately 80% share (REN21, 2023). Despite the increasing contribution of renewable energy sources like wind and solar power, coal, oil, and natural gas still dominate due to their integral role in key sectors such as transportation, electricity generation, and industrial processes. However, the surge in CO2 emissions has raised concerns about the future dominance of fossil fuel (IEA, 2020).

Yet, with the increasing focus on tackling issues associated with climate change, renewable energy sources have been steadily gaining momentum worldwide, especially in countries heavily reliant on traditional fossil fuels attempting to decrease their national carbon footprints (Adedeji et al., 2020a; Kung et al., 2019). As the drawbacks of conventional sources become more apparent, there has been increasing research focused on incorporating renewable energy into various sectors, including power generation, to address its significant energy consumption (Dunmade et al., 2019; Liang et al., 2013). Despite their intermittency and variability, technologies for harvesting solar and wind energies are becoming more acceptable due to their high availability index and pollution-free operation (Adedeji et al., 2020a; Esposito & Romagnoli, 2023). However, meeting the ongoing demand for energy across domestic, industrial, and other sectors necessitates creating a nexus between these various energy sources. Additionally, given that certain RES like solar and wind power depend on resource abundance, which can vary by location, it's crucial to conduct thorough investigations into areas seemingly abundant in RES while ensuring no conflicts with environmental factors or features in viable sites. This underscores the importance of integrating location science into exploring renewable energy through land suitability analysis.

Identifying the most appropriate locations for exploring renewable energy sources is multifaceted and involves considering conflicting variables (Al Garni & Awasthi, 2018; Al Garni & Awasthi, 2017; Badi et al., 2021). This approach ensures that the investment in these resources is environmentally safe, socially acceptable, financially viable, and supportive of relevant policies. Within the realm of multi-criteria decision-making, there are two primary perspectives through which it can be approached: multi-attribute decision-making (MADM) and multi-objective decision-making processes (MODM). MADM models focus on selecting the best alternative from a predefined set based on specific criteria for selection, while MODM models leverage mathematical programming to derive an optimal solution within defined constraints (Adedeji et al., 2020b; Kumar et al., 2017). The flexibility and robustness of these methods make them well-suited for addressing energy system challenges by integrating input from multiple decision-makers and providing valuable insights into the issue at hand from various viewpoints (Ilbahar et al., 2019, Shao et al., 2020).

With the continuous expansion of the global economy and rapid population growth, relying solely on fossil fuels for electricity generation is not a sustainable strategy. The increasing demand necessitates additional energy resources to meet it, but this would lead to greater dependence on finite fossil fuel reserves, environmental pollution, and high lifecycle costs associated with traditional power systems. To tackle these challenges, integrating hybrid electrical systems that combine fossil fuels with renewable energy sources can offer a more sustainable solution while addressing issues such as intermittency and disparities in energy density linked to alternative energies. This requires effective planning of accessible renewable energy sources that can significantly contribute to an enhanced future for the energy sector. Yet, in recent years, there has been a significant increase in the adoption of wind and solar PV resources compared to other renewable energy sources. This surge can be attributed to advancements in technology and the identification of more viable sites for large-scale exploration. Technological improvements have played a crucial role in enhancing the uptake of wind and solar resources. In the past twenty years, Tunisia has made commitments to incorporate green economic strategies into its national planning and policies (Gardumi et al., 2021; Saadaoui & Chtourou, 2022). The country has utilized its accumulated scientific knowledge and technical experience in renewable energies to raise awareness among its population. Tunisia has the potential to lead the adoption of RES through partnerships between international and local entities, potentially positioning itself as a hub for clean energy (Banacloche et al., 2020; Benasla et al., 2019; Souissi, 2021). However, the adoption of these technologies has faced challenges, including poor governance, prolonged socio-political unrest, financial limitations, economic difficulties, and a lack of financing mechanisms. As such, several projects have been either shelved or cancelled. Given Tunisia's geographical advantages, transitioning to clean energy presents diverse opportunities to solidify energy reliability in Tunisia and reduce reliance on fuel imports while countering climate change's drastic impacts. Moreover, RES has a significant potential impact on Tunisia's social and economic landscape (Krarti, 2020; Lehr et al., 2016; Omri et al., 2022; Rekik & El Alimi, 2023; Rocher & Verdeil, 2019). As such, developing renewable energy projects can lead to direct and indirect employment, which stimulates local communities and contributes to sustainable development goals (Cameron & Van Der Zwaan, 2015).

In recent years, Tunisia has shown an incremental interest in prioritizing and promoting its renewable resources. The government has pledged to install 4.7 GW (15% wind, 15% solar PV, and 5% solar CSP) of its electricity generation from renewable energy by 2030 in an attempt to ensure its energy security, diversify its mix, decrease its imports, and rationalize energy subsidies. This ambitious transition highlights the nation's commitment to sustainable development and reducing reliance on traditional sources of power. To this end, the government has already authorized numerous PV and onshore wind projects with capacities ranging from 10 MW to 200 MW without specifying their locations (JCR, 2019). Yet, the challenges lie not just in setting targets but also in ensuring that the chosen locations for implementing renewable projects are viable considering various factors such as meteorological patterns, environmental impact assessment, and economic viability, among others. It is important to consider that sites with abundant solar or wind potential might not always be feasible for installation due to several interconnected variables, with weather conditions being just one aspect. Therefore, careful consideration must be given when choosing a location for these types of green energy projects to maximize their output while minimizing costs.

This study encompasses a comprehensive assessment of various environmental, geomorphological, meteorological, and economic factors that impact solar and wind power plant projects. Furthermore, it delves into an in-depth evaluation of four prominent renewable energy options for electricity generation and investigates the significant barriers impeding their progress in Tunisia. The findings from this research will make a substantial contribution to land use planning at local, regional, and national levels. It aims to provide valuable insights for policymakers, investors, and decision-makers interested in advancing solar and wind power initiatives.

The significance of this research lies in its comprehensive approach to addressing the critical need for sustainable energy solutions through the optimal siting of either single technologies or hybrid renewable energy systems. It presents an essential contribution to the renewable energy field, offering a viable pathway towards a more sustainable and less carbon-intensive energy future through meticulous site selection and the strategic deployment of hybrid energy systems.

The study stands out in its approach in several key aspects. The combined use of GIS and MCDM tools like the AHP, FAHP, SWARA, and DEMATEL provides a robust and systematic framework for evaluating, prioritizing potential sites, and exploring the most potential barriers hindering their development based on a range of relevant criteria. This multidisciplinary method is innovative within the realm of renewable energy site selection research. By examining the combination of solar and wind energy technologies, the study addresses the intermittency issues commonly associated with renewable energy sources. The focus on hybrid systems ensures that energy production is more stable and reliable, increasing the practicality of renewable energy adoption. Moreover, the comprehensive assessment of land suitability that includes environmental, economic, and social factors, among others, showcases how complex decision-making processes can be simplified and made more transparent, thus aiding stakeholders in making informed decisions. In addition, the identification of suitable sites for large-scale deployment of either single technologies or hybrid systems has significant implications for energy independence and security. This could reduce reliance on imported fuels, contributing to national energy sovereignty and economic stability. For the specific case of Tataouine and Kasserine, and by extension, Tunisia, the study demonstrates how regions with favorable renewable energy conditions can exploit these natural resources to foster economic growth and regional development. Interestingly, the methodology used in this study can be adapted and applied to other geographic locations, making the findings globally relevant and providing a model that can be replicated for identifying potential sites for hybrid renewable energy systems elsewhere. Finally, the study provides empirical data and insights that can assist policymakers in strategic planning and decision-making for the large-scale integration of renewable energy systems, taking into account not just the technical aspects but also socioeconomic and environmental considerations. Furthermore, by identifying and addressing the most prominent barriers to implementing renewable energy technologies in Tunisia, it would be possible to foster their adoption and establish a sustainable and renewable energy future.

As previously stated, the main objective of this thesis is to provide a comprehensive elaboration on GIS-based MCDM methodologies for identifying the most suitable locations for large-scale renewable energy systems, taking into account the intricate nature and unpredictability inherent in decision-making processes. The structure of the thesis is as follows:

**Chapter I:**

This chapter offers insights into the importance of transitioning to sustainable energy sources by presenting a concise summary of their progress on both international and domestic scales. It also presents a more comprehensive outlook on the backdrop of increasing energy requirements, climate change, and sustainability objectives. Furthermore, it highlights the pivotal role of GIS-based MCDM approaches in energy planning, specifically focusing on assessing the land use intensity associated with various energy technologies.

**Chapter II:**

This chapter emphasizes the critical role of GIS and MCDM methods in evaluating potential future geographical sites for power plants, while also identifying the various challenges to their implementation. It offers a comprehensive overview of the methodology, illustrating how each component fits together to tackle the core objective of this thesis. The subsequent sections provide an in-depth exploration of the different criteria and detailed elaborations on the application of various MCDM methods, including AHP, FAHP, CRITIC, EDAS, SWARA, and DEMATEL.

**Chapter III:**

This chapter analyzes large-scale solar systems' spatial suitability. The first stage involves utilizing an integrated GIS-FAHP model to analyze Tunisia's entire territory meticulously, identifying optimal locations for constructing these systems. Afterwards, a combined GIS-AHP method is employed to assess land suitability for utilizing solar energy technologies, photovoltaics, and concentrated solar power in Kasserine and Tataouine.

**Chapter IV:**

This chapter employs a GIS-based multi-criteria decision-making approach to develop a spatial suitability analysis in Tunisia, specifically focusing on the Kasserine and Tataouine regions. The main objective is to identify well-suited locations for deploying large-scale wind farms by considering various criteria, such as wind speed, distance from infrastructure, and environmental impact.

**Chapter V:**

This chapter thoroughly evaluates the feasibility of deploying solar and wind hybrid facilities in the regions of Kasserine and Tataouine. It utilizes an integrated GIS-based Analytic Hierarchy Process approach to identify optimal locations for these renewable energy installations, providing valuable insights that significantly contribute to decision-making processes related to site selection. The ultimate goal is to unlock the full potential of renewable energy in these regions through meticulous planning and strategic choices.

**Chapter VI:**

Given the pressing need to thoroughly assess and select the most viable renewable technology, this chapter aims to develop a decision support system using a CRITIC-EDAS method for prioritizing renewable energy options for electricity generation in Tunisia. In addition, the SWARA-DEMATEL model was used to identify and prioritize the major obstacles to their adoption in the country.

**Chapter VII:**

This chapter provides recommendations and summarizes the key findings of the thesis based on the established objectives. It restates the main argument and emphasizes the most significant evidence gathered during this research. Additionally, the chapter offers suggestions for future research on the interplay between energy, economy, and sustainability.

Publications derived from this thesis have been presented.

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# Chapter I: Global and National Overview

## 1.1 Introduction

Energy is a key factor in the pursuit of a sustainable future. The dynamic forces of the expanding global economy, industrial revolution, population growth, urbanization, and improved living standards have all led to an unprecedented surge in energy demand, prompting widespread international concern on future consumption trends (Güney, 2021; Martins et al., 2021).

This surge has had severe implications for the planet's climate system due to the extensive use of fossil fuels, which form the core of contemporary energy infrastructure (IPCC, 2018). This reliance on fossil fuels has led to a climate emergency that poses a threat to global ecosystems and socio-economic stability. Global primary energy consumption is a reflection of humanity's choices on energy sources, including fossil fuels (coal, oil, and natural gas), nuclear power, and renewable sources such as biomass, hydro, wind, solar. It acts as a barometer for economic progress and societal well-being while also reflecting environmental stewardship. The intricate relationship between these factors requires close examination of current trends and potential trajectories in global primary energy usage (Smil, 2017).

The undeniable impact of escalating energy demand on the environment is evidenced by the increasingly severe effects of climate change. Unprecedented heat waves, shifts in precipitation patterns, and the occurrence of extreme weather events are all linked to the excessive use of conventional fuels (Khan et al., 2019; Martins et al., 2019). Therefore, the heavy reliance on fossil fuels has far-reaching consequences that require urgent attention and innovative solutions. As such, curbing carbon emissions and transitioning to renewable energy cannot be overstated in addressing these environmental challenges.

The urgent need to reduce greenhouse gas emissions and mitigate the impacts of climate change highlights the critical importance of adopting sustainable energy alternatives. Renewable energy sources have become indispensable substitutes for conventional fossil fuels, offering a more environmentally friendly and sustainable solution to meeting society's growing energy needs (Barreto, 2018; Holechek et al., 2022; Marques et al., 2018;Mufutau Opeyemi, 2021).

A diverse range of renewable energy sources, including solar power, wind power, geothermal power, and biomass, hold great potential for providing clean and sustainable energy solutions

(Ang et al., 2022; Nataša A. Kablar, 2019; Rahman et al., 2022; Sayed et al., 2021). Solar energy captures sunlight through photovoltaic cells and solar thermal systems to generate electricity and heat. Wind power makes a significant contribution to the global mix of renewable energy sources by converting kinetic energy into electricity using wind turbines. Geothermal energy taps into the Earth's heat for power generation by utilizing natural steam beneath the earth's surface providing a consistent and reliable source of clean energy. Derived from organic materials like wood chips and agricultural residues; biomass offers a renewable source of bioenergy while also helping in waste management processes.

Investing in these alternative energies brings a variety of advantages, including decreased greenhouse gas emissions, ensuring energy security, and job creation (Aleixandre-Tudó et al., 2019; Guchhait & Sarkar, 2023; Ogunrinde et al., 2018; Wei et al., 2022). Moreover, strategic site selection plays key role in optimizing renewable energy projects by determining the most suitable locations for these facilities. In this context, Geographic Information System (GIS) and Multi-Criteria Decision Making (MCDM) tools have proven invaluable in identifying optimal sites for renewable energy installations based on factors like solar radiation, wind speeds, topography features, and transport and grid infrastructure (Aghaloo et al., 2023; Elkadeem et al., 2021; Shao et al., 2024; Shao et al., 2023; Shorabeh et al., 2022).

This chapter provides an understanding of the need for a move towards renewable energy resources by giving a brief overview of their development at the global and national levels. It provides a broader perspective on the context of rising energy demand, climate change, and sustainability goals. It also outlines the role of GIS in energy planning in terms of the land use intensity of different energy technologies

## 1.2 Climate Change

The global energy demand has continued to rise significantly with fossil fuels maintaining a pervasive influence, as illustrated in Fig. 1.1. In light of this growing global demand for energy and the concerning effects of climate change have made it necessary to urgently transition towards renewable energy sources (RES).

Human-induced climate change has emerged as one of the most urgent global environmental concerns of the 21st century. Scientists widely agree that the rapid warming of the planet is primarily caused by the increase in greenhouse gas emissions from human activities (IPCC, 2018). Rapid economic growth is theoretically associated with higher energy consumption, primarily derived from fossil fuels, leading to greenhouse gas emissions, as illustrated in Fig. 1.1. The impacts of climate change are becoming evident through altered weather patterns worldwide. Rising global temperatures are exacerbating extreme weather events such as hurricanes, heat-waves, droughts, and heavy precipitation, leading to extensive consequences for communities, ecosystems, and economies (NOAA, 2021). Yet, these trends are expected to persist with more frequent and severe extreme events (IPCC, 2021).

Climate change poses a threat to biodiversity, leading to irreversible damage to ecosystems such as coral reefs (Hughes et al., 2017; Urban, 2015). Both terrestrial and marine species are facing habitat changes, food scarcity, and an increased risk of extinction (Ceballos et al., 2017). Human health is also affected, with rising temperatures contributing to air pollution, heat-related illnesses, and the spread of disease (Watts et al., 2015). Climate change also impacts agriculture, threatening the food supply and increasing the risk of malnutrition (Myers et al., 2017). Economically, climate change disrupts supply chains, damages infrastructure, and reduces labor productivity, with the potential to reverse economic development and exacerbate global inequalities (Hsiang et al., 2017; WBG, 2010). The cost of inaction is projected to be substantial, emphasizing the need for immediate interventions (Stern, 2015).

At the national level, Tunisia's susceptibility to climate variability and change is tied to its reliance on agriculture and tourism; agriculture accounts for 14% of the country's gross domestic product (GDP) and employs approximately 19% of the workforce, while tourism accounts for 6.5% of GDP and directly supports 6% of Tunisia's workforce (IEA, 2020; WBG, 2021). Likewise, tourism faces serious climate change impacts as a water-intensive industry (Amamou et al., 2018; Mechri & Amara, 2021). Coastal regions, which are home to nearly 90% of tourist activity, are endangered by erosion, high sea levels, and the loss of beaches due to prolonged heat waves. Moreover, water scarcity and the increasing need for electric cooling systems put further strain on tourism facilities, which would lead to rising costs for energy, transportation, food, etc. (Mechri & Amara, 2021; WBG, 2021).

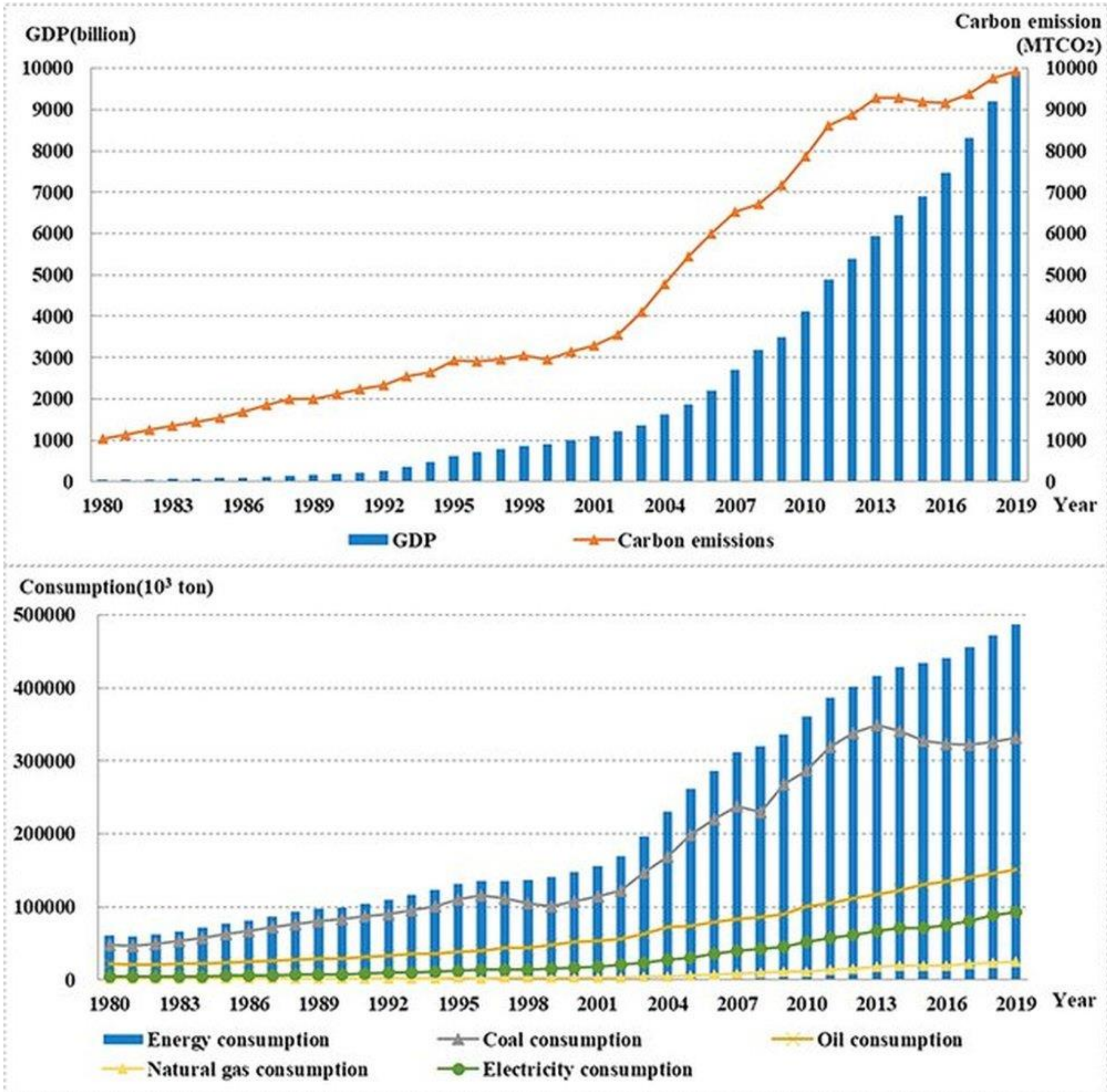


*Fig. 1.1 GDP-Energy Demand-Carbon Emissions nexus (Ma et al., 2022)*

## 1.3 Common renewable energy Sources

Renewable energy sources, such as solar, wind, hydro, and geothermal, represent key pillars in the quest for clean energy solutions, addressing energy security, environmental concerns, and the imperative to mitigate climate change impacts. The following subsections below provide further insight into their characteristics, current status, and future prospects.

- **Solar PV**

Solar PV technology has emerged as a frontrunner in the renewable energy sector, revolutionizing electricity generation with its clean and abundant source of energy (Jaeger, 2021). The growth of solar PV has been remarkable in recent years, with approximately 175 GW of solar PV capacity added globally in 2021 alone, resulting in a total installed capacity exceeding 942 GW (IRENA, 2023). Leading countries such as China, the USA, and India have played significant roles in promoting the expansion of this renewable energy source (IRENA, 2023). Policies and incentives like feed-in tariffs, net metering, tax benefits, and renewable portfolio standards have been instrumental in encouraging investment in solar PV projects by providing regulatory certainty and reducing financial risks (Kılıç & Kekezoğlu, 2022; Mundaca & Samahita, 2020; Wen et al., 2020). These measures have facilitated market growth for solar PV to establish itself as a mainstream energy source across various regions.

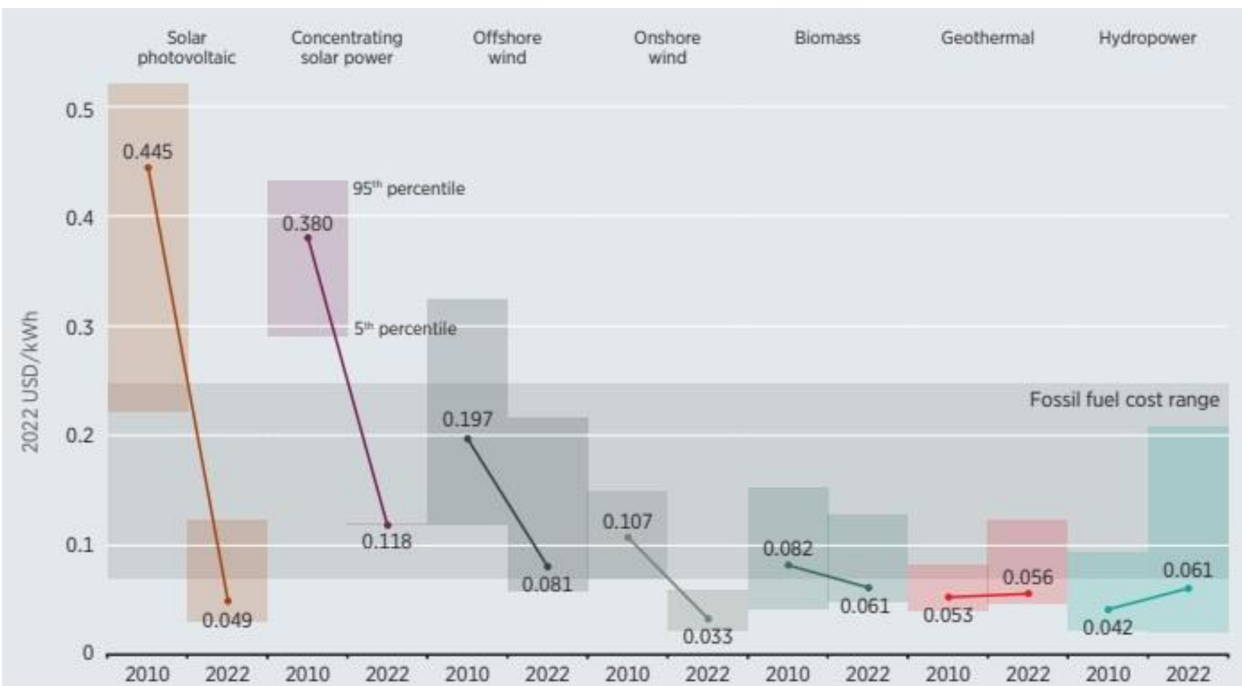


*Fig. 1.2 Global LCOE from newly commissioned utility-scale RETs (IRENA, 2023)*

The future prospects of solar photovoltaic appear promising, with various driving factors leading to its continued expansion and integration into the global energy mix (Nayak et al., 2019; Shubbak, 2019; Wilson et al., 2020). Ongoing research and development efforts continue to push the boundaries of solar PV technology, with advancements in energy storage and emerging technologies like bifacial panels, floating solar, and building-integrated PV systems offering potential for expanded applications and increased efficiency (Durusoy et al., 2020; Gagliano et al., 2021; Kumar et al., 2019; López et al., 2022; Luceño-Sánchez et al., 2019; Maghrabie et al., 2021; Oliveira-Pinto & Stokkermans, 2020; Raina et al., 2021; Singh et al., 2021; Yin et al., 2021). Additionally, as costs continue to decline, there is an increasing likelihood that solar PV will reach cost parity with conventional electricity generation in many regions (Wang et al., 2022). This achievement of grid parity could serve as a catalyst for widespread adoption and further drive the integration of solar PV into mainstream energy systems. Furthermore, PV's inherent modularity and scalability make it well-suited for decentralized energy systems (Asif, 2022; Casquiço et al., 2021). The concept of distributed generation through rooftop solar installations and community solar projects not only enhances energy resilience but also contributes to reducing transmission losses while empowering energy consumers (Galvan et al., 2020; Wang et al., 2022). As decentralized energy systems gain prominence, the role of solar PV becomes pivotal in enabling energy democratization and local energy production. Lastly, it cannot be overlooked that the global shift towards electric vehicles (EVs) offers a potential opportunity for solar PV, particularly in powering EV charging stations (Boström et al., 2021; Diahovchenko et al., 2022).

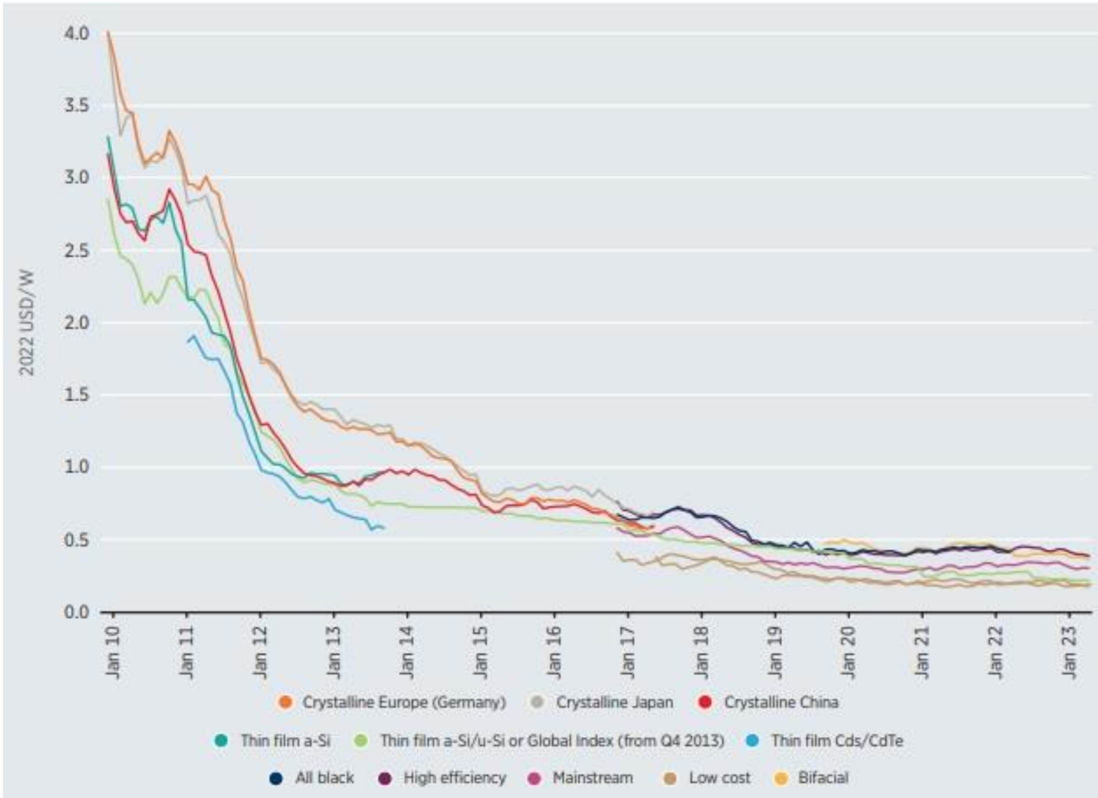


*Fig. 1.3 solar PV module prices by technology and manufacturing country (IRENA, 2023)*

- **Solar CSP**

CSP technology relies on concentrating sunlight onto a receiver to generate heat that powers a turbine for electricity generation, offering particular potential in regions with high solar irradiation (Fernández et al., 2019; Islam et al., 2018). Although not as extensively deployed as solar PV technology, CSP has been implemented in various countries, such as Spain, the United States, Morocco, South Africa, and the United Arab Emirates. Notably, Spain has taken the lead in CSP development, with several large-scale plants demonstrating the capabilities of this technology (IRENA, 2023). One advantage of CSP is its thermal energy storage capability, which allows for power generation even when there is no sunlight available. With this, it is apparent that the future outlook for CSP energy appears promising, with various factors indicating potential for further expansion (Khan et al., 2023; Xu et al., 2022).

Ongoing technological progress is focused on enhancing the efficiency and cost-effectiveness of CSP systems through advancements in receiver designs, heat transfer fluids, and thermal storage systems (Arias et al., 2022; Giaconia & Grena, 2021; Prieto et al., 2020). These innovations aim to improve energy capture and system performance, as well as reduce capital and operational costs (Fig. 1.3). Moreover, integrating CSP with other renewable energy technologies, such as thermal energy storage and hybridization with fossil fuel power plants, can increase the versatility and reliability of CSP systems (Du et al., 2018; Mokheimer et al., 2017; Yousef et al., 2021). Additionally, there are prospects for industrial applications including desalination and process heat generation, which could lead to more sustainable and efficient industrial processes by reducing carbon emissions and water consumption (Mohammadi et al., 2019; Omar et al., 2020).

- **Onshore Wind**

Similar to solar PV, onshore wind power has undergone remarkable expansion and now plays a significant role in global electricity generation in the last decade owing to the remarkable cost decline, as depicted in Fig. 1.3 (Junginger et al., 2020; Rahman et al., 2020). Presently, onshore wind farms are operational in more than 90 countries, with China, the United States, Germany, and India leading in installed capacity. Improved technology for wind turbines, along with enhanced efficiency and economies of scale, have led to substantial cost reductions. Consequently, onshore wind has emerged as one of the most competitive forms of renewable energy (Daaboul et al., 2023; Desalegn et al., 2022; Kiunke et al., 2022). The rise in the deployment of onshore wind farms is also attributable to supportive government policies like feed-in tariffs, tax incentives, and renewable energy targets (Hvelplund et al., 2017; Li et al., 2018; Schumacher & Yang, 2018). The potential for further growth in onshore wind energy looks highly promising due to ongoing technological advancements focused on improving the efficiency and reliability of wind turbines (Fig. 1.4). Innovations in aerodynamics, materials, and control systems are driving enhancements in energy capture and reducing maintenance costs (Darwish & Al-Dabbagh, 2020; Haces-Fernandez et al., 2022; Ryberg et al., 2019; Zhang et al., 2016).

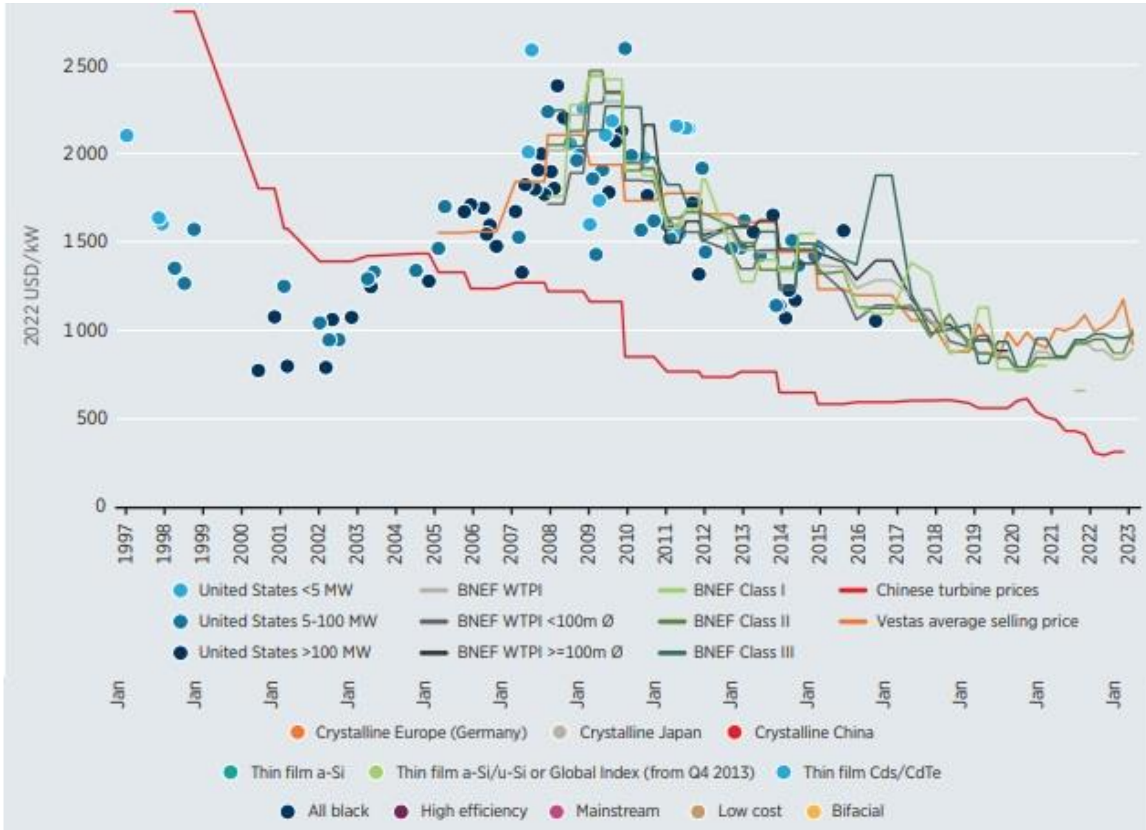


*Fig. 1.4 Wind turbine price trends, 1997-2023 (IRENA, 2023)*

- **Offshore Wind**

The offshore wind industry has rapidly expanded worldwide, becoming a key player in the renewable energy sector and offering significant potential for clean and sustainable power generation (Colmenar-Santos et al., 2016). Offshore wind farms are now established in various countries, including the UK, Germany, China, Denmark, and the Netherlands. Advancements in offshore wind turbine technology, such as larger turbines and improved foundation designs, have significantly increased energy capture and reduced the cost of energy generation (Bilgili & Alphan, 2022; Bento & Fontes, 2019; Clark et al., 2021). Innovations in turbine design along with floating platforms and installation techniques are also contributing to cost reductions while enhancing energy capture capacity especially in deeper waters, as shown in Fig 1.3 (Bilgili et al., 2022; Ghigo et al., 2020; Otter et al., 2021; Rathod et al., 2020).

- **Hydropower**

Hydroelectric power is a major global source, contributing significantly to the world's electricity production. It involves building dams and reservoirs to store and release water through turbines for electricity production. Several countries have extensive HDP infrastructure, including China, Brazil, the United States, Canada, and Russia. Currently, hydropower makes up about 16% of global electricity generation (REN21, 2023). Hydropower remains a reliable renewable energy source that contributes to meeting energy demands and reducing greenhouse gas emissions at both large-scale and small-scale levels. As technology continues to evolve, the future of hydropower looks promising. The development of pumped storage hydropower (PSH) systems offers a solution to the intermittent nature of other renewable energy sources by storing excess electricity and balancing grid demand when needed (Barbaros et al., 2021; Dong et al., 2020; Zhao et al., 2022). In addition, improving and updating existing hydropower facilities creates opportunities for increased efficiency and capacity. Enhancing equipment, optimizing turbine designs, and implementing advanced monitoring systems can improve the performance and sustainability of aging hydropower plants (Quaranta et al., 2020; Rahi & Chandel, 2015; Rahi & Kumar, 2016). Moreover, Run-of-river hydropower plants that do not require large reservoirs have a smaller footprint and are designed to preserve natural river flow conditions while maintaining ecosystems and fish migration routes (Adu et al., 2017; Briones-Hidrovo et al., 2019; Duan et al., 2013; Uddin et al., 2019).

- **Bioenergy**

Bioenergy derived from organic matter or biomass, has become a promising alternative due to growing concerns about climate change and the shift towards cleaner energy sources (Reid et al., 2019; Souza et al., 2017). Currently, Bioenergy accounts for approximately 10% of the world's total primary energy supply and includes various technologies such as biofuels, biogas, and biomass power generation. Its applications span across different sectors including transportation, industrial processes, and heat and power generation. In particular, biofuels like ethanol and biodiesel have gained traction as substitutes for fossil fuels in the transportation sector with several countries implementing blending mandates and offering incentives (Mączyńska et al., 2019; Sadeghinezhad et al., 2014). Moreover, the utilization of biogas, produced through anaerobic digestion of organic waste, is on the rise for electricity and heat generation (Abanades et al., 2021; Whiting & Azapagic, 2014). Additionally, in light of the cost decline (Fig. 1.3), there has been significant growth in biomass power plants that combust organic materials to produce electricity mainly in regions abundant with biomass resources (He et al., 2018; Mohaghegh et al., 2021; Teixeira et al., 2018).

- **Geothermal**

Geothermal energy has attracted considerable attention in recent times due to its intrinsic reliability and long-term sustainability (Rohit R.V et al., 2023; Santos et al., 2022; Solano–Olivares et al., 2024). Geothermal power plants, which operate in over 90 countries globally, are prominent electricity generators. Among the leading producers of geothermal power are the USA, Indonesia, Turkey, the Philippines, and New Zealand. The technology involved in harnessing geothermal energy entails accessing naturally occurring reservoirs of hot water or steam located deep beneath the Earth's surface (Li et al., 2023; Stober & Bucher, 2021; Younger, 2015). These reservoirs are typically found in regions with high geothermal potential such as volcanic areas or locations with elevated heat flow. By utilizing this heat source for powering turbines to generate electricity, geothermal power plants play a significant role. With impressive decrease in costs, there is ongoing development of Enhanced Geothermal Systems aimed at capturing geothermal energy from areas characterized by lower heat flow, advancing the geographic reach for geothermal power generation (Lu, 2018; Olasolo et al., 2016) (Fig. 1.3).

## 1.4 The rise of renewable energy sources

The shift towards new alternative energy sources is essential not only for addressing the environmental impact of energy production but also for ensuring sustainable socio-economic progress. The move toward RES is influenced by a combination of environmental, economic, and security factors. From an environmental perspective, there is a pressing need to decrease greenhouse gas emissions which drives the adoption of clean energy technologies (Jacobson & Delucchi, 2011). This is especially true as fossil fuels remain the main contributor to the global energy mix, as shown in Fig. 1.5. Energy security is another pivotal factor driving this shift, as renewables can help reduce dependence on import-reliant fossil fuels and enhance overall resilience (Hache, 2018; Gökgöz & Güvercin, 2018; Wang et al., 2018).

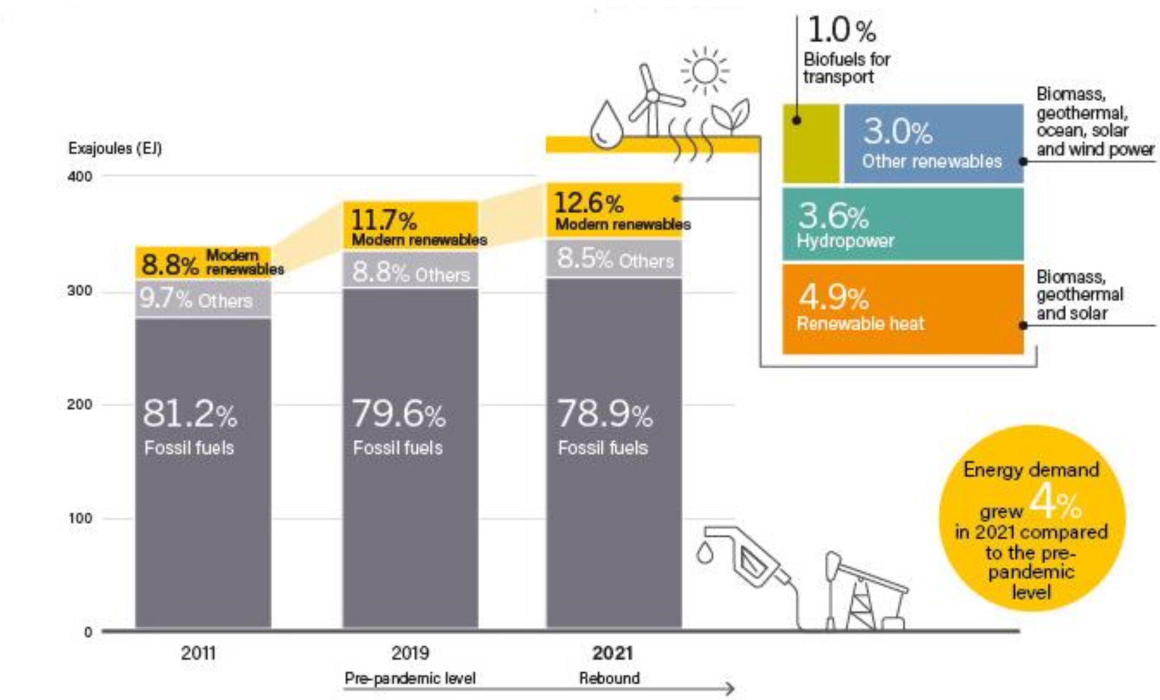


*Fig. 1.5 Total Final Energy Consumption by source, 2011, 2019, and 2021 (REN21, 2023)*

In this context, renewable energy sources have been gaining an increasing share of the global energy portfolio. With declining costs and increasing efficiency, technologies such as wind and solar photovoltaics are no longer marginal but essential components of new energy strategies, which has been translated into a total global installed capacities of nearly 950 and 845 GW for solar PV and wind, respectively, as of 2021, as shown in Fig. 1.6 (IRENA, 2021). However, the shift towards cleaner energy sources faces various challenges, including the requirement for new infrastructure, entrenched economic interests in fossil fuel sectors, and complex geopolitical factors related to countries' energy security considerations. Consequently, it is essential that global energy transitions also address issues related to energy access and equity so that all populations can benefit from sustainable advancements in clean energy (Sovacool, 2016).

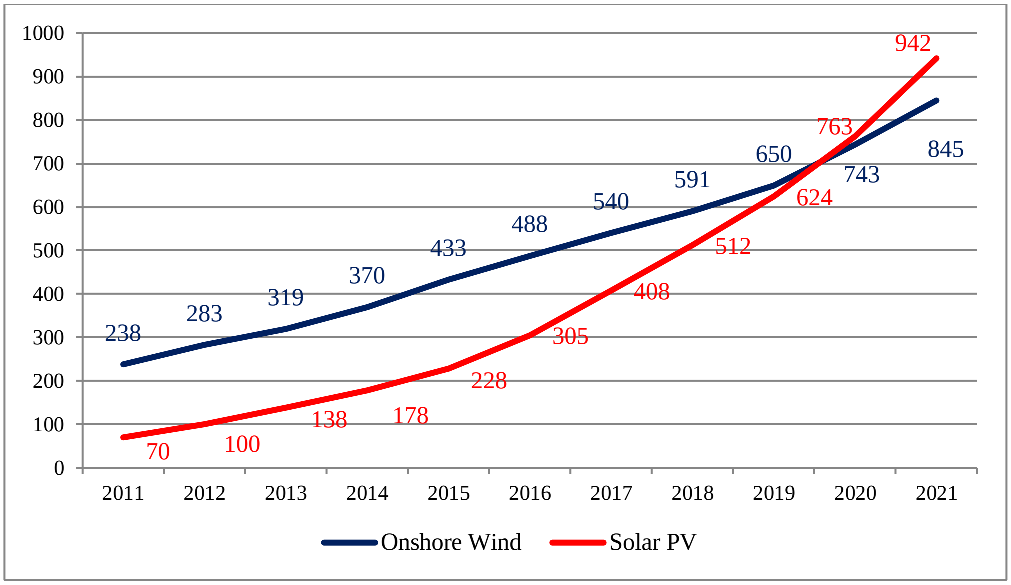


*Fig. 1.6 Wind and Solar PV total installed capacity, 2011-2021 (IRENA, 2021)*

## 1.5 Growth of investment in renewable energy sources

The landscape of renewable energy investments has been on an upward trajectory, illustrating a global consensus on the critical importance of sustainable energy solutions. Solar and wind power, in particular, have experienced substantial growth, benefiting from both policy backing and technological progress. However, the pace of transition varies considerably across different regions, with countries like China making significant strides in renewable energy investment and capacity additions (REN21, 2021). Specifically, investments in solar PV technologies have notably risen with PV module costs dropping by over 80% since 2010. Likewise, onshore and offshore wind sectors have undergone substantial expansion thanks to advances in turbine technology and floating platforms (GWEC, 2020). In addition to this progress, sectors such as bioenergy and geothermal sources are also securing a greater share of investment attention, driven by declining total installed capacity costs, Levelized cost of energy (LCOE), and increasing capacity factors (REN21, 2020) (Fig. 1.7). Furthermore, as the urgency of the climate crisis becomes more apparent, investors are increasingly recognizing renewable energy as an effective solution. This shift in perspective has led them to prioritize sustainable assets and direct capital towards green initiatives (IEA, 2020).

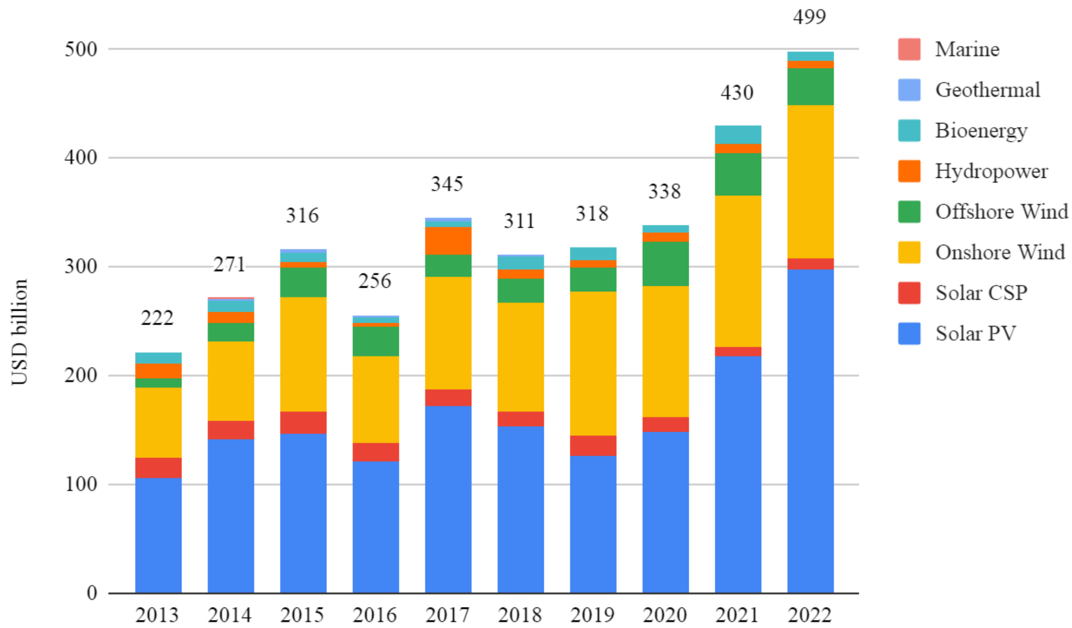


*Fig. 1.7 Investments in renewable energy technologies (REN21, 2023)*

Technological advancements further drive investments by improving the efficiency and integration of renewable power into existing grids; for example, utilizing CSP with thermal storage can enhance stability in power supply and increase its investment appeal (IRENA, 2021). Innovations in Energy Storage System technologies like batteries and pumped hydro systems also play an essential role in addressing fluctuations in renewable energy generation (IRENA, 2021).

Nationally, in 2022, Tunisia has increased its target for renewable energy share in power generation from 30% to 35% by the year 2030 (Anon, 2022; MEMER, 2022). This ambitious goal involves an annual investment of TND 900 million in renewable energy projects. The plan is to add over 4 gigawatts of additional renewable energy capacity by 2030, equating to at least 500 megawatts of new capacity annually over an eight-year period (Anon, 2023). Specifically, the Tunisian Solar Plan outlines targets for installing renewable energy capacities by 2030. These include generating 1,755 MW from wind sources, 1,510 MW from solar PV, and 450 MW through concentrated solar power (MEMER, 2018). Furthermore, the TSP also envisions integrating 100 MW of bioenergy resources into the energy mix within the same timeframe (Fig. 1.8).

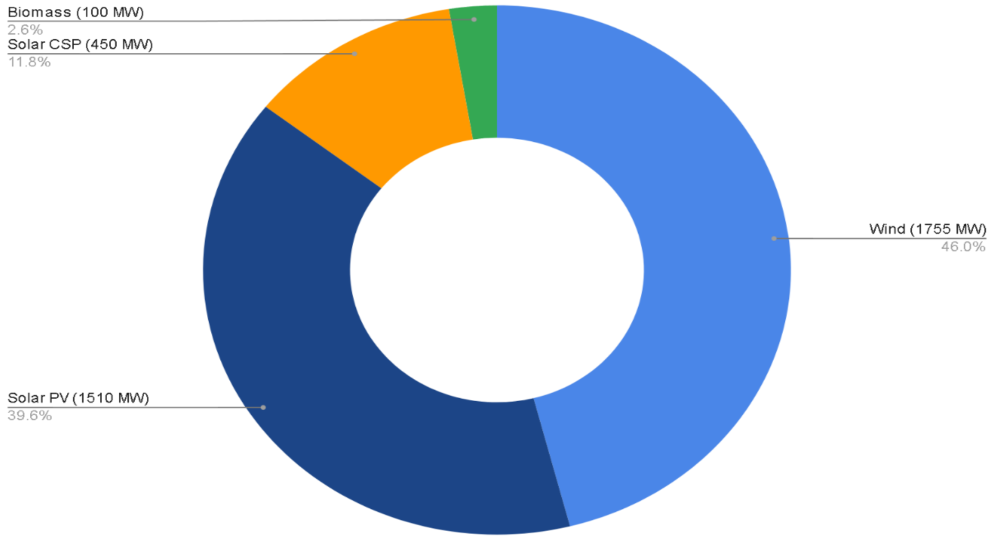


*Fig. 1.8 Technologies considered and objectives of TSP (MEMER, 2018)*

## 1.6 Energy Context in Tunisia

The energy sector plays a crucial role in Tunisia's economy. However, in recent years, the country has faced an escalating energy imbalance due to its heavy dependence on fossil fuels like oil and natural gas to cater to its growing energy demands (ETAP, 2022). This overreliance on imported fossil fuels has led to a significant deficit in the country's overall energy balance. In 2019, for instance, Tunisia experienced a record-high energy deficit of 5,672 ktoe, with approximately 49% of its total consumed energy being sourced from imports (JICA, 2022). This trend is expected to exacerbate as energy demand continues to rise while local production of oil and gas declines, as shown in Fig. 1.9.

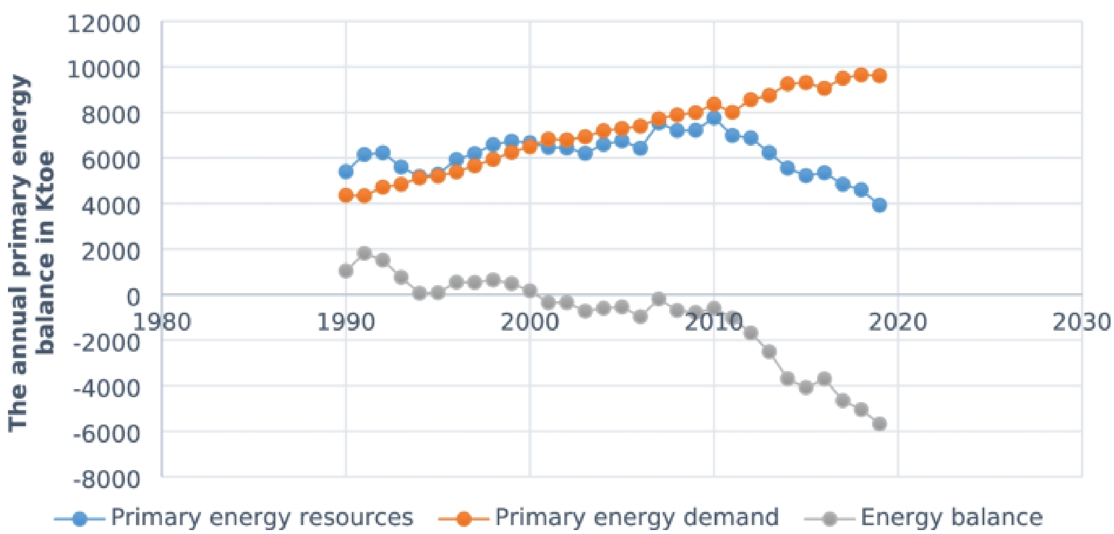


*Fig. 1.9 Primary energy balance in Tunisia (Saadaoui & Chtourou, 2023)*

The increasing reliance on imported sources not only exposes Tunisia economically but also makes it vulnerable socially, especially considering fluctuations in international fuel prices coupled with the local currency devaluation (Saadaoui & Omri, 2023; Schmidt et al., 2017). Since its establishment in 1962, STEG has been the main key player in the Tunisian power system. Since then, it has been in charge of the production, transmission, distribution, import, and export of electricity and natural gas. In addition, STEG still maintains a monopoly on electricity sales, both wholesale and retail. Yet, the Tunisian power system is well-developed and almost universal, with a nearly 100% electrification rate (JICA, 2022). It is also the sole entity authorized to import and export electricity. As of 2022, the Tunisian power generating system's installed capacity has increased to around 6014 MW, with STEG owning and operating 99.8% of this capacity after taking over the two single independent producers, Carthage Power Company (CPC) and Power Turbine Tunisia (PTT) (STEG, 2022). As shown in Fig. 1.10, Tunisia's power system is predominantly based on fossil fuels, namely natural gas. This indicates that the energy mix is almost nonexistent.

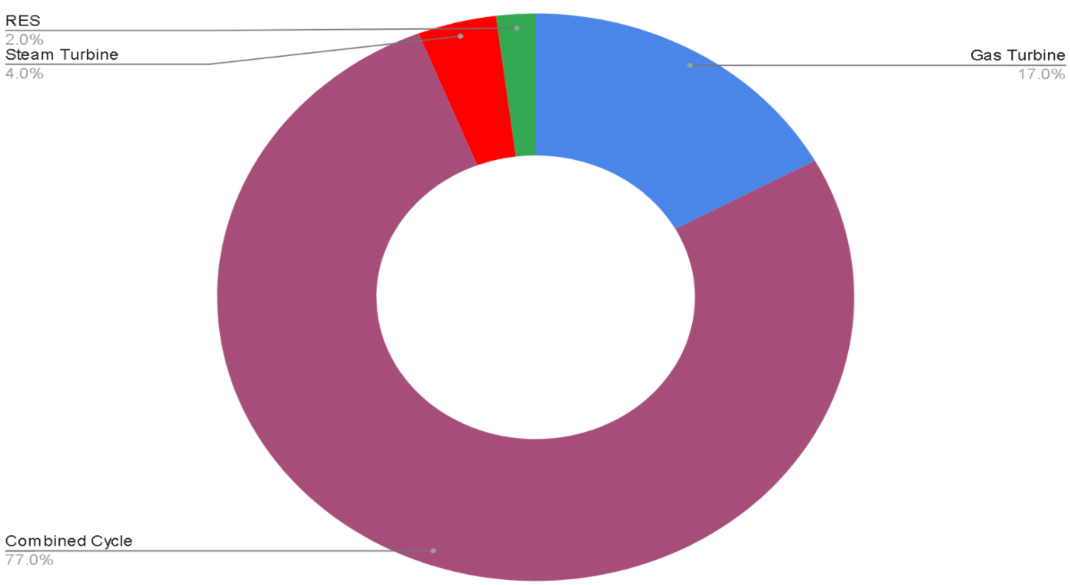


*Fig. 1.10 Electricity generation per type of equipment in 2022 (STEG, 2022)*

Today, despite the economic recession and socio-political instability due to the prolonged political transition phase, electricity demand has been consistently on the rise. In 2022, gross electricity demand and peak load reached 20.093 TWh and 4677 MW, respectively, marking an increase of nearly 15.5% and 16.2% compared to 2017, as illustrated in Figs. 1.11 – 1.12 (STEG, 2023) . According to elaborated long-term projections, these are expected to grow further, up to 28.36 TWh and 6000 MW by 2030, respectively (JICA, 2022). Peak demand has been affected by several factors, such as the change in consumers' habits and the climatic conditions witnessed in recent years, especially during the summer seasons when air conditioning is most needed (Dhakouani et al., 2017).

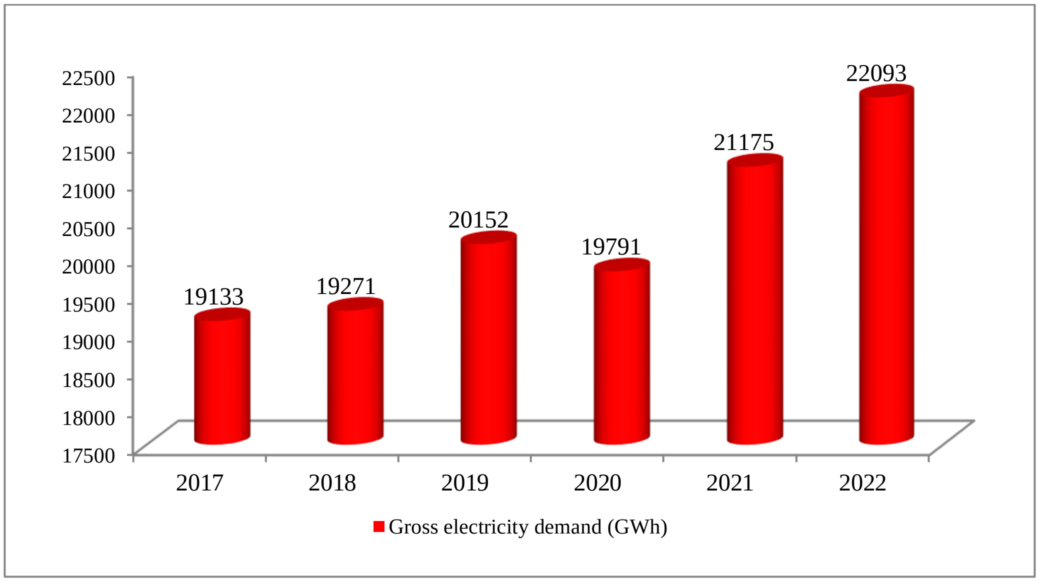


*Fig. 1.11 Gross electricity demand (GWh) (STEG, 2022)*

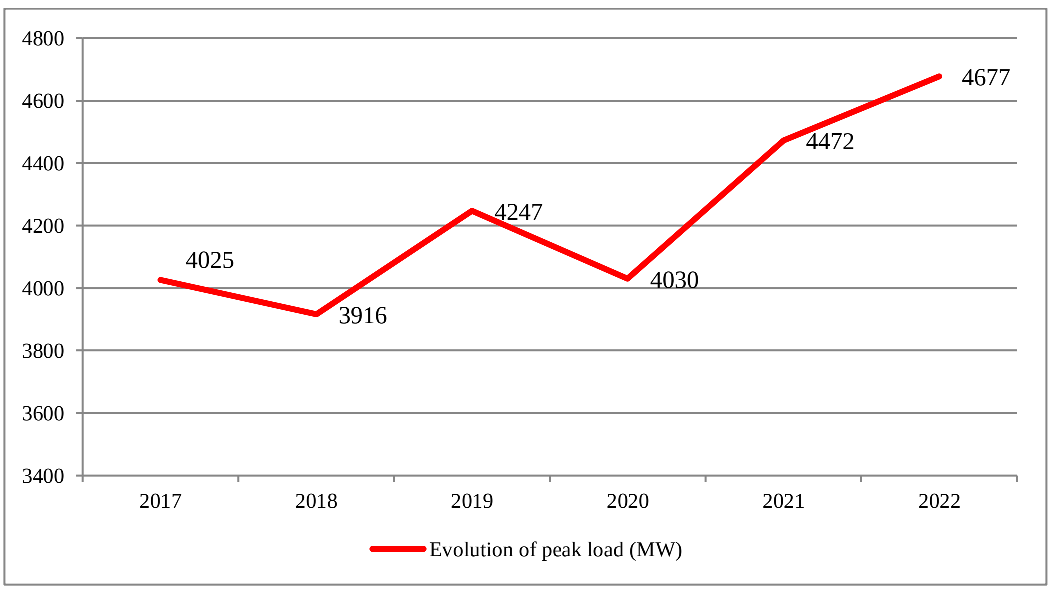


*Fig. 1.12 Evolution of peak load (MW) (STEG, 2022)*

## 1.7 Country portfolio

Tunisia covers a total surface area of 163,610 $km^2$ and has a population of nearly 12,000,000 inhabitants. It is situated in North Africa, sharing borders with Algeria and Libya, and is positioned between 30-37 N latitude and 8-12 E longitude. The Mediterranean Sea forms Tunisia's northern and eastern boundaries. The country is characterized by diverse landscapes and climatic variations. Tunisia has historically been an emerging economic hub and an attractive tourist destination due to its unique climatic features. The country's climate varies from Mediterranean in the north and along the coast to semi-arid within the country and arid conditions in the south. The country experienced substantial economic growth post-2000, with an average annual GDP growth rate of 4.3% between 2000 and 2010, positioning Tunisia as Africa's most competitive economy (Dhakouani et al., 2019; Omri et al., 2022). However, socio-political upheavals followed by a decade of stagnation have slowed its performance significantly. This was further exacerbated by the COVID-19 pandemic, resulting in a decline to 2.52% GDP growth in 2022 (WBG, 2023). Agriculture, tourism, and phosphate remain the main drivers of the Tunisian economy. It is estimated that approximately 70% of the population lives within northern and coastal areas, a fact that illustrates the stark disparities between these regions and internal ones (NIS, 2021; WBG, 2021).

## 1.8 Renewable Energy evolution in Tunisia

Tunisia's energy landscape is undergoing a significant transformation with a growing interest in renewable energy technologies, which are poised to play a key role. While hydrocarbon-based generation currently holds sway, there is growing potential for expansion in wind and solar power generation. The government has shown keen interest in diversifying into renewable energy technologies. The country has taken steps to diversify its energy sources, particularly by encouraging private businesses to generate and use clean energy through policy changes (Gardumi et al., 2021, Saadaoui & Omri, 2023). As of June 2023, Tunisia had an estimated 565 MW of renewable energy capacity installed. This consisted of 240 MW wind power, 263 MW solar power, and 62 MW hydroelectric power, making up around 8% of the national energy production capacity (STEG, 2022). The Tunisian authorities began focusing on wind energy in the year 2000 by implementing wind power plants to contribute to the country's overall power supply. Currently, three large-scale wind farms are operational in Tunisia, with a total electricity output capacity of approximately 240 MW. These installations are situated in Bizerte and El-Haouaria in the north of the country. In contrast, the country did not initiate utility-scale solar PV projects until 2019, with two operational facilities in Tozeur and Tataouine, and another facility under commissioning in Sidi Bouzid. Furthermore, projections indicate that wind and solar energy will account for approximately 46% and 39.5% of the targeted renewable energy capacity by 2030.

### 1.8.1 Solar energy

Owing to its meteorological and geological conditions, Tunisia has significant potential for solar energy, with 3000 hours of sunshine annually and direct normal irradiance (DNI) and global horizontal irradiance (GHI) of 2800 and 2600 kWh/m$^2$/yr, respectively (Attig-Bahar et al., 2021; Balghouthi et al., 2016, Trabelsi et al., 2016; Rekik & El Alimi, 2023a; Rekik & El Alimi, 2023b; Rekik & El Alimi, 2023c; Rekik & El Alimi, 2023e; Rekik & El Alimi, 2024a; Rekik & El Alimi, 2024b).

Despite this potential, solar energy was limited to domestic water heating systems and certain community projects, as it was not considered cost-effective. Yet, the use of photovoltaic solar energy has allowed the electrification of isolated homes and rural schools, street lighting, water pumping stations, and a water desalination station (Dardour et al., 2020; Daghari & El-Zarroug, 2020). Large-scale grid-connected solar farms have not been commissioned until 2019. Currently, there are three operating utility-scale solar PV power plants (30 MW) and one (10 MW) under commissioning. These plants are located in Tozeur, Tataouine, and Sidi Bouzid. Such facilities generate nearly 78 GWh per year and contribute to reducing 37,000 tons of CO2 emissions annually (Jelleli et al., 2024; JICA, 2022).

### 1.8.2 Wind energy

Favorable wind sites for wind energy development are located on the north coast as well as in the central and southern regions of Tunisia. According to the United Nations Environment Programme (UNEP) and Vortex, wind speeds in these areas are conducive to wind power generation (Attig-Bahar et al., 2021). The Global Wind Atlas from the International Renewable Energy Agency (IRENA) indicates that at an altitude of 80 meters and a resolution of 1 kilometer, wind speeds in the northwest areas range between 6 and 7 m/s. In the northeastern coastal part of the country, wind speeds reach 7 m/s, while in the southern regions, wind speeds reach 8 m/s (IRENA, 2021; Rekik & El Alimi, 2023a; Rekik & El Alimi, 2023b; Rekik & El Alimi, 2023d; Rekik & El Alimi, 2023e; Rekik & El Alimi, 2024a).

### 1.8.3 Biomass

Given the significant role of agriculture in Tunisia's economy, it holds substantial potential for generating biomass energy resources from agricultural activities (Banacloche et al., 2020; Herrera et al., 2020; Zribi et al., 2016). Currently, traditional biomass fuels are minimally utilized in Tunisia due to widespread access to electricity. Additionally, there is a lack of comprehensive research outlining the potential biomass resources in the country since the biogas sector has not evolved sufficiently to serve as an energy source, and no large-scale biogas power plants have been built yet (STEG, 2020). Nevertheless, there are plans outlined for 2030 that include establishing a 100 MW biogas power plant to contribute towards electricity generation (MEMER, 2018).

### 1.8.4 Geothermal

Geothermal resources in Tunisia are predominantly found in the form of geothermal water springs. These have been historically utilized for bathing and therapeutic treatments at locations like Korbous, EI-Hamma, and Hammam-Zriba (Ahmed, 2011). Tunisia's geothermal resources are primarily concentrated in the southern part of the country, with an estimated capacity of 4850 liters per second, and a significant portion of this potential is situated in the south (Ben Brahim et al., 2013; Brahim et al., 2020; Naili et al., 2016). The utilization of geothermal energy in Tunisia is predominantly attributed to oasis irrigation, agricultural activities, and serving as tourist attractions. These resources are situated at depths reaching around 5000 meters, with temperatures peaking at approximately 188 degrees Celsius (Brahim et al., 2020). Presently, there are no established geothermal facilities for electricity generation within Tunisia.

### 1.8.5 Hydropower

Tunisia has some hydropower resources, representing about 0.1% of the energy mix in the country, with an installed capacity of 62 MW in 2022 (STEG, 2022). Tunisia's gross theoretical hydropower potential was estimated at 1000 GWh/year in the mid-1990s, with a technically feasible potential of 250 GWh/year (Alnaqbi et al., 2022; Lechtenböhmer et al., 2012). Tunisian utility company STEG is planning and building a pumped hydroelectric storage plant with a capacity of 400 MW. The plant is expected to be operational by 2029 (Anon, 2022).

## 1.9 Regulatory framework

Since 1992, Tunisia has been actively addressing climate change implications by integrating climate adaptation into its development planning at both a global and sector-specific level. Part of these efforts involves advocating for alternative, environmentally friendly energy technologies and prioritizing carbon-neutral energy systems in governmental energy policies. The Tunisian government has also enforced supportive policies to facilitate the shift towards renewable energy, including offering investment incentives for projects related to renewable electricity production while permitting various sectors to generate their own sustainable power. Additionally, a specific law (N°74/2013) allows producers to sell up to 30% of the power they produce to the Tunisian Company of Electricity and Gas at prices equivalent to high-tension prices. Furthermore, producers can utilize the national grid for transporting power by paying a transport fee regulated by the Minister of Energy. The Tunisian energy plan for 2030 envisions a gradual shift away from conventional energy sources. This transition will entail a strategic diversification of the energy mix, with a specific emphasis on promoting solar and wind power (Gardumi et al., 2021). To facilitate this transition, Tunisian authorities have delineated four distinct "régimes" for implementing renewable energy as mandated by the 2015 law and 2016 decree:

1. Large-scale projects are subject to concession through a tender process.
2. Small-scale projects subject to authorization
3. Self-production is subject to requiring authorization.
4. Export projects are subject to concession.

An overview of the measures aimed at reducing climate impact while promoting this needed shift in the country's energy system is presented in Table 1.1.

Table 1.1 Regulatory framework for RES in Tunisia (FAO, 2007; IEA, 2020; MEMER, 2018; MEMER, 2020; UNFCCC, 1993; UNFCCC, 2022; UNFCCC, 2022)

| Year | Action |
|---|---|
| 2019 | Announcing the second round of renewable energy projects for electricity production (wind and solar PV) under the authorization regime.<br>Third round of calls for RES projects for electricity production under the authorization regime. |
| 2018 | Revision of the PPA for the authorization and auto-production regime.<br>Pre-qualification call for 1700 MW under the concession regime<br>Authority acceleration plan for renewable energy implementation |
| 2017 | The publication of the official document outlining the technical requirements for the connection and evacuation of renewable energy installations connected to the low-voltage grid (all regimes). |
| 2016 | Decree N°.1123: Specifying implementation conditions for renewable energy projects (Amended by decree N°.105/2020) |
| 2015 | Electricity production from RES (Law N°. 12) |
| 2014 | Climate protection |
| 2011 | The Decree on connection and access of renewable electricity to the national grid |
| 2010 | Import tax exemptions for RES and energy efficiency equipment materials |
| 2010 | Nationally appropriate mitigation plans |
| 2009 | Tunisian Solar plan 2010/2016. |
| 2008 | National Energy efficiency program |
| 2007 | Air quality law. |
| 2003 | KYOTO protocol ratification |
| 2002 | GHG emission reduction portfolio |
| 1992 | Signing the UNFCCC |

## 1.10 Renewable energy sources and site selection

The demand for renewable energy has increased significantly in recent years due to growing concerns about climate change and the need to reduce greenhouse gas emissions. As a result, there has been a surge in the exploration and utilization of renewable energy sources, such as wind and solar power. This indicates that such resources are anticipated to be a significant and sustainable component of the world's future energy supply. Nonetheless, their development presents specific challenges that need to be addressed, such as resource prioritization, selecting appropriate resources, and determining optimal plant locations and generation capacities. Notably, the process of selecting optimal locations for these resources is a crucial step in establishing a viable power plant structure. This step profoundly impacts electricity-generating capacity as well as potential future socioeconomic benefits. In this regard, integrating Geographic Information Systems with MCDM has played a crucial role in this process by providing valuable tools for spatial analysis and site selection. By utilizing GIS-based MCDM approaches, researchers and practitioners can effectively identify resource-abundant and environmentally non-conflicting sites for renewable energy exploration. This has led to a significant increase in studies and projects focused on optimizing the deployment of renewable energy technologies.

Several studies have been conducted on the use of GIS and MCDM techniques to analyze the suitability of different renewable energy facilities in the literature. For instance, Atwongyeire et al. (2022) conducted a comprehensive investigation into the suitability of Western Uganda for solar energy exploration using the GIS-MCDM approach. Similarly, Colak et al. (2019) and Kocabaldır and Yücel (2023) delved into the assessment of solar PV potential in Turkey, while Rabiul Islam et al. (2023) considered a case study in Bangladesh and Mensour et al. (2019) focused on southern Morocco. In a similar vein, numerous studies have been conducted to assess site suitability for wind energy harvesting using GIS-based MCDM techniques. As an example, Villacreses et al. (2017) undertook an exhaustive evaluation of Continental Ecuador for wind energy exploration. Additionally, Benti et al.'s (2023) and Zalhaf et al.'s (2021) utilization of southern Ethiopia and Sudan as case studies added depth to understanding site suitability for onshore wind harvesting. Moreover, Eroğlu (2021) and Pamucar et al. (2017) presented a thorough investigation of the most feasible wind locations in Turkey, Serbia, and Spain, respectively. Given the intermittent and variable nature of renewable sources, several studies have addressed this issue by combining more than a single approach. This is aimed at taking advantage of varying climatic conditions throughout different times of the day or year, as elaborated in the works presented by Effat and El-Zeiny (2022), Koc et al. (2019), and Sachit et al. (2024).

### 1.10 Research gaps

Given the escalating national demand for renewable energy sources, it has become increasingly crucial to investigate the potential applications of renewable energy systems in Tunisia. Despite the considerable amount of research that has been undertaken in this domain, there exists a significant dearth of studies that specifically examine the implementation of large-scale wind and solar as well as CSP-PV-Wind hybrid power generation systems in Tunisia. To bridge this existing gap, this study explores the feasibility of these facilities on a large scale by incorporating MCDM tools into geographic information systems. This is a promising method for addressing this deficiency through the implementation of a methodical and data-driven approach to site selection. Furthermore, using fuzzy logic to handle uncertainties in decision-making allows for more accurate and efficient decision-making in renewable energy projects. Numerous scholarly articles have utilized integrated or single-component MCDM models to simulate diverse electricity generation scenarios in Tunisia, as evidenced by (Abdelkader et al., 2018; Belouda et al., 2018; Bouzid et al. (2021); Brand and Missaoui, 2014; Elleuch et al., 2021; Hafdhi & Euchi, 2023; Koubaa et al., 2022; Zelt et al., 2019). Even though the GIS-based FAHP approach has the potential to offer more profound insights into effective strategies for large-scale solar, wind, and hybrid power generation systems, it has not yet been widely adopted with respect to the Tunisian context.

Notably, the government's approval of numerous PV and onshore wind projects ranging from 10 MW to 200 MW without location specifications has set the stage for our exploration. By considering a diverse array of criteria, including solar radiation, temperature variations, average cloudy days, wind speeds, soil composition, access to water resources, power grid infrastructure, and major transportation routes, among others, we seek not only to identify suitable sites but also to compare them against operating solar and wind farms and planned projects. This rigorous approach aims to establish a solid foundation for evaluating consistency and reliability through our proposed model. Such thorough validation enhances the credibility of our findings while boosting confidence in their applicability.

Moreover, identifying prime locations for renewable energy projects locations in the central-west, south-east, and south-west would not only guarantee a consistent power supply but also significantly contribute to the generation of employment opportunities. These regions are often labelled as the least developed parts of the country, thus, increased investments in renewable energy infrastructure would stimulate the economy in these areas. Employment opportunities would be generated in numerous sectors, including construction, operations, maintenance, and local support services, through the establishment of such initiatives.

Finally, the study further evaluates the relative merits of different renewable technologies and outlines the primary obstacles facing their widespread adoption. By providing a systematic and data-driven methodology for identifying viable sites for renewable energy generation, this research presents a significant resource for policymakers and developers aiming to harness Tunisia's renewable energy potential. The findings advocate for a strategic approach to overcome existing barriers, facilitating a transition towards a more sustainable and resilient energy system in Tunisia.

## 1.11 Conclusion

In conclusion, this chapter provides an overview of the global and Tunisian energy paradigms, illustrating the dire need for a shift towards renewable energy sources within the context of rising demand, climate change, and sustainability goals. Tunisia, which confronts the dual challenges of climate change impacts and overreliance on imported fossil fuels, embracing renewable energy technologies such as solar, wind, biomass, geothermal, and hydropower can significantly contribute to the diversification of Tunisia's energy mix and the reduction of its carbon emissions, aligned with its target of a 30% contribution from renewables by 2030. This chapter also underlines the key role of integrating GIS and MCDM for optimizing renewable energy site selection. This approach not only ensures the efficiency of resource use but also contributes to the strategic planning of energy infrastructure, with significant socioeconomic benefits for local communities. It is evident from the literature that there remains a gap, particularly in the implementation of large-scale renewable projects such as solar, wind, and hybrid systems in Tunisia, which can be bridged by employing advanced spatial analysis and decision-making tools.

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# Chapter II: Methodology and Formulations

## 2.1 Introduction

Growing environmental concerns and the depletion of conventional fossil fuel reserves are driving the demand for the advancement of sustainable energy. As the limitations of fossil fuels become increasingly apparent, there is a heightened emphasis on renewable energy as a sustainable, environmentally friendly, and long-term solution (Abas et al., 2015; Capellán-Pérez et al., 2014; Holechek et al., 2022).

The site selection process for large-scale renewable energy projects, particularly solar and wind projects, holds significant importance in ensuring the efficiency, sustainability, and long-term viability of such ventures (Al Garni & Awasthi, 2017; Sindhu et al, 2017). Considering the complex interplay of various factors including resource availability, technical feasibility, environmental impacts, social acceptance, and economic considerations, the site selection process plays a crucial role in maximizing energy output, minimizing costs, and reducing environmental footprints (Badi et al., 2021; Ilbahar et al., 2019; Shao et al, 2020).

In this regard, MCDM methods play a crucial role in addressing the challenges of resource prioritization, site selection, and capacity determination for renewable energy (Abu-Taha & Daim, 2011; Løken, 2007; Shimray et al., 2017). These methods are popular due to their ability to consider conflicting objectives and decision-makers' preferences. While different renewable energy sources emphasize varying criteria for site selection, there are similarities in the process of selecting these criteria. By providing a structured framework that evaluates alternatives against multiple criteria, MCDM reduces ambiguity, ensures transparency, and facilitates consistent decision-making (Abu-Taha & Daim, 2011; Estévez et al., 2021; Shimray et al., 2017). Additionally, it offers techniques for handling uncertainty and subjectivity while incorporating stakeholder perspectives to promote fairness and inclusivity in decision-making processes related to renewable energy sites (Horasan & Kilic, 2022; Sitorus & Brito-Parada, 2022).

The primary objective of this chapter is to investigate and highlight the efficacy of integrating MCDM methods with Geographic Information Systems (GIS) for the optimal site selection of renewable energy installations. It aims to demonstrate how this integrated approach can address the complexities and multidimensional aspects of selecting suitable sites for wind and solar energy projects by considering a wide range of criteria, including environmental, technical, social, and economic factors. The chapter seeks to present the application of various MCDM techniques in real-world scenarios to illustrate the practicality and advantages of using these methods in renewable energy site selection processes, thereby providing a compendium of best practices and informed insights for energy planners and decision-makers.

This chapter emphasizes the significance of GIS and MCDM methods in assessing future geographical locations for power plants and identifying the various obstacles to their deployment. It also provides a logical summary of the methodology, demonstrating how all the components work together to address the primary goal of this thesis. To this end, the following sections detail the various criteria and explain the MCDM methods used, namely AHP, FAHP, CRITIC, EDAS, SWARA, and DEMATEL.

## 2.2 Common criteria used in energy planning

The exploitation of renewable energy options is a multifaceted field that requires considering numerous parameters from technical, economic, environmental, social, and political viewpoints. While traditional decision-making methods have focused on cost versus efficiency, the contemporary approach emphasizes a broader range of considerations for strategic energy planning (Al-Garni et al., 2016; Budak et al., 2019). Technical and economic aspects remain crucial factors in decision-making processes; however, there has been an increasing emphasis on environmental sustainability in recent years. Moreover, social and political attitudes towards renewable energy play a significant role in influencing the decision-making process (Saraswat et al., 2021; Sindhu et al., 2017). Table 2.1 summarizes the most commonly used criteria in prioritizing renewable resources. Moreover, allocating optimal sites for renewable energy projects is always associated with various overlapping factors as well as constraints, as illustrated in Table 2.2 (Al-Garni & Awasthi, 2017; Elkadeem et al., 2022). To address the complexities associated with siting such systems, several studies have examined this topic in terms of land availability, resource assessment, environmental and social impacts, as well as infrastructure requirements.

Table 2.1. Summary of the criteria used in prioritizing renewable energy sources

| Criteria | Type | Unit | Description | References |
|---|---|---|---|---|
| Resource availability | Beneficial | $KWh/m^2$ | Availability of renewable resources (wind speed, solar radiations etc.) to generate energy | (Ahmad & Tahar, 2014; Amer & Daim, 2011; Lee & Chang, 2018; Stein, 2013; Yazdani et al, 2020) |
| Efficiency | Beneficial | % | This criterion apprises the operation and performance of the technology for energy policy. | (Ahmad & Tahar, 2014; Boran et al, 2013; Lee & Chang, 2018; Şengul et al, 2015; Saraswat & Digalwar, 2021; Stein, 2013; Yazdani et al, 2020) |
| Capital Cost | Non-Beneficial | US$/kW | It includes expenditure on equipment, installation, infrastructure, and commissioning. | (Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Şengul et al, 2015; Saraswat & Digalwar, 2021; Stein, 2013; Yazdani et al, 2020) |
| Technology maturity | Beneficial | 1-5 Scale | Technology maturity is indicated by how wide-spread technology is at regional, national and international levels. | (Al-Garni et al, 2016; Effatpanah et al, 2022; Lee & Chang, 2018; Haddad et al, 2017; Saraswat & Digalwar, 2021) |
| Electricity cost | Non-Beneficial | $/kWh | Expected cost of the electricity generated by power plant. | (Amer & Daim, 2011; Brand & Missaoui, 2014; Boran et al, 2013; Lee & Chang, 2018; Pappas et al, 2012; Yazdani et al, 2020) |
| Water use | Non-Beneficial | l/KWh | The amount of water needed to generate a unit of energy under different technologies | (Effatpanah et al, 2022; Haddad et al, 2017; Şengul et al, 2015; Wang et al, 2009) |
| Job Creation | Beneficial | Person/GWh | Potential employment opportunities to be created by energy projects. | (Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Yazdani et al, 2020) |
| Land Requirement | Beneficial | $m^2$/GWh | The required area for the installation of technology | (Ahmad & Tahar, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Yazdani et al, 2020) |
| CO2 Emissions | Non-Beneficial | $tCO_2$ /MWh | Direct CO2 emissions of all power plants during the observation period | (Ahmad & Tahar, 2014; Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Stein, 2013; Yazdani et al, 2020) |
| Projected installed capacity | Beneficial | MW | Maximum produced energy on the basis of the usable renewable energy sources and under the manufacturer's specified parameters. | Afrane et al, 2021; Effatpanah et al, 2022; |

Allocating optimal sites for renewable energy projects is always associated with various overlapping factors as well as constraints, as illustrated in Table 2.2 (Al-Garni & Awasthi, 2017; Elkadeem et al., 2022; Rekik & El Alimi, 2023 Tataouine; Rekik & El Alimi, 2023 Kasserine). To address the complexities associated with siting such systems, several studies have examined this topic in terms of land availability, resource assessment, environmental and social impacts, as well as infrastructure requirements. However, identifying potential sites within a specific area is heavily influenced by local factors and requires input from experts involved in the decision-making process (Rekik & El Alimi, 2023, Energy Reports; Sindhu et al, 2017). Therefore, engaging highly qualified experts who possess deep knowledge about the energy status of a particular area is crucial when conducting MCDA research activities.

Table 2.2. Common criteria in selecting optimal sites for RES systems in the literature

| Criteria | Reference |
|---|---|
| **Global Horizontal Irradiance (GHI)** | Ali et al. 2019; Asadi et al. 2023; Harrucksteiner et al. 2023; Waewsak et al. 2020; Zambrano-Asanza et al. 2021 |
| **Direct Normal Irradiance (DNI)** | Aly et al. 2017; Haddad et al. 2021; Gouareh et al. 2021; Mutume, 2023; Yushchenko et al. 2017 |
| **Wind Speed** | Asadi et al. 2023; Harrucksteiner et al. 2023;Waewsak et al. 2020 |
| **Ambient temperature** | Elboshy et al 2022; Günen, 2021; Ouchani et al. 2020; Zambrano-Asanza et al. 2021 |
| **Slope** | Asadi et al. 2023; Effat & El-Zeiny, 2022; Elboshy et al. 2022; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Aspect Orientation** | Ali et al. 2019; Koc et al. 2019; Günen, 2021 |
| **Distance to grid lines** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Distance to major roads** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Distance to residential areas** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Elevation** | Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Albraheem & AlAwlaqi, 2023 |
| **Land use** | Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Waewsak et al. 2020; Zambrano-Asanza et al. 2021 |
| **Population density** | Majumdar & Pasqualetti, 2019; Sabo et al. 2016 |
| **protected Bird areas** | Ali et al. 2019; Baseer et al. 2017; Albraheem & AlAwlaqi, 2023 |
| **Distance to airports** | Ali et al. 2019; Baseer et al. 2017; Harrucksteiner et al. 2023; Albraheem & AlAwlaqi, 2023 |
| **Dust storm** | Merrouni et al. 2018, Xiao et al. 2013 |
| **Distance to water resources** | Aly et al. 2017; Mutume, 2023; Yushchenko et al. 2017 |

## 2.3 The importance of MCDM tools in energy planning

The adaptability of MCDM makes it applicable across various fields including energy planning where it has been used to evaluate potential wind farm or solar plant sites based on factors such as wind speed, solar radiation, land use impact assessment among others (Al-Garni & Awasthi, 2017; Horasan & Kilic, 2022; Sitorus & Brito-Parada, 2022). Yet, identifying the optimal locations for installing renewable energy projects is of prime importance. The geographical and weather conditions of a potential site have a substantial impact on the effectiveness and efficiency of renewable energy generation. Variables such as wind speed and solar radiation play pivotal roles in deciding the suitability of sites for wind farms and solar power plants, respectively. Moreover, proximity to existing power and transportation infrastructure can significantly influence the feasibility and cost-effectiveness of renewable energy projects (Ahmadi et al., 2022; Garni & Awasthi, 2017; Asadi et al., 2023).

Site selection involves prioritizing resources, determining plant locations, and assessing generation capacity, a pivotal step in constructing renewable energy power plants with far-reaching implications for electricity generation capacity and future socioeconomic benefits (Abdel-Basset et al., 2023; Shao et al., 2020). The intricacy of site selection underscores the importance of employing multi-criteria decision-making methods to address the diverse range of variables involved effectively (Ghasempour et al., 2019; Yousefi et al., 2022). Traditional single-criterion approaches prove insufficient when confronted with the complexity inherent in selecting sites suitable for generating renewable energy (Al-Garni & Awasthi, 2017; Elkadeem et al., 2022).

## 2.4 GIS in energy planning

The selection of an ideal location is crucial for ensuring the feasibility of renewable energy projects, such as solar and wind facilities. However, this process comes with several challenges that require careful consideration. In order to fully maximize the potential of renewable energy in a specific area, it is important to take into account various factors beyond just the availability of solar and wind resources (Ali et al., 2019; Asadi et al., 2023; Elkadeem et al., 2022). Elements like topography, infrastructure capabilities, and costs significantly impact power generation. Additionally, variations in weather patterns and seasonal changes add further complexity when assessing solar and wind potential within regions (Rekik & El Alimi, 2023a; Rekik & El Alimi, 2023b).

Given the complexity of screening out the optimal locations for renewable energy projects, to unlock the renewable energy potential in any given region, it is critical to manipulate a large amount of spatial data (Rekik & El Alimi, 2023"Kasrine). In this regard, the use of GIS has proven to be a powerful technique for analyzing and visualizing spatial data, which makes it an indispensable tool in the process of identifying potential sites for solar and wind energy projects (Mihajlović et al., 2019; Zambrano-Asanza).

Geographic Information Systems (GIS) play a pivotal and multifaceted role in energy planning, particularly in the context of selecting optimal sites for renewable energy projects. GIS technology integrates spatial data with various layers of information, enabling energy planners to visualize, analyze, and interpret complex geographical factors critical to decision-making. In energy planning, GIS facilitates the assessment of renewable energy resource availability, such as solar radiation and wind speed, by overlaying these data with topographical features, land use patterns, and infrastructure networks (Colak et al., 2020; Saraswat et al., 2021). This spatial analysis capability allows for the identification of suitable locations for solar farms, wind turbines, and other renewable energy installations based on criteria like proximity to power grids, population centers, and environmental sensitivities. Moreover, GIS supports scenario modeling and impact assessments, enabling planners to simulate different project configurations and evaluate potential risks and benefits associated with each scenario (Gacu et al., 2023; Gašparović & Gašparović, 2019; Wang et al., 2024).

## 2.5 Integrated GIS with MCDM tools in energy planning

By integrating GIS with MCDM methods, energy planners can enhance the accuracy and efficiency of site selection processes, considering a wide array of factors such as land use compatibility, accessibility, environmental impacts, and social acceptance. Ultimately, GIS empowers energy planners to make data-driven, informed decisions that optimize resource utilization, minimize risks, and enhance the overall sustainability and resilience of energy systems (Al-Garni & Awasthi, 2017; Shao et al., 2020). Malczewski (2006) asserts that geo-information systems, when used on their own, are unable to provide correct results. This assertion has been made. On the other hand, MCDM models are used in order to rank the many alternative options, provided that all of the relevant criteria are taken into consideration (Badi et al., 2021; Ijadi Maghsoodi et al., 2018). Therefore, integrating GIS with MCDM is considered a valuable technique for solving problems of this type (Al-Garni & Awasthi, 2017;

Elkadeem et al., 2021). This is because it helps to further enhance decision-making processes related to site selection for alternative renewable energy solutions such as solar and wind power installations, as well as any other problems that involve multiple factors (Ali et al., 2019; Asadi et al., 2023; Elkadeem et al., 2022). By having access to a combination that provides a systematic approach to analyzing various criteria and comparing different options as well as providing visualization and geographical data analysis, decision-makers are empowered with the ability to make educated decisions based on a comprehensive evaluation of all relevant criteria (Ilbahar et al., 2019; Shao et al., 2020).

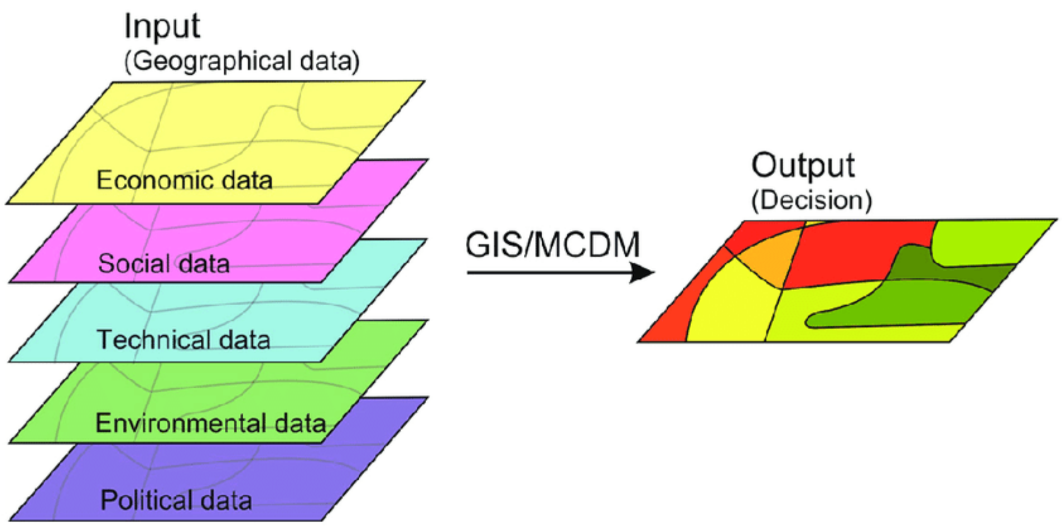


*Fig. 2.1 GIS-based MCDM Spatial Analysis*

## 2.6 Overview of the frequently used MCDM in energy planning

Traditional multi-criteria decision-making (MCDM) approaches are of utmost importance when it comes to the strategic planning of renewable energy. These methodologies enable decision-makers to evaluate and compare different alternatives according to a multitude of criteria, thereby determining the most optimal selection. By providing a comprehensive structure for addressing intricate decision-making situations, these methodologies have been instrumental in assessing the environmental impact of various renewable energy systems.

Therefore, collecting comprehensive data followed by thorough analysis becomes essential for accurately determining the energy generation capacity at a particular site. Nevertheless, conducting these assessments can be challenging due to overlapping criteria during decision-making processes. To address these complexities and make well-informed decisions, researchers have increasingly utilized geographic information systems integrated with multi-criteria decision-making approaches. Some commonly used multi-criteria decision-making methods include:

- Analytic Hierarchy Process (AHP): This is a structured technique for organizing and analyzing complex decisions based on multiple criteria. It involves breaking down a decision into a hierarchical structure and comparing the relative importance of the criteria (Al-Garni & Awasthi, 2017; Bertsiou et al., 2021; Günen, 2021; Rekik & El-Alimi, 2024; Rekik & El-Alimi, 2023).
- Analytic Network Process (ANP): An extension of AHP that allows for the modeling of interdependencies and feedback loops among decision elements (Atmaca & Basar, 2012; Catron et al., 2013; Ebrahimi et al., 2018; Lee et al., 2017; Sakthivel & Ilangkumaran, 2015; Yazdani et al., 2018)
- Complex Proportional Assessment of alternatives (COPRAS): It involves dividing the criteria into positive and negative ones, determining the relative importance of the criteria, and calculating the overall ranking of alternatives based on these assessments. This approach helps in dealing with complex decision-making situations where criteria may have both positive and negative impacts on the alternatives (Guan et al., 2023; Memiş & Karakoç, 2022; Yontar, 2023).
- CRiteria Importance Through Inter-Criteria Correlation (CRITIC): This technique calculates objective weights for criteria based on their correlations, helping to establish the relative significance of each criterion in the decision-making process (Babatunde & Ighravwe, 2019; Rekik & El-Alimi, 2024; Wang et al., 2021).
- Data Envelopment Analysis (DEA): DEA is a non-parametric method used to measure the relative efficiency of decision-making units (DMUs) when they have multiple inputs and outputs. It evaluates the performance of DMUs by comparing their inputs to outputs and identifies the most efficient DMUs, known as the "efficient frontier." (Rezaei-Shouroki et al., 2017; Wang et al., 2022; Wang et al., 2021).
- Decision-Making Trial and Evaluation Laboratory (DEMATEL): It is a methodology used to analyze the relationships among criteria or factors in a decision-making process. It helps in identifying the causal relationships between factors by distinguishing the cause-and-effect relationships in a complex system (Büyüközkan & Güleryüz, 2017; Rekik & El-Alimi, 2023; Yazdani et al., 2018).

- Evaluation based on distance from average solution (EDAS): This method evaluates alternatives based on their distances from the average solution to the criteria. It calculates positive and negative distances to assess the relative performance of alternatives in relation to the criteria. By analyzing the distances, the EDAS method helps identify the most suitable alternative among a set of options (Asante et al., 2020; Rekik & El-Alimi, 2023; Yazdani et al., 2020).
- ELimination Et Choix Traduisant la REalité (ELECTRE): This method uses the majority rule to eliminate alternatives based on unacceptable performance and choose the best alternative (Matulaitis et al., 2016; Sánchez-Lozano et al., 2016; Wu et al., 2016)
- Multi-Attribute utility Theory (MAUT): A framework that quantifies preferences and uncertainties to facilitate decision-making based on utility functions (Hahn, 2015; Karatas & El-Rayes, 2015; Pušnik & Sučić, 2014)
- Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE): A method that evaluates and ranks alternatives based on partial pre-ordering and preference functions (Alsayed et al., 2014; Samanlioglu & Ayağ, 2017; Troldborg et al., 2014)
- Simple Additive Weighting (SAW): SAW is a method that assigns weights to criteria and calculates the overall performance score for each alternative based on the weighted sum of criteria values (Ayshwarya et al., 2019; Zajusz-Zubek & Korban, 2023; Zulherry, 2023).
- Step-wise Weight Assessment Ratio Analysis (SWARA): This is a Multi-Criteria Decision Making (MCDM) technique that enables experts to directly rank criteria without the need for pairwise comparisons. It involves a step-wise process where criteria are evaluated based on their relative importance through expert judgment. SWARA calculates the final weights for criteria by averaging individual rankings, providing a straightforward approach to determining the significance of criteria in decision-making processes (Badi et al., 2021; Ijadi Maghsoodi et al., 2018; Rekik & El-Alimi, 2023; Yücenur & Ipekçi, 2021).
- Technique for Order preference by similarity to ideal solution (TOPSIS): This technique determines the best alternative by calculating the shortest distance to the positive ideal solution and the longest distance to the negative ideal solution (Rezaei-Shouroki et al., 2017; Sánchez-Lozano et al., 2015; Wang et al., 2018).

- VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR): This approach identifies the best compromise solution by ranking alternatives based on both the proximity to the ideal solution and the stability of the rank (Boran, (2018); Büyüközkan & Karabulut, 2017; Lee et al., 2017; Vučijak et al., 2013).
- Weighted Aggregated Sum Product Assessment (WASPAS): This MCDM method combines the aggregation of criteria using both summation and multiplication operations. It allows decision-makers to incorporate different weights for criteria and alternatives, providing flexibility in reflecting the importance of each criterion in the decision-making process. WASPAS aims to aggregate the assessments of criteria and alternatives to generate an overall ranking or preference order based on weighted sum and product calculations (Balezentis et al., 2021; Nie et al., 2017; Yücenur & Ipekçi, 2021).

Although these techniques yield sufficient results, they struggle with uncertainty. Making decisions about renewable energy planning involves a complex interplay of multiple factors, including economic feasibility, technical limitations, environmental impact, political considerations, and social acceptance. Traditional MCDM approaches tend to oversimplify the inherent vagueness and uncertainty in these multifaceted factors, potentially leading to overly simplistic conclusions that do not encapsulate the complexity of real-world decision-making scenarios.

On the other hand, fuzzy MCDM tools play a pivotal role in addressing the ambiguities and uncertainties inherent in real decision-making problems. Traditional decision-making models often struggle to accommodate the complexities and vagueness present in many real-world scenarios (Khashei-Siuki et al., 2020; Shao et al., 2020; Shojaeimehr & Rahmani, 2022). Fuzzy set theory is fundamental in decision-making, aiding in the representation of uncertainty and vagueness. Within renewable energy planning, fuzzy MCDM techniques are indispensable for effectively managing complex and ambiguous criteria. The integration of fuzzy set theory with MCDM methods provides a flexible and comprehensive approach to decision-making. An integral feature of fuzzy set theory involves the use of linguistic terms to articulate degrees of importance or preference. These terms are associated with fuzzy triangular numbers, which adeptly capture the uncertainty present in decision-makers' judgments. For example, phrases such as "Equally important" or "Strongly important" correspond to specific fuzzy triangular numbers, enabling a richer representation of preferences.

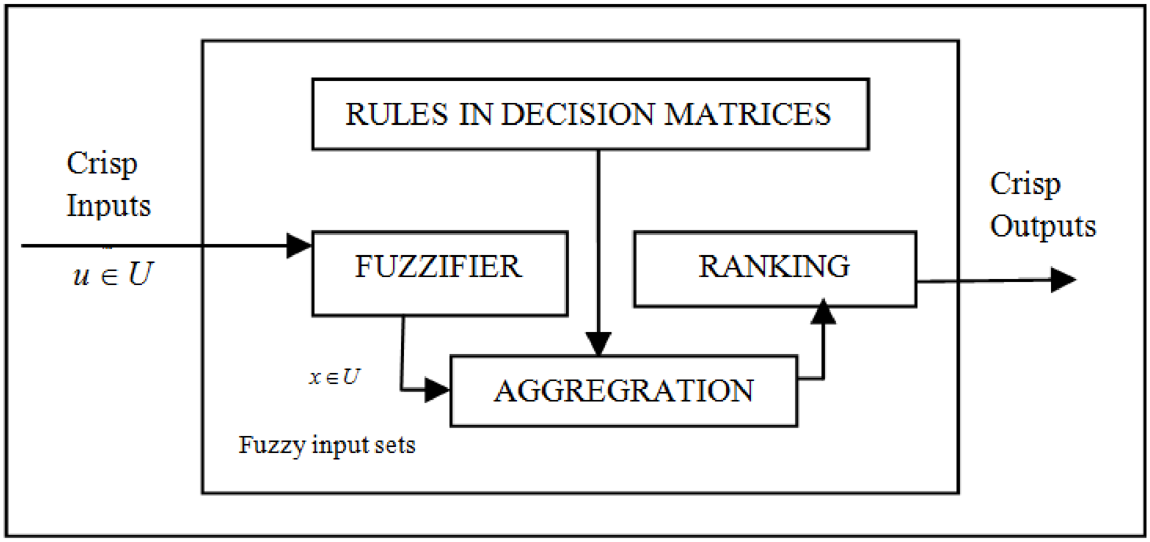


*Fig. 2.2 Fuzzy Logic-Multi Criteria Group Decision-Making*

The application of fuzzy MCDM techniques in renewable energy planning empowers decision-makers to deeply understand and analyze the complex and interdependent relationships between criteria, even when precise data is scarce. By incorporating fuzzy set theory into the decision-making process, planners are able to make well-informed and resilient decisions that effectively account for uncertainties and vagueness present in real-world scenarios (Noorollahi et al., 2016).

Recently, there has been a significant increase in developing comprehensive MCDM models in energy planning. One example is a study that suggested a thorough multi-criteria model which combines DEA, AHP, and FTOPSIS methodologies to evaluate the viability of 13 different cities as potential sites for wind farms in Iran (Rezaei-Shouroki et al., 2017). In China, the FAHP-VIKOR-GIS integrated approach was applied by Xu et al. (2020) to screen out the most suitable locations for onshore wind farms. In a separate study carried out in Vietnam, Wang et al. (2021) managed to identify the well-suited sites for wind facilities using a hybrid DEA-FAHP-FWASPAS method. Solangi et al. (2019) developed F-VIKOR combined AHP to effectively determine ideal locations for solar PV power plants in Pakistan. In Taiwan, a two-stage strategy using DEA-AHP was devised by Wang et al. (2021) to expedite the establishment of solar PV farms in 20 cities. As an example, CRITIC was developed by Shi et al. (2021) to detect and assess power quality issues related to microgrid systems during large power changes. In addition, Gu & Liu (2022) evaluated main power grid resilience under energy transformation and extreme disasters using the CRITIC-TOPSIS model. In Saudi Arabia, to evaluate the potentiality of five renewable energy sources, Yazdani et al. (2020) proposed EDAS combined with Shannon entropy as a multiple attribute decision-making (MADM) technique. In a similar work, a model for Lithuanian microgeneration was developed using EDAS, WASPAS, and TOPSIS (Zhang et al., 2019). MCDM models such as SWARA and DEMATEL are widely utilized to effectively identify and analyze the various barriers faced during the deployment of renewable energy (Badi et al., 2021; Rekik & El Alimi, 2023). For instance, SWARA is employed for weighting purposes, with notable examples including its utilization in evaluating solar projects in Iran as well as selecting suitable sites for solar farms in Libya (Badi et al., 2021; Vafaeipour et al., 2014; Zolfani & Saparauskas, 2013). Meanwhile, DEMATEL provides a visualization of interdependencies among factors relevant to the implementation of renewable energy solutions (Azizi et al., 2014; Büyüközkan & Güleryüz, 2016; Rekik & El Alimi, 2023).

In this thesis, the AHP, FAHP, CRITIC, EDAS, SWARA, and DEMATEL methodologies have been carefully selected for the evaluation of renewable energy planning, owing to their exceptional ability to handle multiple criteria and perspectives. These techniques are renowned for their robustness, comprehensiveness, and adaptability, making them ideal for the complex and intricate decision-making process inherent in renewable energy planning. AHP and FAHP provide a consistent framework for structuring and assessing complex problems, while CRITIC, EDAS, SWARA, and DEMATEL enable the integration of subjective and objective evaluations. The steps followed in each of these methodologies are meticulously explained below.

### 2.6.1 Analytic Hierarchy Process (AHP)

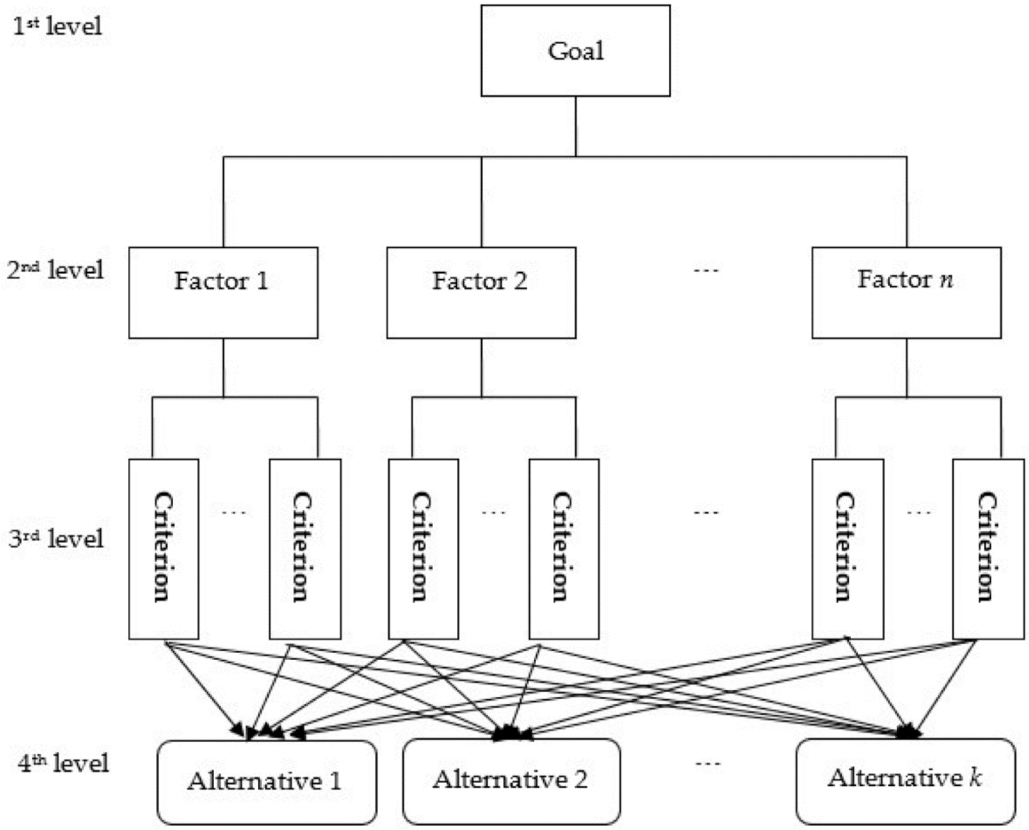


*Fig. 2.3 AHP Hierarchical Diagram*

As drawn from the literature, AHP has been widely used as an MCDM technique in various applications, including renewable energy. Saaty first introduced this technique as a mathematical tool for decision analysis (Saaty & Vargas, 2012). It enables the ranking of alternatives based on multiple factors and conflicting objectives, leading to an optimal compromise (Al-Garni et al., 2016; Sindhu et al., 2017). One of its main advantages is its ability to handle complex issues by breaking them down into more manageable components. Additionally, it can accommodate both quantitative and qualitative data while ensuring consistency through validation procedures (Al-Garni et al., 2016; Ouchani et al., 2020). The key steps of the AHP approach are summarized below (Al-Garni et al., 2016; Rekik & El Alimi, 2023; Sindhu et al., 2017):

1. Construct the initial pairwise comparison matrices. The element $x_{ij}$ of matrix $K_{n\times n}$, denotes the importance of the $i^{th}$ criterion over the $j^{th}$ one, based on Saaty's scale (Saaty & Vargas, 2012), as shown Table. 2.3.

$$K = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{m2} & \cdots & x_{nn} \end{bmatrix} \quad (1)$$

Where $i = 1,2, \dots n \; and \; j = 1,2, \dots n$

2. Normalize the initial matrix $K$
3. Calculate the Eigenvector, maximum Eigen value, and Consistency Index (CI)

$$CI = \frac{\lambda_{max-n}}{n-1} \quad (2)$$

Where $\lambda_{max}$is the maximum eigenvalue for each matrix and n the number of criteria.

4. Compute the consistency ratio (CR) to check the consistency of judgements provided by experts

$$CR = \frac{CI}{RI} \quad (3)$$

Where RI is the random index (Table 2.4).

If $CR \leq 0.10$, the degree of consistency is acceptable; otherwise, serious inconsistencies exist in the pairwise comparison and therefore, the procedure has to be repeated.

Table 2.3 Saaty's Nine-Point Weighting Scale

| **Description** | Scale of Importance | |
|---|---|---|
| | $X_{ij}$ | $X_{ij}$ |
| **Equally important** | 1 | 1 |
| **Intermediate** | 2 | 0.500 |
| **Moderately important** | 3 | 0.333 |
| **Intermediate** | 4 | 0.250 |
| **Strongly important** | 5 | 0.200 |
| **Intermediate** | 6 | 0.167 |
| **Very strongly important** | 7 | 0.143 |
| **Intermediate** | 8 | 0.125 |
| **Extremely important** | 9 | 0.111 |

Table 2.4 Random index for different values of number of elements

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

## 2.6.2 Fuzzy AHP

An extension of classical AHP combined with fuzzy logic, the Fuzzy Analytic Hierarchy Process, appears as a highly effective technique when dealing with hierarchical decision-making problems involving vagueness and ambiguity, providing more comprehensive assessments (Khashei-Siuki et al., 2020). To handle uncertainty, the triangular fuzzy number was utilized, represented as (l, m, u), where l stands for lower bound value; m stands for middle; and u represents upper bound value, which contributes depth to the analysis process by capturing various degrees of imprecision or uncertainty within decision-making contexts (Fig. 2.4). The TFNs' membership function is often given as follows:

$$\mu_M(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & otherwise \end{cases} \tag{4}$$

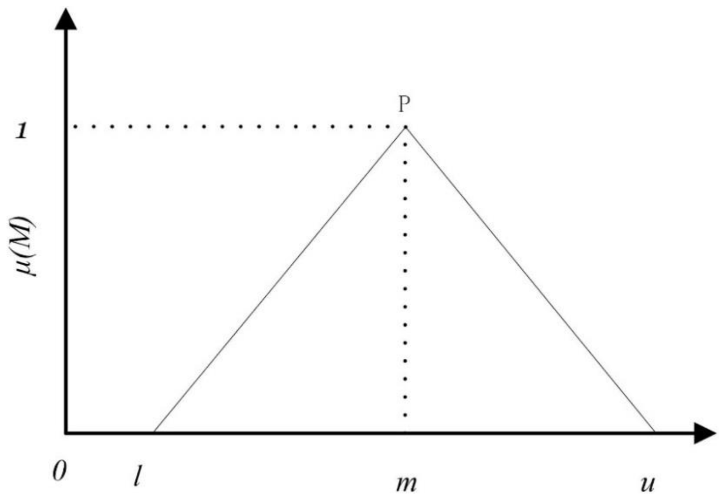


*Fig. 2.4 Triangular membership function*

It is to note that TFNs have various arithmetic operations. Consider any two fuzzy numbers $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, then the following operations can be given as follows (Gani & Assarudeen, 2012; Srichetta, & Thurachon, 2012):

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{5}$$

$$(l_1, m_1, u_1) \ominus (l_2, m_2, u_2) = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \tag{6}$$

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \tag{7}$$

$$(l_1, m_1, u_1) \oslash (l_2, m_2, u_2) = (min\,(l_1/l_2, l_1/u_2, u_1/l_2 \text{ and } u_1/u_2), m_1/m_2, \\ max\,(l_1/l_2, l_1/u_2, u_1/l_2 \text{ and } u_1/u_2) \tag{8}$$

$$(l_1, m_1, u_1)^{-1} = (1/u_1, 1/m_1, 1/l_1) \tag{9}$$

Based on linguistic variables, the Triangular Fuzzy Number (TFN) is used to determine the degree of membership in the FAHP model. Table 2.5 illustrates how the conventional AHP intensity values are transformed into the TFN scale. A detailed elaboration on FAHP and fuzzy logic is provided by (Wang et al., 2018). The model's main steps are presented as follows:

Step 1: Develop the fuzzy pairwise comparison matrix $\tilde{A}^k$

$$\tilde{A}^k = \begin{bmatrix} \tilde{a}_{11}^k & \tilde{a}_{12}^k & \cdots & \tilde{a}_{1n}^k \\ \tilde{a}_{21}^k & \tilde{a}_{22}^k & \cdots & \tilde{a}_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1}^k & \tilde{a}_{n2}^k & \cdots & \tilde{a}_{nn}^k \end{bmatrix} \quad (10)$$

Where $\tilde{a}_{ij}^k$ represents the k$^{th}$ preference of i$^{th}$ criterion over j$^{th}$ one.

Step 2: compute the aggregated matrix of all decision-makers using the following equation:

$$\tilde{a}_{ij} = \sqrt[K]{\tilde{a}_{ij}^1 * \tilde{a}_{ij}^2 \ldots \tilde{a}_{ij}^k} \quad (11)$$

Then the updated matrix:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix} \quad (12)$$

Step 3: Determine the geometric mean of the fuzzy comparisons

$$\tilde{r}_i = \left( \prod_{i=1}^{n} \tilde{a}_{ij} \right)^{1/n}, i = 1,2, \ldots n \quad (13)$$

Step 4: Compute the fuzzy weights

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_i \oplus \tilde{r}_i \oplus \ldots \oplus \tilde{r}_i)^{-1} \quad (14)$$

Step 5: Use the central area method for the defuzzification

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (15)$$

Step 6: compute the normalized weights

$$N_i = \frac{lw_i + mw_i + uw_i}{\sum_{i=1}^{n} M_i} \quad (16)$$

Table 2.5. TFN and linguistic variables

| Saaty Scale | Definition | TFN Scale |
|---|---|---|
| 1 | equally important | (1,1,1) |
| 3 | moderately more important | (2,3,4) |
| 5 | strongly more important | (4,5,6) |
| 7 | very strongly more important | (6,7,8) |
| 9 | extremely more important | (9,9,9) |
| 2 | Intermediate values between two adjacent scales | (1,2,3) |
| 4 | | (3,4,5) |
| 6 | | (5,6,7) |
| 8 | | (7,8,9) |

The consistency of pairwise comparison matrices used in FAHP must be thoroughly assessed to ensure the integrity and accuracy of the decision-making process. This thorough assessment helps in gauging the coherence and stability of judgments, thereby minimizing potential biases and inconsistencies for more reliable results. Unlike traditional AHP methods, fuzzy matrices comprise sets of inherently inconsistent fuzzy numbers. Consequently, some scholars have overlooked validating the consistency of fuzzy pairwise comparison matrices (Chou et al., 2019; Güngör et al., 2009). However, other researchers attempted to verify it specifically for intermediate values of TFNs from relevant fuzzy pairwise comparison matrix (Chen & Huang, 2022; Singh et al., 2020). The eigenvalue method was used in this paper to determine the weights of criteria based on the solution of the following equations to determine the stability of judgments (Singh et al., 2020):

$$A_w = \lambda_{max} * W \tag{17}$$

Where A, $\lambda_{max}$, and *W are* the defuzzified matrix (obtained using the arithmetic mean of the aggregated matrix), maximum eigenvalue, and final weight, respectively.

$$CI = \frac{\lambda_{max\,-\,n}}{n-1} \tag{18}$$

Where CI and n denote Consistency Index and the number of criteria.

$$CR = \frac{CI}{RI} \tag{19}$$

Where CR represents the consistency ratio.

### 2.6.3 CRITIC method

The CRITIC method, as a part of the MCDM approach, considers the level of conflict and disagreement within the problem structure. By using correlation to measure differences between criteria, it calculates their objective weights based on their relative importance (Diakoulaki et al, 1995). It has been widely applied in various fields including manufacturing, construction, medicine, electrical grid systems, and energy and environmental optimization (Lamas et al., 2020; Marković et al., 2020). The fundamental steps pertinent to this approach involves several crucial steps which are outlined as follows (Ali et al., 2020) (Fig. 2.5):

Step 1: The decision matrix $\left[x_{ij}\right] \forall\, i = 1,2,3,\dots m; j = 1,2,3,\dots n.$ is formed:

$$\left[x_{ij}\right] = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{20}$$

Step 2: Decision matrix is normalized according to the following equation, considering the type of criteria (beneficial or non-beneficial).

$$\overline{X}_{ij} = \begin{cases} \dfrac{x_{ij} - x_j^{max}}{x_j^{max} - x_j^{min}} & , x_{ij} \text{ is the beneficial criterion} \\ \dfrac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} & , x_{ij} \text{ is the non} - \text{beneficial criterion} \end{cases} \tag{21}$$

Then, the initial matrix is converted into a matrix with generic elements $\left[r_{ij}\right]$.

Step 3: Each vector has a standard deviation, which quantifies the extent of variation in values relative to the mean value for a certain criterion. Therefore, the standard deviation ($\sigma_j$) of each criterion has to be computed.

Step 4: Create a correlation matrix for the evaluation process. Then, compute the linear correlation coefficient between the criteria measure of the conflict created by criterion

Step 5: Determine the measure of conflict caused by criterion j regarding the decision situation defined by the rest of the criteria.

$$\sum_{k=1}^{m} \left(1 - r_{jk}\right) \tag{22}$$

Step 6: Calculate the quantity of information concerning each criterion.

$$C_i = \sigma_j \sum_{k=1}^{m} \left(1 - r_{jk}\right) \tag{23}$$

Step 7: Finally, calculate the objective weights of each criterion.

$$W_j = \frac{C_j}{\sum_{k=1}^{m} C_j} \quad (24)$$

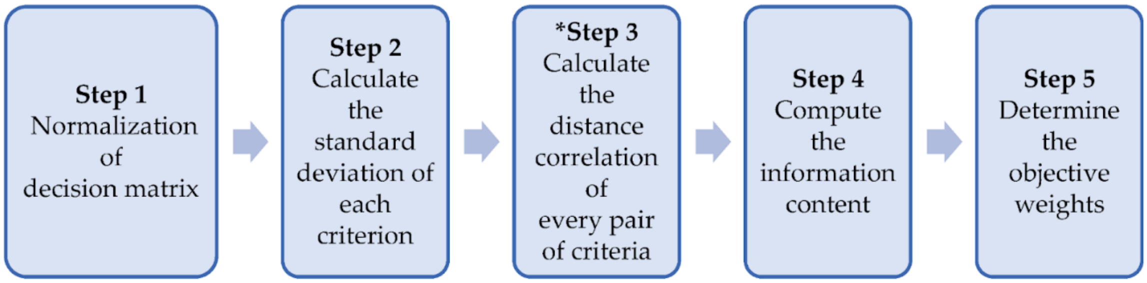


*Fig. 2.5 CRITIC Steps*

### 2.6.4 EDAS method

The EDAS technique has become increasingly prominent in academic literature as a Multi-Attribute Decision Making tool due to its simplified and efficient ranking process requiring fewer computations as opposed to other MCDM methods (Torkayesh et al. 2023). The EDAS approach utilizes two main positive distance from average (PDA) and negative distance from average (NDA) for calculating alternative distances based on each criterion's average solution (Babatunde et al. 2022). When considering n alternatives and m criteria, the essential steps of the EDAS model may be summarized as follows:

Step 1: Construct the decision matrix.

$$[x_{ij}] = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{m2} & \cdots & x_{nm} \end{bmatrix} \quad (25)$$

Where $x_{ij}$ stands for the performance value of alternative i under criterion j.

Step 2. Compute the average solution of each criterion using Eq. (7) and (8)

$$[AV] = [AV_j]_{1\times m} \quad (26)$$

$$AVG = \frac{\sum_{i=1}^{n} x_{ij}}{n} \quad (27)$$

Step 3: Construct the PDA and NDA matrices for the assessment process (Eqs. 9 - 14)

$$[PDA] = [PDA_{ij}]_{n\times m} \quad (28)$$

$$[NDA] = [NDA_{ij}]_{n\times m} \quad (29)$$

In case of $j^{th}$ criterion is beneficial

$$PDA_{ij} = \frac{\max(0, (X_{ij} - AV_j))}{AV_j} \quad (30)$$

$$NDA_{ij} = \frac{\max(0, (AV_j - X_{ij}))}{AV_j} \quad (31)$$

In case of j^th criterion is non-beneficial

$$PDA_{ij} = \frac{\max(0, (AV_j - X_{ij}))}{AV_j} \quad (32)$$

$$NDA_{ij} = \frac{\max(0, (X_{ij} - AV_j))}{AV_j} \quad (33)$$

Where PDAij and NDAij represent the positive and negative distance of the i^th alternative from the average solution in terms of j^th criterion.

Step 4. We calculate the weighted sum of PDA and NDA for all alternatives using Eqs. (15) and (16).

$$SP_i = \sum_{i=1}^{m} w_j \, PDA_{ij} \quad (34)$$

$$SN_i = \sum_{i=1}^{m} w_j \, NDA_{ij} \quad (35)$$

Where $w_j$ is the criterion j weight.

Step 5: Normalize the alternatives' SP and SN values using the following Eqs.

$$NSP_i = \frac{SP_i}{max_i(SP_i)} \quad (36)$$

$$NSN_i = 1 - \frac{SN_i}{max_i(SN_i)} \quad (37)$$

Step 6: Finally, appraisal score (AS) for each alternative is calculated based on:

$$AS_i = A = \frac{1}{2}(NSP_i + NSN_i) \quad (38)$$

### 2.6.5 SWARA approach

The SWARA method, introduced by Keršuliene et al. in (2010), has been effectively utilized as a weighting technique in diverse MADM problems. Unlike other methods like AHP and ANP, SWARA offers a direct approach that enables experts to participate more spontaneously without the need for extensive pairwise comparisons or addressing consistency issues (Badi et al., 2021; Rekik & El Alimi, 2023). In this method, the relevant criteria are assessed and prioritized based on experts' understanding from most significant to least significant. Then, the final ranks are calculated by taking the average of the individual rankings. The key steps of SWARA are explained as follows:

1. Each expert ranks the *n* criteria based on their significance

2. Compute the average attribute value ($\bar{A}_c$) obtained from T experts using the following formula:

$$\bar{A}c = \sum_{t=1}^{T} \bar{A}c \tag{39}$$

3. Calculate the comparative importance $S_j$ of the average value ($\bar{A}_c$) starting from the second ranked criterion, and determine its significance compared to the remaining criteria $C_{j+1}$.

4. Determine the coefficient $K_j$ according to:

$$K_j = \begin{cases} 1 & j = 1 \\ S_{j+1} & j > 1 \end{cases} \tag{40}$$

5. Determine the recalculated weight $q_j$

$$q_j = \begin{cases} 1 & j = 1 \\ \dfrac{q_{j-1}}{K_j} & j > 1 \end{cases} \tag{41}$$

6. Compute the final weight according to:

$$W_j^{SWARA} = \frac{q_j}{\sum_{k=1}^{n} q_j} \tag{42}$$

### 2.6.6 DEMATEL approach

The DEMATEL methodology, which originated at the Battelle Geneva Institute in 1971, is commonly used to address intricate causal issues within complex systems (Braga et al., 2021; Yazdi et al., 2020). Its primary objective is to uncover connections between different factors and identify direct and indirect interdependencies among them (Si et al., 2018). Visualizing influential network relation maps based on graph theory helps achieve this goal by clarifying significant factors and their causal implications within complex problem structures (Fig. 2.6) (Chauhan et al., 2018; Si et al., 2018; Yazdi et al., 2020). Thus, visual planning enables a better understanding of the significant causal factors in complex problem structures.

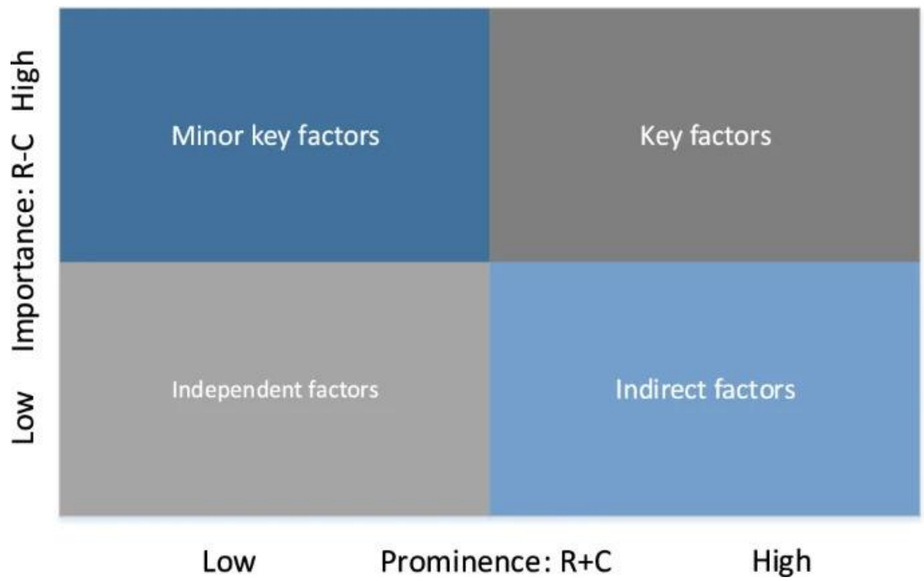


*Fig. 2.6 DEMATEL Diagram*

The following steps outline how to apply the DEMATEL approach:

1. Construct the direct comparison relation matrix for $k$ experts and $n$ criteria, which displays the direct link between variable i and variable j, according to a 5-point scale (Table 3.6).

Table 2.6. DEMATEL influence scale

| Linguistic Terms | Influence score |
|---|---|
| No influence | 0 |
| Low influence | 1 |
| Medium influence | 2 |
| High influence | 3 |
| Very influence | 4 |

$$Z = \left[Z_{ij}^{k}\right] \tag{43}$$

2. Calculate the aggregated matrix of k experts by means of arithmetic mean.

3. Normalize the aggregated matrix using the following equations:

$$L = \frac{1}{\max 1 \leq i \leq n \sum_{j=1}^{n} Z_{ij}} \tag{44}$$

$$X = L \times Z \tag{45}$$

4. Compute the total-relation matrix (T) as:

$$T = X \times (I - X)^{-1} \tag{46}$$

Where $I$ is the identity matrix $[I_n] = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}$

5. From the total matrix compute the sum of rows (Ri) and columns (Ci) according to the following equations:

$$R_i = \sum_{j=1}^{n} T_{ij} \ \forall i \tag{47}$$

$$C_i = \sum_{i=1}^{n} T_{ij} \ \forall j \tag{48}$$

6. Determine the DEMATEL weights as:

$$W_j = \sqrt{(R_i + C_i)^2 + (R_i - C_i)^2} \tag{49}$$

7. Compute the final weights as:

$$W_j^{DEMATEL} = \frac{W_j}{\sum_{k=1}^{n} W_j} \tag{50}$$

The final weights for the overall ranking of the indicators hindering the deployment of RETs are computed based on the following expression (33):

$$W_j = \frac{W_j^{SWARA} \times W_j^{DEMATEL}}{\sum_{k=1}^{n} W_j^{SWARA} \times W_j^{DEMATEL}} \tag{51}$$

## 2.13 Conclusion

In conclusion, this chapter has effectively demonstrated the significance of MCDM methods and GIS integration in enhancing renewable energy planning, site selection, and resource optimization. Techniques such as AHP, Fuzzy AHP, COPRAS, DEMATEL, ELECTRE, SWARA, TOPSIS, fuzzy TOPSIS, VIKOR, and WASPAS have been identified as essential in addressing complex decisions involving a multitude of factors including technical, economic, and socio-environmental considerations.

Ultimately, the study underscores the crucial role of selecting an appropriate MCDM method for any given renewable energy project, a choice that hinges upon the nature of the decision problem, data intricacies, and expert insight availability. By providing a clear exposition of multiple MCDM methods and their respective strengths and applicative contexts, this paper offers a substantial contribution to the field of energy planning, signposting the pathway towards more sophisticated, informed, and sustainable decision-making in the pursuit of renewable energy deployment.

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# Chapter III: Opportunities for Solar Energy in Tunisia

## 3.1 Introduction

In modern societies, energy is not only a tool for driving economic growth and development but also plays an essential role in overall well-being. The increasing demand for energy in recent decades has highlighted the dependence on traditional fuels like oil, coal, and natural gas that still dominate electricity generation (REN21, 2021). However, their depletion, environmental impact, and volatile prices have underscored the need to find more sustainable options (Cherni & Jouini, 2017). Recognizing the intricate relationship between energy, environment, and economy poses significant challenges. Intending to achieve a secure zero-carbon future, countries are now implementing policies and incentives to promote a diversified and environmentally sustainable energy sector, so as to address these challenges (Güney, 2021; Martins et al. 2021).

Renewable energy technologies, such as solar energy, wind energy, and biofuel energy, have attracted widespread interest due to their decreasing costs and remarkable technological advancements. One of the most rapidly growing technologies in this field is solar photovoltaic technology. The cumulative installed capacity of solar PV has soared from 23 GW in 2009 to an impressive 760 GW in 2021 (IRENA, 2021). This remarkable expansion can be credited to the substantial increase in efficiency of PV modules, significant decrease in prices, and the subsequent reduction in power generation costs (El Hammoumi et al. 2022; Griffiths, 20177; IRENA, 2019; Peters et al., 2019).

As a hydrocarbon-scarce state, the Tunisian energy situation is characterized by a growing demand and a diminishing supply. The country boasts a near-universal electrification rate of 100%, placing it among the leading African nations (JCR, 2019). Currently, the national state's utility, Tunisian Electricity and Gas Company (STEG), holds 100% of the total power generation capacity, which stands at 6014 megawatts (STEG, 2022). Despite a prolonged economic downturn, electricity demand has been consistently rising over recent years. In 2021 alone, consumption reached nearly 21.2 terawatt hours (TWh); projections indicate this figure could further increase to between 29 and 33 TWh by 2030 (Dhakouani et al., 2017). Tunisia heavily relies on conventional fuels for its power system, especially natural gas, which accounts for approximately 97%. On the contrary, renewable sources like wind, solar, or hydro only contribute minimally, at just around 3% (Ersoy & Terrapon-Pfaf, 2021; IRENA, 2021; STEG, 2021). This demonstrates an evident lack of diversity in the energy mix. Additionally, the heavy subsidization of these fuels coupled with reliance on imported natural gas presents significant challenges, exacerbated further by geopolitical and geo-economic factors within this sector (Sghari & Hammami, 2016).

Tunisia possesses considerable renewable energy sources, particularly solar and wind energy, due to its meteorological and geological features (Abdelrazik et al., 2022). The estimated capacity for solar photovoltaic, concentrated solar power, onshore wind, and offshore wind is approximately 400 GW, 65 GW, 10 GW, and 250 GW respectively according to multiple sources (Ersoy & Terrapon-Pfaf, 2021; IRENA, 2021). In this regard, Tunisia has displayed a growing commitment to advancing its renewable resources. The government's pledge to allocate 4.7 GW (15% wind, 15% solar PV, and 5% solar CSP) of its electricity generation capacity through renewable energy sources by 2030 signifies a strategic move aimed at ensuring energy security, diversifying the country's energy mix, reducing imports, and rationalizing energy subsidies (Gardumi et al., 2021). However, realizing such an ambitious plan hinges on identifying the most suitable geographic locations within Tunisia before embarking on large-scale project development (Al-Garni & Awasthi, 2017; Idris et al., 2022; Sindhu et al., 2017).

Identifying a suitable site for establishing a solar PV system involves consideration of multiple complex factors beyond just the availability of solar potential. These include conflicting elements that directly impact output power, costs, and social and environmental influences (Shao et al. 2020; Sward et al., 2021). For example, while an arid desert region may offer excellent solar irradiation averages, the high temperatures could negatively affect the efficiency of the modules when constructing a solar PV plant in such areas (Suuronen et al., 2017). Additionally, placing a PV facility far from grid networks and transport links would result in significantly higher costs (Al-Garni & Awasthi, 2017; Al-Shammari et al. 2021). Hence, evaluating geographical and topographic features becomes crucial in identifying potential sites. Accurate knowledge about these factors is crucial prior to deploying such systems (Al-Shammari et al. 2021).

This chapter presents an analysis of spatial suitability for large-scale solar systems using a two-stage MCDM approach based on GIS. First, Tunisia's entire territory has been analyzed using an integrated GIS-FAHP model to identify suitable locations for constructing these systems. Second, the GIS-AHP combined method has been applied to analyze the suitability of land across Kasserine and Tataouine with regard to unlocking their solar potential (photovoltaic and concentrated solar power).

## 3.2 Literature review

To properly evaluate the viability of a solar project, it is imperative to carefully determine the most appropriate location (Al-Garni & Awasthi, 2018; Wang et al, 2022). Yet, this task is complex due to the interplay of various conflicting factors involved in the site selection process (Sward et al., 2021). Extensive literature highlights several common criteria used in land suitability analysis for solar PV sites, as detailed in Table 3.1. Leveraging GIS and MCDM models has gained recognition as effective tools for conducting spatial analysis in this context. These approaches enable the integration of policymakers' perspectives with expert opinions, making them increasingly popular for land suitability and siting applications including renewable energy planning such as large-scale solar PV power plants (Ali et al. 2019; Bohra et al. 2021; Jahangiri et al. 2016; Shao et al. 2020).

A substantial body of research in the field has delved into the integration of GIS-MCDM methods as crucial tools for spatial analysis when it comes to selecting suitable sites for large-scale solar PV installations. Notably, Al-Garni & Awasthi (2018), Shao et al. (2020), and Sward et al. (2021) have conducted comprehensive reviews, shedding light on the increasing use of GIS-based MCDM techniques in identifying optimal locations for solar PV projects. Their findings underscored that by combining GIS with MCDM approaches, a thorough assessment of site suitability for large-scale solar PV developments can be achieved. Adding to this discourse, Spyridonidou & Vagiona (2023) carried out a systematic review at a global scale, focusing on analyzing and appraising key factors associated with solar PV site selection.

Table 3.1. Common used decision criteria for developing solar systems in the literature

| Reference | Criteria |
|---|---|
| **Sánchez-Lozano et al., (2013)** | Solar radiation, average temperatures, slope, aspect, distance from grid, distance from roads, distance from urban areas, plot area |
| **Tahri et al., (2015)** | Solar radiation, average temperatures, slope, aspect, distance from grid, distance from roads, distance from urban areas, land use |
| **Alami Merrouni et al., (2018)** | Solar radiation, slope, aspect, dust storm, distance from water resources, humidity, distance from grid, distance from roads, distance from urban areas |
| **Singh Doorga et al., (2019)** | Solar radiation, slope, aspect, distance from grid, distance from roads, distance from urban areas |
| **Rediske et al., (2020)** | Solar radiation, slope, distance from grid, distance from roads, distance from urban areas, land use |
| **Giamalaki & Tsoutsos, (2019)** | Solar radiation, slope, aspect, distance from water resources, distance from grid, distance from roads, distance from urban areas, elevation, land use |
| **Ghasemi et al., (2019)24** | Solar radiation, average temperatures, slope, aspect, distance from water resources, distance from grid, distance from roads, distance from urban areas, land use |
| **Guaita-Pradas et al., (2019)** | Solar radiation, slope, aspect, distance from water resources, distance from grid, distance from roads, distance from urban areas, elevation, land use, distance from wildlife, plot area |
| **Sabo et al., (2016)** | Solar radiation, slope, distance from water resources, distance from grid, distance from roads, distance from urban areas, population density, elevation, land use, plot area |
| **Majumdar & Pasqualetti, (2019)** | Solar radiation, slope, distance from water resources, distance from grid, distance from roads, distance from urban areas, population density, elevation, land use, distance from wildlife, plot area |

Wang et al. (2022) integrated Data Envelopment Analysis with Grey-Based MCDM to strategically allocate solar PV power plants in Vietnam, while Badi et al. (2021) investigated the possibility of deploying solar plants in the Misrata District, Western Libya, based on a hybrid SWARA-DEMATEL approach combined with GIS. In another study, Villacreses et al. (2022) utilized a wide range of MCDM techniques, including AHP, ARAS, OCRA, PSI, SMART, TOPSIS, and VIKOR, along with GIS analysis, to identify optimal locations for constructing solar PV power plants in Ecuador. Rediske et al. (2020) developed a GIS-based AHP-TOPSIS approach to screen potential sites for large-scale PV projects in Brazil, whereas Al-Shammari et al. (2021) incorporated the GIS-AHP model to evaluate the potential sites capable of hosting large-scale PV systems in Saudi Arabia.

Also for Saudi Arabia, Al-Garni and Awasthi, (2017) conducted a comprehensive land suitability analysis using the GIS-AHP method to assess the entire area of Saudi Arabia. The purpose was to identify optimal locations for utility-size PV power plants. Their findings revealed that 16% of the country's total land area showed significant promise for development of such power plants. Similarly, Settou et al. (2021) undertook a comparable study in Algeria by employing the same technique to designate suitable sites for large solar PV installations. They considered three different scenarios AHP, equal weights, and higher economic weights, it was found that 17% of the study area exhibited high suitability. Moreover, under the AHP technique specifically, it was observed that the land suitability index surpassed those obtained from both equal weight and higher economic scenarios.

In a study conducted in Morocco, Tahri et al. (2015) utilized GIS and MCDM methods to comprehensively evaluate the land suitability for large-scale solar photovoltaic installation in the southern region. Their assessment considered various factors, such as location, orography, land use, and climate criteria. The findings pointed out that flat and south-facing grounds were identified as optimum locations for solar PV projects. Similarly, Merrouni et al., (2018) and Ouchani et al. (2020) also employed this technique to allocate promising sites for large solar PV farms in the regions of Marrakesh and Eastern Morocco while considering analogous criteria. In both instances, their results demonstrated that these designated areas provided highly competitive opportunities for harnessing solar energy, with approximately 24.3% and 19% suitable areas in both regions. Moving onto another geographical area, Munkhbat & Choi, (2021) conducted a spatial analysis utilizing GIS-based AHP to delineate the most suitable sites for installing large-scale solar PV systems in Mongolia. The objective was to identify ideal regions for hosting large-scale solar PV farms. It was found that about 3.27% of the entire area studied qualified for installing such power plants, focusing primarily on the central region of the country.

Given the escalating national demand for renewable energy sources, Tunisia is placing an increasing emphasis on the investigation of potential applications for renewable energy systems. Despite the considerable amount of research that has been conducted in this field (Attig-Bahar et al., 2021; Balghouthi et al., 2016; Rekik & El Alimi, 2023a; Rekik & El Alimi, 2023b; Trabelsi et al., 2016), a notable gap in studies exists with regard to the implementation of large-scale solar PV power generation systems in Tunisia. In order to bridge this gap, a methodical and data-centric strategy for site selection is necessary. Integrating the FAHP and AHP with GIS is a potentially effective approach to accomplishing this. By considering numerous criteria and employing fuzzy logic to combat uncertainty and inconsistency in the decision-making processes, this methodology facilitates more effective and accurate decision-making in renewable energy applications. Numerous studies have identified the optimal solar and wind locations in Tunisia and modeled a variety of electricity generation scenarios by integrating individual MCDM models with GIS. Previous papers have applied either single MCDM approaches or integrated them with GIS to model various electricity generation scenarios and identify promising solar and wind locations in Tunisia. This demonstrates an evolving landscape that holds promise for enhancing renewable energy efforts within the country while addressing existing gaps (Bahar et al., 2022; Brand & Missaoui, 2014; Doring et al., 2018; Rekik & El Alimi, 2023a; Rekik & El Alimi, 2023b; Zelt et al., 2019).

However, despite widespread decision-making challenges related to solar site selection globally, the GIS-based FAHP approach has not seen significant application in the context of large-scale solar PV power generation systems in Tunisia. Furthermore, it has been deduced from the literature that the regions of Kasserine and Tataouine have been overlooked in terms of renewable energy projects. This study will address this gap by specifically focusing on large-scale solar PV farms (greater than 10 MW) with a special emphasis on Kasserine and Tataouine, taking into account Tunisia's geographical location and considering a diverse set of criteria such as solar radiation temperature, average cloudy days, soil texture, access to water resources, power grid, major roads, etc. By comparing selected sites with operational solar farms and planned projects while also acknowledging the government's approval of numerous PV projects ranging between 10 MW and 200 MW without specified locations (JCR, 2019). This study aims to demonstrate the consistency and reliability of its proposed model. The results are expected to enhance credibility and confidence in suitability assessment within this context while providing valuable insights into decision-making processes for sustainable solar development through the integration of GIS with MCDM.

The primary objective of this chapter is to analyze and assess potential sites in Tunisia, with a special emphasis on the regions of Kasserine and Tataouine, for hosting large-scale solar power facilities. This research draws from a wide range of datasets collected from diverse open sources, government agencies, and related studies. A comprehensive list of eleven decision criteria has been identified after consulting with experts and conducting an extensive review of relevant literature. A summary of the experts' details can be found in Table A. 2 in Appendix A. These factors include global solar irradiance, slope, ambient temperatures, average cloudy days, aspect, land use, soil texture, proximity to power lines and road networks as well as access to water resources and residential areas (see Table A. 1 in Appendix A). Subsequently, a methodological framework was developed based on the integration of GIS with FAHP and AHP techniques. Fig. 3.1 illustrates the step-by-step process followed for performing the spatial analysis.

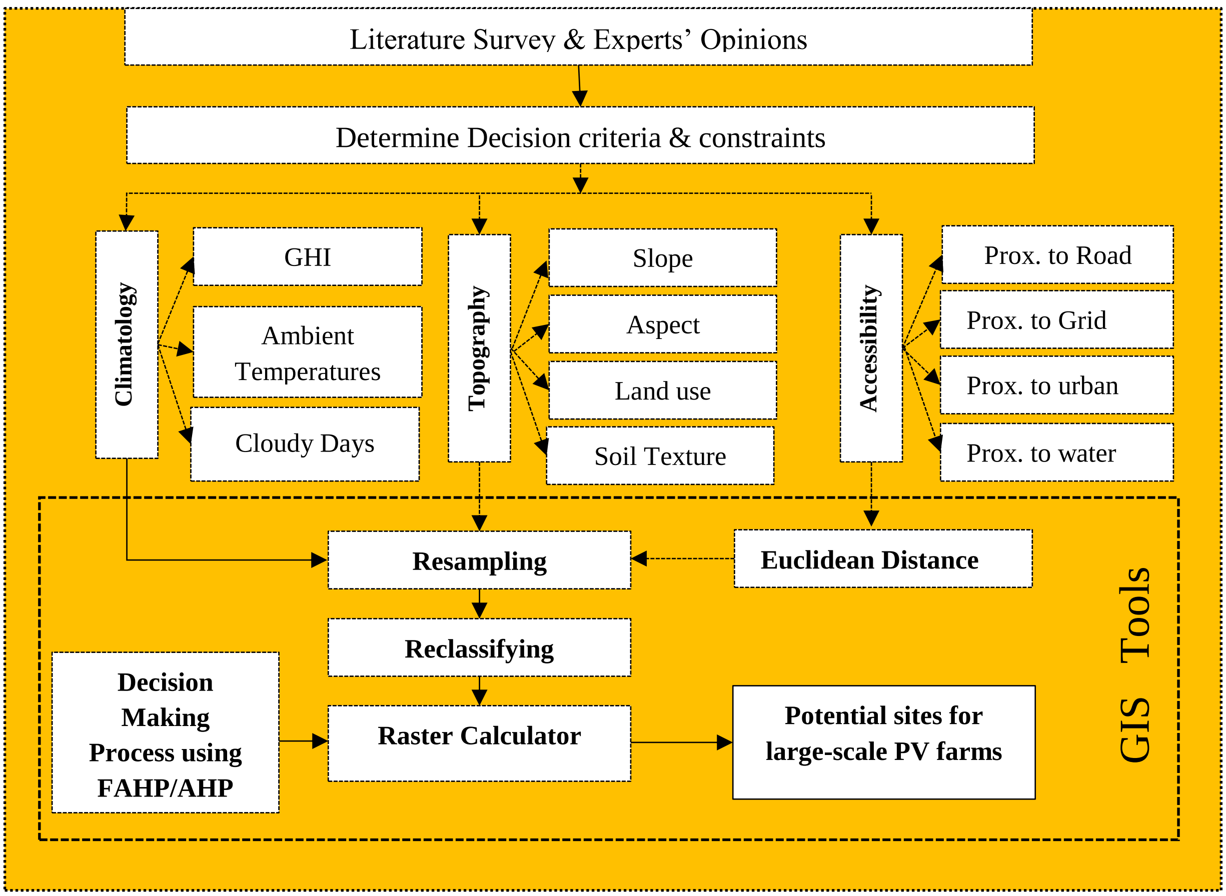


*Fig. 3.1. The steps for identifying the most suitable sites for large-scale solar farms*

### 3.3 Decision criteria

GIS-based multi-criteria decision analysis methods have garnered significant research interest in recent years for identifying suitable locations for the installation of solar PV power plants, taking into account technical, economic, and environmental factors (Colak et al., 2019; Shorabeh et al., 2019). However, the identification of feasible sites within a specific region is heavily influenced by local conditions and requires input from experts involved in the decision-making process (Ruiz et al., 2020; Yousefi et al., 2018; Zoghi et al., 2017). Engaging highly qualified experts to assess the importance of different factors is crucial in MCDA research activities (Archana et al., 2022; Sindhu et al., 2017). In this study, a team of five experts with expertise in Tunisia's energy context was tasked with providing feedback on proposed criteria and making pairwise comparisons using fuzzy sets theory.

#### 3.3.1 Climatic criteria

In terms of climatology, solar radiation plays a critical role in determining the suitability of a location for a solar photovoltaic or CSP facility, as it acts as the primary energy source for PV panels or CSP systems. Consequently, it is vital to confirm that the chosen site receives sufficient sunlight throughout the year. Research indicates that an economically viable PV and CSP system typically require at least 1300 kWh and 1800 kWh/m$^2$ per year, respectively (Aly et al., 2017; Spyridonidou & Vagiona, 2023). However, the efficiency of PV modules is influenced by solar radiation intensity and ambient temperature. Higher temperatures can reduce system performance, with approximately 0.4%–0.5% of generated energy being lost for every 1°C increase in cell temperature above 25°C (Doorga et al., 2019; Günen, 2021). This aspect represents a significant limitation of PV systems. Additionally, factoring in the average number of cloudy days enables an assessment of their potential impact on system performance and an accurate estimation of energy production levels. Therefore, selecting a location with fewer cloudy days ensures consistent and maximum solar irradiance, leading to higher electricity generation and improved economic viability of the solar PV system (Mokarram et al., 2020). Accurate raster data on solar radiation and temperature has been obtained from SOLARGIS Company's model developed at www.solargis.com for precise information. As illustrated in Figs. 3.2–3, higher solar radiation and temperature values are mostly prevalent in the central and southern parts of Tunisia. On the other hand, the northern part of the country, particularly the north-western regions, experiences a higher percentage of cloudy days (Fig. 3.4).

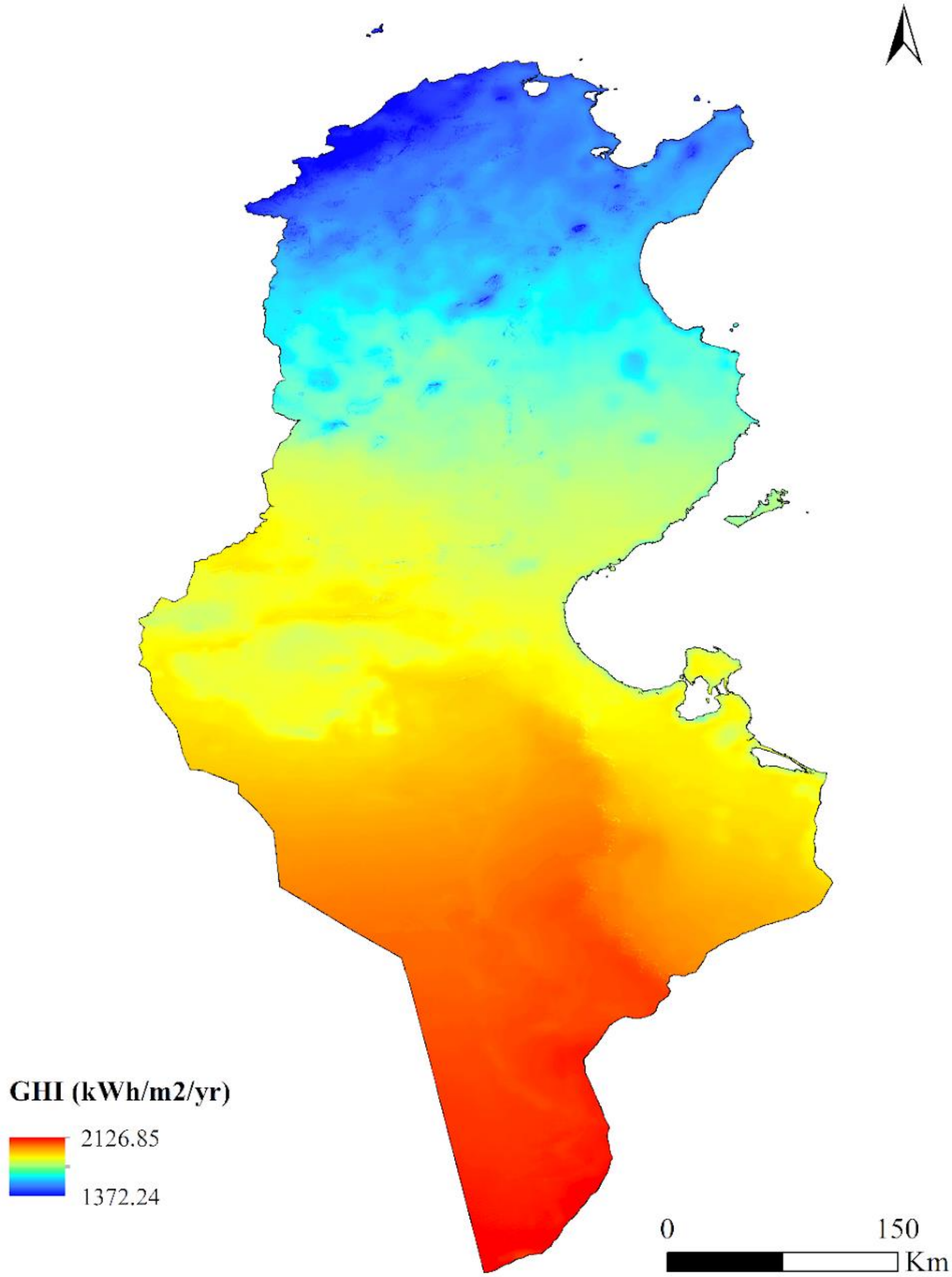


*Fig. 3.2 Annual Global Horizontal Irradiance (kWh/m2/yr)*

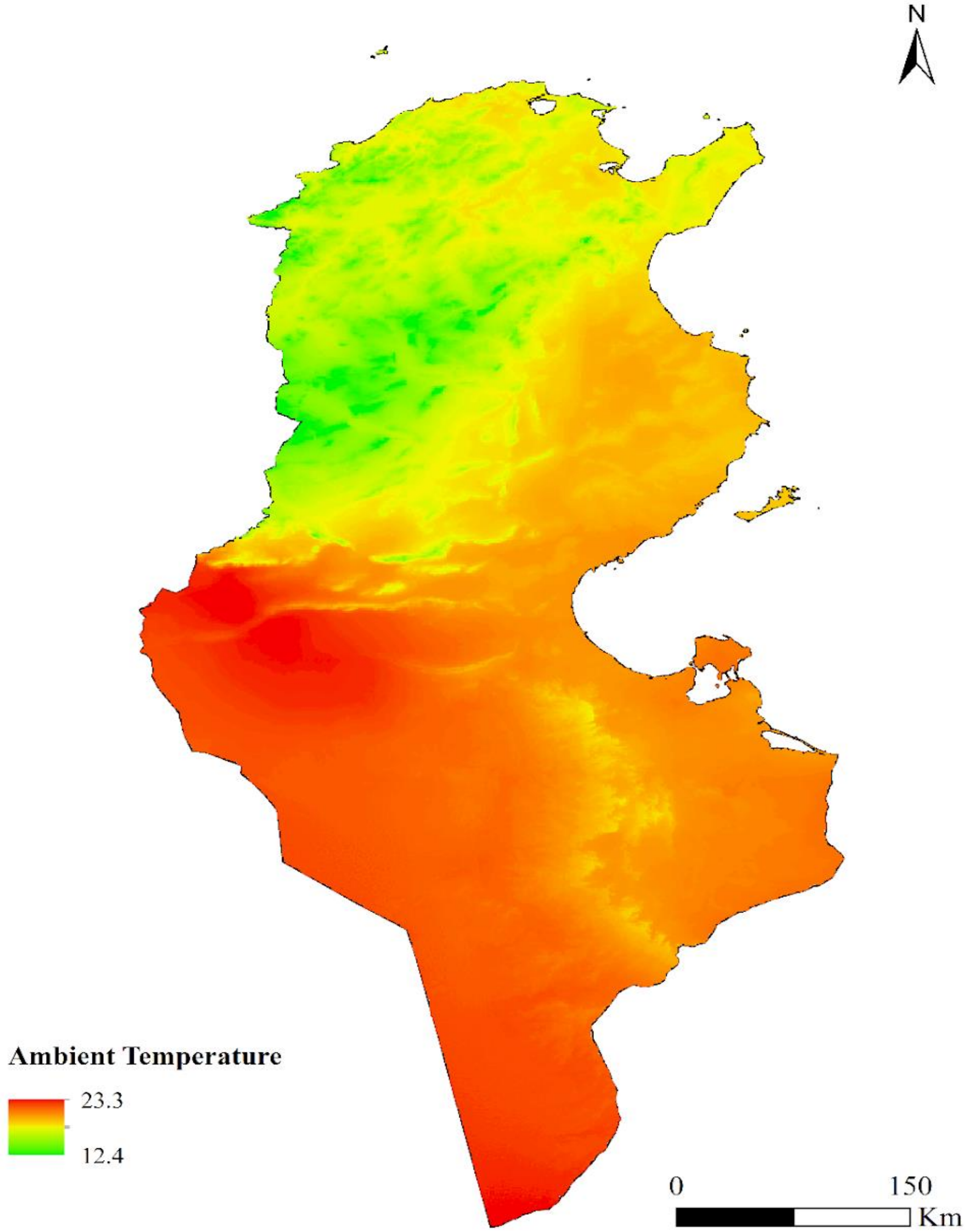


*Fig. 3.3 Annual average ambient temperatures (℃)*

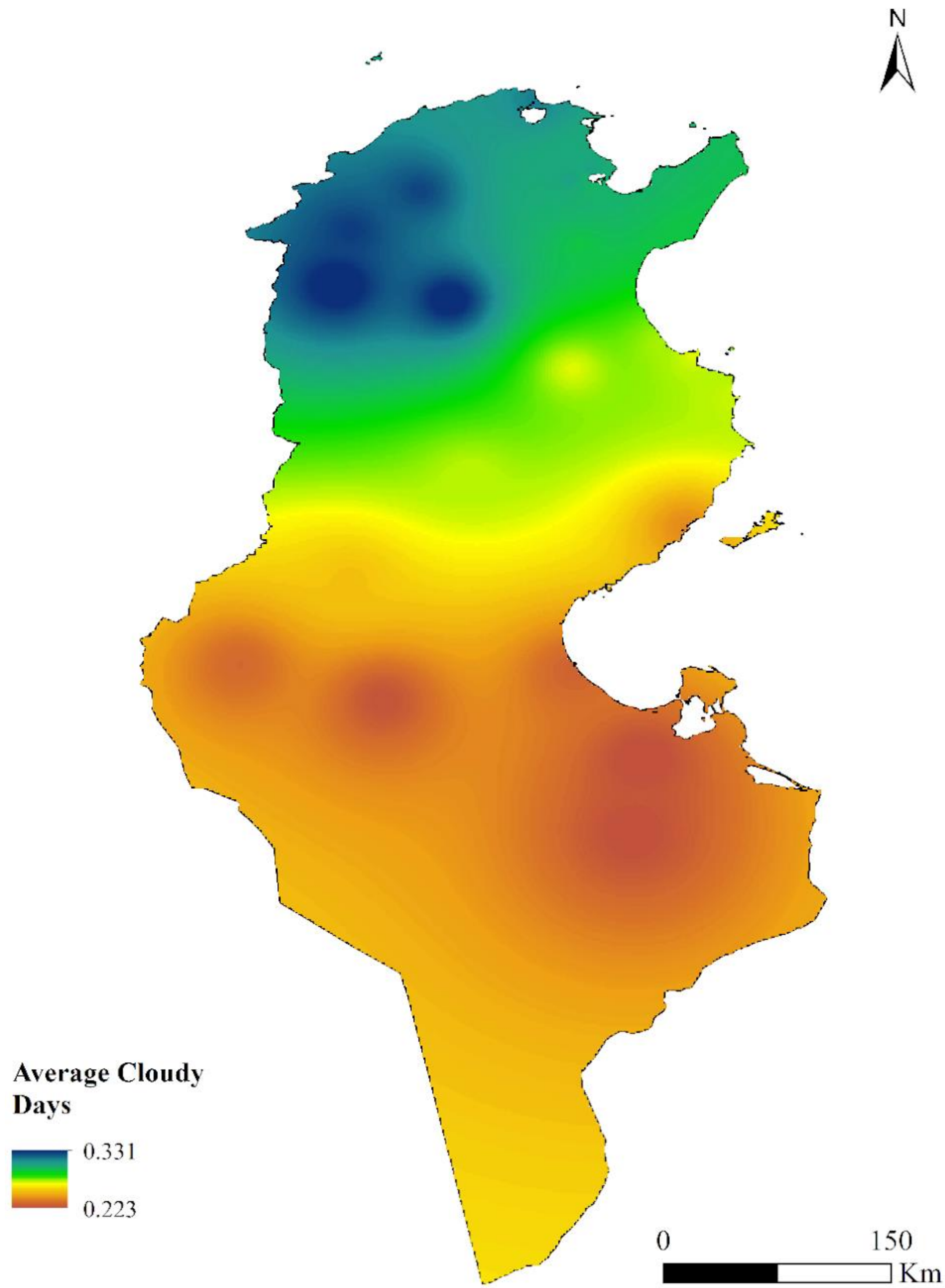


*Fig. 3.4 Percentage of average Cloudy Days (%)*

### 3.3.2 Accessibility

The proximity of a solar power plant to the grid is essential for its long-term viability, as distribution costs and power losses are directly influenced by the distance between the power plant and end users. Reduced line spacing can decrease power delivery expenses and improve overall effectiveness. Studies have shown that being closer to the grid leads to decreased power loss and connection costs (Ari & Gencer, 2020; Günen, 2021a; Günen, 2021b). Furthermore, transportation infrastructure significantly impacts total costs (Brewer et al., 2015; Watson and Hudson, 2015). Accessible sites can reduce construction and logistical expenses during both building and operation phases (Günen, 2021b; Tercan et al., 2020). Thus it is not recommended to deploy solar PV farms in areas with challenging access. Additionally, proximity to populated areas is beneficial as it ensures a reliable power supply while reducing the need for energy transmission over long distances, thereby improving efficiency (Kazak et al., 2017; Günen, 2021a'). Nevertheless, on some occasions distant locations are preferred to avoid obstructing future urban development (Al-Garni & Awasthi, 2017; Aydin et al., 2013). Furthermore, the availability of water resources is also significant factor for constructing and operating solar CSP as well as solar PV facilities, especially in dusty areas (Alami Merrouni et al., 2018; Aly et al., 2017; Mutume, 2023). Fig. 3.5 - 6 depict that the majority of Tunisia seems to have sufficient grid and transportation infrastructure as well as water resources to support large-scale solar facilities.

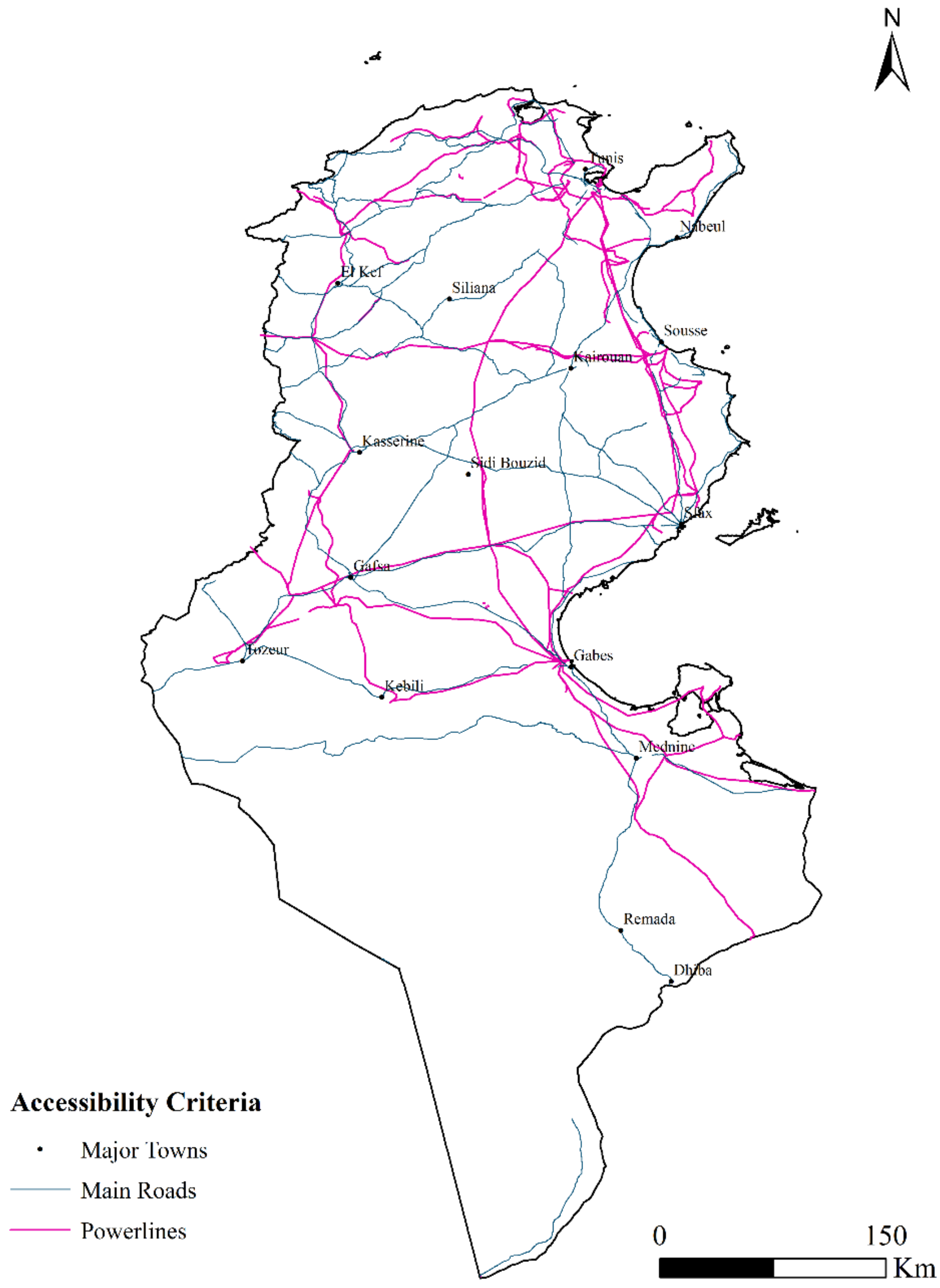


*Fig. 3.5 Accessibility Criteria*

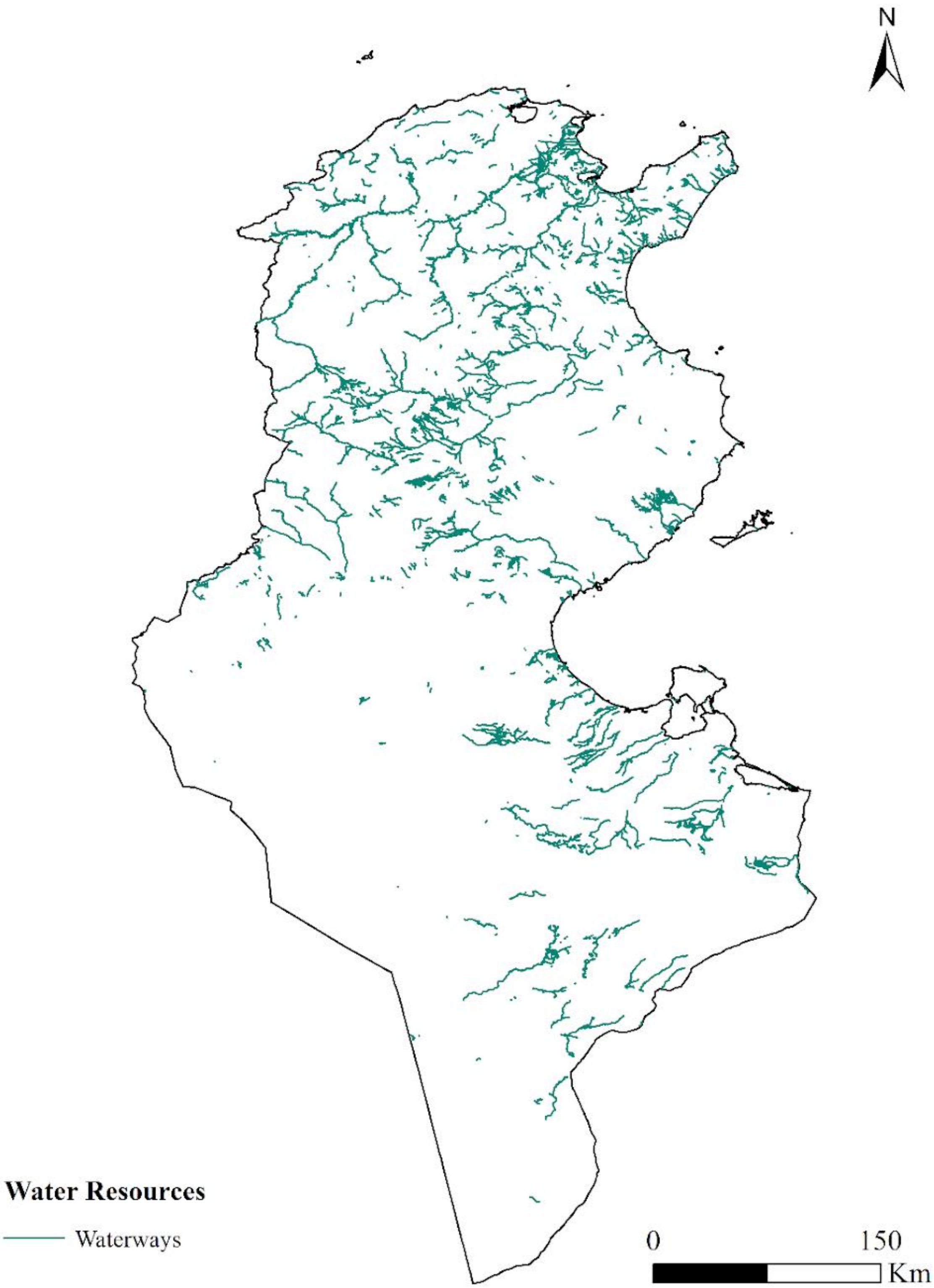


*Fig. 3.6 Proximity to Water Resources*

### 3.3.3 Topography

Solar farms, either PV or CSP, need to be located on flat land or on gentle slopes in order to remain economically viable, as steeper slopes can result in higher costs. Furthermore, greater slopes may create shadows that negatively affect the performance of PV systems (Badi et al., 2021). Therefore, regions with more gradual inclines are typically preferred (Al-Garni & Awasthi, 2018; Günen, 2021b). The generally accepted slope threshold for solar PV is between 3% and 5%. Additionally, slopes facing southeast to southwest are usually deemed most suitable in the northern hemisphere due to their exposure to sunlight. These criteria were determined using a 30-meter Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission provided by NASA. Such criteria are depicted in Figs. 3.7 - 8.

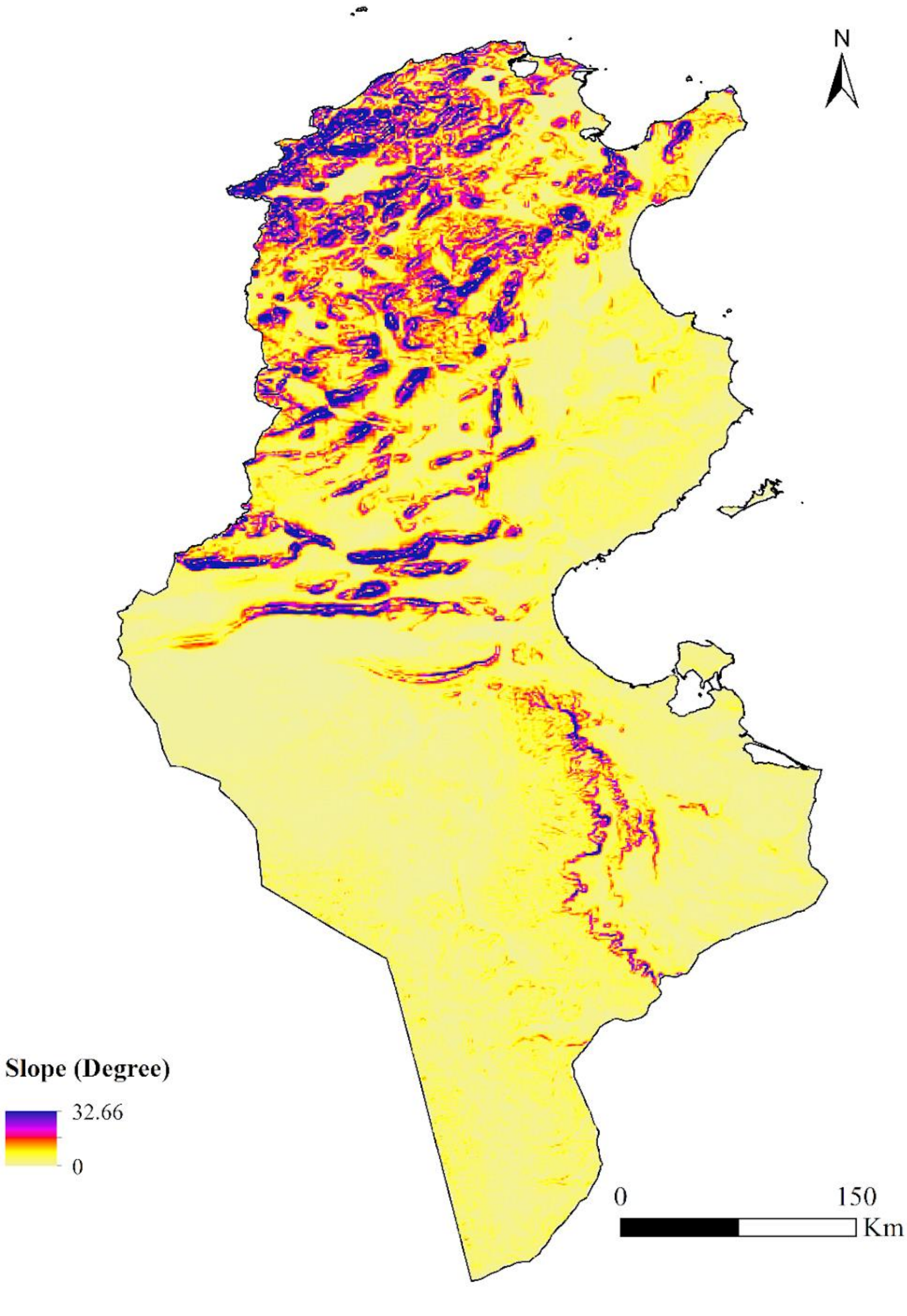


*Fig. 3.7 Slope gradient in degrees*

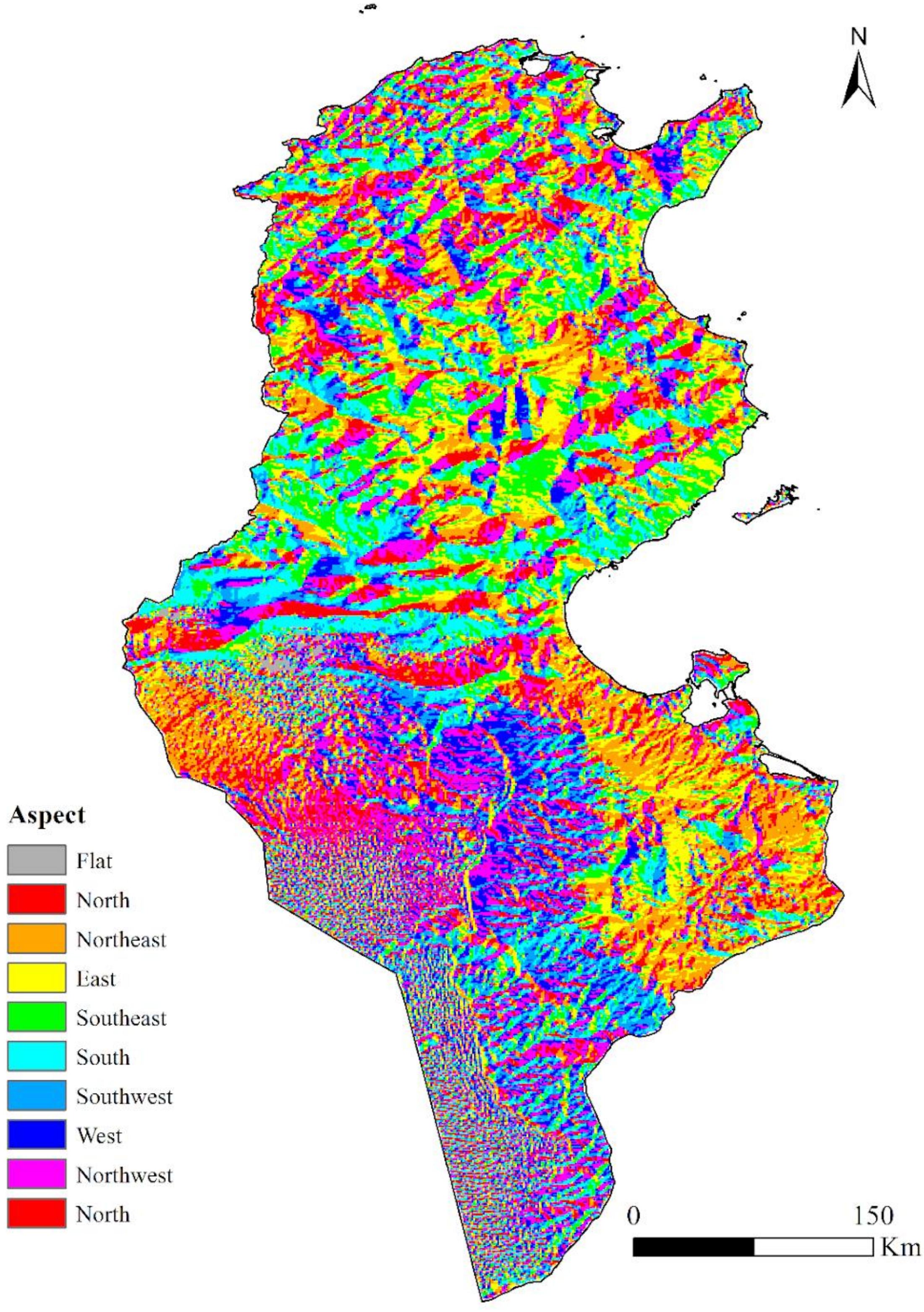


*Fig. 3.8 Aspect Orientation*

Moreover, selecting sites for solar PV plants involves dealing with various constraints related to land use, which form an essential part of spatial planning processes (Tahri et al., 2015). This challenge is inherent in every site selection process, according to Brewer et al. (2015). For instance, while excellent climatic conditions might exist at certain locations, they may not be feasible if there are limitations related to land use, such as forests, water bodies, archaeological sites, or military zones present in those areas. Hence, ideal sites should have no significant restrictions on land use. As illustrated in Fig. 3.9, baregrounds and rangelands are prevalent across central and southern regions.

Installing a PV or CSP system on a suitable soil texture is crucial for its long-term stability and performance. The ideal soil texture for large-scale solar PV systems is well-drained soil with a sandy or loamy composition. These types of soils allow effective water drainage and provide a stable foundation for the installation of solar panels, with better load-bearing capacity to support the weight of the PV system. On the other hand, clay soil, known for poor drainage properties, high water retention, and low load-bearing capacity, is unsuitable as it can lead to issues such as erosion, shifting, and instability of the solar PV system (Prieto-Amparán et al., 2021). As shown in Fig. 3.10, it is clear that the majority of the soil in Tunisia is loam.

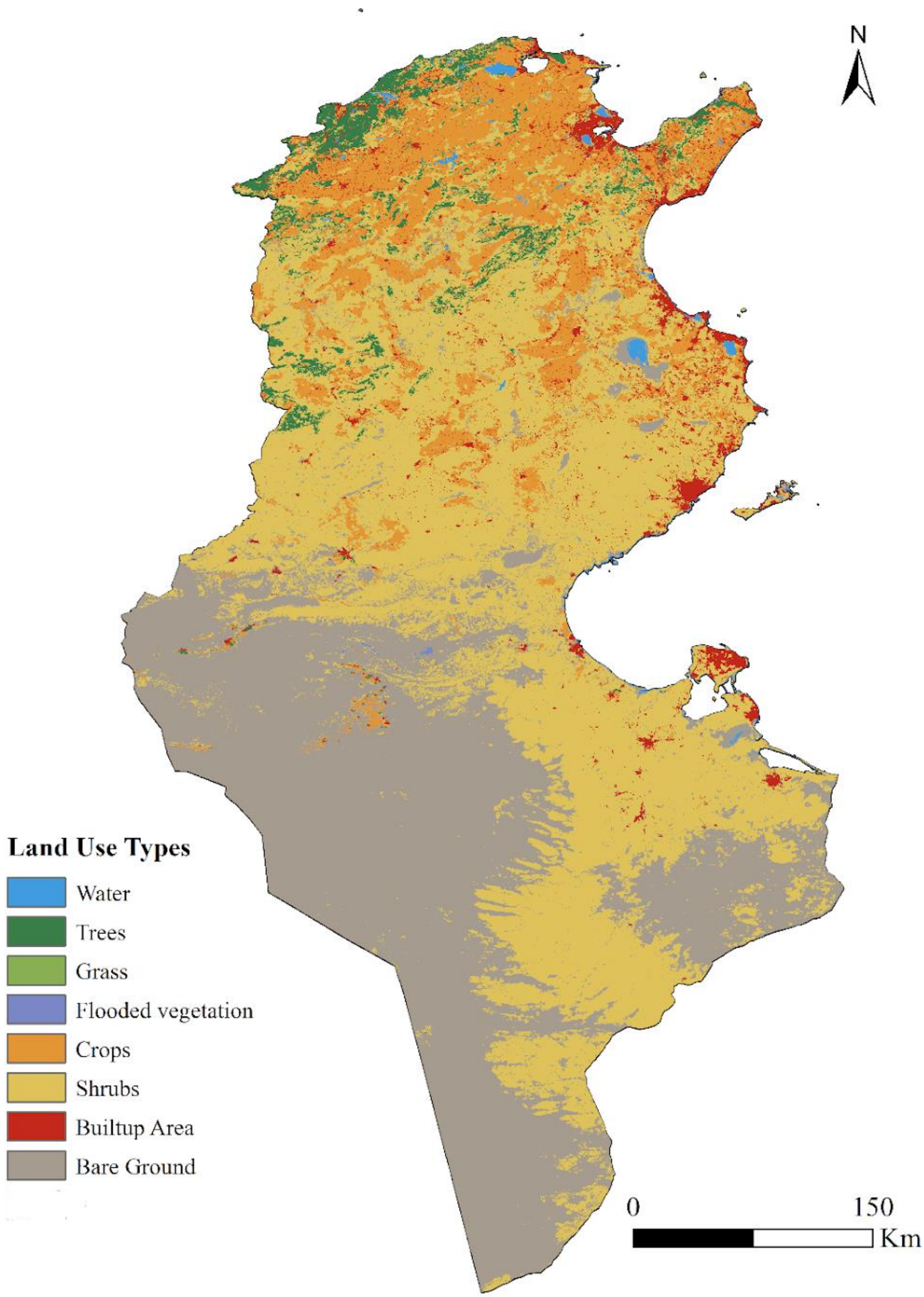


*Fig. 3.9 Landuse Types*

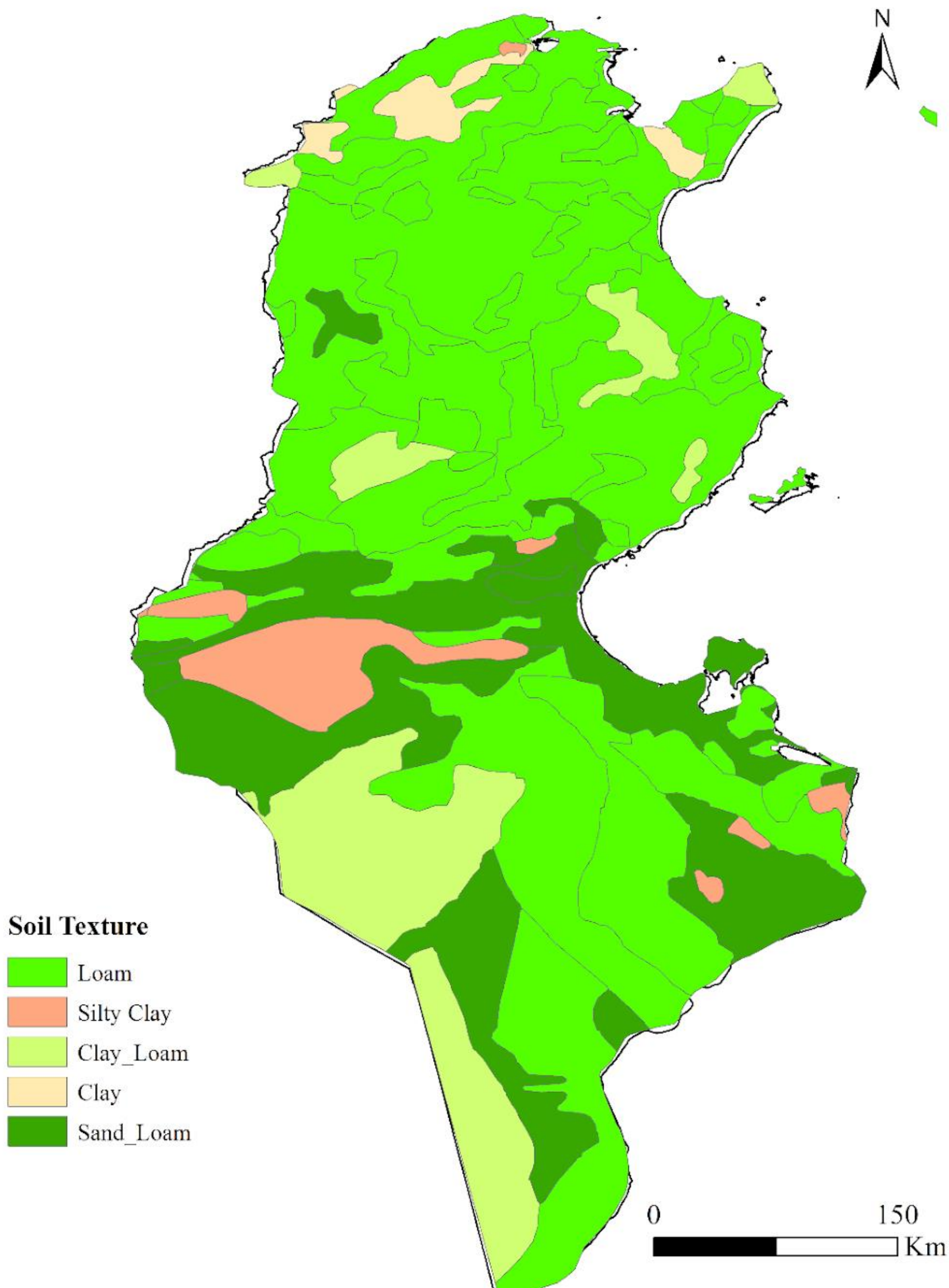


*Fig. 310 Soil Texture*

## 3.4 Constraints

Areas where constructing solar facilities is not viable or would have adverse effects on the environment or human well-being should be eliminated (Al-Garni & Awasthi, 2017; Badi, 2021). The limitations presented in Table 3.2 were identified through an extensive literature review. Subsequently, these constraints were integrated and merged into a single layer using Boolean algebra (1 and 0) within the integrated tools of ArcGIS 10.8 as shown in Fig.3.11. A "1" represents no restrictions for developing solar farms while "0" indicates constraints that prohibit such development. Considering these limitations led to excluding approximately 12.61% of the entire study area for potential use.

Table 3.2. Considered Constraints

| **Constraint layer** | **Boolean algebra restriction** |
|---|---|
| Distance from protected areas | $x < 0.5\ km$ |
| Distance from grid | $x < 0.3\ km\ and\ x > 20\ km$ |
| Distance from roads | $x < 0.5\ km\ and\ x > 20\ km$ |
| Distance from residential areas | $x < 2\ km\ and\ x > 25\ km$ |
| Slope | $x > 10\%$ |
| Landuse | $x \neq$ *Bare ground, shrubland, and medium grassy vegetation* |


*Fig. 3.11 Constraints Map*

## 3.5 Results & Discussion

In this comprehensive study, a rigorous spatial analysis was conducted, encompassing rescaling, resampling, and reclassifying multiple input layers. The application of the fuzzy membership function within the spatial analyst tool added depth to the processing of each input layer. Furthermore, FAHP and AHP were used to allocate scores to factors based on their relative importance. To identify optimal locations for large-scale solar facilities with precision, a minimum threshold of 1 $km^2$ was applied as part of an intricate process. This rigorous methodology resulted in generating a comprehensive suitability map that accurately delineates the best-suited locations for establishing large-scale solar PV and CSP farms at both national and regional levels.

### 3.5.1 Pairwise Comparisons

According to the experts' assessment, the FAHP technique revealed that the resource criterion of solar radiation carried the most weight at nearly 27.4%, as illustrated in Table 3.3. It's widely accepted that higher available resources lead to greater electricity generation. Following closely in importance were proximity to the grid and transportation infrastructure, with scores of 17.9% and 11.7%, respectively. Additionally, ambient temperatures and slope were identified as influential factors, each with relative weights of 10.6% and 8.5%. The consistency of fuzzy matrices was verified using Eqs. 17 – 19 from chapter 2 (see Table B. 1– 4 in Appendix B).

Table 3.3. The calculated weights for the considered criteria for solar PV at national level

| **Goal** | **Main criteria** | **Local weight** | **Sub-criteria** | **weight** | **Global Weight** |
|---|---|---|---|---|---|
| **Determine well-suited locations for large-scale Solar PV systems** | climate | 0.438 | GHI | 0.625 | 0.274 |
| | | | Temperatures | 0.242 | 0.106 |
| | | | Avg. Cloudy | 0.133 | 0.058 |
| | Accessibility | 0.402 | Prox. to Grid | 0.446 | 0.179 |
| | | | Prox. to Roads | 0.291 | 0.117 |
| | | | Prox. to Urban | 0.139 | 0.056 |
| | | | Prox. to Water Resources | 0.124 | 0.05 |
| | Topography | 0.160 | Slope | 0.533 | 0.085 |
| | | | Aspect | 0.253 | 0.041 |
| | | | Land use | 0.157 | 0.025 |
| | | | Soil texture | 0.057 | 0.011 |

Literature suggests that PV systems are highly sensitive to ambient temperatures; increased temperatures can reduce cell efficiency significantly. On the other hand, the scores for variables including access to water resources, aspect orientation, distance to residential areas, and average number of cloudy days varied from 4.1% to 5.8%. With respect to the land use type and soil texture, their perceived influence was comparatively lower, as evidenced by their respective scores of 2.5% and 1.1%. In order to optimize power generation and minimize expenses associated with technical modifications, it is imperative that a large-scale solar PV system be installed on suitable land with reliable grid and transportation infrastructure. Failing to do so will result in the imposition of additional construction costs, which will subsequently impact the economic feasibility of the system. The consistency of fuzzy matrices was verified using equations from 13 through 15 (see fuzzy AHP section in chapter 2). As for the Kasserine and Tataouine cases, in general terms, the AHP analysis followed a similar trend as the FAHP one, with solar radiation and slope having the highest weights among all other criteria. However, given the fact that solar CSP requires adequate water resources during construction and operation, this criterion appeared to have significant importance, ranking third just after direct normal irradiance and slope in both regions, with scores of nearly 17% and 12% for Tataouine and Kasserine, respectively (Table 3.4).

Table 3.4. AHP weighting results for solar PV and CSP in Kasserine and Tataouine

| Goal | Main criteria | Sub-criteria | Tataouine | | Kasserine | |
|---|---|---|---|---|---|---|
| | | | PV | CSP | PV | CSP |
| **Determine well-suited locations for large-scale Solar PV systems** | climate | GHI | 0.342 | - | 0.312 | - |
| | | DNI | - | 0.344 | - | 0.336 |
| | | Temperatures | 0.084 | - | 0.101 | - |
| | Accessibility | Prox. to Grid | 0.134 | 0.119 | 0.068 | 0.081 |
| | | Prox. to Roads | 0.117 | 0.074 | 0.072 | 0.092 |
| | | Prox. to Urban | 0.031 | 0.048 | 0.029 | 0.059 |
| | | Prox. to Water Resources | - | 0.167 | - | 0.118 |
| | Topography | Slope | 0.144 | 0.184 | 0.179 | 0.187 |
| | | Aspect | 0.082 | - | 0.096 | - |
| | | Land use | 0.063 | 0.064 | 0.148 | 0.116 |

### 3.5.2 Spatial Analysis

Based on the results of the site suitability assessment, it was determined that an estimated 28781 $km^2$, which accounts for 17.6% of the total study area, were identified as suitable for large-scale installation of solar PV systems, as depicted in Fig. 3.12. Particularly, the central and southwestern regions, southeastern areas, as well as the eastern coastal parts exhibited numerous locations highly suitable for the installation of solar PV facilities. Conversely, the northern regions with extensive croplands and continuous mountain ranges are considered inappropriate for the development of PV infrastructure on a large scale. To provide a more comprehensive understanding of site suitability, it would be valuable to classify the results into three distinct categories: most suitable, suitable, and moderate suitability (Fig. 3.13). From this classification, it was revealed that an extensive area totaling nearly 5251 $km^2$, which accounts for approximately 3.31% of the available surface area, demonstrates high potential for solar PV development (refer to Fig. 3.14).

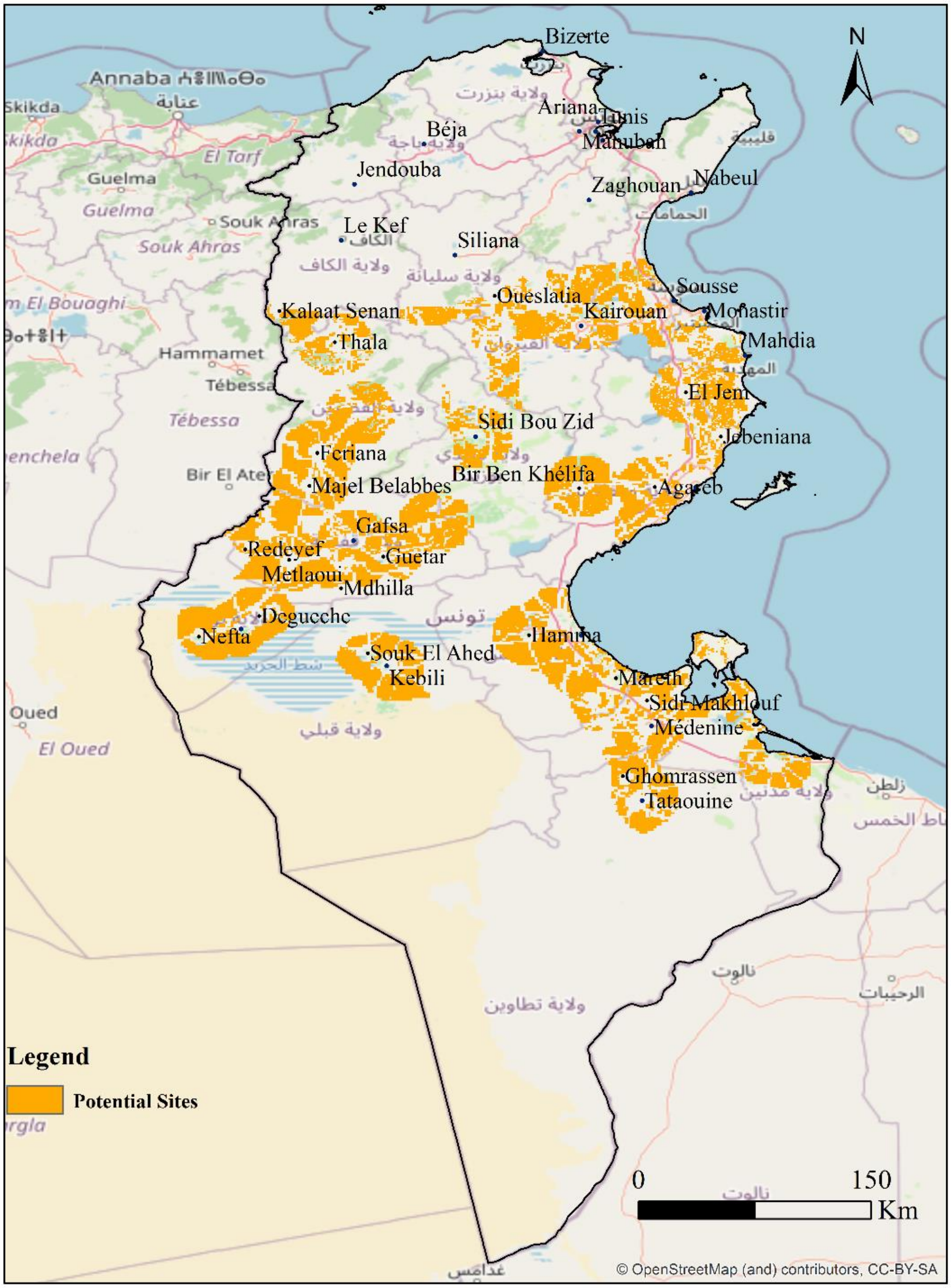


*Fig. 3.12 Solar suitability map for potential sites*

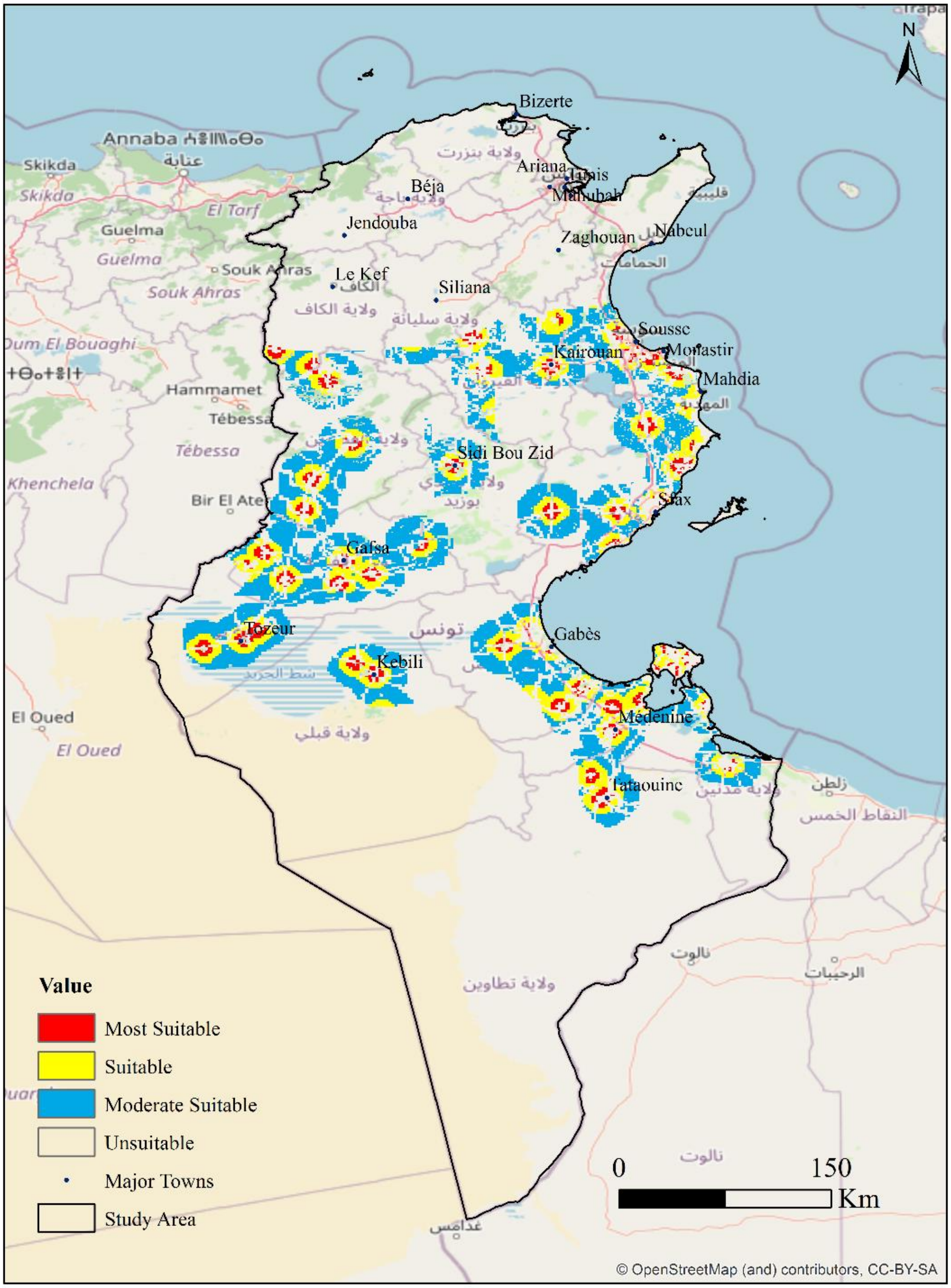


*Fig. 3.13. Spatial Distribution of Land Suitability*

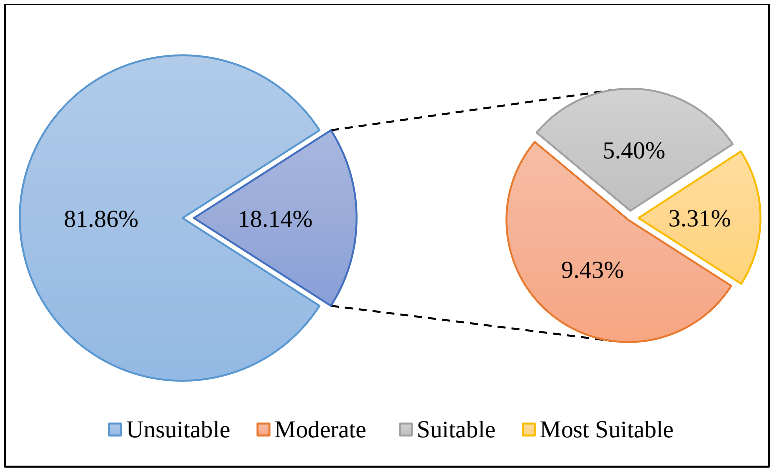


*Fig. 3.14. Land spatial distribution for the promising sites*

Additionally, at the regional level, the land suitability assessment has identified 92 sites as being highly promising locations. Sidi Makhlouf, Hamma, Ali Ben Khélifa, Kassérine Sud, and Metlaoui collectively made up almost 18.35% of these areas due to their outstanding climatic and topographic conditions. Subsequently, in view of their substantial solar radiation ranging from 1786.7–2068.9 kWh/m$^2$/yr, coupled with flat land covering 79.27%–97.5%, as well as adequate grid and transport infrastructure, the viability of investing in solar PV farms in these localities is extremely lucrative. Table 3.5 provides insight into the spatial distribution across the whole territory of the country.

Table 3.5 Total land area distribution across all regions (km2)

| | Region | Most suitable | suitable | Moderately suitable | Unsuitable | | Region | Most suitable | suitable | Moderately suitable | Unsuitable |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Ariana | NA | NA | NA | 524.50 | 13 | Manubah | NA | NA | NA | 1912.49 |
| 2 | Béja | NA | NA | NA | 3493.45 | 14 | Médenine | 616.14 | 697.35 | 1288.90 | 1010.26 |
| 3 | Ben Arous | NA | NA | NA | 676.49 | 15 | Monastir | 116.97 | 78.23 | 146.77 | 622.85 |
| 4 | Bizerte | NA | NA | NA | 3219.27 | 16 | Nabeul | NA | NA | NA | 2692.54 |
| 5 | Gabès | 529.72 | 774.83 | 1274.00 | 5400.72 | 17 | Sfax | 578.89 | 888.82 | 1657.69 | 4564.80 |
| 6 | Gafsa | 897.76 | 1233.77 | 2591.21 | 3646.18 | 18 | Sidi Bouzid | 136.34 | 331.54 | 818.04 | 6394.59 |
| 7 | Jendouba | NA | NA | NA | 2936.91 | 19 | Siliana | 35.02 | 111.75 | 254.80 | 4408.34 |
| 8 | Kairouan | 387.42 | 902.98 | 1208.44 | 4709.34 | 20 | Sousse | 134.85 | 302.48 | 625.83 | 1840.97 |
| 9 | Kassérine | 595.28 | 892.55 | 1788.82 | 5383.59 | 21 | Tataouine | 274.17 | 415.73 | 645.20 | 37816.24 |
| 10 | Kebili | 276.41 | 590.06 | 825.49 | 20477.15 | 22 | Tozeur | 355.38 | 767.38 | 1147.35 | 4236.99 |
| 11 | Le Kef | 105.05 | 84.93 | 72.27 | 4701.14 | 23 | Tunis | NA | NA | NA | 238.41 |
| 12 | Mahdia | 214.57 | 495.44 | 613.90 | 6167.36 | 24 | Zaghouan | NA | NA | NA | 2855.70 |

A comprehensive comparison of the locations of both existing and planned projects in the region was conducted in order to assess the accuracy and practicality of this spatial planning. Presently, there are three operational solar PV farms situated in Tozeur, Ghomrassen, and Al-Miknassi. Additionally, five large-scale PV projects with a total capacity of 759 MW were recently approved by the government under the concession regime. The operating farms of Tozeur (20 MW) and Ghomrassen (10 MW) were within the "Most suitable" areas as indicated by Fig. 3.15; however, the Al-Meknassi project (10 MMW) was situated slightly further away from these designated areas. As for planned projects, it was observed that Hecha (197MW), Segdoud (100MW), and Metbassta (100MW) aligned with "most suitable" areas while Remada (200MW) and Khobna (162MW) did not fall into those zones, as depicted in Fig. 3.15. Consequently, it can be inferred that the proposed model was consistent.

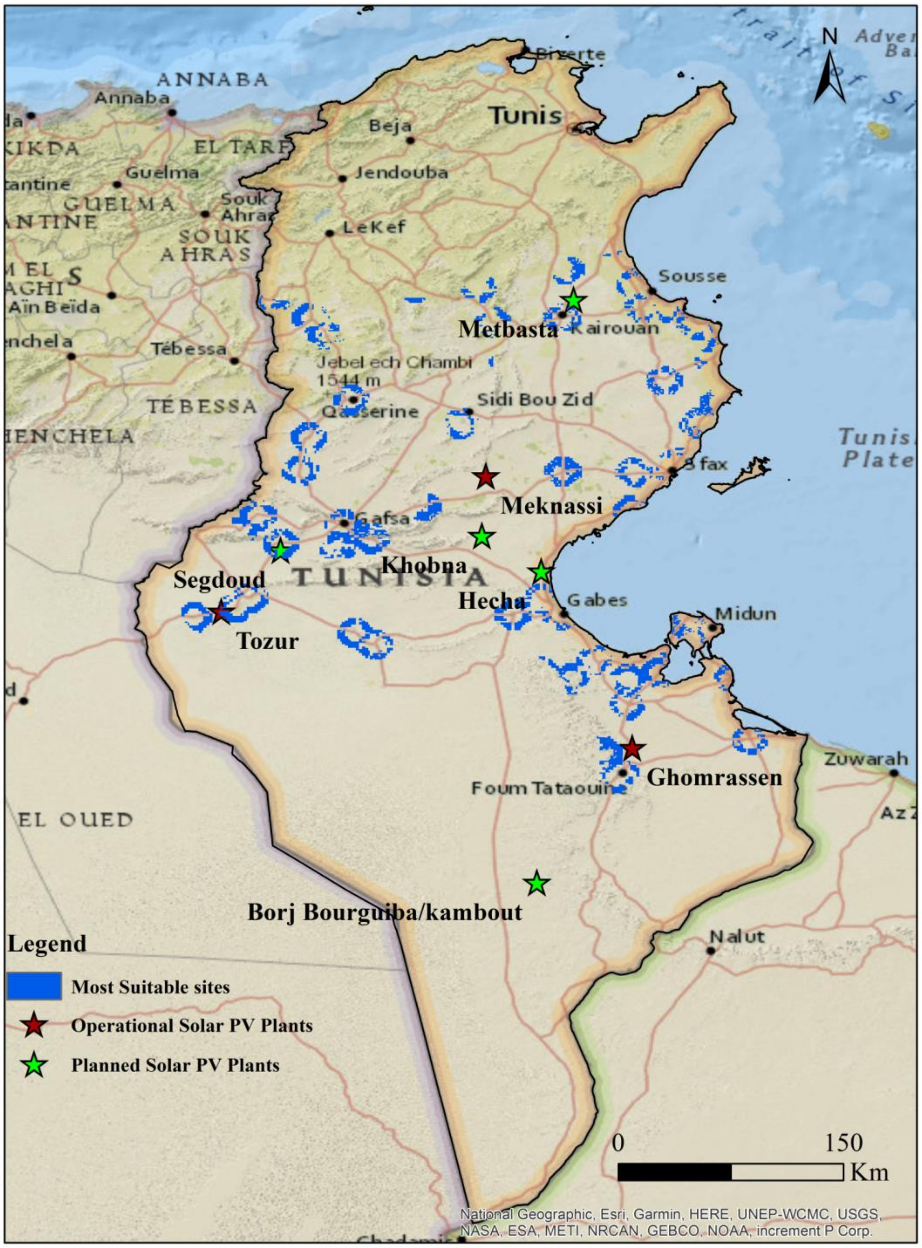


*Fig. 3.15. Operating and Planned Solar PV Projects*

## 3.6 Kasserine and Tataouine regions

Tataouine, the largest governorate in Tunisia, spans 38,889 km$^2$ and encompasses about 24% of the country's total land area. It is situated at approximately 31.98˚ North latitude and 9.96˚ East longitude in the southernmost part of Tunisia with a population of around 151,750 residents (INS, 2023). Tataouine is surrounded by Algeria to the west, Libya to the east, and Kebili and Mednine to the north (Fig. 3.16). The climate in this area is arid with long hot summers and short mild winters. On the other hand, Kasserine, a landlocked region, covers a total area of 8260 km2 and home to a population of 463,500 inhabitants (INS, 2023). Situated in central-western Tunisia, it is positioned between 35.25° north latitude and 8.78° east longitude. It shares its borders with El-Kef to the north, Algeria to the west, Gafsa to the south, and Sidi Bouzid and Siliana to the east (see Fig. 3.17).

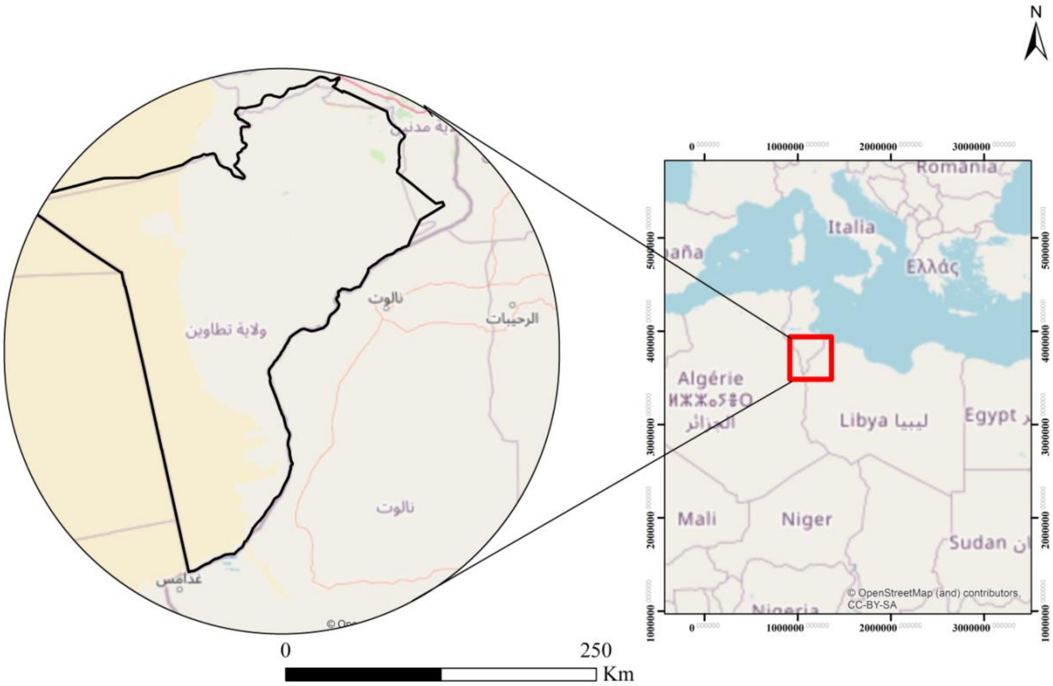


*Fig. 3.16 Tataouine map*

The area experiences a semi-continental climate, characterized by cold and wet winters and relatively hot, dry summers. Agriculture is the primary economic activity in both regions. Yet, Tataouine has experienced significant growth in Saharan tourism recently. Nevertheless, Kasserine and Tataouine have always been grappling with persistent challenges such as unemployment, marginalization, and development disparities. These issues have led to economic and social inequalities, particularly when compared to the more prosperous coastal and northern regions. Due to significant regional disparities, Kasserine and Tataouine are excluded from the industrial network, given that 92% of industries are concentrated around three major cities: Tunis, Sfax, and Sousse (Cimini, 2019). Consequently, both regions have become well-known centers of instability due to their socio-economic marginalization. The prevalence of substantial challenges is also evident in various statistical measures. Kasserine and Tataouine register the highest unemployment rates in the country at approximately 36.3% and 32%, respectively—almost double the national average (17.4%), primarily impacting young people (Romdhani, 2020). Furthermore, they rank lowest on the regional development index developed by the Ministry of Development, Investment, and International Cooperation (OCDE, 2018). Nevertheless, in these regions, with their specific conditions and status as the most marginalized areas of the country with high national poverty and unemployment rates, there is a need for deeper exploration regarding solar-based power generation systems, including solar PV and solar CSP systems (Rekik & El Alimi, 2023c; Rouine & Roche, 2022). Identifying optimal sites for installing these projects not only ensures a stable power supply but also has significant potential to create job opportunities within these most deprived communities. This could drive economic growth through increased investments in renewable energy infrastructure. Therefore, it was crucial to provide detailed insights into these areas to enable more precise and effective planning for local renewable energy projects.

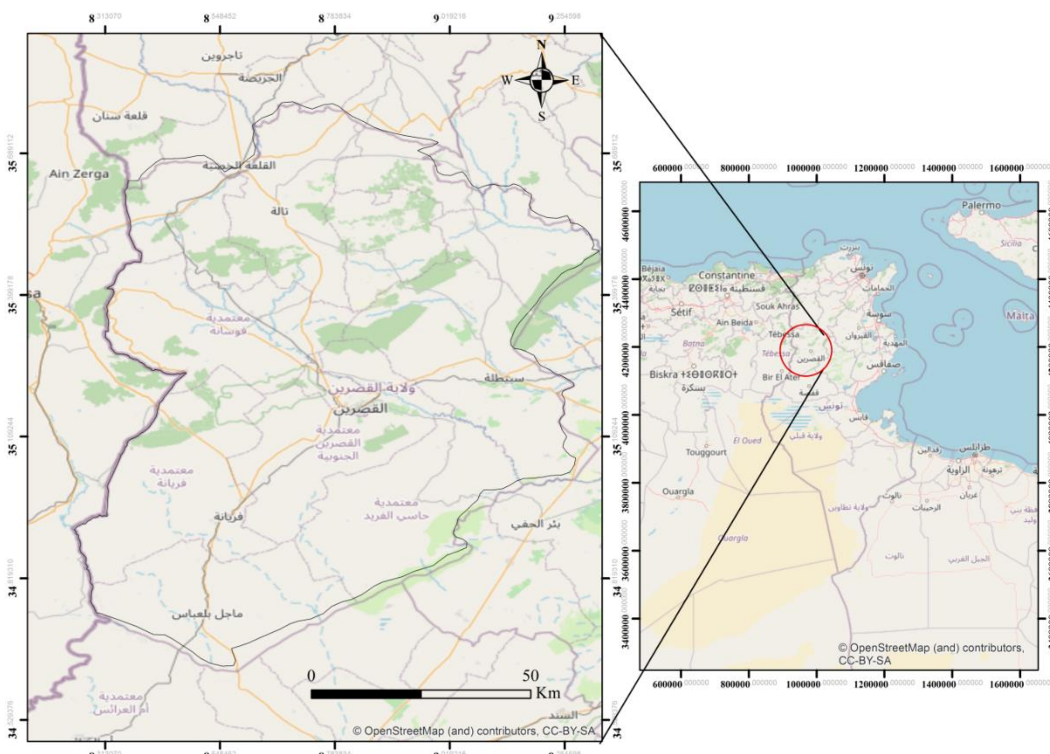


*Fig. 3.17 Kasserine map*

### 3.6.1 Kasserine and Tataouine solar potential

From the Kassérine solar suitability map, it was observed that nearly 8% of the total available area, which is equivalent to 643 km$^2$, is highly suitable for hosting large-scale solar PV facilities. Such areas are densely scattered across the southern west, central, and, to a lesser extent, the north and northern west parts of the region (Fig.3.18). Comprising slightly more than 84% of areas of high suitability, Majel Belabbes and Feriana stood out as ideal locations for hosting PV systems. On the other hand, the spatial analysis for CSP systems showed a similar trend to the one for PV. However, CSP's most promising sites covered an area of 337 km$^2$, which represents 4.18% of the total surface area. All those identified sites are located in Majel Belabbes, Kasserine Sud, and Feriana.

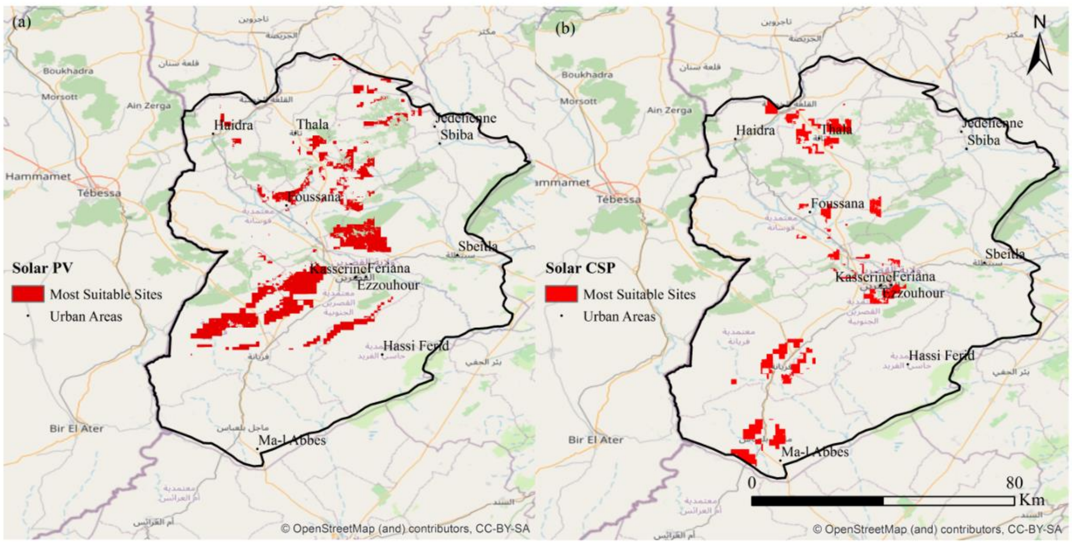


*Fig. 3.18 Kasserine solar potential: (a) Solar PV (b) Solar CSP*

In the case of Tataouine, after conducting a detailed land suitability analysis, it was found that approximately 1740 km$^2$, which accounts for 4.48% of the total available area, were deemed most suitable for the installation of CSP power plants. With regards to the geographical distribution of highly desirable sites, it was found that Remada and Dhiba accounted for more than 95% of the best-suited sites. Conversely, spatial analysis revealed that locations well-suited for solar PV technology were slightly less than those designated for CSP, covering an extensive area spanning 1426 km$^2$, which is around 3.67% of the total surface area extending from the southern east to the southernmost parts of Tataouine (Fig. 3.19).

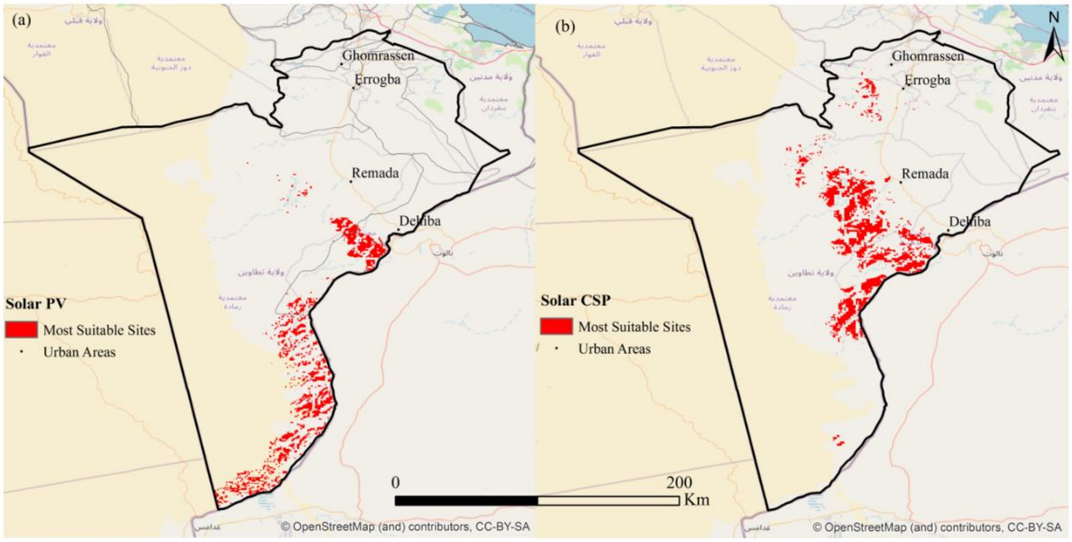


*Fig. 3.19 Tataouine solar potential: (a) Solar PV (b) Solar CSP*

In terms of generated output power, statistically speaking, it was found that the delineated sites within the Kasserine region were capable of producing an annual power of 130 TWh and 138 TWh for PV and CSP, respectively. Meanwhile, the predicted energy in Tataouine was estimated at 260 TWh/yr and 752 TWh/yr for PV and CSP, in respective order. Consequently, it can be concluded that both regions have significant potential for solar energy production, either PV or CSP.

### 3.7 Solar Estimated Energy

In theory, solar power production is described as the availability of abundant solar resources in an ideal location for the installation of solar PV or solar CSP systems, taking into account the many technical aspects of current technologies, including efficiency, capacity factor, and system performance, as shown in Table 3.6 (Anwarzai et al., 2017; Ghasemi et al., 2019; Sabo et al., 2016). Hence, the solar potential is calculated using the suggested methodology, which involves ruling out all limitations from the final suitability maps. Thus, the annual solar energy yield was calculated using the following equation:

$$AEP = GHI \text{ or } DNI * Efficiency * Available\ Area * Area\ Factor \quad (1)$$

Where area factor (%) denotes the fraction of the total available area that can be covered by solar panels.

Table 3.6 Technologies used to compute the solar technical potential

| Technology | Technology Type | Efficiency (%) | Performance ratio (%) |
|---|---|---|---|
| **PV** | Mono crystalline silicon | 15 - 22 | 70 - 85 |
| **CSP** | Parabolic trough steam cycle | 15 - 21 | NA |

Based on the numerical calculations, it is evident that PV technology exhibits exceptional energy production of 1059.7 TWh/yr (Fig. 4.12). If it is to consider only 10% of those highly desirable sites, it would be possible to produce an annual 106 TWh, which is roughly 5 times the entire demand as of 2022 (STEG, 2022). These findings underscore Tunisia's potential to emerge as a leader in solar PV energy production.

Considering the designated regions of Kasserine and Tataouine, statistically speaking, it was found that the delineated sites within the Kasserine region were capable of producing an annual power of 130 TWh and 138 TWh for PV and CSP, respectively. Meanwhile, the predicted energy in Tataouine was estimated at 260 TWh/yr and 752 TWh/yr for PV and CSP, in respective order. Consequently, it can be concluded that both regions have significant potential for solar energy production, either PV or CSP.

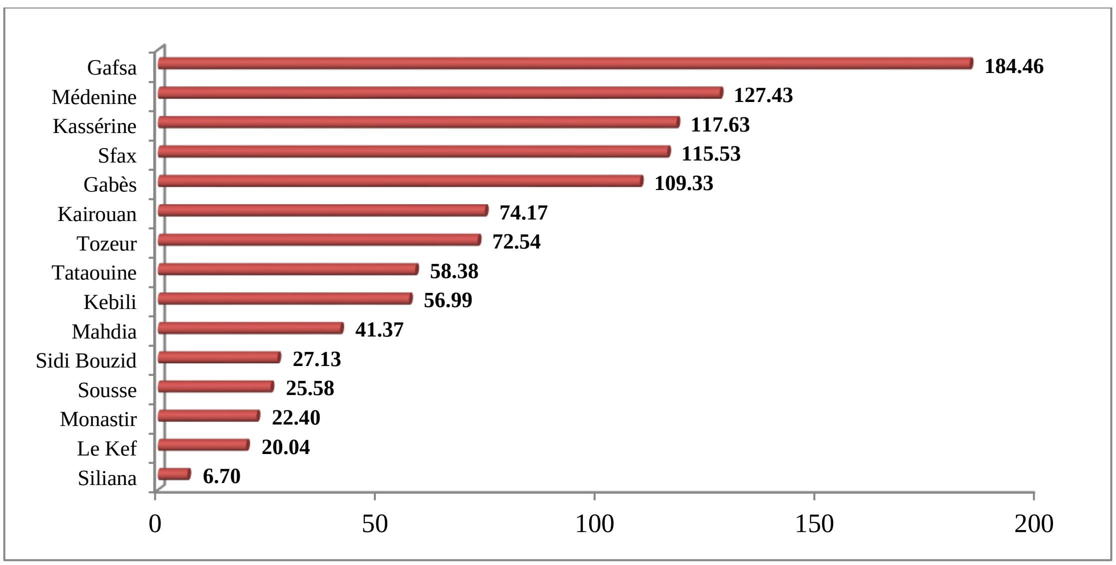


*Fig. 3.20 Estimated technical potential of the most suitable sites (TWh/yr)*

### 3.8 Discussion

The development of solar power plants would generate a cascading impact on multiple facets. By strategically selecting key locations along the eastern coast, which is home to densely populated areas and a flourishing tourism sector, the proposed projects would not only aid in addressing the soaring energy demand, especially during peak summer months, but also significantly contribute to promoting the overall sustainability of these areas. Additionally, deploying solar systems within the south-east, south-west, and central-west areas could serve as a critical step towards ensuring a consistent and reliable power supply while fostering substantial job creation opportunities. These relatively underdeveloped regions have often been overlooked; however, increased investments in renewable energy infrastructure through solar PV and CSP systems would drive economic growth by generating employment across multiple sectors, including construction operations and maintenance services, among others, which would spur economic growth while fostering sustainable development on a broader scale.

Notwithstanding the shared characteristics of solar site selection challenges, including resource availability, favorable topography, and essential infrastructure, our findings are very encouraging for policymakers and developers alike. These outcomes highlight Tunisia's potential compared to other nearby Mediterranean regions (Merrouni et al., 2018; Al-Garni, 2017; Asakereh et al., 2014; Badi, 2021; Effat, 2022; Elboshy, 2022; Mokarram et al., 2020; Settou et al., 2021). Yet, particular local factors significantly influenced the deployment of solar energy in Tunisia. Primarily due to the prolonged socio-political unrest financial and regulatory barriers (Rekik & El Alimi, 2023e). Hence, in order to fully harness the capabilities of these resources, Tunisia must confront these obstacles, foster a proactive policy climate, and put forth a novel economic framework that facilitates collaborations between the public and private sectors while addressing regional disparities. It is worth noting that, with the exception of Sfax, all regions hosting optimal locations are situated in the least developed areas of the entire nation, like Kasserine and Tataouine. Therefore, by actively investing in solar projects, these regions could experience improvements in social welfare and living standards. Additionally, collaboration with local communities is essential for a smooth transition to renewable energy, as effective communication facilitates the development of trust and the resolution of potential conflicts (Akermi et al., 2017a; Akermi et al., 2017b).

### 3.9 Conclusion

The potential for solar energy in Tunisia is robust, with an immense capacity to generate a significant amount of electricity, which can contribute not only to the national energy mix but also to social and economic development, especially in marginalized regions with high unemployment and poverty rates, like Kasserine and Tataouine. The challenges, like socio-political issues, financial constraints, and the need for regulatory evolution, must be addressed to facilitate the realization of this renewable energy potential. Overall, the study provides valuable insights and a strategic framework for policymakers and stakeholders, emphasizing the importance of renewable energy integration for a sustainable future in Tunisia and the potential role it could play in regional development and social equity.

While the current study provides a promising framework for solar PV site selection in Tunisia using geographic and technical criteria, future work will be essential in further refining the assessment. Additional research should delve into the economic feasibility and environmental impact assessments of the identified sites. Given the dynamic nature of markets and policies, it would be beneficial to explore different economic scenarios and how they may affect the implementation of these solar projects. Socio-cultural acceptance and the involvement of local communities in the decision-making process are paramount for successful project implementation and should be incorporated into future studies.

Major limitations of this work include the reliance on data that may be limited in availability and vary in accuracy, potentially affecting the study's findings. The subjective nature of FAHP and AHP methods in determining criterion weights also introduces subjective biases that could influence site selection results. Additionally, practical constraints such as changes in land use policies, socio-political changes, and the physical verification of the sites need further attention in subsequent research. Furthermore, it is essential for future work to perform detailed regional studies to refine land suitability assessments and generate tailored development recommendations. Lastly, the impact of climate change on solar resource availability is an emerging concern that should be integrated into long-term solar energy planning. Addressing these gaps will help overcome regulatory barriers and regional disparities and foster sustainable energy development in less advanced areas such as Kasserine and Tataouine.

In conclusion, this study has systematically identified optimal locations for large-scale solar power projects in Tunisia, with a particular focus on the regions of Kasserine and Tataouine. Employing a GIS-based MCDM methodology, including both FAHP and AHP, the study offers a comprehensive spatial analysis, shedding light on the most suitable areas based on a blend of climatic, topographical, soil, and accessibility criteria while also acknowledging critical environmental and social constraints.

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# Chapter IV: Opportunities for Onshore Wind Energy in Tunisia

## 4.1 Introduction

Energy has evolved to become a fundamental driver of economic growth, development, and overall societal well-being in the present era. The demand for energy has witnessed a substantial surge in recent decades. While traditional fuels like oil, coal, and natural gas still dominate electricity generation with an approximately 80 percent share, their depletion, detrimental environmental impact over time, and volatile prices on the global market render them an unsustainable choice (REN21, 2021). Recognizing the escalating challenges posed by the interconnection of energy-environment-economy dynamics, many nations have redirected their policy focus towards transitioning to renewable energy sources through incentivized frameworks aimed at cultivating a diversified energy sector that fosters sustainability, security, and zero-carbon emissions (Güney, 2021; Martins et al. 2021). Consequently, renewable energy technologies such as wind power have gained considerable traction owing to significant cost reductions and impressive technological advancements (El Hammoumi et al. 2022; Griffiths, 20177; IRENA, 2019; Peters et al., 2019).

In Tunisia, a country characterized by limited natural resources, the energy situation is becoming increasingly challenging due to rising demand and depleting supply. Despite enduring an extended economic downturn, demand continues to surge and has reached almost 21.2 terawatt hours as of 2021. Forecasts indicate that this demand will only continue to grow significantly, potentially reaching between 29-33 TWh by the year 2030 (Dhakouani et al., 2017). The Tunisian power system heavily relies on conventional fuels, particularly natural gas which accounts for approximately 97% of its energy mix. In contrast, renewable sources hold a minimal share of only about 3%, including wind, solar, and hydro energy (Ersoy & Terrapon-Pfaf, 2021; IRENA, 2021; STEG, 2021). This disparity in the composition of the energy mix presents significant challenges for sustainable development efforts. Furthermore, extensive government subsidies supporting fossil fuels coupled with heavy dependence on imported natural gas have further complicated Tunisia's energy landscape amidst geopolitical uncertainties (Sghari & Hammami, 2016). However, it is essential to note that despite these challenges, Tunisia possesses abundant renewable resources owing to its favorable meteorological and geological conditions (Abdelrazik et al., 2022). Most notably, solar and wind energies offer immense potential, Solar PV, solar CSP, onshore wind, and offshore are estimated at 400 ,65 ,10,and250 gigawatts, respectively. This substantial potential provides promising opportunities for diversifying Tunisia's energy portfolio while reducing reliance on conventional fuel sources (Ersoy & Terrapon-Pfaf, 2021; IRENA, 2021).

Recently, Tunisia has shown a significant commitment to prioritizing the development of its renewable energy resources. The government has set an ambitious target of achieving 4.7 gigawatts of electricity generation from renewable sources by 2030, with specific allocations for wind (15%), solar photovoltaic (15%), and concentrated solar power (5%) (Gardumi et al., 2021). This initiative reflects a strategic effort to bolster energy security, diversify the energy mix, decrease dependence on imports, and streamline energy subsidies.

Yet, identifying the best geographical locations for a large-scale wind farm involves more than just finding areas with high wind speeds (Idris et al., 2022; Shao et al., 2020; Sindhu et al., 2017). Factors such as output power, costs, and social and environmental impacts must also be taken into account (Sward et al., 2021). For example, while a region may have great wind power density, being far from power grids and transportation links would result in significant additional expenses (Al-Shammari et al. 2021; Baseer et al., 2017). Therefore, evaluating the suitability of a potential site depends on understanding its geographical and topographic characteristics. Accurate knowledge of these factors is essential when considering potential locations for large-scale photovoltaic farms within a country (Baseer et al., 2017).

In this chapter, a GIS-based MCDM approach is employed to develop a spatial suitability analysis in Tunisia, with a special focus on the Kasserine and Tataouine regions. The main objective is to identify well-suited locations for deploying large-scale wind farms. To achieve this, the fuzzy Analytic Hierarchy Process method was used to assign weights to the identified criteria, and the raster calculator and fuzzy overlay tools within ArcGIS were employed to compute spatial analyses and generate the suitability maps of potential sites.

## 4.2 Literature Review

Site selection is a critical step in the success of wind energy projects. The process comes with its own set of challenges, making it essential to understand these obstacles in order to fully unlock the wind energy potential in any region. Merely relying on the availability of wind sources is not enough; factors such as topography, infrastructure, costs, weather patterns, and seasonal variations directly impact power output (Ali et al., 2019; Asadi et al., 2023; Ekadeem et al., 2022). Furthermore, wind potential varies significantly across different regions due to weather patterns and seasonal variations (Baseer et al., 2017; Villacreses et al., 2022). As such, comprehensive data collection and analysis are crucial for determining a site's energy generation capacity, but this task is far from simple due to multiple overlapping criteria outlined in Table 4.1. Given these complexities, integrating GIS with MCDM approaches has emerged as an invaluable tool for decision-making processes related to wind site selection (Badi et a., 2021; Bohra & Anvari-Moghaddam, 2021; Sánchez-Lozano et al., 2016; Merrouni et al., 2018).

Table 4.1. Frequently used criteria for developing wind facilities in the literature

| Criteria | Reference |
|---|---|
| **Average Wind Speed** | Albraheem & AlAwlaqi, 2023Ali et al. 2019; Asadi et al. 2023; Harrucksteiner et al. 2023; Waewsak et al. 2020 |
| **Wind power density** | Asadi et al. 2023; Azizi et al. 2014; Effat & El Zeiny, 2022; Unal et al. 2022 |
| **Percentage of windy days** | Azizi et al. 2014 |
| **Slope** | Albraheem & AlAwlaqi, 2023; Asadi et al. 2023; Effat & El Zeiny, 2022; Zambrano-Asanza et al. 2021 |
| **Distance to grid lines** | Albraheem & AlAwlaqi, 2023; Al-Garni & Awasthi, 2017; Asadi et al. 2023; Badi et al. 2021 |
| **Distance to major roads** | Albraheem & AlAwlaqi, 2023; Al-Garni & Awasthi, 2017; Asadi et al. 2023; Badi et al. 2021 |
| **Distance to residential areas** | Albraheem & AlAwlaqi, 2023; Al-Garni & Awasthi, 2017; Asadi et al. 2023; Badi et al. 2021 |
| **Elevation** | Albraheem & AlAwlaqi, 2023; Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Waewsak et al. 2020 |
| **Land use** | Albraheem & AlAwlaqi, 2023; Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Waewsak et al. 2020; Zambrano-Asanza et al. 2021 |
| **Population density** | Koc et al. 2019; Majumdar & Pasqualetti, 2019 |
| **protected Bird areas** | Albraheem & AlAwlaqi, 2023; Ali et al. 2019; Baseer et al. 2017 |
| **Distance to airports** | Albraheem & AlAwlaqi, 2023; Ali et al. 2019; Harrucksteiner et al. 2023; Baseer et al. 2017 |

From the existing literature, it is evident that a diverse range of MCDM techniques have been effectively employed by researchers to tackle the challenge of selecting optimal geographic locations for the installation of wind systems. These encompass widely utilized methods such as the AHP (Bertsiou et al., 2020; Günen, 2021; Rekik & El Alimi, 2023), FAHP (Noorollahi et al., 2016; Rekik & El Alimi, 2023), TOPSIS (Sindhu et al., 2017), DEA (Wang et al., 2022), and many other approaches.

For instance, to determine optimal wind locations in Iran, Azizi et al. (2014) used a GIS-based DEMATEL approach. In Vietnam, DEA, FAHP, and Fuzzy-WASPAS were used by Wang et al. (2018) to identify the best-suited sites to construct wind facilities. In an Iranian case, Rezaei-Shouroki et al., (2017) developed DEA-AHP-FTOPSIS along with GIS to investigate the land suitability for installing wind systems in the province of Fars. In another work, a novel network data envelopment analysis (NDEA) was utilized by Khanjarpanah et al., (2018) to investigate the feasibility of constructing solar-wind hybrid systems in Iran. Konstantinos et al., (2019) applied an integrated model of AHP, TOPSIS, and GIS to screen out the ideal wind power locations in Greece. Another study by Xu et al., (2020), focused on optimizing wind sites in China's Wafangdian region through combining FAHP and VIKOR with GIS. In a recent paper, Effat and El-Zeiny, (2022) incorporated classical AHP and GIS to determine the suitable locations for installing hybrid solar PV and wind power plant site selection in Assiut, Egypt. Several recent papers that have applied GIS-MCDM for wind energy site selection are presented in Table 4.2.

Table 4.2 Summary of GIS-MCDM methods used in literature

| **MCDM Technique** | **Renewable Technology** | **Location** | **Reference** |
|---|---|---|---|
| AHP | Solar PV, Onshore wind, and Biomass | Thailand | Waewsak et al. 2020 |
| FAHP | Offshore wind | Morocco | Taoufik & Fekri, 2021 |
| AHP | Solar PV and Onshore wind | India | Saraswat et al. 2021 |
| AHP | Onshore Wind | Knjazevac-Serbia | Potić et al. 2021 |
| FAHP and FAD | Onshore wind | China | Feng et al. 2020 |
| FDEA | Onshore Wind | Indonesia | Pambudi & Nananukul, 2019 |
| Fuzzy Logic Modeling | Solar PV and onshore wind | Mauritius | Dhunny et al. 2019 |
| AHP | Offshore wind | Egypt | Mahdi & Bahaj, 2017 |
| FTOPSIS | Solar PV and Onshore wind | Fars, Iran | Rezaei & Mostafaeipour, 2018 |
| DEMATEL, ANP, and MABAC | Onshore wind | Serbia | Gigović et al. 2017 |

To identify and assess the most prominent sites for establishing large-scale onshore wind power plants in Tunisia, with a special focus on the regions of Kasserine and Tataouine. Given the fact that Kasserine and Tataouine have always been grappling with persistent challenges such as unemployment, marginalization, and development disparities. These issues have led to economic and social inequalities, particularly when compared to the more prosperous coastal and northern regions.

The study involved extensive analysis of diverse datasets obtained from open sources, government agencies, and pertinent research. After conducting an exhaustive literature survey and referring to well-informed experts, a list of six decision criteria was formulated. The considered criteria included factors such as average wind speeds, slope, land use patterns, proximity to power lines, road networks, and residential areas. Then, methodological frameworks incorporating GIS-based FAHP and AHP techniques were developed to delineate the most promising sites across the whole country and the designated regions of Kasserine and Tataouine, respectively. Fig. 4.1 outlines the steps used.

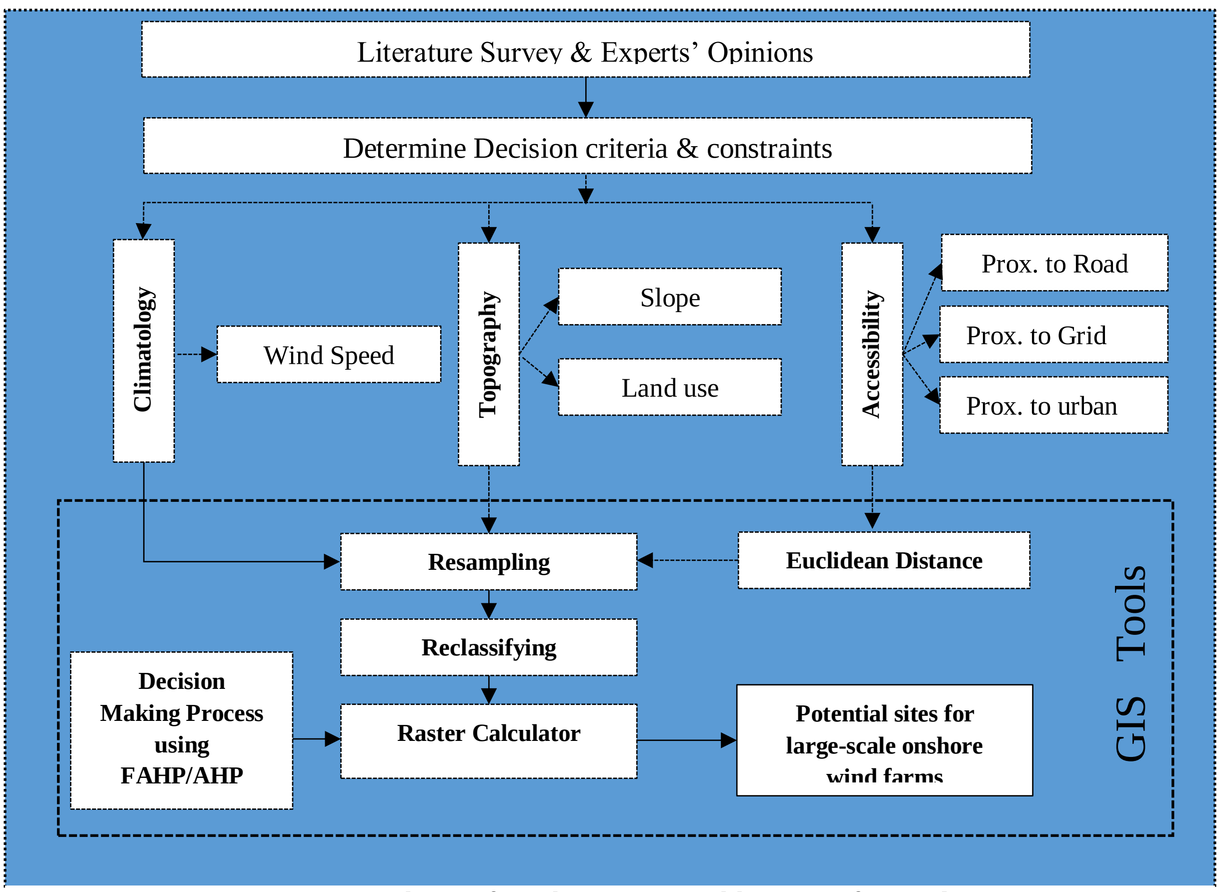


*Fig. 4.1 Conceptual steps for selecting optimal locations for wind systems*

## 4.3 Restrictive constraints and Decision criteria

To effectively assess the suitability of different areas for developing wind power plants, a comprehensive set of constraints must be taken into account. In this study, an extensive review of existing literature was conducted to identify and determine the relevant constraints (see Table 4.3). Utilizing Boolean algebra within ArcGIS 10.8 software allowed for the generation and aggregation of these factors into a unified layer. Within this aggregated layer, cells assigned with a value of "1" indicate no restrictions, thus signifying potential for constructing wind systems in those areas. Conversely, cells designated with a value of "0" represent substantial limitations that render it unfeasible to install such facilities in those locations. These identified restrictive constraints are visually depicted in Fig. 4.2.

Table 4.3. Restrictive constraints

| Restrictive layer | Boolean algebra restriction |
|---|---|
| Distance from protected areas | $x < 0.5\ km$ |
| Distance from grid | $x < 0.3\ km\ and\ x > 20\ km$ |
| Distance from roads | $x < 0.5\ km\ and\ x > 20\ km$ |
| Distance from residential areas | $x < 2\ km\ and\ x > 25\ km$ |
| Slope | $x > 10\%$ |
| Landuse | $x \neq$ *Bare ground, shrubland, and medium grassy vegetation* |


*Fig. 4.2 Constraints Map*

## 4.4 Evaluating criteria

It is important to note that identifying potential sites within a specific area is heavily influenced by local factors and requires input from experts taking part in the decision-making process. Therefore, engaging highly qualified experts who possess in-depth knowledge about the energy status of a particular area is critical when conducting MCDA research activities (Archana et al., 2022). Experts' details are provided in Table A.2 in Appendix A.

Yet, determining a suitable location for the construction of a wind farm in a specific area, it is crucial to consider climatic factors such as average wind speeds, wind power density, and the frequency of windy days (Azizi et al., 2014; Baseer et al., 2017; Effat & El Zeiny, 2022; Ruiz et al., 2020). Many studies have emphasized the importance of higher wind speeds within an optimal range as an indicator of favorable wind resource availability. Fig. 4.3 represents the considerable wind potential across the entire country, varying between 1.86 – 16.18 m/s at the altitude of 50m.

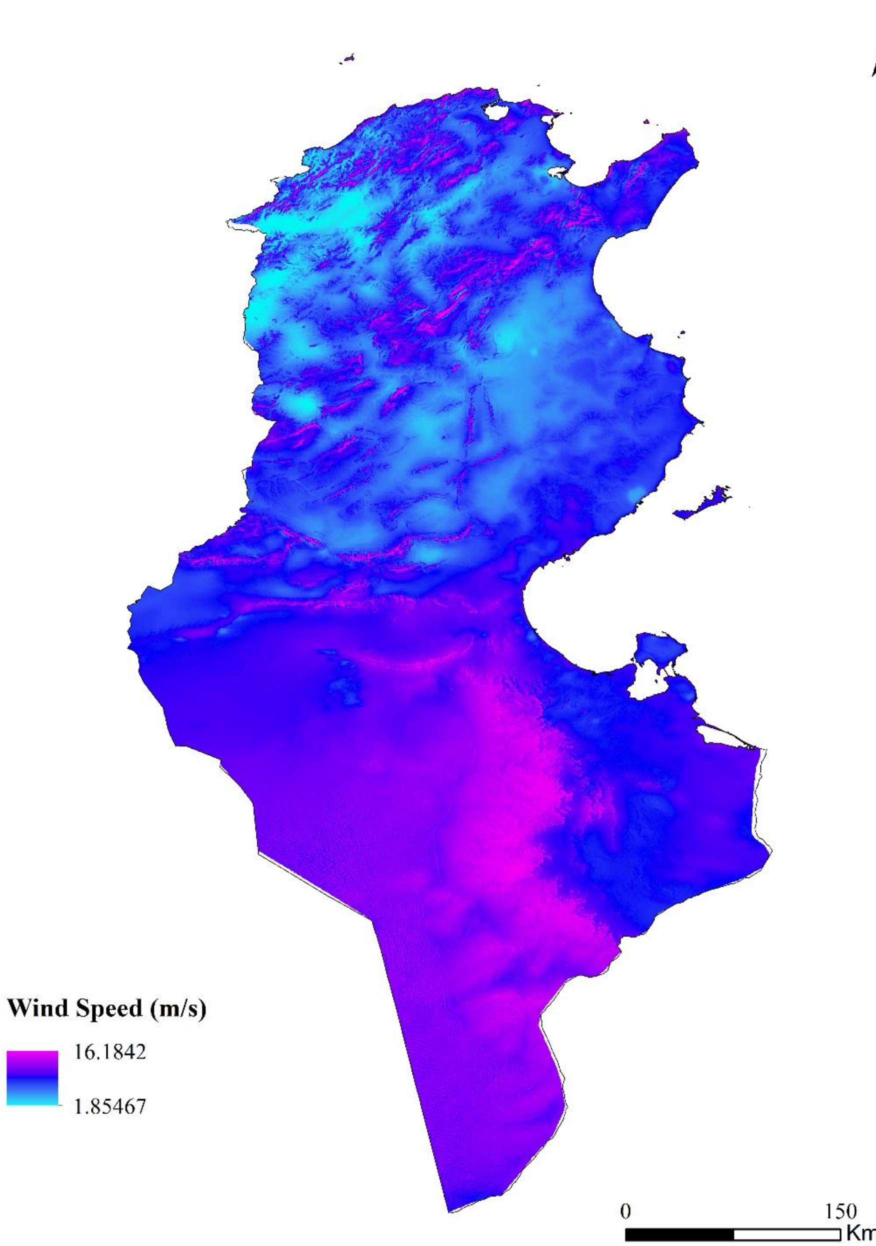


*Fig. 4.3 Wind Speed at 50 m*

In this study, comprehensive data on regional wind patterns was acquired from both the Global Wind Atlas (www.globalwindatlas.info/area/Tunisia) and the National Institute of Meteorology (www.meteo.tn/fr/donnees-climatiques). Moreover, choosing a well-suited location for a wind energy facility is influenced by various restrictions associated with slope and land usage, which is crucial in spatial planning. Fig. 4.4 shows that vast areas are less than 1 degree of slope.

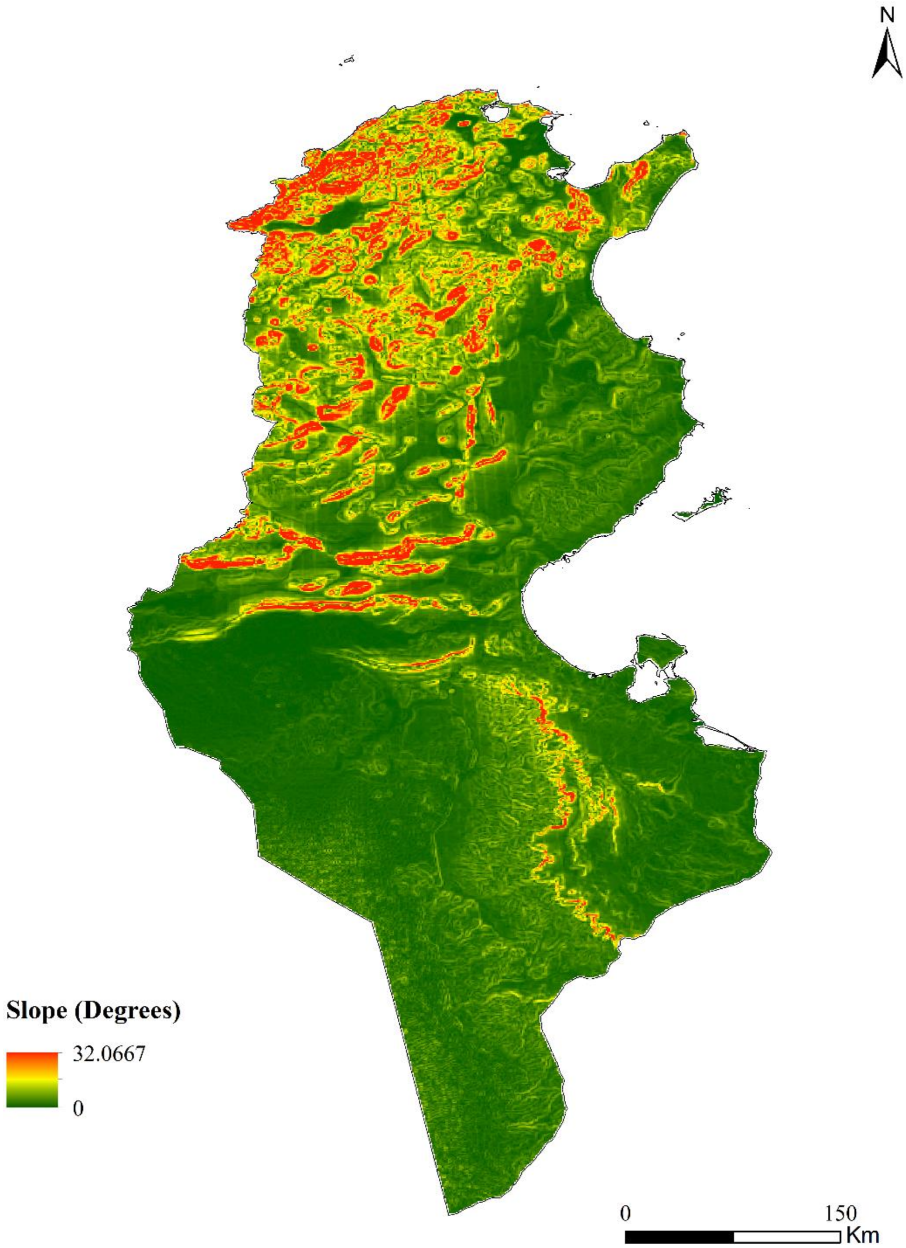


*Fig. 4.4 Slope (Degree)*

This limitation is widespread in all site selection processes across different scenarios. While favorable weather conditions may be present, inappropriate land use can impede the viability of such a venture (Al Garni & Awasthi, 2017; Badi et al., 2021). Hence, ideal sites should encompass areas without significant constraints on land utilization, such as mountains, sand dunes, forests, water bodies and military sites, as shown in Fig. 4.5. This criterion was derived from an intricate map produced by the European Space Agency with a resolution of 10 meters per pixel.

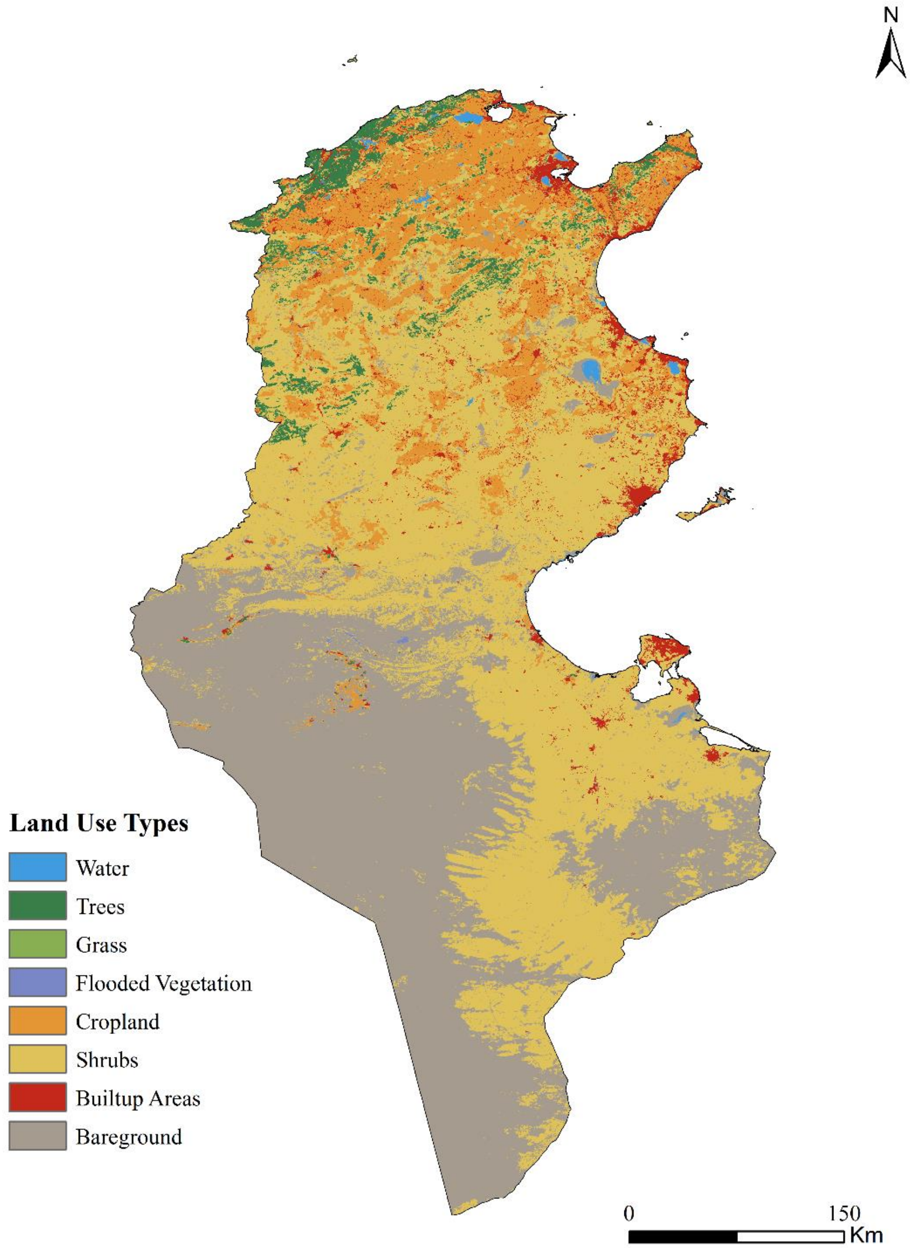


*Fig. 4.5 Landuse types*

In addition, the successful integration of wind power plants with the grid hinges on their proximity, as it directly affects distribution costs and power losses. Minimizing the distance from end-users can significantly enhance efficiency and reduce power delivery expenses (Ari & Gencer, 2020; Badi et al., 2021; Kazak et al., 2017). Additionally, it is crucial to consider transportation infrastructure as well, since it has a significant impact on overall costs (Brewer et al., 2015; Watson & Hudson, 2015). Easy access at a site is essential for decreasing construction-related expenses during both the building phase and operational stages (Tercan et al., 2020). Deploying these facilities in areas with challenging accessibility would not be advisable based on these considerations. As illustrated in Fig. 4.6, it appears that most of Tunisia possesses adequate grid and transport infrastructure to host onshore wind facilities on a large scale.

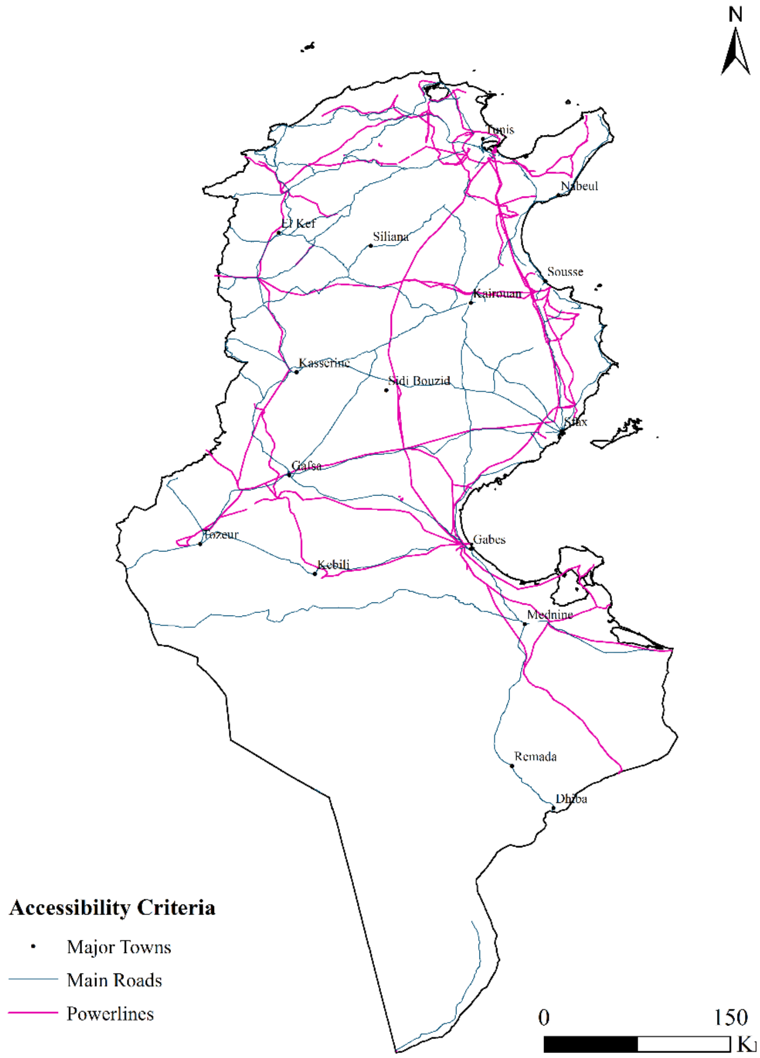


*Fig. 4.6 Accessibility Criteria*

## 4.5 Wind Energy at Regional level

A considerable amount of academic work has been dedicated to exploring options for using renewable energy sources in Tunisia, as demonstrated by prior research (Attig-Bahar et al., 2021; Balghouthi et al., 2016; Rekik & El Alimi, 2023; Trabelsi et al., 2016; Zelt et al., 2019). Nonetheless, the practical application of wind turbines, particularly in the Kasserine and Tataouine regions, has not yet been comprehensively studied. In response to this gap, a GIS-based AHP integrated model has been utilized. This section contributes to sustainable energy planning in southern and central western Tunisia by methodically assessing land suitability and presenting clear results on optimal locations for installing onshore wind systems. As such, a major emphasis is placed on the potential of wind energy projects as a viable solution for supplying increasing electricity needs associated with population growth, urbanization, and industrialization. To delineate the most promising sites within these regions, the same key decision criteria as well as constraints in the first stage were used, as illustrated in Figs. 4.4 – 7. This comprehensive approach enables policymakers to consider multiple criteria when evaluating potential sites so that selected locations are suitable for wind energy production while aligning with sustainability principles and social acceptance norms. It is thus unique in that it provides an extensive analysis of wind resources within the designated regions and their potential deployments. From Fig. 4.7 - 8, it is apparent that both regions are well-endowed with wind potential reaching as high as almost 10 and 11.5 m/s in Tataouine and Kasserine, respectively.

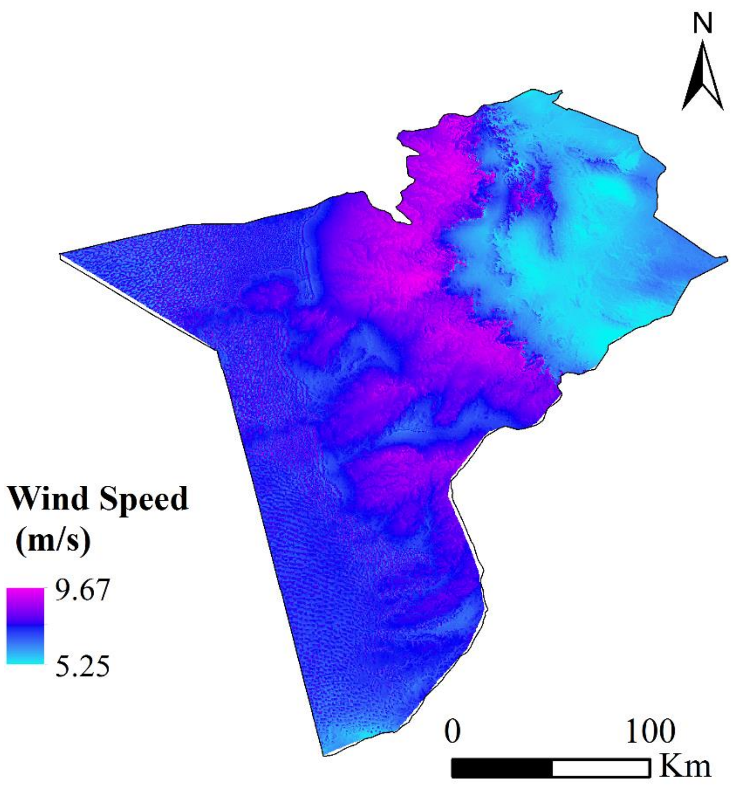


*Fig 4.7 Tataouine Wind Speed (m/s) at 50 m*

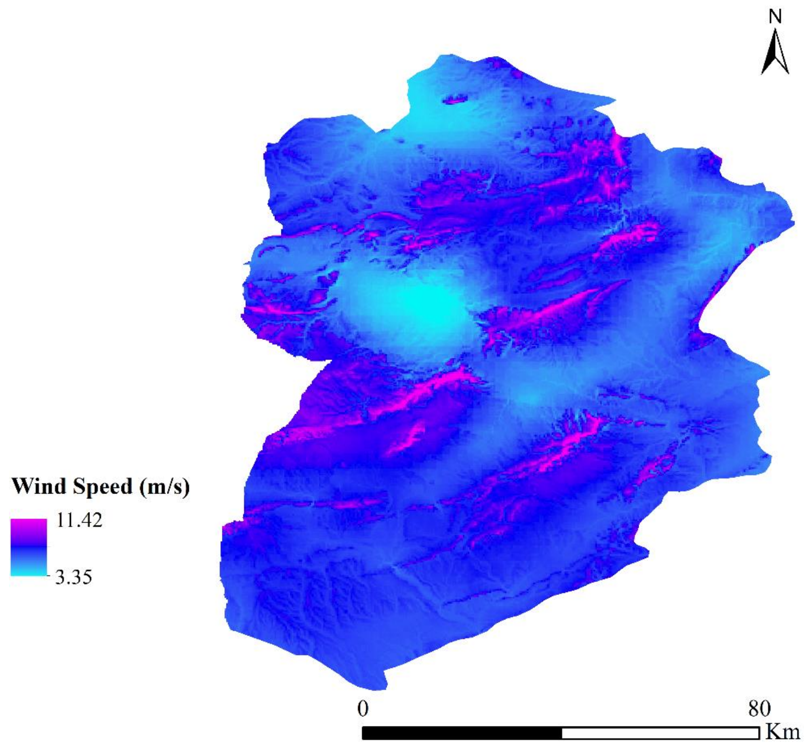


*Fig 4.8 Kasserine Wind Speed (m/s) at 50 m*

In terms of topography, it appears that Tataouine and Kasserine are suitable regions for installing wind systems with large swathes of areas with favorable slopes and landuse types, as illustrated in Figs. 4.9 - 12.

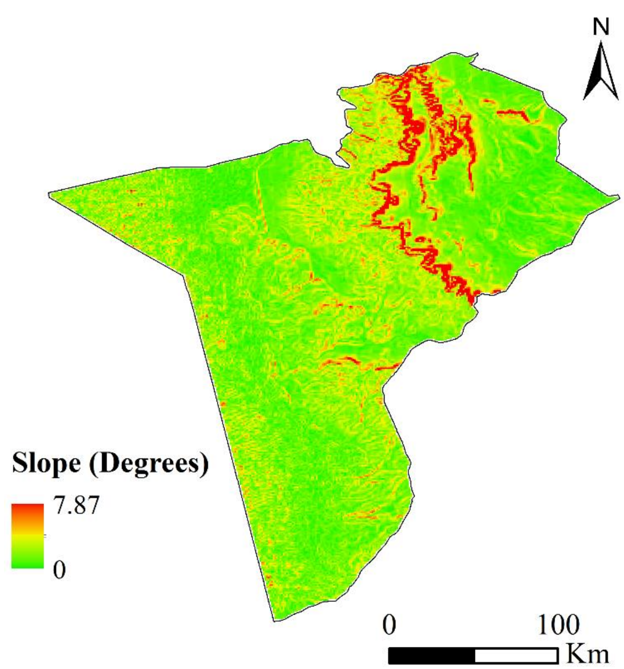


*Fig. 4.9 Tataouine Slope (Degree)*

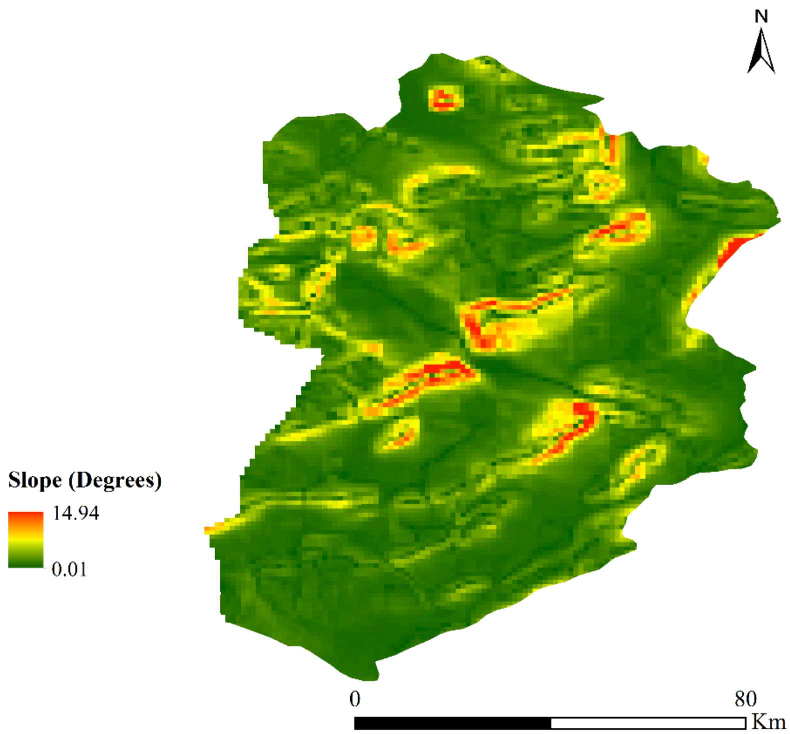


*Fig. 4.10 Kasserine Slope (Degree)*

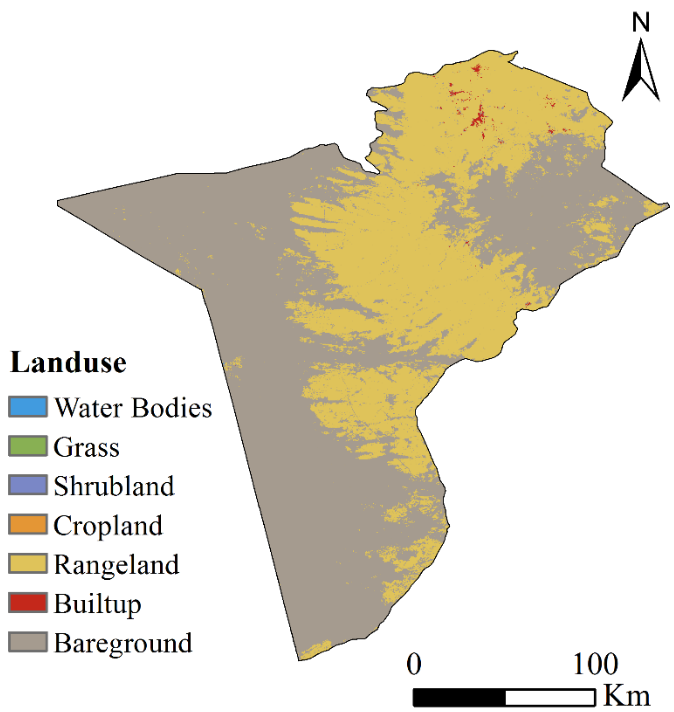


*Fig. 4.11 Tataouine Landuse Types*

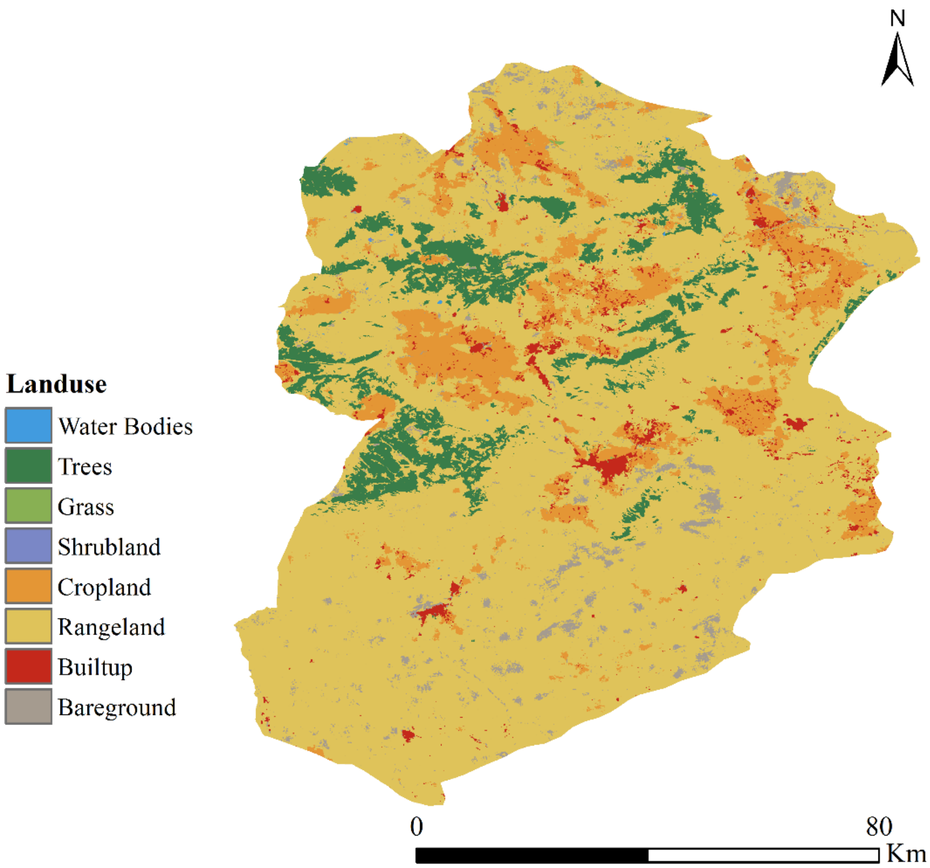


*Fig. 4.12 Kasserine Landuse Types*

Figs. 4.13 - 14 depict the necessary accessibility factors, including grid network and transport infrastructure as well as the major residential spots in both regions.

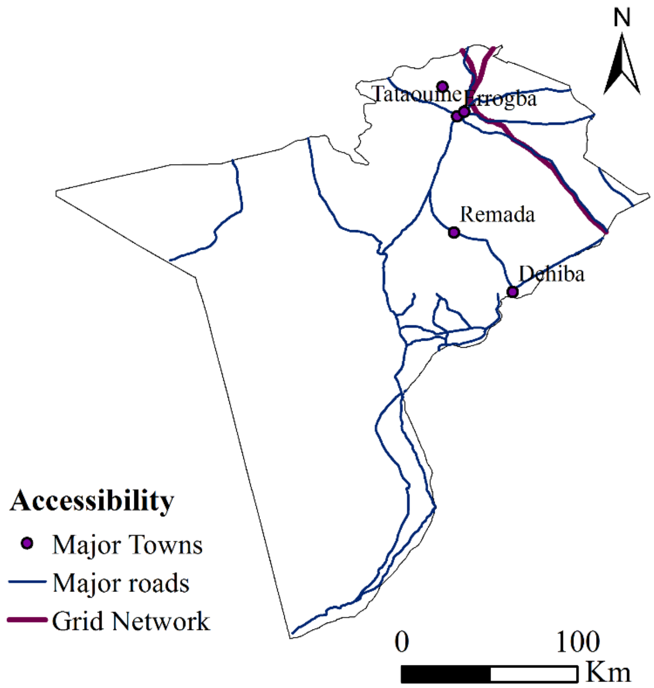


*Fig. 4.13 Tataouine Accessibility factors*

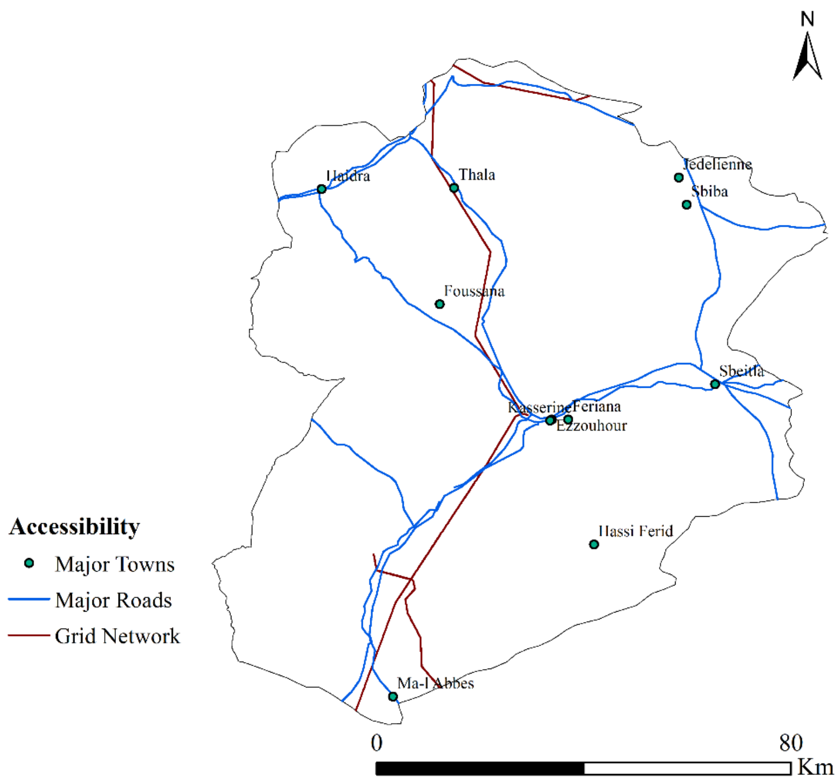


*Fig. 4.14 Kasserine Accessibility Factors*

## 4.6 Results and Discussion

In this study, spatial analyses were conducted by adjusting the scale, sampling, and classification of various input layers (Table 4.4). Each individual input layer was then processed using the fuzzy membership function within the spatial analyst tool. Afterwards, the FAHP technique was used to assign weights to the factors based on their relative importance. Subsequently, weights were assigned to factors based on their relative importance using the FAHP technique. The final suitability maps for large-scale wind farms were generated based on a GIS-based MCDM model by utilizing the fuzzy overlay tool with a minimum threshold of 1 km$^2$ set to identify the most suitable locations.

Table 4.4 Classified wind site selection decision criteria

| Decision Criteria | Attribute Values | Suitability Rate |
|---|---|---|
| **Wind Speed (m/s)** | < 4.99 | 1 |
| | 5 – 5.99 | 2 |
| | 6 – 6.99 | 3 |
| | 7 – 7.99 | 4 |
| | > 8 | 5 |
| **Slope (degree)** | > 10 | 1 |
| | 8 - 10 | 2 |
| | 5 - 8 | 3 |
| | 2 - 5 | 4 |
| | < 2 | 5 |
| **Land use** | Built-up, Water bodies, Forests, etc. | 1 |
| | Cropland | 2 |
| | Shrubland | 3 |
| | Sparse Vegetation | 4 |
| | Bare Lands | 5 |
| **proximity to major Roads (km)** | > 15 | 1 |
| | 10 - 15 | 2 |
| | 5 - 10 | 3 |
| | 1 - 5 | 4 |
| | 0.5 - 1 | 5 |
| **Proximity to Power lines (km)** | > 15 | 1 |
| | 10 - 15 | 2 |
| | 5 - 10 | 3 |
| | 1 - 5 | 4 |
| | 0.3 - 1 | 5 |
| **Proximity to Residential Areas (km)** | 20 – 25 | 1 |
| | 15 - 20 | 2 |
| | 10 - 15 | 3 |
| | 5 - 10 | 4 |
| | 2- 5 | 5 |

### 4.6.1 Pairwise Comparison

Based on the extensive evaluation by experts, it has been determined that the availability of resources holds significant influence, with a weightage of 38%, as shown in Table 4.5. This implies that greater accessibility to resources directly correlates with increased power generation. Furthermore, aspects such as slope and land use have also been identified as pivotal factors in topography, securing second and third positions with weights of 15.9% and 15.6% respectively. In terms of accessibility criteria, proximity to transport links and power lines garnered weights of 12.7% and 11.9% correspondingly, underscoring their crucial role in minimizing additional construction costs. On the other hand, proximity to residential areas was considered relatively less important at a score of only 5.8%. At the regional level, criteria followed exactly the same trend as at the national level (Table 4.6).

Table 4.5 FAHP Final weights

| Goal | Criteria | weight |
|---|---|---|
| Identify the best-suited locations for large-scale onshore wind systems across the whole of Tunisia | Wind Speed | 0.380 |
| | Slope | 0.159 |
| | Land use | 0.156 |
| | Prox. to Grid | 0.127 |
| | Prox. to Roads | 0.119 |
| | Prox. to Urban | 0.058 |
| RI | | 1.24 |
| $\lambda max$ | | 6.287 |
| CI | | 0.057 |
| CR | | 4.60% |

Table 4.6 AHP weighting results for wind farms in Kasserine and Tataouine

| Goal | Criteria | weights | |
|---|---|---|---|
| | | Kasserine | Tataouine |
| Identify the best-suited locations for large-scale onshore wind systems in Kasserine & Tataouine | Wind Speed | 0.399 | 0.432 |
| | Slope | 0.208 | 0.223 |
| | Land use | 0.159 | 0.058 |
| | Prox. to Grid | 0.08 | 0.139 |
| | Prox. to Roads | 0.079 | 0.099 |
| | Prox. to Urban | 0.068 | 0.056 |
| RI | | 1.24 | 1.24 |
| $\lambda max$ | | 6.304 | 6.449 |
| CI | | 0.061 | 0.089 |
| CR | | 4.90% | 7.24% |

#### 4.6.2 Spatial Analysis

The results of the site suitability assessment showed that about 33138.14 $km^2$ (21.06% of the total study area) were considered appropriate for the installation of large-scale wind systems (Fig. 4. 15). The southeastern regions (Médenine, Gabès, and Tataouine), central and southwestern regions (Gafsa, Kassérine, Tozeur, and Kebili), eastern coastal areas (Mahdia, Sousse, and Monastir), and, to a lesser extent, the northeastern (Nabeul) and utmost north (Bizerte) have a multitude of places that are very suitable for onshore wind installations. Conversely, the northern regions, which include the most extensive agricultural areas and continuous mountain ranges, are considered unfavorable for the deployment of wind facilities on a large scale.

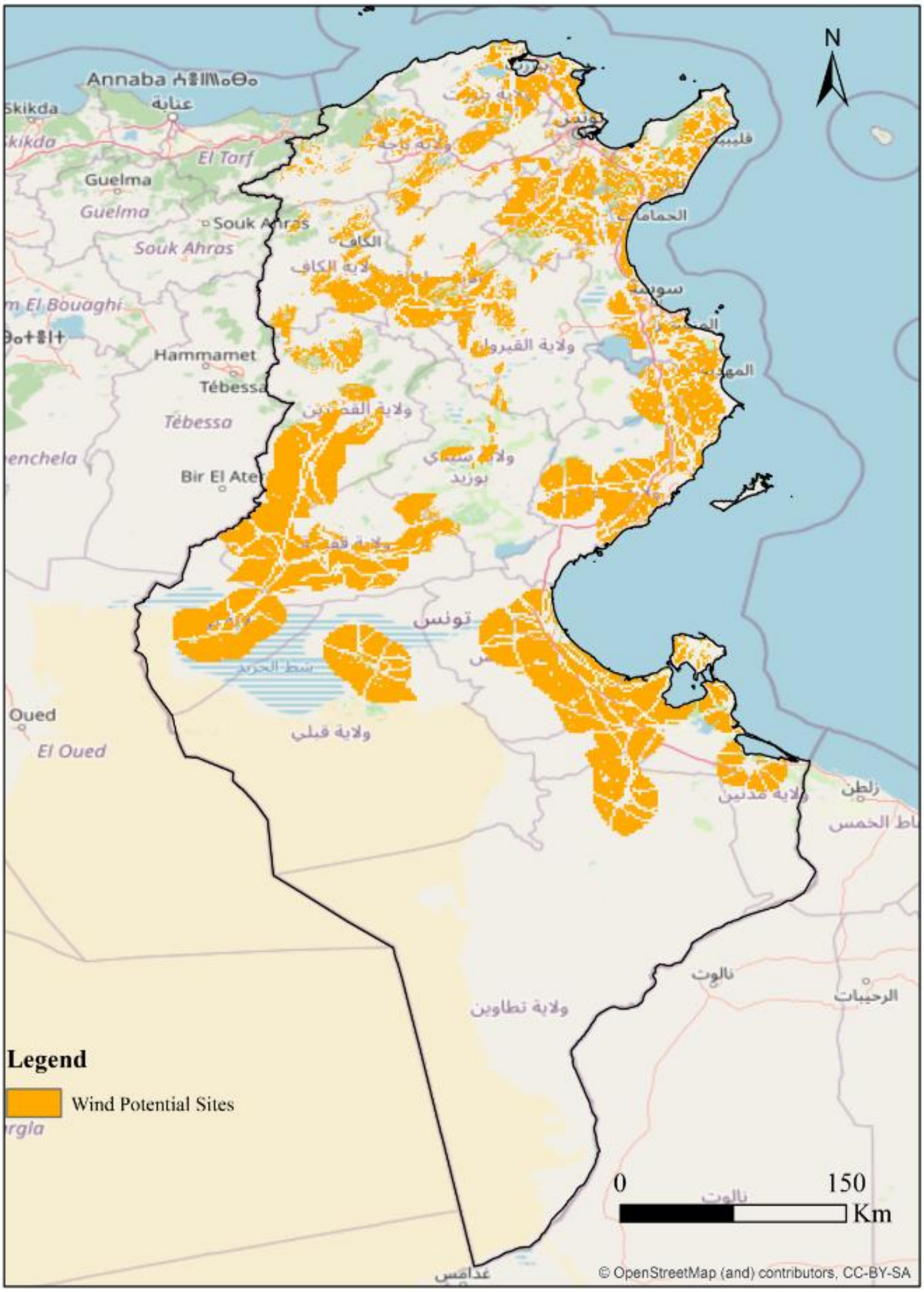


*Fig. 4. 15 Wind Suitability map for wind potential sites*

The integration of the Fuzzy Analytical Hierarchy Process with fuzzy membership within ArcGIS significantly enhances the precision of evaluation by effectively considering uncertainties in the available data. This approach provides a more comprehensive assessment of site suitability, taking into account diverse factors and their relative importance with greater accuracy. The classification of results into three distinct categories: "most suitable," "suitable," and "moderately suitable" enables stakeholders to easily interpret and prioritize potential locations for renewable energy projects based on a deeper understanding of the nuances involved. This refined classification not only enables informed decision-making but also ensures that resources are allocated effectively to maximize the impact of these sustainable energy initiatives. Utilizing this classification approach reveals that approximately 6912.46 $km^2$ (4.39% of the total land area) exhibit great potential for onshore wind development (see Fig. 4. 16).

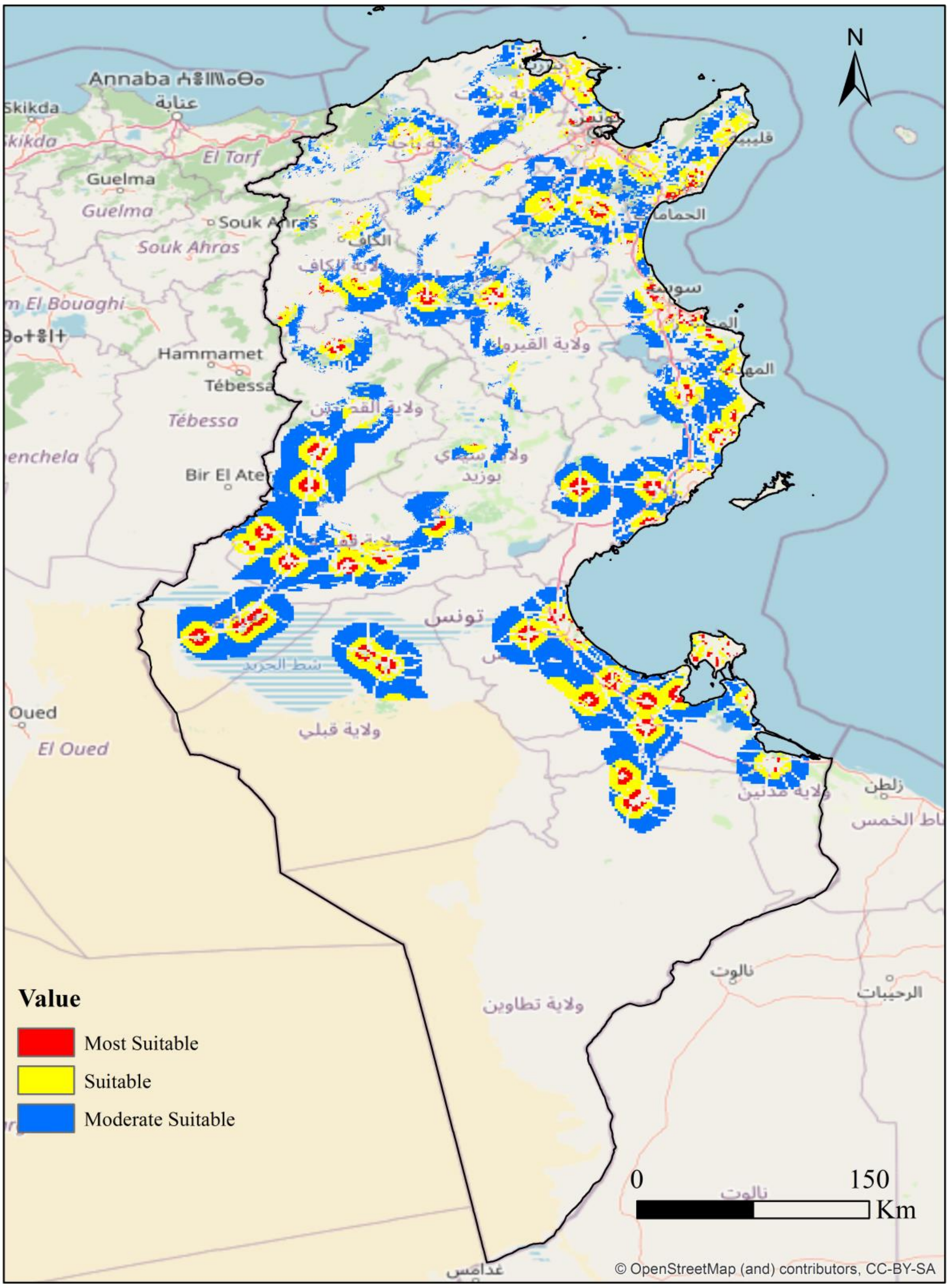


*Fig. 4.16 Wind Spatial Distribution of Land Suitability*

Furthermore, a total of 149 sites have been identified as exceptionally prospective locations at the regional level. Among these sites, Majel Belabbes, Metlaoui, Souk El Ahed, Tataouine Sud, and Feriana account for approximately 14% of those total sites (Fig. 4.17). This high level of promise is attributed to the exceptional climatic and topographic conditions prevalent in these areas.

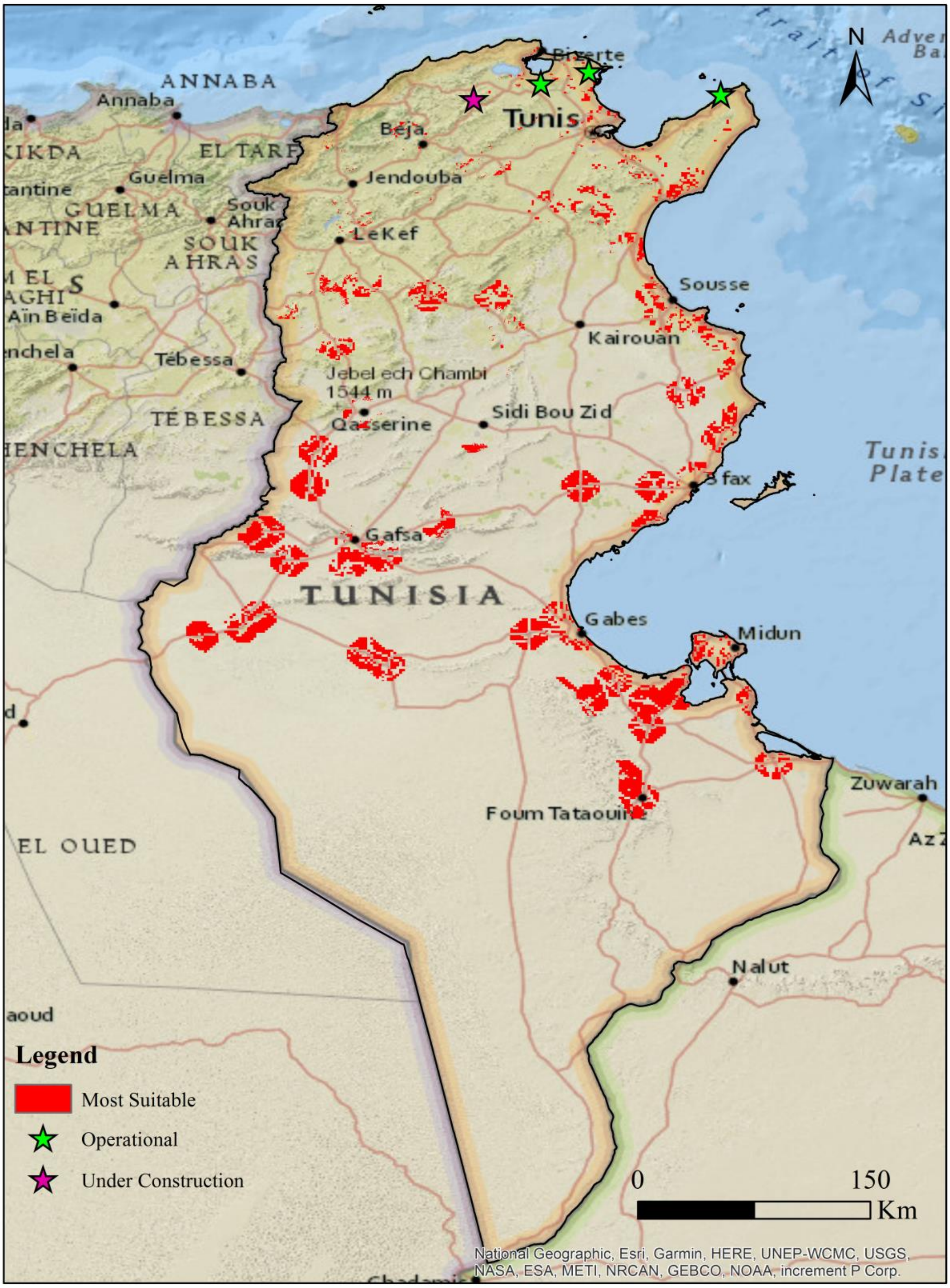


*Fig. 4.17 Wind most suitable sites*

### 4.6.3 Kasserine and Tataouine wind potential

The Kasserine wind suitability map depicted an allocation where only around 7.61% (612 km$^2$) constituted 'highly suitable' sites out of the total surface area analyzed (see Fig. 4.18a). Locations falling within categories labeled "suitable," "moderately suitable," and "unsuitable" accounted respectively for 9.71%, 24.62%, and 58.07%. Moreover, highly suitable areas were found to be densely scattered across the southern, central, and most northern parts of the Kasserine region, with standout locations including Majel Belabbes, Kasserine Sud, Feriana, and Thala appearing to be by far the most favorable candidate locations for installing wind facilities as they represent nearly 78% of those sites (see Fig. 4.18b).

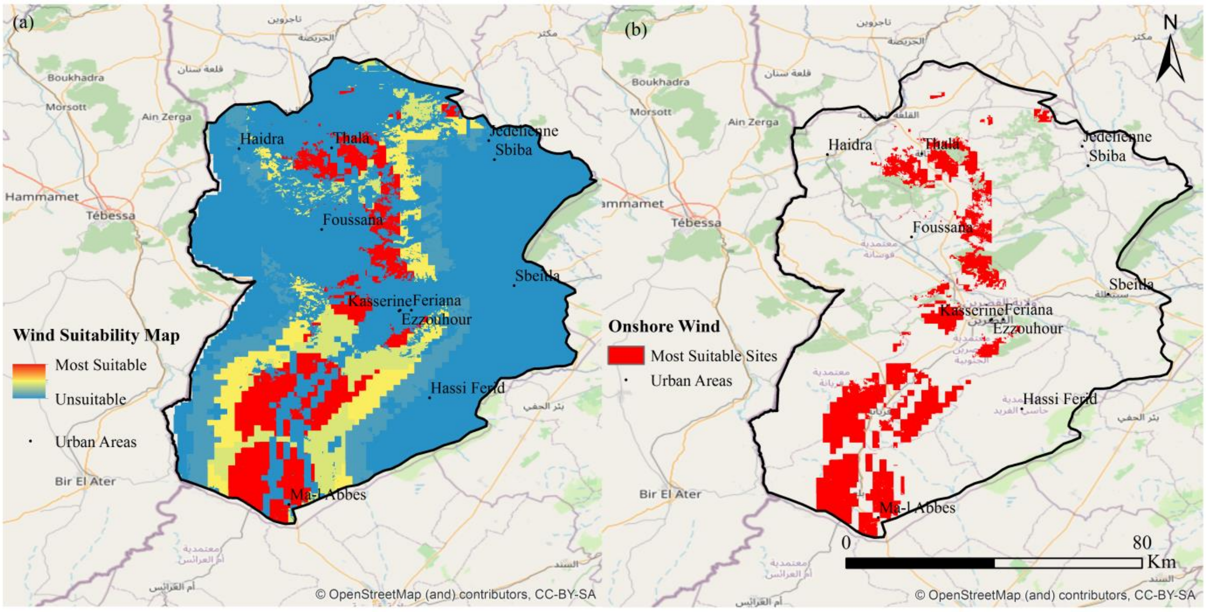


*Fig. 4.18 Kasserine Wind maps: (a) Wind Suitability Map (b) Most Suitable Sites*

On the other hand, the examination of the Tataouine wind suitability map (Fig. 4.19a) reveals that only about 1.26% of the total surface area, approximately equivalent to 499.62 km$^2$, is highly suitable for wind energy generation. The remaining areas have been categorized as "suitable," "moderately suitable," and "unsuitable," constituting 1.87%, 2.65%, and 94.22% of the total area, respectively. The spatial analysis further indicates that the most favorable locations for wind are dispersed densely, primarily in the northernmost to northeast and central to southern east parts of the region, with Remada and Dhiba identified as particularly promising locations, hosting nearly 83% of those sites (see Fig. 4.19b)

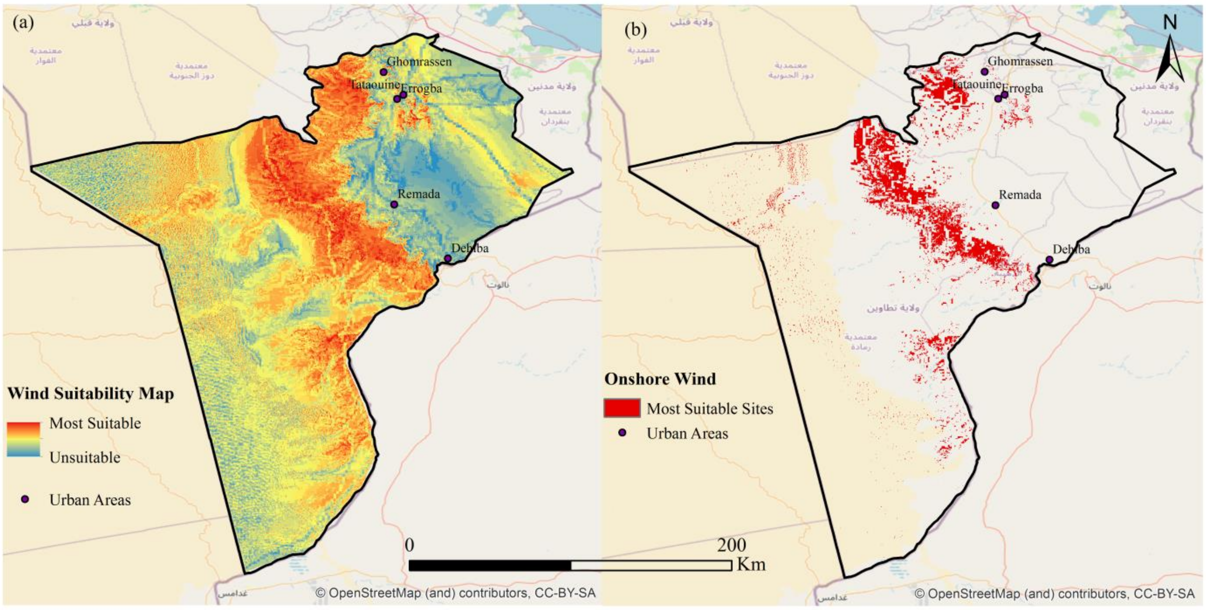


*Fig. 4.19 Tataouine Wind maps: (a) Wind Suitability Map (b) Most Suitable Sites*

## 4.7 Estimated wind energy production

To generate utility-scale output power from large wind farms, it is recommended to use large turbines due to their higher performance and ability to produce more energy even in low and moderate winds (Katsigiannis & Stavrakakis, 2014). Nevertheless, the placement of turbines within the farm has a direct impact on the expenses for installation, the functioning of the turbines, and the amount of energy generated. Wind farms are often planned with a distance that is 3 to 15 times the diameter of the turbine's rotor (Anwarzai & Nagasaka, 2017; Marmidis et al., 2008). In this investigation, a spacing factor of 10D was used, where D indicates the diameter of the turbine, since there was no available wind direction data. The installed capacity potential was determined by analyzing a representative selection of commercially available big wind turbines, which have capacities ranging from 3.518 to 4.8 MW per square kilometer (Table 4.7). To assess the wind energy potential, we considered an installed capacity potential of 4 MW per square kilometer for this research. A height of 120 m was selected as it best correlates with the average hub heights of the considered turbines, which range between 80 m (Siemens IIB) and 164 m (Nordex III). Measurements at 120 m were extrapolated using the power law equation.

$$V_z = V_{ref} \left(\frac{Z}{Z_{ref}}\right)^P \qquad (1)$$

Where $V_z$ is the wind speed at height $Z$, $V_{ref}$ is the reference wind speed at height $Z_{ref}$, and $p$ is the power law exponent.

Then, the wind annual energy production was estimated based on the following Eq. (2).

$$AEP\ (GWh) = \sum(\text{ICP} * 8760 * \text{Capacity Factor}) \qquad (2)$$

Table 4.7. Sample of the large wind turbines available in the market (Anwarzai et al., 2017)

| Turbine | | Hub height (m) | Rotor diameter (m) | Name plate capacity (MW) | Area per turbine ($Km^2$) | installed capacity ($MW/km^2$) |
|---|---|---|---|---|---|---|
| **Vestas** | III | 84 - 119 | 112 | 3.8 | 0.794 | 4.157 |
| **Vestas** | III | 80 - 105 | 90 | 1.8 | 0.405 | 4.444 |
| **Eno** | III | 92 - 142 | 126 | 3.5 | 0.794 | 4.409 |
| **Siemens** | IIB | 80 | 108 | 2.3 | 0.583 | 3.944 |
| **Gamesa** | III | 109 | 97 | 2.0 | 0.470 | 4.251 |
| **Mitsubishi** | II | 80 | 100 | 2.4 | 0.500 | 4.800 |
| **Nordex** | III | 164 | 116.8 | 2.4 | 0.682 | 3.518 |

The capacity factor of a wind turbine is a measure commonly used to assess its technical performance. It is dependent on the wind speed distribution and the specific model of the wind machine (Mohamadi et al., 2021). In literature, it is often assumed that the capacity factor falls within the range of 20 to 30 percent (McKenna et al., 2021). However, Maatallah et al. (2013) in their study on wind energy from various altitudes in Tunisia, found that the capacity factor for eight different turbines ranged from 24% to 45%. Taking this into consideration, an average capacity factor of 35% was chosen for this investigation. The obtained results reveal that the estimated total wind energy could reach as high as 72281.93 GWh per annum, which is nearly 3.5 times the entire demand as of 2022 (see Fig 4.20) (STEG, 2022).

On the other hand, from the Kasserine and Tataouine's findings emerged a promising prospect: statistically speaking, there is potential to generate an annual output power of approximately 6127 and 7511 GWh for the regions of Kasserine and Tataouine, respectively. This means that not only do these highly suited areas present ample opportunity for energy production, but they also have significant capacity well beyond what's currently required.

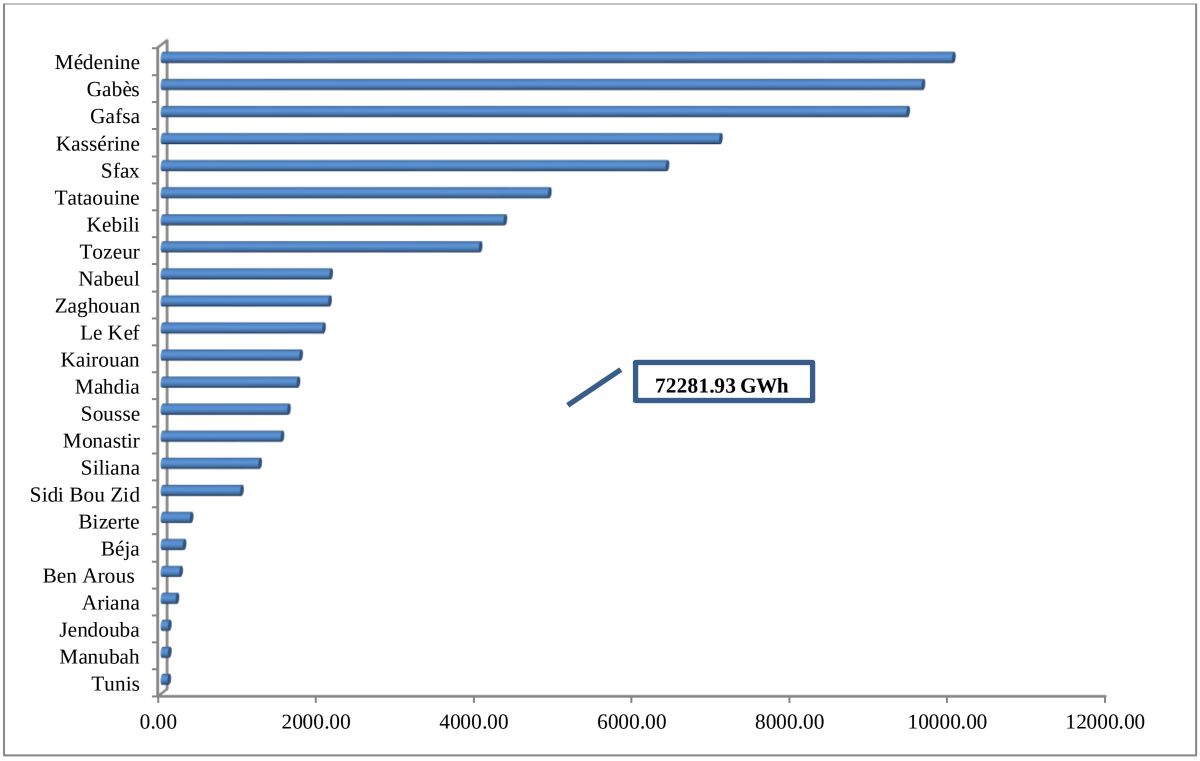


*Fig. 4.20 Wind estimated energy yield from the most suitable sites*

## 4.8 Discussion

The study findings align well with existing literature on the decision-making process for selecting wind sites, as they share common considerations such as resource abundance, topographic features, and necessary infrastructure. This body of research involves in-depth collaboration with experts to carefully weigh and assess various criteria, aiming to provide a comprehensive evaluation of the physical and geographical potential for renewable energy installations. The obtained results not only offer valuable insights for policymakers and planners but also serve as a crucial decision-support tool that emphasizes sustainability and strategic development in site selection for wind energy projects. The specific focus on the regions of Kasserine and Tataouine is driven by their status as one of the most marginalized areas within the country. Consequently, strategically deploying wind facilities in these designated regions could potentially catalyze economic growth across multiple sectors, including construction, operations, maintenance, and local support services. Notably recognized for their significant wind potential, both Kasserine and Tataouine present promising opportunities not just for policymakers but also investors.

As a renewable energy source, wind energy offers numerous financial benefits over traditional energy sources. After installation, wind energy systems typically incur minimal operating and maintenance costs in comparison to traditional power plants. Moreover, the costs related to generating energy from wind are highly predictable due to the absence of fuel costs impacted by market fluctuations. This predictability can lead to greater stability in long-term energy prices (Karimi-Arpanahi et al., 2023; Xu et al., 2022).

Developing wind energy projects is anticipated to bring about the generation of both direct and indirect employment opportunities (Xue et al., 2022). Direct jobs are likely to stem from activities related to the construction, operation, and maintenance of wind installations. Meanwhile, indirect employment prospects could arise in supporting sectors such as component manufacturing, transportation, and the provision of services essential for sustaining the operation of these systems. For regions grappling with economic challenges like Kasserine and Tataouine, this has the potential to make a substantial contribution towards local job creation and skill development.

These findings reveal their significance when compared to similar studies conducted in other regions (Baseer et al., 2017; Effat & El Zeiny, 2022; El Kadeem et al., 2022; Elmahmoudi et al., 2020; Genc & Karipoglu, 2021). However, the geographically diverse research utilized a range of methodologies and criteria tailored to regional specifics and priorities for renewable energy development.

Nonetheless, despite the Tunisian government's ambitious goal to generate 30% of its electric power from renewable sources by 2030, there remains a significant gap between this vision and current progress. Complex social and political challenges, limited funding, and an unfavorable investment climate have collectively stalled the implementation of this plan aimed at achieving energy independence, diversifying the energy mix, reducing fossil fuel imports, and lowering emissions levels. Given that Kasserine and Tataouine are among the most economically and socially marginalized regions of the country, concrete measures must be implemented to facilitate investment in wind energy projects as a means of uplifting and promoting the development of these economically and socially disadvantaged areas (Khammassi et al., 2021). This involves not only identifying optimal locations for wind energy but also expanding grid infrastructure, improving transportation systems, establishing manufacturing facilities, and enhancing educational and training centers (Saraswat et al., 2021). Social welfare and living standards within these designated regions can be significantly improved by investing in these essential aspects in conjunction with renewable energy projects (Singh et al., 2022; Sward et al., 2021).

## 4.9 Conclusion

As Tunisia aims to meet its ambitious renewable energy goals by 2030, the insights from this study facilitate data-driven decision-making, promoting not just the optimization of resource allocation but also socio-economic development in marginalized areas. The substantial wind energy potential presents opportunities for achieving energy independence, fostering job creation, and spurring local economic growth. However, this study also highlights the necessity of overcoming various challenges through coordinated policies, enhanced infrastructure, access to funding, and socio-political engagement. Successful implementation of these recommendations could serve as a blueprint for other countries transitioning towards a sustainable energy future, making it an exemplary model in the quest for balanced and sustainable advancement.

Future work should expand upon the existing research by diversifying the criteria used for site selection to include environmental impact assessments that would incorporate biodiversity, local wildlife habitats, and potential displacement or disturbance of residents. The paper could benefit from the development of a comprehensive risk assessment framework to better understand the impacts and mitigate potential drawbacks of wind farm installation. Moreover, this research could serve as a baseline for longitudinal studies monitoring the actual impacts versus the predicted benefits of wind energy projects post-implementation, which would provide invaluable feedback on the accuracy of the prediction models used. Subsequent studies could also explore the integration of wind energy with other renewable sources in a unified grid system, examining its stability, storage solutions, and transmission efficiency.

Regarding limitations, the current approach did not address the broader socio-political dynamics that could affect project feasibility, such as land ownership issues, community acceptance, and legislative hurdles that could impact the pace of wind energy adoption. Additionally, the economic models used were not discussed in depth, and future analyses should incorporate a cost-benefit analysis that considers the fluctuating costs of wind technology as well as the economic conditions within Tunisia.

Lastly, the success of such projects is often contingent upon local capacity building and workforce development. Therefore, future studies should include assessments of educational and vocational training needs and propose strategies for developing local expertise in sustainable energy technologies.

In conclusion, this chapter significantly contributes to the discourse on sustainable energy transition in Tunisia, with a specific focus on onshore wind energy systems. The study's use of a GIS-based multi-criteria decision-making approach offers a strategic methodology for selecting suitable locations for wind energy infrastructure, taking into account a wide array of factors crucial to the success of such initiatives. With approximately one-fifth of the target study area deemed suitable and the potential for wind energy production far exceeding current demands, the findings underscore the untapped potential in regions like Kasserine and Tataouine.

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# Chapter V: Hybrid Renewable Energy Systems in Tunisia

## 5.1 Introduction

In recent years, significant transformations have occurred in the energy industry, prompting a reassessment of our energy requirements, production techniques, and utilization. This evolution has given rise to a fresh energy framework. The predominance of traditional fuels like natural gas is being scrutinized due to concerns regarding pollution, reliance on producing states and associations, escalating prices, resource depletion, and depleting reserves Capellán-Pérez et al., 2014; Day & Day, 2017; Höök & Tang, 2013). Consequently, there is an increasing need to manage energy usage while advocating for new alternatives such as renewable energy sources that do not generate carbon emissions (Esposito & Romagnoli, 2023; Kung et al., 2019). This shift towards cleaner forms of energy is restructuring the energy sector landscape by ushering in new participants and varieties of power sources. Renewable energies are gaining traction with an emphasis on facilitating affordable and readily available electricity while upholding environmental preservation objectives (Gudlaugsson et al., 2023; Güney, 2021; Kuleli Pak et al., 2016; Majeed et al., 2023). However, one obstacle associated with these sustainable resources is their dependency on fluctuating weather patterns and climatic conditions which makes ensuring a consistent supply of power using just one type of renewable source challenging (Zhou et al., 2018; Sovacool, 2009).

Tunisia, as a net energy importer, encounters obstacles in its energy system due to its heavy reliance on natural gas and limited use of renewable sources. Despite these challenges, Tunisia holds substantial solar and wind potential, particularly in its central and southern regions Abdelrazik et al., 2022; Attig-Bahar et al., 2021). The Tunisian government has committed to installing a sizable amount of renewable energy capacity by 2030 to harness these resources and enhance energy security (Gardumi et al., 2021). However, effectively implementing this strategy necessitates a careful assessment of selecting suitable sites beforehand (Elkadeem et al., 2021; Idris et al., 2022). Simply considering solar and wind potential availability is insufficient due to various conflicting factors directly impacting output power and costs (Badi et al., 2021; Sward et al., 2021). Detailed knowledge of geographical and topographic characteristics plays a critical role when evaluating location suitability (Al-Garni & Awasthi, 2017; Badi et al., 2021).

This chapter assesses the feasibility of deploying solar and wind hybrid facilities in the regions of Kasserine and Tataouine using an integrated GIS-based Analytic Hierarchy Process approach. The research aims to identify optimal locations for these renewable energy installations while providing valuable insights that aid decision-making processes regarding site selection, with the ultimate goal of unlocking these regions' renewable energy potential.

## 5.2 Literature review

Given the numerous challenges it involves, optimizing the selection of a site is fundamental for the success of renewable energy projects, such as solar and wind facilities. To fully exploit the potential of renewable energy in a particular area, it is essential to consider factors beyond merely resource availability (Ali et al., 2019; Asadi et al., 2023; Elkadeem et al., 2022). Topography, infrastructure capabilities, and costs are factors that exert significant influence on power generation (Garni & Awasthi, 2017). Furthermore, regional weather variations and seasonal fluctuations introduce complexity when evaluating solar and wind potential. Thus, comprehensive data collection and meticulous analysis are imperative for accurately assessing the energy generation capacity at a specific location (Ahmadi et al., 2022; Garni & Awasthi, 2017; Asadi et al., 2023). Yet, carrying out such assessments can be challenging due to overlapping diverse criteria during decision-making processes, as indicated in Table 5.1. To navigate through these intricacies and make informed decisions, researchers have increasingly turned to GIS integrated with MCDM approaches. These techniques have been adept at determining viable geographical sites for erecting renewable energy facilities. Some commonly employed MCDM methods encompass AHP, fuzzy AHP, COPRAS, DEMATEL, ELECTRE, VIKOR, WASPAS, TOPSIS, and several other methods and many other techniques.

Recent years have witnessed a significant upsurge in the development of comprehensive decision-making models within the field of renewable energy site selection. For instance, Rezaei-Shouroki et al. (2017) applied an inclusive multi-criteria model that integrated DEA, AHP, and FTOPSIS techniques to investigate land suitability for potential locations for wind farms in 13 different cities in Iran. Likewise, Xu et al. (2020) utilized FAHP combined with VIKOR technique through GIS data analysis to optimize site selection for wind farms. Furthermore, Wang et al. (2021) employed DEA, FAHP, and FWASPAS to identify areas with significant potential for wind farms in Vietnam. Other research studies have successfully identified optimal locations for solar PV power plants utilizing methods such as F-VIKOR and

AHP which have played a key role in identifying realistic geographical areas suitable for establishing renewable energy facilities. Due to the intermittency and variability of individual technologies used in renewable energy production systems; researchers are now increasingly concentrating on hybrid systems aiming at ensuring a more reliable and continuous supply of energy resources. Diemuodeke et al. (2019) applied GIS-based TOPSIS approach towards determining ideal locations required by hybrid wind-PV systems specifically within southern Nigeria. Additionally, Khanjarpanah et al. (2018) assessed the feasibility of implementing hybrid wind and solar PV power plants using NDEA specific to Iran's context. Furthermore, Yunna & Geng (2014) tackled allocation of suitable locations for installing solar-wind facilities in China from a managerial perspective using GIS-AHP-based model. Aly et al. (2017) and Yushchenko et al. (2018) employed the same approach to assess the potential locations for implementing solar PV-CSP systems in Tanzania and the ECOWAS region in western Africa. Despite the fact that fuzzy models like FAHP, FTOPSIS, and FDEMATEL are well-suited to tackle ambiguities associated with decision-making problems due to their ability to capture nuanced relationships among variables (Khashei-Siuki et al., 2020; Shojaeimehr and Rahmani, 2022). Nonetheless, the AHP approach has been widely used for several reasons (Ilbahar et al., 2019; Shao et al., 2020). AHP remains popular due to its simplicity, capability to handle both quantitative and qualitative data effectively, and its seamless integration with other techniques such as TOPSIS, EDAS, and fuzzy sets (Ilbahar et al., 2019; Manirambona et al., 2022). Additionally, AHP allows for in-depth sensitivity analyses regarding criteria by considering the consistency or inconsistency of alternatives (Moradi et al., 2020; Shaaban et al., 2018). Its sufficiency in determining optimal locations for project allocation is evident as the results obtained do not significantly differ from those generated by more complex techniques like FAHP (Mosadeghi et al., 2015).

Table 5.1. Most frequently applied criteria in deploying hybrid renewable energy systems

| Criteria | Reference |
|---|---|
| **Global Horizontal Irradiance (GHI)** | Ali et al. 2019; Asadi et al. 2023; Harrucksteiner et al. 2023; Waewsak et al. 2020; Zambrano-Asanza et al. 2021 |
| **Direct Normal Irradiance (DNI)** | Aly et al. 2017; Haddad et al. 2020; Gouareh et al. Mutume, 2023; Yushchenko et al. 2018 |
| **Wind Speed** | Asadi et al. 2023; Harrucksteiner et al. 2023;Waewsak et al. 2020 |
| **Ambient temperature** | Elboshy et al 2022; Günen, 2021; Ouchani et al. 2020; Zambrano-Asanza et al. 2021 |
| **Slope** | Asadi et al. 2023; Effat & El-Zeiny, 2022; Elboshy et al. 2022; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Aspect Orientation** | Ali et al. 2019; Koc et al. 2019; Günen, 2021 |
| **Distance to grid lines** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Distance to major roads** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Elkadeem et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Distance to residential areas** | Al-Garni & Awasthi 2017, Asadi et al. 2023; Badi et al. 2021; Albraheem & AlAwlaqi, 2023; Zambrano-Asanza et al. 2021 |
| **Elevation** | Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Albraheem & AlAwlaqi, 2023 |
| **Land use** | Ali et al. 2019; Badi et al. 2021; Harrucksteiner et al. 2023; Waewsak et al. 2020; Zambrano-Asanza et al. 2021 |
| **Population density** | Majumdar & Pasqualetti, 2019; Sabo et al. 2016 |
| **protected Bird areas** | Ali et al. 2019; Baseer et al. 2017; Albraheem & AlAwlaqi, 2023 |
| **Distance to airports** | Ali et al. 2019; Baseer et al. 2017; Harrucksteiner et al. 2023; Albraheem & AlAwlaqi, 2023 |
| **Dust storm** | Alami Merrouni et al. 2018, Xiao et al. 2013 |
| **Distance to water resources** | Aly et al. 2017; Mutume, 2023; Yushchenko et al. 2018 |

While there is ample literature discussing the potential for using renewable energy sources in Tunisia, there is currently a deficiency in research when it comes to examining the implementation of hybrid CSP-PV-wind turbine-based power generation systems, particularly in the areas of Kasserine and Tataouine. To bridge this gap, the study utilizes a GIS-based AHP integrated model to systematically assess land suitability and offer clear insights into optimal locations for installing these systems. By highlighting the significance of hybrid renewable energy projects as a workable solution for meeting rising electricity demand due to population growth, urbanization, and industrial development, the study seeks to contribute to sustainable energy planning in central and southern Tunisia. The holistic approach enables policymakers to thoroughly analyze and evaluate multiple criteria when assessing potential locations for hybrid energy production. This ensures that the identified sites not only have suitable resources but also align with principles of sustainability and social acceptance. As a result, this study stands out for its inclusive assessment, which encompasses an in-depth analysis of both the available resources within the designated regions and their potential deployment.

This chapter's objective is to conduct an initial assessment aiming to identify the most suitable locations in the Kasserine and Tataouine regions that have the potential for accommodating CSP-PV-Wind hybrid systems. To accomplish this goal, a GIS-based AHP method was employed. Advanced satellite imagery, in combination with additional geospatial data, was utilized to assess the geographical characteristics and ground conditions of potential areas in the regions of Kasserine and Tataouine. Fig. 5.1 depicts the methodology used for determining optimal sites for solar and wind hybrid systems.

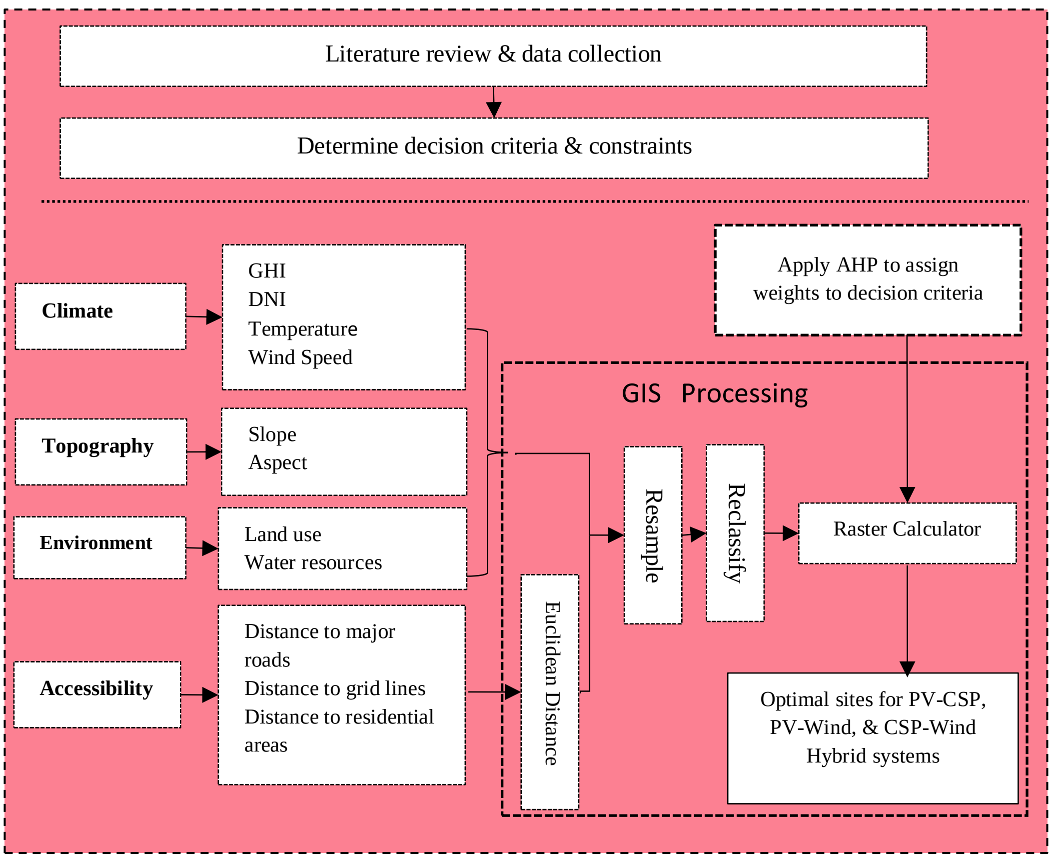


*Fig. 5.1 Key steps in determining optimal locations for hybrid systems*

## 5.3 Constraints and decision criteria

Optimal site selection for renewable energy projects involves a comprehensive assessment of multiple factors and limitations. This evaluation should extend beyond economic and technological considerations to encompass socio-political and environmental aspects. The involvement of experienced experts using MCDM methods is crucial for accurately evaluating these factors. Assigning relative scores to the identified factors is essential in assessing their significance relative to each other. As part of this research, five experts with extensive experience in Tunisia's renewable energy sector were tasked with conducting pairwise comparisons to identify the most influential factors within the Tunisian energy context. Further information about these experts' backgrounds can be found in Table A.2.

### 5.3.1 Constraints

In this investigation, the process of determining suitable sites for incorporating renewable energy technologies involved a thorough evaluation of various economic, technical, and environmental constraints. These constraining factors were identified through an extensive review of existing literature, as outlined in the associated table. In ArcGIS 10.8, these limitations were combined into a unified layer using Boolean algebra with values represented by "1" and "0," as illustrated in Figs. 5.2 – 3. A value of "1" denotes areas without any restrictions, rendering them appropriate for hybrid systems development. Conversely, a value of "0" indicates the presence of limiting factors that make such developments unviable.

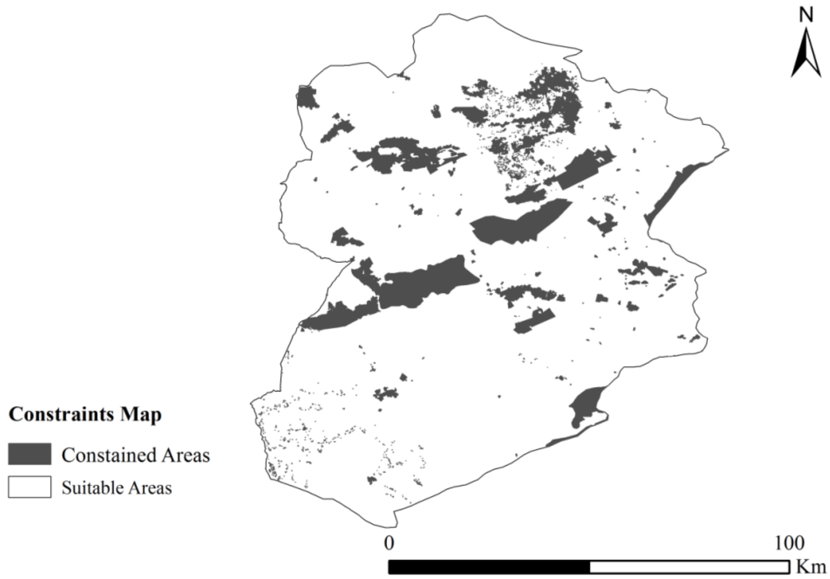


*Fig. 5.2 Kasserine constraints' map*

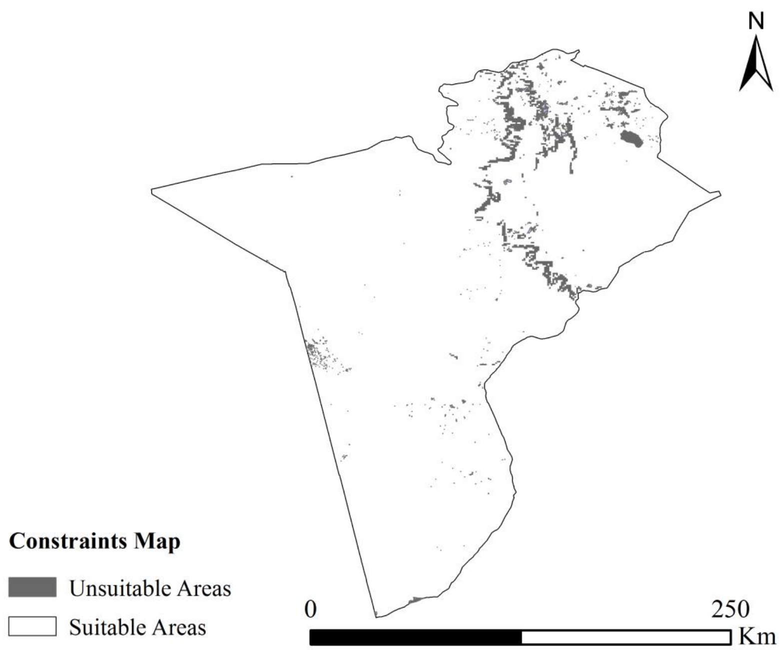


*Fig. 5.3 Tataouine Constraints' map*

### 5.3.2 Decision criteria

The optimal location for solar PV-CSP or wind power plants depends significantly on climate elements like solar radiation, wind velocities, and temperatures. These factors are crucial in determining the potential power generation capacity (Baseer et al., 2017; Effat & El-Zeiny, 2022; Ghasemi et al., 2019; Mutume, 2023). Therefore, it is essential to ensure that the chosen site receives sufficient sunlight throughout the year. Previous research has shown that achieving economic feasibility in typical PV and CSP systems requires minimum annual global horizontal irradiance and direct normal irradiance thresholds of 1477 kWh/$m^2$ and 1800 kWh/$m^2$, respectively (Aly et al., 2017; Spyridonidou & Vagiona, 2023). As it can be seen in Figs. 5.4 – 7, Tataouine and Kasserine are well-endowed with solar potential.

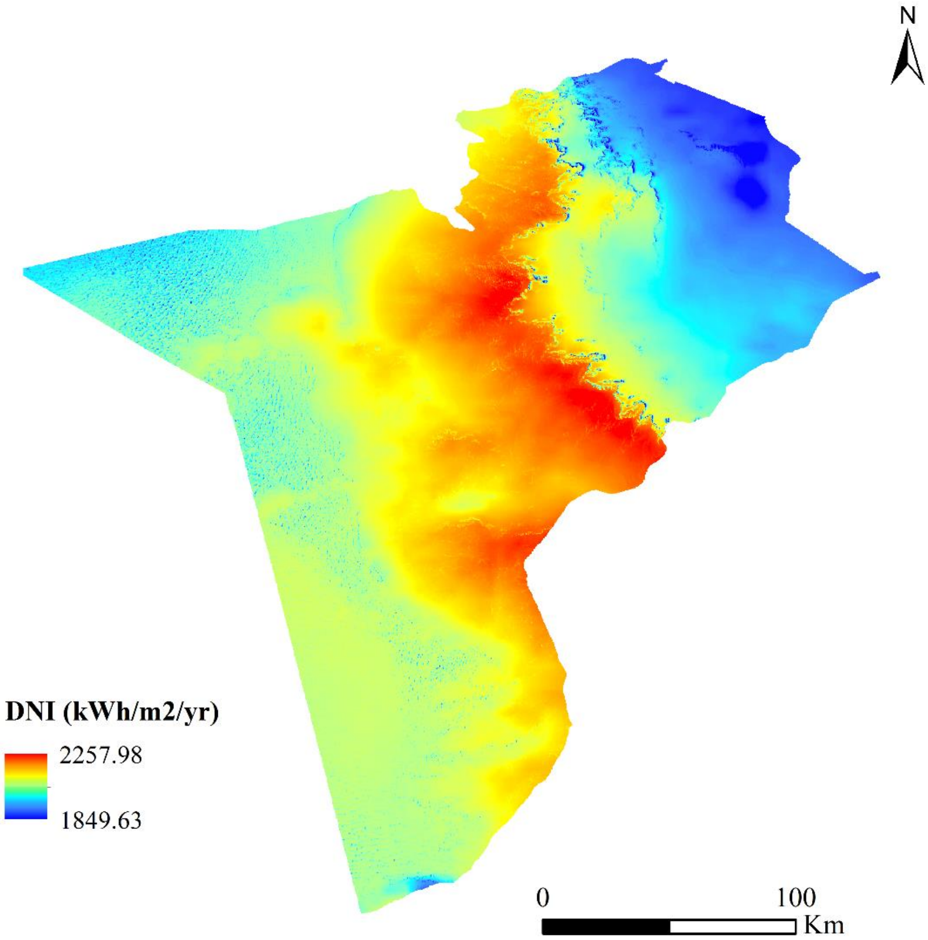


*Fig 5.4 Tataouine Direct Normal Irradiance (kWh/$m^2$/yr)*

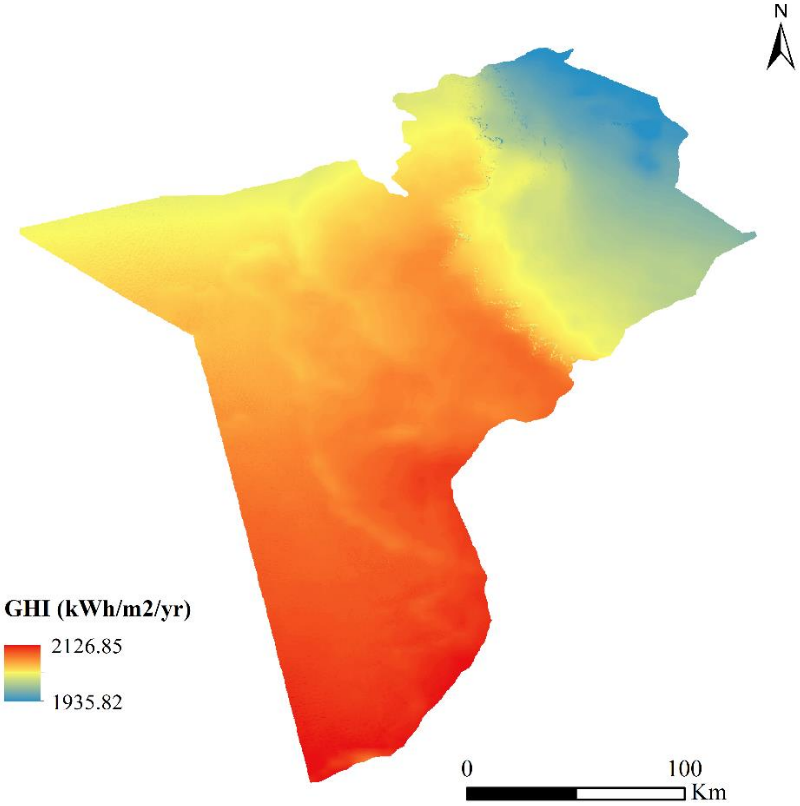


*Fig. 5.5 Tataouine Global Horizontal Irradiance (kWh/m$^2$/yr)*

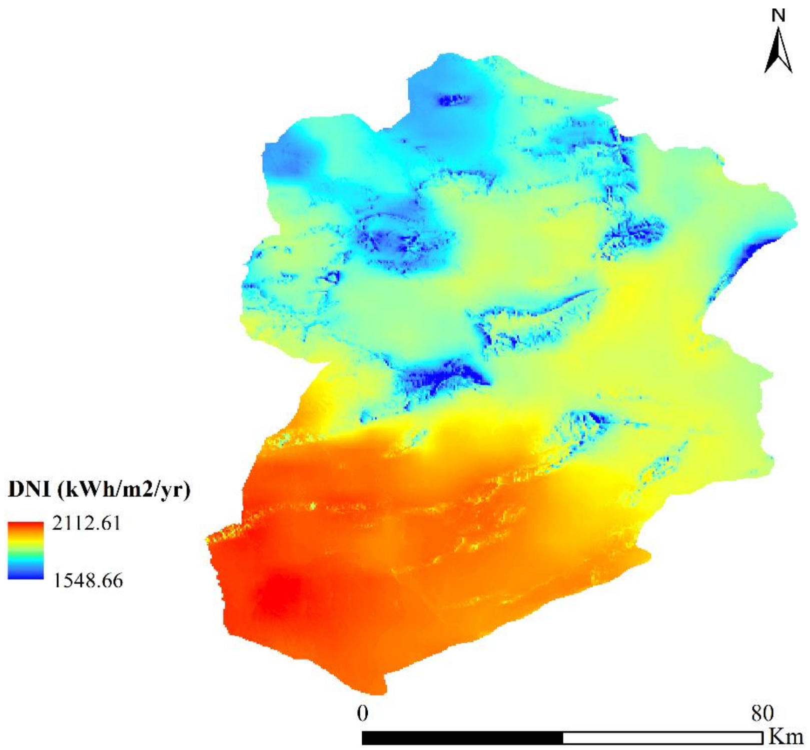


*Fig 5.6 Kasserine Direct Normal Irradiance (kWh/m$^2$/yr)*

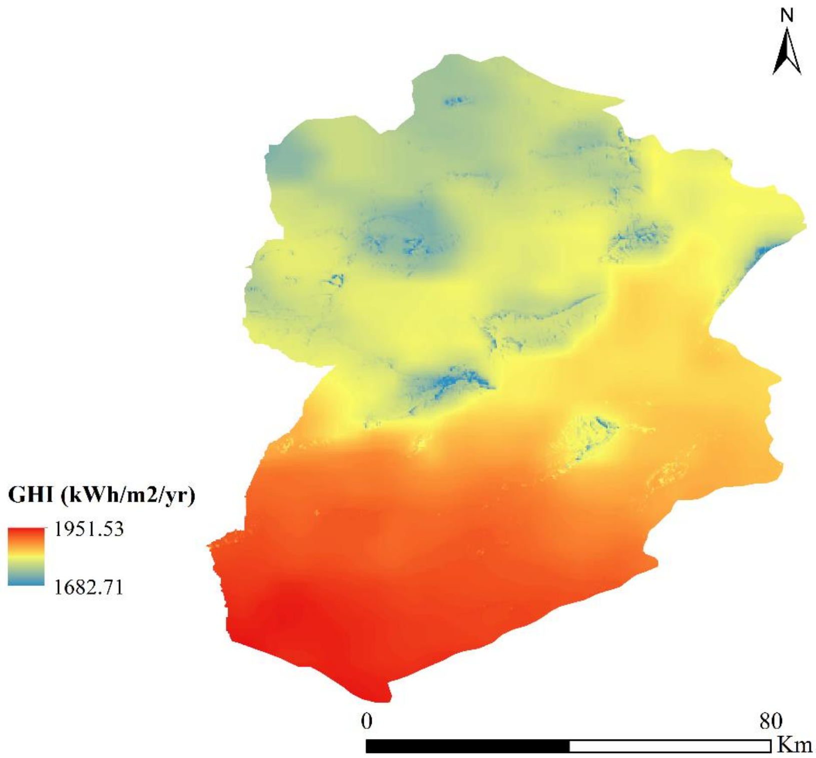


*Fig. 5.7 Kasserine Global Horizontal Irradiance (kWh/m$^2$/yr)*

It is noteworthy that the efficiency of PV modules is affected by ambient temperature, higher temperatures can negatively impact system performance, resulting in energy losses averaging around 0.4%–0.5% per degree Celsius increase beyond 25°C (Günen, 2021). Figs. 5.8 – 9 illustrate the ambient temperatures across both regions. Likewise, the average wind speed is also a key factor in selecting a location for the construction of wind farms. From Figs. 5.10 – 11, it appears that both regions possess enormous wind potential with wind speeds reaching as high as 11.5 m/s and 9.7 m/s in Kasserine and Tataouine, respectively. This data was gathered from the SOLARGIS portal (www.solargis.com), from the Global Wind Atlas (www.globalwindatlas.info/area/Tunisia), and from the National Institute of Meteorology (www.meteo.tn/fr/donnees-climatiques).

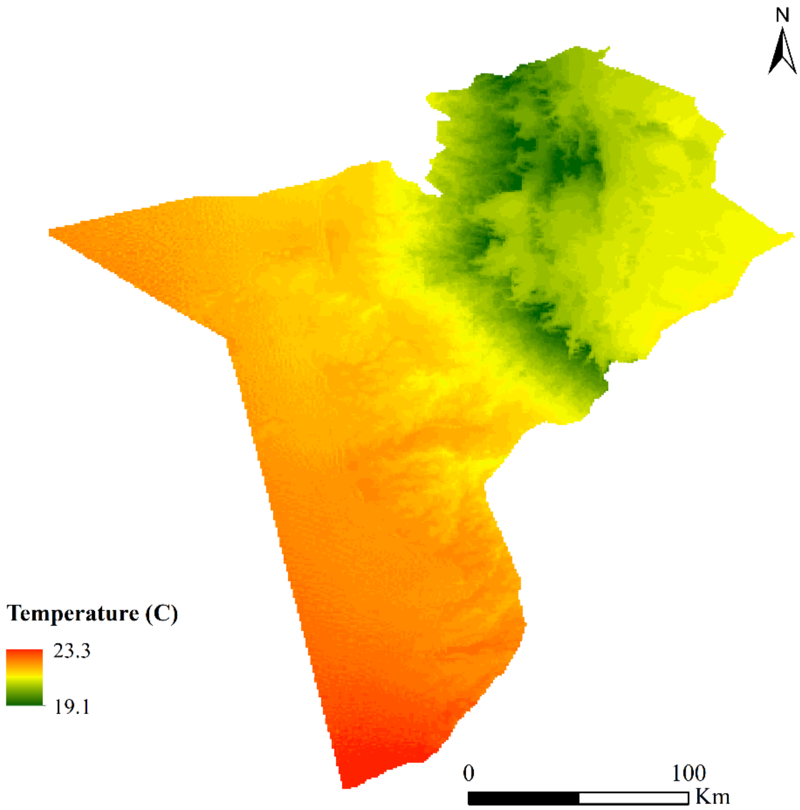


*Fig. 5.8 Tataouine Ambient Temperature (°C)*

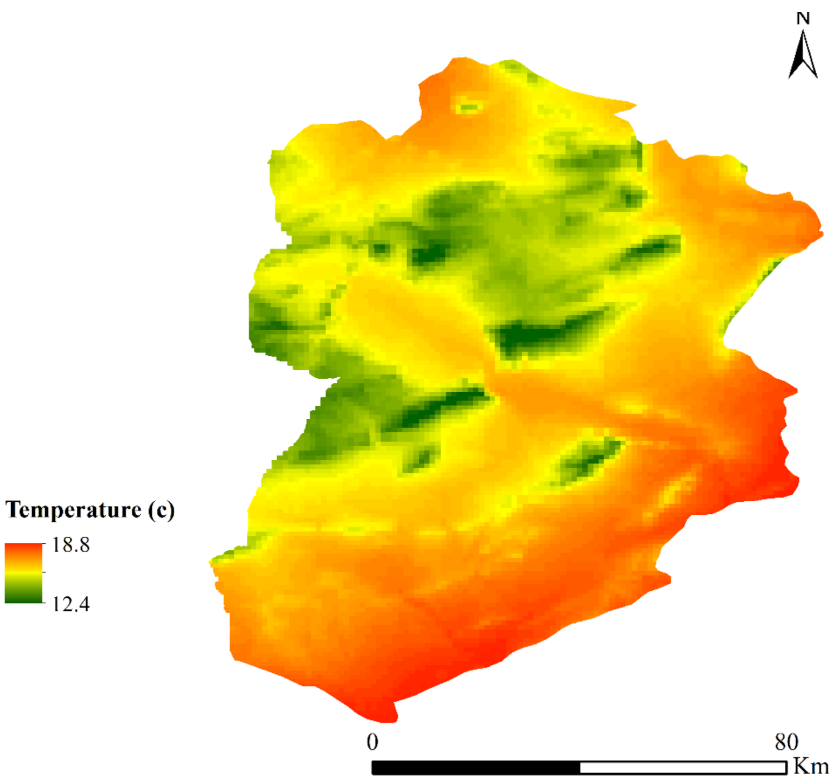


*Fig 5.9 Kasserine Ambient Temperature (°C)*

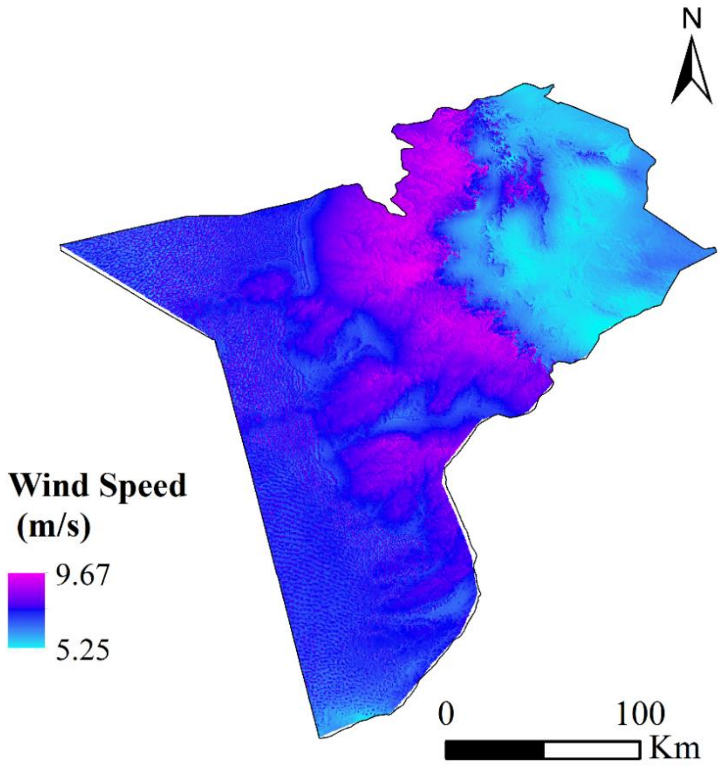


*Fig 5.10 Tataouine Wind Speed (m/s) at 50 m*

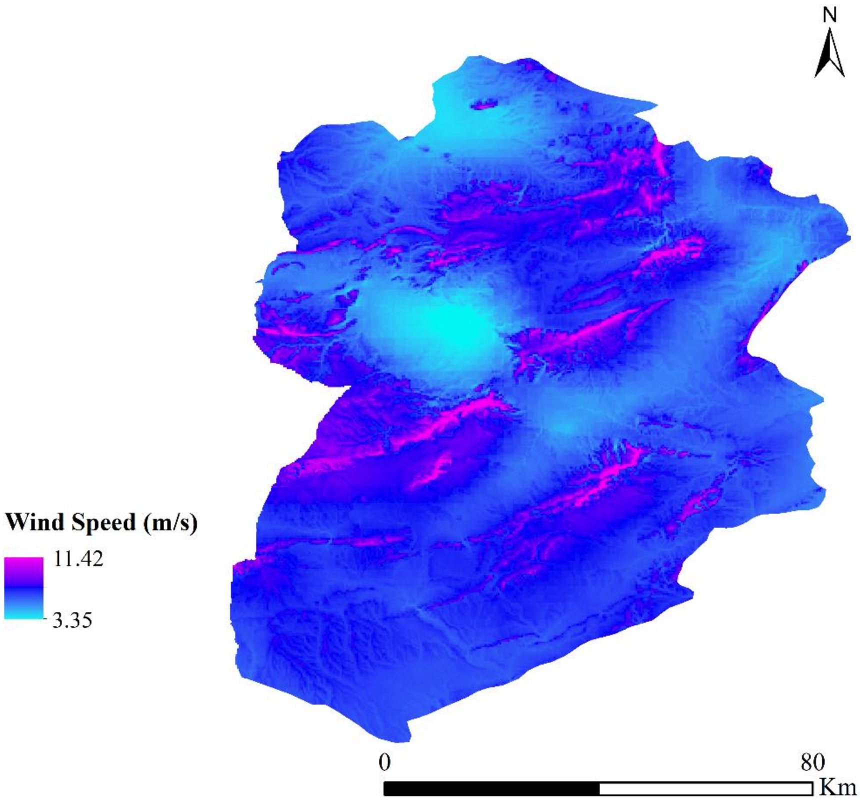


*Fig 5.11 Kasserine Wind Speed (m/s) at 50 m*

Furthermore, ensuring the economic feasibility of solar and wind facilities requires careful consideration of their location's topographic features. It is crucial to position these facilities on flat terrain or areas with gentle slopes, as steeper inclines can result in higher construction and maintenance costs. As shown in Figs. 5.12 – 13, areas with higher slopes tend to be more than those in Tataouine. Additionally, steep slopes may cast shadows that negatively impact photovoltaic system performance. Hence, regions with lower slopes are highly favorable (Ali et al., 2019; Ghasemi et al., 2019; Günen, 2021). As a result of their maximum exposure to sunlight, slopes facing southeast to southwest are often considered to be ideal in the Northern Hemisphere. Figs. 5.14 – 15 illustrate the aspect orientation in Tataouine and Kasserine.

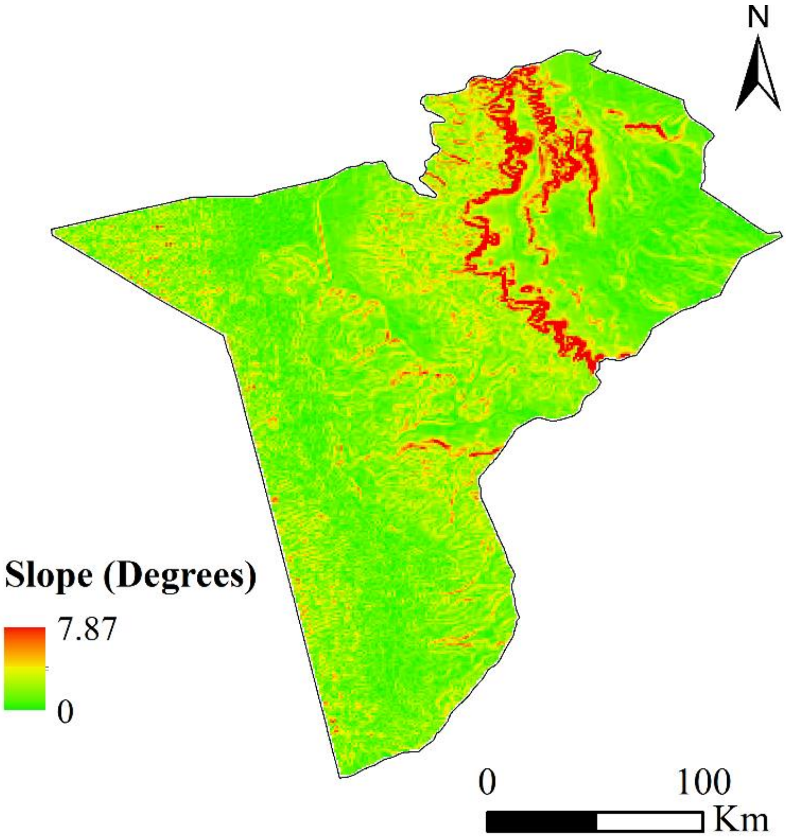


*Fig. 5.12 Tataouine Slope (Degree)*

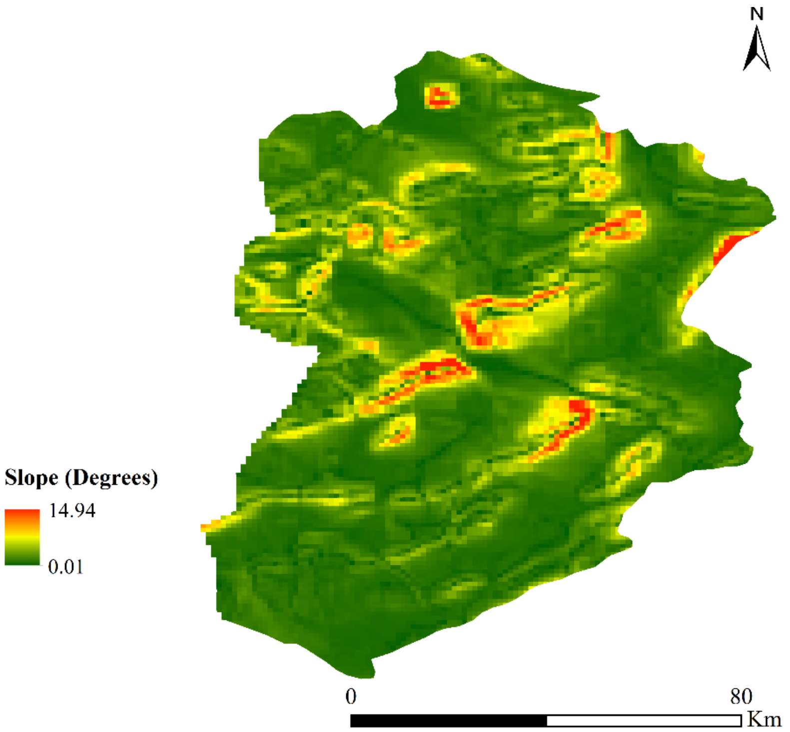


*Fig. 5.13 Kasserine Slope (Degree)*

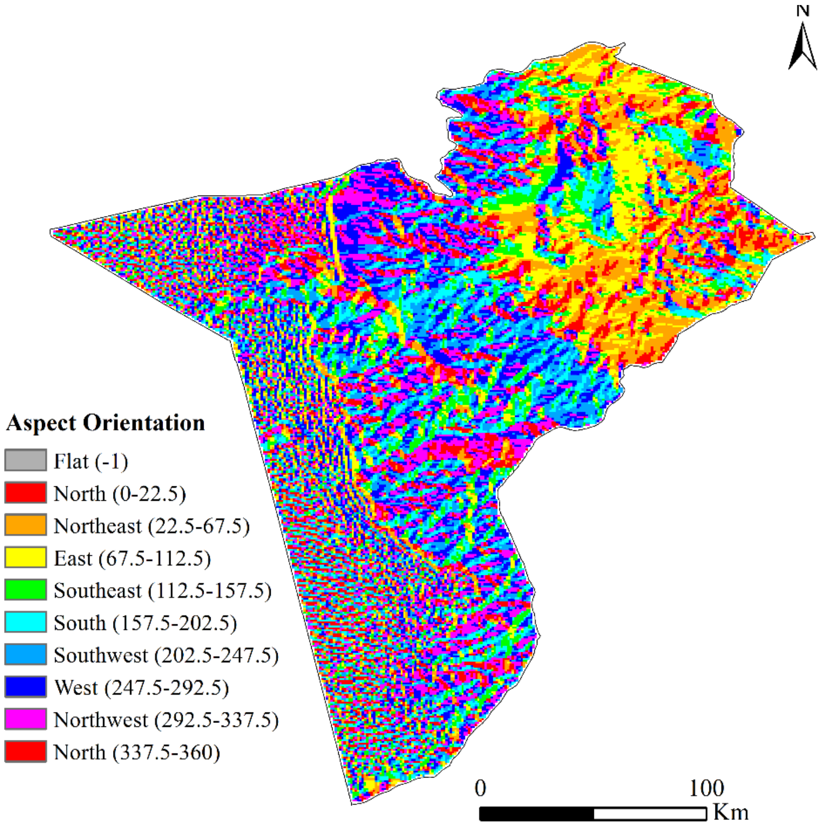


*Fig. 5.14 Tataouine Aspect Orientation*

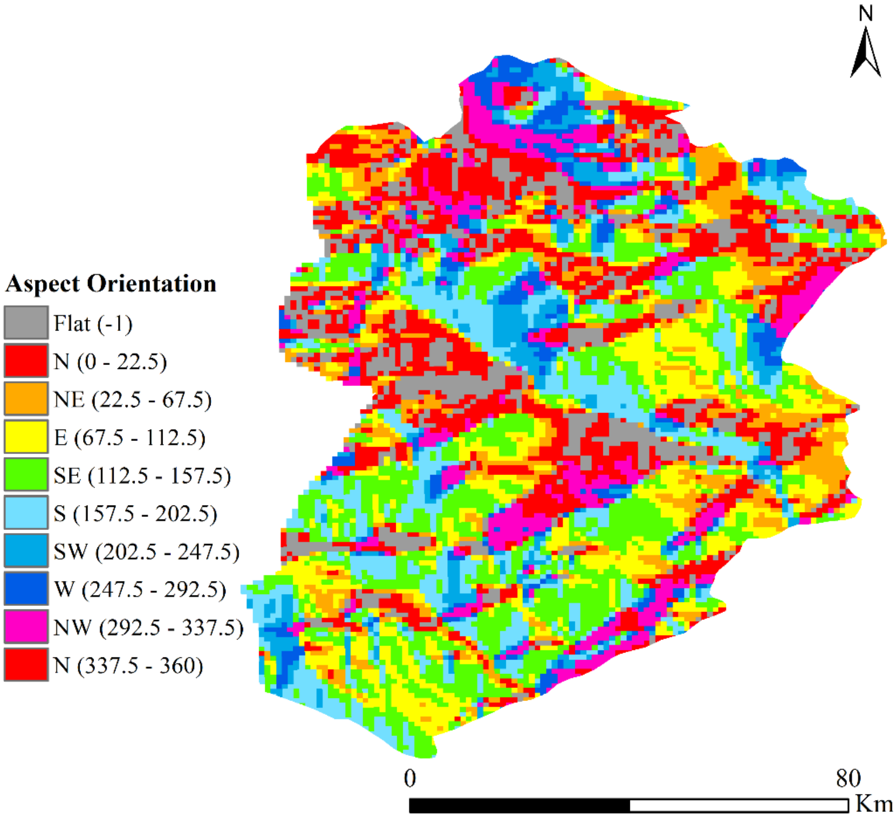


*Fig. 5.15 Kasserine Aspect orientation*

Moreover, locating solar and wind systems in close proximity to the grid network is essential for ensuring their long-term sustainability. This is due to the direct correlation between power losses, distribution costs, and distance from end-users, underscoring the need to minimize this distance. Moreover, transportation infrastructure significantly influences overall project expenses, making it a crucial factor in site selection (Elkadeem et al., 2021; Albraheem & AlAwlaqi, 2023). Convenient access at prospective sites not only reduces construction-related costs during both the building and operational phases but also improves efficiency (Günen, 2021; Tercan et al., 2020). Hence, selecting sites with favorable accessibility is imperative. It appears from Figs. 5.16–17 that the density of transportation and grid infrastructure is rather low, which indicates that both regions are lagging in terms of development and well-being. These criteria for accessibility have been sourced from the open street map project of 2022 (http://download.geofabrik.de/africa/tunisia.html).

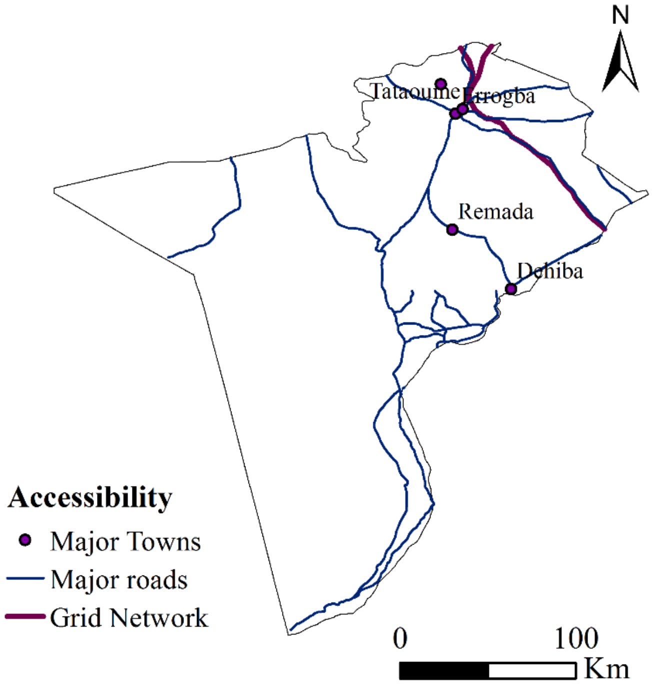


*Fig. 5.16 Tataouine Accessibility factors*

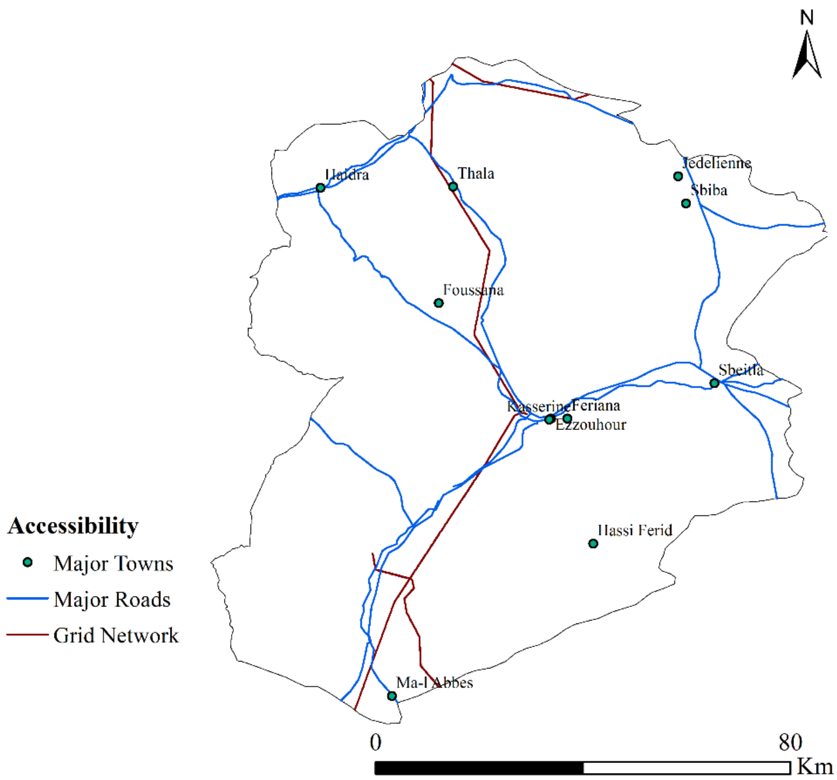


*Fig. 5.17 Kasserine Accessibility Factors*

In addition, from an environmental standpoint, the placement of renewable energy facilities holds substantial significance. Constraints related to land use, including areas such as sand dunes, forests, mountains, water bodies, archaeological sites and military zones can pose significant hurdles to the deployment of these facilities. The literature suggests that bare grounds and rangelands with sparse vegetation are the most suitable types of land for installing renewable energy projects. Fig. 5.18 illustrates the landuse features characterizing the Kasserine region, while Fig. 5.19 depicts the common land cover types prevalent in Tataouine.

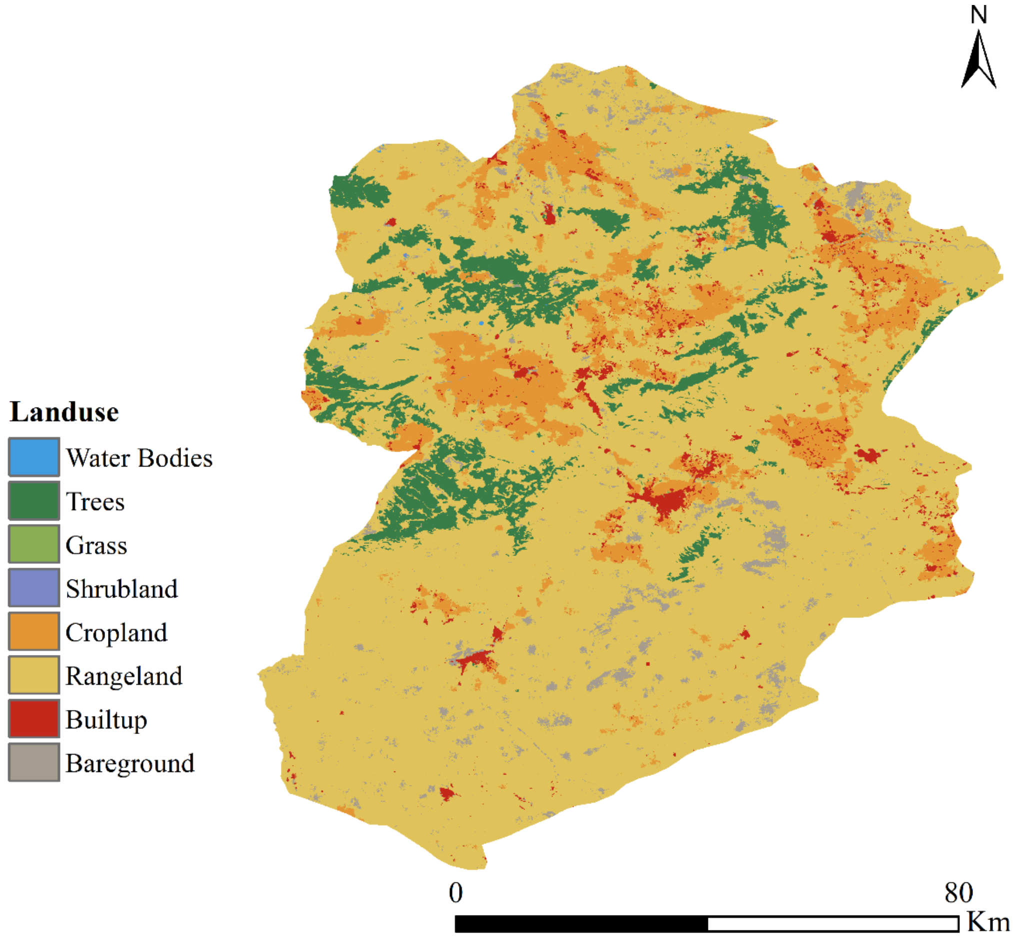


*Fig. 5.18 Kasserine Landuse Types*

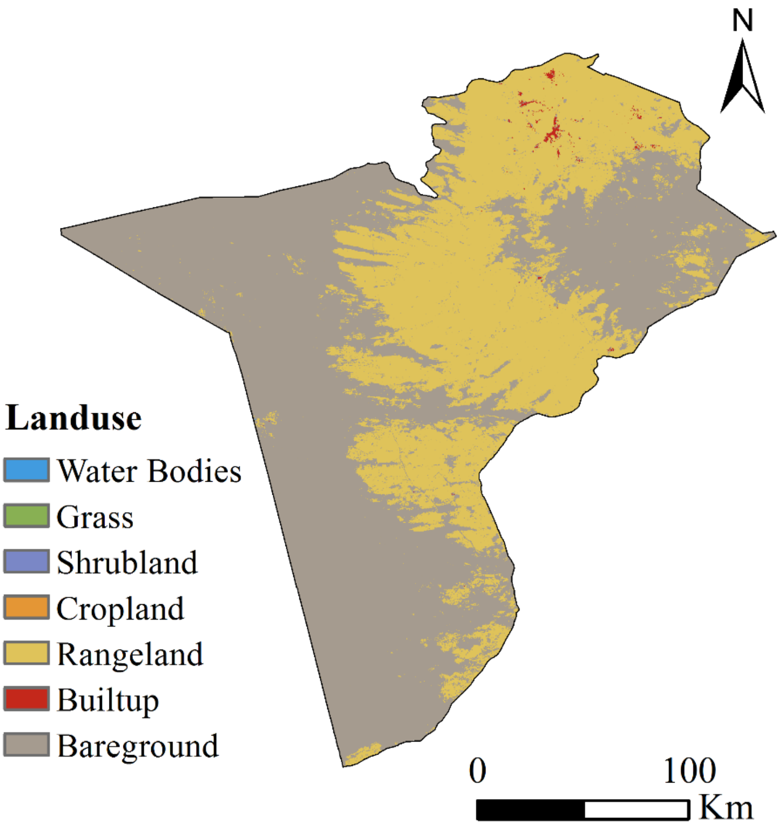


*Fig. 5.19 Tataouine Landuse Types*

Furthermore, certain renewable technologies like Concentrated Solar Power plants require substantial amounts of water for their construction and operation (Aly et al., 2017; Mutume et al., 2023; Yushchenko et al., 2018). Henceforth it becomes imperative to ensure access to ample water resources for efficient functioning of CSP plants due to heavy reliance on water for cooling systems and steam generation. The perusal of Figs. 5.20–21 showcase the access to water resources in Tataouine and Kasserine, respectively.

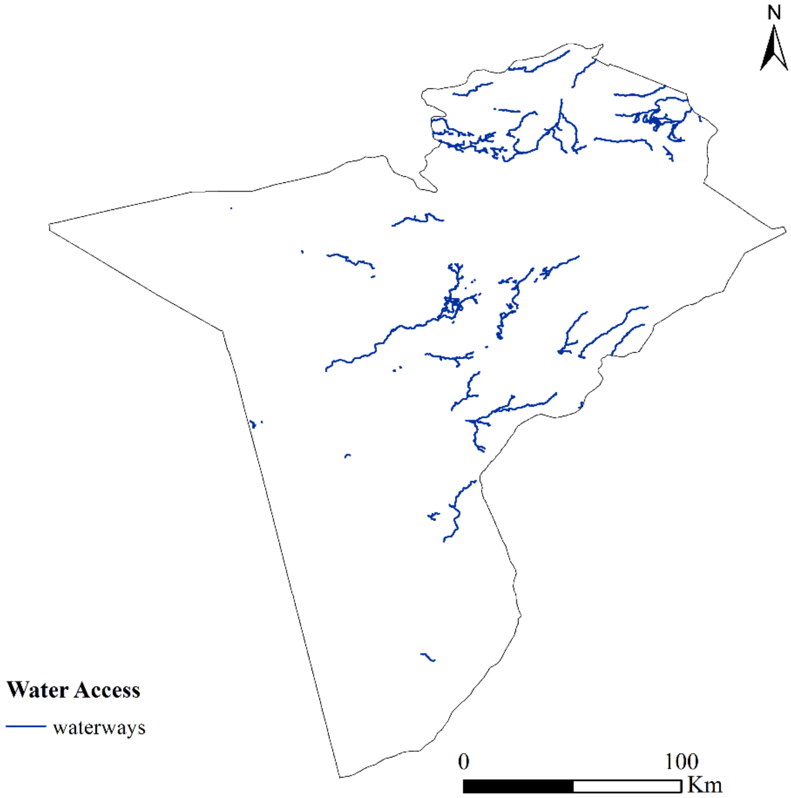


*Fig. 5.20 Tataouine Water Resources*

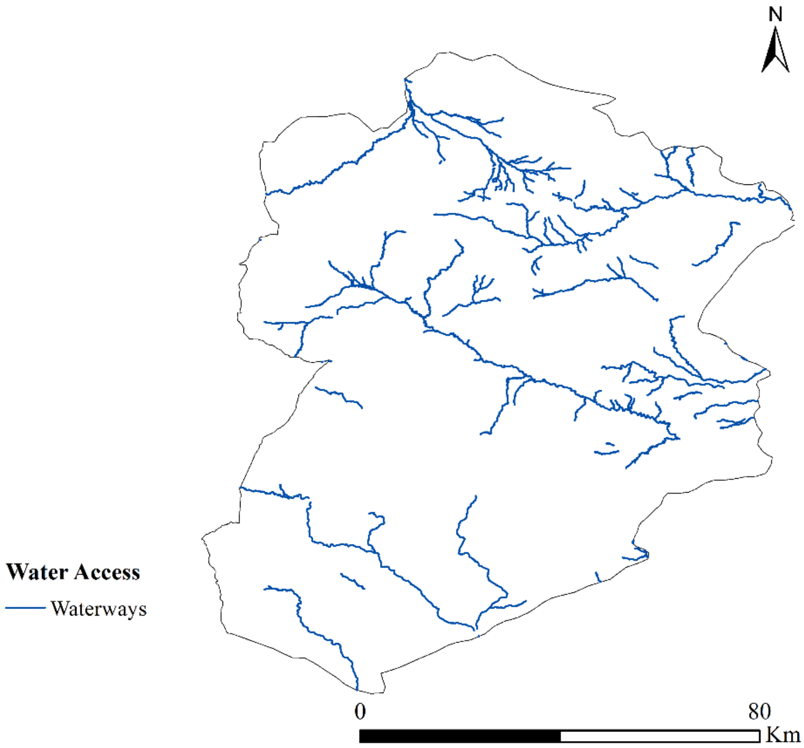


*Fig. 5. 21 Kasserine Water Resources*

## 5.4 Results and discussion

After ruling out the restrictive layers, a spatial analysis was carried out to identify the best locations for implementing PV-Wind, PV-CSP, and CSP-Wind hybrid systems in the Kasserine and Tataouine regions. Spatial Analyst tools within ArcGIS 10.8 were utilized for this study, known for their effectiveness in handling intricate site selection challenges. Data from various layers were standardized onto a common scale and reclassified accordingly (See Table C.1 in Appendix C). Each reclassified input layer was given weight based on its relative importance using the AHP technique. The final maps displaying suitability levels for each system were extracted using the raster calculator tool. Integration of satellite data allowed comprehensive evaluation of climatic and topographical factors in the areas under study, significantly enhancing precision in decision-making methods through a combined approach. Additionally, remote sensing data indicated that selected sites had high solar irradiance levels and consistent wind speeds, pointing towards substantial potential for solar and wind energy generation.

### 5.4.1 AHP Results

The AHP results highlighted the paramount importance of resource and topography criteria, particularly emphasizing wind speed, Global Horizontal Irradiance, Direct Normal Irradiance, and slope as essential factors for site selection, as illustrated in Table 5.2. Climate conditions were found to be significant determinants for wind, solar Concentrated Solar Power, and solar Photovoltaic technologies, with respective influence scores of 40.2%, 31.2%, and 33.6% for Kasserine and 43.2%, 34.4%, and 34.26%, for Tataouine respectively. This underscores the direct correlation between resource availability and electricity generation potential. Additionally, the influence of slope on site selection decisions is notable across all three technologies, positioning it prominently on the importance scale after climate criteria. It is imperative to ensure that these facilities are situated on flat or gently sloping terrain while minimizing proximity to transport links or power grids in order to mitigate additional expenses. Consequently, grid and transport infrastructure have been assigned higher weights due to their critical role in supporting all the technologies. Based on the extensive literature, it has been concluded that solar PV systems are directly affected by temperature and aspect, respectively, whereas CSP systems perform at their best when there are adequate water resources available. For PV technology, these factors were almost equally weighted in both regions, whereas water resources received a score of 16% and 12% for Tataouine and Kasserine, respectively. Finally, based on expert feedback, proximity to residential areas ranked lowest among influential factors.

Table 5.2. AHP weights for evaluating CSP-PV-Wind installation

| Factor | criteria | Kasserine | | | Tataouine | | |
|---|---|---|---|---|---|---|---|
| | | Onshore wind | Solar CSP | Solar PV | Onshore wind | Solar CSP | Solar PV |
| climate | $C_1$ | - | - | 0.312 | - | - | 0.342 |
| | $C_2$ | - | 0.336 | - | - | 0.344 | - |
| | $C_3$ | 0.402 | - | - | 0.432 | - | - |
| | $C_4$ | - | - | 0.101 | - | - | 0.084 |
| Topography | $C_5$ | 0.207 | 0.187 | 0.179 | 0.223 | 0.184 | 0.144 |
| | $C_6$ | - | - | 0.096 | - | - | 0.083 |
| Accessibility | $C_7$ | 9.9% | 0.092 | 0.072 | 0.099 | 7.4% | 0.112 |
| | $C_8$ | 13.9% | 0.081 | 0.068 | 0.139 | 11.9% | 0.134 |
| | $C_9$ | 4.6% | 0.059 | 0.029 | 0.046 | 4.8% | 0.031 |
| Environment | $C_{10}$ | 0.156 | 0.116 | 0.148 | 0.061 | 0.064 | 0.063 |
| | $C_{11}$ | - | 0.118 | - | - | 16.7% | - |
| | RI | 1.24 | 1.32 | 1.41 | 1.24 | 1.32 | 1.41 |
| | $\lambda$max | 6.229 | 7.479 | 8.842 | 6.449 | 7.582 | 8.733 |
| | CI | 0.046 | 0.079 | 0.121 | 0.089 | 0.097 | 0.105 |
| | CR | 3.69% | 6.04% | 8.53% | 7.24% | 7.35% | 7.42% |

$C_1$: GHI; $C_2$: DNI; $C_3$: Wind Speed; $C_4$: Temperature; $C_5$: Slope; $C_6$: Aspect; $C_7$: Distance to transport links; $C_8$: Distance to grid; $C_9$: Distance to residential areas; $C_{10}$: Land use; $C_{11}$: Water resources

### 5.4.2 Land suitability analysis for hybrid systems

The GIS-AHP integrated approach allowed for the identification of potential locations capable of supporting various hybrid combinations of PV-wind, CSP-PV, and CSP-wind in the regions of Kasserine and Tataouine, as illustrated in Figs. 5.22 – 23. Through the assessment of the geographical alignment of suitable sites in Kasserine, it was determined that 189 km$^2$ of land are highly favorable for PV-CSP hybrid systems. In contrast, potential sites for installing PV-Wind and CSP-PV hybrid systems were significantly less than those for the PV-CSP combination, covering areas of 87.6 km$^2$ and 50 km$^2$, respectively. Notably, Majel Belabbes, Feriana, and Kasserine Sud emerged as particularly suitable locations for these hybrid energy systems, as all of the hybrid combinations lie within these areas (Fig. 5.22).

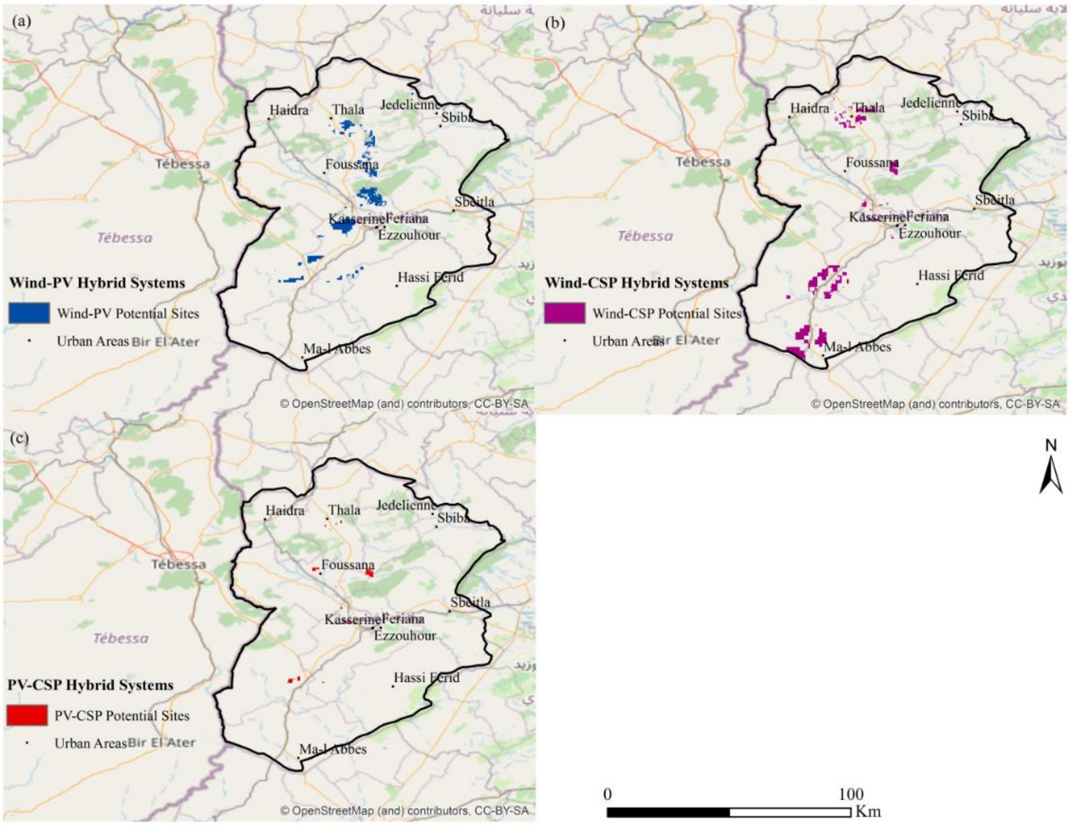


*Fig. 5.22 Kasserine's potential hybrid sites: a) PV-Wind Potential sites. b) CSP-Wind Potential sites. c) PV-CSP Potential sites*

As for the Tataouine region, the land suitability analysis showed that the best-suited sites for CSP-Wind combinations were higher by a lengthy margin than the other configurations, accounting for 191.6 km$^2$. On the other hand, PV-CSP and PV-Wind hybrid systems had only 92.25 and 74.5 km$^2$, respectively. It has been observed that Remada and Dhiba appeared to be the most promising sites to deploy these hybrid combinations (Fig. 5.23). These findings underscore the importance of employing these hybrid systems to achieve balanced power generation profiles and optimized resource utilization. Additionally, with shared infrastructure and innovative storage solutions, it would be possible for these hybrid electricity facilities to further enhance reliability and grid integration due to their complementary nature.

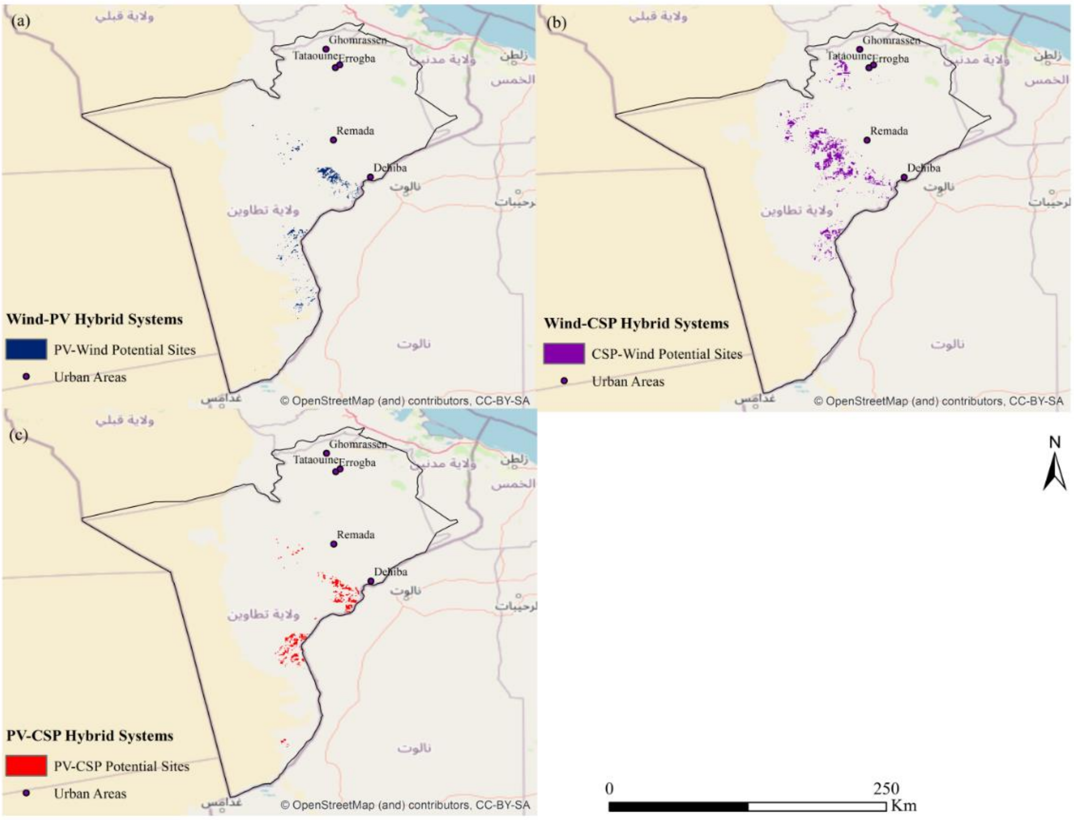


*Fig. 5.23 Tataouine's potential hybrid sites: a) PV-Wind Potential sites. b) CSP-Wind Potential sites. c) PV-CSP Potential sites*

## 5.5 Estimated energy yield

From theoretical perspective, solar and wind power generation can be described as the evaluation of wind and solar resources in an ideal area for installing wind, solar photovoltaic, or concentrating solar power plants using available technologies. Calculating the technical annual power generated by solar systems involves considering various factors such as solar radiation potential, efficiency, system performance, and capacity factor (Anwarzai et al., 2017; Ghasemi et al., 2019; Mutume, 2023), as detailed in Table 5.3. As such, the annual output power (AEP) can be computed as follows:

$$AEP = GHI \text{ or } DNI * Efficiency * Available\ Area * Area\ Factor \quad (1)$$

Where area factor (%) denotes the fraction of the total available area that can be covered by solar panels.

Table 5.3 Technologies used to compute the solar technical potential.

| Technology | Technology Type | Efficiency (%) | Performance ratio (%) |
|---|---|---|---|
| **PV** | Mono crystalline silicon | 15 - 22 | 70 - 85 |
| **CSP** | Parabolic trough steam cycle | 15 - 21 | NA |

Wind turbines at utility scale benefit from the use of large, efficient turbines that can produce more power even in low wind speeds. The placement of these turbines directly affects their effectiveness, output power, operational capabilities, and installation costs (Hartman, 2023). Typically, most wind farms have turbine spacing ranging from three to fifteen times the diameter of the rotor (Meyers & Meneveau, 2011; Stevens et al., 2016). In cases where wind direction data is unavailable, a spacing factor of 10D was used for equal spacing. In this analysis assumed an installed capacity potential of 4 MW/km$^2$ was assumed based on a range of commercial wind turbines available on the market (ranging from 3.518 to 4.8 MW), as detailed in Table 5.4. Afterwards, the annual wind output power (AEP) was calculated as follows:

$$AEP\ (GWh) = \sum(\text{ICP} * 8760 * \text{Capacity Factor}) \qquad (2)$$

Table 5.4. Sample of the large wind turbines available in the market (Anwarzai et al., 2017)

| Turbine | | Hub height (m) | Rotor diameter (m) | Name plate capacity (MW) | Area per turbine (Km$^2$) | installed capacity (MW/km$^2$) |
|---|---|---|---|---|---|---|
| **Vestas** | III | 84 - 119 | 112 | 3.8 | 0.794 | 4.157 |
| **Vestas** | III | 80 - 105 | 90 | 1.8 | 0.405 | 4.444 |
| **Eno** | III | 92 - 142 | 126 | 3.5 | 0.794 | 4.409 |
| **Siemens** | IIB | 80 | 108 | 2.3 | 0.583 | 3.944 |
| **Gamesa** | III | 109 | 97 | 2.0 | 0.470 | 4.251 |
| **Mitsubishi** | II | 80 | 100 | 2.4 | 0.500 | 4.800 |
| **Nordex** | III | 164 | 116.8 | 2.4 | 0.682 | 3.518 |

When assessing the energy output of a hybrid energy system, a power distribution ratio is frequently taken into account. Several factors influence this ratio, including the objective of the project, the availability of resources, and the specific design of the system. This study used a 50/50 power distribution ratio, with each technology contributing 50% to the total installed capacity. In hybrid systems, the technical potential for electricity generation is affected by a variety of factors, such as the type of wind turbine or solar panel used as well as system efficiency, which have a significant effect on actual potential in comparison with theoretical potential. Statistically speaking, based on the computational analysis, the annual energy yield from the Kasserine potential sites was projected at 76415 GWh for PV-CSP, 20390 GWh for CSP-wind, and 9273 GWh for PV-wind (Fig. 5.24). Meanwhile, the Tataouine promising sites were anticipated to generate 41400 GWh for CSP-Wind, 19826 GWh for PV-CSP, and 14052 GWh for PV-Wind, in respective order (Fig. 5.25).

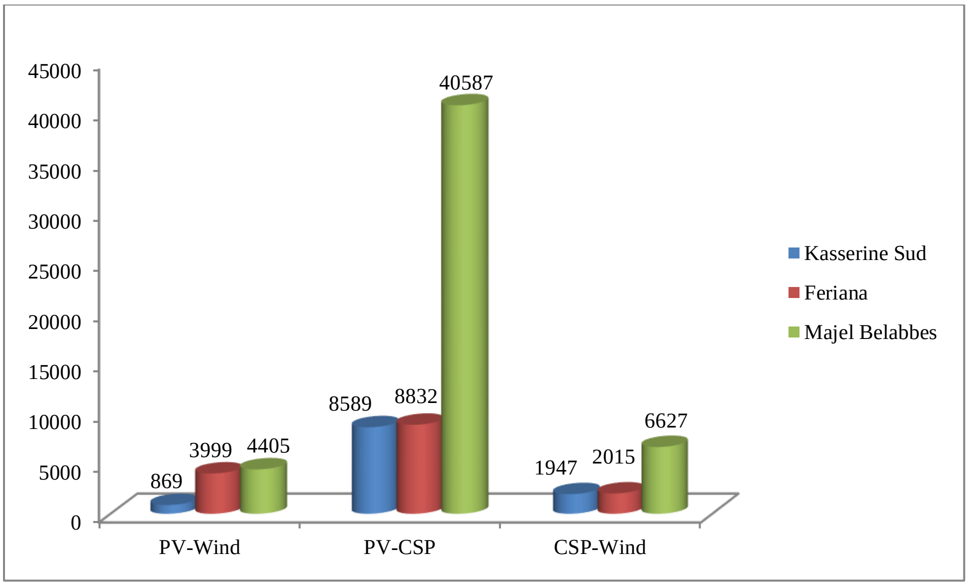


*Fig. 5.24 Kasserine's estimated energy yield of hybrid systems*

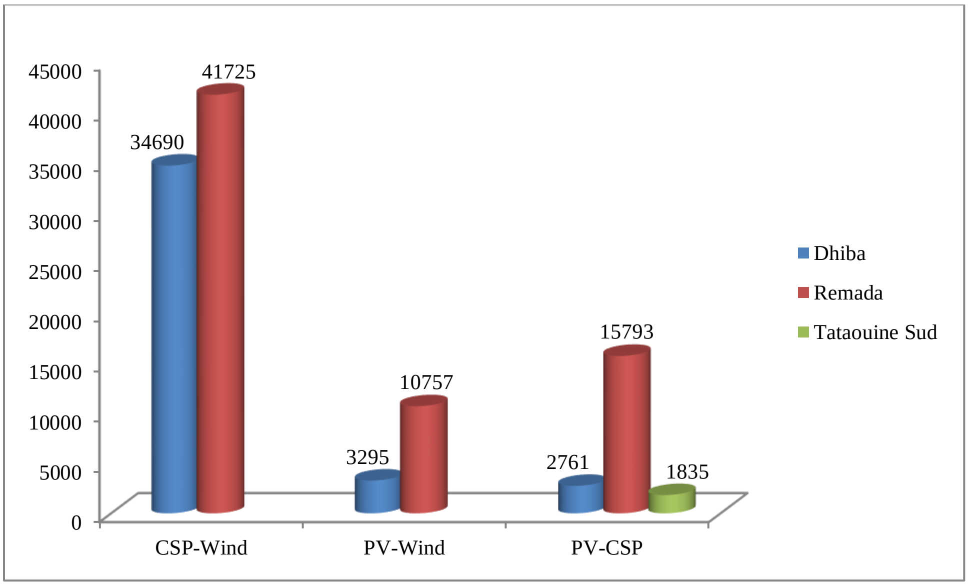


*Fig. 5.25 Tataouine's estimated energy yield of hybrid systems*

These figures highlight significant renewable potential in the regions of Kasserine and Tataouine, where CSP-PV hybrid systems showed higher levels in Kasserine compared to other combinations. Conversely, CSP-Wind hybrid systems appeared to be superior to the remaining configurations in Tataouine. Covering nearly all suitable areas considered, Majel Belabbes, Feriana, Kasserine Sud, Remada, and Dhiba emerged as particularly favorable locations due to exceptional climatic conditions along with gentle slopes and appropriate land use dominant in those regions.

### 5.6 Discussion

The study's outcome suggests that the potential for the adaptation of hybrid renewable energy facilities within the Kasserine and Tataouine regions is significant. The performance of CSP-PV, PV-Wind, and CSP-Wind hybrid systems has been shown to be optimal under observed geographical and climate conditions. The use of AHP as an MCDM tool has had a substantial impact on our research results by effectively handling both quantitative and qualitative data, confirming its versatility and broad applicability (Kumar et al., 2017; Messaoudi et al., 2019; Shao et al., 2020). Compared to similar works conducted in Egypt, Morocco, and Kenya, the findings were found to be particularly significant and present highly competitive opportunities for the designated regions of Kasserine and Tataouine as well as the entire country (Effat & El-Zeiny, 2022; Elkadeem et al., 2021; Jbaihi et al., 2022). This underscores the importance of hybrid power systems such as CSP-PV, PV-wind, and CSP-wind, suggesting them as potential solutions for regions with shared attributes. It also highlights that hybrid renewable energy systems could make an enormous contribution in addressing energy challenges.

In light of the myriad of socio-economic challenges facing both regions, it is imperative to implement comprehensive measures that actively promote and incentivize investment in hybrid systems (Khammassi et al., 2021; Rouine & Roche, 2022). The identification of ideal locations for these projects necessitates not only allocating suitable sites but also enhancing grid infrastructure, transportation systems, manufacturing facilities, as well as educational and training centers (Saraswat et al., 2021). Consequently, the development of such hybrid systems can stimulate economic growth by creating employment opportunities and fostering skill development within local communities. Furthermore, these integrated systems provide a more dependable power supply while simultaneously reducing reliance on traditional fuels and mitigating the carbon footprint (Abbasi et al., 2020; Bashir et al., 2022; Liu et al., 2022).

## 5.7 Conclusion

The increasing emphasis on sustainable energy production has led to the rise of hybrid renewable energy systems such as solar PV-wind, PV-CSP, and CSP-wind. As this sector undergoes rapid expansion, determining ideal locations that can host such systems is critical. Therefore, this chapter addresses this need by undertaking a comprehensive research initiative to identify suitable sites for PV-CSP, PV-wind, and CSP-wind hybrid systems in the Kasserine and Tataouine regions of central and southern Tunisia. This involved the development of an integrated GIS-based AHP model that took into account critical factors including global horizontal irradiance, direct normal irradiance, wind speed, water resources, land use, proximity to grid and transport infrastructure, as well as residential areas.

The obtained outcomes indicated that the designated regions are suitable for deploying hybrid technologies owing to their unique climate and geographical features. The regions exhibited high levels of solar radiation, consistent wind patterns, favorable topography, and sufficient infrastructure. It has been demonstrated that Kasserine and Tataouine have substantial potential to accommodate PV-CSP, CSP-wind, and PV-wind configurations over approximately 50–189 $km^2$ in Kasserine and 74.5–192 $km^2$ in Tataouine. As for the predicted electricity generation capacity, these hybrid systems were projected to produce an annual output power ranging between 9273 and 58008 GWh from Kasserine's potential sites, while Tataouine's best-suited areas were predicted to generate an energy yield varying between 13675 and 41400 GWh per year. It is believed that adopting these sustainable and innovative approaches can lead to an increase in energy production, enhanced reliability, and a more stable and balanced power supply. An important point can be seen from this study, which serves as a valuable model for other regions or countries intending to make use of their renewable energy potential through evidence-based site selection methods. Nonetheless, the decision-making process would benefit from future research focusing on the architecture and modeling of CSP-PV-Wind hybrid systems with the aim of optimizing output power while minimizing costs and ensuring the long-term sustainability of renewable energy projects.

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# Chapter VI: Prioritizing RES and Identifying their Challenges in Tunisia

## 6.1 Introduction

Countries around the world and local governments have been striving to diversify their energy systems in order to address the intersecting challenges related to energy, environment, and economy while working towards achieving the Sustainable Development Goals (SGDs). The share of renewable energy sources has now surpassed 27% of global power generation, with a substantial addition of over 200 gigawatts in 2019 (IRENA, 2023). However, the selection of feasible RES options requires meticulous consideration across various dimensions. Choosing the most suitable renewable technology thoughtfully can enhance economic benefits, contribute to local employment and energy security, as well as mitigate environmental degradation. Conversely, opting for an unsuitable technology may result in severe consequences such as financial burdens (Haddad et al, 2017; Wu et al, 2020; Yazdani et al, 2020). Yet, conducting an assessment of RES is however a complex undertaking due to the diverse interdisciplinary data and conflicting criteria involved in the evaluation process (Al-Garni et al, 2016; Lehr et al, 2016; Yazdani et al, 2020).

Therefore, determining the optimal energy mix involves a comprehensive examination of various factors beyond just assessing renewable energy sources potentials in a particular region. The implementation of RESs is indeed confronted with numerous challenges that have significant impacts on environmental, social, and economic aspects, especially in developing countries like Tunisia (Fashina et al., 2018). The exploration of renewable energy sources in Tunisia has been ongoing for years due to its favorable meteorological conditions, which provide abundant potential for solar and wind resources (Abdelrazik et al., 2022; Rekik & El Alimi, 2023b). The country has made significant progress in advancing its renewable energy sector in recent years. To promote the integration of renewable energy technologies into the energy mix at a faster pace, the government has authorized several wind and solar projects ranging from 10 MW to 200 MW(Ministère de l’Energie, des Mines et des Energies Renouvelables de Tunisie, 2023).

However, a successful transition to renewable energy sources involves high upfront costs, the need for an encouraging investment climate, supportive government policies, social acceptance, and more. It is crucial to identify and prioritize the barriers inherent in renewable energy projects due to their reliance on new and untested technologies (Qazi et al., 2021). Failing to address these barriers can lead to substantial financial setbacks, project delays or even cancellations (Oryani et al., 2021; Hulio et al., 2022). In response, multi-criteria decision-making tools have effectively been utilized to evaluate and scrutinize the myriad challenges related to advancing RES projects. As such, it is anticipated that this will offer policymakers valuable insights to develop effective strategies for overcoming these barriers and expediting the deployment of RETs in the country.

In light of the importance of evaluating and choosing the most feasible renewable technology, this chapter aims to create a decision support system using a CRITIC-EDAS method for prioritizing renewable energy options for generating electricity in Tunisia. The focus is on solar photovoltaics, concentrated solar power, onshore wind, and biomass while considering technical, economic, environmental, and social factors. Additionally, a SWARA-DEMATEL model has been utilized to recognize and prioritize the key obstacles to implementing renewable energy sources in Tunisia.

## 6.2 Literature review

The process of selecting the most practical and environmentally friendly RET involves numerous conflicting factors and diverse sets of data from different fields. In this context, MCDM methods have become highly adaptable tools for assisting decision-makers in comprehensively addressing the problem by handling a wide array of variables. Various MCDM approaches have been effectively applied in energy-related projects, with a focus on allocating weights to the considered criteria and ranking alternatives based on defined criteria (Yazdani et al., 2020). More recently, more advanced models have been developed in this area, with CRITIC and EDAS being frequently utilized by many scholars either independently or in combination with other models.

Shi et al. (2021) applied a CRITIC decision-making tool for identifying and evaluating power quality issues linked to microgrid systems during significant capacity load changes. In Nigeria, Akinyele et al. (2019) proposed a STEEP framework based on CRITIC and PROMETHEE in a fuzzy environment to address the sustainability of solar PV microgrids in rural communities. Similarly, Babatunde et al. (2019) presented an analysis for deploying hybrid renewable energy systems within low-income households using the CRITIC-TOPSIS technique. Gu & Liu (2022) utilized the same model to assess grid resilience amid energy transformation and extreme disasters' impacts. Additionally, in Bangladesh, Ali et al. (2020) employed a novel CRITIC-CODAS model to explore deploying hybrid renewable energy sources in coastal regions, while Narayanamoorthy et al. (2021) used an expanded version of the MCDM approach using NWHF-CRITIC-NWHF-MAUT methods for optimal wind turbine selection involving factors like capacity, voltage level, power rating, and quality considerations.

Yazdani et al. (2020) proposed the combination of EDAS with Shannon Entropy as an approach for multiple attribute decision-making to assess the potential of five renewable energy sources in Saudi Arabia: solar PV, solar thermal, wind power, biomass, and geothermal. Zhang et al. (2019) developed an integrated model based on EDAS, WASPAS, and TOPSIS for selecting Lithuania's most feasible micro-generation alternative. Ramezanzade et al. (2021) utilized hybrid MCDM methods, including EDAS, ARAS, MOORA, and VIKOR, in a fuzzy environment to prioritize renewable energy projects in Northern Khorasan, Iran. Karatop et al. (2021) integrated EDAS with AHP and FMEA to support optimal investment decisions in Turkey's renewable energy sector, while Asante et al. (2020) combined EDAS with MULTIMOORA to address barriers limiting the advancement of renewable technologies in Ghana. In another study, Babatunde et al. (2022) applied CRITIC-EDARS' integrative methodology for analyzing ideal off-grid hybrid systems for sustainable development within Nigeria`s institutional buildings. The authors emphasized the importance of finding a balanced trade-off among different criteria in selecting the most economically viable system. They noted that prioritizing sustainability over total cost could lead to a different best alternative. Similarly, Moitra et al. (2021) introduced a decision support system based on EDAS and CRITIC for choosing the optimal battery energy storage system. It has been deduced from the literature, CRITIC was employed to assess the relative significance of the criteria under consideration, while EDAS was utilized to rank the alternatives in accordance with these criteria.

To effectively enhance the integration of RETs, it is crucial to recognize and assess the different obstacles linked to their implementation. In this regard, MCDM techniques like SWARA and DEMATEL have been extensively utilized to overcome the prominent barriers associated with them.

Due to its simplicity and directness, SWARA has been increasingly employed as a weighting method in various fields, including renewable energy systems. For instance, Zolfani and

Saparauskas (2013) and Vafaeipour et al. (2014) utilized SWARA to investigate the feasibility of solar projects in Iran. In Turkey, an optimal marine power plant was determined using a combined SWARA-WASPAS model by Yücenur and Ipekçi. (2023). On the other hand, the DEMATEL technique has proven useful for visualizing interdependencies among factors related to RESs' implementation. For instance, Azizi et al. (2014) proposed a GIS-based DEMATEL approach to explore interrelationships among different factors when selecting optimal wind sites in Iran. To prioritize different power generation scenarios in Turkey, Büyüközkan and Güleryüz (2016) developed an integrated DEMATEL-ANP model. Additionally, Qiu et al. (2020) applied fuzzy DEMATEL along with TOPSIS and VIKOR to evaluate the systematic risks related to wind energy projects in seven countries, such as China, Brazil, India, Indonesia, Mexico, Russia, and Turkey. The authors found that exchange rates, political stability, and social conflicts were among the major barriers. Recent studies have also focused on various obstacles hindering the advancement of RETs in emerging economies using the DEMATEL approach (Gedam et al., 2021; Payel et al., 2023; Siraj et al., 2023). Interestingly, to take advantage of the SWARA and DEMATEL approaches, Rekik and El Alimi (2023) and Badi et al. (2021) combined both methods to identify suitable sites for solar and wind as well as hybrid systems in Tunisia and Libya. Based on the literature review, findings indicate that SWARA and DEMATEL techniques have been highly effective in identifying potential obstacles and understanding interdependencies among factors related to RETs' installation.

In Turkey, Büyüközkan and Güleryüz (2016) developed an integrated DEMATEL-ANP model to prioritize various power generation scenarios. Qiu et al., (2020) used fuzzy DEMATEL in conjunction with TOPSIS and VIKOR to assess the systematic risks pertinent to wind energy projects in seven countries, including China, Brazil, India, Indonesia, Mexico, Russia, and Turkey. The authors stated that exchange rates, political stability, and social conflicts were the most potential barriers. Recently, several studies have addressed the various obstacles hindering the promotion of RES in emerging economies using the DEMATEL approach (Gedam et al., 2021; Payel et al., 2023; Siraj et al., 2023). According to the reviewed literature, it has been demonstrated that the use of SWARA and DEMATEL techniques were very effective in exploring and determining the most potential obstacles as well as understanding the interdependencies among the various factors associated with RETs' installation.

While there is a significant amount of literature on the use of RETs in Tunisia, as evidenced by Attig-Bahar et al. (2021); Balghouthi et al. (2016); Rekik & El Alimi (2023a); and Trabelsi et al. (2016), there is still insufficient research dedicated to prioritizing and analyzing the various challenges that hinder RETs deployment in the country. This is particularly notable as previous commitments have not been fully upheld (Rouine & Roche, 2022; Ben Ammar, 2022). Addressing this knowledge gap demands a methodical and evidence-based approach to prioritizing different renewable technologies and analyzing barriers related to their utilization. To do so, hybrid MCDM models, including CRITIC, EDAS, SWARA, and DEMATEL, have been used. Firstly, the CRITIC-EDAS model ranks the most feasible and sustainable RETs in Tunisia, while the SWARA-DEMATEL approach highlights prominent obstacles hindering their acceleration. These findings can provide policymakers with valuable insights for developing appropriate strategies to promote the implementation of these renewable energy sources. This will provide policymakers with a clearer understanding of how to develop effective strategies to promote the implementation of these RESs.

Failing to make the appropriate choice or neglecting to recognize the major obstacles associated with these projects can result in substantial repercussions. Thus, a two-stage method was employed in chapter. Firstly, a decision-making framework using CRITIC-EDAS is suggested for evaluating four widely recognized renewable energy technologies: solar photovoltaic, concentrated solar power, onshore wind, and biomass.

In addition to the literature review, input from a panel of experts with practical experience in renewable energy was sought to ensure a comprehensive understanding of the relevant criteria. Table 6.1 – 6.2 summarize the comprehensive lists of potential criteria for evaluating RETs and their relevant barriers, taking into account Tunisia's unique economic, environmental, and social context.

Table 1Table 6.1. Summary of the criteria used in prioritizing RES

| Criteria | Type | Unit | Description | References |
|---|---|---|---|---|
| Resource availability | Beneficial | $KWh/m^2$ | Availability of renewable resources (wind speed, solar radiations etc.) to generate energy | (Ahmad & Tahar, 2014; Amer & Daim, 2011; Lee & Chang, 2018; Stein, 2013; Yazdani et al, 2020) |
| Efficiency | Beneficial | % | This criterion apprises the operation and performance of the technology for energy policy. | (Ahmad & Tahar, 2014; Boran et al, 2013; Lee & Chang, 2018; Şengul et al, 2015; Saraswat & Digalwar, 2021; Stein, 2013; Yazdani et al, 2020) |
| Capital Cost | Non-Beneficial | US$/kW | It includes expenditure on equipment, installation, infrastructure, and commissioning. | (Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Şengul et al, 2015; Saraswat & Digalwar, 2021; Stein, 2013; Yazdani et al, 2020) |
| Technology maturity | Beneficial | 1-5 Scale | Technology maturity is indicated by how wide-spread technology is at regional, national and international levels. | (Al-Garni et al, 2016; Effatpanah et al, 2022; Lee & Chang, 2018; Haddad et al, 2017; Saraswat & Digalwar, 2021) |
| Electricity cost | Non-Beneficial | $/kWh | Expected cost of the electricity generated by power plant. | (Amer & Daim, 2011; Brand & Missaoui, 2014; Boran et al, 2013; Lee & Chang, 2018; Pappas et al, 2012; Yazdani et al, 2020) |
| Water use | Non-Beneficial | l/KWh | The amount of water needed to generate a unit of energy under different technologies | (Effatpanah et al, 2022; Haddad et al, 2017; Şengul et al, 2015; Wang et al, 2009) |
| Job Creation | Beneficial | Person/GWh | Potential employment opportunities to be created by energy projects. | (Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Yazdani et al, 2020) |
| Land Requirement | Beneficial | $m^2$/GWh | The required area for the installation of technology | (Ahmad & Tahar, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Yazdani et al, 2020) |
| CO2 Emissions | Non-Beneficial | $tCO_2$ /MWh | Direct CO2 emissions of all power plants during the observation period | (Ahmad & Tahar, 2014; Brand & Missaoui, 2014; Haddad et al, 2017; Lee & Chang, 2018; Saraswat & Digalwar, 2021; Şengul et al, 2015; Stein, 2013; Yazdani et al, 2020) |
| Projected installed capacity | Beneficial | MW | Maximum produced energy on the basis of the usable renewable energy sources and under the manufacturer's specified parameters. | Afrane et al, 2021; Effatpanah et al, 2022; |

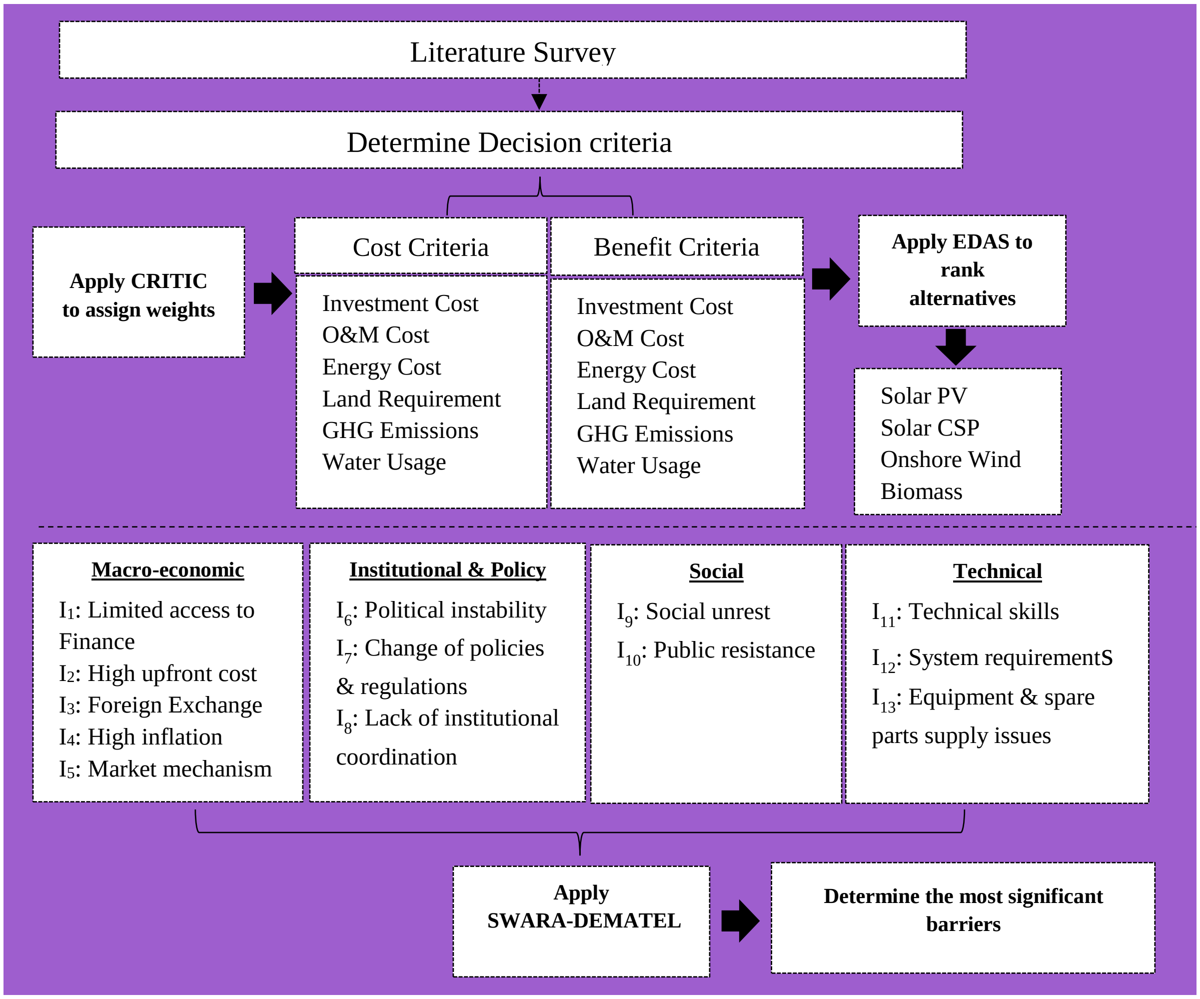


*Fig. 6.1. Main steps for prioritizing RETs and identifying their pertinent barriers in Tunisia*

The SWARA technique was then used to rank these barriers based on their impact on RET development in Tunisia. Subsequently, the DEMATEL approach was applied to reveal interdependencies among factors and establish cause-and-effect relationships through indirect linkages. Fig. 6.1 illustrates the steps involved in prioritizing suitable

RETs and identifying significant barriers for their utilization in Tunisia.

Table 6.2. Barriers hindering the deployment of RETs

| Category | denotation | Indicator | Reference |
|---|---|---|---|
| Macroeconomic | I 1 | Limited Access to Finance | Solangi et al.2021 |
| | I 2 | High Upfront Cost | Payel et al. 2023 |
| | I3 | Foreign Exchange Fluctuation | Wu et al. 2020 |
| | I 4 | High Inflation | Elmahmoudi et al. 2020 |
| | I 5 | Market access mechanism | Elmahmoudi et al. 2020 |
| Institutional & Policy | I 6 | Political Instability | Pathak et al. 2022, Solangi et al. 2021 |
| | I 7 | Change of Policies & Regulations | Solangi et al.2021, Wu at al. 2021 |
| | I 8 | Lack of Institutional coordination | Wu et al. 2020 |
| Social | I 9 | Social Unrest | Wu et al. 2020 |
| | I 10 | Public Resistance | Wu et al. 2020 |
| Technical | I 11 | Technical Skills | Wu et al. 2020 |
| | I 12 | System Requirements | Elmahmoudi at al. 2020, Wu et al. 2020 |
| | I 13 | Equipment & Spare parts supply issues | Elmahmoudi at al. 2020, Wu et al. 2020 |

## 6.3 Results and Discussion

The chapter's results cover the outputs of the hybrid MCDM tools used. At a first stage, the RETs are prioritized according to the CRITIC-EDAS findings, while the most predominant obstacles are highlighted using the SAWARA-DEMATEL, as outlined in the subsections below.

### 6.3.1 CRITIC Results

Weights for the relevant criteria were assigned by following all the specified steps of the CRITIC methodology, as demonstrated in Tables 6.3 – 6.

Table 6.3. CRITIC initial input data matrix

| | Cost criteria | | | | | | Benefit criteria | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
| Solar PV | 800 | 20 | 0.05 | 35 | 49.61 | 1.00 | 4.00 | 20 | 1800 | 0.87 |
| Solar CSP | 4700 | 141 | 0.11 | 40 | 16.11 | 3.02 | 3.00 | 21 | 2000 | 0.23 |
| Wind | 1300 | 39 | 0.03 | 100 | 30.14 | 0.00 | 5.00 | 35 | 570 | 0.17 |
| Biomass | 1250 | 62.5 | 0.07 | 5000 | 162.15 | 135.00 | 4.00 | 25 | 200 | 0.21 |
| Best | 800 | 20 | 0.03 | 35 | 16.11 | 0.00 | 5.00 | 35 | 2000 | 0.87 |
| Worst | 4700 | 141 | 0.11 | 5000 | 162.15 | 135.00 | 3.00 | 20 | 200 | 0.17 |

$C_1$: investment cost; $C_2$: O&M cost; $C_3$: energy cost; $C_4$: landuse; $C_5$: GHG emissions
$C_6$: water use; $C_7$: technical maturity; $C_8$: efficiency; $C_9$: resources; $C_{10}$: job creation

Table 6.4. Normalized matrix & Standard deviation (σ)

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Solar PV | 0.00 | 0.00 | 0.20 | 0.00 | 0.23 | 0.01 | 0.50 | 1.00 | 0.11 | 0.00 |
| Solar CSP | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.02 | 1.00 | 0.93 | 0.00 | 0.91 |
| Wind | 0.13 | 0.16 | 0.00 | 0.01 | 0.10 | 0.00 | 0.00 | 0.00 | 0.79 | 1.00 |
| Biomass | 0.12 | 0.35 | 0.46 | 1.00 | 1.00 | 1.00 | 0.50 | 0.67 | 1.00 | 0.94 |
| (σ) | 0.46 | 0.44 | 0.43 | 0.50 | 0.46 | 0.50 | 0.41 | 0.46 | 0.50 | 0.48 |

Table 6.5. Correlation matrix

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $C_1$ | 1.00 | 0.97 | 0.89 | -0.29 | -0.45 | -0.27 | 0.77 | 0.32 | -0.55 | 0.40 |
| $C_2$ | 0.97 | 1.00 | 0.94 | -0.04 | -0.22 | -0.02 | 0.78 | 0.31 | -0.37 | 0.52 |
| $C_3$ | 0.89 | 0.94 | 1.00 | 0.06 | -0.08 | 0.09 | 0.94 | 0.61 | -0.48 | 0.26 |
| $C_4$ | -0.29 | -0.04 | 0.06 | 1.00 | 0.98 | 1.00 | -0.01 | 0.01 | 0.71 | 0.33 |
| $C_5$ | -0.45 | -0.22 | -0.08 | 0.98 | 1.00 | 0.98 | -0.09 | 0.06 | 0.69 | 0.14 |
| $C_6$ | -0.27 | -0.02 | 0.09 | 1.00 | 0.98 | 1.00 | 0.02 | 0.04 | 0.69 | 0.32 |
| $C_7$ | 0.77 | 0.78 | 0.94 | -0.01 | -0.09 | 0.02 | 1.00 | 0.83 | -0.65 | -0.07 |
| $C_8$ | 0.32 | 0.31 | 0.61 | 0.01 | 0.06 | 0.04 | 0.83 | 1.00 | -0.68 | -0.57 |
| $C_9$ | -0.55 | -0.37 | -0.48 | 0.71 | 0.69 | 0.69 | -0.65 | -0.68 | 1.00 | 0.53 |
| $C_{10}$ | 0.40 | 0.52 | 0.26 | 0.33 | 0.14 | 0.32 | -0.07 | -0.57 | 0.53 | 1.00 |

Table 6.6 (1 – Correlation) matrix

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $C_1$ | 0.00 | 0.03 | 0.11 | 1.29 | 1.45 | 1.27 | 0.23 | 0.68 | 1.55 | 0.60 |
| $C_2$ | 0.03 | 0.00 | 0.06 | 1.04 | 1.22 | 1.02 | 0.22 | 0.69 | 1.37 | 0.48 |
| $C_3$ | 0.11 | 0.06 | 0.00 | 0.94 | 1.08 | 0.91 | 0.06 | 0.39 | 1.48 | 0.74 |
| $C_4$ | 1.29 | 1.04 | 0.94 | 0.00 | 0.02 | 0.00 | 1.01 | 0.99 | 0.29 | 0.67 |
| $C_5$ | 1.45 | 1.22 | 1.08 | 0.02 | 0.00 | 0.02 | 1.09 | 0.94 | 0.31 | 0.86 |
| $C_6$ | 1.27 | 1.02 | 0.91 | 0.00 | 0.02 | 0.00 | 0.98 | 0.96 | 0.31 | 0.68 |
| $C_7$ | 0.23 | 0.22 | 0.06 | 1.01 | 1.09 | 0.98 | 0.00 | 0.17 | 1.65 | 1.07 |
| $C_8$ | 0.68 | 0.69 | 0.39 | 0.99 | 0.94 | 0.96 | 0.17 | 0.00 | 1.68 | 1.57 |
| $C_9$ | 1.55 | 1.37 | 1.48 | 0.29 | 0.31 | 0.31 | 1.65 | 1.68 | 0.00 | 0.47 |
| $C_{10}$ | 0.60 | 0.48 | 0.74 | 0.67 | 0.86 | 0.68 | 1.07 | 1.57 | 0.47 | 0.00 |

The results indicated that resource availability (C9) was ranked the highest with a weight of 14.03%, in contrast to other criteria. Efficiency (C8) closely followed with a score of 11.48%, as depicted in Table 6.7. Investment cost (C1) and job creation (C10) both received nearly identical relative weights of 10.64% and 10.38% respectively. Interestingly, energy cost (C3) was found to have relatively low significance, with a weight of 7.77%. Despite financial constraints being commonly viewed as a major obstacle to global energy project implementation, the CRITIC technique did not identify this factor as the most influential parameter.

Table 6.7. Obtained weights using CRITIC method

| | Sum | $\sigma_j$ | $C_j$ | $W_j$ | Rank |
|---|---|---|---|---|---|
| Investment Cost | 7.200 | 0.463 | 3.334 | 10.64% | 3.00 |
| O&M Cost | 6.142 | 0.439 | 2.699 | 8.40% | 8.00 |
| Energy Cost | 5.769 | 0.433 | 2.496 | 7.77% | 10.00 |
| Land Requirement | 6.248 | 0.498 | 3.110 | 9.68% | 6.00 |
| GHG Emissions | 6.988 | 0.456 | 3.184 | 9.91% | 5.00 |
| Water usage | 6.155 | 0.495 | 3.047 | 9.49% | 7.00 |
| Technical Maturity | 6.476 | 0.408 | 2.644 | 8.23% | 9.00 |
| Efficiency | 8.073 | 0.457 | 3.687 | 11.48% | 2.00 |
| Resources | 9.101 | 0.495 | 4.507 | 14.03% | 1.00 |
| Job Creation | 7.200 | 0.478 | 3.417 | 10.38% | 4.00 |

### 6.3.2 EDAS Ranking

At this step, the evaluation of power source alternatives using the EDAS approach involved comprehensive computations and thorough analysis. The initial decision matrix criteria and positive and negative distances from average (PDA & NDA) were carefully computed using various equations (see EDAS section in chapter 2), as shown in Tables 6.8–10. The appraisal score of each alternative was then meticulously computed, revealing that solar PV technology emerged as the optimal choice among other alternatives with the highest appraisal score of 0.486, followed by onshore wind and CSP securing second and third positions, respectively, as demonstrated Table 6.11. In contrast, biomass recorded the lowest score, indicating it is a worse option than others considered in the assessment process.

Table 2Table 6.8. EDAS initial input data matrix

| | Cost criteria | | | | | | Benefit criteria | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
| weightage | 0.106 | 0.084 | 0.077 | 0.097 | 0.099 | 0.095 | 0.082 | 0.115 | 0.140 | 0.103 |
| Solar PV | 800 | 20 | 0.05 | 35 | 49.61 | 1.00 | 4.00 | 20 | 1800 | 0.87 |
| Solar CSP | 4700 | 141 | 0.11 | 40 | 16.11 | 3.02 | 3.00 | 21 | 2000 | 0.23 |
| Wind | 1300 | 39 | 0.03 | 100 | 30.14 | 0.00 | 5.00 | 35 | 570 | 0.17 |
| Biomass | 1250 | 62.5 | 0.07 | 5000 | 162.15 | 135.00 | 4.00 | 25 | 200 | 0.21 |
| $Av_j$ | 2012.5 | 65.63 | 0.06 | 1293.75 | 64.5 | 34.76 | 4.00 | 25.25 | 1142.5 | 0.37 |

Table 6.9. Positive distance from average (PDA)

| | Solar PV | Solar CSP | Wind | Biomass |
|---|---|---|---|---|
| Investment Cost | 0.063 | 0.000 | 0.037 | 0.039 |
| O&M Cost | 0.058 | 0.000 | 0.034 | 0.004 |
| Energy Cost | 0.019 | 0.000 | 0.037 | 0.000 |
| Land Requirement | 0.094 | 0.094 | 0.089 | 0.000 |
| GHG Emissions | 0.023 | 0.074 | 0.053 | 0.000 |
| Water usage | 0.092 | 0.087 | 0.095 | 0.000 |
| Technical Maturity | 0.000 | 0.000 | 0.021 | 0.000 |
| Efficiency | 0.000 | 0.000 | 0.044 | 0.000 |
| Resources | 0.081 | 0.105 | 0.000 | 0.000 |
| Job Creation | 0.144 | 0.000 | 0.000 | 0.000 |

Table 6.10. Negative distance from average (NDA)

| | Solar PV | Solar CSP | Wind | Biomass |
|---|---|---|---|---|
| Investment Cost | 0.000 | 0.139 | 0.000 | 0.000 |
| O&M Cost | 0.000 | 0.096 | 0.000 | 0.000 |
| Energy Cost | 0.000 | 0.053 | 0.000 | 0.004 |
| Land Requirement | 0.000 | 0.000 | 0.000 | 0.277 |
| GHG Emissions | 0.000 | 0.000 | 0.000 | 0.150 |
| Water usage | 0.000 | 0.000 | 0.000 | 0.274 |
| Technical Maturity | 0.000 | 0.021 | 0.000 | 0.000 |
| Efficiency | 0.024 | 0.019 | 0.000 | 0.001 |
| Resources | 0.000 | 0.000 | 0.070 | 0.116 |
| Job Creation | 0.000 | 0.040 | 0.058 | 0.046 |

Table 6.11. EDAS final ranking results

| | $SP_i$ | $SN_i$ | $NSP_i$ | $NSN_i$ | $AS_i$ | Rank |
|---|---|---|---|---|---|---|
| Solar PV | 0.574 | 0.360 | 0.410 | 0.043 | 0.486 | 1 |
| Solar CSP | 0.360 | 0.368 | 0.128 | 0.868 | 0.181 | 3 |
| Wind | 0.410 | 0.628 | 0.715 | 0.075 | 0.305 | 2 |
| Biomass | 0.043 | 0.576 | 0.853 | 0.913 | 0.034 | 4 |

### 6.3.3 Sensitivity analysis

The results obtained indicate a leaning towards solar PV; however, it is essential to acknowledge that this inclination may not be conclusive as it is based on specific input data. To uphold the accuracy and reliability of the decision-making process, performing a sensitivity analysis would be beneficial. This method can uncover alternative scenarios and offer a more comprehensive insight into the outcomes, ensuring that the decision-making process remains robust amidst fluctuating subjective assessments and potentially unstable input data (Haddad et al., 2017; Sindhu et al., 2017). The sensitivity analysis entails adjusting the weights assigned to different criteria to assess their impact on the final ranking of alternatives.

Accordingly, the sensitivity analysis was carried out in a series of steps as follows:

a) Adjusting the weights assigned to the criteria individually or combined. This involved five scenarios: prioritizing technical factors (such as technical maturity, efficiency, and resource abundance), favoring economic factors (capital and O&M costs), giving higher weight to environmental considerations (water usage, land requirement, and emissions), emphasizing social criteria, and applying equal weights.
b) Recalculating the rankings of the RETs using the adjusted weights to determine if there were any changes in their order of preference or significance.
c) Comparing the new rankings with the original ones to identify which RETs are most sensitive to changes in weighting. This reveals which criteria have greater influence on decision-making.
d) Assessing the stability and robustness of the original results by checking if rankings remain consistent despite changes in weights. A high level of robustness suggests that initial results can be relied upon even when weighting criteria change.

It became clear from this analysis that solar PV technology was the most prominent alternative in all the scenarios considered, with onshore wind closely following behind, as shown in Fig. 6.2. It is worth noting that when focusing on investment and O&M costs, biomass and CSP displayed almost identical rankings.

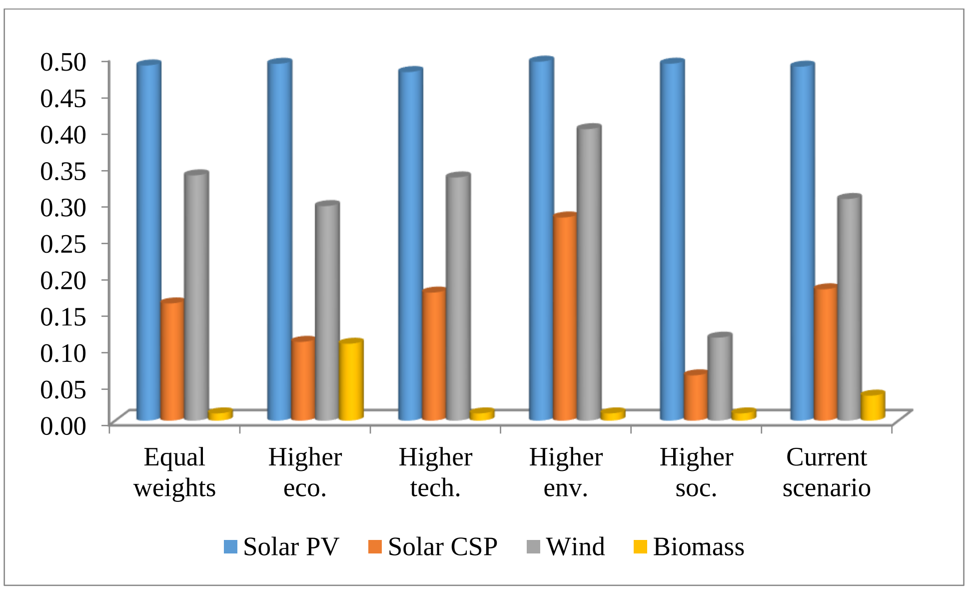


*Fig. 6.2 Sensitivity analysis with respect to influential criteria*

### 6.3.4 SWARA-DEMATEL Results

Experts with extensive experience in the Tunisian energy sector were initially asked to use the SWARA technique to assign weights to the identified indicators based on their own knowledge, as shown in Table 6.12. Following this, they utilized the DEMATEL approach to analyze interdependencies among these indicators (see Tables D.2–D.4 in Appendix D).

Table 6.12. Experts' ranking and scoring of indicators

| Indicator | Expert 1 | | Expert 2 | | Expert 3 | | Expert 4 | | $\bar{A}$ |
|---|---|---|---|---|---|---|---|---|---|
| | Rank | Score | Rank | Score | Rank | Score | Rank | Score | |
| $I_1$ | 1.00 | 1.00 | 3.00 | 0.75 | 3.00 | 0.80 | 4.00 | 0.80 | 0.832 |
| $I_2$ | 2.00 | 0.90 | 2.00 | 0.80 | 2.00 | 0.95 | 2.00 | 0.95 | 0.898 |
| $I_3$ | 5.00 | 0.70 | 6.00 | 0.55 | 5.00 | 0.60 | 7.00 | 0.55 | 0.597 |
| $I_4$ | 6.00 | 0.70 | 7.00 | 0.50 | 6.00 | 0.60 | 8.00 | 0.45 | 0.554 |
| $I_5$ | 7.00 | 0.65 | 4.00 | 0.65 | 4.00 | 0.70 | 3.00 | 0.85 | 0.708 |
| $I_6$ | 3.00 | 0.85 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.960 |
| $I_7$ | 10.00 | 0.45 | 10.00 | 0.25 | 12.00 | 0.05 | 13.00 | 0.10 | 0.154 |
| $I_8$ | 11.00 | 0.30 | 8.00 | 0.45 | 7.00 | 0.55 | 9.00 | 0.35 | 0.402 |
| $I_9$ | 4.00 | 0.75 | 5.00 | 0.60 | 6.00 | 0.55 | 6.00 | 0.60 | 0.621 |
| $I_{10}$ | 8.00 | 0.60 | 13.00 | 0.05 | 9.00 | 0.35 | 10.00 | 0.20 | 0.214 |
| $I_{11}$ | 9.00 | 0.55 | 9.00 | 0.30 | 8.00 | 0.50 | 5.00 | 0.70 | 0.490 |
| $I_{12}$ | 13.00 | 0.10 | 12.00 | 0.10 | 11.00 | 0.10 | 12.00 | 0.15 | 0.111 |
| $I_{13}$ | 12.00 | 0.20 | 11.00 | 0.15 | 10.00 | 0.20 | 11.00 | 0.20 | 0.186 |

From SWARA analysis, it was observed that factors such as political instability (I6), high upfront costs (I2), and limited access to finances (I1) were identified as the most influential indicators, while the change of policy & regulations (I7) and system requirements (I12) were considered less significant, as presented in Table 6.13. On the other hand, according to the DEMATEL approach, it was noted that policy & institutional, and macroeconomic aspects belonged to the cause group (Ri + Ci > 0), whereas technical and social aspects were part of the effect group (Ri – Ci < 0) (Fig. 6.3).

Table 6.13. SWARA results

| Indicator | $\bar{A}$ | $S_j$ | $K_j$ | $q_j$ | $W^{SWARA}$ |
|---|---|---|---|---|---|
| I6 | 0.960 | | 1.000 | 1.000 | 0.113 |
| I2 | 0.898 | 0.062 | 1.062 | 0.941 | 0.107 |
| I1 | 0.832 | 0.065 | 1.065 | 0.883 | 0.100 |
| I5 | 0.708 | 0.124 | 1.124 | 0.786 | 0.089 |
| I9 | 0.621 | 0.087 | 1.087 | 0.723 | 0.082 |
| I3 | 0.597 | 0.024 | 1.024 | 0.706 | 0.080 |
| I4 | 0.554 | 0.043 | 1.043 | 0.677 | 0.077 |
| I 11 | 0.490 | 0.064 | 1.064 | 0.636 | 0.072 |
| I8 | 0.402 | 0.089 | 1.089 | 0.584 | 0.066 |
| I 10 | 0.214 | 0.187 | 1.187 | 0.492 | 0.056 |
| I 13 | 0.186 | 0.028 | 1.028 | 0.479 | 0.054 |
| I 7 | 0.154 | 0.032 | 1.032 | 0.464 | 0.053 |
| I 12 | 0.111 | 0.043 | 1.043 | 0.445 | 0.050 |

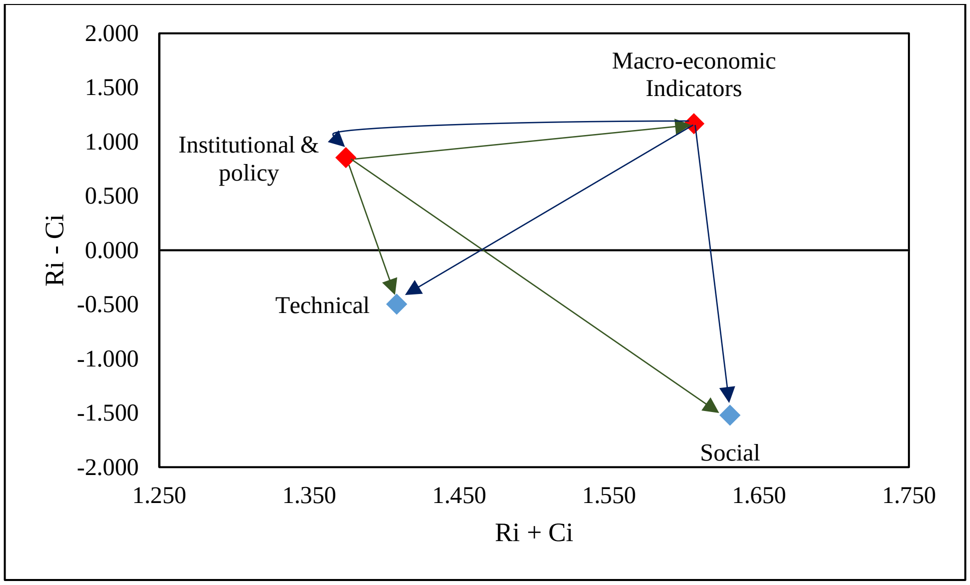


*Fig. 6.3 Influential relation map of the main factors*

An influential relationship map visually represents the connections between different factors or indicators and their mutual impact. Indicator weights measure the relative importance of each factor among all factors. In an INRM, higher weights signify that the indicator carries more influence or is more crucial within decision-making processes. When used in an IRM, highly weighted indicators serve as focal points, signaling policymakers to areas with significant potential to either facilitate or impede the adoption of renewable energy technologies. Therefore, identifying barriers with the most substantial influence directs efforts and resources towards overcoming these obstacles. To illustrate the impactful connections between the identified indicators, an INRM was constructed using Ri and Ci vectors, along with a threshold value of the total relationship matrix (α), to highlight the most important relationships (Table 6.14 and Fig. 6.5).

In terms of ranking, the DEMATEL findings showed some variation compared to the SWARA results. While I6 and I2 had identical rankings in both methods, social unrest (I9) and high inflation (I4) were ranked as the third and fourth most influential indicators, respectively, as shown in Table 6.15. Fig. 6.4 depicts the overall indicator ranking.

Table 6.14. Total relation matrix

| | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $I_6$ | $I_7$ | $I_8$ | $I_9$ | $I_{10}$ | $I_{11}$ | $I_{12}$ | $I_{13}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 0.084 | 0.099 | 0.137 | **0.205** | **0.163** | 0.103 | 0.093 | 0.114 | 0.104 | **0.197** | **0.169** | 0.132 | 0.143 |
| $I_2$ | 0.127 | 0.061 | 0.128 | **0.175** | 0.122 | 0.075 | **0.160** | 0.113 | **0.166** | 0.129 | 0.111 | **0.180** | 0.096 |
| $I_3$ | 0.052 | 0.094 | 0.031 | 0.107 | 0.032 | 0.066 | 0.060 | 0.074 | 0.031 | 0.113 | 0.033 | 0.038 | 0.075 |
| $I_4$ | 0.058 | 0.013 | 0.014 | 0.027 | 0.016 | 0.007 | 0.012 | 0.040 | 0.036 | 0.071 | 0.055 | 0.097 | 0.025 |
| $I_5$ | **0.160** | 0.143 | 0.099 | 0.141 | 0.060 | 0.075 | 0.140 | 0.113 | 0.108 | **0.203** | **0.174** | 0.116 | 0.139 |
| $I_6$ | **0.209** | **0.185** | **0.174** | 0.135 | 0.158 | 0.049 | **0.187** | **0.200** | 0.125 | **0.200** | **0.194** | 0.132 | 0.147 |
| $I_7$ | **0.178** | 0.126 | 0.065 | 0.139 | 0.110 | 0.072 | 0.052 | 0.144 | 0.108 | **0.188** | 0.104 | **0.174** | 0.073 |
| $I_8$ | 0.059 | 0.083 | 0.053 | 0.067 | 0.082 | 0.016 | 0.027 | 0.026 | 0.058 | 0.037 | 0.058 | 0.030 | 0.026 |
| $I_9$ | 0.022 | 0.010 | 0.009 | 0.052 | 0.010 | 0.024 | 0.007 | 0.051 | 0.008 | 0.012 | 0.011 | 0.010 | 0.028 |
| $I_{10}$ | 0.075 | 0.076 | 0.065 | 0.154 | 0.065 | 0.018 | 0.047 | 0.051 | 0.051 | 0.044 | 0.053 | 0.049 | 0.028 |
| $I_{11}$ | 0.088 | 0.047 | 0.059 | 0.130 | 0.035 | 0.020 | 0.104 | 0.104 | 0.144 | 0.131 | 0.034 | 0.093 | 0.099 |
| $I_{12}$ | 0.029 | 0.009 | 0.007 | 0.020 | 0.019 | 0.004 | 0.005 | 0.058 | 0.007 | 0.010 | 0.009 | 0.007 | 0.017 |
| $I_{13}$ | 0.095 | 0.061 | 0.043 | 0.078 | 0.035 | 0.014 | 0.020 | 0.043 | 0.022 | 0.083 | 0.026 | 0.047 | 0.021 |

Table 6.15. DEMATEL results

| | $R_i$ | $C_i$ | $R_i + C_i$ | $R_i - C_i$ | $W^{DEMATEL}$ | Group |
|---|---|---|---|---|---|---|
| I6 | 2.098 | 0.545 | 2.642 | 1.553 | 11.89% | Cause |
| I2 | 1.758 | 0.592 | 2.350 | 1.166 | 10.17% | |
| I5 | 1.491 | 0.526 | 2.017 | 0.964 | 8.67% | |
| I1 | 1.053 | 0.395 | 1.448 | 0.658 | 6.17% | |
| I11 | 0.883 | 0.397 | 1.279 | 0.486 | 5.31% | |
| I8 | 0.608 | 0.511 | 1.119 | 0.097 | 4.36% | |
| I12 | 0.806 | 0.884 | 1.690 | -0.079 | 6.56% | Effect |
| I7 | 0.588 | 0.916 | 1.504 | -0.328 | 5.97% | |
| I10 | 0.255 | 0.968 | 1.223 | -0.713 | 5.49% | |
| I13 | 0.200 | 1.107 | 1.307 | -0.907 | 6.17% | |
| I3 | 0.725 | 1.232 | 1.956 | -1.107 | 8.72% | |
| I4 | 0.776 | 1.417 | 2.193 | -1.241 | 9.77% | |
| I9 | 0.367 | 1.927 | 2.293 | -1.560 | 10.76% | |

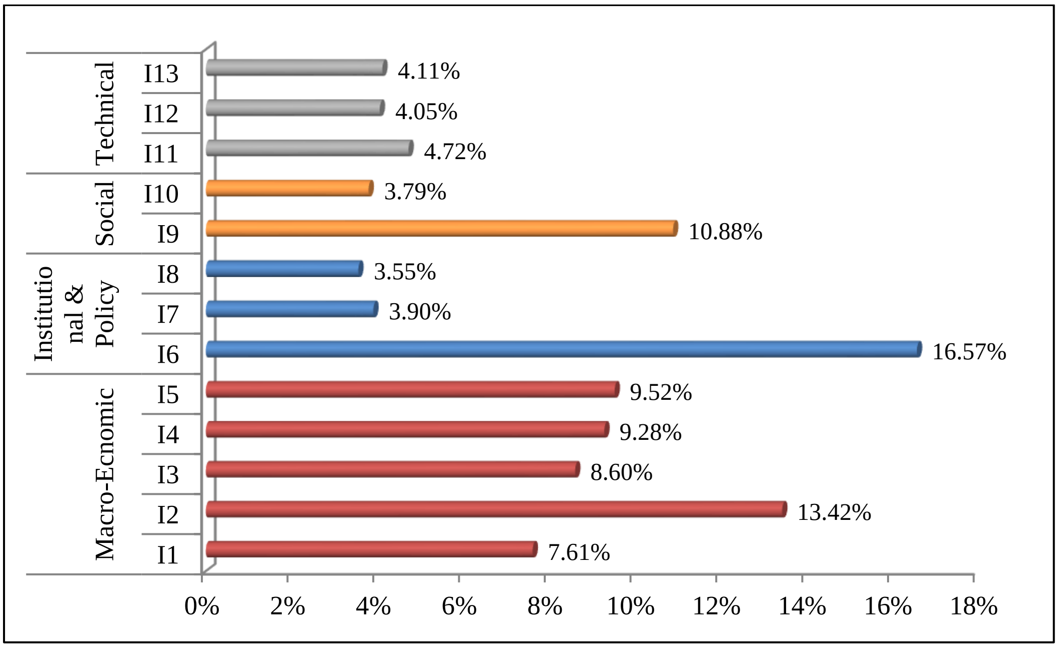


*Fig. 6.4 Indicators overall weights*

To illustrate the impactful connections between the identified indicators, an INRM was constructed using Ri and Ci vectors, along with a threshold value of the total relationship matrix (α), to highlight the most important relationships, as depicted in Fig. 6.5.

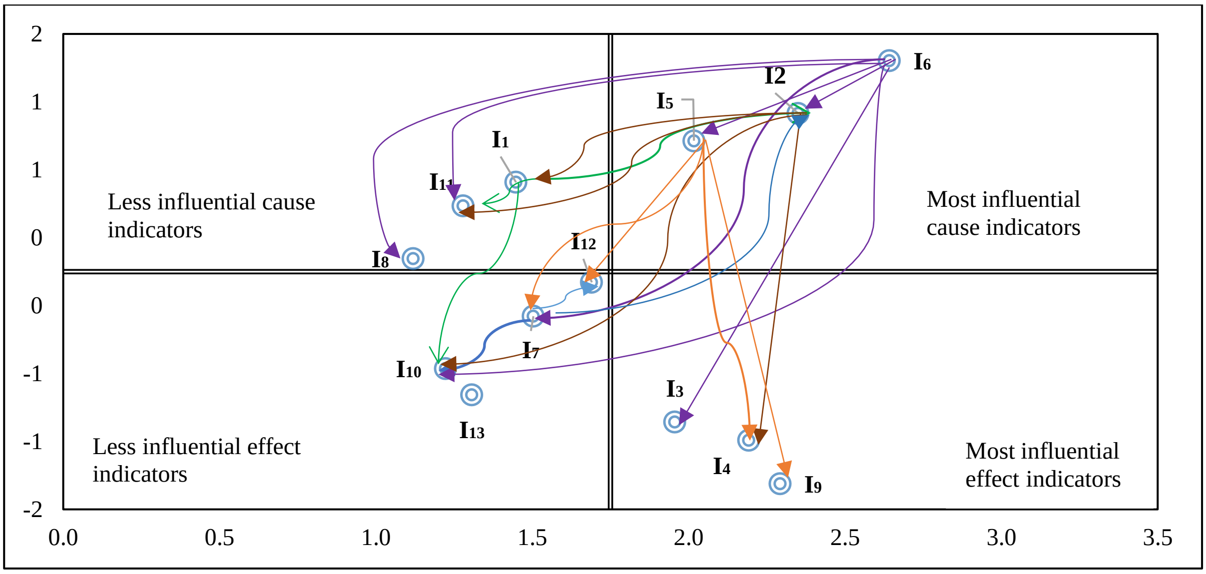


*Fig. 6.5 Influential relation map of the indicators*

The perusal of the diagram reveals that political instability (I6), high upfront costs (I2), and market access mechanisms (I5) were the primary causative indicators. Without a favorable and supportive political environment, it would be extremely challenging to attract investments for implementing renewable energy technologies, potentially leading to significant delays or even project cancellations (Solangi et al., 2021; Pathak et al., 2022). For example, due to the political unrest in Tunisia over the past decade, only 40 MW of PV projects have been completed out of the planned 4.7 GW announced in 2009.

Moreover, renewable energy projects are often associated with substantial initial expenses (I2), which poses a significant challenge to the adoption of RETs. Developing countries like Tunisia encounter difficulty in securing the required funding for these ambitious initiatives. Furthermore, the absence of a transparent market access mechanism (I5), such as Feed-in-Tariff, deters potential investors from entering the industry. In addition, restricted access to financial resources (I1) proves to be a notable barrier as the nation grapples with engaging international financial institutions for essential funds. Similarly, technical expertise (I11) and inadequate institutional coordination (I8) are also identified as impeding factors within this category. Without a proficient workforce and efficient collaboration among involved organizations, implementing, operating, and sustaining large-scale RETs projects would be challenging.

In terms of the effect group, although they do not directly influence the structure, they remain significantly important. Social unrest (I9) has been identified as the third major indicator. An illustrative instance is the recurrent demonstrations against the installation of RETs in southern areas of the country, in which local communities have been restricted from conducting their agricultural activities or have even been evicted from their lands without being adequately compensated (Ben Ammar, 2022). Hence, addressing these effect indicators concurrently with causative ones is essential.

### 6.4 Discussion

In recent years, Tunisian energy policies have placed a growing emphasis on promoting RETs as part of the country's broader strategy to move away from fossil fuels and decrease its reliance on foreign energy sources. However, the adoption of renewable technologies faces several challenges, such as technical barriers, financial constraints, and resistance from established interests within the traditional energy sector (Fashina et al., 2018; Rocher & Verdeil, 2019; Schmidt et al., 2017). Consequently, there are conflicting perspectives on the future of Tunisia's energy landscape, leading to contested efforts to advance renewable energy technologies.

This chapter explores the complexities surrounding the adoption of RETs in Tunisia by prioritizing the most feasible option and determining the most prominent barriers impeding their implementation. Interestingly, the findings were consistent with previous research. The preference for solar PV and onshore energy sources is not surprising, as they are more accessible than other forms of renewable energy in the country (Attig-Bahar et al., 2021; Balghouthi et al., 2016; Rekik & El Alimi, 2023a; Trabelsi et al., 2016). This trend is also observed in other emerging economies with similar socio-economic profiles, geographical characteristics, and energy needs. Additionally, political instability, financial constraints, societal opposition, and technological limitations have all been highlighted as major barriers, indicating that Tunisia's challenges are typical of those faced by similar economies, as illustrated in Table 6.16.

Additionally, this analysis emphasizes the significance of political and spatial dynamics in Tunisia's energy transition, building on the research by Rocher & Verdeil (2013), Rocher & Verdeil (2019), and Verdeil (2014). These dynamics highlight the urgent need for policy reform and cohesive governance within the sector (Solangi et al., 2019; Tang & Solangi, 2023; Xu & Solangi, 2023). Moreover, challenges related to land use conflicts, regulatory issues, financial limitations, and social acceptance have been recognized as key barriers hindering progress in solar power projects (Rocher & Verdeil, 2013; Payel et al., 2023; Siraj et al., 2023). Furthermore, improving institutional collaboration and technical expertise is crucial for promoting the advancement of renewable energy technologies (Rocher & Verdeil, 2013). Thus, concentrating on these areas could facilitate a smoother integration of renewable energy projects into existing energy systems (Shah & Solangi, 2019).

Table 6.16. Comparison with similar emerging economies

| Study | Ref | Optimal RETs | Methodology |
|---|---|---|---|
| This study | | Solar PV, Wind | CRITIC-EDAS |
| Egypt | Abdel-Basset et al. 2021 | Solar PV, Wind | AHP - TOPSIS – VIKOR |
| Libya | Ali et al. 2023 | Wind-PV, Wind | VIKOR, TOPSIS, COPRAS |
| Morocco | Gouraizim et al. 2023 | Solar PV, Wind | CAR-PROMETHEE |
| Algeria | Haddad et al. 2017 | Solar PV, Wind | AHP |
| | | Major barriers | |
| This study | | Political instability, investment costs, & market mechanism | SWARA-DEMATEL |
| Libya | Badi et al. 2023 | Policy framework | AHP- CoCoSo |
| Ghana | Asante et al. 2022 | Absence of enabling policy initiatives | CRITIC-Fuzzy TOPSIS |
| Jordan | Alkhalidi et al., 2019 | Strategic and business | AHP |
| Turkey | Kul et al. 2020 | Economic & business risk | Delphi, AHP, FWASPAS |
| Dominican | Guerrero-Liquet et al. 2016 | Technical and financial risks | AHP |
| Pakistan | Solangi et al. 2021 | Economic & Financial, Political & Policy, Market | SWOT-AHP-Fuzzy TOPSIS |

## 6.5 Conclusion

This chapter focuses on prioritizing sustainable energy alternatives and recognizing obstacles to their adoption in Tunisia using the integrated CRITIC-EDAS and SWARA-DEMATEL methods. The findings indicate that solar photovoltaic and land-based wind power are the most feasible options, while concentrated solar power and biomass perform less satisfactorily across various criteria, particularly with regard to capital costs. The sensitivity analysis supports the superiority of solar PV and onshore wind, highlighting the need for specific measures to hasten their integration. Furthermore, the study recognizes macroeconomic and socio-political impediments to implementing renewable energy technologies in Tunisia, emphasizing the necessity of addressing these barriers to establish a sustainable future powered by renewables.

It is important to note that while the study provides valuable insights, its scope is limited to select renewable technologies, omitting others such as geothermal and offshore wind, which could also yield significant advantages. Expanding upon this study's momentum, future studies might consider alternative decision-making frameworks, such as fuzzy multi-criteria decision-making, to provide a more refined approach for addressing uncertainties in the evaluation process. Prioritizing engagement with stakeholders is essential, incorporating extensive input from various sources, including local communities, industry representatives, and policymakers, to ensure that the findings are contextually relevant and practically applicable.

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# Chapter VII: Final Conclusions and Recommendations

## 7.1 Final Conclusion

This thesis delved into four interconnected challenges associated with renewable energy planning in Tunisia. The first problem addressed the feasibility of installing large-scale solar power plants, with a specific focus on the regions of Kasserine and Tataouine. Similarly, the second problem focused on assessing the site suitability for utility-size onshore wind systems at national and regional levels. Next, the third problem involved an in-depth exploration of installing hybrid renewable energy systems, including PV-CSP, PV-Wind, and CSP-Wind, in Kasserine and Tataouine. Lastly, the fourth problem was dedicated to prioritizing the most viable renewable energy technology and determining the prominent barriers pertinent to their adoption in Tunisia.

For Problem 1 (chapter 3), a two-stage GIS-based MCDM approach was used to conduct a broad assessment of the suitability of possible locations for constructing large-scale solar power plants. Firstly, a land suitability analysis was performed at the national level to investigate the feasibility of deploying PV technology across the whole territory of Tunisia. Secondly, a spatial analysis was conducted to unlock the solar potential in terms of PV and CSP technologies, specifically in the regions of Kasserine and Tataouine. The analyses were evaluated in accordance with the corresponding criteria, with the exclusion of any limitations. Precise real-time meteorological data, such as air temperature and solar irradiance, are taken into account alongside the corresponding infrastructure information. The findings revealed that approximately 17.6% of Tunisia's total land is fit for solar PV projects, with the regions of Kasserine and Tataouine particularly favorable for sustainable solar infrastructure. Additionally, it was found that the most suitable sites were capable of generating an estimated annual energy yield of 1059.7 TWh. Meanwhile, the PV and CSP output power from areas within Kasserine was projected at 130 TWh/yr and 138 TWh/yr, while 260 TWh/yr and 752 TWh/yr were predicted in Tataouine.

Likewise, in problem 2 (chapter 4), the same two-stage GIS-MCDM integrated method was utilized to conduct spatial suitability analyses in Tunisia, with a particular emphasis on the Kasserine and Tataouine regions. The primary goal was to identify highly suitable locations for the implementation of large-scale wind farms. The obtained results indicated that slightly more than 4.39% of the Tunisian territory, equivalent to 6912 $km^2$, was deemed extremely suitable for installing onshore wind facilities on a large scale. At a regional level, Kasserine and Tataouine exhibited great potential for onshore wind development, with the best-suited areas covering 612 $km^2$ and 500 $km^2$ for Kasserine and Tataouine, respectively. In terms of estimated energy yield, it was found that the wind technical power could reach as high as 72282 GWh per year at a national level, whereas the potential sites within Kasserine and Tataouine were predicted to generate an annual technical power ranging between 6127 and 7511 GWh.

Given the variability and intermittent nature of solar and wind energy, problem 3 (chapter 5) delved into the viability of deploying solar and wind hybrid systems in the regions of Kasserine and Tataouine. The outcomes showcased suitable sites within an area of 50–189 $km^2$ in Kasserine and 74.5–192 $km^2$ in Tataouine for the following combinations: PV–CSP, PV–Wind, and CSP–Wind. It was observed that Tataouine favors CSP-Wind with a 41400 GWh potential annually, while Kasserine is ideal for PV-CSP with an annual energy output of 58008 GWh.

Finally, problem 4 (chapter 6) involved an exhaustive assessment of the electricity generation potential of four prominent energy technologies, including solar PV, onshore wind, geothermal, and biomass. It also identified the barriers associated with their deployment in Tunisia using a hybrid MCDM approach. Significantly, the findings highlighted solar PV as the most promising alternative due to its highest weightage of 48.6%, closely followed by onshore wind. Furthermore, limited access to finance, high initial costs, political instability, and a lack of institutional coordination were found to be the most prominent obstacles hindering the adoption of such technologies.

## 7.2 Recommendations

This thesis draws inspiration from the ambitious targets for renewable energy sources that numerous countries have set, reflecting a global push towards sustainability. The core aim of this research is to provide valuable insights for guiding informed decision-making processes related to the implementation of solar, wind, and hybrid renewable energy systems. Each chapter of this thesis delves into the intricate details undertaken to achieve this pivotal objective. However, there are still unresolved matters that might be regarded as subjects for future research:

- It would be valuable to enhance the proposed models by incorporating additional decision criteria such as visual impact, land ownership, policy regulation, and population density. Such factors can have a substantial impact on the economic viability and implementation of these systems. Additionally, it is important to consider factors like sandstorms, which are common in arid and deserted regions, as they significantly impact PV performance. Excluding these areas will result in more efficient PV systems.

- Moreover, integrating real long-term data from wind and solar monitoring sensors nationwide could greatly improve their modeling in ArcGIS.
- Accommodating large-scale renewable energy systems may necessitate upgrades to existing grid infrastructure, potentially leading to an overall increase in costs. Therefore, a comprehensive financial evaluation encompassing capital expenditures (CAPEX), operational expenditures (OPEX), internal rates of return (IRR), and Levelized cost of electricity (LCOE) is vital.
- While the study offers valuable insights into certain renewable technologies, its scope is limited and it omits other promising options such as geothermal and offshore wind. These overlooked technologies also have the potential to offer substantial benefits that should not be disregarded.
- To further improve the accuracy of decision-making processes, future research should delve into the intricate architecture and detailed modeling of CSP-PV-wind hybrid systems. This will enable these systems to achieve optimal output power while effectively minimizing associated costs.
- Engagement with stakeholders should be a top priority, entailing the incorporation of comprehensive and varied feedback from a wide range of sources. This includes local communities, industry stakeholders, policymakers, and other relevant entities. It is essential to ensure that the findings are not only contextually relevant but also practically applicable in real-world scenarios.

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# Appendix A

Table A.1 The decision criteria used in this study

| Climate Criteria | | | Topography Criteria | | | | Accessibility Criteria | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **GHI ($kwh/m^2$)** | Temp (C) | Cloudy days (%) | Slope (%) | Aspect | Landuse | Soil Texture | Grid (km) | Transport (km) | Urban (km) | Water Res. (km) | **Suitability Rating** |
| **< 1300** | > 23 | > 35 | > 10 | Flat | Settlements, water bodies, Forests | Silty Clay | > 15 | > 15 | 20 – 25 | > 15 | 1 |
| **1700 - 1900** | 22 - 23 | 35 | 8 - 10 | N, NE, NW | Cropland and trees | Clay | 10 - 15 | 10 - 15 | 15 - 20 | 10 - 15 | 2 |
| **1900 - 2000** | 21- 22 | 30 | 5 - 8 | E, W | shrubs | Clay-Loam | 5 - 10 | 5 - 10 | 10 - 15 | 5 - 10 | 3 |
| **2000 - 2100** | 20 - 21 | 25 | 2 - 5 | SE, SW | Grass land & Sparse vegetation | Loam | 1 - 5 | 1 - 5 | 5 - 10 | 1 - 5 | 4 |
| **> 2100** | < 20 | < 20 | 0 - 2 | S | Bare land | Sand-Loam | 0.3 - 1 | 0.5 - 1 | 2- 5 | 0.5 - 1 | 5 |

Sources: (Ali et al, 2019;Effat & El-Zeiny, 2022;Ghasemi et al, 2019;Koc et al, 2019; Rekik & El Alimi, 2023)

Table A.2 Experts' Profile

| | **Designation** | **Organization** | **Field of experience** | **Years of experience** |
|---|---|---|---|---|
| **1** | University Professor | l'Ecole Nationale d'Ingénieurs de Tunis (ENIT) | Renewable Energies and Energy Efficiency | 38 |
| **2** | General Director | Solar Energy Department at Agence Nationale pour la Maîtrise de l'Energie ANME | Solar and Wind energy policies | 27 |
| **3** | Senior technical manager of Solar and Wind Farms | STEG (Société Tunisienne de l'Electricité et du Gaz) | Solar and Wind energy | 27 |
| **4** | Senior Engineer | STEG (Société Tunisienne de l'Electricité et du Gaz) | Research and Development | 26 |
| **5** | General Director | Alcor research and consulting firm | PhD, Economist specializing in energy and climate change | 25 |

# Appendix B

Table B.1 Fuzzy inputs and results of the main criteria

| | Aggregated Fuzzy Matrix (Ã) | | | Fuzzy Geometric Mean (r̂) | Defuzzified. weight | Normalized weight |
|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | | | |
| $C_1$ | (1,1,1) | (1.00,1.00, 1.11) | (2.35,2.99,3.59) | (0.41,0.46,0.94) | 0.447 | 0.439 |
| $C_2$ | (0.72,1.00,1.25) | (1,1,1) | (2.00,2.37,2.70) | (0.15,0.22,0.39) | 0.408 | 0.401 |
| $C_3$ | (0.28,0.33, 0.43) | (0.37,0.42, 0.50) | (1,1,1) | (0.09,0.13,0.19) | 0.163 | 0.160 |
| **λmax = 3.028** | | CI = 0.014 | | | CR = 0.024 | |
| **$C_1$ Climate, $C_2$ Accessibility, $C_3$ Topography** | | | | | | |

Table B.2 Fuzzy inputs and results of the climate sub-criteria

| | Aggregated Fuzzy Matrix (Ã) | | | Fuzzy Geometric Mean (r̂) | Defuzzified. weight | Normalized weight |
|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | | | |
| $C_1$ | (1,1,1) | (1.93,3.03,4.08) | (3.56,4.57,5.58) | (0.41,0.46,0.94) | 0.663 | 0.625 |
| $C_2$ | (0.25,0.33,0.51) | (1,1,1) | (1.32,1.78,2.17) | (0.15,0.22,0.39) | 0.257 | 0.242 |
| $C_3$ | (0.18,0.22, 0.28) | (0.46,0.56, 0.76) | (1,1,1) | (0.09,0.13,0.19) | 0.141 | 0.133 |
| **λmax = 3.033** | | CI = 0.017 | | | CR = 0.029 | |

**$C_1$ GHI, $C_2$ Ambient temperatures, $C_3$ Average cloudy days**

Table B.3 Fuzzy inputs and results of the topography sub-criteria

| | Aggregated Fuzzy Matrix (Ã) | | | | Fuzzy Geometric Mean (r̂) | Defuzzified. weight | Normalized weight |
|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | C4 | | | |
| $C_1$ | (1,1,1) | (1.95,3.04,4.05) | (3.58,4.55,5.57) | (4.51,5.53,6.54) | (0.35,0.55,0.80) | 0.665 | 0.535 |
| $C_2$ | (0.25,0.33,0.51) | (1,1,1) | (1.32,1.78,2.15) | (3.76,4.82,5.85 | (0.16,0.24,0.41) | 0.268 | 0.253 |
| $C_3$ | (0.17,0.19,0.26) | (0.45,0.54,0.74) | (1,1,1) | (3.10,4.26,5.34) | (0.11,0.16,0.24) | 0.166 | 0.157 |
| C4 | (0.15,0.18,0.22) | (0.17,.21,0.27) | (0.19,0.24,0.33) | (1,1,1) | (0.04,0.06,0.09) | 0.061 | 0.057 |
| **λmax = 4.219** | | | CI = 0.073 | | CR = 0.081 | | |
| **$C_1$ Slope, $C_2$ Aspect, $C_3$ Land use, $C_4$ Soil Texture** | | | | | | | |

Table B.4 Fuzzy inputs and results of the accessibility sub-criteria

| | Aggregated Fuzzy Matrix (Ã) | | | | Fuzzy Geometric Mean (r̂) | Defuzzified. weight | Normalized weight |
|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | C4 | | | |
| $C_1$ | (1,1,1) | (3.10,4.26,5.34) | (1.52,2.27,2.93) | (1.40,2.10,3.03) | (0.24,0.39,0.60) | 0.410 | 0.446 |
| $C_2$ | (0.19,0.24,0.34) | (1,1,1) | (1.25,1.74,2.13) | (0.24,0.32,0.80 | (0.07,0.11,0.20) | 0.127 | 0.139 |
| $C_3$ | (0.34,0.44,0.66) | (0.47,0.57,0.80) | (1,1,1) | (0.37,0.42,0.50) | (0.07,0.11,0.16) | 0.114 | 0.124 |
| C4 | (0.33,0.48,0.72) | (2.05,3.17,4.23) | (2.00,2.37,2.71) | (1,1,1) | (016,0.25,0.39) | 0.267 | 0.291 |
| **λmax = 4.145** | | | CI = 0.048 | | CR = 0.054 | | |
| **$C_1$ Proximity to grid, $C_2$ Proximity to main roads, $C_3$ Proximity to urban areas, $C_4$ Proximity to water resources** | | | | | | | |

## Appendix C

Table C. 1 Solar PV, Solar CSP, and onshore wind site selection decision criteria

| Main factor | Decision Criteria | Attribute Values | Suitability Rate |
|---|---|---|---|
| Climate | GHI (kWh/m$^2$/year) | < 1477 | 1 |
| | | 1478 - 1799 | 2 |
| | | 1800 - 1899 | 3 |
| | | 1900 - 1999 | 4 |
| | | > 2000 | 5 |
| | DNI (kWh/m$^2$/year) | < 1799 | 1 |
| | | 1800 - 1899 | 2 |
| | | 1900 - 1999 | 3 |
| | | 2000 - 2099 | 4 |
| | | > 2100 | 5 |
| | Wind Speed (m/s) | < 4.99 | 1 |
| | | 5 – 5.99 | 2 |
| | | 6 – 6.99 | 3 |
| | | 7 – 7.99 | 4 |
| | | > 8 | 5 |
| | Temperature (C˚) | > 23 | 1 |
| | | 22 – 22.99 | 2 |
| | | 21 – 21.99 | 3 |
| | | 20 – 20.99 | 4 |
| | | < 19.99 | 5 |
| Topography | Slope (degree) | > 10 | 1 |
| | | 8 - 10 | 2 |
| | | 5 - 8 | 3 |
| | | 2 - 5 | 4 |
| | | < 2 | 5 |
| | Aspect | Flat | 1 |
| | | N, NE, NW | 2 |
| | | E, W | 3 |
| | | SE, SW | 4 |
| | | S | 5 |
| Accessibility | proximity to major Roads (km) | > 15 | 1 |
| | | 10 - 15 | 2 |
| | | 5 - 10 | 3 |
| | | 1 - 5 | 4 |
| | | 0.5 - 1 | 5 |
| | Proximity to Power lines (km) | > 15 | 1 |
| | | 10 - 15 | 2 |
| | | 5 - 10 | 3 |
| | | 1 - 5 | 4 |
| | | 0.3 - 1 | 5 |
| | Proximity to Residential Areas (km) | 20 – 25 | 1 |
| | | 15 - 20 | 2 |
| | | 10 - 15 | 3 |
| | | 5 - 10 | 4 |
| | | 2- 5 | 5 |
| Environment | Land use | Built-up, Water bodies, Forests, etc. | 1 |
| | | Cropland | 2 |
| | | Shrubland | 3 |
| | | Sparse Vegetation | 4 |
| | | Bare Lands | 5 |
| | Proximity to water resources (km) | > 15 | 1 |
| | | 10 - 15 | 2 |
| | | 5 - 10 | 3 |
| | | 1 - 5 | 4 |
| | | 0.5 - 1 | 5 |

# Appendix D

Table D.1 CRITIC/EDAS input data

| | Criteria | Unit | Solar PV | Solar CSP | Onshore wind | Biomass |
|---|---|---|---|---|---|---|
| Benefit | Technical Maturity | - | 4.00 | 3.00 | 5.00 | 4.00 |
| | Efficiency | % | 20.00 | 21.00 | 35.00 | 25.00 |
| | Resources | kWh/m$^2$/year | 1800.00 | 2000.00 | 570.00 | 200.00 |
| | Job creation | Total job-years/GWh | 0.87 | 0.23 | 0.17 | 0.21 |
| Cost | Investment Cost | USD/kW | 800.00 | 4700.00 | 1300.00 | 1250.00 |
| | O&M Cost | USD/kW/year | 20.00 | 141.00 | 39.00 | 62.50 |
| | Energy Cost | USD/kWh | 0.05 | 0.11 | 0.03 | 0.07 |
| | Landuse | m$^2$/kW | 35.00 | 40.00 | 100.00 | 5000.00 |
| | GHG emissions | g/kWh | 49.61 | 16.11 | 30.14 | 162.15 |
| | Water use | kg/kWh | 1.00 | 3.02 | 0.00 | 135.00 |

Table D.2 Matrices of expert comparisons in pairs of indicators

| Exp: 1 | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $I_6$ | $I_7$ | $I_8$ | $I_9$ | $I_{10}$ | $I_{11}$ | $I_{12}$ | $I_{13}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 0 | 1 | 2 | 4 | 3 | 1 | 1 | 2 | 1 | 3 | 4 | 2 | 4 |
| $I_2$ | 2 | 0 | 3 | 4 | 3 | 1 | 4 | 0 | 3 | 2 | 1 | 4 | 1 |
| $I_3$ | 1 | 3 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 3 | 0 | 0 | 2 |
| $I_4$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 3 | 1 |
| $I_5$ | 3 | 3 | 2 | 1 | 0 | 1 | 3 | 1 | 2 | 4 | 3 | 2 | 3 |
| $I_6$ | 4 | 4 | 4 | 0 | 3 | 0 | 3 | 4 | 0 | 2 | 4 | 1 | 2 |
| $I_7$ | 4 | 3 | 1 | 1 | 2 | 1 | 0 | 3 | 3 | 4 | 1 | 4 | 1 |
| $I_8$ | 1 | 3 | 2 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| $I_9$ | 1 | 0 | 0 | 2 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 1 |
| $I_{10}$ | 2 | 3 | 2 | 4 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| $I_{11}$ | 2 | 1 | 1 | 2 | 0 | 0 | 3 | 0 | 4 | 3 | 0 | 2 | 3 |
| $I_{12}$ | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| $I_{13}$ | 2 | 2 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| Exp: 2 | | | | | | | | | | | | | |
| $I_1$ | 0 | 0 | 2 | 4 | 4 | 4 | 1 | 1 | 3 | 3 | 2 | 3 | 1 |
| $I_2$ | 2 | 0 | 3 | 4 | 4 | 2 | 1 | 2 | 4 | 1 | 1 | 4 | 1 |
| $I_3$ | 0 | 1 | 0 | 3 | 0 | 1 | 2 | 1 | 0 | 3 | 0 | 0 | 1 |
| $I_4$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 1 | 2 | 0 |
| $I_5$ | 3 | 3 | 1 | 1 | 0 | 2 | 3 | 3 | 1 | 4 | 4 | 1 | 3 |
| $I_6$ | 1 | 4 | 3 | 0 | 3 | 0 | 4 | 3 | 2 | 4 | 3 | 2 | 3 |
| $I_7$ | 4 | 3 | 0 | 3 | 3 | 1 | 0 | 2 | 2 | 3 | 1 | 4 | 0 |
| $I_8$ | 2 | 3 | 1 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| $I_9$ | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 1 |
| $I_{10}$ | 2 | 1 | 0 | 4 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| $I_{11}$ | 0 | 0 | 1 | 2 | 0 | 0 | 2 | 3 | 3 | 2 | 0 | 2 | 3 |
| $I_{12}$ | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| $I_{13}$ | 3 | 1 | 2 | 2 | 1 | 0 | 0 | 1 | 0 | 3 | 0 | 0 | 0 |
| Exp: 3 | | | | | | | | | | | | | |
| $I_1$ | 0 | 2 | 4 | 3 | 4 | 2 | 1 | 1 | 0 | 4 | 4 | 1 | 3 |
| $I_2$ | 1 | 0 | 2 | 1 | 0 | 1 | 4 | 2 | 4 | 1 | 3 | 3 | 2 |
| $I_3$ | 0 | 2 | 0 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 0 | 0 | 2 |
| $I_4$ | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 2 | 0 |
| $I_5$ | 2 | 2 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 3 | 4 | 1 | 2 |
| $I_6$ | 4 | 2 | 3 | 1 | 2 | 0 | 4 | 4 | 2 | 2 | 4 | 1 | 2 |
| $I_7$ | 1 | 1 | 0 | 1 | 0 | 2 | 0 | 3 | 3 | 4 | 2 | 3 | 1 |
| $I_8$ | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| $I_9$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $I_{10}$ | 0 | 1 | 2 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 |
| $I_{11}$ | 2 | 0 | 1 | 3 | 0 | 0 | 3 | 3 | 4 | 3 | 0 | 1 | 1 |
| $I_{12}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| $I_{13}$ | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |

Table D.3 DEMATEL initial aggregated matrix

| | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $I_6$ | $I_7$ | $I_8$ | $I_9$ | $I_{10}$ | $I_{11}$ | $I_{12}$ | $I_{13}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 0.00 | 1.00 | 2.67 | 3.67 | 3.67 | 2.33 | 1.00 | 1.33 | 1.33 | 3.33 | 3.33 | 2.00 | 2.67 |
| $I_2$ | 1.67 | 0.00 | 2.67 | 3.00 | 2.33 | 1.33 | 3.67 | 1.33 | 3.67 | 1.33 | 1.67 | 3.67 | 1.33 |
| $I_3$ | 0.33 | 2.00 | 0.00 | 2.00 | 0.00 | 1.67 | 1.00 | 1.33 | 0.00 | 2.33 | 0.00 | 0.00 | 1.67 |
| $I_4$ | 1.33 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.67 | 0.67 | 1.67 | 1.33 | 2.67 | 0.33 |
| $I_5$ | 2.67 | 2.67 | 1.33 | 1.33 | 0.00 | 1.33 | 2.67 | 1.33 | 1.33 | 3.67 | 3.67 | 1.33 | 2.67 |
| $I_6$ | 3.67 | 3.33 | 3.33 | 0.33 | 2.67 | 0.00 | 3.67 | 3.67 | 1.33 | 2.67 | 3.67 | 1.33 | 2.33 |
| $I_7$ | 3.67 | 2.33 | 0.33 | 1.67 | 1.67 | 1.33 | 0.00 | 2.67 | 1.67 | 3.67 | 1.33 | 3.67 | 0.67 |
| $I_8$ | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| $I_9$ | 0.33 | 0.00 | 0.00 | 1.33 | 0.00 | 0.67 | 0.00 | 1.33 | 0.00 | 0.00 | 0.00 | 0.00 | 0.67 |
| $I_{10}$ | 1.33 | 1.67 | 1.33 | 3.67 | 1.33 | 0.00 | 0.67 | 0.67 | 0.67 | 0.00 | 0.67 | 0.33 | 0.00 |
| $I_{11}$ | 1.33 | 0.33 | 1.00 | 2.33 | 0.00 | 0.00 | 2.67 | 2.00 | 3.67 | 2.67 | 0.00 | 1.67 | 2.33 |
| $I_{12}$ | 0.67 | 0.00 | 0.00 | 0.30 | 0.33 | 0.00 | 0.00 | 1.67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.33 |
| $I_{13}$ | 2.33 | 1.33 | 0.67 | 1.33 | 0.33 | 0.00 | 0.00 | 0.67 | 0.00 | 1.67 | 0.00 | 0.67 | 0.00 |