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Site Selection for Sustainable Wind-Solar Hybrid Energy Harvesting Plant

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Abstract

The world's energy landscape is undergoing rapid transformation as societies strive towards renewable and sustainable power sources in response to the need for energy security and climate change. Depletion of fossil fuels and increasing focus on environmental sustainability have been significant drivers in this global shift towards renewables. Among the promising solutions, solar-wind hybrid energy systems have gained attention, capitalizing on the complementary nature of solar and wind resources. However, selecting the optimal site for these hybrid plants is crucial for their successful implementation and efficiency. This research introduces a comprehensive methodology for site selection, seamlessly integrating the Delphi method and Analytic Hierarchy Process (AHP). The Delphi method harnesses expert consensus to distil essential criteria, while AHP offers a structured framework to evaluate and prioritize these criteria. The results showed successful utilization of the AHP and Delphi techniques for evaluating the optimal location selection among different cities for solar-wind hybrid energy harnessing in the northwest region of Pakistan. The key factors for selection of optimal location were identified through expert feedback and analysis. Among the selected key main criteria, resource availability and infrastructure and socio-economic factors emerged as the top-ranked criteria in this study. The results of this study hold significant relevance and should be duly considered for solar-wind power project site selection, while also offering opportunities for further enhancements in the future.

Keywords: *Multi Criteria Decision Making, Site Selection, Renewable Energy, Analytic Hierarchy Process, Delphi method*

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1. Introduction

The energy landscape at a global scale is experiencing a notable shift, driven by the growing awareness and recognition of transition towards sustainable and renewable energy sources. This transformation is being embraced by societies worldwide, reflecting a collective understanding of the pressing need to address environmental concerns and ensure a more sustainable future. The depletion of fossil fuels, growing environmental concerns, and the increasing need for energy security have prompted a global transition towards cleaner and more sustainable energy alternatives (World Energy Outlook, 2020). Renewable Energy (RE) resources, including solar and wind energy, have gained remarkable attention due to their abundance, scalability, and minimal environmental impact (Renewable Capacity Statistics, 2021).

As of 30 June 2022, Pakistan's power generation capacity stands at 43,775 MW, comprising various sources. The overall power capacity is derived from various sources. Thermal power contributes 26,683 MW, hydroelectric power provides 10,635 MW, wind power contributes 1,838 MW, solar power stands at 630 MW, bagasse power contributes 369 MW, and nuclear power provides 3,620 MW (List of power stations in Pakistan, n.d.). These various sources contribute significantly to the country's electricity generation and act as a vital role in fulfilling power requirements. However, Pakistan possesses significant potential in RE sources that can help encounter its requirements of growing energy.

In Pakistan, where solar and wind energy exhibit complementary patterns in terms of time and region, the careful assessment of the most optimal locations for wind-solar hybrid energy harnessing becomes imperative. While solar and wind power offer numerous advantages individually, combining these two technologies in a hybrid system can provide enhanced energy generation and improved reliability (Vasant & Pawar, 2017). Specifically, in the north Punjab region, the monsoon climate leads to strong winter winds and low solar radiation intensity, while summers have weaker winds and high solar radiation intensity. The synergistic relationship between solar and wind resources presents an opportunity to maximize energy output and potential of these sources can be effectively harnessed.

However, the efficient output of solar-wind hybrid energy plants heavily depends on the selection of an optimal site. Although there are existing methods as employed by Asadi et al. (2023) for site selection in renewable energy projects, limited studies have focused specifically on the combination of Analytic Hierarchy Process (AHP) technique along with Delphi method for solar-wind hybrid energy projects. Hence, this research aims to utilize a framework by combination of Delphi and AHP in the context of site selection of hybrid energy harnessing. According to Solangi et al. (2019) and Marttunen et al. (2017), problem arises from the need to consider multiple criteria, expert opinions, and prioritize them effectively to identify optimal sites among different required sites in Pakistan that maximize energy production, minimize costs, and ensure long-term viability and sustainability. In this case, the integration of Delphi and AHP has promising potential.

The Delphi method is an approach utilized in qualitative research, where consensus is sought from experts group through a multiple questionnaires and iterative feedback rounds (Linstone, 1975). It facilitates the identification of essential criteria and the consolidation of expert perspectives, offering valuable insights into intricate issues. On the other hand, the AHP method is a systematic decision making process developed by Saaty in 1980. It is a technique utilized for making decisions by facilitating the systematic evaluation and prioritization of criteria through weightage gain from judgment of experts and finally prioritize/rank the different decision alternatives (Brunelli, 2014).

While previous research has extensively examined the site selection for renewable energy projects (i.e. Tafula et al., 2023; Khazael & Al-Bakri, 2021; Kocabaldır & Yücel, 2020; Wissing, 2013; Goh et al., 2022; Spyridonidou & Vagiona, 2023; Deveci et al., 2021; Hosseinzadeh et al., 2023; Soydan, 2021), there remains a notable gap in the literature concerning location selection for solar-wind hybrid energy projects using the Delphi approach and AHP methods. To address this gap, this study aims to develop a comprehensive approach by conducting a literature review to identify critical factors for site selection. Expert opinions were gathered through the Delphi method to refine and assess the importance and weightage of the obtained criteria/factors through literature review. By utilizing these criteria obtained from expert consensus into the structured decision-making technique of AHP, this research intends to create a robust framework for location selection among different cities in the northwest Punjab region of Pakistan, including Rawalpindi, Islamabad, Taxila, Wah Cantt, and Khanpur, facilitating informed decision-making and promoting the development of sustainable solar-wind hybrid energy harvesting plants. These locations are highlighted in figure 1.

Figure 1

Cities/Alternatives for Present Study

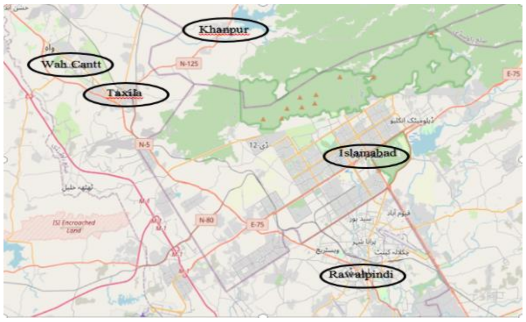


Table 1

Positional Coordinates of Alternative Cities

Name of city	Longitude	Latitude
Islamabad	73.043 E	33.721 N
Taxila	72.785 E	33.740 N
Wah Cantt	72.751 E	33.771 N
Rawalpindi	73.071 E	33.626 N
Khanpur	70.656 E	28.647 N

2. Literature Review

2.1. Assessment of Criteria and sub-Criteria for Site Selection

Many countries endowed with substantial solar and wind power source actively pursuing the development of this environment friendly and pollutant-free energy source. Methods of multi criteria decision making (MCDM) have become progressively common in the energy sector for various applications, including site selection, environmental management, and equipment assessment and evaluating projects, and these techniques have been applied to various decision problems, including site selection. For instance, Acar et al. (2003) employed decision-making techniques to evaluate potential landfill sites for solid waste. Similarly, Heo et al. (2010) utilized the Fuzzy AHP technique to evaluate the effectiveness of RE distribution program. Meanwhile, Cavallaro (2010) applied Fuzzy TOPSIS to compare and prioritize different storage options of thermal energy related to systems of solar potential and Lee et al. (2012) applied Fuzzy Analytic Network Process (fuzzy ANP) to assess wind turbines by considering multiple criteria. In a recent study by Kollati and Debnath (2021), the techniques employed for site selection over the past few decades were systematically examined, providing a comprehensive analysis that has been widely utilized by the scientific community and policymakers.

Various academic researchers have focused on the selection of location for solar-wind hybrid energy harnessing. For example, Aydin et al. (2013) utilized fuzzy decision approach along with GIS to identify the most appropriate location for wind-solar hybrid energy harnessing. Yunna and Geng (2014) formulated a decision framework using AHP to prioritize optimal places for wind-solar hybrid potential harnessing. On the other hand, on the framework assigns priorities to alternatives based on their suitability, Yun-na et al. (2013) employed the ideal matter-factor model and ELECTRE II method to find the optimal macro-site for hybrid energy harnessing. When Lee et al. (2009) utilized AHP to examine the costs, risks, opportunities, and benefits of wind solar-PV systems, they suggested different criteria and an integrated process for evaluating power system projects. Hence, several studies used various techniques, methods, approach and process. For example, Van Haaren and Fthenakis (2011) investigated the selection process of sites for farms of wind using Spatial MCDM examination, Wanderer and Herle (2015) created a spatial decision support system in Spain, which was web based and utilized a multi criteria analysis approach, Tahri et al. (2015) integrated GIS and MCDM methods to evaluate appropriateness of different sites for renewable energy projects in Morocco, Brewer et al. (2015) employed MCDM analysis approach based on GIS in state of Idaho, USA to find economically viable and socially acceptable area for solar projects, Dawod and Mandoer (2016) conducted a study in Egypt to find optimal locations for solar energy plant, employing a multi criteria scheme based on GIS and Latinopoulos and Kechagia (2015) utilized a multi criteria assessment approach with GIS to get optimal locations for installing wind projects in Greece.

The previous studies also considered various factors, including economic, technological social, and environmental aspects in the site selection. For instance, Azizi et al. (2014) took into account technical, ecological and financial factors during the process of selecting sites for wind energy project. While Gigović et al. (2017) identified eleven criteria for the assessment of appropriate sites in Serbia such as distance from telecommunication infrastructure, land use, land slope, wind speed, population density, approach from power lines, approach from roads, land aspects, nearby tourist facilities, distance from protected areas and proximity to urban areas, Ali et al. (2018) only recognized six primary criteria including wind speed/density, conveyance cost, nearness to power station, and population bulk. Other authors identified various factors such as appropriateness of land considering multiple aspects such as wind potential, proximity to roads, energy demand historical sites natural features and slope (Al-Yahyai et al., 2012), technical, environmental, financial, community criteria, visual impact, wind resources, proximity to the power station, land value and land cover (Tegou et al., 2010), financial, technical, ecological, and topographical factors (Noorollahi et al., 2016), land cover/use, approach from main communication distance, slope, grid access, wind speed average and orientation aspect (Pamučar et al., 2017) and security and quality, financial, policy, environment and ecosystem, and social impression (Yeh & Huang, 2014). Other studies considered the various factors while integrating other techniques. For instance, Baloch et al. (2019) put forward a proposal for generating off-grid energy from six wind places located in Pakistan, Wątróbski et al. (2015) conducted a feasibility study for selection of farms site for wind project located in Szczecin city, Poland using AHP and PROMETHEE, Wu et al. (2016) worked on decision process in which selection of location is carried out for offshore wind by utilizing ELECTRE III, and Sánchez-Lozano et al. (2016) joint fuzzy methods from different MCDM approaches in order to dealt with problem in making decision for selection of location for building wind project onshore. The various factors generated from the literature are summarized in table 2.

Table 2

List of Criteria & sub-Criteria Obtained from literature

No.	Criteria	Sub Criteria
1.	Resource Availability	Average wind speed
2.		Average Wind turbulence
3.		Wind patterns and variability
4.		Solar irradiance levels
5.		Annual Sunshine Duration
6.		Shading Analysis
7.	Environmental factors	Area of Flat Land & Without protected areas
8.		Threatened or endangered species
9.		Bird migration patterns
10.		Impact on Biodiversity and Habitat Preservation
11.		Noise and visual impact
12.		Distance to residential areas
13.		Noise restrictions and regulations
14.		Scenic or protected views
15.	Infrastructure & Connectivity	Access to power grid
16.		Population Density
17.		Communication Network Coverage
18.		Roads Accessibility
19.		Road conditions and suitability
20.		Water availability
21.	Land Characteristics	Size and Acquisition of the avail land
22.		Land use restrictions/zoning regs.
23.		Topography and elevation
24.		Suitability for wind/solar
25.		Soil conditions and stability
26.	Climatic Conditions	Risk of hurricanes, tornadoes, etc.
27.		Lightning frequency and intensity
28.		Temperature range and variation
29.		Cooling requirements for solar panels
30.	Socio-Economic Factors	Cost of land
31.		Operation and maintenance expenses
32.		Public Acceptance & Job Creation
33.		Energy production demand
34.		- Renewable energy targets and subsidies

2.2. Renewable Energy resources in Pakistan

The Islamic Republic of Pakistan is situated in South Asia. The country is gifted with sufficient amount of RE resources. These resources comprise wind, hydro, geothermal, biomass and solar energy. These sources offer substantial potential for generating electricity. Though the adoption and utilization of these sources have been sluggish in Pakistan, presently, they contribute only a minor portion to the country's total energy. In line with the RE Strategy of 2006, Pakistan has set an ambitious goal of incorporating 10,000 MW of power generated using renewable sources into its energy portfolio by the year 2030 (Farooqui, 2014). Nevertheless, the actual estimated potential of renewable energy far exceeds this figure. With the ever-increasing energy demand, it is crucial to harness the maximum potential of renewable energy sources. Table 3 presents a comprehensive overview of the estimated capacity of these renewable energy sources and the existing energy generation potential derived from these sources in Pakistan.

Table 3

The assessment of renewable energy potential and installed capacity across different sources in Pakistan

Renewable Source	Potential	Installed
Solar	2,90,000 MW	200
Wind	346,000 MW	308

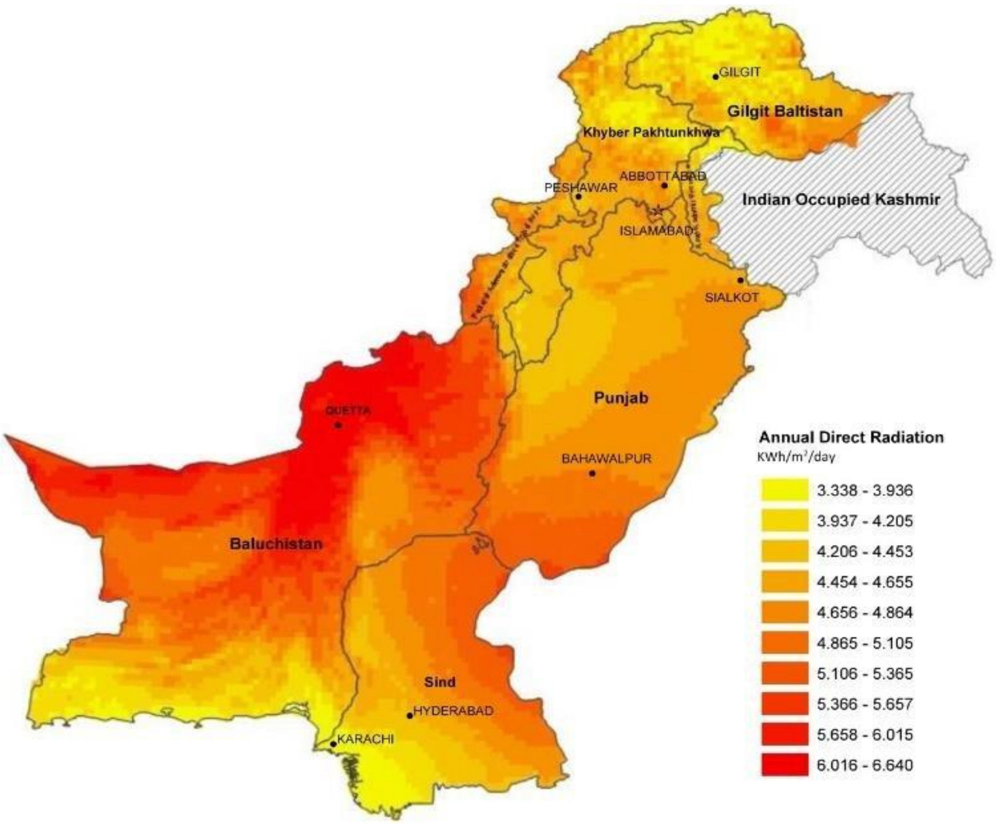
Source: (Shaikh, Ji, & Fan, 2015) (Zafar, Ur Rashid, Khosa, Khalil, & Rahid, 2018)

Solar Resource. Pakistan is rapidly evolving annually, increasing the requirement of energy demand. This necessitates exploration of alternative energy sources. Among these alternatives, solar power stands out as a promising option due to its distributed nature and holds great potential to address this energy shortage. The country is fortunate to receive ample sunlight throughout the year, making solar energy a viable and abundant renewable resource that can help address the prevailing energy shortage across the nation (Rauf et al., 2015). The country possesses a remarkable solar energy providing a significant opportunity to fulfill the nation's energy demand. However, despite having abundant solar potential, Pakistan has not fully utilized its capacity for solar power plant development.

Pakistan has a rich solar energy resource, with over 300 sunlight days and an average annual radiation of 1800-2200 kWh/m2 and average temperature of 26-28°C. This translates to a solar energy potential of 5.5-6 kilowatt hour per sq meter in one day (Wakeel et al., 2016) as shown in figure 2. Pakistan possesses solar energy capacity estimated to exceed 50,000 MW, with over 2500 hours of annual sunlight availability. Baluchistan and Sindh, in particular, have excellent potential for solar energy projects, receiving 7-8 hours of sunlight per day, approximately 2300-2700 hours annually (Rauf et al., 2015).

Figure 2

Average solar radiation distribution of Pakistan



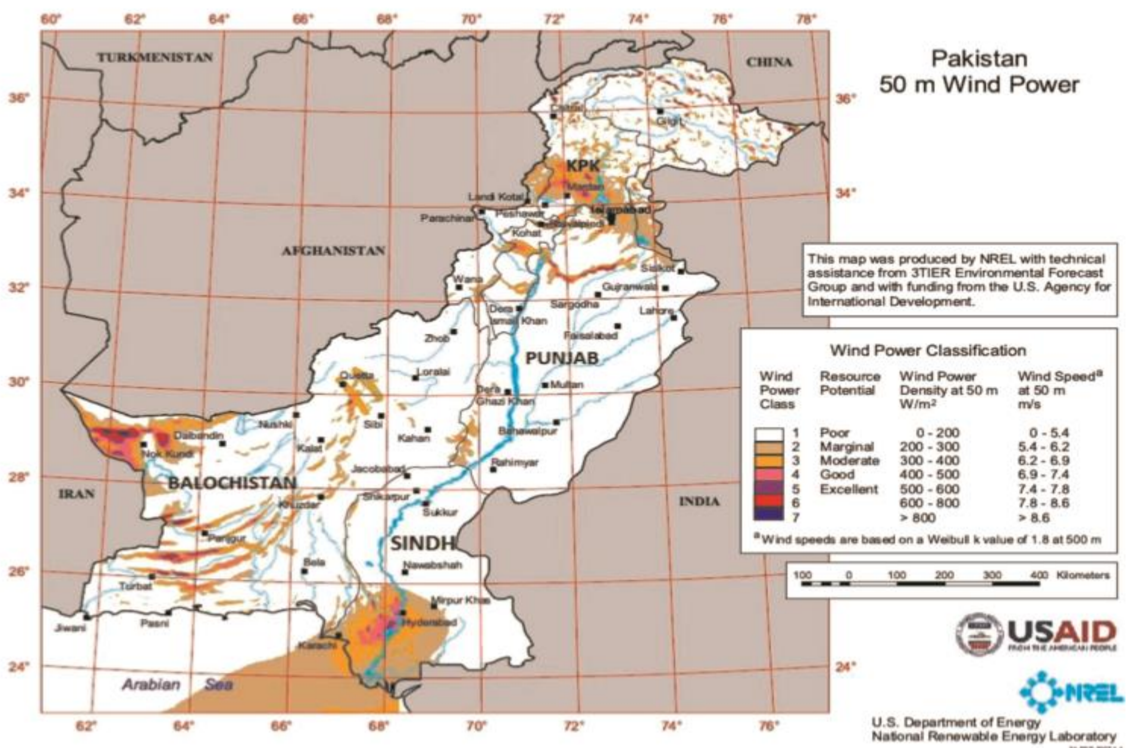
Source: NREL.PakistanResourceMapsandToolkit, 2017

Despite the favorable geographical conditions, the progress in developing renewable energy resources, particularly solar potential for energy generation, is still in its infancy in Pakistan, primarily due to the absence of government attention and obligation (Cantarero, 2020). However, individual efforts by electricity customers such as individual photovoltaic units ranging from 100-500 Watt, have been observed. Yet, these efforts face challenges related to operational maintenance, availability of spare parts, and sustainability. Based on predictions, approximately 40,000 towns in Pakistan have the potential to be electrified by leveraging the annual average sunlight of 8-8.5 hrs/day (Abdullah et al., 2017)

Wind Energy Resource. In recent years, significant progress and development across various sectors have resulted in an increased reliance on technology, leading to a growing demand for energy and power generation in Pakistan. At present, conventional methods like, fossil fuels, coal and oil largely dominate the country's energy generation. However, as these finite resources are depleting, it becomes imperative to explore and adopt alternative energy sources to ensure a sustainable and secure energy future for Pakistan (Ullah et al., 2020).

Figure 3

Integrated Delphi-AHP Decision framework



Source: PakistanResourceMapsandToolkit—NREL, 2017

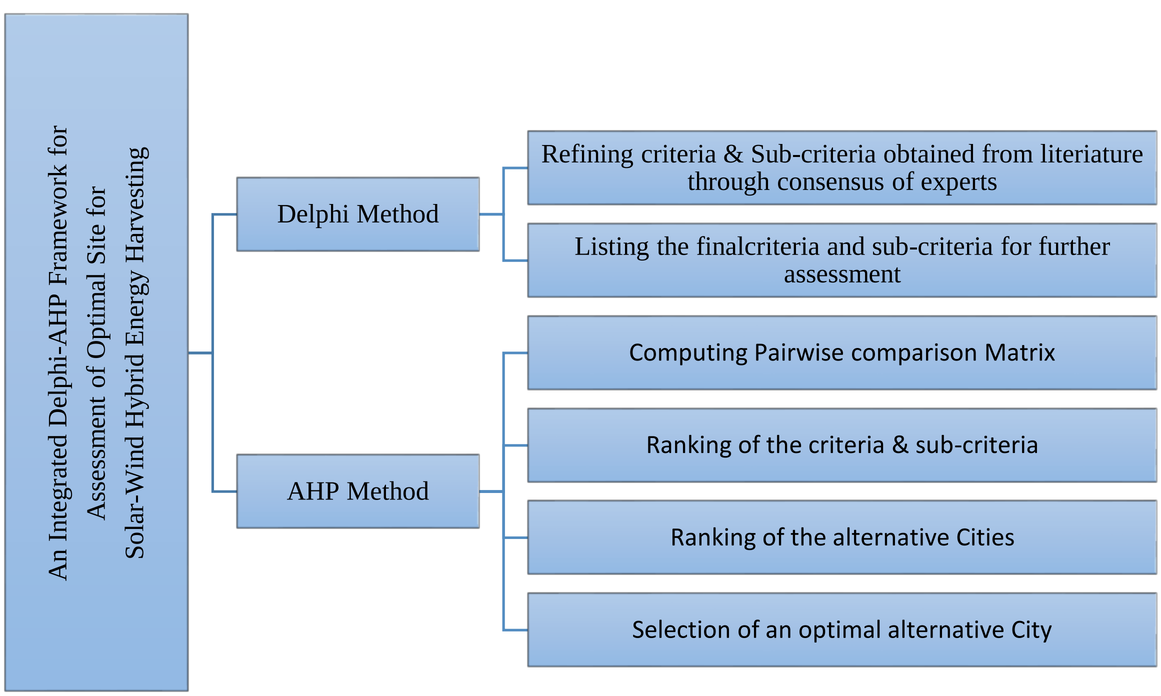
Pakistan possesses a substantial wind energy potential that can be harnessed for electricity generation. As early as 2003, wind projects with unit capacities ranging from 150 to 100 Mega Watts were established in the wind corridor of Sindh province. These projects collectively contributed to a cumulative capacity of 500 MW (Sheikh, 2010). The Renewable Energy Council of Pakistan (PCRET) built 26 wind projects, with a capability of 500W individually, in town named Gul Muhammad, marking Pakistan's first village that is wind power-electrified. The country is estimated to have the capacity to produce nearly 346,000 Mega Watt of power from wind (Solangi et al., 2018). Though the first wind energy harnessing project became operational in 2013 in Pakistan, a study indicated a significant wind energy source in the southern areas of province Baluchistan and Sindh estimated to be around 50,000 MW, while the Punjab province was estimated to carry a wind energy potential of 1000-1500 Mega Watt. The Pakistan Meteorological Department conducted measurements of speed of wind in the Baluchistan and Sindh coastal areas and identified steady wind speeds of 5-7 metre /second (Wind Energy Project, 2017). In particular, the Gharo and Keti Bandar regions in Sindh shown excellent wind potential for large-scale wind farm projects, an average wind velocity is recorded around 6.86 m/s. These figures indicate the area's economic feasibility and its suitability for wind energy harnessing. The capacity of wind energy in Pakistan is illustrated in Figure 3.

3. Methodology

The research methodology is the backbone of any study, guiding the entire process of data collection and analysis. The research begins by extensive review of existing literature to gain insights of previous studies and collection of criteria and sub-criteria related to the problem. Integrated Delphi-AHP Decision framework is presented in figure 4.

Figure 4

Integrated Delphi-AHP Decision framework



The Delphi technique is employed to assess and refine key criteria and sub-criteria that influence site selection decisions. The research focuses on case studies of five cities in the northwest region of Pakistan, namely Islamabad, Taxila, Rawalpindi, Khanpur, and Wah Cantt. The AHP is then employed and through pairwise comparisons, the weights of the criteria are obtained, providing a rational and transparent basis for the final evaluation and incorporates sensitivity analysis to explore any potential changes due to variations in criteria weights.

3.1 Delphi Method

This method is implemented to facilitate gathering of expert opinions, consensus building, and refinement of criteria and their importance. The process involves iterations, enabling the gradual convergence of opinions and the refinement of decision criteria. In this study, a panel of 8 professionals was engaged, including specialists from renewable energy field and industries and academia. However, the participation rate for the study survey was limited as only 5 experts consented to participate in the research.

Experts were presented with the list of criteria obtained through literature review. They ranked each criterion on a numerical scale based on their importance, considering their expertise and knowledge. The ratings provided by the experts is collected and examined to get the priority ranking of each factor.

Delphi method focus on achieving consensus among the expert panel regarding the final set of criteria and their relative importance. Feedback from the experts is shared with each other to facilitate the convergence of opinions. A feedback report summarizing the group's ratings, the range of opinions, and any points of disagreement is provided to the experts. They were given the opportunity to revise their ratings based on the feedback and engage in a structured discussion to address any divergent viewpoints. The process continues until a consensus is reached, indicating a high level of agreement among the experts regarding the final set of criteria and their priorities.

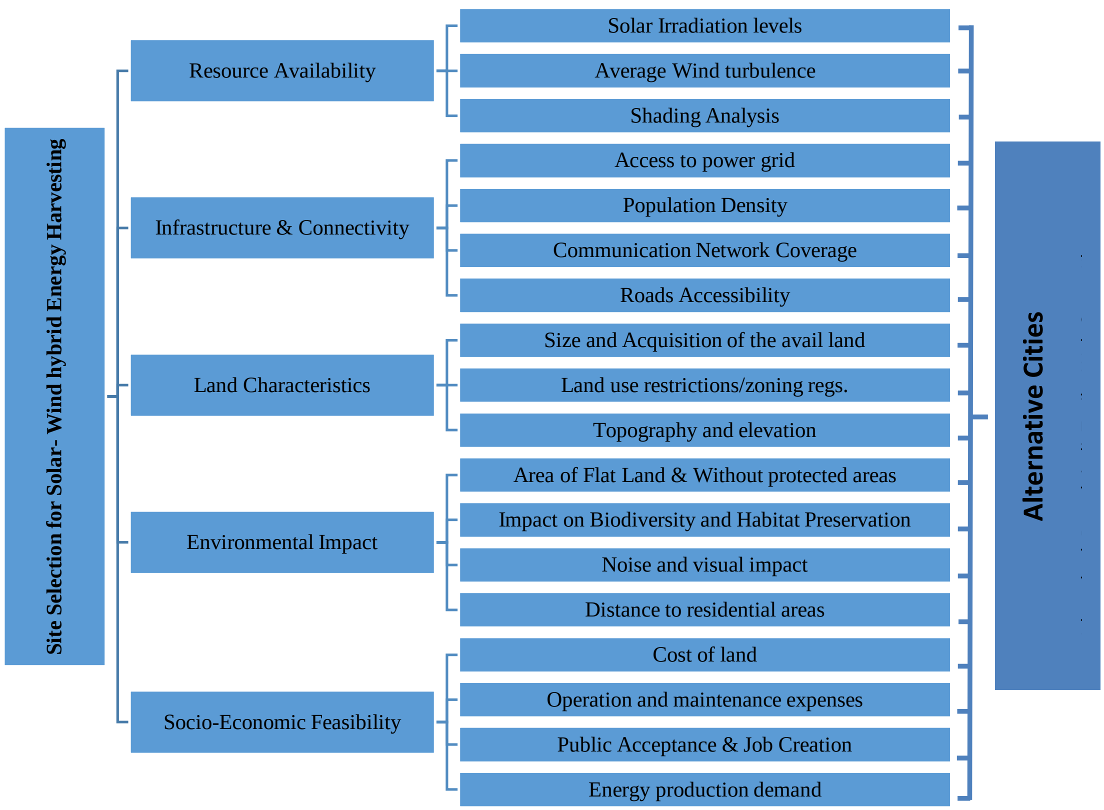
3.2 Analytic Hierarchy Process (AHP)

MCDM method is an effective tool in decision problems. One of the widely used MCDM technique pioneered in 1970s by Thomas L. Saaty is AHP. It offers a systematic and structured approach to tackle intricate decision-making challenges by decomposing them into manageable sub-problems. AHP involves pairwise comparisons of criteria and alternatives to determine numerical priority weights, which are then used to calculate overall priorities. The AHP process consists of several steps:

Hierarchical Structure: Hierarchy formation is the first step of this technique which consist of a structure containing criteria linked with their sub-criteria for achieving goal. Decision-makers then brainstorm and organize these elements in descending form to form a hierarchy as shown in Figure 5.

Figure 5

Derived Hierarchy



Pairwise Comparisons: After establishing the hierarchy, decision-makers make pairwise comparisons matrix (table 4) based on judgements of experts between elements using scale (table 5) to express the relative significance of one factor over another. The comparisons are done for elements at the lower levels with respect to elements at the higher levels.

Calculation of Priority Weights: The comparative weightage is derived for every level in the hierarchy through pairwise judgments. The number of matrices needed is determined by the quantity of elements at every level. The maximum eigenvalue and global weights of each matrix are calculated.

Table 4

Pair wise Comparison matrix

	Criteria x	Criteria y
Criteria x	1	Rating point
Criteria y	1/Rating point	1

Table 5

Saaty Rating Scale

Rating Values	Definition (Comparing factor X to Y)
1	X Equally important to Y
3	X Moderately important to Y
5	X Strongly important to Y
7	X Very Strongly important to Y
9	X Extremely important to Y
2,4,6,8	Middle values

Synthesis: In the synthesis, the values from the obtained matrix are summed and normalized. The mean of the values in rows of this matrix is computed to obtain the relative priorities of elements.

Consistency Check: Decision-makers' consistency is crucial in the obtained responses of experts. The reliability of judgments is ensured using Consistency Ratio (CR) which can be obtained by taking ratio of Consistency and random Index (CI & RI), Consistency is considered satisfactory if this value is less than 10%.

Consistency index can be calculated by Formula mentioned below using Eigen value.

$$\text{Consistency Index} = \frac{\lambda\text{max} - 1}{n - 1}$$

The consistency ratio is computed using Equation.

$$Consistency\ Ratio = \frac{Consistency\ Index}{Random\ Index}$$

Overall Priority and Ranking*:* The overall priority for ranking alternatives is developed using composite weights derived from the relative weights of elements at different levels. A decision support system called "Expert Choice" is based on AHP and designed to facilitate more logical and unbiased decision-making processes. It organizes data in a hierarchical structure and performs computations on pairwise comparisons to help users solve complex problems involving multiple criteria and alternatives.

The questionnaire served as a tool to gather the valuable opinions and judgments of the expert panel. It is carefully structured in the form of pairwise comparison matrix to collect pertinent information regarding site selection criteria, their respective importance, and the decision making process. Participants assigned numerical values representing the relative importance or preference between each pair of criteria. The selection of an expert panel is crucial for obtaining diverse perspectives and domain-specific knowledge. The experts were invited to participate in the study and contribute their insights throughout the Delphi method and AHP analysis. Their involvement ensured a comprehensive and well-informed decision-making process, taking into account multiple viewpoints and expertise. In this study, the experts include professionals based on their experience and expertise from academia, renewable industry, and government departments like council of Pakistan for RE Technologies (PCRET) and local authorities from different sites. There were around 31 pairwise comparison questionnaires filled by these experts to prioritize the cities for solar wind hybrid energy harvesting plant.

The AHP approach is advantageous as it provides a structured framework for evaluating alternatives and enables decision-makers simultaneously examine both qualitative and quantitate data. It is particularly useful when dealing with large numbers of alternatives and selection factors. However, maintaining consistency in judgments can be challenging, and the AHP process involves several steps to ensure the validity of the results. Hence, AHP is a powerful decision-making method used in various domains. By following a structured approach of hierarchical decomposition and pairwise comparisons, AHP helps decision-makers make informed and rational choices in complex decision-making scenarios. Additionally, decision support systems like ‘Expert Choice’ based on AHP facilitate the implementation of this methodology and handle large amounts of data efficiently.

4. Results

4.1 Delphi Results

Based from the literature review, considerable number of criteria were listed down and used for valid research as shown in Table 1. Due to the large number of criteria listed, it was impractical to utilize all of them for pairwise comparisons. Therefore, panel of specialists of 5 members related to renewable energy field were presented questionnaire in which they ranked out refined and key factors. In the end, 5 criteria and 18 sub-criteria were selected for further assessment. Table 6 presents the refined factors which are found vital for evaluation of location for harnessing hybrid energy.

Table 6

Selected Factors

No.	Criteria	Sub Criteria
1.	Resource Availability	Solar Irradiation levels
2.		Average Wind turbulence
3.		Shading Analysis
4.	Environmental factors	Area of Flat Land & Without protected areas
5.		Impact on Biodiversity and Habitat Preservation
6.		Noise and visual impact
7.		Distance to residential areas
8.	Infrastructure & Connectivity	Access to power grid
9.		Population Density
10.		Communication Network Coverage
11.		Roads Accessibility
12.	Land Characteristics	Size and Acquisition of the avail land
13.		Land use restrictions/zoning regs.
14.		Topography and elevation
15.	Socio-Economic Factors	Cost of land
16.		Operation and maintenance expenses
17.		Public Acceptance & Job Creation
18.		Energy production demand

4.2 AHP Results

To obtain the weights of factors in this method, a collaborative and systematic process of decision making was adopted. A total of 31 specialists participated and provided their judgments in the form of pairwise comparison matrices for criteria, sub-criteria, and alternatives. To consolidate the input from individual specialist, the method of taking geometric mean was utilized to compute their weights. The implementation of the AHP involved two distinct phases. Initially, the matrix main criteria were processed and their weights were measured, and similarly, the weights were determined for sub criteria. Table 7 presents the outcomes of this process.

Table 7

Results of pairwise comparison

Criteria	Sub Criteria	Local Weights	Global weights	Overall Ranking
Resource Availability		0.613		1st(criteria)
	Solar Irradiation levels	0.472	0.289	1st
	Average Wind Speed	0.444	0.272	2nd
	Shading Analysis	0.084	0.051	5th
Environmental factors		0.053		4th(criteria)
	Area of Flat Land & Without protected areas	0.361	0.019	10th
	Impact on Biodiversity and Habitat Preservation	0.224	0.012	13th
	Noise and visual impact	0.097	0.005	18th
	Distance to residential areas	0.318	0.017	12th
Infrastructure & Connectivity		0.193		2nd(criteria)
	Access to power grid	0.468	0.090	3rd
	Population Density	0.143	0.028	8th
	Communication Network Coverage	0.059	0.011	14th
	Roads Accessibility	0.330	0.064	4th
Land Characteristics		0.062		5th(criteria)
	Size and Acquisition of the avail land	0.460	0.033	7th
	Land use restrictions/zoning regs.	0.319	0.021	9th
	Topography and elevation	0.221	0.009	16th
Socio-Economic Factors		0.079		3rd(criteria)
	Cost of land	0.529	0.042	6th
	Operation and maintenance expenses	0.101	0.008	17th
	Public Acceptance & Job Creation	0.134	0.011	15th
	Energy production demand	0.236	0.018	11th

The next step is to perform comparison assessment of alternatives which included all the criteria. It is basically a question which asks experts to compare alternatives based on each criteria. This is done by numbering using the scale. When all the pairwise comparisons are performed, geometric mean is used to aggregate individual judgments (Saaty, 1990). These were analyzed by using the Expert Choice software. This software is used to calculate consistency ratio (CR) and weights of criteria and alternatives.

The judgment is accepted if CR≤ 0.10. The questionnaire was presented back to expert if their values was greater than 0.10. These experts were explained the meaning of inconsistency in AHP. Many participants were able to achieve this value. The specialists were free to complete the questionnaire is their own way

After completion of pairwise comparison of factors, the next step is to find pairwise comparison of alternatives using each criteria and sub criteria as shown in figure 6 by utilizing judgements recorded by the experts.

Figure 6

Pairwise comparison of Cities using each criteria/sub Criteria

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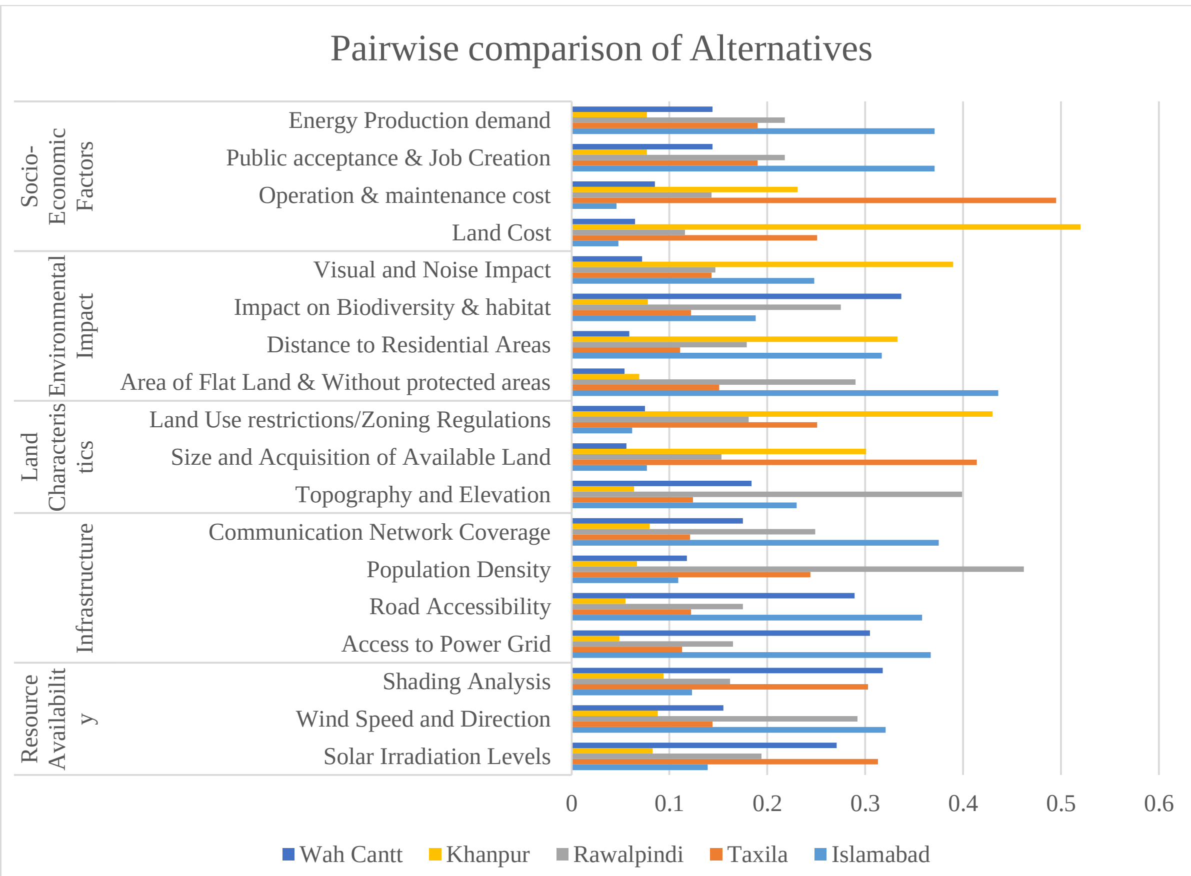

Finally, overall priorities of decision alternatives are synthesized using the criteria priorities that have been calculated in previous steps as shown in table 8.

Table 8

Final Ranking of Alternative Cities

Alternative Cities	Priority weight	Rank
Rawalpindi	0.244	1
Islamabad	0.183	2
Khanpur	0.095	6
Taxila	0.083	7
Wah Cantt	0.101	5

4.3 Sensitivity Analysis

In order to examine the potential impact on result due to change in expert's preferences, sensitivity analysis is executed in this research. The focus was to assess the significance of weights of criteria in relation to the priorities of cities as alternatives. Five variations were examined, and it was observed that the sequence of alternatives priorities remained consistent and did not vary. Table 9 shows the weightage of the criteria for the different variations and Table 10 shows the results and priorities calculated from the sensitivity analysis for these variations.

Variation 1 is the weights obtained in this research, while other variations are computed to analyze sensitivity aspect. Table 10 indicates that the alternatives ranking remained unchanged in variation 2 and 3, while the rankings were altered in variation 4 and 5.

Table 9

Criteria weights used in different Variations for sensitivity analysis

Criteria	Variation 1	Variation 2	Variation 3	Variation 4	Variation 5
Resource Availability	0.613	0.503	0.437	0.170	0.292
Infrastructure & Connectivity	0.193	0.248	0.255	0.134	0.329
Land Characteristics	0.062	0.08	0.044	0.308	0.030
Environmental Factors	0.053	0.069	0.038	0.300	0.312
Socio Economic Factors	0.079	0.101	0.226	0.088	0.037

Table 10

Results of the Alternatives ranking for each Variation

Alternatives	Variation 1	Variation 2	Variation 3	Variation 4	Variation 5
Islamabad	1	1	1	1	1
Rawalpindi	2	2	2	3	2
Taxila	3	3	3	2	4
Wah cantt	4	4	4	5	3
Khanpur	5	5	5	4	5

In conclusion, the sensitivity analysis demonstrates that the main findings of the study remain unchanged, indicating that altering the weights of the obtained results would have an insignificant impact. The highest-ranked alternative remains Islamabad, with Rawalpindi, Taxila, Wah Cantt, and Khanpur following in that order. Based on the conducted analysis and findings, the findings of the research are deemed valid and robust. The rigorous methodology employed and the careful consideration of various factors ensure the reliability and credibility of the study's outcomes.

5. Discussion

This study utilized a comprehensive research framework and implemented various methodologies, resulting in valuable insights and significant findings. As a result, energy specialists and policy creators can rely on the research framework and relevant findings to make informed decisions regarding selection of location for solar-wind harnessing.

The successful utilization of the Delphi and Analytic Hierarchy Process (AHP) methods has effectively addressed the process to make decision for selection of optimal city for solar-wind harnessing in the northwest area of Pakistan. The final rankings and results of this research are obtained by a robust methodology and appropriate utilization of expert opinions and related work. Among the selected key criteria identified in this research, namely resource availability, infrastructure and connectivity, land characteristics, environmental impact, and socio-economic factors, resource availability has been recognized as the most significant factor due to its direct impact on the energy generation potential and overall plant efficiency. Infrastructure and connectivity is considered the second most important factor in the process of selection of location. The prioritization of criteria in this research aligns with the perspective of a typical developing country, where the scarcity of funding resources poses a significant challenge for renewable energy project development. It is noteworthy that the respondents ranked the environmental aspect as the lowest priority. This lower ranking indicates that the local population is unaware regarding the significance of environmental ecological balance.

The results and rankings of the sub-criteria reveal that the quality of solar and wind resources, distance from grid, road accessibility, land availability, cost, and land acquisition are ranked as the top factors. These rankings reflect a robust outcome, emphasizing the critical significance of these criteria in the decision process of optimal city for solar-wind energy harnessing projects.

This ranking of different cities in the northwest region holds significant importance as it is based on a scientifically guided decision-making process and incorporates essential factors and a robust methodology. Islamabad, Rawalpindi, and Taxila are highly suggested as the optimal cities for installation and investments of solar-wind hybrid energy harnessing. Islamabad, in particular, performs well across various criteria, including resource availability, infrastructure, land characteristics, environmental impact, and socio-economic factors. Its favorable access to the power grid, road accessibility, topography, elevation, and public acceptance contribute to its high ranking. These recommended locations have favorable conditions, including an adequate number of solar-windy days throughout the year and the presence of appropriate infrastructure. The complementary nature of solar and wind energy makes them an ideal combination for harnessing renewable energy potential. Solar-wind energy, in particular, shows promise and a valuable solution for addressing the current energy and power crises in the country. Hence, government authorities and decision makers can get valuable insights from this research in prioritizing optimal sites and implementing solar-wind harnessing projects not only in the northwest region but also in other regions of the country.

6. Conclusion

The comprehensive and systematic decision support framework was developed successfully in this research by utilization of the AHP and Delphi techniques for evaluating the optimal location selection among different cities for solar-wind hybrid energy harnessing in the northwest region of Pakistan. This research study presented a robust framework and a robust assessment of criteria often overlooked in site selection process that can be effectively employed by developers, policymakers and investors to select optimal decisions and maximize the potential of RE resources. By considering the specific criteria and involving relevant stakeholders, the implementation of sustainable and efficient solar and wind hybrid energy projects becomes feasible, thereby contributing to a greener and more sustainable future.

Solar and wind energy have significant potential offering numerous advantages like reducing dependence of energy mix on fossil fuels, stimulating both regional and national economic growth, employment opportunities and offers significant potential to drive sustainable development. Hence, prioritizing decision of selecting optimal and best locations to build solar-wind energy harnessing project becomes very crucial. Considering the absence of a systematic framework for decision of selecting solar-wind project location in Pakistan, this research aimed to bridge this gap by proposing a systematic decision framework specifically for the North West region of the country. The key factors for selection of optimal location were identified through expert feedback and analysis where experts from academia, industry, and the renewable and environmental field contributed their valuable insights and judgments to the implementation of the AHP decision model.

Among the selected key main criteria, resource availability and infrastructure and socio-economic factors emerged as the top-ranked criteria in this study. Based on the framework developed for supporting decision, the city of Islamabad was determined to be the optimal location for solar-wind harnessing, followed by Rawalpindi, Taxila, Wah Cantt, and Khanpur. It is important to emphasize that the outcomes and results of this research rely on the expert judgments collected at each assessment level, and therefore, engaging different experts and stakeholders, as well as exploring alternative MCDM methods, may slightly influence the results. Nonetheless, this study holds significant relevance and should be duly considered for solar-wind power project site selection, while also offering opportunities for further enhancements in the future.

The outcomes and findings of this research have several recommendations for practice and future research in the field of solar and wind hybrid energy site selection. The following recommendations/future research are put forth based on the conclusions drawn from this study:

Engagement of stakeholders: To ensure comprehensive decision-making in the site selection process, it is advised to actively involve a diverse range of stakeholders. This may include local communities, government agencies, and environmental experts, among others.

Long-term monitoring: Continuous monitoring and evaluation of the selected site's performance should be undertaken to validate the site selection decision. This will help assess the accuracy of the initial assessments and identify any changes or improvements that may be required.

Technological advancements: As technology in the renewable energy sector advances, it is important to regularly update the site selection criteria and evaluation methods. New advancements may introduce additional factors to consider, such as the integration of energy storage systems or smart grid capabilities.

Economic viability: Further research is needed to explore the economic viability of solar and wind hybrid energy plants in different regions. This includes analyzing the cost-effectiveness of hybrid systems compared to individual solar or wind installations and identifying potential financial incentives or support mechanisms.

Environmental impact assessment: In-depth studies should be conducted to assess the environmental impact of solar and wind hybrid energy projects on local ecosystems, wildlife, and natural resources. This will help ensure sustainable development and minimize any adverse effects on the environment.

Social acceptance and community engagement: Future research should focus on understanding the social acceptance of renewable energy projects and the factors that influence public perception. Community engagement strategies should be developed to promote awareness, participation, and support for solar and wind hybrid energy initiatives.

References

Abdullah, Zhou, D., Shah, T., Jebran, K., Ali, S., Ali, A., & Ali, A. (2017). Acceptance and Willingness to Pay for Solar Home System: Survey Evidence from Northern Area of Pakistan. *Energy Rep.*, 3, 54–60.

Acar, I., Özkan, A., & Banar, M. (2003). Evaluation of the Alternative Solid Waste Landfill Sites by Decision Analysis with Multiple Criteria: A Case Study in Eskişehir City/Turkey. *8th Annual International Conference on Industrial Engineering-Theory*.

Ali, Y., Butt, M., Sabir, M., Mumtaz, U., & Salman, A. (2018). Selection of suitable site in Pakistan for wind power plant installation using analytic hierarchy process (AHP). *Journal of Control and Decision*, 5(2), 117-128.

Al-Yahyai, S., Charabi, Y., Gastli, A., & Al-Badi, A. (2012). Wind farm land suitability indexing using multi-criteria analysis. *Renewable Energy*, 44, 80-87.

Aydin, N. Y., Kentel, E., & Duzgun, H. S. (2013). GIS-based site selection methodology for hybrid renewable energy systems: A case study from western Turkey. *Energy conversion and management*, 70, 90-106.

Azizi, A., Malekmohammadi, B., Jafari, H. R., Nasiri, H., & Amini Parsa, V. (2014). Land suitability assessment for wind power plant site selection using ANP-DEMATEL in a GIS environment: case study of Ardabil province, Iran. *Environmental monitoring and and assessment*, 186, 6695-6709.

Baloch, M. H., Chauhdary, S. T., Ishak, D., Kaloi, G. S., Nadeem, M. H., Wattoo, W. A., & Hamid, H. T. (2019). Hybrid energy sources status of Pakistan: An optimal technical proposal to solve the power crises issues. *Energy Strategy Reviews*, 24, 132-.

Brewer, J., Ames, D. P., Solan, D., Lee, R., & Carlisle, J. (2015). Using GIS analytics and social preference data to evaluate utility-scale solar power site suitability. *Renewable energy*, 81, 825-836.

Brunelli, M. (2014). *Introduction to the analytic hierarchy process.* Springer.

Cavallaro, F. (2010). Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems. *Applied Energy*, 87(2), 496-503.

Dawod, G., & Mandoer, M. S. (2016). Optimum sites for solar energy harvesting in Egypt based on multi-criteria GIS. *In the first Future University international conference on new energy and environmental engineering*, pp. 11-14.

Farooqui, S. Z. (2014). Prospects of renewables penetration in the energy mix of Pakistan. *Renewable and Sustainable Energy Reviews*, 29, 693-700.

Gatzert, N., & Kosub, T. (2016). Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks. *Renewable and Sustainable Energy Reviews*, 60, 982-998.

Gigović, L., Pamučar, D., Božanić, D., & Ljubojević, S. (2017). Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia. *Renewable energy*, 103, 501-521.

Goh, H.H., Li, C. & Zhang, D. (2022). Application of choosing by advantages to determine the optimal site for solar power plants. *Sci Rep* **12**, 4113 (2022). https://doi.org/10.1038/s41598-022-08193-1

Heo, E., Kim, J., & Boo, K. J. (2010). Analysis of the assessment factors for renewable energy dissemination program evaluation using fuzzy AHP. *Renewable and sustainable energy reviews*, 14(8), 2214-2220.

Hosseinzadeh, S., Etemad-Shahidi, A., & Stewart, R. A. (2023). Site Selection of Combined Offshore Wind and Wave Energy Farms: A Systematic Review. *Energies*, *16*(4), 2074. MDPI AG. Retrieved from http://dx.doi.org/10.3390/en16042074

Khazael, S. M. & Al-Bakri, M. (2021). The Optimum Site Selection for Solar Energy Farms using AHP in GIS Environment, A Case Study of Iraq. *Iraqi Journal of Science*, *62*(11), 4571–4587. https://doi.org/10.24996/ijs.2021.62.11(SI).36

Klessmann, C., Held, A., Rathmann, M., & Ragwitz, M. (2011). Status and perspectives of renewable energy policy and deployment in the European Union—What is needed to reach the 2020 targets? *Energy policy*, 39(12), 7637-7657.

Kocabaldır, C. & Yücel, M. A. (2020). GIS-Based Multi-Criteria Decision Analysis of Site Selection for Photovoltaic Power Plants in Çanakkale Province. *International Journal of Environment and Geoinformatics*, 7 (3) , 347-355 . DOI: 10.30897/ijegeo.689570

Kollati, H., & Debnath, A. (2021). A short review on different techniques used for site selection of air quality monitoring stations. *Journal of Industrial Engineering and Decision Making*, 2(1), 27-30.

Latinopoulos, D., & Kechagia, K. (2015). A GIS-Based Multi-Criteria Evaluation for Wind Farm Site Selection. A Regional Scale Application in Greece. *Renewable Energy* , 78, 550–560.

Lee, A. H., Chen, H. H., & Kang, H. Y. (2009). Multi-criteria decision making on strategic selection of wind farms. *Renewable Energy*, 34(1), 120-126.

Lee, A. H., Hung, M. C., Kang, H. Y., & Pearn, W. L. (2012). A wind turbine evaluation model under a multi-criteria decision making environment. *Energy Conversion and Management*, 64, 289-300.

Linstone, H. A. (1975). *The delphi method.* MA: Addison-Wesley.

List of power stations in Pakistan. (n.d.). Retrieved from wikipedia: https://en.wikipedia.org/wiki/List_of_power_stations_in_Pakistan#cite_note-:0-1

Muhammet Deveci, M., Cali, U. & Pamucar, D. (2021). Evaluation of criteria for site selection of solar photovoltaic (PV) projects using fuzzy logarithmic additive estimation of weight coefficients. *Energy Reports*. Volume 7, November 2021, Pages 8805-8824. https://doi.org/10.1016/j.egyr.2021.10.104

Noorollahi, Y., Yousefi, H., & Mohammadi, M. (2016). Multi-criteria decision support system for wind farm site selection using GIS. *Sustainable Energy Technologies and Assessments*, 13, 38-50.

NREL.PakistanResourceMapsandToolkit. (2017, January 1). Retrieved from NREL: https://www.nrel.gov/international/ ra_pakistan.html

PakistanResourceMapsandToolkit—NREL. (2017, January 1). Retrieved from NREL: https://www.nrel.gov/international/ ra_pakistan.html

Pamučar, D., Gigović, L., Bajić, Z., & Janošević, M. (2017). Location selection for wind farms using GIS multi-criteria hybrid model: An approach based on fuzzy and rough numbers. *Sustainability*, 9(8), 1315.

Rauf, O., Wang, S., Yuan, P., & Tan, J. (2015). An overview of energy status and development in Pakistan. *Renewable and Sustainable Energy Reviews*, 48, 892-931.

Rediske, G., Siluk, J., Gastaldo, N., Rigo, P. & Rosa, C. (2018). Determinant factors in site selection for photovoltaic projects: A systematic review. *International Journal of Energy Research*. Volume 43, Issue 5. 1689-1701. https://doi.org/10.1002/er.4321

Renewable Capacity Statistics. (2021). Retrieved from International Renewable Energy Agency (IRENA): https://www.irena.org/publications/2021/Apr/Renewable-Capacity-Statistics-2021

Sánchez-Lozano, J. M., García-Cascales, M. S., & Lamata, M. T. (2016). GIS-based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain. *Applied Energy*, 171, 86-102.

Shaikh, F., Ji, Q., & Fan, Y. (2015). The Diagnosis of an Electricity Crisis and Alternative Energy Development in Pakistan. *Renew. Sustain. Energy Rev.* , 52, 1172–1185.

Sheikh, M. A. (2010). Energy and renewable energy scenario of Pakistan. *Renewable and Sustainable Energy Reviews*, 14(1), 354-363.

Solangi, Y. A., Tan, Q., Khan, M. W., Mirjat, N. H., & Ahmed, I. (2018). The selection of wind power project location in the Southeastern Corridor of Pakistan: A factor analysis, AHP, and fuzzy-TOPSIS application. *Energies*, 11(8), 1940.

Soydan, O. Solar power plants site selection for sustainable ecological development in Nigde, Turkey. *SN Appl. Sci.* **3**, 41 (2021). https://doi.org/10.1007/s42452-020-04112-z

Spyridonidou, S. & Vagiona, D.G. (2023). A systematic review of site-selection procedures of PV and CSP technologies. *Energy Reports*. Volume 9, December 2023, Pages 2947-2979. https://doi.org/10.1016/j.egyr.2023.01.132

Tafula, J.E.; Justo, C.D.; Moura, P.; Mendes, J.; Soares, A. Multicriteria Decision-Making Approach for Optimum Site Selection for Off-Grid Solar Photovoltaic Microgrids in Mozambique. *Energies* 2023, 16, 2894. https://doi.org/ 10.3390/en16062894

Tahri, M., Hakdaoui, M., & Maanan, M. (2015). The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: Case study in southern Morocco. *Renewable and sustainable energy reviews*, 51, 1354-1362.

Tegou, L. I., Polatidis, H., & Haralambopoulos, D. A. (2010). Environmental management framework for wind farm siting: Methodology and case study. *Journal of environmental management*, 91(11), 2134-2147.

Ullah, Z., Ali, S. M., Khan, I., Wahab, F., Ellahi, M., & Khan., B. (2020). Major Prospects of Wind Energy in Pakistan. *International Conference on Engineering and Emerging Technologies (ICEET), 2020,*, (pp. pp. 1-6).

Van Haaren, R., & Fthenakis, V. (2011). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. *Renewable and sustainable energy reviews*, 15(7), 3332-3340.

Vasant, L. G., & Pawar, V. R. (2017). Solar-wind hybrid energy system using MPPT. *In 2017 international conference on intelligent computing and control systems (ICICCS)*, (pp. pp. 595-597).

Wakeel, M., Chen, B., & Jahangir, S. (2016). Overview of energy portfolio in Pakistan. *Energy Procedia*, 88, 71-75.

Wanderer, T., & Herle, S. (2015). Creating a spatial multi-criteria decision support system for energy related integrated environmental impact assessment. *Environmental Impact Assessment Review*, 52, 2-8.

Wątróbski, J., Ziemba, P., & Wolski, W. (2015). Methodological aspects of decision support system for the location of renewable energy sources. *In 2015 Federated Conference on Computer Science and Information Systems (FedCSIS)*, pp. 1451-1459.

WIND ENERGY PROJECT. (2017, November 22). Retrieved from PMD : http://www.pmd.gov.pk/wind/Wind_Project_files/ Page767.html

Wissing, T. (2013). "Renewable Ocean Energy Site Selection Using a GIS: Gulf Coast Potential" (2013). Master's Theses. 524. https://aquila.usm.edu/masters_theses/524

World Energy Outlook. (2020). Retrieved from International Energy Agency (IEA): https://www.iea.org/reports/world-energy-outlook-2020

Wu, Y., Zhang, J., Yuan, J., Geng, S., & Zhang, H. (2016). Study of decision framework of offshore wind power station site selection based on ELECTRE-III under intuitionistic fuzzy environment: A case of China. *Energy Conversion and Management*, 113, 66-81.

Yeh, T. M., & Huang, Y. L. (2014). Factors in determining wind farm location: Integrating GQM, fuzzy DEMATEL, and ANP. *Renewable Energy,*, 66, 159-169.

Yunna, W., & Geng, S. (2014). Multi-criteria decision making on selection of solar–wind hybrid power station location: A case of China. *Energy Conversion and Management*, 81, 527-533.

Yun-na, W., Yi-sheng, Y., Tian-tian, F., Li-na, K., Wei, L., & Luo-jie, F. (2013). Macro-site selection of wind/solar hybrid power station based on Ideal Matter-Element Model. *International Journal of Electrical Power & Energy Systems*, 50, 76-84.

Zafar, U., Ur Rashid, T., Khosa, A., Khalil, M., & Rahid, M. (2018). An Overview of Implemented Renewable Energy Policy of Pakistan. *Renew. Sustain. Energy Rev.*, 82, 654–665.