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Thesis No.: M-368-MSREE-2022-2023

Suitability and Techno-Economic Feasibility of Hybrid — Solar and Wind — Power Plant in Nepal

by
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A THESIS
SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
IN PARTIAL FULFILLMENT TO THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE IN
RENEWABLE ENERGY ENGINEERING

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
LALITPUR, NEPAL

OCTOBER, 2023

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ACKNOWLEDGEMENT

I extend my deepest gratitude to my supervisor, Prof. Dr. Laxman Poudel, whose unwavering support, insightful guidance, and expertise have been instrumental in shaping this thesis. His dedication to my academic growth and commitment to excellence have been a constant source of inspiration.

My appreciation is extended to Assoc. Prof. Dr. Hari Bahadur Darlami, the coordinator of MSREE, for his support and motivation throughout my research period. I would also like to thank the Assoc. Prof. Dr. Ajay Kumar Jha for providing me with valuable insights and guidance on developing and strengthening the research idea. Additionally, I am also immensely grateful to Asst. Prof. Laxman Motra, Deputy Head of Department (Mechanical and Aerospace Engineering), whose technical expertise and meticulous attention to detail have greatly enriched the quality of this work.

My family deserves special recognition for their strong encouragement and belief in my abilities. Their love and support provided the bedrock upon which I built this thesis.

I would like to thank the teachers of Department of Mechanical and Aerospace Engineering, and all my friends and colleagues for their support and encouragement. Finally, a special appreciation goes to Er. Shweta Sah and Er. Ashok Subedi for their valuable suggestions, support and time.

Thank you all for being an integral part of this journey.

ABSTRACT

In the past decade, there has been a significant increase in worldwide energy demand primarily met by fossil fuels, resulting in ecological and environmental impacts, leading to a growing interest in sustainable energy options such as wind and solar power that have minimal ecological effects and are well-suited for remote areas and rural electrification goals.

This study identifies suitable regions for solar, wind, and hybrid energy generation in Nepal by collecting criteria from literature, analyzing their relevance in the Nepalese context, and categorizing them into five suitability classes; these classes were determined based on factors' significance, contextual appropriateness, impact on energy capacity, adaptability, economic considerations, and environmental effects, while the Analytic Hierarchy Process (AHP) was used to assign weights through pairwise comparisons, ultimately resulting in weighted overlay maps using ArcMap 10.8 to select optimal wind and solar sites. Furthermore, we analyzed the prepared suitability map, and available literature to select a site for the techno-economic feasibility analysis. Based on the inputs—location details, load profile, other technical characteristics and cost— the feasibility of different power systems i.e. solar, wind and hybrid (solar and wind) were analyzed using HOMER, and the technically suitable system with the least cost was selected as the best system for the implementation.

The final suitability map illustrates that 'suitable' regions for solar, wind, and hybrid energy comprise 7.0%, 3.2%, and 2.3% of the total surface area, respectively, with a predominant presence of moderately suitable areas for each energy system and fewer less suitable areas; notably, the suitable zones are primarily concentrated in the Terai regions due to their flatter terrain, enhanced infrastructure, and improved accessibility. After analyzing the Net Present Cost (NPC) and the cost of electricity (COE), the results depicts that PV-wind hybrid power plants with battery storage are the most cost-effective choice. In contrast, PV-battery power plants are the least favorable option. In the analysis, wind power alone falls short in meeting the load demand due to limited power generation capacity, primarily because of unfavorable wind resource data.

Incorporating wind and solar systems into Nepal's energy mix, especially in regions with ample resources, addresses intermittent energy issues and eases the load on

hydroelectric plants during high demand or seasonal shortages, boosting Nepal's energy resilience; this study offers strong evidence of wind, solar, and hybrid energy system potential in Nepal, promoting the need to diversify energy sources and fostering a path toward a sustainable and robust energy future that stakeholders should actively support through investments. Also, the techno-economic assessment validates that strategically combining wind and solar energy systems enhances reliable and economically efficient energy supply. This integration improves overall energy generation and addresses the inherent intermittency challenges associated with renewable sources.

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LIST OF ABBREVIATIONS

AEPC	Alternative Energy Promotion Center
AHP	Analytical Hierarchy Process
ASP	Aspect
CR	Consistency Ratio
DFA	Distances from airports
DFPP	Distance from power plants
DFR	Distance from roads
DFTL	Distance from transmission lines
DFUA	Distance from urban areas
DWB	Distance from water bodies
DWD	Distance from wildlife designations
ELE	Elevation
GHI	Global Horizontal Irradiance
GON	Government of Nepal
HOMER	Hybrid Optimization of Multiple Electric Renewables
LaRC	Langley Research Center
LU	Land use
NASA	National Aeronautics and Space Administration
NEA	Nepal Electricity Authority
OSM	Open Street Maps
POWER	Prediction of Worldwide Energy Resource
PV	Photovoltaic

RPGCL	Rastriya Prasaran Grid Company Limited
SLP	Slope
SPV	Solar Photovoltaic
SR	Solar Radiation
WTB	Wind Turbine
WV	Wind Velocity

CHAPTER ONE: INTRODUCTION

1.1. Background

Over the last decade, there has been a remarkable upsurge in global energy demand and utilization, primarily relying on fossil fuels to meet this requirement. The utilization of fossil fuels and other non-renewable energy forms has had a substantial impact on our ecological systems and the overall environment (Bhandari et al., 2017). One of the most promising avenues for sustainable energy involves harnessing alternative sources of energy like wind and solar power to generate electricity. These sources have minimal ecological impact. Moreover, they represent the most viable solution for energy systems in remote areas, aligning with objectives such as electrifying rural regions (Bista, Khadka, Shrestha, & Bista, 2020).

Nepal, a developing nation, holds remarkable promise in the sector of renewable energy production. However, the utilization of renewable sources remains limited, contributing only a minor fraction to the overall energy demand, whereas the predominant share is fulfilled by fossil fuels and forest-derived resources (NEA, 2021). Given the context of escalating fossil fuel costs, the utilization of solar and wind energy could potentially signify a milestone in the development of the renewable energy sector, in addition to the current development in hydroelectric power (Poudyal, Loskot, Nepal, Parajuli, & Khadka, 2019).

1.2. Problem Statement

Run-of-river projects, which constitute Nepal's primary power source, rely on the stream flow for generation capacity; this reliance results in a significant energy deficiency during the dry season due to limited flow in river. To address this issue, there is a need for an alternative energy solution capable of meeting energy demands both during the dry season and periods of high consumption. A viable solution to this problem could be hybrid wind and solar energy system. Furthermore, due to their minimal environmental impact, wind and solar energy present themselves as more desirable options compared to fossil fuels and even hydropower. Also, this aligns with our objective of adopting environmentally friendly energy sources to fulfill our climate commitments. Hybrid energy systems can also be designed to provide uninterrupted power to vital services in rural areas, including telecom towers and healthcare centers (as in Mityal hybrid power plant)

1.3. Rationales of Research

In today's world, where the environment and global commitments to combat climate change are crucial, it's important to shift to clean and sustainable energy sources that limits the environment degradation. While evaluating the suitability of environmental friendly energy source, we will evaluate the areas that are favorable for hybrid energy source— wind and solar—to meet the energy demand. The identification of areas suitable for generation of solar, wind and hybrid energy helps policy maker take informed decision based on the areas for prioritizing the development of energy system. Furthermore, we also validate the scheme implementation through techno-economic lens in the context of Nepal. Hence, the rationale of this research is to find areas that are favorable for solar, wind and hybrid power system using geospatial analysis, and evaluate the technical and economic analysis of site for the hybrid system.

1.4. Research Objectives

1.4.1 Main Objective

The main objective of this research is to identify the suitable areas of hybrid (solar and wind) energy generation in Nepal. Furthermore, we will use a site in Thingan, Makwanpur as a case study to evaluate the techno-economic feasibility of hybrid system.

1.4.2 Specific Objectives

The Specific Objectives of this research are:

(i) To identify the suitable areas for solar, wind and hybrid system using geo-spatial analysis.
(ii) To evaluate the technical and economic feasibility of a site for hybrid power system.

1.5. Assumptions and Limitations

The assumption and limitations of this research are:

(i) We used satellite images from the openly available sources that may have coarse resolution

(ii) We used secondary datasets from the project implemented area to record the information.

CHAPTER TWO: LITERATURE REVIEW

2.1. Global and Nepalese Energy Scenario

2.1.1 Global Scenario

The exponential increase in use of fossil fuels to produce energy for increasing global demand has been a worldwide issue due to the increased climate emission. To address environmental concerns and reduce carbon emissions, developed nations have committed to adopting cleaner energy sources. However, a major challenge of renewable energy is its inconsistent electricity supply (Sterl et al., 2020). While renewable energy is preferred, its intermittent nature presents a significant problem. In this context, the idea of combining different renewable energy sources into a hybrid system has gained attention. Such a hybrid approach aims to counter the variability seen in individual sources. By merging these sources, hybrid systems offer a way to smooth out fluctuations, enhance reliability, and consequently reduce the reliance on fossil fuels.

The use of renewable energy reduces carbon emissions and lowers the cost of energy production. Chade Ricosti and Sauer (2013) noted that the expense of generating wind energy in Brazil is nearly 60% lower than the cost of geo-thermal energy production. In a study conducted in West Africa, Sterl et al. (2020) projected that by 2030, wind and solar renewable sources would fulfill half of the region's energy requirements and incur lower expenses than natural gas.

Energy transmission expenses in rural areas often outweigh the financial gains. However, affordable and clean energy access is considered a fundamental human right, as acknowledged by the United Nations' Sustainable Development Goals. The solution lies in harnessing renewable resources available in proximity. Micro-grids, which are self-contained energy systems that can be managed by local communities, hold the potential to generate, distribute, store, and regulate energy (Canziani, Vargas, & Gastelo-Roque, 2021). As highlighted by Canziani et al. (2021), the success of a hybrid renewable energy system rests on the acceptance by the local community and the transfer of technological knowledge to the community.

2.1.2 Nepalese Scenario

The Alternative Energy Promotion Center (AEPC) in Nepal plays a pivotal role in steering the country's trajectory towards renewable energy sources. In this context, "renewables" denote energy derived from resources such as wind, solar, biomass, micro-hydro, and biofuel. Through partnerships with donor organizations, AEPC has undertaken endeavors aimed at ensuring access to sustainable and enduring renewable energy alternatives.

Hydropower stands as Nepal's predominant energy source. While the nation experiences surplus power generation during the wet season, the Run of River hydropower system faces limitations in meeting energy demands during the dry season. This circumstance presents a challenge for Nepal. While there is the issue of surplus power export during rainy periods, the deficit in energy supply during the dry season compounds the challenges for Nepal's already modest industrial sector (NEA, 2021). Adding to this issue, the ongoing global energy crisis, influenced by geopolitical factors such as the turmoil involving Russia, the largest supplier of fossil fuels, has exacerbated Nepal's energy scenario.

The installation of extensive electricity transmission lines for transmitting and distributing power faces technical and economic challenges in Nepal's rural areas, where communities are scattered. This situation prompts the adoption of hybrid generation systems as a practical solution. This is exemplified by two notable cases: the Bhorleni hybrid plant, combining 15 kW of solar and 10 kW of wind, serving 131 local households at a monthly cost of $1.4 per household; and the Dhaubadi hybrid plant, with a solar-wind setup generating 12 kW. These instances underline the relevance and feasibility of solar-wind hybrid systems in Nepal's specific context (Poudyal et al., 2019).

2.2. Suitability Analysis using Geo-spatial tools

The identification of the suitable areas for wind, solar and hybrid energy systems requires defining the criteria for the suitability analysis, collecting the data and building the database, using the appropriate tool through GIS to overlay the data, analyzing by assigning scores to each criteria through different expert based method, and finally integrating all those information in the GIS environment to visualize the final suitability of the area (Ali, Taweekun, Techato, Waewsak, & Gyawali, 2019; Dehghan, Pourfayaz, & Shahsavari, 2022; Effat & El-Zeiny, 2022).

2.2.1 Geo-spatial analysis

The identification of suitable location for power plants has been investigated by employing various methodologies (Dehghan et al., 2022). Among these methodologies, Geographic information system (GIS) emerge as a relatively accessible approach with the advancement in the technology in recent years. GIS facilitates the storage, manipulation, and visualization of geospatial data; this serves to extract the physical characteristics of the Earth's surface, socio-economic characteristics, technical information (such as wind velocity and solar radiation), and environmental aspects (Koc, Turk, & Sahin, 2019; Saraswat, Digalwar, Yadav, & Kumar, 2021). Additionally, GIS provides the requisite data infrastructure to facilitate spatial analysis and visualization of geographic contexts.

The identification of potential sites for harnessing solar and wind electricity involves a comprehensive assessment of multiple influencing factors on power generation capacity. Deshmukh, Wu, Callaway, and Phadke (2019) and Saraswat et al. (2021) utilized a combination of technical parameters, geographic and topographical attributes, and socioeconomic considerations to delineate favorable regions within India for solar and wind power installations. Employing a similar approach, Effat and El-Zeiny (2022) applied relevant criteria and methodologies using GIS tools to identify optimal locations for hybrid solar-wind energy development in Egypt. This strategy, demonstrated in both the Indian and Egyptian contexts, establishes a scientific basis for the selection of sites suitable for utility-scale wind and solar projects (Effat & El-Zeiny, 2022; Saraswat et al., 2021).

2.2.2 Multi-criteria decision analysis

The Multiple Criteria Decision-Making (MCDM) technique is a useful method for tackling complex issues where many factors affect a single goal. It helps by comparing different options based on their unique characteristics and finding the best choice. In the context of renewable energy, various multi-criteria decision-making techniques have been effectively utilized to gather and synthesize information for optimal site selection (Elkadeem, Younes, Sharshir, Campana, & Wang, 2021). Among these techniques, the analytical hierarchy process (AHP) is the most prominent. AHP involves a sequence of pairwise comparisons, enabling decision makers to select the most suitable option from a set of choices based on their constraints, preferences, and priorities (Koc et al., 2019; Saaty, 1990; Saraswat et al., 2021).

2.2.3 Weighted overlay

In the ArcGIS environment, the weighted overlay tool is a popular option to employ as a rapid and accurate statistical method to merge and consolidate criteria, and weightage from AHP resulting in the generation of final suitability maps (Elkadeem et al., 2021). GIS overlay tool is located within the spatial analysis toolkit in ArcGIS that helps in the merging of the maps with assigned weights. This approach has been used in different context to spatially visualize and integrate the information acquired through multiple approach uniformly (Ali et al., 2019).

2.3. Techno-economic analysis of energy system

The HOMER (Hybrid Optimization Model of Electric Renewable) program, among many simulation software and tools for designing hybrid energy systems to determine the optimal size and type of each component, possess unique and state-of -the-art tool that have been utilized by numerous researchers (Bahramara, Moghaddam, & Haghifam, 2016; Dehghan et al., 2022; Pradhan, Lakhemaru, Motra, & Poudel, 2021). Chang et al. (2021) employed the HOMER Pro software to simulate various geographical, climatic, environmental, and demographic limitations. This allowed them to identify the optimal energy generation capacity that offers cost-effective energy while minimizing negative environmental impacts. Similarly, Kolhe, Ranaweera, and Gunawardana (2015) explored designing an efficient hybrid energy system for a rural community in Sri Lanka. They used HOMER to select suitable technologies and optimize component scaling. HOMER stands out for its comprehensive analytical capabilities and advanced prediction accuracy through sensitivity analysis. This makes it a prominent choice for such ideal planning purposes. Additionally, HOMER presents the opportunity to pick the best-suited hybrid system from a diverse range of outcomes ranked by their energy cost, enabling well-informed decision-making (Chowdhury, Kim, Cho, Shin, & Park, 2015).

CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Study Area

In Nepal, we evaluated regions suitable for harnessing solar, wind and hybrid energy sources. In addition, we selected Thingan Power Plant, a hybrid power plant in Nepal, as our case study. The village of Thingan in the Makwanpur District of Bagmati Province was selected for the technical and economic assessment of this hybrid system (in Figure 3.1). This power plant has an 8 kW generation capacity, comprising 5 kW from a photovoltaic (PV) solar system and 3 kW from a windmill.

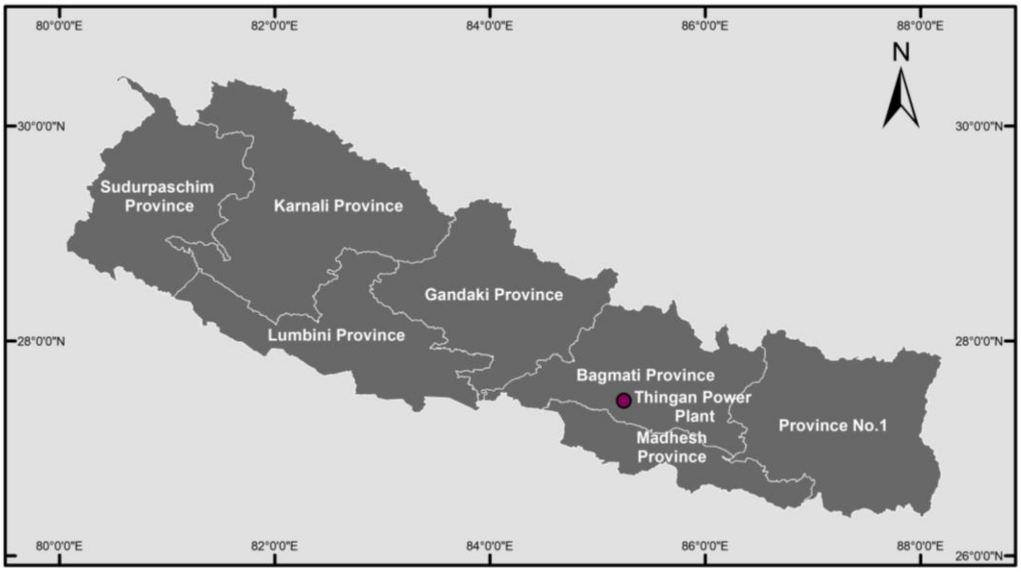

Figure 3.1: Study Area (Location map and site photo for Case study)

3.2. Method

The methodological framework for the study is presented in Figure 3.2. The aim of this study is to map appropriate regions for implementing hybrid energy systems and to assess the technical and economic viability of a specific hybrid power plant.

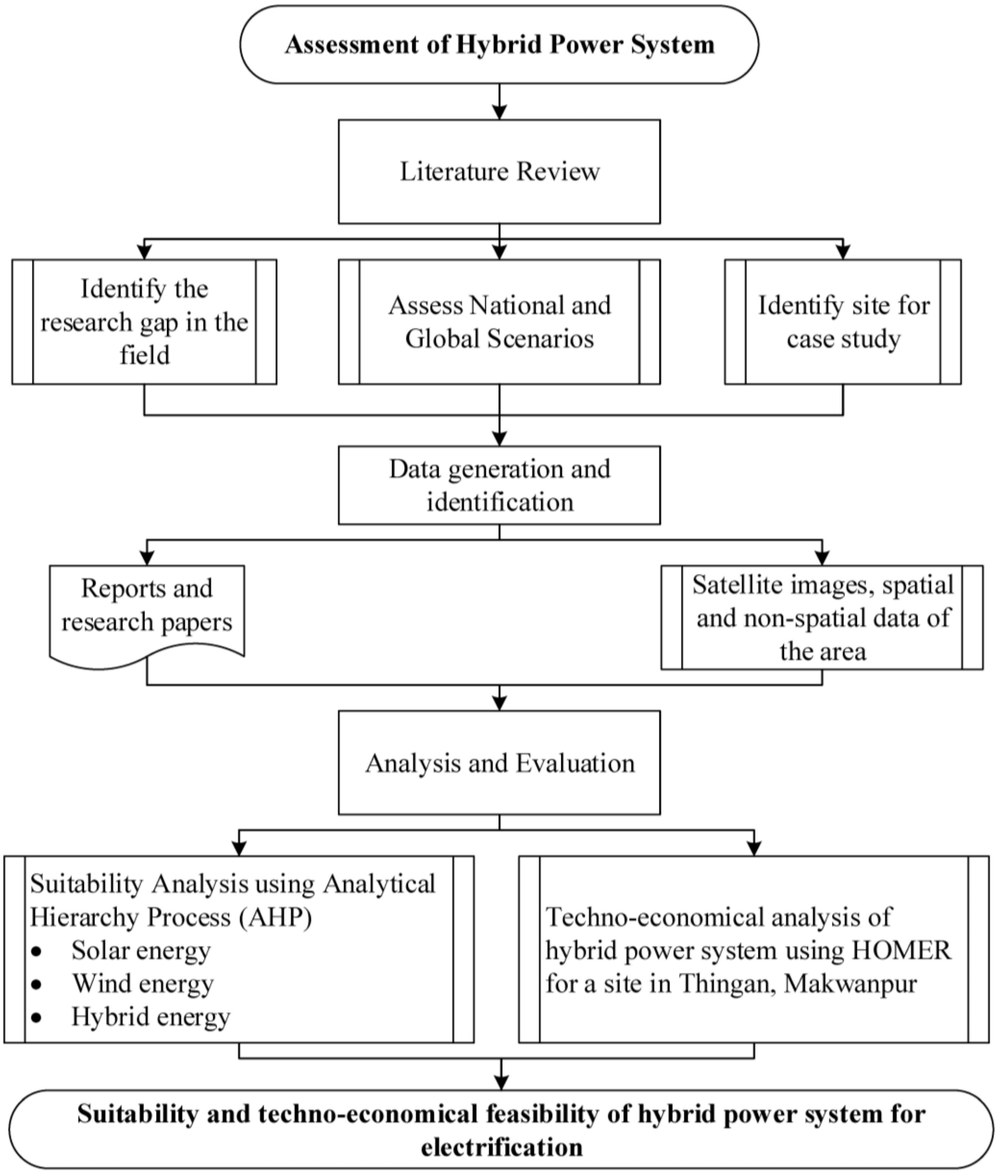

Figure 3.2: Methodological Framework for the current study

3.2.1 Suitability analysis of different power system

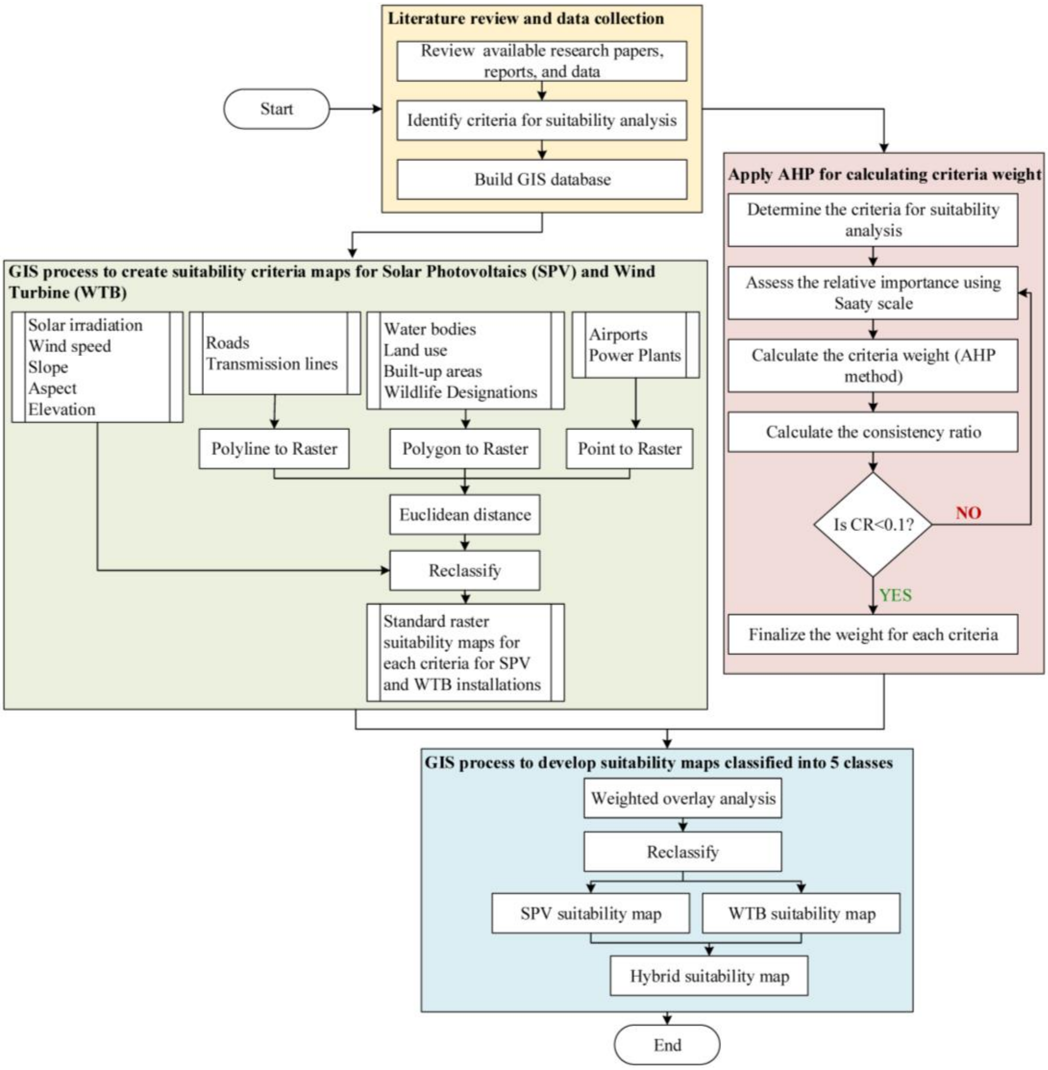

Figure 3.3: Methodological framework for suitability analysis of different power system

3.2.1.1 Literature review and data collection

Different factors are collected from the literature that helps in identify the suitable areas for the generation of solar power, wind power, and its combination (Ali et al., 2019; Dehghan et al., 2022; Effat & El-Zeiny, 2022). The availability of the data in Nepal and its relevance in Nepalese scenarios are analyzed and relevant criteria are included in the study.

3.2.1.2 Factors for evaluation

The factors used in the current study, and the sources of the data utilized are depicted in Table 3.1.

Table 3.1: Different factors used in the suitability analysis

Factors	**Source**
Solar Radiation	Solargis (2021)
Wind Velocity	DTU (2015)
Slope	Prepared using digital elevation model from United States Geological Survey: USGS (https://earthexplorer.usgs.gov/)
Aspect (facing direction)	
Elevation	
Water bodies locations	OSM (2023)
Airports	ICIMOD (2008)
Wildlife Designation	GON (2021)
Land Use	ICIMOD (2021)
Urban areas	ICIMOD (2021)
Roads alignment	ICIMOD (2009)
Transmission lines alignment	Digitized from RPGCL (2018)
Power plants locations	

3.2.1.3 Create suitability maps of each factors

Each of the factors or criteria utilized in this study has been systematically classified into five distinct suitability classes. The assignment of these classes is based upon a comprehensive evaluation of several considerations, including the relative significance of the factors, their contextual relevance within the Nepalese setting, their consequential influence on potential energy generation capacity, their adaptability across varied accessibility scenarios, their economic implications, and their corresponding environmental ramifications. (Aydin, Kentel, & Sebnem Duzgun, 2013; Koc et al., 2019; Neupane, Kafle, Karki, Kim, & Pradhan, 2022; Saraswat et al., 2021). The factors selected for suitability analysis of solar power (in Table 3.2) and wind power (in Table 3.3) provides the basis for the evaluation of overall suitability of power system.

Table 3.2: Different factors used in the suitability analysis of solar power with their classification

Criteria	Classes of Suitability				
	Highly Suitable	Suitable	Moderately Suitable	Less Suitable	Not Suitable
	1	2	3	4	5
Solar Radiation $(\frac{kWh}{m^2 day})$	> 5.6	5.0 – 5.6	4.4 – 5.0	3.8 – 4.4	< 3.8
Slope (in °)	0 – 2	2 – 3	3 – 5	5 – 10	> 10
Aspect (direction of slope)	South direction, Flat slope	South-east direction and South-west direction	East direction and West direction	North-east direction and North-west direction	North direction
Elevation (in m)	< 300	300 – 700	700 – 1100	1100 – 1500	> 1500
Distance from water bodies (in km)	> 28	21 – 28	14 – 21	7 – 14	< 7

Distance from Airports (in km)	> 28	21 – 28	14 – 21	7 – 14	< 7
Distance from Wildlife Designation (in km)	> 40	30 – 40	20 – 30	10 – 20	< 10
Land Use type	Barren	Grassland	Cropland	Wetland	Forest and Built-up area
Distance from urban areas (in km)	> 40	30 – 40	20 – 30	10 – 20	< 10
Distance from roads (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40
Distance from transmission lines (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40
Distance from power plants (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40

Table 3.3: Different factors used in the suitability analysis of wind power with their classification

Factors	Classes of Suitability				
	Highly Suitable	Suitable	Moderately Suitable	Less Suitable	Not Suitable

	1	2	3	4	5
Wind Velocity $(\frac{m}{s})$	> 6	5 – 6	4 – 5	3 – 4	< 3
Slope (in °)	0 – 6	6 – 9	9 – 12	12 – 15	> 15
Aspect (direction of slope)					
Elevation (in m)	< 500	500 – 1000	1000 – 1500	1500 – 2000	> 2000
Distance from water bodies (in km)	> 28	21 – 28	14 – 21	7 – 14	< 7
Distance from Airports (in km)	> 28	21 – 28	14 – 21	7 – 14	< 7
Distance from Wildlife Designation (in km)	> 40	30 – 40	20 – 30	10 – 20	< 10
Land Use type	Barren	Grassland	Cropland	Wetland	Forest and Built-up area

Distance from urban areas (in km)	> 40	30 – 40	20 – 30	10 – 20	< 10
Distance from roads (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40
Distance from transmission lines (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40
Distance from power plants (in km)	< 10	10 – 20	20 – 30	30 – 40	> 40

3.2.1.4 Analytical Hierarchy Process (AHP)

AHP (Analytical Hierarchy Process) is among the most prominent method for Multiple Criteria Decision Analysis (MCDA) because of its potential to systematically structure complex decision problems involving multiple criteria and alternatives (Effat & El-Zeiny, 2022). MCDA deals with situations where decisions need to be made considering various conflicting and diverse criteria. According to Saaty's scale (in Table 3.4), the AHP is used for pairwise comparison of study criteria (Saaty, 1990). In this study, we determined pairwise comparison scores through literature review (Koc et al., 2019).

Table 3.4: Fundamental scale by Saaty (1990)

Importance Score	Definition (Importance)	Meaning

1	Equal	Equal contribution by two activities
3	Moderate	One activity is moderately more important than other in experience
5	Essential or strong	One activity is strongly more important than other in experience
7	Very strong	One activity is strongly more important than other in practice
9	Extreme	One activity is strongly more important than other with highest level of confirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	If an activity X is compared with an activity Y, and the assigned score is one from the above. Then, when Y is compared with X, it has the reciprocal value of the above.	

Based on the scores obtained from the pairwise comparisons, we constructed pairwise comparison matrices (denoted as Mx) to facilitate the process of selecting optimal wind and solar sites, as depicted in equation (1).

$$M_x = \begin{vmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ . & . & . & . \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{vmatrix} \qquad (1)$$

$M_x = \left|A_{ij}\right| \forall i, j = 1,2,3...,n$ for n criteria used in the study that controls the suitability of power system, where A_{ij} depicts the importance of the one suitability criteria A_i relative to A_j ;the importance of A_j relative to A_i will be A_{ji} or $\frac{1}{A_{ij}} \forall i \neq j$; and $A_{ii} = 1$ (Ali et al., 2019). So, we evaluated all the criteria using the matrix described in equation (1). After that we used weightage based on normalized individual Eigen vectors.

During the process of assigning scores in the context of pairwise comparisons, it is possible for inconsistencies to occur. To address this, we used a method developed by Saaty that checks for inconsistencies using consistency ratio (CR). For the results to be acceptable in the assessment, the CR value should be less than 0.1.

To calculate CR, we need to know the value of Consistency Index (CI). The equation to calculate CI is given below:

$$CI = \left(\frac{\lambda_{\max} - n}{n-1} \right) \qquad (2)$$

Where,

$\lambda_{\max}$ = maximum Eigen value

n = Size of matrix is n x n

CR is calculated by employing equation (3):

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

Where,

RI = Random consistency index, and its values is based on matrix size

3.2.1.5 Generate suitability map by weighted overlay method

After obtaining the categorized map for each suitability criteria in five standard suitability classes, and the weight of each suitability criteria based on the relative importance score from the AHP; we prepared final suitability maps using weighted overlay tool available in ArcMap 10.8. Weighted overlay is a precise statistical tool that eases the integration of information based on the criteria and its classes using Eq. (4) (Elkadeem et al., 2021). The raster maps of the suitability classes were multiplied with the weight values obtained from AHP, and the result for each suitability criteria for a grid cell was added to obtain the final value of suitability index for the grid cell.

Similarly, the analysis was continued for each grid cell to obtain the suitability index value of the study area.

$$SI_b = \sum_{a=1}^{n} w_a \times x_{a,b} \qquad (4)$$

Where,

SI_b = Suitability index for grid cell "b",

n = Number of Criteria used in analysis

w_a = Weight of the criteria "a" (e.g. solar irradiation, wind speed, slope, aspect, etc.) and

$x_{a,b}$ = Suitability score of grid cell "b" under criteria "a".

3.2.1.6 Generate suitability map for hybrid system

After obtaining the suitability map of wind and solar power system, we analyzed the area for hybrid system by adopting the lowest grid suitability value among wind and solar suitability. For instance, if a grid is highly suitable for solar energy but only moderately suitable for wind energy, it is considered moderately suitable for the hybrid system. If there is no available data for solar/wind suitability, those grids are assigned a "no data" status.

3.2.2 Techno-economic analysis

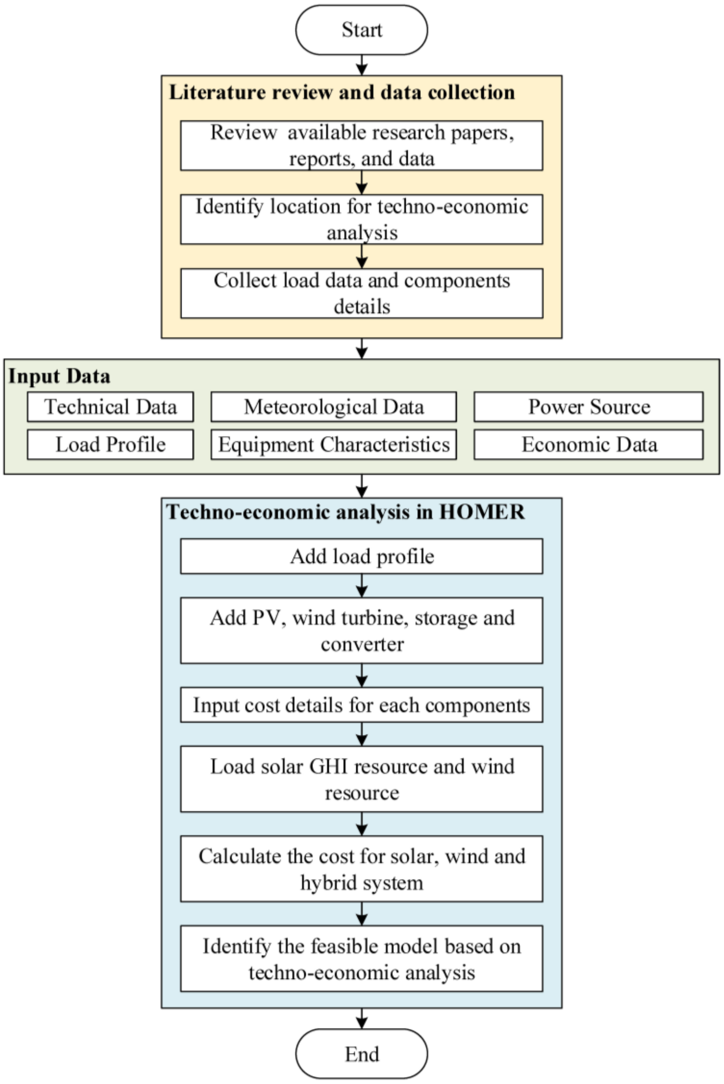

Figure 3.4: Methodological framework for techno-economic feasibility analysis

3.2.2.1 Literature review and data collection

We analyzed the prepared suitability map, and available literature to select a site for the techno-economic feasibility analysis. The data sources for the site case study was identified, and collected for the analysis process.

3.2.2.2 Input data preparation

Poudel and Shakya (2017) and Bhandari et al. (2014) was used to collect data on the location details, load profile, and other technical characteristics for the hybrid power system. Furthermore, solar resource data and wind resource data was collected from the NASA's open data portal (https://data.nasa.gov/). The cost information were collected from Bista et al. (2020).

3.2.2.3 Assess techno-economic feasibility in HOMER

Based on the inputs the feasibility of different power systems i.e. solar, wind and hybrid (solar and wind) were analyzed, and the technically suitable system with the least cost was selected as the best system for the implementation.

CHAPTER FOUR: ANALYSIS

4.1. Suitability analysis criteria

The selection of the criteria for the evaluation of wind and solar suitability were obtained through a relevant literature analysis. Each of the criteria for evaluation are classified into 5 classes with 1 being "highly suitable" and 5 being "not suitable". The area where the data are not available are classified as "no data".

4.1.1 Solar Radiation

Solar radiation (SR), electromagnetic energy from sun, provides the energy needed to generate electricity through photovoltaic processes (Koc et al., 2019). The sites with higher solar radiation level ensures greater energy output and efficiency for solar power installation sites. For the evaluation of areas suitable for solar power plants, we have classified solar radiation obtained from Solargis (2021) into five classes: i) highly suitable (> 5.6 kWh/m^{2}day), ii) suitable (5.0 – 5.6 kWh/m^{2}day), iii) moderately suitable (4.4 – 5.0 kWh/m^{2}day), iv) less suitable (3.8 – 4.4 kWh/m^{2}day), and v) not suitable (< 3.8 kWh/m^{2}day) (in Figure 4.1).

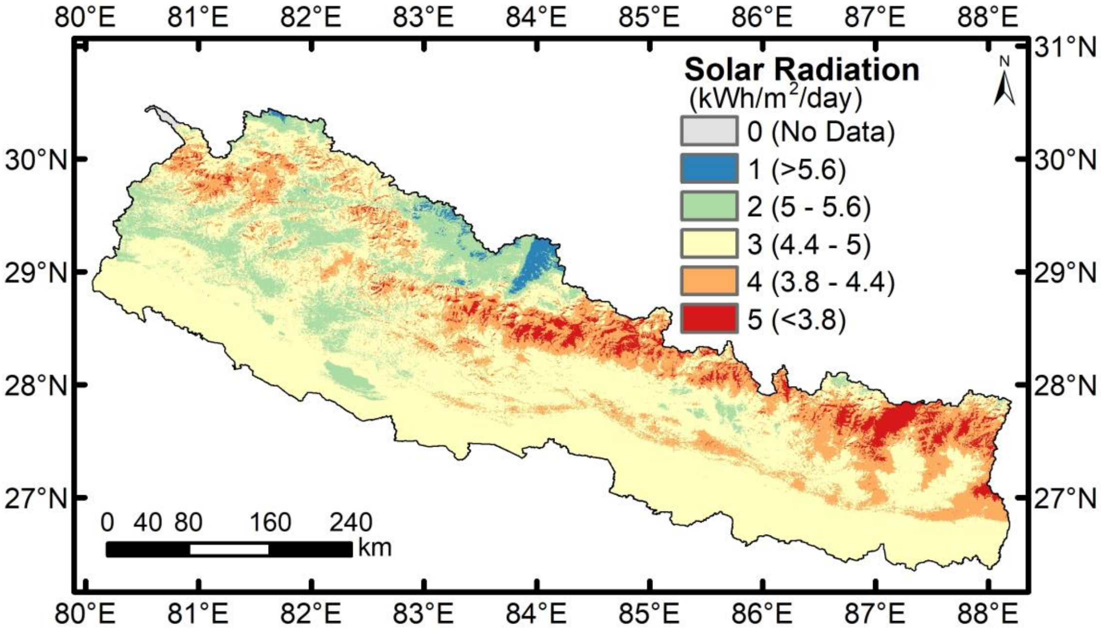

Figure 4.1: Solar radiation criteria classification for solar power plant

4.1.2 Wind Velocity

The average wind velocity (WV) is an essential factor in assessing the economic viability and technical feasibility of sites for installing wind energy systems (Saraswat et al., 2021). We have obtained the data for wind velocity from (DTU, 2015), and classified the data into five classes: i) highly suitable (> 6 m/s), ii) suitable (5 – 6 m/s), iii) moderately suitable (4 – 5 m/s), iv) less suitable (3 – 4 m/s), and v) not suitable (<3 m/s) (in Figure 4.2).

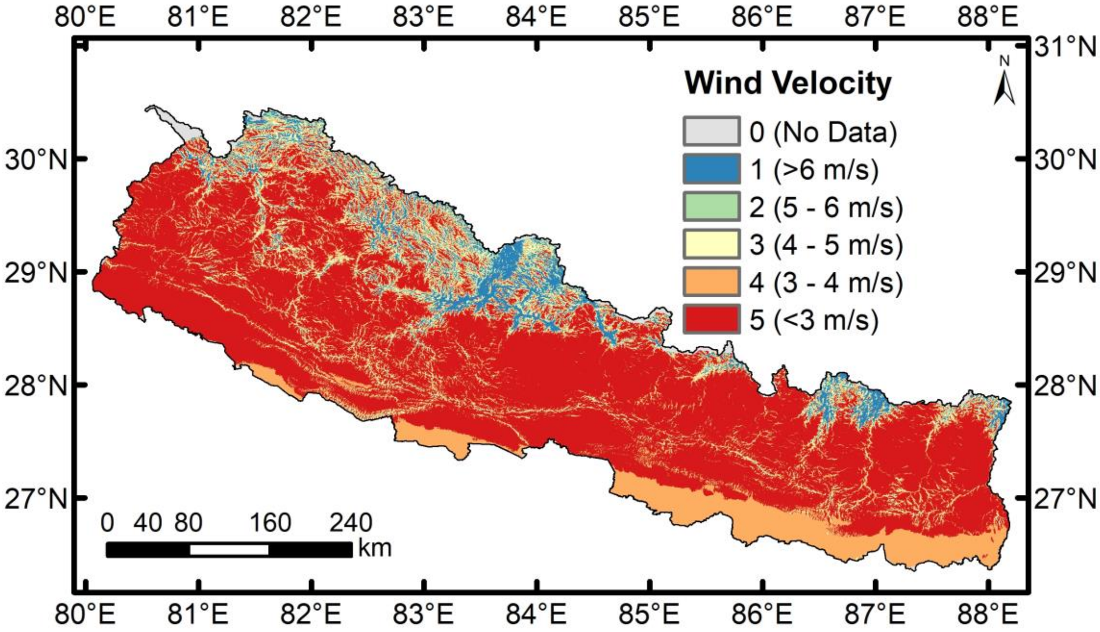

Figure 4.2: Wind velocity criteria classification for wind power plant

4.1.3 Slope

The slope (SLP) inclination is one of the major criteria to identify the site for solar and wind power generation; it mainly influences the output potential and the construction cost for solar and wind power (Koc et al., 2019). The digital elevation model from USGS is used to extract the slope inclination for the area. The slope inclination for solar suitability area are preferred at slightly lower inclination; so we classified slope into five classes: i) highly suitable (0° – 2°), ii) suitable (2° – 3°), iii) moderately suitable (3° – 5°), iv) less suitable (5° – 10°), and v) not suitable (> 10°) (in Figure 4.3). The slope inclination for wind suitability area can accommodate slightly steeper slope inclination; so we classified slope into five classes: i) highly suitable (0° – 6°), ii) suitable (6° – 9°), iii) moderately suitable (9° – 12°), iv) less suitable (12° – 15°), and v) not suitable (> 15°) (in Figure 4.4).

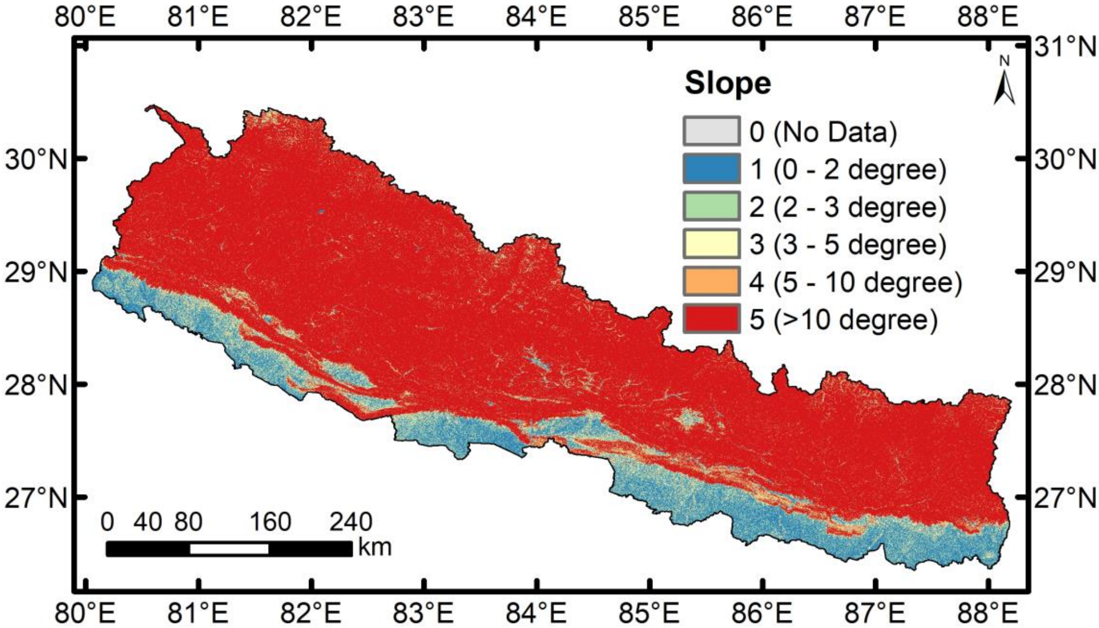

Figure 4.3: Slope criteria classification for solar power plant

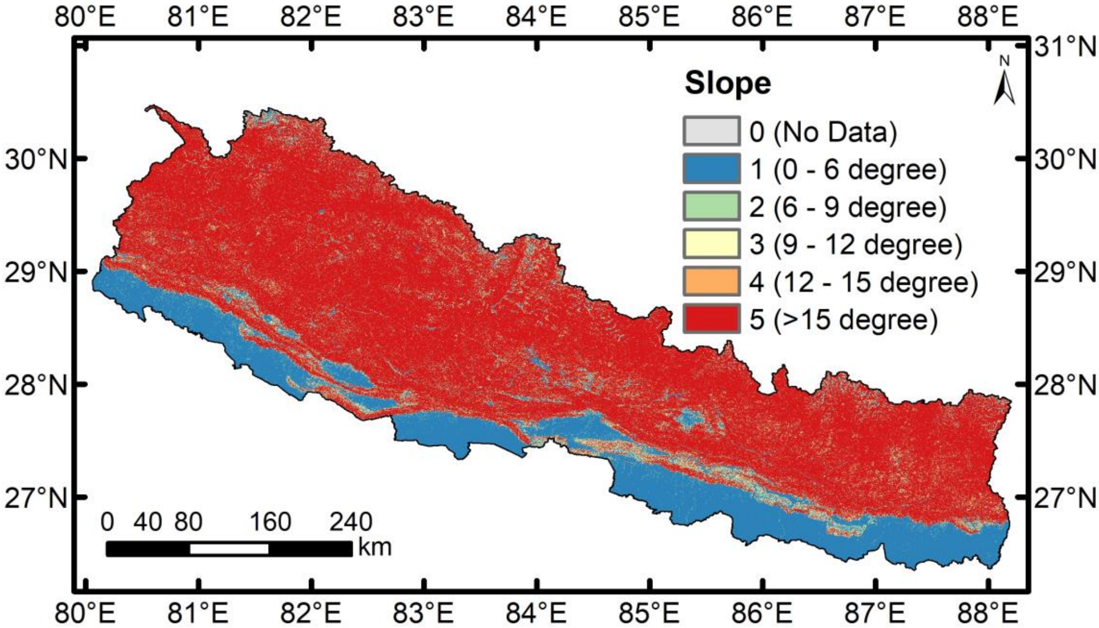

Figure 4.4: Slope criteria classification for wind power plant

4.1.4 Aspect

Aspect (ASP) is pivotal in determining the efficiency of solar energy plants, as it helps to determine the optimum direction to receive maximum solar radiation. As Nepal is located in northern hemisphere, maximum solar radiation is received towards the south direction (Saraswat et al., 2021). The digital elevation model from USGS is used to extract the aspect direction for the area. We have classified aspect into five classes: i) highly suitable (South and Flat), ii) suitable (Southeast and Southwest), iii) moderately suitable (East and West), iv) less suitable (Northeast and Northwest), and v) not suitable (North) (in Figure 4.5).

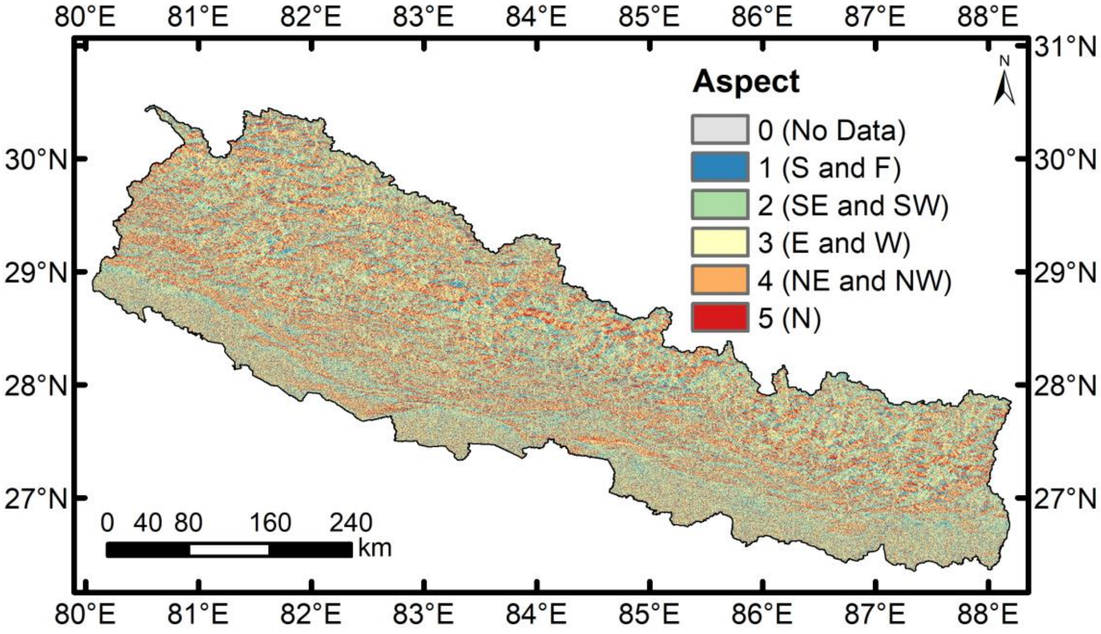

Figure 4.5: Aspect criteria classification for solar power plant

4.1.5 Elevation

Saraswat et al. (2021) and (Ali et al., 2019) defined elevation (ELE) as an important factor to determine suitability for solar and wind power plants, and recommends lower elevation for the establishment of the wind and solar power plants. The digital elevation model from USGS is used to extract the elevation for the area. Based on these, for solar power plant, we have classified elevation into five classes: i) highly suitable (< 300 m), ii) suitable (300 – 700 m), iii) moderately suitable (700 – 1100 m), iv) less suitable (1100 – 1500 m), and v) not suitable (> 1500 m) (in Figure 4.6). Similarly, for wind power plant, we have classified elevation into five classes: i) highly suitable (< 500 m),

ii) suitable (500 – 1000 m), iii) moderately suitable (1000 – 1500 m), iv) less suitable (1500 – 2000 m), and v) not suitable (> 2000 m) (in Figure 4.7).

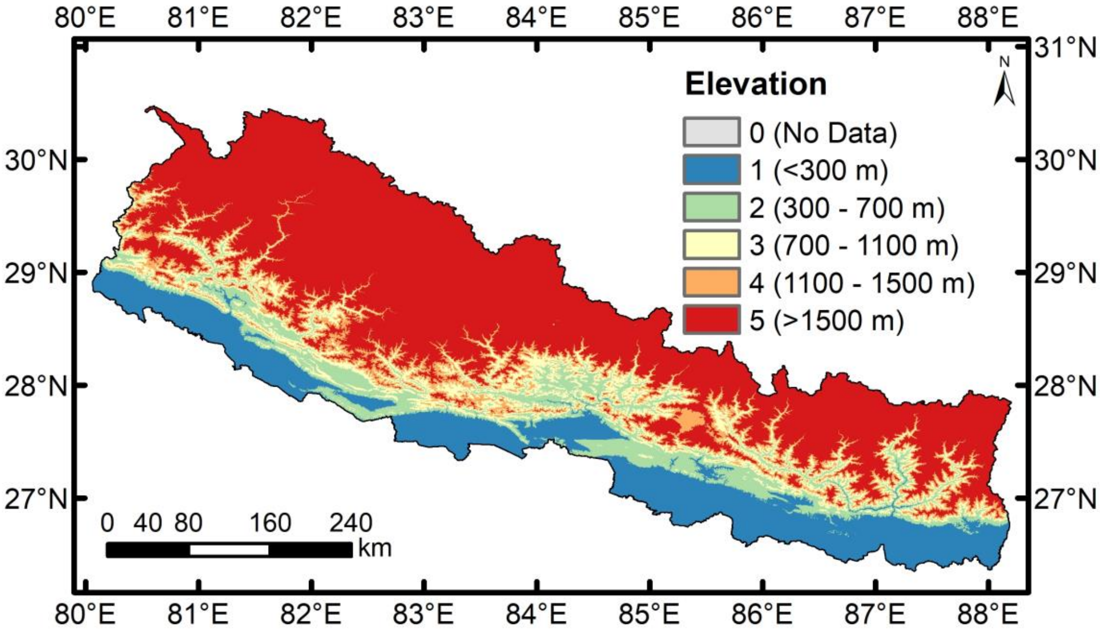

Figure 4.6: Elevation criteria classification for solar power plant

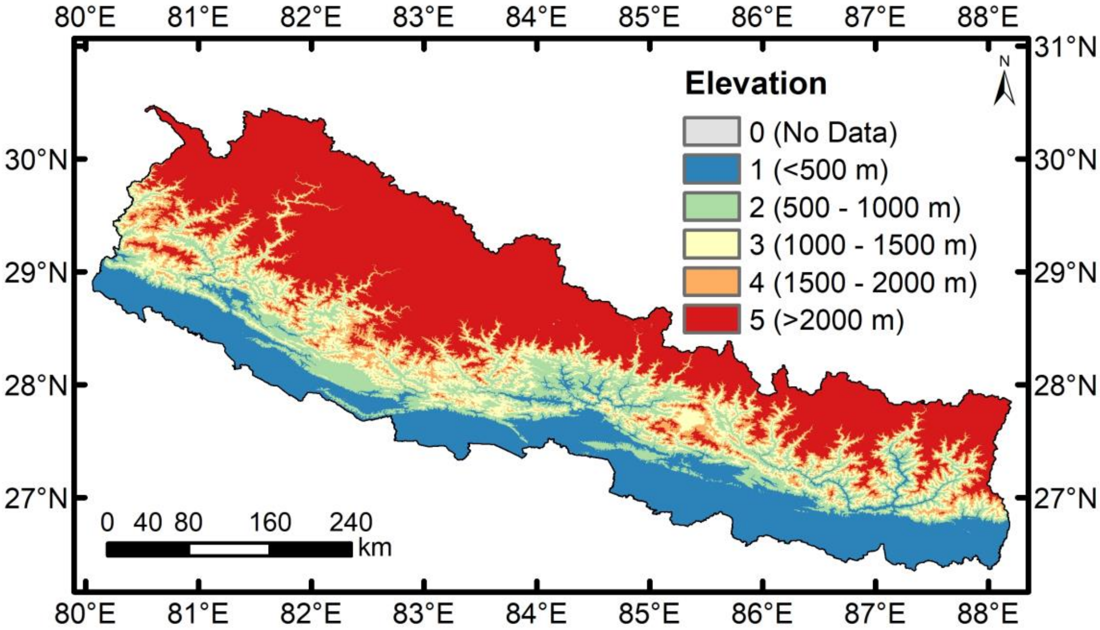

Figure 4.7: Elevation criteria classification for wind power plant

4.1.6 Distance from water bodies

The distance from water bodies (DWB) criteria is used to protect the solar and wind energy infrastructures from extreme events like flooding, and also to limit the negative effects or prevent contamination of water sources for solar and wind installations (Ali et al., 2019; Saraswat et al., 2021). The distance from water bodies data was obtained and modified from OSM (2023). For solar and wind power plants, we have classified distance from water bodies into five classes: i) highly suitable (> 28 km), ii) suitable (21 – 28 km), iii) moderately suitable (14 – 21 km), iv) less suitable (7 – 14 km), and v) not suitable (< 7 km) (in Figure 4.8).

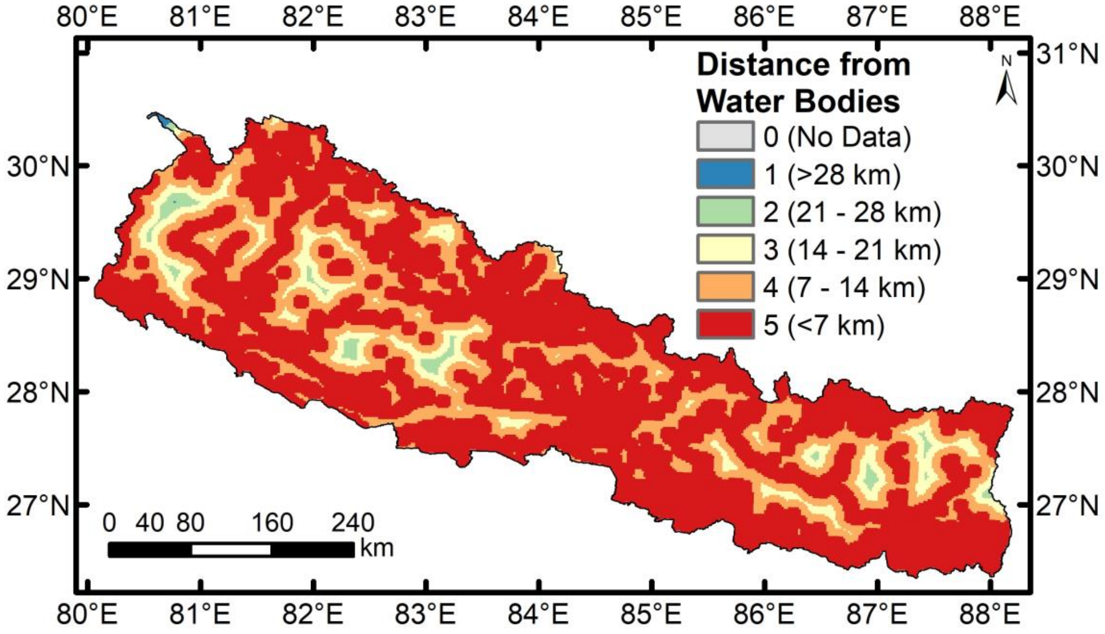

Figure 4.8: Distance from water bodies criteria classification for wind and solar power plant

4.1.7 Distances from airports

For solar farms, the reflection of sunlight (glint and glare) from panels can potentially interfere with pilots' visibility and negatively affect radar systems when panels are closely positioned (Ali et al., 2019). Similarly, wind turbines can disrupt crucial airport surveillance radar signals, which are essential for air traffic control (Saraswat et al., 2021). The locations of airports in Nepal was obtained from ICIMOD (2008). For solar and wind power plants, we have classified distance from airports (DFA) into five classes: i) highly suitable (> 28 km), ii) suitable (21 – 28 km), iii) moderately suitable (14 – 21 km), iv) less suitable (7 – 14 km), and v) not suitable (< 7 km) (in Figure 4.9).

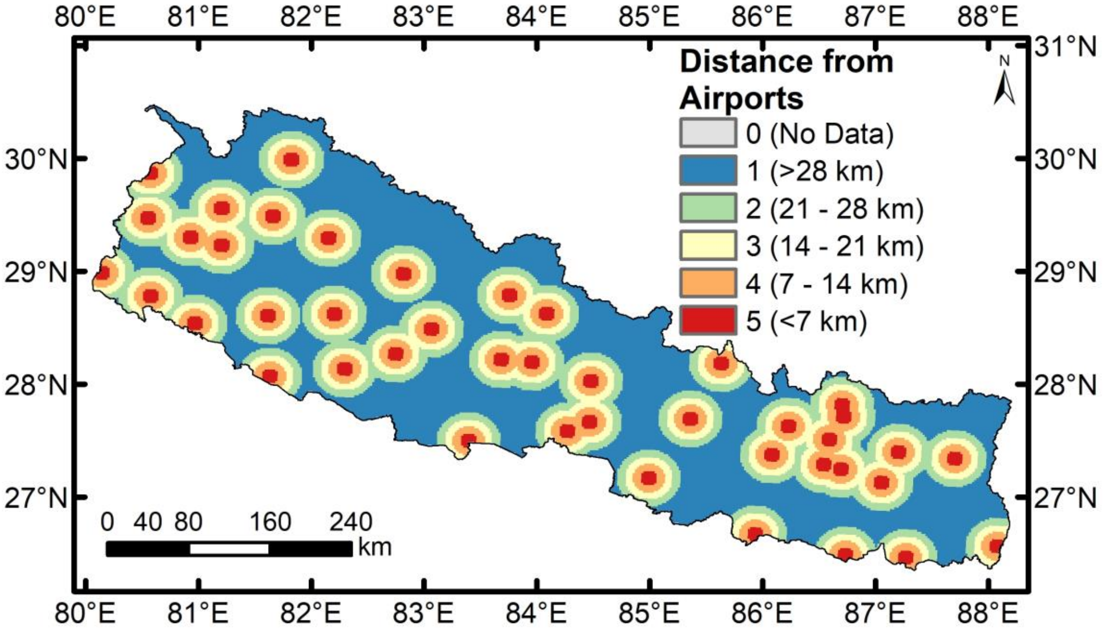

Figure 4.9: Distance from airports criteria classification for wind and solar power plant

4.1.8 Distance from wildlife designations

The protected areas in the country, such as, national parks, hunting reserves and other wildlife designated areas should be protected from the intervention due to infrastructural construction. Therefore, the buffer for the protection of these areas is instrumental to be considered while identifying suitable areas for the construction of energy schemes (Saraswat et al., 2021). The location of wildlife designations were identified from GON (2021). For solar and wind power plants, we have classified distance from wildlife designations (DWD) into five classes: i) highly suitable (> 40 km), ii) suitable (30 – 40 km), iii) moderately suitable (20 – 30 km), iv) less suitable (10 – 20 km), and v) not suitable (< 10 km) (in Figure 4.10).

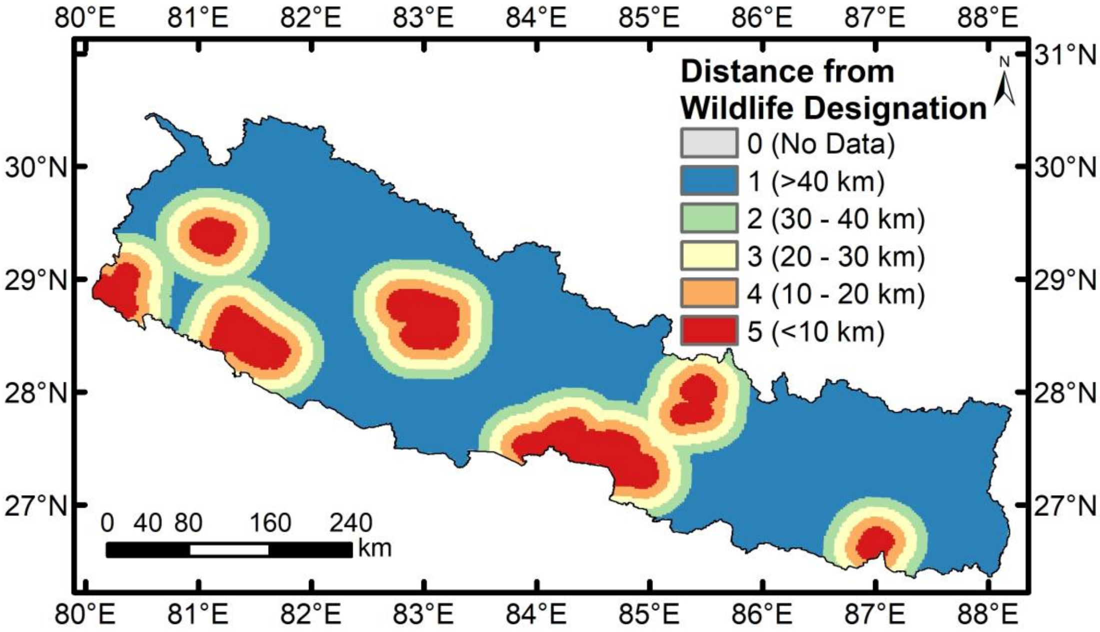

Figure 4.10: Distance from wildlife designations criteria classification for wind and solar power plant

4.1.9 Land use

The development of wind and solar energy projects prioritizes areas with limited land cover (i.e. barren land) as most feasible, and in case of the vegetated land areas, the areas with short vegetation are preferred to the tall ones. In case of wind turbines, taller vegetation increases the turbulence and may cause the rotary elements of the turbine to fail; and in case of solar PV panels, tall vegetation directly obstructs the solar insolation that will decrease the efficiency and generation capacity (Ali et al., 2019). The land use (LU) of the areas was analyzed using the data from ICIMOD (2021).For solar and wind power plants, we have classified distance from land use into five classes: i) highly suitable (barren), ii) suitable (grassland), iii) moderately suitable (cropland), iv) less suitable (wetland), and v) not suitable (forest and built-up areas) (in Figure 4.11).

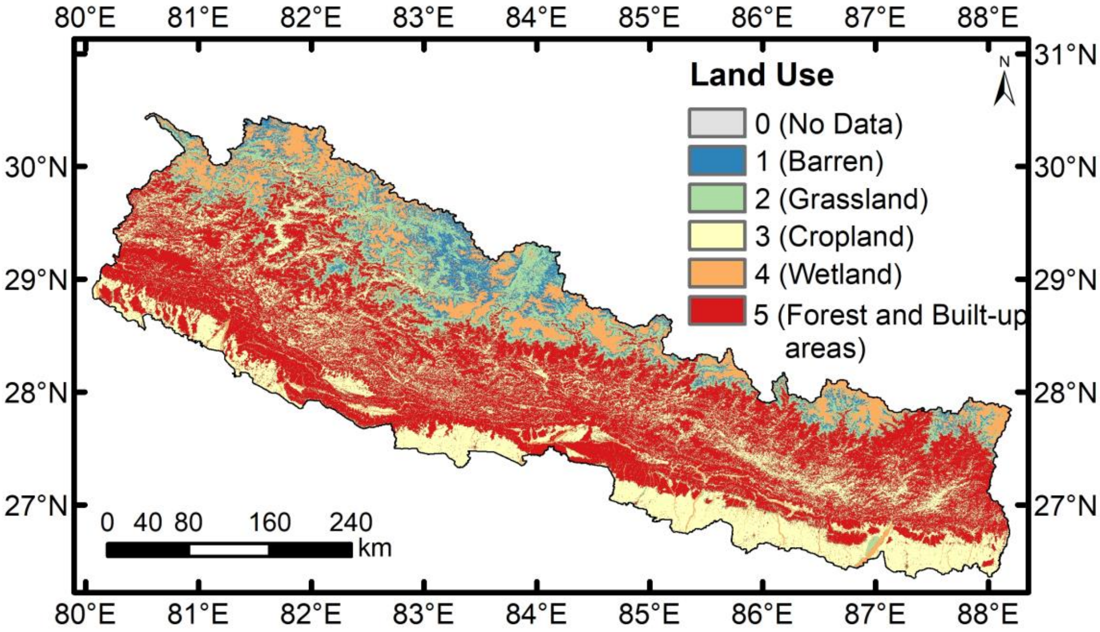

Figure 4.11: Land use criteria classification for wind and solar power plant

4.1.10 Distance from urban areas

The distance from the built-up areas is an important factor to consider while selecting the suitable areas for solar and wind power plants. A considerable distance helps prevent problems like visual disruption, noise issues, and allows opportunities for future expansion of built-up areas. The built-up area of Nepal was extracted from ICIMOD (2021). For solar and wind power plants, we have classified distance from urban areas (DFUA) into five classes: i) highly suitable (> 40 km), ii) suitable (30 – 40 km), iii) moderately suitable (20 – 30 km), iv) less suitable (10 – 20 km), and v) not suitable (< 10 km) (in Figure 4.12)

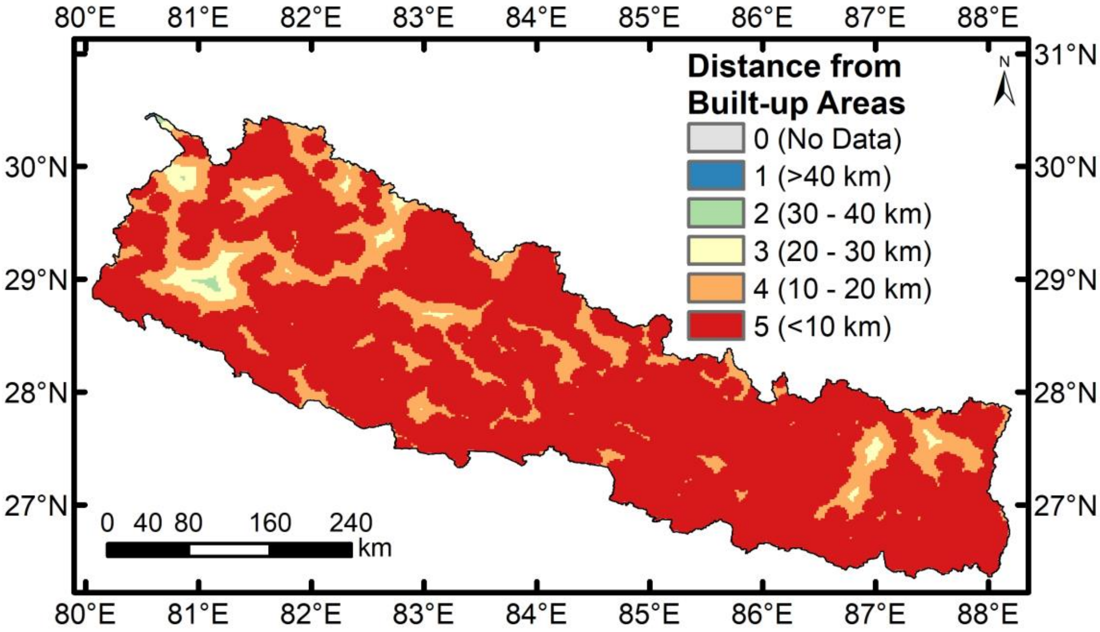

Figure 4.12: Distance from built-up area criteria classification for wind and solar power plant

4.1.11 Distance from roads

This factor is also vital for economics and the environment viewpoint. Ideal spots should be near to road networks to minimize environmental harm and road-building expenses (Saraswat et al., 2021). The distance to roads and transmission lines strongly influences the cost of energy projects (Ali et al., 2019). Longer distances can lead to increased construction expenses and greater power line losses. The location of the road infrastructure were obtained from ICIMOD (2009). For solar and wind power plants, we have classified distance from roads (DFR) into five classes: i) highly suitable (< 10 km), ii) suitable (10 – 20 km), iii) moderately suitable (20 – 30 km), iv) less suitable (30 – 40 km), and v) not suitable (> 40 km) (in Figure 4.13).

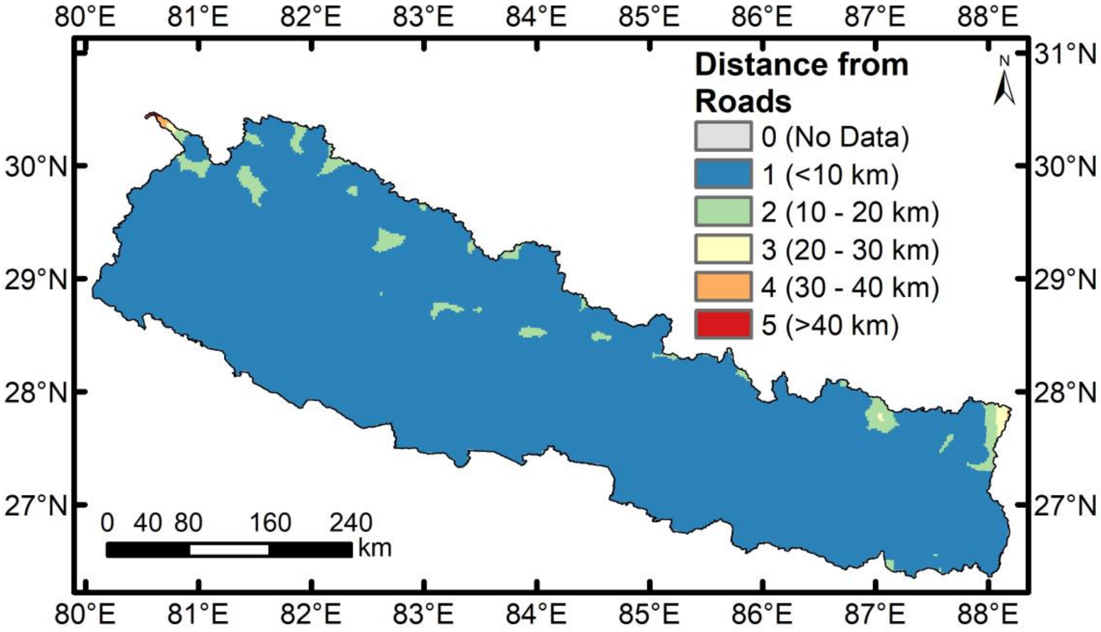

Figure 4.13: Distance from roads criteria classification for wind and solar power plant

4.1.12 Distance from transmission lines

Much like the preceding factors, this criteria is important from economic and environmental viewpoints. The presence of an established transmission network diminishes construction expenditures, ecological harm, and energy losses (Saraswat et al., 2021). The location of the transmission lines were obtained by digitizing Nepal Power Transmission Network Map by RPGCL (2018). For solar and wind power plants, we have classified distance from transmission lines (DFTL) into five classes: i) highly suitable (< 10 km), ii) suitable (10 – 20 km), iii) moderately suitable (20 – 30 km), iv) less suitable (30 – 40 km), and v) not suitable (> 40 km) (in Figure 4.14).

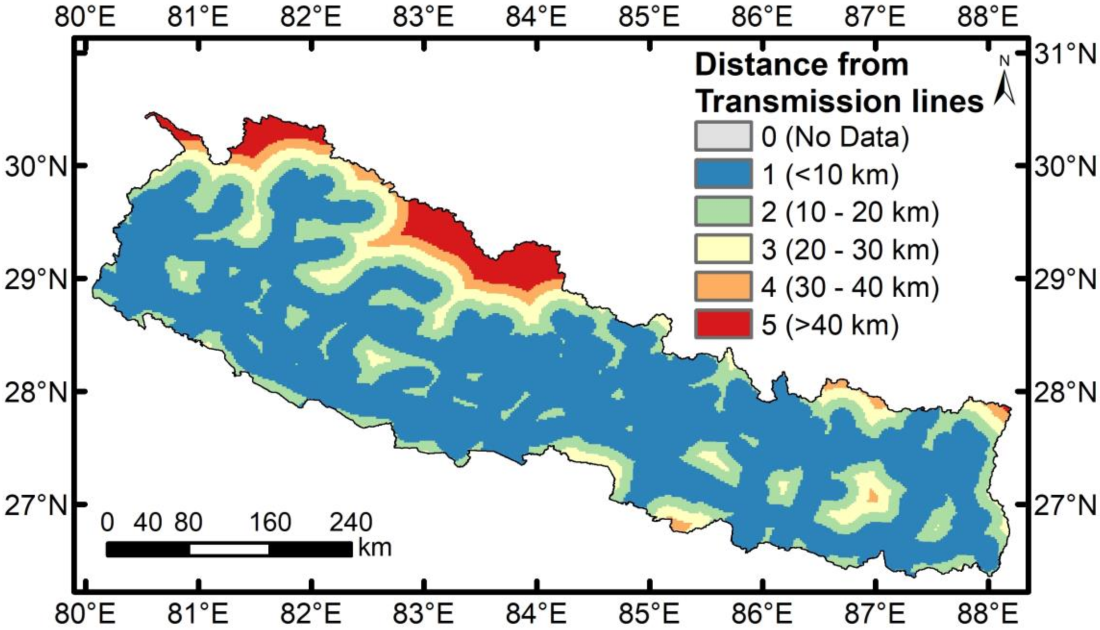

Figure 4.14: Distance from transmission lines criteria classification for wind and solar power plant

4.1.13 Distance from power plants

Saraswat et al. (2021) contend that situating solar and wind power plants close to existing power facilities mitigates challenges related to access, such as road and transmission infrastructure, leading to enhanced economic and environmental feasibility. The location of the power plants were obtained by digitizing Nepal Power Transmission Network Map by RPGCL (2018). For solar and wind power plants, we have classified distance from power plants (DFPP) into five classes: i) highly suitable (< 10 km), ii) suitable (10 – 20 km), iii) moderately suitable (20 – 30 km), iv) less suitable (30 – 40 km), and v) not suitable (> 40 km) (in Figure 4.15).

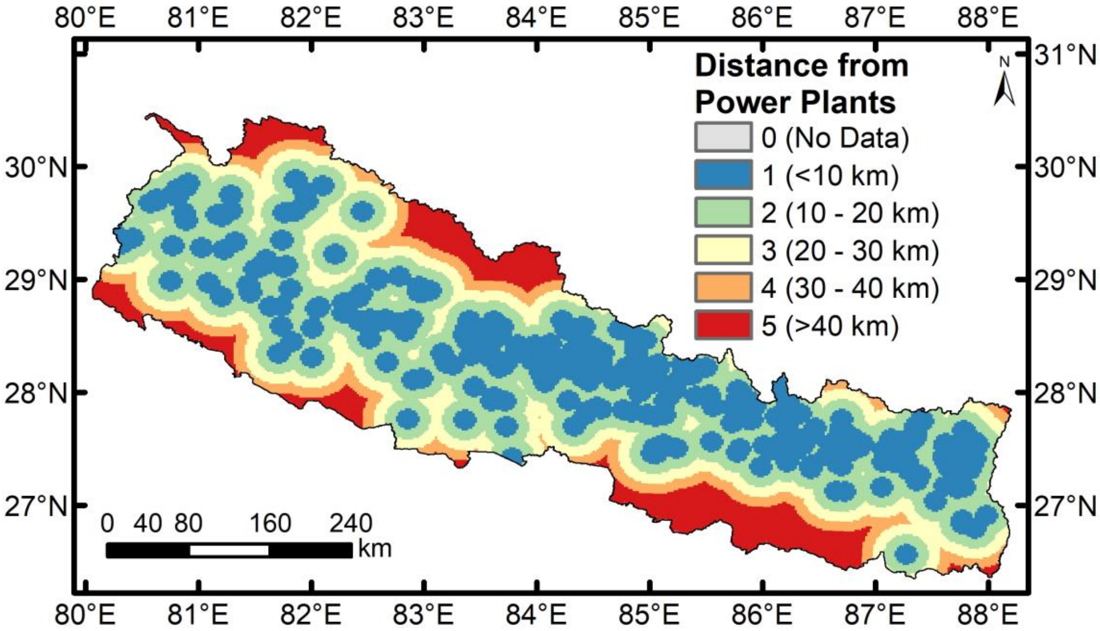

Figure 4.15: Distance from power plants criteria classification for wind and solar power plant

4.2. Weightage from Analytical Hierarchy Process (AHP)

The score from the pairwise comparison matrix is presented in Table 4.1 and Table 4.2. The calculation is done in MS Excel using AHP calculation sheet. The weightage for each criteria and their CR is presented in Table 4.3.

Table 4.1: Priority Matrix for Solar Suitability

Compare	SR	SLP	ASP	ELE	DWB	DFA	DWD	LU	DFUA	DFR	DFTL	DFPP
SR	1	2	2	2	4	5	3	2	3	2	2	4
SLP	0.5	1	0.5	1	2	2	1	1	1	1	1	2
ASP	0.5	2	1	1	3	3	2	1	2	2	1	3
ELE	0.5	1	1	1	2	2	2	1	2	1	1	2
DWB	0.25	0.5	0.333333	0.5	1	1	1	0.5	0.5	0.5	0.5	1
DFA	0.2	0.5	0.333333	0.5	1	1	0.5	0.5	0.5	0.5	0.333333	1
DWD	0.333333	1	0.5	0.5	1	2	1	0.5	1	0.5	0.5	1
LU	0.5	1	1	1	2	2	2	1	1	1	1	2
DFUA	0.333333	1	0.5	0.5	2	2	1	1	1	1	1	2
DFR	0.5	1	0.5	1	2	2	2	1	1	1	1	2
DFTL	0.5	1	1	1	2	3	2	1	1	1	1	2
DFPP	0.25	0.5	0.333333	0.5	1	1	1	0.5	0.5	0.5	0.5	1

Table 4.2: Priority Matrix for Wind Suitability

Compare	WV	SLP	ELE	DWB	DFA	DWD	LU	DFUA	DFR	DFTL	DFPP
WV	1	2	2	4	3	3	3	4	3	2	4
SLP	0.5	1	1	2	2	1	2	3	2	0.5	2
ELE	0.5	1	1	3	2	1	2	3	1	1	3
DWB	0.25	0.5	0.333333	1	0.5	1	0.5	1	0.5	0.5	0.5
DFA	0.333333	0.5	0.5	2	1	0.5	0.5	1	0.5	0.333333	1
DWD	0.333333	1	1	1	2	1	0.5	1	1	0.5	2
LU	0.333333	0.5	0.5	2	2	2	1	2	1	0.5	2
DFUA	0.25	0.333333	0.333333	1	1	1	0.5	1	1	0.5	2
DFR	0.333333	0.5	1	2	2	1	1	1	1	1	2
DFTL	0.5	2	1	2	3	2	2	2	1	1	2
DFPP	0.25	0.5	0.333333	2	1	0.5	0.5	0.5	0.5	0.5	1

Table 4.3: Weightage and consistency ratio for solar and wind energy from AHP

Criteria	Solar Energy		Wind Energy	
Solar Radiation/ Wind Velocity	0.18	CR = 0.009 <0.1(OK) and Principal Eigen Value = 12.16	0.21	CR = 0.029 <0.1(OK) and Principal Eigen Value = 11.44
Slope (degree)	0.08		0.11	
Aspect (slope direction)	0.12			
Elevation	0.1		0.12	
Water bodies	0.04		0.05	
Airports	0.04		0.05	
Wildlife Designation	0.06		0.07	
Land Use	0.09		0.08	
Urban areas	0.07		0.06	
Roads	0.08		0.08	
Transmission lines	0.09		0.12	
Power plants	0.04		0.05	

4.3. Assumptions and Input Parameter for techno-economic analysis in HOMER

4.3.1 Electric Load

In 2012 AD, Bhandari et al. (2014) conducted a load demand assessment survey for households, and we used the same data for electrical demand analysis. The load profile, derived from this survey provides demand trend in the region. Figure 4.16 illustrates the daily load profile, with a scaled yearly average load of 307 kWh/d and a load factor of 0.21. Accounting for 10% day-to-day fluctuation and 15% time-step variability, average and peak demand stand at 12.79 kW and 61.49 kW.

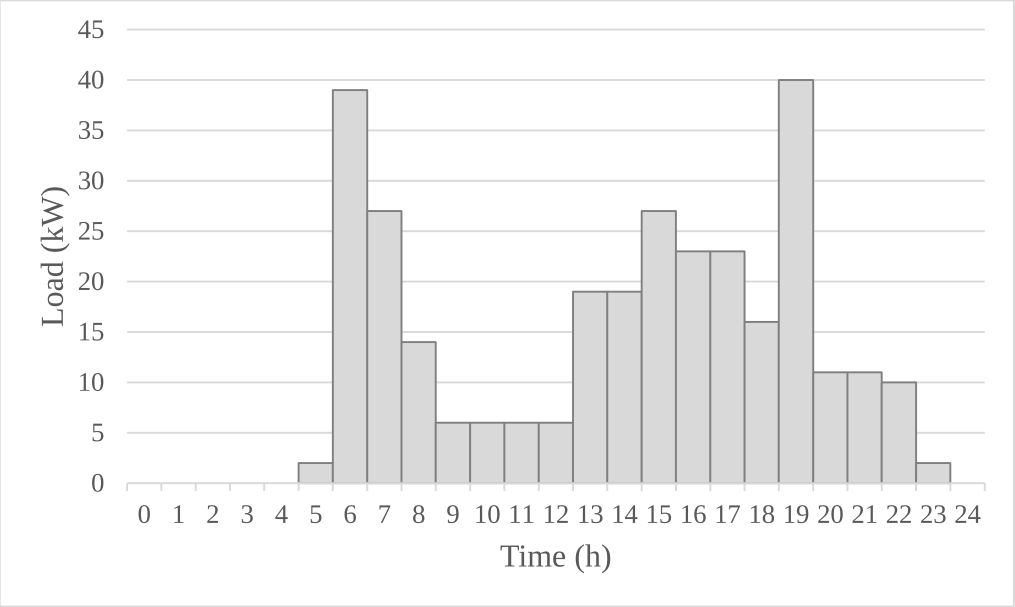

Figure 4.16: Load profile of Thingan, Makwanpur

4.3.2 Solar radiation

The solar radiation data with clearness index was obtained from NASA and used in modeling the solar resource is presented in Figure 4.17. The region experiences a yearly average daily solar radiation of 5.24 kWh/m²/d, coupled with an average clearness index of 0.603.

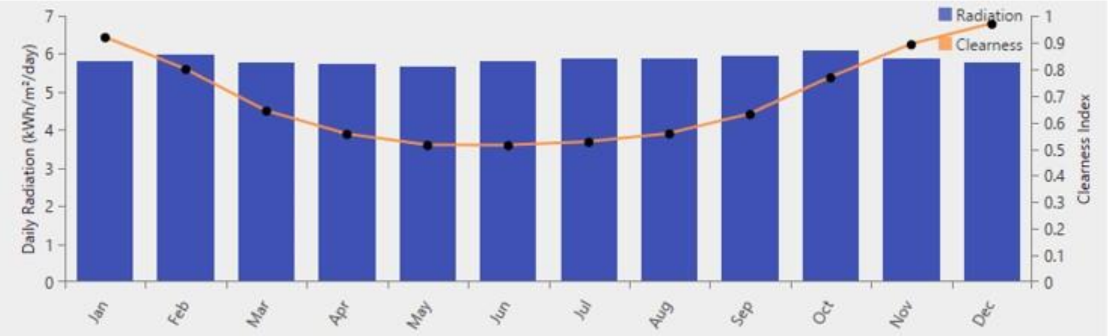

Figure 4.17: Monthly Average Solar Irradiation with clearness index

4.3.3 Wind speed

The Wind speed data obtained from NASA and used in modeling the wind resource is presented in Figure 4.18. Using the data, the area's average annual wind speed is 3.2 m/s at a 10 m anemometer height.

Figure 4.18: Monthly Average Wind Speed

4.3.4 Schematic diagram of the hybrid system

We have used simulation in HOMER to identify the optimal energy system in the region based on the technical and economic criteria. The schematic layout of the proposed hybrid system is presented in Figure 4.19.

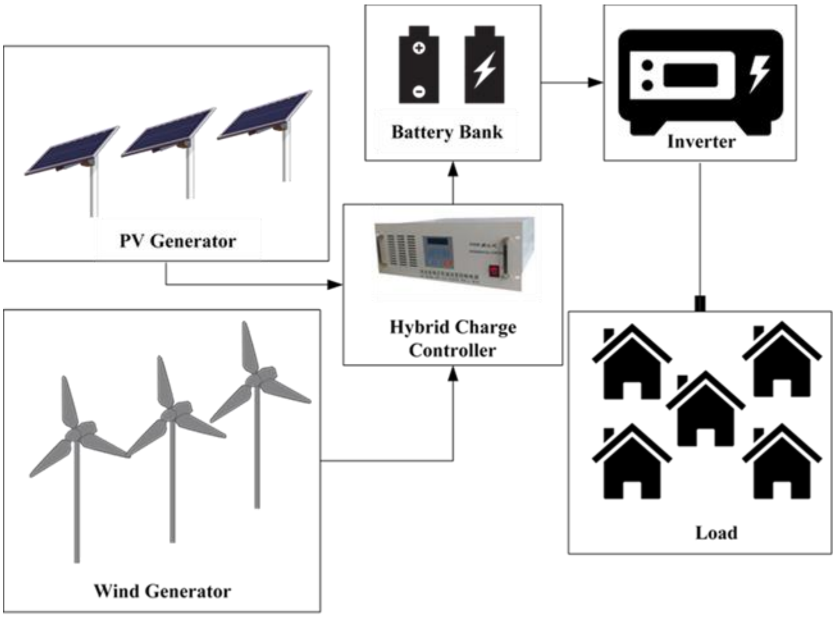

Figure 4.19: Schematic diagram of hybrid power plant

4.3.5 Cost of components

Based on the components required in accordance to the schematic presented, we have collected the cost details of different components from Bista et al. (2020). The details of the component cost are presented in Table 4.4.

Table 4.4: Cost details of the components used in techno-economic analysis

Component	Rating	Capital Cost ($)	Replacement cost ($)	O& M cost ($/yr)	Minimum life (year)	Additional information
Solar PV	1 kW	1000	1000	0	25	Derating factor: 80% Slope: 30degree Azimuth: 0 degree Ground reflectance: 20%
Wind	3 kW	1300	1300	50	20	Hub height: 10m Weibull k: 2 Autocorrelation factor: 0.85
Battery	1 kWh	300	300	10	5	4V, 1900Ah, 7.6kWh
Converter	1 kW	145	145	0	5	Inverter efficiency: 90% Rectifier efficiency: 85%

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1. Suitable areas for different power systems

The evaluation of areas for harnessing energy from solar and wind sources was conducted by integrating suitability maps of each criteria in the GIS with the weight of each criteria obtained from AH and standard suitability classes for each criteria using the weighted overlay tool in ArcMap 10.8 software. For the hybrid system, the lowest suitability value for the grid is taken, for e.g., if a grid is suitable for solar energy but moderately suitable for wind energy, it is taken as moderately suitable for hybrid system; also, if a data is not available for solar/wind suitability, it is assigned to no data. The final maps (depicted in Figure 5.1, Figure 5.2 and Figure 5.3) for solar, wind and hybrid energy sources were categorized to five distinct classes: i) highly suitable, ii) suitable, iii) moderately suitable, iv) less suitable, and v) not suitable. We did not find any region on the suitability classes of not suitable and highly suitable in the current analysis of solar, wind and hybrid system.

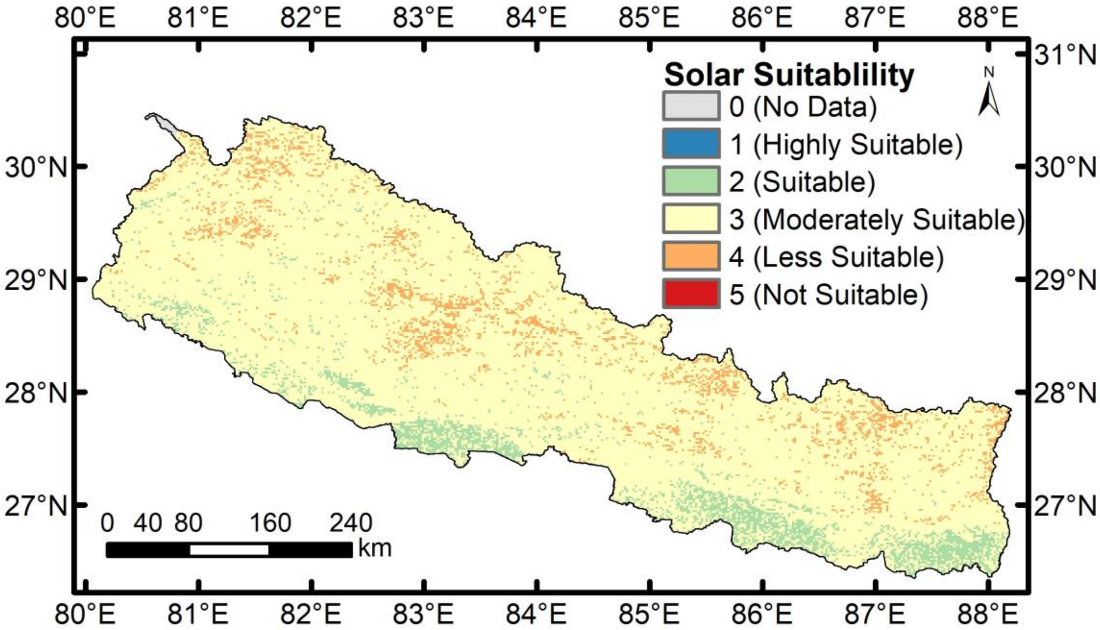

Figure 5.1: Solar Suitability Map

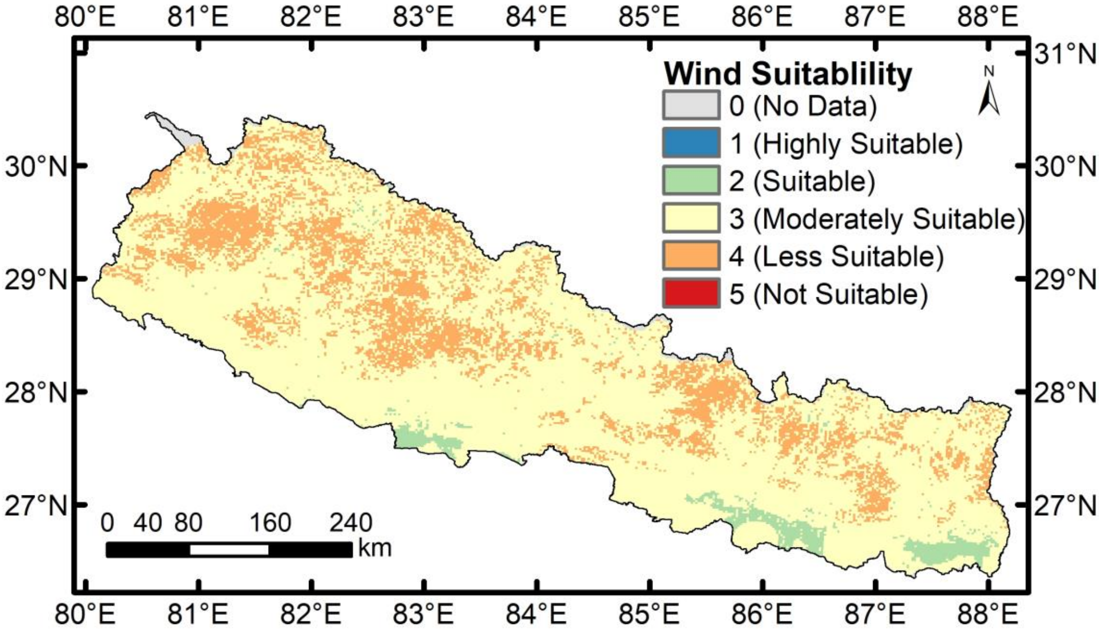

Figure 5.2: Wind Suitability Map

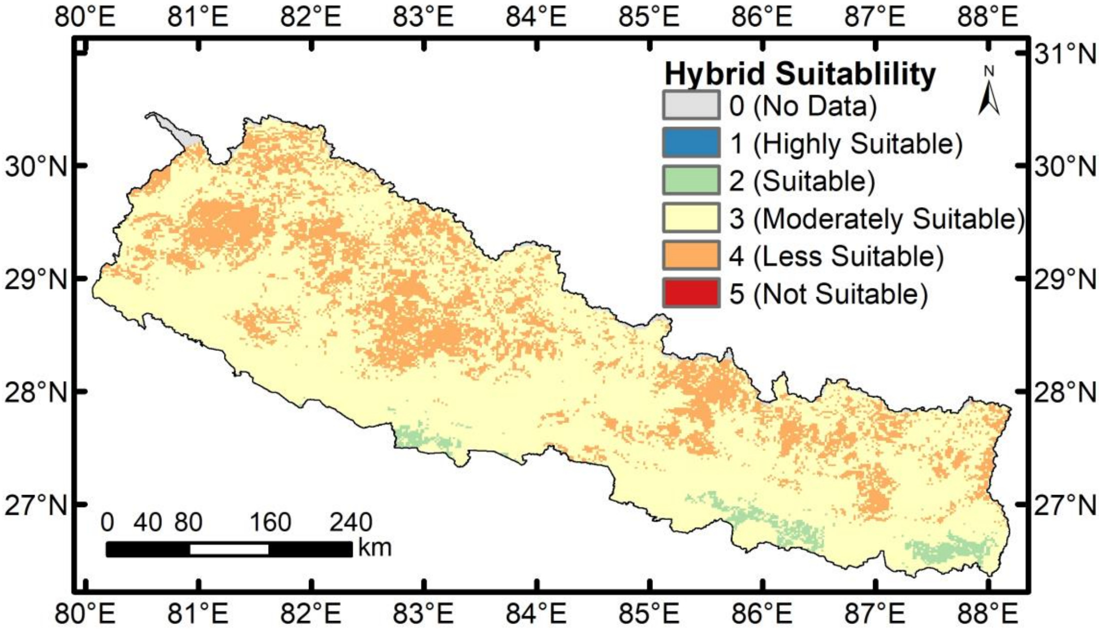

Figure 5.3: Hybrid Suitability Map

The final suitability map depicting the suitability of areas for solar energy, wind energy and hybrid energy highlights that regions classified as 'suitable' accounts for 7.0%, 3.2% and 2.3% of the overall surface area, respectively (in Figure 5.4). It depicts most of the area are moderately suitable for each energy systems, while only some areas are less suitable. The areas that are suitable lies mainly in the Terai regions where the slope is flatter, and other infrastructure related services are abundantly available for the easier access and connectivity.

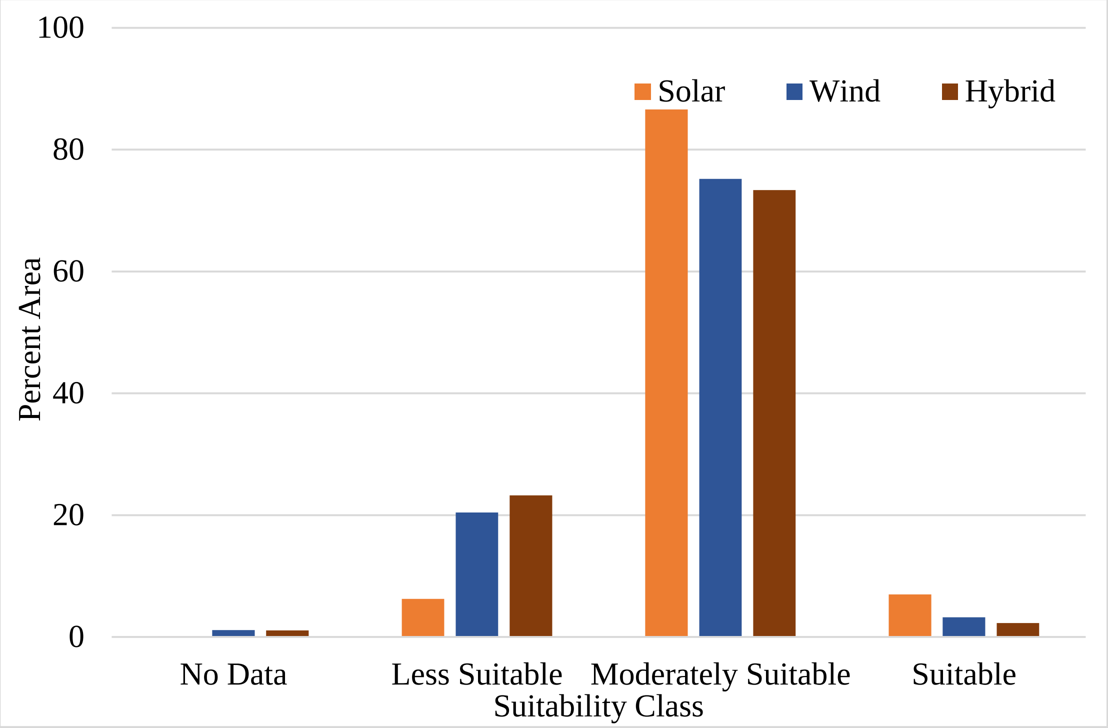

Figure 5.4: Suitability classes for solar, wind and hybrid system

Nepal comprises seven provinces, among these, the Madhesh province stands out with the largest percent area in suitable class for solar, wind, and hybrid energy (in Table 5.1). Furthermore, Lumbini provinces constitutes the second largest portion in percentage area suitable for solar energy. While it is counterintuitive that the Madhesh province constitutes the largest percentage area for wind energy system, infrastructural factors (like roads, power plants and transmission lines), socio-environment factors (like urban areas, airport, etc.), and terrain factor (like slope) are highly conducive for wind energy system in this region and these factors has a greater influence in designating this region as 'suitable'. Furthermore, highest relative importance is provided in pairwise comparison during AHP for the technical factor or energy source (i.e. solar radiation for solar energy and wind velocity for wind energy), so that its weightage is highest among others and provides the most importance basis for the suitability analysis. Also, there is significant potential to increase locations for energy system by improving the transmission networks, road networks, and other infrastructures that positively support the energy generation system.

Table 5.1: Land suitability for different Provinces of Nepal

		Suitability Class (in Percent Area for each province)			
Power Type	Province	No Data	Less Suitable	Moderately Suitable	Suitable
Solar	Koshi	0.03	8.23	82.01	9.73
	Madhesh	0.11	0.00	67.33	**32.56**
	Bagmati	0.03	7.49	90.98	1.50
	Gandaki	0.01	8.71	90.24	1.04
	Lumbini	0.04	2.14	81.47	**16.35**
	Karnali	0.01	6.95	91.93	1.10
	Sudur Pashchim	0.89	5.64	90.07	3.40
Wind	Koshi	0.96	15.24	77.75	6.04
	Madhesh	0.31	0.78	79.10	**19.80**
	Bagmati	1.45	25.79	72.61	0.14
	Gandaki	1.53	17.72	80.41	0.35
	Lumbini	0.28	12.85	81.39	5.47
	Karnali	0.77	28.93	69.90	0.39
	Sudur Pashchim	2.36	28.48	69.07	0.09
Hybrid	Koshi	0.92	19.69	74.61	4.78
	Madhesh	0.32	0.78	84.72	**14.18**
	Bagmati	1.41	28.24	70.35	0.00

Gandaki	1.49	22.49	76.00	0.02
Lumbini	0.27	13.39	82.33	4.01
Karnali	0.73	32.41	66.80	0.06
Sudur Pashchim	2.30	29.77	67.92	0.01

We have employed multi-criteria decision analysis via AHP to determine the logical influence of each criteria for the suitability of the energy systems, and the result must be verified using technical measurements at site such as, wind speed and solar irradiation and socio-economic indicators such as load usage, social acceptance of energy systems, cost-benefit analysis before implementing the energy scheme in the areas.

It's clear that Nepal has significant untapped solar and wind resources. Therefore, the result positively influences the policymakers and investors to invest in clean energy system — that limits the carbon emission, reduces fossil fuel imports, and diversifies our energy mix. Furthermore, the process of identifying suitable locations has a positive influence in enhancing electricity grid and transportation infrastructure, establishing manufacturing facilities, and creating educational and training centers. These could have an overall positive effect in the economic and social development of region.

5.2. Technical and economic analysis of energy systems

5.2.1 Overall energy performance

The study's energy and economic parameters, along with its assumptions, led to the simulation analysis generating a total of 2680 solutions, with 1016 of them being viable options while 1664 solutions were deemed unfeasible due to storage capacity limitations. Out of these numerous solutions, only two were classified as categorized solutions. These optimized solutions are presented in Figure 5.5 for the Thingan, Makwanpur, which experiences an average daily global solar radiation of 5.24 kWh/m²/day and an annual mean wind speed of 3.2 m/s.

Upon examining the Net Present Cost (NPC) and cost of electricity (COE), it's evident from the Figure 5.5 that PV-wind hybrid power plants (with battery storage) with 189kW PV, 15 kW wind turbine and 174 no. of batteries and 66.8kW converter is the most economically favorable option than the PV-battery power plants with 201 kW PV and 174 no. batteries. For the PV-wind hybrid system, solar energy contributes to 99.1% of the hybrid energy system, while wind energy contributes 0.875%, indicating its viability.

Specifically, the cost of electricity (COE) for the PV-wind-battery system is \$0.284/kWh, while the COE for the PV-battery system is slightly higher at \$0.285/kWh.

Wind power alone is deemed inadequate to meet the load demand due to insufficient power generation, mainly attributed to unfavorable wind resource data resulting in a limited capacity for the wind plant.

Architecture									Cost			
				PV (kW)	wind	storage	Converter (kW)	Dispatch	NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)
				189	5	174	66.8	CC	\$411,759	\$0.284	\$11,918	\$257,684
				201		174	65.3	CC	\$412,284	\$0.285	\$11,562	\$262,813

Figure 5.5: Simulation Results from HOMER

5.2.2 Electricity generation

Table 5.2 outlines the electricity output from the PV-wind-battery hybrid power plant, considering a base scenario with a wind speed of 3.2 m/s and global solar radiation of 5.24 kWh/m²/day.

For the PV-wind-battery hybrid power plant, the generated electricity amounts to 329,847 kWh/year, comprising 326,960 kWh/year (99.1%) from solar PV and 2,887 kWh/year (0.875%) from wind. The utilization of this electricity is as follows: 34.25% (111,988 kWh/year) meets household electrical loads, 58.2% (191,870 kWh/year) constitutes excess generation, and 7.54% accounts for losses in the power conversion system (including converter/inverter and battery losses).

For the PV- battery power plant, the generated electricity amounts to 347,438 kWh/year. The utilization of this electricity is as follows: 32.23% (111,996 kWh/year) meets household electrical loads, 60.2% (209,114 kWh/year) constitutes excess generation, and 7.57% accounts for losses in the power conversion system (including converter/inverter and battery losses).

The hybrid power plant, featuring a 189 kW solar PV, 15 kW wind turbine, 66.8 kW converter/inverter, and 174 Surrette 4KS25P batteries, meets the required electrical load and also produces a surplus. The excess electricity can address deferrable loads like water pumping and community center needs, as well as any unforeseen additional electrical demand.

Table 5.2: Energy generation details output from HOMER

Parameters	Hybrid	Solar
Total electricity	329847 kwh/year	347438 kwh/year
Excess electricity	191870 kwh/year (58.2%)	209114 kwh/year (60.2%)
Unmet electric load	66.5 kwh/year	58.9 kwh/year
Capacity shortage	111 kwh/year	106 kwh/year

5.3. Implications for wind, solar and hybrid energy systems in Nepal

The evaluation of renewable energy sources has gained popularity as a pivotal solution to address global energy challenges and environmental concerns. In the specific context of Nepal, an investigation into the potential of wind, solar, and hybrid energy systems reveals promising opportunities for sustainable energy development. In addition, through a techno-economic analysis for a site, this research establishes a foundation for informed decision-making by investors and policymakers, promoting the transition towards cleaner energy alternatives.

Our findings underscore that wind, solar, and hybrid energy systems hold substantial promise within Nepal. Notably, a significant portion of the country's regions falls under the categories of moderately suitable and suitable areas for these renewable sources. This classification serves as a compelling incentive for stakeholders to catalyze the advancement and enhancement of Nepal's clean energy infrastructure.

One of the critical advantages highlighted by this research is the potential reduction in carbon emissions through the adoption of clean energy systems. By mitigating reliance on traditional energy sources, the development of wind, solar, and hybrid solutions aligns with climate-friendly imperatives. Furthermore, the versatility of these systems in addressing diverse energy demands contributes to a sustainable trajectory for Nepal's energy landscape.

Notably, our suitability analysis emphasizes that the most favorable areas for solar, wind, and hybrid energy systems are predominantly situated in Nepal's Terai regions. The topographical characteristics and robust infrastructure of these areas facilitate optimal deployment. In contrast, hilly and mountainous regions exhibit challenges related to terrain features and infrastructure availability, which limits their suitability. To fully harness the potential of these regions, strategic improvements in transmission networks, road infrastructure, and supporting facilities are paramount. These findings align with the insights presented in the Solar and Wind Energy Resource Assessment in Nepal (SWERA) report by AEPC (2008), thereby reinforcing the robustness of our research outcomes.

The techno-economic analysis provides empirical support for the integration of wind and solar energy systems, strategically combining their potential to establish a consistent energy supply. Considering the inherent variability, intermittency, and occasional insufficiency of each individual renewable source, their collaborative implementation helps to optimize energy generation while mitigating the intrinsic intermittency challenges of renewable energy systems. Furthermore, areas with abundant wind and solar resources can be integrated to the national grid, acting as supplementary energy contributors. This integration effectively alleviates the strain on hydroelectric power facilities during peak demand periods, specifically during dry seasons.

Despite the comprehensive insights provided by this study, it is essential to acknowledge its limitations. The employment of multi-criteria decision analysis (AHP) based on the weightage of each criteria serves as a preliminary tool to assess suitability. Therefore, the results should be validated through direct technical measurements such as wind speed and solar irradiation, as well as socio-economic indicators like load usage and public acceptance, to ensure the feasibility of energy implementation.

In the broader energy context of Nepal, which traditionally focuses on hydropower, our research introduces a compelling case for diversification. By incorporating wind, solar, and hybrid energy systems, Nepal can fortify its energy portfolio against seasonal variations, enhance energy security, and mitigate the repercussions of climate change-induced flow fluctuations in rivers.

In conclusion, this study offers a comprehensive exploration of Nepal's clean energy potential, showcasing the viability of wind, solar, and hybrid energy systems. With actionable insights derived from techno-economic analysis and suitability assessments, this research paves the way for a sustainable and resilient energy future, urging stakeholders to embrace and invest in Nepal's clean energy transition.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

- The evaluation of wind, solar, and hybrid energy systems in Nepal reveals significant promise, especially in moderately suitable and suitable areas. The study emphasizes that Nepal's Terai regions, specifically Madhesh province, offer the most favorable conditions for solar, wind, and hybrid systems due to its robust infrastructure and flatter topography, while challenges in hilly and mountainous areas necessitate improved infrastructural facilities.
- The integration of wind and solar systems into the national grid, particularly in areas with abundant wind and solar resource, mitigates intermittency challenges and reduces strain on hydroelectric facilities during peak demand and/or seasonal deficit, enhancing Nepal's energy resilience. Overall, the research provides compelling evidence for the potential of wind, solar, and hybrid energy systems in Nepal. It encourages diversification from hydropower, paving the way for a sustainable and resilient energy future that stakeholders should invest in.
- The techno-economic analysis validates the strategic integration of wind and solar energy systems to ensure a consistent and cost-effective energy supply, to enhance energy generation, and to mitigate the inherent intermittency issues of renewables.

6.2. Recommendations

- Future research work can focus on enhancing the integration of renewable energy sources (e.g., solar, wind) into existing energy grids.
- In future research works, other criteria like population growth, land availability, grid capacity, noise levels, etc. may be incorporated to enhance the model.
- In future work, the feasibility and cost-effectiveness of various energy sources can be assessed for grid-scale applications using direct technical measurements and up-to-date demand scenarios.

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