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Suitability of Hybrid—solar and wind — power plant in Nepal

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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. 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. 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.

Keywords
suitability, hybrid energy, renewable energy

1. Introduction

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 [1]. 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 [2].

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 [3]. 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 [4]. However, a major challenge of renewable energy is its inconsistent electricity supply [5]. 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 identification of suitable location for power plants has been investigated by employing various methodologies [6]. 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 [7, 8]. 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.

In this context, we aim identify the suitable areas for solar, wind and hybrid system using geo-spatial analysis. In this research, we delineate appropriate areas for generating solar, wind, and hybrid energy in Nepal based on relevant criteria that affects the suitability considering the technical, economic, environmental and social factors. This study integrates the influencing criteria information collected from various sources, ranks their relative importance based on AHP, prepares suitability criteria maps, and integrates both through weighted overlay tool using ArcMap 10.8. The map will assist policy makers and stakeholders as a decision support tool to prioritize the areas to develop the power plant, and support diversifying the energy mix.

2. Methodology

In Nepal, we evaluated regions suitable for harnessing solar, wind and hybrid energy sources. Different factors were collected from the literature that helps in identifying the suitable areas for the generation of solar power, wind power, and its combination [9, 6, 10]. The availability of the data in Nepal and its relevance in Nepalese scenarios were analyzed and relevant criteria were included in the study; this factors were classified in five standard suitability classes for evaluation. Multi-criteria decision-making techniques have been effectively utilized to gather and synthesize information for optimal site selection [11]; in this study, we have used the analytical hierarchy process (AHP) that 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 to calculate weight for each criteria [8, 12, 7]. In the ArcGIS environment, the weighted overlay tool is used to merge the suitability criteria maps with assigned weights. Figure 1 depicts the methodology of the current study.

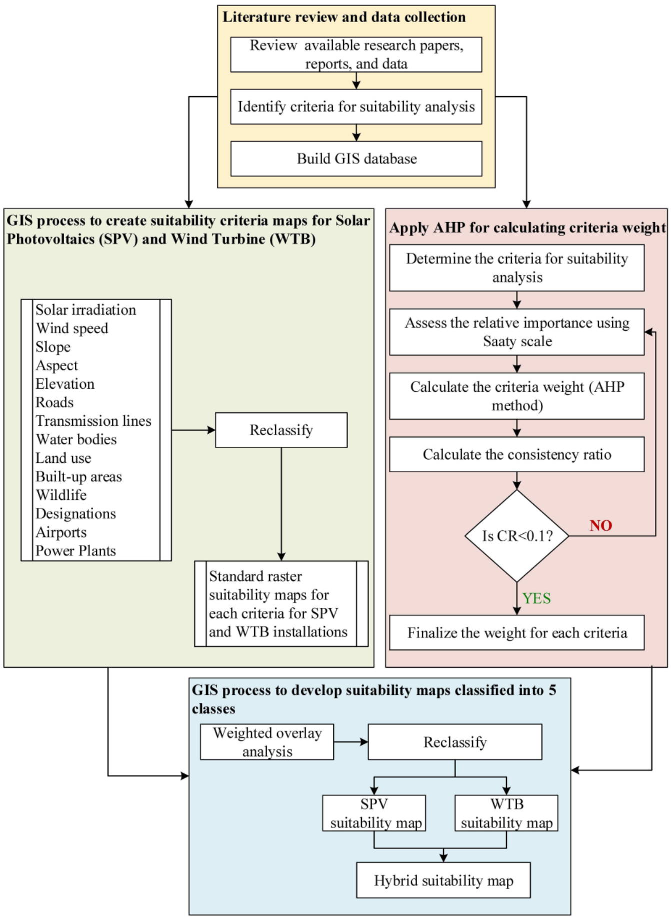

Figure 1: Methodological framework for suitability analysis of different power system

2.1 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 [9, 6, 10]. The availability of the data in Nepal and its relevance in Nepalese scenarios are analyzed and relevant criteria are included in the study. The factors used in the current study, and the sources of the data utilized are depicted in Table 1.

Table 1: Different factors used in the suitability analysis

Factors	Source
Solar Radiation	[13]
Wind Velocity	[14]
Slope Aspect (facing direction) Elevation	Prepared using digital elevation model from [15]
Water bodies locations	[13]
Airports	[16]
Wildlife Designation	[17]
Land Use	[18]
Urban areas	[18]
Roads alignment	[19]
Transmission lines alignment Power plants locations	Digited from [14]

2.2 GIS process to create suitability criteria maps

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 [20, 8, 21, 7]. The factors selected for suitability analysis of solar power and wind power in Table 2 provides the basis for the evaluation of overall suitability of power system.

2.3 Apply Analytical Hierarchy Process (AHP) for calculating weight

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 [10]. MCDA deals with situations where decisions need to be made considering various conflicting and diverse criteria. According to Saaty's scale, the AHP is used for pairwise comparison of study criteria [12]. In this study, we determined pairwise comparison scores through literature review [8].

Based on the scores obtained from the pairwise comparisons, we constructed pairwise comparison matrices (denoted as M_x to facilitate the process of selecting optimal wind and solar

Table 2: Different factors used in the suitability analysis of solar power and wind power with their classification

Criteria	Classes of suitability				
	Highly Suitable	Suitable	Mod. Suitable	Less Suitable	Not Suitable
	1	2	3	4	5
Solar Radiation $\left(in\frac{kWh}{m^2 day}\right)^{**}$	> 5.6	5.0 – 5.6	4.4 – 5.0	3.8 – 4.4	< 3.8
Wind Velocity $\left(in\frac{m}{s}\right)^{***}$	> 6	5 – 6	4 – 5	3 – 4	< 3
Slope (in °)**	0 – 2	2 – 3	3 – 5	5 – 10	> 10
Slope (in °)***	0 – 6	6 – 9	9 – 12	12 – 15	> 15
Aspect (slope direction) **	S and F	SE and SW	E and W	NE and NW	N
Elevation (in m) **	< 300	300 – 700	700 – 1100	1100 – 1500	> 1500
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 Designat- ion (in km)*	> 40	30 – 40	20 – 30	10 – 20	< 10
Land Use type*	Barren	Grass land	Crop land	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 transmiss- ion 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

* Criteria for both Solar and Wind,
** Criteria for Solar Only and
*** Criteria for Wind Only

sites, as depicted in equation 1.

$$M_x = \begin{vmatrix} A_{11} & A_{12} & .... & A_{1n} \\ A_{21} & A_{22} & .... & A_{2n} \\ . & . & ... & . \\ . & . & ... & . \\ A_{n1} & A_{n2} & .... & A_{nn} \end{vmatrix} \tag{1}$$

$M_x = |A_{ij}|\forall i, j = 1,2,3.....,n$ 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_{ij} or $\frac{1}{A_{ij}}\forall i \neq j$; and

$A_{ii} = 1$ [11]. 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 in equation 2:

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

where, λ_{max}=maximum Eigen value n=Size of matrix n x n CR is calculated by employing equation 3.

$$CR = \frac{CI}{RI} \tag{3}$$

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

2.4 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 equation 4 [11]. 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.

$$SI_b = \sum_{a=1}^{n} w_a \times w_{a,b} \tag{4}$$

2.5 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. Analysis

3.1 Suitability maps for each criteria

Based on the Table 2, we prepare maps for each suitability criteria for wind and solar power system into five classes and are depicted in Figure 2.

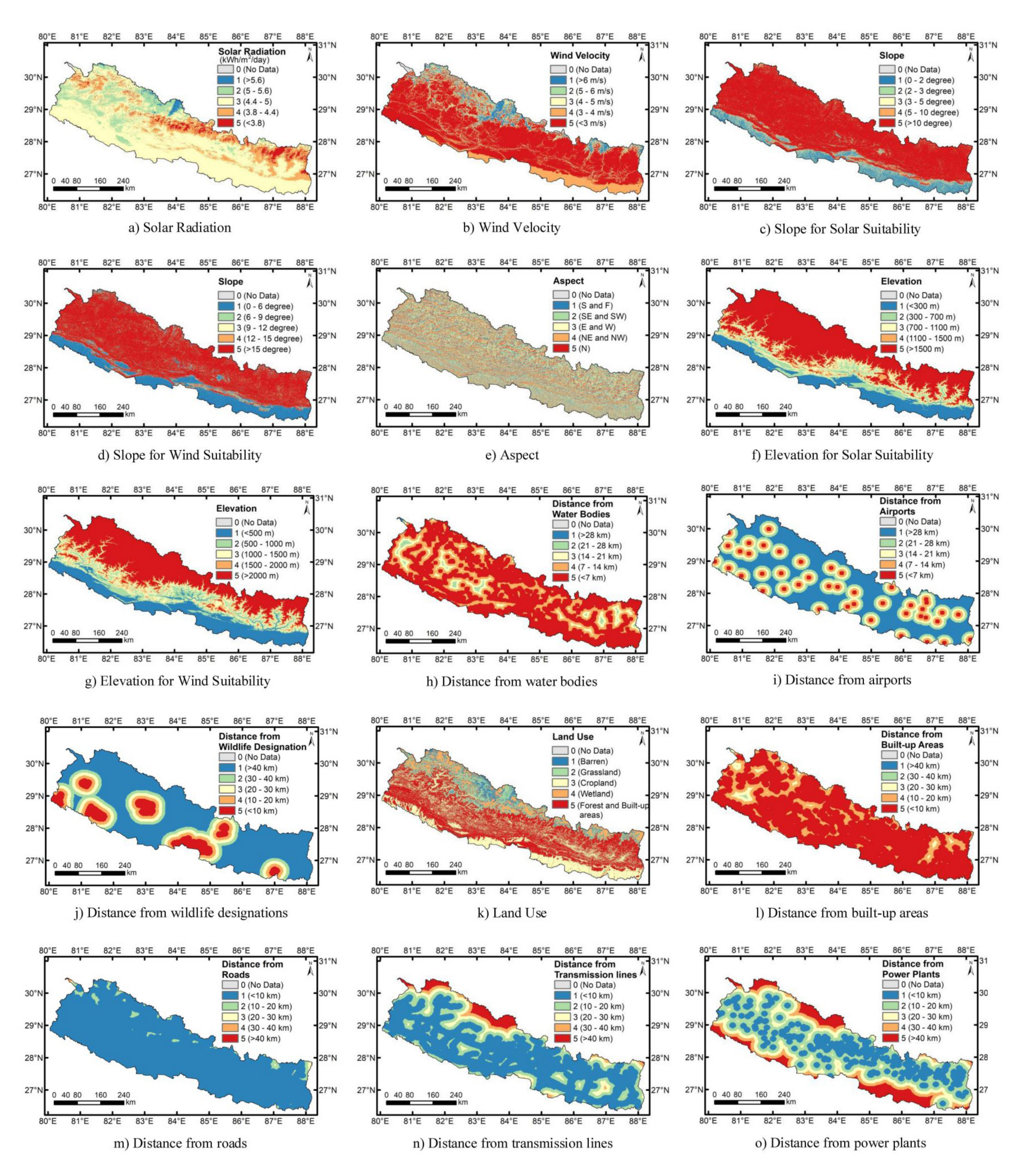

Figure 2: Suitability criteria maps

3.2 Weightage from Analytical Hierarchy Process (AHP)

The score from the pairwise comparison matrix is presented in Figure 3 and Figure 4. The calculation is done in MS Excel using AHP calculation sheet. The weightage for each criteria and their CR is presented in Table 3.

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	0.33	0.5	1	1	1	0.5	0.5	0.5	0.5	1
DFA	0.2	0.5	0.33	0.5	1	1	0.5	0.5	0.5	0.5	0.33	1
DWD	0.33	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	0.33	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	0.33	0.5	1	1	1	0.5	0.5	0.5	0.5	1

Figure 3: Priority matrix for solar 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	0.33	1	0.5	1	0.5	1	0.5	0.5	0.5
DFA	0.33	0.5	0.5	2	1	0.5	0.5	1	0.5	0.33	1
DWD	0.33	1	1	1	2	1	0.5	1	1	0.5	2
LU	0.33	0.5	0.5	2	2	2	1	2	1	0.5	2
DFUA	0.25	0.33	0.33	1	1	1	0.5	1	1	0.5	2
DFR	0.33	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	0.33	2	1	0.5	0.5	0.5	0.5	0.5	1

Figure 4: Priority matrix for wind suitability

4. Results and Discussion

4.1 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 AHP 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, Figure 6 and Figure 7) 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.

Table 3: Weightage and consistency ratio for solar and wind energy from AHP

Criteria	Solar Energy		Wind Energy	
Solar Radiation	0.18		–	
Wind Velocity	–		0.21	
Slope	0.08		0.11	
Aspect (slope direction)	0.12			
Elevation	0.1		0.12	
Water bodies	0.04	CR = 0.009 < 0.1 (OK)	0.05	CR = 0.029 < 0.1 (OK)
Airports	0.04		0.05	
Wildlife Designation	0.06		0.07	
Land Use type	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	

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 8). 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.

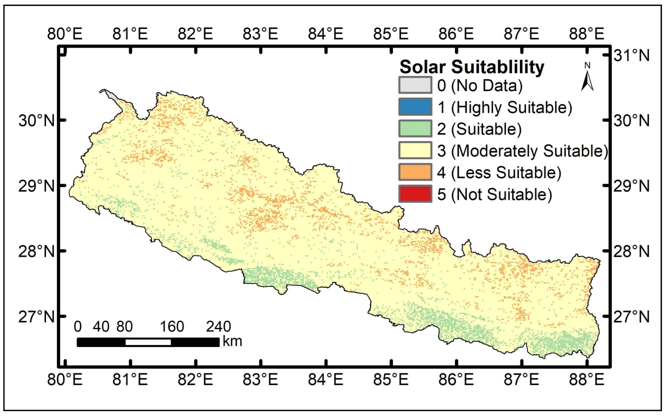

Figure 5: Solar Suitability Map

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 4). 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.

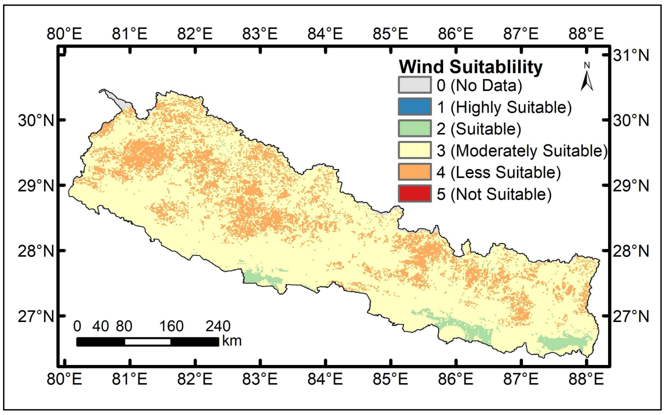

Figure 6: Wind Suitability Map

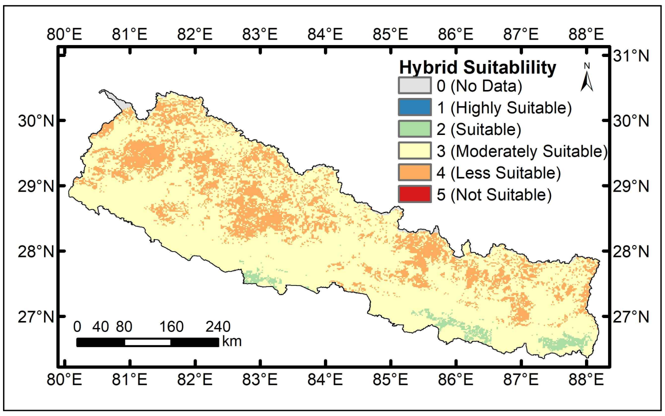

Figure 7: Hybrid Suitability Map

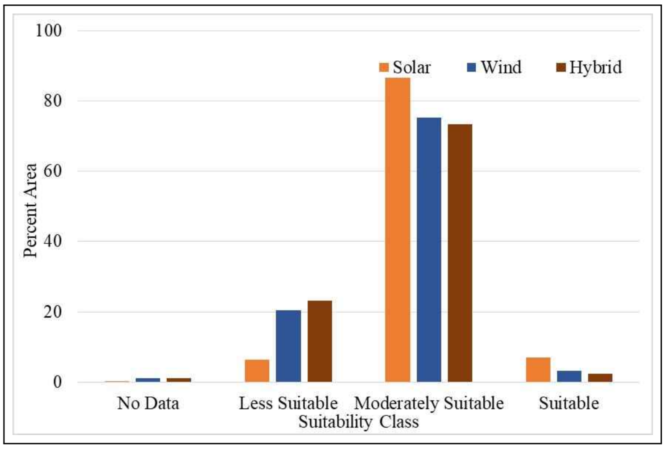

Figure 8: Suitability classes for solar, wind and hybrid system

Table 4: Land suitability for different Provinces of Nepal

Power Type	Province	Suitability Class (in Percent Area for each province)			
		No Data	Less Suitable	Mod. 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.

4.2 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. 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 [22], thereby reinforcing the robustness of our research outcomes.

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 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.

5. Conclusion and Recommendation

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.

Furthermore, 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 focus on strategic improvements in transmission networks, road infrastructure, and supporting facilities in hilly and mountainous regions will help in harnessing full renewable energy potential. Also, policy and incentive mechanisms to encourage the integration of wind, solar, and hybrid energy systems to diversify Nepal's energy portfolio beyond traditional hydropower will enhance energy security, better manage seasonal variations, and mitigate the impacts of climate-induced changes in river flow patterns

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