TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PASHCHIMANCHAL CAMPUS

A REPORT ON

‘GIS-Based Analytical Hierarchy Process for Optimal Solar Plant Site Identification in Bagmati Province, Nepal’

SUBMITTED BY:

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DIPESH CHAULAGAIN	(PAS077BGE020)
LOKESH CHAUDHARY	(PAS077BGE023)
NABIN SHRESTHA	(PAS077BGE024)
RAJESH BAJGAIN	(PAS077BGE031)

PROJECT SUPERVISOR

Asst. Prof. Er. Saurav Gautam

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE BACHELOR’S DEGREE IN GEOMATICS ENGINEERING

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DEPARTMENT OF GEOMATICS ENGINEERING

POKHARA, NEPAL

April 25, 2025

DECLARATION

We, hereby declare that the project entitled **'GIS-Based Analytical Hierarchy Process for Optimal Solar Plant Site Identification in Bagmati Province, Nepal'** submitted to the Department of Geomatics Engineering, Pashchimanchal Campus, Institute of Engineering, Tribhuvan University, is our original piece of work done under the supervision of Asst. Prof. Er. Saurav Gautam, and is submitted in partial fulfillment of the requirements for the bachelor's degree in Geomatics Engineering. All sources of information used for this project have been duly acknowledged and cited. We take full responsibility for any errors or omissions contained herein.

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ABSTRACT

The rising global demand for energy and environmental concerns are driving a global shift to cleaner sources. Solar power is emerging as a viable alternative in Nepal, where it can diversify the hydropower-heavy energy mix and enhance resilience to climate impacts. This study aims to use AHP technique together with GIS technology to conduct a suitability analysis and identify the best locations for constructing solar power plant in Bagmati Province, where the energy demand is expected to increase up to 786 MW in 2030 and 2282 MW in 2050. In the study, three different criteria; Climate (Solar Irradiance, Average annual temperature), Economic (Distance to road, Distance to sub-station), and Environmental (Elevation, Aspect, Slope, Land use/land cover (LULC)) have been considered. Also, sensitivity analysis was performed to confirm the stability of the model. A suitability map was prepared using the weighted overlay of the criteria. The result showed that 10.41% of Bagmati Province (2,111.31 sq. km) falls under 'most suitable' class and 49.33% (10,004.44 sq. km) falls under 'suitable' class for solar power development. The generated suitability maps can support precise planning for the construction of solar power plant within the Bagmati Province.

Keywords: Solar Photovoltaic, Site Suitability, AHP, GIS, Spatial Analysis, Sensitivity Analysis

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LIST OF ABBREVIATION

AHP	Analytical Hierarchy Process
ASTER	Advanced Space borne Thermal Emission and Reflection radiometer
CR	Consistency Ratio
DEA	Data Envelopment Analysis
DEM	Digital Elevation Model
FAHP	Fuzzy Analytical Hierarchy Process
FANP	Fuzzy Analytical Network Process
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
GIS	Geographic information system
GTI	Global Tilted Irradiance
ICIMOD	International Centre for Integrated Mountain Development
IEA	International Energy Agency
LPG	Liquefied Petroleum Gas
MCDA	Multi-Criteria Decision Analysis
MW	MegaWatt
PJ	Petajoule
PV	Photovoltaic
PVOUT	Photovoltaic Power Potential
RI	Random Index
SAR	Synthetic Aperture Radar
SPV	Solar Photovoltaic
UTM	Universal Transverse Mercator

CHAPTER ONE: INTRODUCTION

1.1 Background

Global energy consumption is rising with the increase in the degree of affluence in the livelihood of the majority of population among the countries throughout the world. The planet has witnessed the series of biggest growths in the energy consumption within the past decades, one following the other, due to newly emerging economies like China and India. The standard of living in these countries is improving as the advancement in the technologies have made the access to the tools/devices and technologies easier and affordable, consequently making the sophisticated lifestyle easier. The energy use in the middle-income countries is high. The global population is increasing. It reached 8 billion in 2022 and is expected to increase by nearly 2 billion persons in the next 30 years, from the current 8 billion to 9.7 billion in 2050 (United Nations, 2022). With it, the global energy consumption is also increasing. Since 2000, global energy consumption has increased by about a third and is projected to continue to grow in the foreseeable future. The world's demand for electricity grew by 2.2% in 2023, less than the 2.4% growth observed in 2022 (IEA, 2024) and in a business-as-usual scenario, by 2040 global energy consumption will reach 740 million terajoules - equivalent to an additional 30% growth. From 2000 to 2040, this will amount to a 77% increase in global energy consumption. From 1980 to 2050, global energy use could triple from around 300 to 900 million terajoules (Enerdata, 2024).

83 percent of the energy we use comes from fossil fuels (The World Counts, n.d.). Fossil fuels, such as coal, oil and gas, are by far the largest contributor to global climate change accounting for over 75 percent of global greenhouse gas emissions and nearly 90 percent of all carbon dioxide emissions (United Nations, 2022). This makes green energy innovation absolutely essential. Burning more coal and gas is not only bad, but it adversely affects the climate and ecosystem, which pose a great threat to our planet, causing environmental pollution and global warming. Many countries are adopting strategies to transition to low-carbon economies and use clean, environmentally-friendly energy sources. Paris Agreement sets long-term goals to guide all nations on how to accelerate action across all areas; mitigation, adaptation, and finance by 2030, including a call on governments to speed up the transition away from fossil fuels to renewable

energy such as wind and solar power in their next round of climate commitments. To better frame the efforts towards the long-term goal, the Paris Agreement invites countries to formulate and submit long-term strategies (United Nations, 2015).

One of the most important sources of renewable energy is solar energy. The main advantages of solar energy systems are reliability, low utilization costs, economic and easy maintenance, free energy source, clean energy, availability, production close to the consumer, low environmental impact, lower emission of greenhouse gases and silence. In contrast, the main disadvantages include high initial cost, large installation area, high dependence on technological development and weather conditions (Hasanzadeh et al., 2024). In 2023, solar photovoltaic energy made up three-quarters of renewable capacity additions around the world, which is equivalent to 1629.9 TWh (Lagana, 2024).

Solar energy in Nepal presents a promising avenue to diversify the country's energy mix. Currently, Nepal's domestic electricity supply is almost entirely reliant on hydropower, which is susceptible to seasonal variations and the impacts of climate change, such as altered rainfall patterns and reduced snowmelt. This vulnerability highlights the critical role solar energy in Nepal can play in stabilizing and expanding its domestic renewable energy supply. Furthermore, it adds the possibility of creating an energy export economy for the country, which could be pivotal in boosting the country's historically low per-capita GDP and lackluster export sector. Investment and growth in the solar industry represent a pathway for the country to not only enhance its energy security and reduce its carbon footprint but also improve the livelihood of its citizens. Nepal possesses a remarkable potential for harnessing solar energy, characterized by an average of 300 sunny days and 6.8 hours of sunshine. The specific solar photovoltaic (PV) electricity output capacity in the country falls within the range of 1400 kWh/kWp to 1600 kWh/kWp, resulting in an average daily total ranging from 3.8 to 4.4 kWh/kWp. The mountainous regions, with their higher elevations and cooler air temperatures, exhibit even greater potential for PV energy yield (Chhetri & Ghimire, 2023). Nepal has an estimated potential solar generation of 50,000 TWhs annually, which is 7,000 times more electricity than the country currently uses. However, the country's solar energy sector is underdeveloped, and just a fraction of solar energy is captured. Nepal has an installed solar capacity of around 55 MW, which produces over 133 GWh of energy annually. This accounts for just over 1% of the country's electricity generation (Koons, 2024).

While still small, the country's solar generation capacity has steadily grown over the last decade and is seven times larger than in 2015 (Koons, 2024). The government of Nepal has formulated a plan to establish a minimum of 200 MW solar power plants in Nepal (Shrestha et al., 2022a). With increasing interest and investment in solar photovoltaics, it is necessary to have an overview for developers during the initial stage of planning for suitable sites to establish a solar power plant. There have been limited previous studies for optimal solar site identification in the Nepalese context. So, this study aims to address the gap in the existing research.

Geographic information systems (GIS) are commonly used together with multi-criteria decision analysis (MCDA) to determine the optimal locations for constructing solar power plants and performing spatial analysis (Hasanzadeh et al., 2024). The Analytical Hierarchy Process (AHP) is a commonly used tool in various MCDA methods, which was developed by T. Saaty (1977) and is one of the best known and most widely used MCA approaches. It allows users to assess the relative weight of multiple criteria or multiple options against given criteria in an intuitive manner. Suitability mapping involves using a variety of data sources in which weights are assigned to geographical criteria.

This study aims to use AHP technology to conduct a suitability analysis and identify the best locations for constructing solar power plant in Bagmati Pradesh. In this study, three different criteria; Climate (Global Horizontal Irradiance (GHI), Average annual temperature), Spatial (Distance from roads, Distance from urban area), Environmental (Elevation, Aspect, Slope, Land use/land cover) have been considered to assess the suitability of locations for building a solar power plant, and each criterion have been prepared as a raster layer. The weight of each criteria can be determined using AHP. The weighted overlay of data after reclassification, combines potentially unrelated weighted data in a meaningful manner (Brewer, 2015). Specific exclusion criteria (Restrictive area; terrain with elevation higher than 4100 meters above MSL; protected areas; terrain with slope greater than forty degrees; water bodies and built-up area) have been considered and applied to eliminate areas naturally not suitable for the installation of large-scale photovoltaic (PV) solar plants.

1.2 Study Area

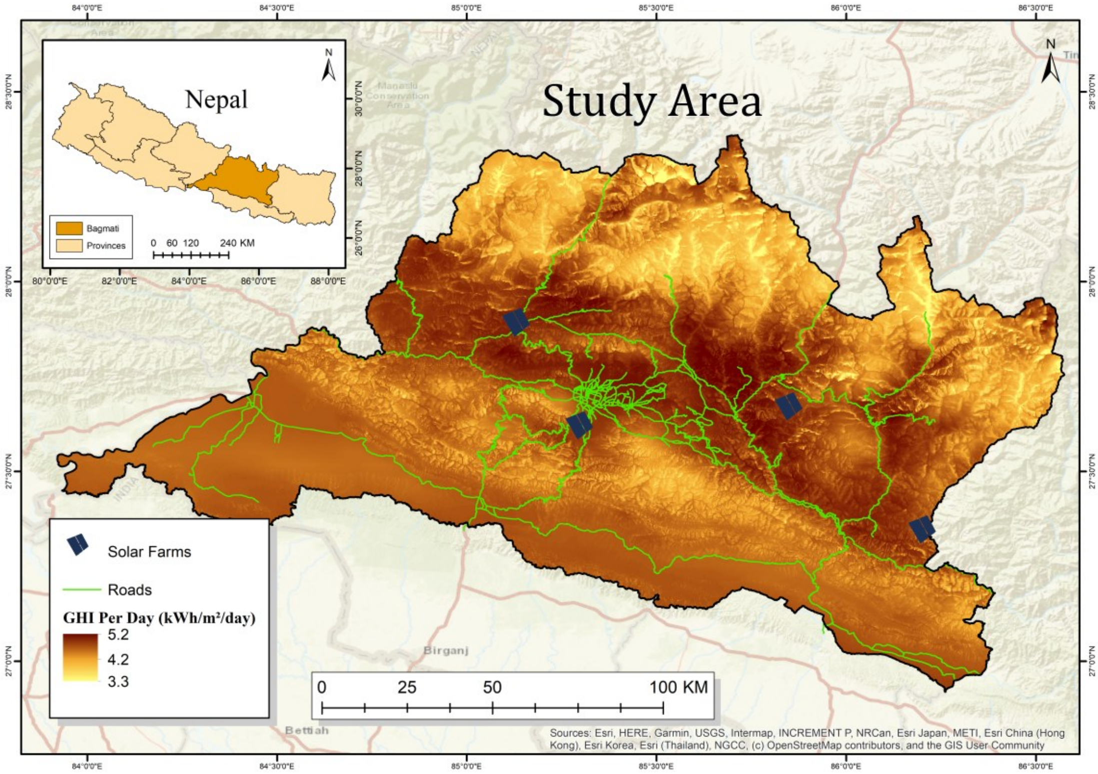

Figure 1: Study Area Map

Bagmati Province, located between 83°55′ and 86°34′ East longitude and 26°55′ and 28°23′ North latitude, covers an area of approximately 20,300 square kilometers, constituting 13.79% of Nepal's total area. About 27.29% of the province is forested. It is bordered by Madhesh Province and India to the south, China to the north, Gandaki Province to the west, and Koshi Province to the east (Nepal Outlook, n.d.)

Topographically, Bagmati Province can be divided into four main regions: the high Himalayan region (above 5000 meters) in the north, the mid-hill region, the Mahabharat range, and the low plain Terai (below 500 meters) in the south. Annual precipitation varies from 150-200 mm in the high Himalayas to 1100-3000 mm in the southern plains. Similarly, the average annual temperature fluctuates between below 3°C in the high mountains to around 25°C in the lowlands (Nepal Outlook, n.d.).

The province contains six operating solar farms, as reported by the Nepal Electricity Authority, and two more are under construction. There are 16 substations within the province for transmitting the generated electricity.

1.3 Statement of Problem

The total energy consumption of Bagmati Province is 83.53 PJ (2249.8 GWh) with fuelwood occupying the major share of 32.73%. Diesel and LPG occupied share of about 21.34% and 13.68% in the total energy consumption respectively. While other fuel types such as gasoline, electricity, solar, biogas, fuelwood, agricultural residue, etc. constitute the remaining share. The energy demand is expected to increase from 83.53 PJ to 115.91 PJ (786 MW) in 2030 and 308.75 PJ (2282 MW) in 2050, while the demand of other fuels is expected to decrease. As in this scenario, electricity is expected to be replacing other sources of energy, as a result the power plant capacity requirement would grow dramatically (*Water and Energy Commission Secretariat*, n.d.). Nepal aims to increase renewable energy adoption, with Bagmati province targeted for at least 200 MW of solar power plants. However, selecting optimal solar sites presents a challenge. Improper site selection can lead to additional expenses for grid connection, land acquisition in unsuitable areas, or maintenance challenges due to difficult terrain. Focusing on less suitable areas might overlook highly efficient locations that could contribute more significantly to Nepal's renewable energy goals. These limitations hinder Nepal's ability to achieve clean energy targets efficiently and capitalize on the full potential of solar power in Bagmati province. Traditional methods for site selection often rely on limited data or subjective criteria, which leads to:

1.3.1 Energy Demand and Supply Gap

Bagmati Pradesh faces a growing energy demand due to rapid urbanization and industrialization. Current energy supply is insufficient and heavily reliant on hydroelectric power, which is susceptible to seasonal fluctuations.

1.3.2 Need for Renewable Energy

There is a growing need to diversify energy sources to include more sustainable and reliable alternatives. Solar energy presents a viable option due to Nepal's high solar insolation levels.

1.3.3 Challenges in Site Identification

Identifying optimal sites for solar energy installations is complex and involves multiple criteria such as solar radiation, land use, topography, and proximity to the grid. Existing methods for site identification are often inefficient, relying on manual assessment and lacking comprehensive spatial analysis.

1.3.4 Lack of Integrated Methodologies

There is a lack of integrated methodologies that combine multiple criteria decision analysis (MCDA) techniques with geographic information systems (GIS) for systematic and precise site selection. The Analytical Hierarchy Process (AHP) offers a structured way to prioritize various factors, but it has not been adequately applied in conjunction with GIS for this purpose in Bagmati Province.

1.4 Objectives

The primary objective of this study is to develop and apply a combined AHP and GIS approach to identify the most suitable sites for solar energy installations in Bagmati Province.

The secondary objective is to identify the criteria responsible for determining optimal solar plant sites, to classify each criterion based on its relative importance, and to determine the weight of each criterion.

CHAPTER TWO: LITERATURE REVIEW

2.1 Solar Energy

Solar energy is the radiant light and heat from the Sun that is captured through various technologies, including solar power for electricity generation, solar thermal energy (like solar water heating), and solar architecture. So far, among all the long-term natural resources, solar energy is the most abundant and reasonably priced (Awasthi et al., 2020). One of the best methods to use solar power to create electricity is through solar photovoltaic (PV) technology, which uses sunlight to create direct current in solar cells. The fundamental component of a solar energy generating system that quickly converts sunlight into electrical energy is a photovoltaic cell. A device with a p-n junction is the solar cell. The terms ‘n-type’ and ‘p-type’ denote the negatively charged electrons that donor impurity atoms donate and the positively charged holes that acceptor impurity atoms make, respectively. Multiple solar cells are connected in parallel and series to generate a specific amount of power in solar panels (Al-Ezzi & Ansari, 2022).

Solar energy is the most promising clean energy resource that can be used to produce electricity. The most promising sustainable energy source that can be used to produce electricity straight away is solar energy. At a reasonable operating cost, it can nearly deliver consistent electricity. Solar energy has grown quickly in the last few years due to the rising need for sustainable energy. Research and development are still being done on solar cell efficiency, though, as it is largely dependent on the environment and basic characteristics of the solar module. Numerous input elements, including shading effects, the PV materials used, temperature, received radiation intensity, parasitic resistances, weather, solar cell design, doping level, material characteristics and quality, etc., can affect a solar cell's output power. In order to increase the acquired power efficiency, these factors need to be tuned (Al-Ezzi & Ansari, 2022).

2.2 Solar Potential in Nepal

The majority of Nepal's energy is produced and used hydroelectrically, with imports from India and hydropower meeting the nation's energy needs. In Nepal, Run of River (RoR) hydropower plants make up the majority of the plants; during the dry season, their capacity decreases dramatically. India is the source of imports that meet the demand for electricity at this time. As suggested by the government, adding solar power to the national grid can be a viable alternative energy source. With its current installed solar capacity of about 55 MW, Nepal generates around 133 GWh of electricity each year. This is just over 1% of the nation's total electrical production. (Department of Electricity Development, 2022; Nepal Electricity Authority, 2022).

With an average of 300 days of sunshine per year and roughly 6.8 hours of sunshine each day, Nepal has a significant potential for solar energy (Poudyal, 2019). A specific solar photovoltaic (PV) electricity generation capacity of 1400 kWh/kWp to 1600 kWh/kWp is available in Nepal. This corresponds to daily average totals of between 3.8 and 4.4 kWh/kWp. Just 1423.33 GWh of the 179190.42 GWh of energy consumed in 2022 came from solar energy, or just 0.79% of the country's total energy consumption (Energy Synopsis Report, 2023).

The potential for photovoltaic energy yield is larger in mountainous places because of their lower air temperatures and higher elevation. In very cold conditions, solar panels can actually perform above their rated efficiency. For example, at 0°C (32°F), a panel might produce 5-7% more power than its rated output. A typical crystalline silicon solar panel might lose 0.3% to 0.5% of its efficiency for every 1°C increase in temperature above 25°C due to the inverse relationship between temperature and Photovoltaic cell efficiency (*Solar Panel Efficiency vs. Temperature (2024)*, n.d.). Consequently, Nepal's hills and lower-elevation mountains are seen to be the best places for solar PV systems because to their good GHI and cooler temperatures (Energy Synopsis Report, 2023). But the selection of an optimal site for establishing a solar power plant depends on many criteria and is not solely based on the GHI value. The criteria may comprise, among other things, the land's physical characteristics, environmental considerations, land use limitations, social concerns, and the need for electrical infrastructure (Brewer, 2015). These major criteria can include a number of sub-criteria that are analyzed to find the optimal site. The criteria have been chosen based on the study area location and may vary depending on the researcher.

2.3 Analytical Hierarchy Process

Multicriteria decision aid (MCDA) techniques support decision-making in scenarios involving competing economic, environmental, social, technological, and aesthetic goals. Consequently, MCDA is increasingly used to tackle sustainable development issues (Montis, 2000). One of the methods under MCDA is the Analytic Hierarchy Process (AHP). AHP is a general theory of measurement that derives ratio scales from both discrete and continuous paired comparisons. These comparisons can be based on actual measurements or on a fundamental scale reflecting the relative strength of preferences and feelings. AHP places special emphasis on measuring and addressing inconsistencies and on the dependencies within and between groups of elements in its structure. It is widely applied in multicriteria decision making, planning, resource allocation, and conflict resolution (Whitaker, 1987). Numerous researchers worldwide have conducted AHP-based site selection analyses.

2.4 GIS for Energy Management

A geographic information system, or GIS, is a collection of hardware, software, and data used for gathering, organizing, processing, and presenting geographic data. It helps practitioners comprehend physical aspects, relationships, patterns, and trends by enabling them to observe, identify, generate, and visualize data in a variety of formats, including maps, reports, and charts. GIS was first applied to landform and forest surveys, but it has since been used to visualize resources, traffic, and weather as well. Its capabilities have been improved by the creation of databases and tools for spatial analysis, which has facilitated data access and sharing for professionals in a variety of sectors. GIS data can be layered to update information and applied to a variety of research topics. It is frequently free and simple to obtain. GIS applications in renewable energy include (1) Identifying suitable locations and infrastructures, (2) Assessing potential energy sources and applications, (3) Determining energy demands related to the capacity and size of renewable sources (Y. Li & Feng, 2023).

Geothermal energy distributions are found using moderate-resolution imaging satellites like Landsat equipped with thermal radiometers like ASTER. The use of thermal, microwave, hyperspectral, and multispectral remote sensing techniques can provide evidence of natural heat transfer processes. Remote sensing and GIS methods such as SODAR, LiDAR, and SAR are used in wind energy development and optimization to investigate design conditions and evaluate offshore wind potential. Moreover, GIS is used to map solar, biomass, and mineral energy. To assess the biophysical characteristics of biomass energy, passive (optical) and active (radar and LiDAR) sensors are used (Y. Li & Feng, 2023).

2.5 Case Studies of Solar Plant Site Selection

Before delving into our proposed methodology, it's essential to review existing case studies that have explored solar plant site selection methodologies. These case studies provide valuable insights into the diverse approaches and methodologies employed in different geographical contexts.

Alhammad et al. (2022) developed a framework for optimal solar plant site identification in the Al-Qassim region of Saudi Arabia. The authors used three criteria namely environmental, climatic and economic for AHP analysis and subsequently developed five sub-criteria for the optimal analysis. On the other hand, Hasanzadeh et al. (2023) used the Fuzzy Analytical Hierarchy Process (FAHP) with four criteria and 11 sub-criteria to analyze the suitability for solar farms throughout Iran. The 11 defined sub-criteria include solar radiation, average annual temperatures, distance from power transmission lines, distance from major roads, distance from residential areas, elevation, slope, land use, average annual cloudy days, average annual humidity, and average annual dusty days. Alhammad et al. (2022) who did the small and specifically located study used Random forest classification for classifying the residential area and also determined the Potential Photovoltaic Electricity Production. Hasanzadeh et al. (2023) in Iran used FAHP method instead of AHP because of the uncertainty associated with AHP. In the study they ranked the districts of Iran based on the priority for exploiting solar PV farms and also revealed that 14.7%, 17.2%, 19.2%, 11.3% and 1.8% of Iran's area are positioned as excellent, good, fair, low and poor classes, respectively.

In another significant study, done on the Markazi Province of Iran by Yousefi et al. (2018) employed Boolean logic and defined a range of selection criteria evaluated by fuzzy functions. The results identified some areas in the vicinity of several cities as suitable for solar energy utilization. The research also validated the combined method as a suitable approach for solar power plant site selection.

Another noteworthy small-scale study, conducted by Abd (2018), focused on Najaf City to pinpoint optimal locations for solar cell deployment using GIS and remote sensing techniques. The study integrates easily accessible data using remote sensing and GIS approaches. In order to determine the ideal spatial location, he used the Kriging approach, and he emphasizes the potential of using GIS to find locations for solar power facilities.

Large-scale site examination is addressed in a research by Khan & Rathi (n.d.) which provides a decision-making process and technique for identifying possible locations for solar photovoltaic (SPV) plants that take into account a number of variables. The research concentrated on the exclusion criteria, include site topography, local climate variations, module soiling, and geotechnical political issues, and the analysis criteria includes the availability of solar radiation and vacant land, the distance from highways, and the presence of transmission lines. The first step in producing a series of maps that show potential places for a large-scale SPV power plant is to create, organize, analyze, and visualize geographic data about a place on Earth using desktop GIS software. Exclusion criteria then analyzes the resulting sites and an optimal site is chosen on the basis of the highest solar radiation available.

The use of GIS for solar panel installation and site selection at the University of Waterloo and the city of Waterloo was investigated in a study by Li (2013). A microscale analysis was carried out to quantify the accumulated radiation in clear and cloudy conditions for rooftop installations on the university campus using Light Detection and Ranging (LiDAR) data. To generate solar radiation maps for the city's ground-mounted systems, a macroscale analysis was carried out using data from the Digital Elevation Model (DEM) and ArcGIS software. Using a multicriteria approach, environmental and socioeconomic issues were included in this research. The study produced a shadow map as well as monthly and annual maps of solar radiation for building rooftops. However, the analysis's thoroughness was limited because it lacked a suitability index for the final suitability map and neglected to take topographic factors into consideration when calculating slope and aspect.

Wang et al. (2020) focused on the Mekong Delta of Vietnam and employed an integrated approach combining Data Envelopment Analysis (DEA) and the Fuzzy Analytical Network Process (FANP) for optimal site selection. The study evaluated multiple criteria, categorized into five main factors: economic factors, technological factors, site characteristics, environmental factors, and social factors. The study resulted in a ranking of the top five locations based on suitability, indicating that Ben Tre (DEL03) is the optimal location for investing in solar power plants in the Mekong Delta, Vietnam.

The study by Gacu et al. (2023) on Sibuyan Island, Philippines, selected parameters influenced by government policies, such as protected areas, proximity to rivers, roads, faults, ancestral domains, and proclaimed watersheds, among various other criteria. The study incorporated parameters weighted using GIS, and suitability levels highlighted using AHP, revealing that about 5.88% of the island was categorized as highly suitable for a solar farm.

In Nepal, there has been a noticeable lack of studies on the suitability of sites for solar power plants using GIS and AHP techniques. However, three notable studies have incorporated GIS-based AHP methods for identifying suitable locations. Paneru (2016) analyzed potential sites in the Kathmandu Valley, Shrestha et al. (2022) examined optimal locations in Madhesh Province, and Bhandari & Pangali Sharma (2023) conducted a suitability analysis for PV solar power plant sites in Gandaki Province.

Paneru (2016) utilized various geospatial datasets, including Digital Elevation Model, road data, solar radiation data, and land use/land cover data, to identify the optimal land for establishing a Solar Energy Collection Plant within Kathmandu Valley. Operations conducted on the DEM included generating Aspect, Slope, and Solar Radiation data, which underwent reclassification prior to performing weighted overlay analysis. Additionally, Land Use/Land Cover data and road data underwent reclassification and processing to determine Euclidean distance. The weighted overlay process integrated Aspect, Slope, Solar Radiation, Land Use/Land Cover, and Road data layers, with Analytical Hierarchy Process (AHP) employed as an influencing factor for each layer. Identification of restricted areas within the Land Use/Land Cover layers, along with their buffer zones, was followed by weighted overlay analysis. Consequently, distinct classes of suitable sites were delineated based on the analysis conducted. The research identified four categories of sites for solar energy collection plants, ranging from not suitable to highly suitable. Most areas on the outskirts of densely populated Kathmandu city are suitable, with 1711 potential sites identified for solar power plants with a capacity of at least 680 kWp, indicating available land for commercial-grade solar energy collection plants to power households in Kathmandu valley.

In a similar vein, Shrestha et al., (2022) devised a comprehensive three-step framework by integrating AHP and GIS methodologies. They generated weighted raster images for distinct criteria, including restricted areas, and amalgamated all raster data into a single image using GIS software. Criteria and sub-criteria weights were determined through the AHP model based on expert judgments. The evaluation encompassed various factors such as solar irradiance, temperature, proximity to infrastructure, elevation, aspect, and land use, resulting in a grading of areas from least to most suitable. The study identified the most favorable locations primarily in districts like Saptari, Siraha, Dhanusa, and Mahottari, while less suitable areas were predominantly located in the western region districts.

Similarly, in their study, Bhandari & Pangali Sharma, (2023) utilized AHP methodology incorporating criteria such as solar radiation, slope, aspect, land use/land cover, and proximity to roads and substations. These criteria were reassessed and categorized into suitability classes guided by expert opinions and established guidelines. The findings revealed that highly suitable regions covered 5.64% of the total area, while areas least suitable for power generation sites encompassed 28.74% of the Gandaki Province's total area.

A sensitivity analysis is performed to assess the robustness and stability of the model developed. The sensitivity analysis reveals how the suitability index of the model would change with the different criteria's weightage (Bandira et al., 2022). Sensitivity analysis is a vital component in the GIS-based Analytical Hierarchy Process (AHP) framework for optimal solar plant site identification, as it ensures the robustness and reliability of the suitability model amidst the region's diverse topographic and climatic conditions. By evaluating how variations in criteria weights, such as solar radiation, slope, and proximity to infrastructure, impact the final suitability map, sensitivity analysis helps validate the model's stability against subjective weight assignments and data uncertainties (Albraheem & Alabdulkarim, 2021). This is particularly crucial in Region, where factors like seasonal rugged terrain, and limited ground-based solar data introduce variability. Conducting sensitivity analysis, as demonstrated by Albraheem and Alabdulkarim (2021), allows for testing scenarios like equal weighting or exclusion of dominant criteria, ensuring that the model remains consistent in identifying suitable sites despite changes in priorities. This process not only enhances confidence in the model's outcomes but also supports decision-making by addressing local challenges, such as land use conflicts and stakeholder preferences.

In the site identification study, a significant gap was identified regarding the validation of the resulting suitability map. Bandira et al. (2022) were among the few who conducted model validation using existing solar farm data. They validated the generated suitability maps using two approaches. First, they performed a visual qualitative comparison by overlaying the existing solar farm layer with the 'highly suitable layer' for solar farm identification; a value of more than 60% indicated model suitability. Second, they used the receiver operating characteristic (ROC) to assess the spatial coincidence between predicted potential sites and existing solar farms. The ArcSDM toolbox generated the ROC curve to calculate the area under the curve (AUC), where an AUC of 1 indicates a perfect model and 0.5 indicates random prediction. Although existing solar plant locations result from economic, social, and environmental trade-offs and may not be optimal, comparing them with model recommendations aids in validating the model's effectiveness in identifying feasible sites (Bandira et al., 2022).

CHAPTER THREE: METHODOLOGY

3.1 Data Collection

The data required to determine the optimal site were collected from various sources. The *Table 1* below presents the data sources, their resolutions, and descriptions, while the data itself is displayed in the *Figure 3*.

Table 1: Data Source

Data	***Resolution***	***Source***	***Remarks***
Solar Radiation	251m	Global Solar Atlas (globalsolaratlas.info/download/nepal)	The long-term average of daily GHI totals, measured in kWh/m²/day, for the period 1999 –2020, published in 2021.
Average Annual Temperature	900m	Global Solar Atlas (globalsolaratlas.info/download/nepal)	The long-term annual average air temperature, measured in degrees Celsius (°C), for the period 1999–2020.
Roads	Vector	Open Street Map (www.openstreetmap.org)	Highways classified with the tags *trunk, primary, secondary,* and *tertiary* were extracted using the QGIS's plugin.
Substation	-	Nepal Electricity Authority (www.nea.org.np)	The list of substations was sourced from *A Year in Review: Fiscal Year 2023/2024*, published by the Nepal Electricity Authority.
Elevation	30m	ASTER GDEM (search.earthdata.nasa.gov)	The ASTER GDEM offers a global digital elevation model (DEM) of Earth's land areas at 1-arc-second resolution (~30 meters at the equator).
Slope	30m	ASTER GDEM (search.earthdata.nasa.gov)	”

Aspect	30m	ASTER GDEM (search.earthdata.nasa.gov)	”
Land Cover	30m	ICIMOD (https://rds.icimod.org/DatasetMasters/BulkDownload/1972729)	Created through the National Land Cover Monitoring System (NLCMS) for Nepal.

3.2 Workflow

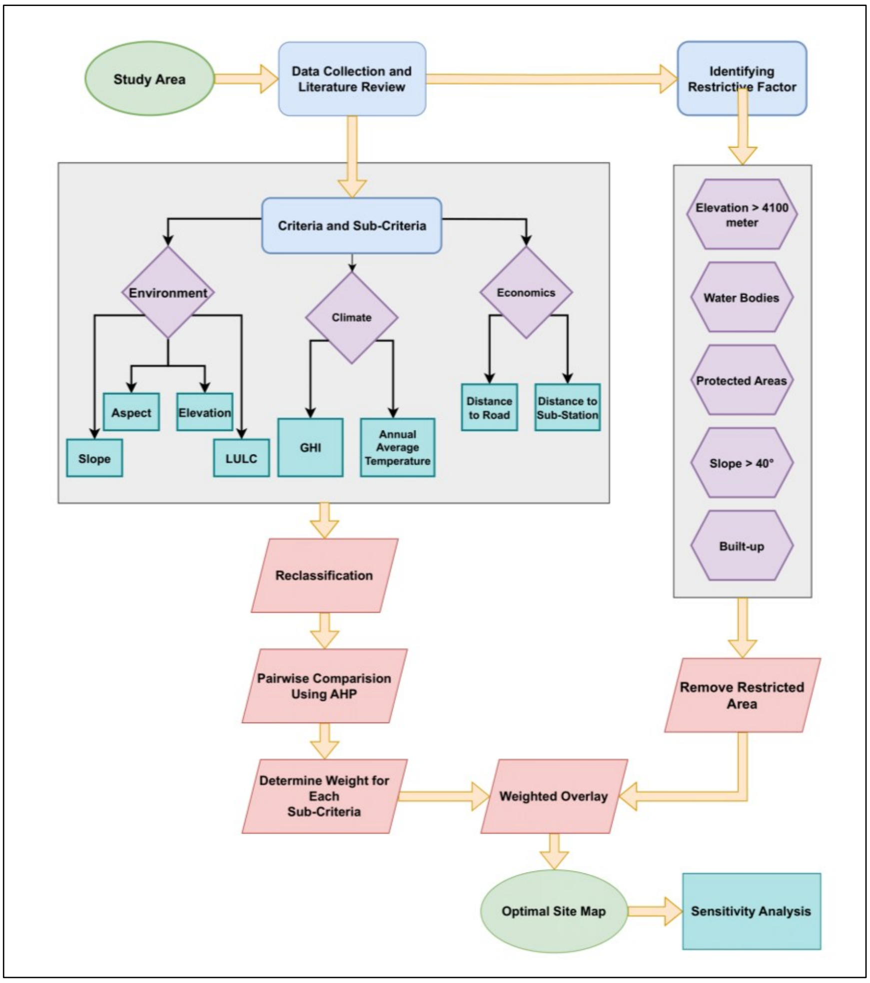

Figure 2: Methodology

3.3 Data Preparation

This research utilized eight different datasets. For the weighted overlay procedure, all data must be in the same resolution, format, and projection system. Therefore, the datasets, which were primarily in the WGS-84 coordinate system, were projected into the 45N UTM projection, and the vector data were rasterized. Consistent resolution across raster datasets is essential for ensuring accurate spatial representation, proper alignment, and reliable computation of results. As a result, the datasets were resampled to a resolution of 30 meters, which matches the spatial resolution of the Elevation data.

For specific exclusion criteria (Restrictive area; terrain with elevation higher than 4100 meters above MSL; protected areas; terrain with slope greater than forty degrees; water bodies and built-up area) that were considered; dataset for Protected area (National Parks and Conservation Area) was fetched from "The UNEP World Conservation Monitoring Centre". Terrain with elevation higher than 4100 meters above mean sea level and terrain with a slope greater than 40 degrees were extracted from the elevation and slope datasets, respectively, by reclassifying the raster cells that met these criteria with a value 1, while assigning a value of 0 to all other cells. The raster classified cells with value 1 ware converted into polygon. Water bodies and built-up area were extracted form LULC dataset. The raster cells representing water bodies and built-up area were converted to polygon. All the polygons representing the exclusion criteria were combined and rasterized to the raster with resolution of 30m.

3.4 Criteria Selection

Site selection for the solar plant is a critical issue as it has direct impact on different factors like power performance, economic, environmental, social aspects and existing as well as future infrastructures (Al Garni & Awasthi, 2018). Various studies have considered different criteria for evaluating the optimal site selection. Among them aspect, temperature, slope, irradiance, land use land cover, distance from road and distance to power lines and substations are the most common criteria's (Shrestha et al., 2022a). These criterions are broadly divided into three categories: economic, environmental, and technical.

3.4.1 Economic Criteria:

Economic criteria include proximity to roads, and existing power stations. Power plant proximity to roads and power stations is crucial for solar power plant viability, as it reduces transportation costs and losses. Access to transportation networks cuts power plant transportation costs. To reduce energy waste, it's crucial to build power plants near transmission lines. Managers should prioritize locations closest to transmission lines for final site selection (Yousefi et al., 2018b). This study focuses on two of the economic criteria namely: proximity to road and substation.

3.4.2 Environmental Criteria:

Land use and cover, agrological capacity, and carbon emission savings are critical in solar panel site selection. Ideal sites are large, open, and non-agricultural to minimize environmental disruption and land-use conflicts. Areas with poor soil quality are preferred to preserve fertile land for agriculture. Maximizing carbon emission savings involves selecting locations with high solar exposure and proximity to existing transmission infrastructure to reduce reliance on fossil fuels and minimize the environmental footprint of new construction. These factors ensure that solar projects are both environmentally sustainable and efficient in energy production (Al Garni & Awasthi, 2018). This study focuses on the environmental criteria: Slope of the terrain, Aspect, Elevation from the mean sea level, and Land Use and Land Cover.

3.4.3 Climatic Criteria:

Several technical criteria related to climatic factors are essential for selecting solar plants, including temperature, precipitation, humidity, and sunshine hours. Integrating the temperature effect enhances the reliability and efficiency of the plants. High precipitation areas have more particulate matter, which absorbs and reflects shortwave radiation, while regions with high relative humidity reduce solar radiation absorption due to water vapor (Yousefi et al., 2018b). Despite various climatic considerations, this study focuses on two of the climatic criteria namely: solar radiation, and average annual temperature.

3.5 Rating Criteria and Reclassification

Because the Solar Plant Site suitability of Bagmati Province was analyzed through comparison, this study assigned rated values of 1, 2, 3, and 4 for each of eight criteria on a relative scale, where the conditions at the applicable site were evaluated as strong, good, fair, and poor, respectively.

Table 2: Sub Criteria Division

Criterion	Class	Rated Value	Remark
Global Horizontal Irradiation ($kWh/m^2/day$)	4.67 - 5.21	1	Most Suitable
	4.13 - 4.67	2	Suitable
	3.6 - 4.13	3	Moderate
	1.26 – 3.6	4	Unsuitable
Slope (degree)	0 – 10	1	Most Suitable
	10 – 20	2	Suitable
	20 – 30	3	Moderate
	30 - 40	4	Unsuitable
Aspect	Flat, S	1	Most Suitable
	SE, SW	2	Suitable
	E, W	3	Moderate
	N, NE, NW	4	Unsuitable
Land use and Land cover	Bare Soil Bare Rock Grassland	1	Most Suitable
	Cropland Woodland	2	Suitable
	Forest Snow	3	Moderate
	Water body Built Up River bed Glacier	4	Unsuitable
Temperature (°C)	17 – 25.7	1	Most Suitable
	9 – 17	2	Suitable
	0 – 9	3	Moderate
	-14.74 – 0	4	Unsuitable
Distance from a main road (km)	< 2	1	Most Suitable
	2 – 7	2	Suitable
	7 - 15	3	Moderate
	>15	4	Unsuitable

Distance from a power station (km)	< 5	1	Most Suitable
	5 – 15	2	Suitable
	15 – 30	3	Moderate
	> 30	4	Unsuitable
Elevation (m)	89 – 1100	1	Most Suitable
	1100 – 2100	2	Suitable
	2100 – 3100	3	Moderate
	> 3100	4	Unsuitable

3.5.1 GHI

PV systems perform most at 4 kWh/m^2/day of solar irradiance for economic use, owing to the efficiency of PV systems in the sunlight zone (Suh & Brownson, 2016). So, in this study, the classification is made such that the classes with higher GHI are ranked more in the preference scale than the lower GHI and the raster cell with GHI value less than 3.6 kWh/m^2/day have been reclassified to poor class.

3.5.2 Temperature

Most solar panels are rated under Standard Test Conditions (STC), which assume a temperature of 25°C; the peak of their optimal range. Efficiency drops with each degree rise, based on the panel's temperature coefficient (Hasan et al., 2022). In contrast, cold conditions can boost performance; at 0°C, a panel may generate 5–7% more power than its rated output (Solar Panel Efficiency vs. Temperature, 2024)

Despite potential electrical benefits, extreme cold poses major challenges such as snow and ice buildup, increased material degradation, and the need for specialized mounting and maintenance, often outweighing efficiency gains (EcoFlow, 2023).

In Bagmati Province, colder areas are in high-altitude regions with poor accessibility and limited infrastructure for solar development (WECS, 2024; PMAMP, 2024). Therefore, this study prefers temperatures around 25°C, with extreme cold being least favored.

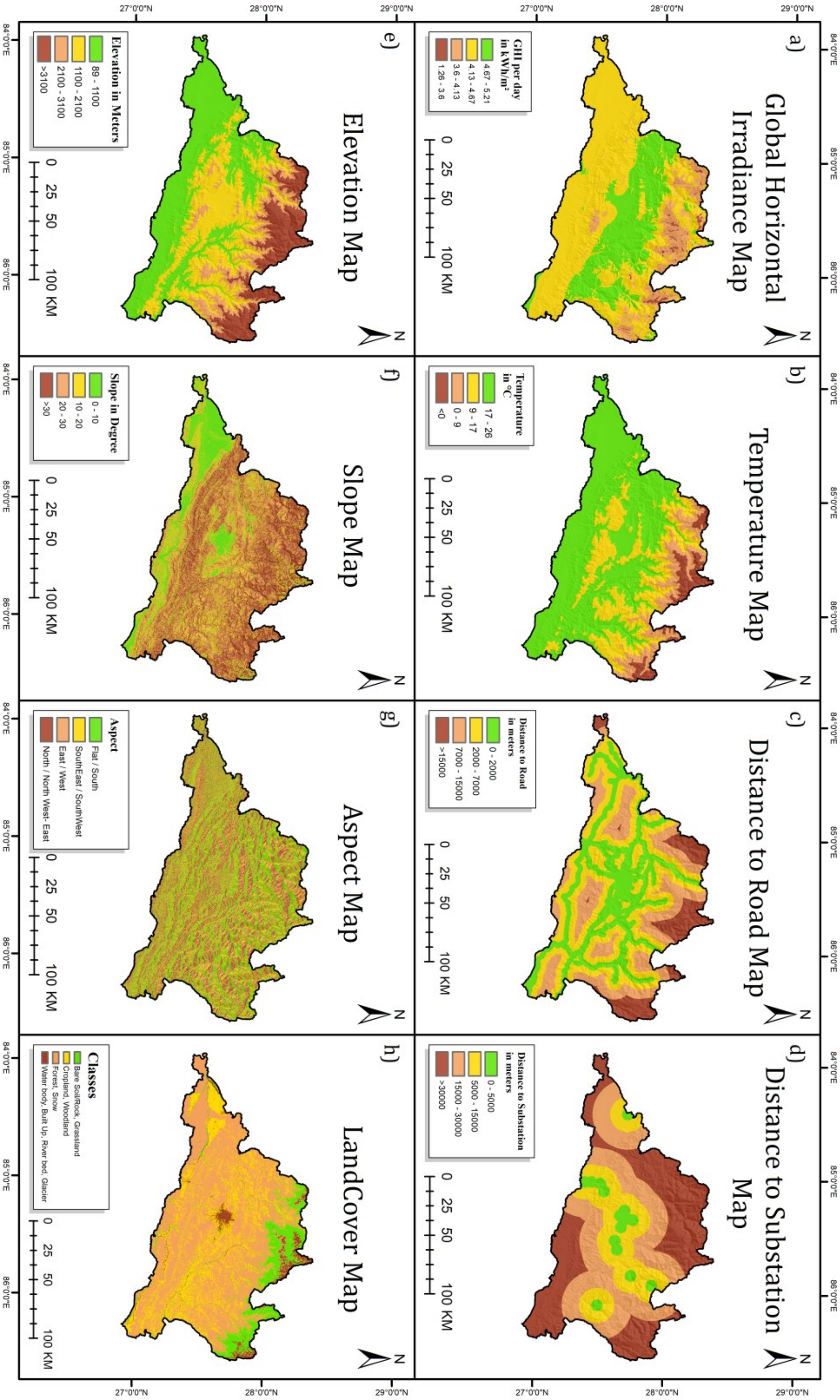

Figure 3: Factors affecting solar site suitability

3.5.3 Elevation

The thickness of atmosphere influence the entrance of both shortwave energy of the sun and longwave energy of the earth. The lower the elevation of a region from sea level, the greater the atmosphere thickness. Thus, elevated regions enjoy a greater solar radiation potential than lower regions due to the fact that they receive a great deal of energy (Noorollahi et al., 2016).

Despite these radiation advantages, higher elevations in Bagmati Province lack adequate roads and transmission infrastructure, significantly increasing development costs. High-altitude sites face difficult year-round access for maintenance, particularly during the monsoon and winter seasons. In Bagmati, most of the electricity demand and existing grid infrastructure are concentrated in the valleys and lower-elevation regions.

The classification acknowledges this fundamental trade-off: while solar radiation increases with elevation, the practical implementation challenges eventually outweigh the benefits in Bagmati's context. Thus lower altitude level with flat lands (Terai) and availability of infrastructure are preferred than higher altitude levels.

3.5.4 Land Use Land Cover

Land use is an important environmental factor for site selection. In this study, land use was evaluated at four levels: bare soil, bare rock, and grassland as most suitable; cropland and woodland as suitable; snow and forest as moderately suitable; and water bodies, built-up areas, glaciers, and riverbeds as unsuitable. Barren areas were considered the most favorable, while irrigated areas had the lowest priority for solar farm development

3.5.5 Slope and Aspect

Many previous studies on site suitability analysis for PV systems considered that slopes 10 degree are typically unsuitable for PV system installation, as panels will shade adjacent rows, reducing the PV system’s efficiency, and thereby impacting economic viability (Sánchez-Lozano et al., 2013). Therefore, in this study, areas with slopes < 10 degree and located in the south, southeast, or southwest were highly rated.

3.5.6 Proximity to Infrastructure

The availability of infrastructure influence the economic viability for the construction of Solar Power Plant. Thus, the areas that are near to the main road as well as power station or transmission lines are preferred. In this study, areas with distances of < 2 km from main roads and <5 km power transmission lines were rated as good sites for installing PV power plants.

3.5.7 Restrictions

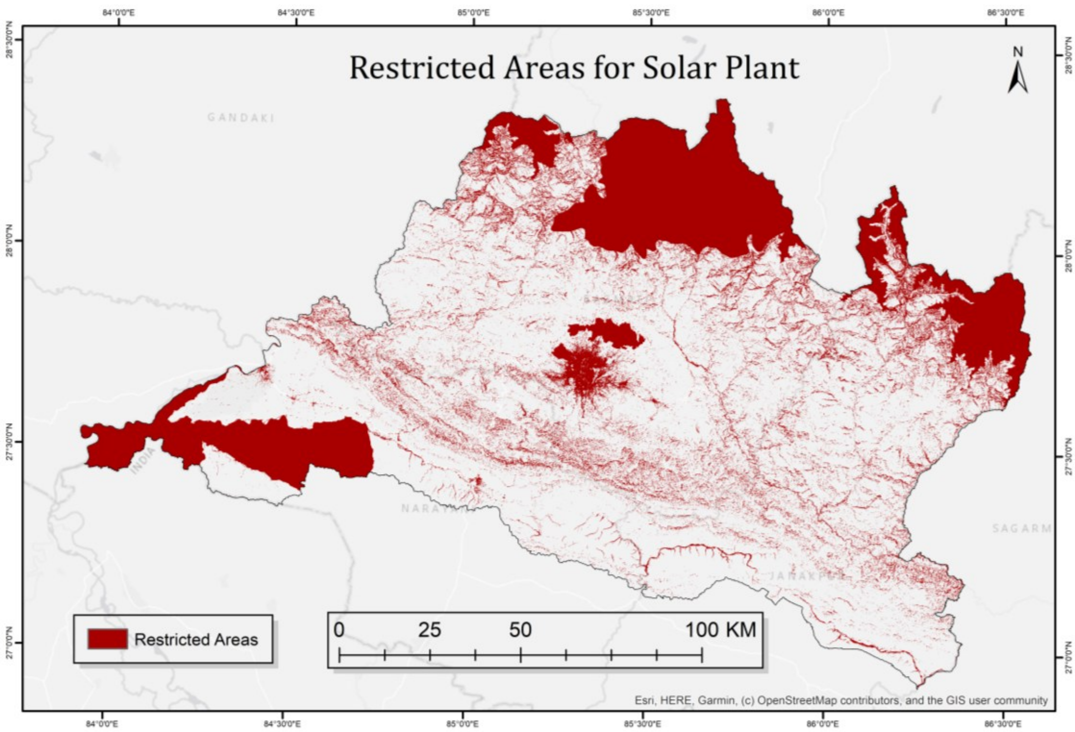

Figure 4: Restricted Area

After the weighted overlay for the analysis of suitability, specific exclusion criteria were applied to eliminate areas naturally not suitable for the installation of large-scale photovoltaic (PV) solar plants. In line with approaches taken in earlier studies (Yousefi et al., 2018; Hasanzadeh et al., 2023; Khan & Rathi, n.d.; Shrestha et al., 2022b), the following areas were excluded: areas of protected land and national parks, areas of development or built-up areas, water bodies, areas of steep slopes and gradient greater than or equal to 40 degrees, and areas at elevations above or more than 4000 meters. These areas were excluded both on technical and legislative grounds. Protected and national parks are environmentally fragile or legally reserved areas and hence not available for use for industrial-scale development (Gacu et al., 2023; Bandira et al., 2022). Built-up areas usually do not have the spatial coherence necessary in order to efficiently deploy solar farms and are preferable areas for rooftop-based solar systems compared to ground-based arrays (Li, 2013).

Besides, steep slopes and high altitudes bring structural and logistically-related challenges. In the view of Sánchez-Lozano et al. (2013), slopes above 10 degrees cause shading effects and raise the installation cost, and more inefficiency is experienced above 30–40 degrees. In the same manner, elevations above 4000 meters are not just hard to reach, but also belong to Nepal's high Himalayas, characterized by harsh climatic conditions and low infrastructural support (Munkhbat & Choi, 2021; Noorollahi et al., 2016). These limitations ensure that the sites selected are not only technically feasible but also in consonance with land use sustainability, reducing the conflict with conservation and humans settlements.

3.6 Analytical Hierarchical Process

The Analytical Hierarchical Process (AHP) was developed by Saaty in 1980 (Shrestha et al., 2022a), and is one of the most popular tools for Multi-Criteria Decision Analysis. The AHP helps determine the importance of different tangible and intangible factors in a multicriteria decision problem by providing a relative scale of importance in numerical value as shown in *Table 3*.

Table 3: Pairwise Comparison scale

Importance Degree	**Definition**	**Description**
1	Equally preferred	Both the activities have equal contributions towards achieving the objective
3	Moderately preferred	One of the activities is slightly favored over the other.
5	Strongly preferred	One of the activities is strongly favored over the other.
7	Very strongly preferred	One of the activities is very strongly favored over the other.

9	Extremely preferred	One of the activities is favored over the other of the highest possible degree.
2,4,6,8	Intermediate values	Between the degrees of importance

The weight or the importance of the factor is then calculated through a pairwise decision matrix based on the relative priority between different criteria and sub-criteria. The formation of the pairwise matrix includes the following steps (Shrestha et al., 2022a).

a) For an "N" number of criteria with their preference score, a pairwise matrix "M" of size N*N is created such that if M_{ij} is the entry in the i^{th} row and j^{th} column, the product of M_{ij} and M_{ji} must be unity.
b) Then, a normalized pairwise matrix is prepared by dividing each entry of the column by the total sum of the elements of the same column.
c) The average of each entry of the row provides the relative weight of the criteria.

After the computation of the weights, a factor called the consistency ratio (CR) is employed to check the consistency of the AHP and the weights. It is the ratio of the Consistency Index and the Random Index. The Consistency Index is calculated using Equation 1 as follows:

$$CR = \frac{\alpha_{max} - N}{N - 1}$$

Where, α_{max} is the maximum eigenvalue of the pairwise comparison matrix. The random index as defined by Saaty (1980) and depends on the number of criteria being considered as shown in *Table 4.*

Table 4: Random Index for different number of criteria

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

If the Consistency Index is less than 0.10, the results obtained are considered to be satisfactory; otherwise, recalculation must be performed due to inconsistencies in the pairwise comparison (Shrestha et al., 2022a)

Weights of each criterion and sub-criterion are calculated based on the decision matrix as described above. The global weight of an attribute is then determined by the product of weights of criteria and sub-sub-criteria; the total score of the weightage is determined by the summation of the global weight of each sub-criterion (Shrestha et al., 2022a).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 AHP Weightage

Determining solar site suitability requires careful consideration of various criteria that influence the potential of an area for solar development. In this study, the Analytical Hierarchy Process (AHP) method was used to calculate the weighted sum of all conditioning factors, resulting in the final solar site suitability map.

The conditioning factors are as follows:

1. GHI
2. Slope
3. Aspect
4. LULC
5. Surface Temperature
6. Distance From Road
7. Distance From Substation
8. Elevation

The study utilized eight criteria to determine the most suitable location for solar plant installation by integrating the AHP and GIS methods. The pairwise comparison matrix for these criteria is presented in Table 5, while Table 6 outlines the corresponding weights assigned to each criteria. The methodology for constructing the pairwise comparison matrix is detailed in above section. A pairwise comparison matrix was created based on the extensive study of literature.

Table 5: Pair wise comparison matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1	2	2	3	3	4	4	5
2	1/2	1	1	2	2	3	3	3
3	1/2	1	1	2	2	3	3	3
4	1/3	1/2	1/2	1	2	2	2	3
5	1/3	1/2	1/2	1/2	1	2	2	2
6	1/4	1/3	1/3	1/2	1/2	1	1	2
7	1/4	1/3	1/3	1/2	1/2	1	1	2
8	1/5	1/3	1/3	1/3	1/2	1/2	1/2	1

The calculated consistency ratio is well below 0.1 which indicates that the pairwise comparison is consistent. Solar irradiation was assigned with the highest weight followed by annual mean temperature, while land use was assigned the minimum weightage and are shown below in *Table 6.*

Table 6: Inconsistency Check

Inconsistency Check	
αmax	8.156
Consistency Index,CI	0.37
Random Index,RI	1.41
Consistency Ratio,CR	0.016

Each criterion includes its own set of sub-criteria, which are rated on a scale from 1 to 5. A rating of 1 represents highly suitable location, 2 indicates suitable location, 3 signifies moderately suitable location, 4 denotes unsuitable location, and 5 corresponds very unsuitable location. The combined weights of criteria are shown in *Table 8.*

Table 7: Weights of Criteria

Criterion	**Weightage (%)**
Global Horizontal Irradiation (kWh/m^2/day)	28.02
Slope (degree)	16.98
Aspect	16.98
Land use And Land cover	11.49
Temperature (°C)	9.22
Distance from a main road (km)	6.18
Distance from Substation (km)	6.18
Elevation (m)	4.43

4.2 Suitability Map

The weighted overlay of eight different criteria in GIS produced a suitability map classified into four categories. The restricted area was overlaid over the suitability map prepared from weighted overlaying of eight different criteria resulting in the final suitability map with five categories As illustrated in the figure, the study area has locations deemed 'most suitable' for establishing a solar plant, around the mid-hill region near Kathmandu valley, characterized by high intensity of the received solar radiation, proximity to infrastructure and adequate elevation and temperature. The study showed that 10.47% of Bagmati Province (2111.31 sq. km) is 'most suitable' and 49.33% (10004.44 sq. km) is 'suitable' for solar power development displaying that the study area is predominantly characterized by 'suitable location'.

Table 8: The suitability ranked zones, their areas and area percentages

Suitability Rank	Area (sq. KM)	Area Percentage
Most Suitable	2111.31	10.41
Suitable	10004.44	49.33
Moderate	2561.79	12.63
Unsuitable	44.51	0.22
Restricted	5558.64	27.41

Although the Nepal Electricity Authority has not explicitly specified the minimum area required for a solar power plant, *the 2024 Request for Proposal for Grid-Connected Solar PV Power Projects* requires bidders to have at least 0.25 hectares of land per MW of solar electricity production. A minimum of 1 MW of energy production is also needed to qualify as a grid-connected project. Accordingly, only individual units exceeding 0.25 hectares were considered among the most suitable areas. The total area was found to be 2,001.15 sq. km (200,115 hectares), accounting for 9.8% of the total area. The extent of the most suitable area meeting this criterion is shown in the *figure 6*.

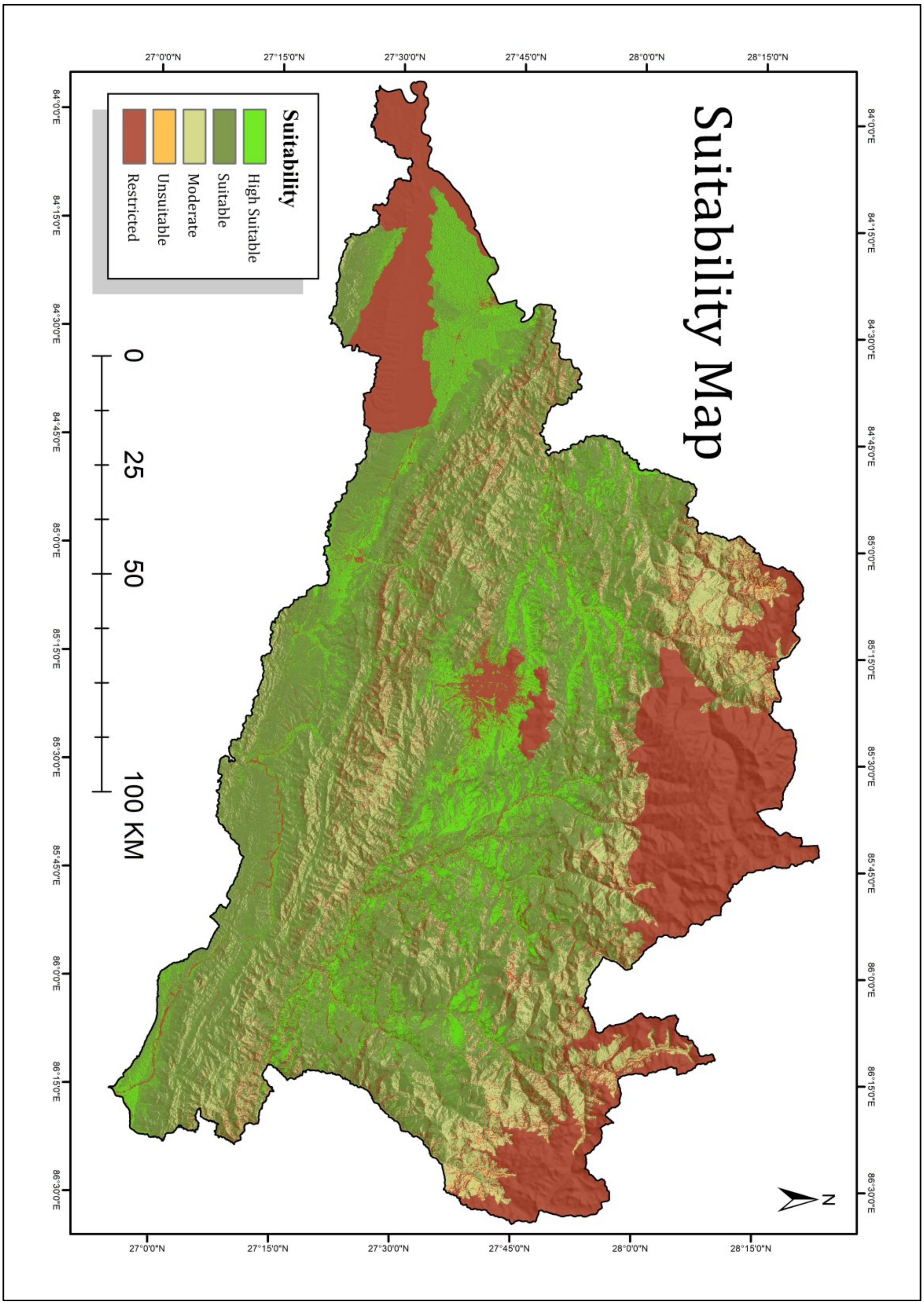

Figure 5: Suitability Map

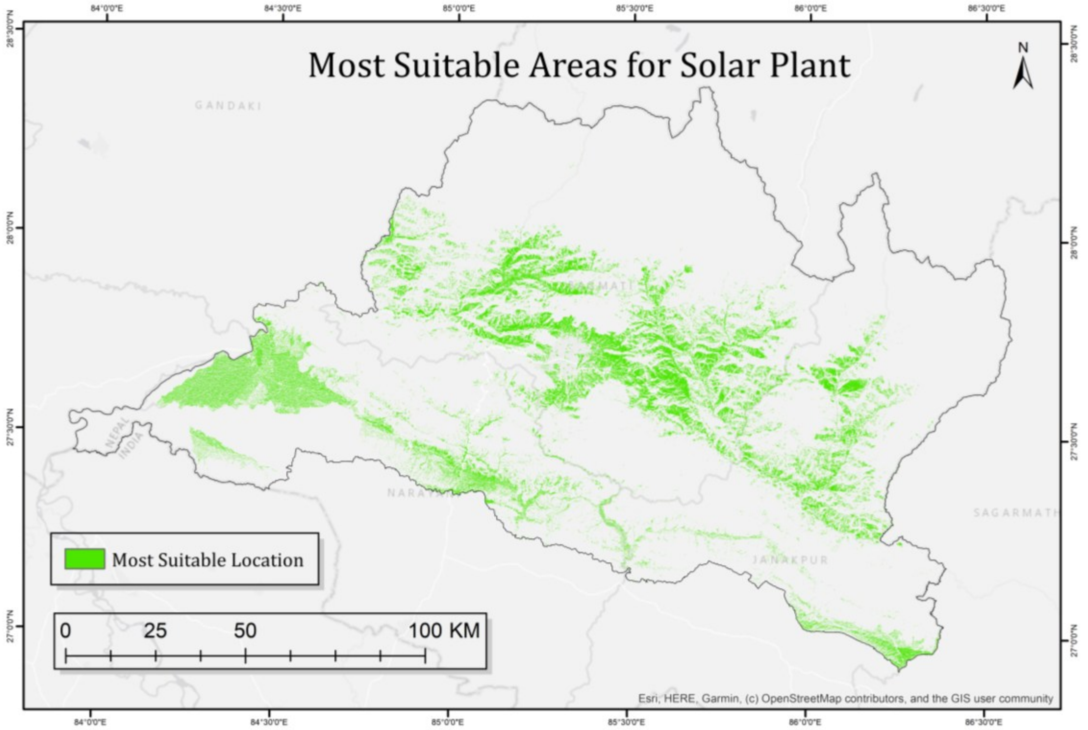

Figure 6: Most Suitable Area

4.3 Assessment of Criteria Alignment with Solar Suitability Zones

A comparative analysis of how well the most suitable areas for solar site selection align with the most preferred zones of various reclassified criteria layers is shown in *Table 9*. The "Suitability Match%" column represents the proportion of the most suitable area that overlaps with the highest-preference areas of each individual criterion. Among the criteria, Distance to Substation shows the highest suitability match at 30.03%, indicating that nearly a third of the preferred areas for solar installation with respect to distance to substation optimally contain the overall most suitable location for the solar plant. Slope and Distance to Road also exhibit relatively high alignment, at 28.88% and 24.73%, respectively, suggesting these factors play significant roles in overall site suitability. On the other hand, LULC (Land Use Land Cover) shows the weakest match at only 4.71%, implying a potential conflict between land use preferences and areas otherwise deemed most suitable. This analysis highlights which factors most strongly influence or align with the final site suitability output and can guide targeted improvements in site selection criteria or reclassification thresholds.

Table 9: Matching Preferred Criteria with Optimal Solar Zones

Criteria	Most Preferred Area (sq. km)	Most Suitable Area within High Preferability (sq. km)	Suitability Match %
GHI	5418.99	1433.65	26.46
Slope	3562.99	1028.95	28.88
Aspect	5476.55	1288.47	23.53
Temperature	12215.78	1945.92	15.93
LULC	2310.42	108.83	4.71
Elevation	8294.87	1284.13	15.48
Distance to Road	5603.06	1385.78	24.73
Distance to Substation	1013.33	304.32	30.03

4.4 Sensitivity Analysis

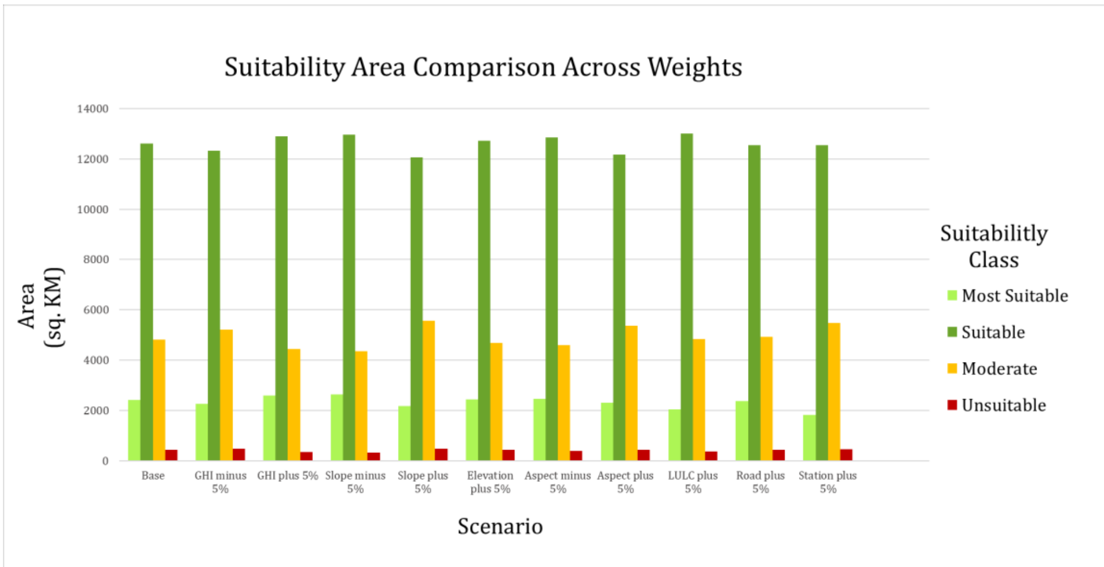

Figure 7: Change in Area per change in Weight

Sensitivity analysis in Multi-Criteria Decision Analysis (MCDA) models like the Analytical Hierarchy Process (AHP) is essential for assessing how changes in input (criteria weights) affect the final decision. It evaluates the robustness and reliability of the model by showing how varying criteria weights influence the suitability index. This also reveals how optimal sites for solar farm installation can shift based on different perspectives of decision-makers (Bandira et al., 2022). Since weight assignment is inherently subjective-often based on expert opinion or literature-sensitivity analysis ensures the reliability of results (Hasanzadeh et al., 2023). This study performs sensitivity analysis by systematically varying all criteria weights and examining their impact on the solar site suitability map.

Table 10: Change in Area of Suitability Class per Change in Weight

	Percentage Area in Most Suitable Class	**Percentage Area in Suitable Class**	**Percentage Area in Moderate Class**	**Percentage Area in Unsuitable Class**
Base	11.90	62.23	23.79	2.08
GHI minus 5%	11.15	60.85	25.66	2.33
GHI plus 5%	12.82	63.59	21.88	1.71
Slope minus 5%	13.04	63.91	21.46	1.59
Slope plus 5%	10.74	59.51	27.41	2.34
Elevation plus 5%	11.99	62.75	23.10	2.17
Aspect minus 5%	12.09	63.37	22.64	1.90
Aspect plus 5%	11.37	60.05	26.48	2.10
LULC plus 5%	10.03	64.23	23.89	1.85
Road plus 5%	11.70	61.93	24.28	2.10
Station plus 5%	8.92	61.86	26.99	2.23

The sensitivity analysis was done to show the uncertainties of the criteria and to minimize bias of criteria selection of the experts. When solar irradiation criteria weight was increased by five percent, the other criteria were decreased proportional to their original weight. Thus, a small change in the suitability area for each of the suitability classes was noted. A decrease in solar irradiation by a factor of five has decreased the 'most suitable' from 11.9% to 11.15% as evident in the Table 10. In a similar manner the weightage of each factors was changed by five percentage and the corresponding change in the suitability area for each class was noted. The results show that the model has a low sensitivity on the weightage, implying that the identified location is robust, concerning these criteria.

4.5 Comparison with Existing Solar Installations

Table 11: Existing Solar Farms in Bagmati Province

S.N	Solar Farm	Capacity (MW)	Location
1	Solar Energy	0.68	Bungamati (Lalitpur)
2	Block No 1 Solar Farms Project	5.1	Charghare (Nuwakot)
3	Block No 2 Solar Farms Project	8.3	Charghare (Nuwakot)
4	Grid Connected Solar Project Block 4, Nuwakot	1.37	Bidur N.P. (Nuwakot)
5	Grid Tied Solar Farm Project	3.09	Charghare (Nuwakot)
6	Grid Tied Solar Farm Project Block n. 5	6.5	Bidur N.P. (Nuwakot)
7	Subha Solar PV Project	9.9	Lisankhu (Sindhupalchok)
8	Saghutar Saurya Vidyut Aayojana	5	Sanghutar (Ramechhap)

A limited number of preexisting solar farms were found to exist within Bagmati Province to somewhat verify the result of the suitability class. Most of the solar farms were found to be located in a district within very close proximity. Nonetheless, the comparison of the preexisting solar farms with the suitable classes was conducted. The number of solar farms, as quantified by the Department of Electricity within Bagmati Province, was eight, with six operating and two under construction. However, only six solar farms were taken into consideration since the remaining two were too close to other farms to be deemed individual.

Out of those six farms, three farm lay in the most suitable class, two farms lay in the suitable class, and one of them lay in the moderate class, displaying an overall success rate of 83%.

Table 12: Number of Solar farms per Suitability Class

Suitability Class	**Solar Farms**
Most Suitable	3
Suitable	2
Moderate	1
Unsuitable	0
Restricted	0

$$Success\ Rate = \frac{Solar\ farms\ in\ Most\ Suitable\ or\ Suitable\ Class}{Total\ Solar\ Farms} \times 100\%$$

i.e. Success Rate = (5/6) × 100 = 83%

4.5 Discussion

The study aimed to find optimal areas for solar power plant installation in Bagmati Province through the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) technology. The analysis was based on three broad criteria: climatic, economic, and environmental, each including several sub-criteria. AHP was employed to assign weights to the sub-criteria and implement them in GIS for preparing a suitability map.

The research showed that 10.41% of Bagmati Province (2,111.31 sq. km) is 'most suitable' and 49.33% (10,004.44 sq. km) is 'suitable' for solar power development. Suitable areas are predominantly in the mid-hill belts around the Kathmandu Valley. This distribution aligns with regions of maximum solar radiation, agreeable slope orientation, and proximity to infrastructure, based on AHP weight priorities.

Among all variables, AHP results indicated that Global Horizontal Irradiance (GHI) carried the highest weight (28.02%), followed by slope (16.98%) and aspect (16.98%). The importance of mid-hill sites, as opposed to high mountain regions with potentially higher solar radiation, highlights the need to consider multiple factors such as infrastructure and accessibility.

The results of the sensitivity analysis strongly support the effectiveness of the AHP-based suitability model used in this study. By controlled adjustment of the weights assigned to specific criteria and examination of the resulting changes in suitability classification, the analysis showed that the model is not significantly affected by minor variations. A 5% change in the weight of GHI altered the 'most suitable' area, but the change was still within a rational and reasonable threshold. The same moderate effects were felt with the other criteria, indicating no single factor disproportionately influences the model. This shows that the decision model is properly balanced for multiple factors. The fact that high-suitability zones are stable between different weighting scenarios is an assurance of the model's reliability.

Despite these results, the study shows some limitations. Accuracy depends on available input data and resolution. Also, the AHP method is based on subjective pairwise comparisons, introducing some uncertainty. Alternative methods like fuzzy AHP or other MCDA techniques could be explored in the future to better address this uncertainty.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

This study effectively applied an integrated GIS-based Analytical Hierarchy Process to identify optimal locations of solar power plants within Nepal's Bagmati Province. The evaluation made use of eight factors in three categories (environmental, economic, and climatic) to produce a comprehensive suitability map that classifies the province into four classes of suitability, along with restricted areas.

About 10.41% of Bagmati Province falls under the category of 'most suitable' for solar plant development, while another 49.33% falls under category of 'suitable'. These locations are mainly found in the mid hill areas, specifically around Kathmandu Valley. Global Horizontal Irradiance (GHI), slope, and aspect were determined to be the most significant criteria for site suitability, contributing a combined weight of 61.98% to the AHP analysis. Sensitivity analysis confirmed the stability of the model. Existing solar installations in the province match well with sites identified as suitable by the model, confirming the value of the GIS-AHP approach. The found suitable areas are sufficient to provide space for big solar capacity development, which will be capable of fulfilling the expected growth in Bagmati Province's energy demand up to 786 MW by 2030.

This research assists in fulfilling Nepal's energy requirements, particularly in terms of diversification beyond hydropower and reducing foreign energy reliance. The method developed and implemented in this research provides a reproducible model that can be implemented for solar site selection in other regions of Nepal and other similar mountainous countries.

Future research on solar energy in Nepal can improve by using more factors in the analysis. Researchers could look at social and economic factors. These details can help in choosing the best locations for solar projects. Another important area is studying how solar energy changes with time. Looking at seasonal and daily variations in sunlight can give a clearer idea of energy production and the challenges of using solar power with the current grid.

It would also be useful to study small regions, like districts within Bagmati Province. This way, project development can have more focused and detailed guidance. Combining solar energy with other power sources like hydropower might help optimize the country's overall energy system. Similar methods can be applied in other provinces to choose the best areas for solar energy nationally. Finally, research could consider how climate change might affect sunlight availability and the success of these projects. Exploring ways to identify and use land for solar energy and other multiple purpose, could also make better use of available space.

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