



DILLA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL
STUDIES

SITE SUITABILITY ANALYSIS FOR SOLAR
PHOTOVOLTAICS: A CASE STUDY OF ABAYA
WOREDA, SOUTHERN ETHIOPIA

MSc. THESIS

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OCTOBER, 2021

DILLA, ETHIOPIA

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A THESIS SUBMITTED TO DILLA UNIVERSITY IN PARTIAL
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MASTER OF SCIENCE IN GIS AND REMOTE SENSING

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APPROVAL SHEET FOR EXAMINING COMMITTEE

We the undersigned, certify that the thesis prepared by DEGU DEMISE ABDISA, ID.NO: RPPGIS-003/18, entitled "SITE SUITABILITY ANALYSIS FOR SOLAR PHOTOVOLTAICS: A CASE STUDY OF ABAYA WOREDA, SOUTHERN ETHIOPIA" and submitted in partial fulfillment of the requirements for the degree of Master of Science in GIS and Remote Sensing complies with the regulation of the University and meets the accepted standard with respect to originality and quality.

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DECLARATION

I, the undersigned, declare that this thesis, entitled “SITE SUITABILITY ANALYSIS FOR SOLAR PHOTOVOLTAICS: A CASE STUDY OF ABAYA WOREDA, SOUTHERN ETHIOPIA” , is my original work, that it has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate, that I followed all ethical and technical principles of scholarship in the data collection, data analysis and preparation of this the report, and that all the sources that I have used or quoted have been indicated and acknowledged.

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Abbreviations and acronyms

AHP	Analytic hierarchy process
ASTER.....	Advanced Space-borne Thermal Emission and Reflection Radiometer
DI.....	Direct Irradiance
EEP.....	Ethiopian Electric power
ESMAP.....	Energy Sector Management Assistance Program
ESRI.....	Environmental Systems Research Institute
GHI.....	Global Horizontal Irradiance
GTZ.....	Deutsche Gesellschaft für Technische Zusammenarbeit GmbH (German: German Agency for Technical Cooperation)
GWh.....	Gigawatts hour
IAE.....	International Energy Agency
Kwh	Kilowatts hour
MWh	Megawatt hour
MoWIE.....	Ministry of Water, Irrigation and Energy
NASA.....	National Aeronautics and Space Administration
PV.....	Photovoltaic
SHS	Solar Home Systems
TWh.....	Terawatt-hour
UNICEF.....	United Nations Children's Fund United Nations International Children's Emergency Fund
WHO.....	World Health Organization

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Abstract

Energy is becoming a very important input into our daily lives. Abaya woreda is known for its rare electrification, where only less than 6.5% of households have access to clean energy. With a prime objective, this study investigates the suitability of sites for the development of solar farms considering different conflicting factors in Abaya woreda. To make the study more objective and comprehensive, different spatial data was acquired from different sources and processed for further analysis. Solar insolation data was acquired from the global solar atlas and masked to the extent of the study area. Land use/cover was processed from Landsat 8 operational Land Imager (OLI) using ERDAS IMAGINE. A Digital elevation model was used to derive topographic factors, whereas road networks were digitized from topographic maps. Each factor was reclassified into four suitability layers. The weights for each parameter are calculated using the pairwise comparison method of the AHP family in the ArcGIS AHP extension. The inconsistency, which may result from subjective decisions, was checked before proceeding to the overlay process. The reclassified thematic maps were overlaid using the popular overlay method, weighted overlay. The final suitability map was produced, containing four different suitability classes: highly suitable, suitable, marginally suitable, and least suitable. In total, 6.26% of the study area was found to be highly suitable for solar farm developments, while 47.8%, 20.82%, and 25.09% of the study area were found to be suitable, marginally suitable, and least suitable for solar farm developments, respectively. A calculation was performed to estimate the power generation potential of the highly suitable or feasible area, and the area has an annual power generation of 146390 MWh/year. Although the woreda has tremendous energy potential, most people are still dependent on conventional energy sources for their power needs. Using geospatial technology can help resolve spatial problems, and most parts of Abaya woreda can be electrified by a solar farm if it is constructed with the available solar radiation and suitable sites.

Key words: *Solar insolation, suitability analysis, AHP, weighted overlay*

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Energy is an important input for the provision of basic human needs and services, including cooking, clean water, efficient, affordable, and reliable lighting, transportation, and telecommunications (IEA, 2020). For a couple of decades, the need for energy has been increasing as a result of increased population and industrial developments. But the world lacks safe, low-carbon, and cheap large-scale energy alternatives to fossil fuels, and many are forced to rely on conventional energy sources like firewood, crop stacks, and animal waste. Currently, the world's leading energy source is fossil fuels, whose prices and availability fluctuate from time to time. According to the International Energy Agency (2017), the energy demand is growing for all forms of energy and this demand cannot be met by "business as usual" energy production. Due to annually increasing energy demand, the fluctuation in prices of fossil fuels, and their adverse long-term impact on the environment and human health, the world is searching for alternative energy sources which are clean and secure. Ethiopia, for example, is targeted to connect 65% of its population with national grids and 35% with off-grid and mini-grids by 2025 (MoWIE, 2019).

These alternative energies are hoped to be harnessed mainly from solar, wind and biomass energy sources. Following the current advancements in technology and the decline in prices of solar panels, the energy from solar (both CSP and PV) is expected to grow many folds in the next decades (Panwar *et al.*, 2011). Additionally, its abundance and availability around the world make it a better choice for future energy supply. Solar energy can be exploited through solar photovoltaic (PV) and solar thermal technologies for various applications. Using photovoltaic (PV) technology, solar radiation can be converted directly into electricity, offering a clean and renewable source of energy (Yousefi *et al.*, 2018). Despite the potential of solar energy as a future energy source, site-specific measurements and accurate data are rare.

It is important to note that one of the barriers to solar energy development is the difficulty of measuring and its geographical variability from one place to another. Resource assessment and suitable site selection are a crucially important step for the development of renewable energy projects (Izeiroski *et al.*,2018). Site selection involves relying on multiple factors that have different characteristics. The acquisition of such data and its analysis for decision making requires the use of advanced technologies.

The development of geographical information systems and remote sensing can therefore be considered essential both for acquiring spatial data and for storing and analysing it. The integration of geographic information systems and Multiple Criteria decision-making (MCDM) helps to facilitate the decision-making related to site selection for photovoltaic solar energy systems (Wee *et al.*, 2012). MCDM assists decision makers by providing flexible tools for handling and bringing together a wide range of variables evaluated in a variety of ways. Therefore, coupling the capacity of GIS in spatial data handling and analysis with MCDM brings promising results in the selection of the best sites for sitting solar panels.

1.2. Statement of the problem

Energy is the primary and universal measure of all kinds of work done by human beings and nature. Everything in the world is the expression of the flow of energy in one of its forms (Benjamin, 2004). Ethiopia is doing very well concerning generating electricity through hydropower and other renewable sources, but there is a need to diversify the power mix. The country is currently overly dependent on hydropower as a source of renewable and clean energy, which is becoming less reliable as droughts intensify. The country's hydropower plants will remain the main source of baseload power, but they will need to be supplemented by other alternative energy sources such as wind and solar to be able to deal with peak demand. Currently, less than 45% of Ethiopia's population has access to the electricity grid, which has improved greatly, compared to 5% in 2000 (Solar Plaza, 2019). However, the rural communities are still dependent on traditional power sources, mainly fuelwood, and there is a high demand for electrification. Being located in a tropical region, Ethiopia is endowed with plentiful solar insolation which can light up the whole country if utilized properly. Still, more than half of the population lives

without electricity. In order to bridge the gap between plentiful resources and unmet needs, the government is expected to outline a plan to achieve universal access to electricity by promoting off-grid, micro and mini-grid scales of energy production from alternative energy sources, mainly solar and wind power, to reach the unconnected households to the national grids. In Ethiopia as a general and in Abaya woreda specifically, there is a limited holistic energy resource assessment. Additionally, there is no enough assessment of the identification of potential sites for future alternative energy developments.

Most parts of the country have a non-uniform solar radiation distribution, with an average solar radiation of 5.2 kWh/m²/day. Abaya Woreda, which is found in the West Guji Zone, is among the rural woredas of Ethiopia that have limited access to electric power. Although solar radiation is everywhere in the area, installing solar panels everywhere is impossible. Choosing the best sites for the development of new projects is dependent on different conflicting factors. These factors cannot be handled in a traditional way, since they have different characteristics. So, the conflicts between the factors require a sophisticated multi-discipline approach to be resolved for better results. Suitable areas need to be selected using available technologies prior to dimly installing the panels. In this regard, Geographic Information System based multi-criteria decision making plays a leading role in dealing with such issues.

1.3. General Objective

The general objective of this study is to analyze the suitable sites for solar photovoltaics in the study area

1.3.1. Specific objectives

- To examine spatio-temporal distribution of solar radiation in the study area
- To estimate the solar electricity generating potential of the study area
- To identify potential sites for solar panels installation in the study area

1.4. Research questions

1. Does the distribution of solar radiation vary spatially and temporally?

2. What are the governing factors in selecting best sites for solar photovoltaics?
3. What are the best sites for the development of solar farms?
4. How much energy can be generated from solar PV systems?

1.5. Significance of the study

The purpose of this study was to examine the suitability of sites for solar farm development. The findings of this study will be significant for the following reasons: The findings of this study will offer better insights for solar energy developers by revealing information about the study's results that will lead to better choices of where to develop solar farms generating energy. It will be used as a benchmark for further studies related to solar energy. With necessary modifications, the method can be used for other areas to analyze the best area for solar panel installations.

1.6. Scope of the study

This study focuses on analyzing the suitability of sites for solar photovoltaics. Even though there are several woredas in the west Guji Zone, only Abaya Woreda was selected for this study. Furthermore, the solar panel installation plan requires consideration of technical, environmental, and economic factors. This paper focused only on the technical part, which is finding the best site for sitting solar panels. Other concerns, such as the number of panels required, types and number of batteries needed for full functioning of the system, were not included in the current study. Detailed analysis such as economic feasibility was not included in the current study. Additionally, the study is confined to Abaya woreda.

1.7. Limitation of the study

This study focused on finding suitable sites for the installation of solar panels. A great deal of effort is put into to ensure that the results of the study are conclusive. This research, however, is subject to some limitations. There are two main limitations to this study that could be addressed in future research. The study used multiple datasets to identify the most suitable locations for solar PV. However, due to the lack of long-term solar insolation data in the study area specifically and in the country in general, satellite data was used for the current study. In addition, the study area does not contain any

previously developed solar farms. Therefore, the final output is validated by observation and by overlaying the final map on Google Earth.

CHAPTER TWO

REVIEW OF RELATED LITERATURES

2.1. World energy demand and supply

Modern energy services are crucial to human well-being and to a country's economic development and access to them is critical for the provision of clean water, sanitation, and healthcare and for the provision of reliable, affordable, and efficient lighting, heating, cooking, mechanical power, transport, and telecommunications services (IEA, 2020). However, the world lacks safe, low-carbon, and cheap large-scale energy alternatives to fossil fuels and many are forced to rely on conventional energy sources like firewood, crop stacks, and animal waste. If the challenges are not resolved, the world will continue to face further energy challenges. These issues range from greenhouse gas emissions to hundreds of millions of people lacking adequate energy access, all with disastrous consequences for themselves and the environment (Our World in Data, 2018).

The dominant global energy production is 80% fossil. About 16% of global energy comes from low-carbon sources, which include nuclear and renewable energy (Our World in Data, 2019). According to the World Energy Council 2013, by 2030, electricity will absorb 44% of primary energy resources for its production and now it is already responsible for 40% of the CO₂ emissions resulting from human activities. More than 1.3 billion people are currently without electricity, and poor Africa consumes less than 3% of all electricity, 40% of all electricity is consumed by a single nation (the Republic of South Africa), which represents 5% of the African continent's 1 billion inhabitants.

The world's energy demand and supply vary by country, because developed countries produce and consume more energy than developing countries. Primary energy differs from final energy consumption because much of the energy that is acquired by humans is lost as other forms of energy (IEA, 2018) during the process of its refinement into usable forms of energy and its transport from its initial place of supply to consumers. For example, in 2014, world primary energy supply amounted to 155,481 terawatt-hour (TWh) while the final energy consumption was about 70% of it.

Despite progress in several countries (e.g., Kenya, Ethiopia, Ghana, Senegal, Rwanda), current and planned efforts to provide access to modern energy services barely outpace population growth. According to the IEA (2019), 90% without access to electricity and 50% without access to clean cooking are found in African countries.

2.2. Renewable energy sources

Renewable energy is useful energy that is collected from renewable resources, which are naturally replenished on a human timescale (Ellabban *et al.*, 2014), including carbon neutral sources like sunlight, wind, rain, tides, waves, and geothermal heat. The switch from conventional energy to clean and renewable energy sources is increasing because these energy sources can be used for electricity, air and water heating/cooling, transportation, and rural (off-grid and mini-grid) energy services (Harbour Tax Group, 2010).

With growing concerns over global imbalances between petroleum demand and supply (Warf, 2010), as well as the need to mitigate global climate change and other environmental impacts related to energy consumption, renewable energy has gained increased attention. IEA (2012), notes that in addition to environmental concerns, advancements in energy conversion and management technology have made it possible for many nations to invest in the development of renewable energy sources.

As a result of their ability to reduce carbon dioxide emissions by displacing fossil fuels in the energy generation sector and the transportation sector, renewable energy technologies have gained popularity (Edenhofer *et al.*, 2010). Aside from reducing carbon emissions, renewable energy sources are being used to electrify rural areas, particularly in developing countries where access to the grid is difficult due to economic and geographic factors (IED, 2013). The advancement of technologies and the growing need for renewable energy sources could increase the diversity of electricity sources, minimizing the reliance of nations on non-renewable energy sources, such as coal and oil (Nouni *et al.*, 2008).

2.3. Solar radiation at the Earth's surface

The knowledge of solar radiation at ground level is very important for a wide range of applications, including solar farms, agriculture, and many climate applications (Zhang *et al.*, 2017; Fan *et al.*, 2019). The spatial distribution of solar insolation can be mapped using radiation data obtained from ground-mounted measurement stations. Such a method is however not applicable to many areas of the globe due to the lack of sufficient data for reliable interpolation (Wild *et al.*, 2013). Moreover, the cost of measuring equipment and specific maintenance and calibration requirements result in solar radiation measurements becoming unavailable in many locations around the world (Besharat *et al.*, 2013; Wu *et al.*, 2017).

For these reasons, different models have been developed to estimate solar radiation on the surface of the earth. The direct measurement of solar radiation and its components (direct and diffuse) is done in two basic ways as well. In either case, measurements are made using ground-based instrumentation like pyranometers or remotely with satellites. In many cases, these methods are used in combination to validate one another (Muneer, 2007). Satellite-based solar radiation is currently gaining popularity due to its widespread availability (Gastli and Charabi, 2010), and the derived data can be used to produce higher-resolution solar radiation maps. Thus, derived hourly values have proved to be at least as accurate as interpolation from ground stations at a distance of 25 km (Zelenka *et al.*, 1999).

Currently, various organizations provide solar data with better spatial resolution for the entire world. Solargis, whose development is funded by the World Bank Group, provides free solar data with a 250 m spatial resolution for its member countries (Global Solar Atlas, 2020). Generally, satellite data are better used to forecast solar radiation than density and number of monitoring stations, since these factors do not always capture variations in solar radiation.

2.3.1. Spatial and temporal variation of solar radiation at the Earth's surface

Earth's surface is the primary source of energy for life, and our habitats' climate is determined by the weather patterns caused by solar radiation. It also has major practical

implications, including solar energy technologies and agricultural productivity (Wild *et al.*, 2009). As such, understanding its variability over time and space is crucial as it is a critical input parameter for the design, performance, prediction, and monitoring of solar energy devices (Monforti *et al.*, 2014; Davy and Troccoli, 2012).

Typically, a 1m² (square meter) area perpendicular (90°) to the Sun's rays directly above the Earth's atmosphere receives about 1,365 watts of solar power (Coddington *et al.*, 2016). But this amount of radiation is not the same everywhere on earth because the amount of radiation received is influenced by several factors on a global and local scale (Kopp *et al.*, 2011). Daily insolation at the landscape level is characterized by strong spatio-temporal variability (Badosa *et al.*, 2013). Topography plays a major role in determining the spatial variability of insolation at landscape scales. Variation in elevation, orientation (slope and aspect), and shadows cast by topographic features all affect the amount of insolation received at different locations (ESRI, 2019).

In addition to geography, the change in seasons also affects the available solar radiation on various parts of the Earth (ESMAP, 2020). Total solar irradiance changes slowly on decadal and longer timescales, which is caused by solar changes. According to Krivova *et al.* (2007), not all variations in insolation are due to solar changes, but are due to the Earth moving between its perihelion and aphelion, or changes in the latitudinal distribution of radiation. These orbital changes have caused radiance variations of as much as 25% (locally; global average changes are much smaller) over prolonged periods (Steinhilber *et al.*, 2009). Globally, due to the slight ellipticity of the Earth's orbit around the Sun, the amount rises or falls by ±3.4 percent throughout the year, peaking on January 3, when the Earth is closest to the Sun (Encyclopaedia Britannica, 2020).

2.4. Energy demand and supply in Ethiopia

Having access to modern energy sources is essential for economic development and livelihood improvement (Reddy, 2015). Ethiopia has a total final energy consumption of around 40,000 GWh, with domestic appliances accounting for 92%, transportation accounting for 4%, and industry accounting for 3%. The share of electricity is

~9000GWh, which is dominantly generated from hydropower (96%), followed by wind (4%) (IEA, 2014).

Ethiopia's energy supply is reliant on traditional biomass energy due to limited access to modern energy sources to meet a growing demand (Md Alam, 2018). Ethiopia has more than 100 million people, out of which about 83% reside in rural areas. According to the International Energy Agency-IEA (2016), the country has one of the lowest rates of access to modern energy services, with biomass serving as the primary energy source. With a share of 92.4% of Ethiopia's energy supply, waste and biomass are the country's primary energy sources, followed by oil (5.7%) and hydropower (1.6%). Despite its limited access, the country is making significant progress in the power sector. For example, between 2012 and 2016, the number of electricity customers of EEP (Ethiopian Electric Power) reached over four million from two million at the beginning of the period (World Bank Group, 2016).

The energy demand in the country is quickly increasing by ~30%, which puts high pressure on the existing grids, leading to continuous power outages in many parts of the country (Capital Ethiopia, 2017). To solve these persistent problems, and to achieve additional mass electrification, the country is working to diversify its energy sources. The country is focusing on the production of electricity from a mix of cheap and clean renewable primary energy sources like hydropower or wind power, and photovoltaics (MoWIE, 2013), and recently the Ministry of Water, Irrigation and Energy launched a holistic National Electrification Program (NEP) with the motto of "Lighting to All", which enhances additional power generation capabilities to meet future energy demand (MoWIE, 2019). These bold plans are expected to electrify rural areas, particularly through the development of standalone and mini-grid photovoltaics.

2.5. Renewable energy potential of Ethiopia

Ethiopia is reliant on traditional biomass fuels to meet its energy needs, but has access to abundant and diverse renewable resources as well as electricity generating technologies that offer an opportunity to move away from the current energy system (Jillian, 2011). Developing and utilizing the available potential could significantly alter Ethiopia's energy

situation, which would lead to a shift from conventional energy usage towards mass electrification using clean and renewable sources (Guta, 2017). In addition to strengthening the country's energy security, reducing pollution, planning for climate change, and developing regional electricity exports, these resources can be used for a range of purposes like energy exports.

Being in the tropics, Ethiopia is endowed with ample solar radiation. Although there is not enough accurate ground data recorded at the landscape level, on average the country's solar radiation is estimated to be 5.2 kWh/m²/day (Mondal et al., 2018, International Energy Agency, 2019). During the daytime, the country's most populous regions receive a low amount of irradiance, while the rift valley and eastern lowlands receive a higher amount, estimated at 6 kWh/m²/day (Shanko, 2009). MoWIE, (2013), indicates that the value ranges between 4 and 6 kWh/m²/day, with spatial and temporal variability. It creates a fantastic opportunity for solar energy development in rural areas where access to the grid may be limited.

Ethiopia has more than twelve river basins and approximately 122 billion cubic meters of surface runoff per year. With these and a number of other rivers, Ethiopia is known as the "Water tower of Eastern Africa" (GTZ, 2007), which has an installed electricity capacity of 45,000 MW.

2.6. Photovoltaics (PV) systems

The photovoltaic system converts light from the sun into usable electricity. It comprises the solar array and the balance of system components. A PV array is a linked collection of photovoltaic modules that operate as a single electricity producing component, while the balance of the system indicates all the components except PV modules, such as solar inverters, mounting, wiring, instrumentation, and control systems to assemble a functioning system (Andrews *et al.*, 2013). Bazilian *et al.* (2013), state that solar PV systems have long been used as standalone installations and grid-connected systems since the 1990s.

In the last few decades, solar panels were rack-mounted on roofs, but this is changing due to government incentives and the continuous decrease in the cost of solar panels (Joern

et al., 2014; Justin, 2013). In utility-scale solar power stations, the panels are mounted on the ground and not tracked with expensive tracking devices. Normally, solar panels of these types require a large piece of land.

China and Taiwan have dominated the production of solar panels in recent years (Erica, 2016), with the United States and other European countries accounting for less than 5% of the total production. Until recently, solar installations were limited to Europe, but now they are spreading rapidly throughout the world, particularly in sunnier regions (EPIA, 2014).

Despite the popularity of photovoltaics worldwide, their efficiency is low (Furkan and Mehmet, 2010). PV cells are not fully able to convert all of the sunlight they receive into electricity. In real-world use, 100% efficiency is impossible because, solar panel operating efficiency is dependent on many external factors. These factors, which differ depending on the local environmental conditions, can reduce the efficiency of the panels as well as the overall system performance. According to Kita *et al.*, 2019, there are always unavoidable losses (such as reflection of radiation off the surface of the panels, transmission losses, or shading losses) that greatly contribute to the low efficiency of solar panels. Nonetheless, the average efficiency of panels has increased from 15% to over 20% in the last few years due to many advancements in photovoltaic technology (clean energy reviews, 2021). In recent years, PV systems have become more popular because of a decline in price and improved efficiency and are hoped to be the leading renewable energy in the near future.

2.7. Roles of geospatial technology in renewable energy development

Geographical Information Systems differ from other information systems in terms of the data they contain and the properties of that data. The ability to address the location of objects or events (phenomena) on earth is a characteristic of such data. For this reason, the locations of objects or events and their relationships with each other can be visualized and this visualization is called a "map" (Türk *et al.*, 2021).

Geographic information systems play a major role in the development and expansion of renewable energy sources such as solar, biomass, geothermal, wind, and hydro/wave energy (Sensors and Systems, 2019). Most applications relate to site location, but other applications include analyzing the renewable energy as a global source for electricity (Mapline, 2017), meteorological forecasting, spatial/network analysis, geospatial modelling, facilities management, and economic analysis and forecasting. In order to assist in planning for the introduction of renewable technologies to rural areas that lack electrical infrastructure, numerous models are formulated and these analytical tools are valuable for policymakers, utility companies, and environmentalists. The GIS is being utilized by different researchers worldwide to identify best sites for development of solar farm, wind farm and other renewable energies. Besides GIS which provides numerous tools that can ease analysis and storage of spatial data; Remote Sensing can be very important for renewable resources. As energy use and supply continue to grow, new and cleaner energy methods are emerging worldwide. Depending on the type of energy source being used, trying to find the right locations to place the technology can be time-consuming and draining of not only money, but resources as well. A remote sensing system eliminates the middle man, a surveyor who collects data for months, and allows the data to be reported back in an instant (Calaudi *et al.*, 2016; Young *et al.*, 2020)

The application of GIS and Remote Sensing was utilized in Oman to identify best sites for sitting solar panels (Charabi and Gastli, 2011), Gerbo *et al.*, 2020, used ArcGIS solar analyst tool to estimate available solar radiation in East Shewa Zone, and Türk *et al.*, (2021), used GIS based AHP approach to find best sites for solar farm in Erzurum province/Turkey.

2.8. GIS based Multicriteria Decision Analysis (MCDA)

Nowadays Lots of the short-term and long-term problems people have been of a geographic nature and hence coupling GIS with MCDA is impactful. Spatial problems typically involve a large set of feasible alternatives and multiple, conflicting and incommensurate evaluation criteria. A Multicriteria decision analysis is a commonly used approach for supporting decision makers who are faced with numerous and conflicting evaluations (Abu-Taha, 2011), and its significance has been increasing steadily over time.

The rapid development of Geospatial technologies has transformed the way we organize and manage spatial data (Yousefi *et al.*, 2017; Noorollahi *et al.*, 2016) to solve spatial problems across multiple disciplines (Lewis, 2015).

The majority of GIS-based site suitability studies are built upon multi-criteria analysis (MCA) to synthesize complex problems with multiple variables. This decision-making tool is used in environmental systems analysis to evaluate a problem (Hermann *et al.*, 2007) by giving an order of preference for multiple alternatives on the basis of several criteria that may have different units (ESRI, 2014).

GIS-based multi-criteria analysis basically relies on two main approaches: Boolean overlay operators and weighted summations procedures (Yosoon *et.al.*, 2019). The Boolean tools evaluate the inputs only as True or False conditions and return the result of the particular tool as a 1 or 0 (True or False) Boolean value. The Combinatorial tools identify unique combinations of input values based on the logic of the particular tool and return a different value for each unique combination (ESRI, 2019). This approach simply determines whether any conditions are satisfied, and analyzes the suitable area that satisfies all conditions. The Boolean tools have no capability of dealing with criteria having different weights. But the weighted overlay tool applies one of the most used approaches for overlay analysis to solve multicriteria problems such as site selection and suitability models. This tool gives the decision maker the opportunity of defining the problem, breaking the model into sub models and identify the input layers. By doing so it remains popular in decision making analysis. Most of the time the input criteria will come in different numbering systems with different ranges. To combine them in a single analysis, each cell for each criterion must be reclassified into a common preference scale such as 1 to 5, with 5 being the most favorable (ESRI, 2019).

2.9. Estimation of photovoltaics energy output

Photovoltaic cells' efficiency is limited by many losses. Few of them are controllable and few of them are uncontrollable. Today, PV panels convert energy from sunlight into electricity within the range of 12%-19% (Mekhilef *et al.*, 2011; Sánchez Reinoso *et al.*, 2010). But the final energy output of the system is governed by different factors, like

available solar insolation, efficiency of the panels (type of cell), number of connected solar panels, or partial shading, and cell operating temperature (Hosenuzzaman *et al.*, 2014). Because every solar panel system is different, it's hard to say exactly how much electricity they generate. Different researchers use different formulas to estimate the final energy generation of PV systems. The mostly known formula for estimation of solar electricity form a parcel of land is the used by (Charabi and Gastli, 2010, and Gerbo *et al.*, 2020). The formula considers the available GHI per year, area of suitable land, number of sunshine hours, and efficiency of the panels.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Study area description

Abaya woreda is one of the woredas in the West Guji zone Oromia regional state of Ethiopia. It is part of the former Galena Abaya woreda that was divided into the Abaya and Gelana woredas. The woreda is found at the south direction of capital city of Addis Ababa at a distance of 372 kilometres. The area is geographically located between latitude $6^{\circ} 06' 0''$ N – $6^{\circ} 32' 30''$ N and longitude $37^{\circ} 50' 30''$ E – $38^{\circ} 18' 30''$ E and covering a total area of 1205.24 km^2 . The altitude of this woreda ranges from 1,132 to 2,316 meters above sea level (Figure 1). The woreda is composed of different land use land covers like; shrub land, wood land, agroforestry, agricultural land, waterbody, wetland, bare lands, and others (Abaya Woreda Agriculture and rural development office, 2020).

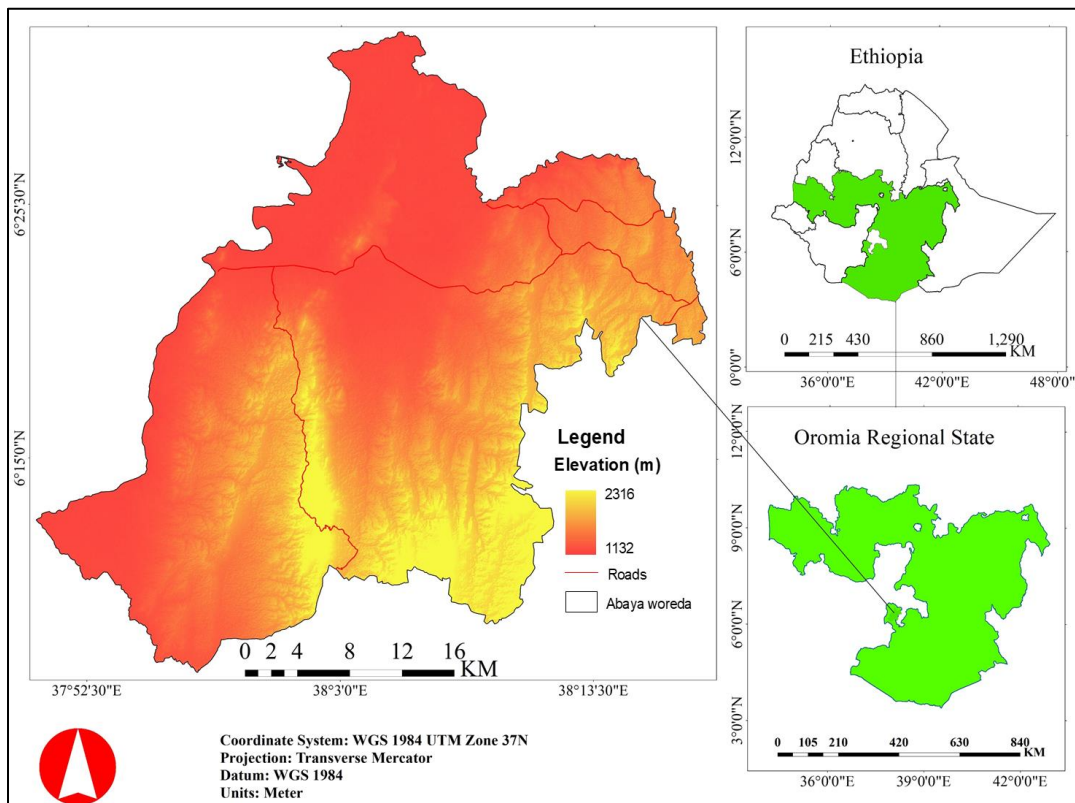


Figure 1. Location map of the study area

The dominant land use/cover is bush/shrub land while the least is bare land. The study area receives an average GHI of about 5.6 Kwh/m²/day or 2055 Kwh/m²/year which shows a variation spatially and temporally (Global Solar atlas, 2020). According to the Ethiopian agro-climatic zones classification the woreda is divided into two agro climatic zones namely: *kolla* which accounts about 80915.94 hectare (67.12%) and *weyna dega* which covers 39625.92 hectares (32.87%) of the total area. The temperature of the area ranges from the minimum 19 °c to the maximum 31 °c with an average of 25 °c. Most part of the *weyna dega* experiences relatively minimum temperature while the *kolla* has a temperature which can exceed 31°C. As other most parts of Ethiopia the woreda experiences four climatic seasons where the summer months of June, July and August are characterized by heavy rain falls and clouds while in contrast, in the winter dry season that falls in the months between December, January and February is known for its clear sky and long day sunshine.

3.1.1. Population size and Access to electricity

The Woreda is currently home to 152,703 people, who lives in 27 kebeles. Only 5% of the population lives in urban area, while the rest of the population lives in rural.

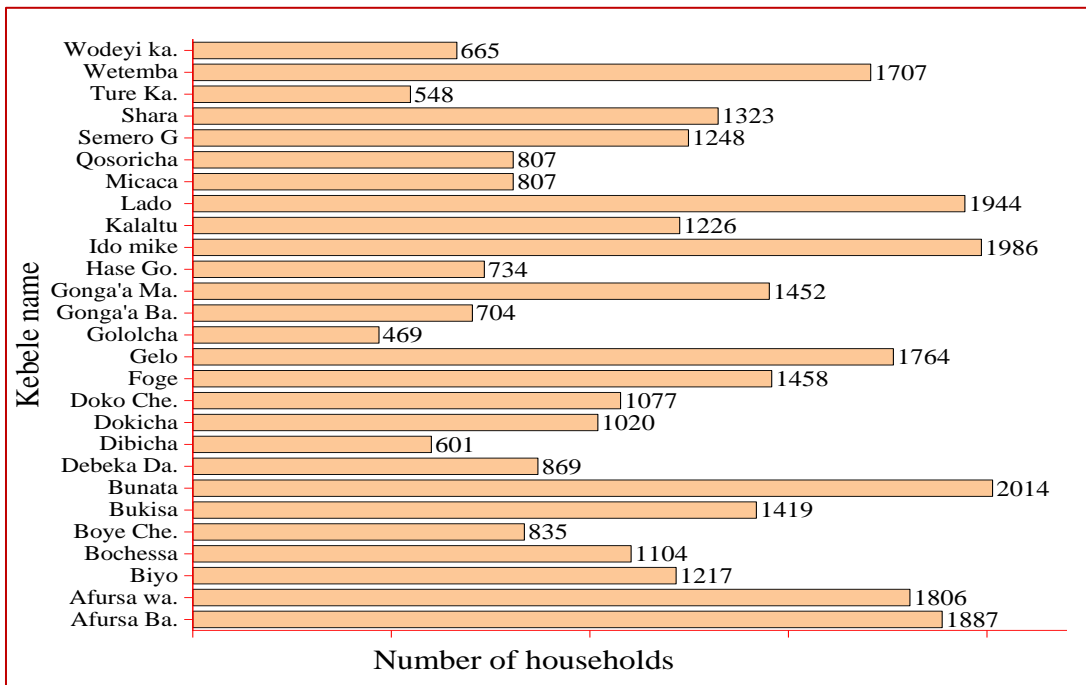


Figure 2. Number of households by Kebele (Abaya woreda electric utility office)

Most of the kebeles are out of the national grid and highly reliant on conventional energy sources for their energy needs (Abaya Woreda water irrigation and energy bureau, 2020). Most of the households practice agriculture, livestock rearing, and charcoal production for living. According to the data from Abaya woreda Health office (2020) there are about 32691 households, while the figure varies from kebele to kebele.

Since more than 95% of the population live in rural, they are dependent on traditional energy sources to meet their energy demand. As of 2020 there are only 650 installed electric meters in 8 kebeles allowing less than 6.5% of the population to have electricity. This number is higher in Gangua town which accounts about 500 electric meters, followed by Semero Gambela kebele where there are about 48 electric meters. Only 8 kebeles are connected to grid with six of them only have less than fifteen electric meters. Those kebeles which are connected to the grid experiences power outages two to three times a week. Other kebele are still dependent on conventional energy sources either for cooking or lighting their homes.

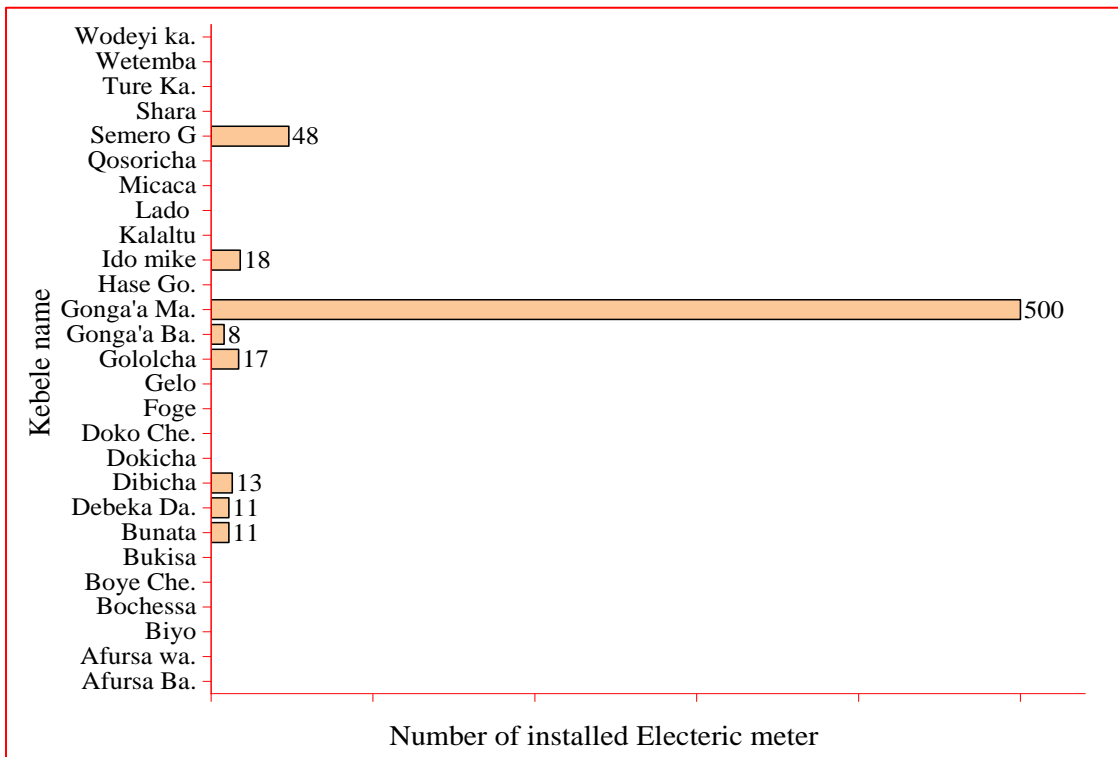


Figure 3. Number of installed Electric-meter by Kebele (Source: AWHO)

3.2. Research Approach and Design

This study examines the suitability of a site for the installation of solar panels. Site selection for such a purpose is not only determined by a single factor. It is necessary to examine a variety of factors separately and sum them up to determine where the best and poor sites for solar farms are. These factors include; solar insolation, land use/cover, proximity to existing roads, proximity to populated areas, slope, and direction of slope (aspect). Each parameter has different characteristics with varying suitability layers. These parameters are spatial in nature and have varying effects on the final suitability result. In order to produce the final suitability map, these factors need to be weighted considering the influence they have in relation to one another. So, a relational research design was employed. Relational research design is ideal for gathering data quickly from natural settings that helps to generalize findings to real-life situations. This makes it a proper choice since it can provide insights into complex real-world relationships, helping researchers develop theories and make predictions (Bhandari, 2019).

3.2.1. Materials

3.2.1.1. Data type and sources

To meet the proposed objectives, different spatial and non-spatial datasets were obtained from various sources and processed using multiple GIS (Geographic Information Science) and Remote Sensing tools for analysis and mapping purposes. Solar radiation data is a primary input for determining the suitability of a site for solar panels to be installed on the ground. Ethiopia has a large and diverse solar power generation potential (World Bank Group, 2019). At the local level, solar intensity records can be collected at a specific station using pyranometers or actinographs, and can be interpolated to create a continuous raster for the rest of the area. In Ethiopia, it is difficult to find recorded solar resource data at all locations because the meteorological stations that are capable of recording solar irradiance are only limited to zone levels. This makes it difficult to use this data for analysis. Nowadays, many organizations provide satellite-based and validated solar data at local and global levels. For this study, the solar irradiance data with a spatial resolution of 250m and sub-hourly time resolution was obtained from Solar Atlas, a project funded by the World Bank Group ESMA. The organization provides

average daily-monthly and annual data for its member countries free of cost. In addition to solar radiation potential, the selection of ideal sites for ground-mounted solar panel installations requires other data, such as land use/cover, existing road network, slope, aspect and settlement area. The land use/cover of the study area was processed from a 30m spatial resolution Operational Land Imager (OLI) Landsat image using ERDAS IMAGINE® and ArcGIS software. The road network was obtained by digitizing a topographic map of the study area with scale of 1:50,000. Since the topographic map used for digitizing road data was published many decades ago, the newly constructed road data was not included. The slope and aspect of the study area were derived using ArcMap from a 30m spatial resolution ASTER (<https://search.earthdata.nasa.gov/search>) digital elevation model (DEM). The Settlement data was collected using Garmin 72h GPS (Global Positioning System), and converted into an Esri shapefile in ArcGIS. Additional settlement data where there was a security problem was collected using the online version of Google Earth (www.earth.google.com). The summary of the data used in this study with respect to its format, resolution and sources is summarized in (Table 1).

Table 1. Summary of datasets used in the study

Data	Sources	Data type	Spatial Resolution
DEM	NASA (https://earthdata.nasa.gov)	Raster	30m
Solar Radiation	Global Solar Atlas	Raster	250m
Land use/cover	Processed from Landsat image	Raster	30m
Slope	Generated from Digital Elevation Model (DEM)	Raster	30m
Aspect	Generated from Digital Elevation Model (DEM)	Raster	30m
Road network	Digitized from topo sheet	(Converted to raster)	30m
Settlement	GPS and Google Earth	Point/polygon (converted to raster)	30m

3.2.2. Methods: Data acquisition and preparation

For this study, data were collected from different sources with different formats and had to be formatted using various GIS toolsets to spatial data formats for specific evaluation criteria. These layers were combined to create a final map of potential PV panel installation sites. To develop a process for solar panel placement site selection, different methods were implemented for macro-scale level mini-grids (ground-mounted installations) systems. Several data preprocessing steps were performed, including acquiring daily, and yearly solar radiation maps to assist site selection for mini-grid PV installations. Land use/cover of the area was mapped using a Landsat 8 Operational Land Imager (OLI) satellite image of 2020. Road networks were prepared by digitizing a 1:50,000 topographic map (sheet number: 0638C1= KOTI, 0638C2 = DILLA, and 0638C3 = YIRGA CHEFE). The aspect and slope of the area were generated from a 30m spatial resolution ASTER Digital Elevation Model. The areas where dense settlements exist were collected using GPS data and Google Earth.

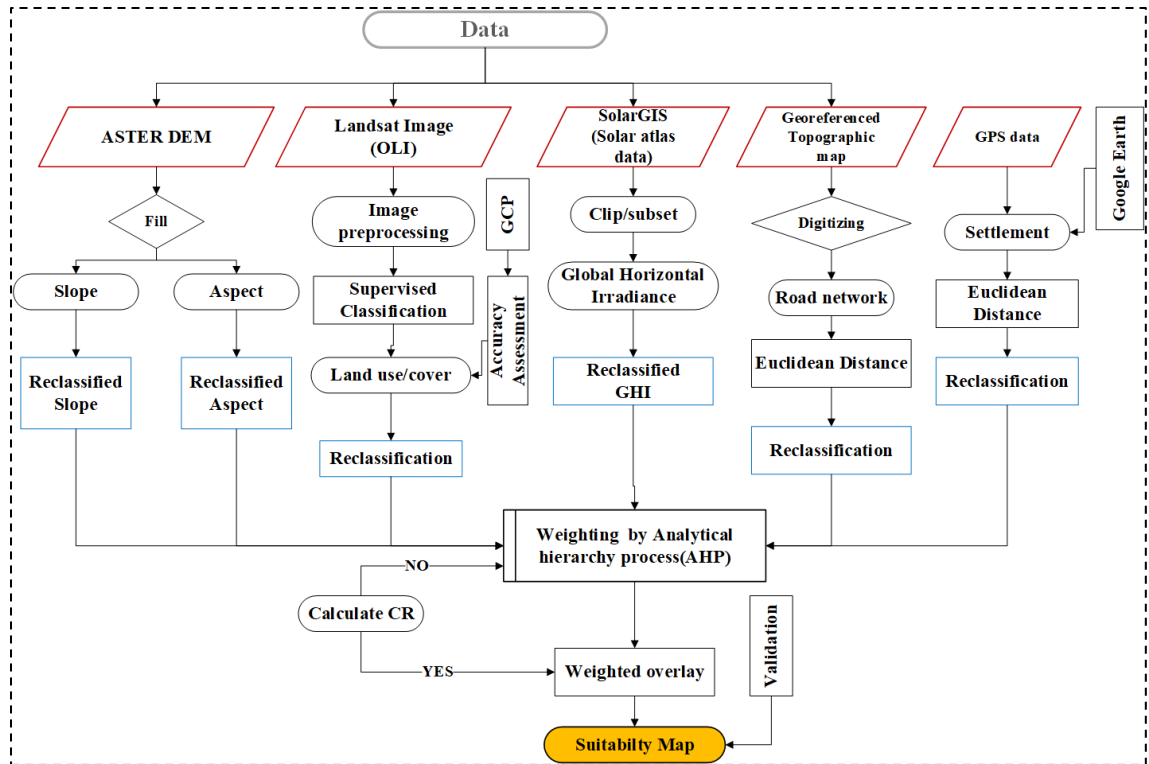


Figure 4. General workflow

3.2.2.1. Solar Radiation

Solar radiation is the main consideration when proposing or installing solar PV (photovoltaics) or CSP (Concentrated Solar Power) plants. Hence, it is essential to identify areas where solar radiation is abundant to predict the spatial and temporal distribution of solar radiation for effective solar resource utilization. Solar panel installation sites must be able to generate an adequate electricity supply to ensure the long-term sustainability for supporting energy demands. Abaya woreda located in the regions of the solar belt experiences a high amount of solar radiation resources which have the capability to generate an ample amount of energy (Solar plaza, 2019). Accurate and location based solar resources data can be recorded using different instruments and modelled using various models. The best way of knowing the amount of global solar radiation is to install pyranometers or photovoltaic sensors at as many locations as possible in a given region and follow their day-to-day recording. However, site specific solar data recording is expensive and it requires timely calibration of the instruments. This makes its availability very scarce. In Ethiopia, most of the meteorological stations

are installed and monitored by the Ethiopian National Meteorological Agency. The organization manages meteorological stations almost in all woredas of the country. But these stations have no instruments to record GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance), and DI (Diffused Irradiance). The Ethiopian meteorological Agency has a long-dated data which was recorded three decades ago at zone levels. The available data were acquired from the organization for Arba minch, Hawassa, and Sodo stations which was measured in Cal/cm²/day (Calorie per square centimetre per day). In most cases, it is not accurate to use the nearest weather station in one's analysis by creating a raster surface using interpolation, due to the variability of solar radiation with terrain, vegetation cover, ground structures and weather. When there is a shortage of locally measured solar data, Zelenka et al., (1999), recommends the use of satellite derived solar data, since they are proven to be at least as good as the accuracy of interpolation from ground stations at a distance of 25 km.

Nowadays, various companies and organizations provide solar data with varying spatial and temporal resolutions across the globe. For this study the data from global solar atlas archive was used. This data layer is prepared by Solargis global solar model. It has been delivered for the Global Solar Atlas (<https://globalsolaratlas.info/>), online platform funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank, under a global initiative on Renewable Energy Resource Mapping (Global Solar Atlas, 2020). In this case, the World Bank Group is supporting Ethiopia's efforts through a program called "Scaling Solar", a program designed to boost the use of renewable sources of energy such as solar (Solar Plaza, 2019). For this study, the free version of the data with 250m spatial resolution and daily total and yearly temporal resolution was downloaded from the Global solar atlas website (<https://globalsolaratlas.info/>) in a GeoTIFF GIS data format. The downloaded (Annex 2) data were unzipped, and the area of interest was clipped to the extent of the study area in ArcMap (Figure 5).

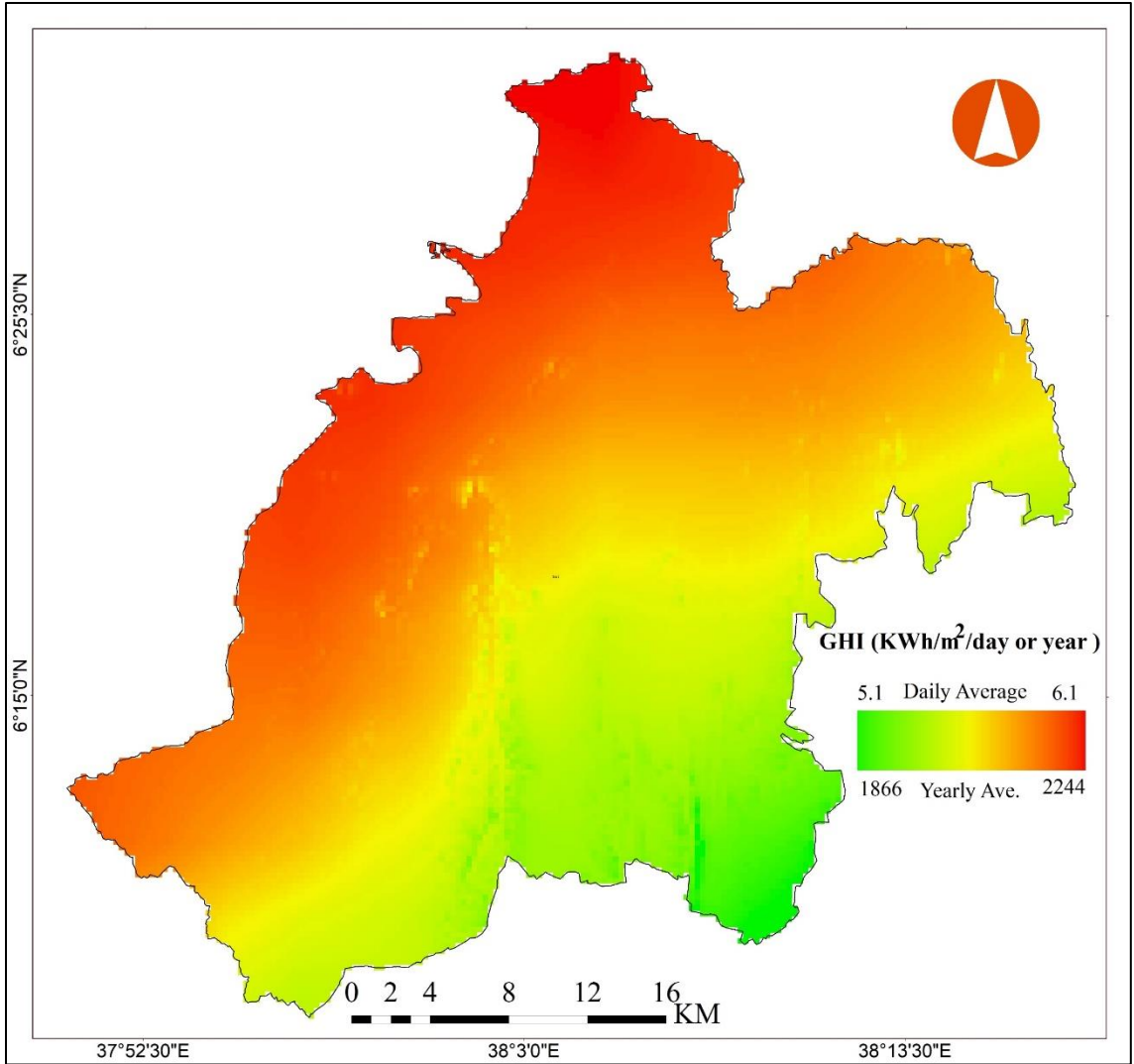


Figure 5. Daily and Annual solar insolation (1994 – 2018 Average)

3.2.2.2. Land Use/Cover

Land use/land cover is an important environmental factor in determining the location of solar farms. In this study, the land use and land cover map were created by processing the USGS (United States Geological Survey) Landsat image using ArcGIS and ERDAS IMAGINE® software. First, the Landsat 8 image, Operational Land Imager (OLI) was downloaded from USGS (<https://earthexplorer.usgs.gov>) for two paths/rows (168/056 and 169/056) with Object ID: (Annex 1). Since the study area is covered by two tiles of images, there was a need to mosaic and prepare the images to fit the area of interest.

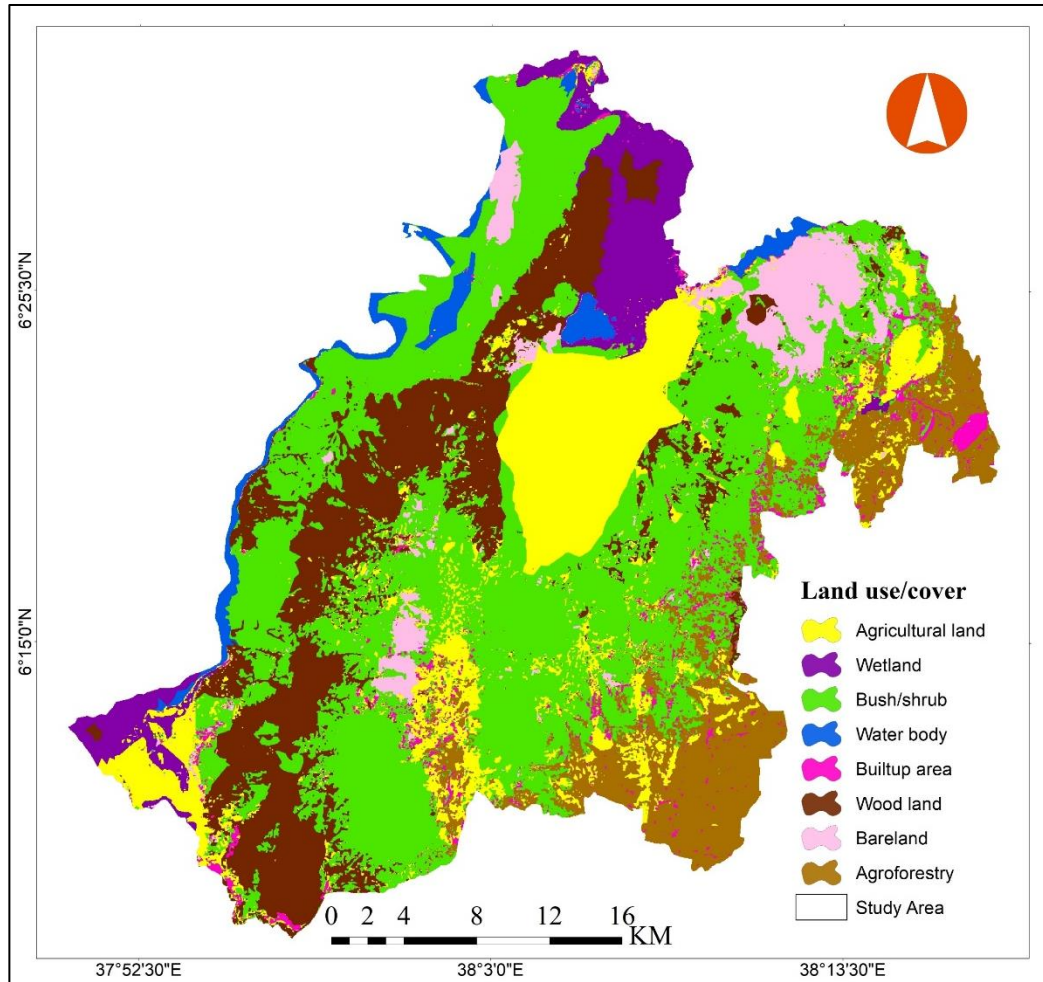


Figure 6. Land use/cover map (2020)

The two Landsat tiles were layer stacked separately and mosaicked to give a single image in the ERDAS IMAGINE ® environment, version 14. The 5-4-3 band combination was used for the RGB colour composite, as it provides a significant amount of information and allows for easy differentiation of different land uses and land covers (NASA, 2011). By collecting signature values for each land use/cover, the final classification was made in the ERDAS IMAGINE ® environment. Finally, the land use/cover map was produced using supervised maximum likelihood classifier (Figure 6). To validate the accuracy of the classification, accuracy assessment was made using independently collected ground control points and a confusion matrix was generated in ERDAS Imagine. The confusion matrix result is found under (Annex 4)

3.2.2.3. Existing road networks

Proximity to roads and good site accessibility is a critical economic factor, influencing site construction costs (Brewer et al., 2015). The road network of the study area is rarely available. So, the road network was digitized from a 1:50,000 scale topographic map of the study area.

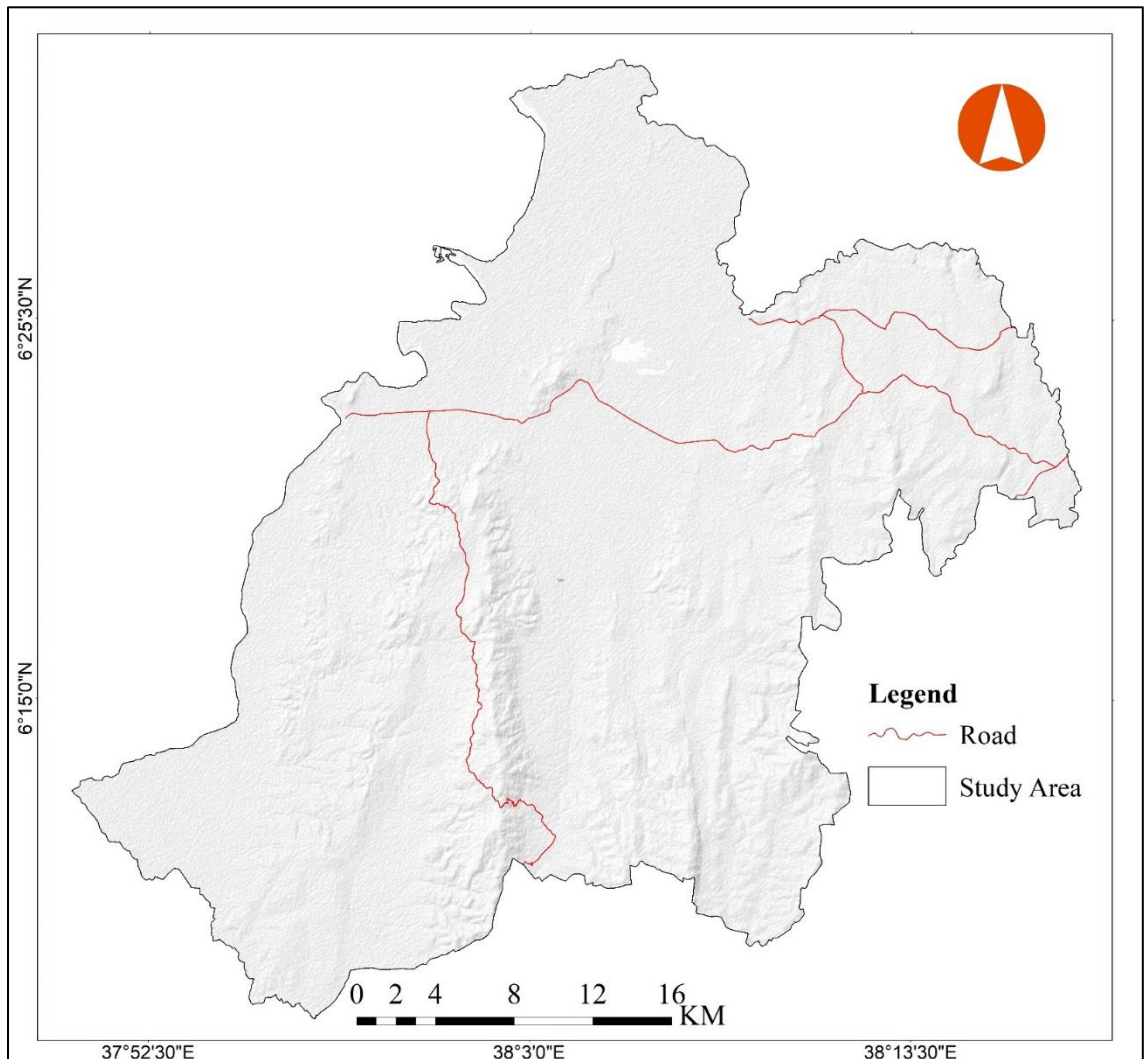


Figure 7. Road network map

The topographic map of the study area was prepared three decades ago, so it doesn't contain all the roads, especially those constructed since the last decade. Additional roads were obtained from EthiGIS and spatial adjustments were made using ArcGoogle in ArcMap. The data was converted into raster data format with spatial resolution of 30m (Figure 7).

3.2.2.4. Settlement (populated area)

Settlement is an essential criterion for planning and installation of solar farm in a specific region. Especially when there is no national grid around, the generated energy needs to be consumed by the local community by connecting them using a mini grid system. For this study, the places where there are densely populated were collected by hand held GPS and converted into GIS file format in ArcMap. The places where it is difficult to access due to security problems were digitized from ArcGoogle in ArcMap. Finally, the two data sets were converted into the same data format and prepared for further analysis (Figure 8).

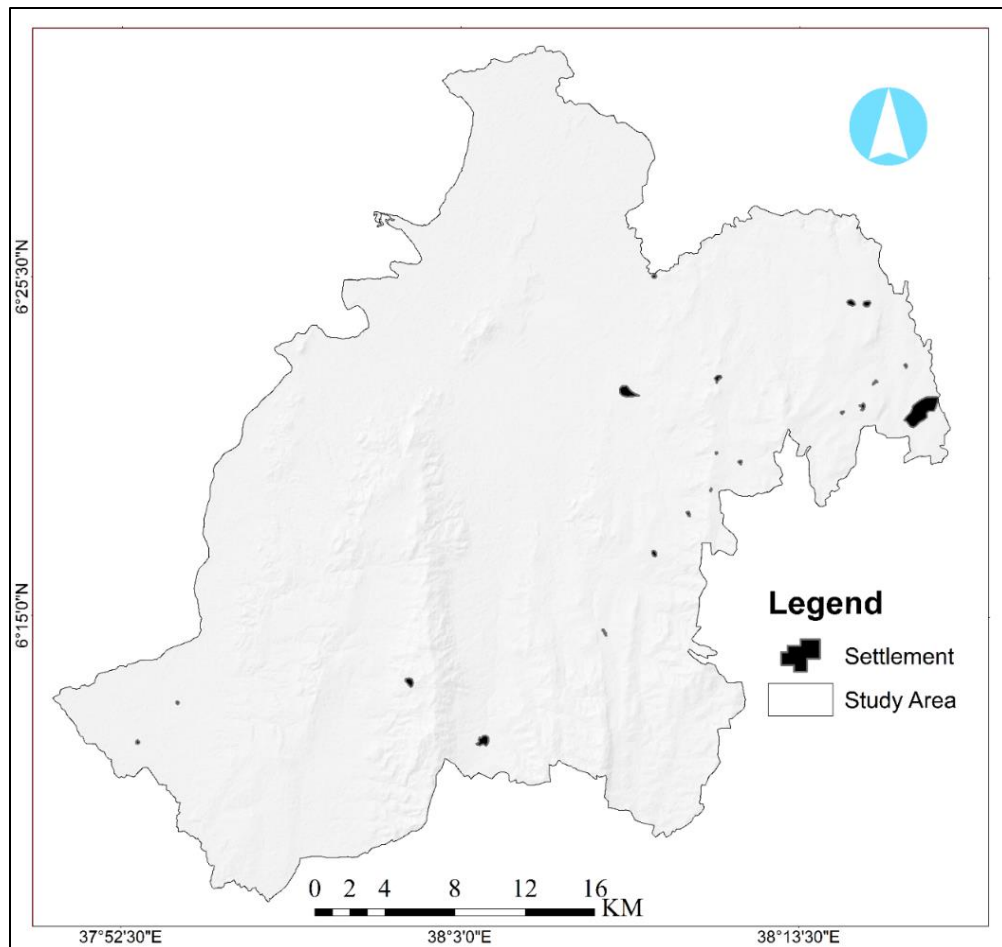


Figure 8. Settlement (populated) area map

3.2.2.5. Slope

The slope is one of the highly important factors in site selection for PV farms. The selection of a suitable slope is required in order to harness solar power to the greatest

extent possible. When combined with other variables, slope can greatly aid in the solution of problems in site analysis and many other fields. Scientists have developed many methods to measure slopes in small or large-scale areas. Many of these methods are limited to small areas and, most of the time, measurement at the landscape level is time-consuming and requires many personnel. But the development of geospatial technologies over the past half century has brought promising solutions to these problems.

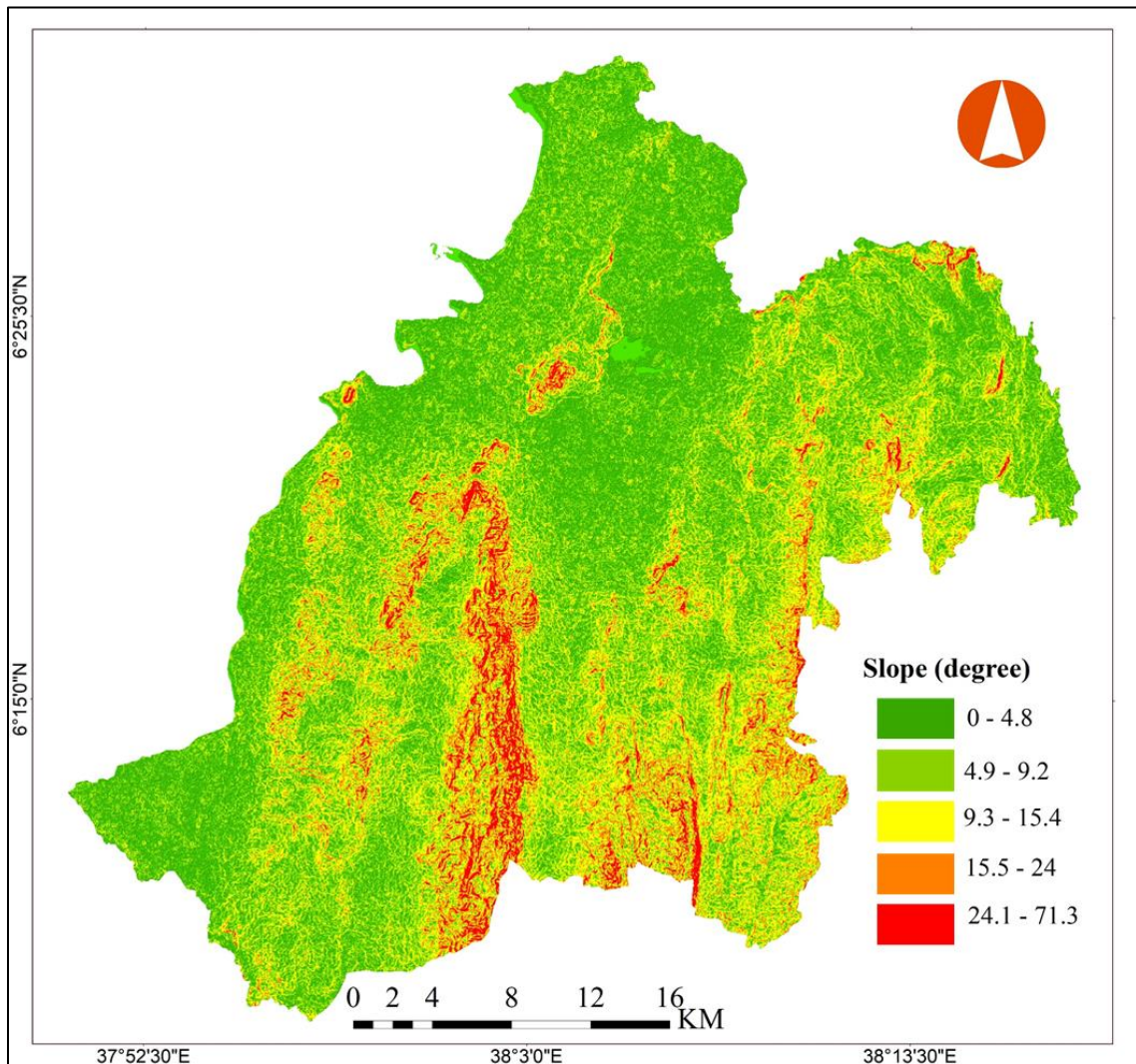


Figure 9. Slope map

Currently, the USGS and other organizations are providing better spatial resolution elevation data almost for the whole globe for free. ESRI, ArcGIS provides a wonderful tool to generate slopes from elevation data. For this study, Digital Elevation Model data was downloaded from the USGS (<https://search.earthdata.nasa.gov/search>) and the slope

in degree was generated from the data using the ArcMap spatial analyst tool (slope). The slope of the study area ranges from 0° flat to 71° (Figure 9)

3.2.2.6. Aspect

Aspect (slope direction) like other factors plays an important role in determining the best site for solar panel installation, particularly in determining the good and bad direction of sun radiation. It shows the slope direction which is measured clockwise from north in degrees ranging from 0 to 359.9. Flat cells with zero slope are assigned an aspect of -1.

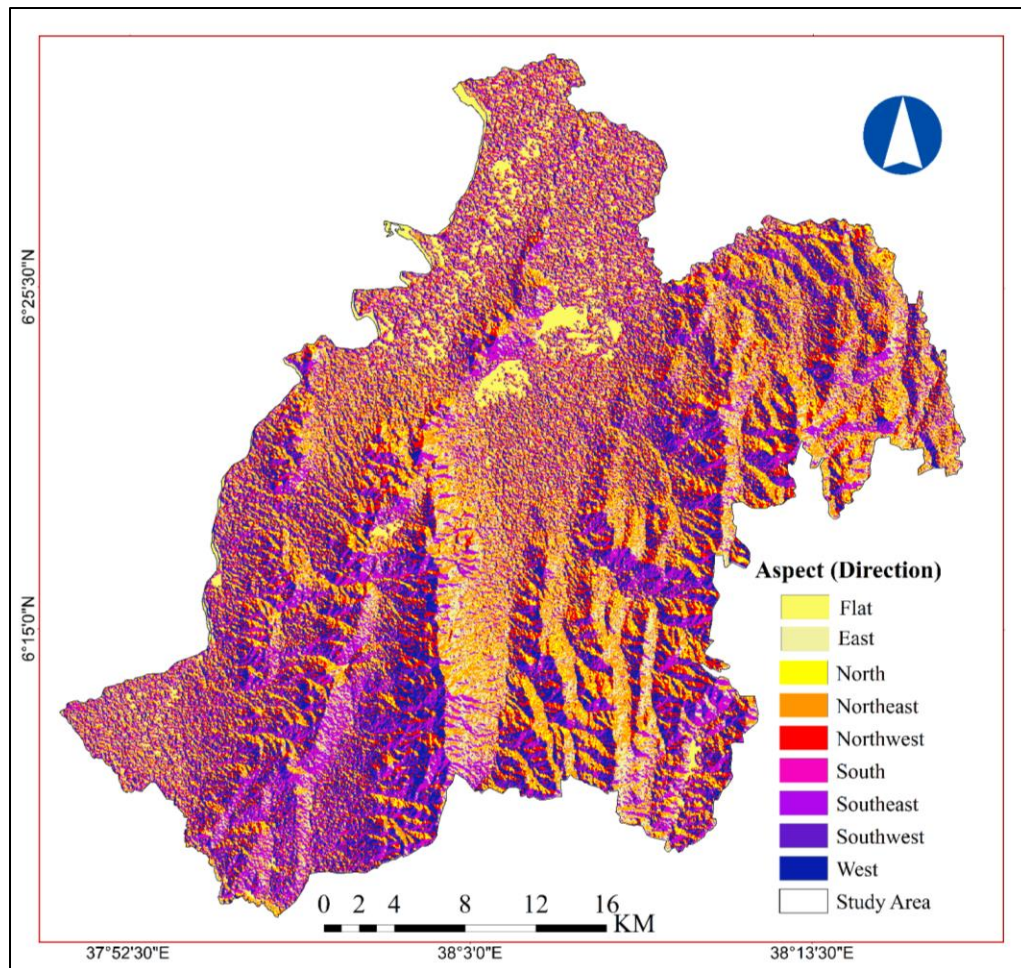


Figure 10. Aspect map

The spatial analyst tool aspect produces an aspect from elevation data with nine classes and eight directions. For this study, the aspect was generated from a 30m spatial resolution Digital Elevation Model in ArcMap using a spatial analyst tool (aspect). The value was divided into nine classes with eight directions and flat (Figure 10).

3.2.3. Software used

For this study, different software was used for data analysis and visualization. For image processing and land cover mapping, ERDAS IMAGINE was used. Additionally, it was used to create confusion matrixes for accuracy assessment. Digitalization of roads from topographic maps was performed in ArcMap. The ArcGIS AHP extension was also used to calculate factor weights. A weighted overlay analysis and all reclassifications were made using ArcMap Software. In addition, the hourly based monthly insolation heat map was created with Origin Software.

3.2.4. Reclassification of the criteria

All the preprocessed spatial datasets were projected to the same coordinate system (WGS_1984_UTM_Zone_37N) and prepared for further analysis. All datasets were converted to the same data format (raster), and converted to the common 30m spatial resolution for ease of analysis. Each pixel value of the original data has different suitability layers. This variability in the suitability layer of individual data influences the final overlay. So, the data needs to be reclassified to create new suitability layers to assist the analysis of the overall suitability mapping. For this study, factors that may affect photovoltaics site selection were reviewed according to their level of influence. These criteria are solar radiation, land use land/cover, slope, aspect (slope direction), proximity to existing roads, and settlement. The reclassification was made based on the original data for land use/cover, slope, solar radiation, and aspect (slope direction). But for proximity to road and settlement, first Euclidean distance was calculated in ArcGIS, and reclassification was made later on. The factors were individually reclassified into 1-4 common preference scale classes with 4 highly suitable and 1 the least suitable following ESRI rules for reclassification. The preference values were not assigned relative to each other within the layer, but they are reclassified to have the same meaning. The reclassification of the factors was employed based on literature (Charabi & Gastli, 2011; Brewer et al, 2015; Gerbo *et al.*, 2020 and Dawud, 2016), national and international standards, and expert opinions.

3.2.5. Determining Criterion Weights and overlaying

A weight is a value assigned to an evaluation criterion that indicates its importance relative to the other criteria under consideration. In this study, the weights were calculated using an analytic hierarchy process. The Analytic Hierarchy Process (AHP) is due to Saaty (1980) and is quite often referred to as the Saaty method. It is popular and widely used in decision making and in a wide range of applications. In the AHP method of weighting criteria first, pairwise comparisons are carried out for all factors to be considered, and the matrix is completed. While comparing one factor with the other, there are always inconsistencies. So, before applying the weights obtained from the pairwise comparison matrix, the consistency ratio must be checked. As a rule of thumb, Saaty recommends acceptable consistency ratio of less than 0.1 (10%). If the consistency ratio is greater than 10%, the judgements are untrustworthy, so they need to be repeated. If the criteria for consistency ratio are met, one can proceed to the next step. For this study, the weights (influence) of the factors were calculated using the AHP method by comparing all the parameters one by one.

The process was performed in the AHP ArcGIS extension, which was developed by Oswald Marinoni in 2014. The extension was downloaded from the Esri website (www.esri.com). This extension gives the weights of each parameter in percentage and automatically calculates the consistency ratio (CR) using the built-in algorithm. After the weights are assigned to each dataset by ranking, the final suitability map is produced by combining the weighted datasets using the weighted overlay method. ESRI, 2016 recommends the use of weighted overlay when: (i) one needs to find the rankings of suitability for cells in a raster dataset; (ii) one needs to find next-best site options in addition to finding an ideal site; (iii) the user wants to rank different criteria as more or less important in finding an ideal site. Additionally, its versatility makes it popular over other methods of overlaying datasets for finding suitable site. Thus, for this study the weighted overlay method was employed to overlay the datasets which has their own suitability layer and level of influence. Finally, after the final output of the suitable site, site observation and Google Earth were used to validate the reliability of the work done so far.

The consistency ratio of the pairwise comparison was calculated using the following formula. Fortunately, the AHP ArcGIS extension developed by Marinoni is capable of handling the weights of parameters and can also calculate the consistency ratio simultaneously.

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

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

Where, CI is consistence ratio

λ_{\max} is Principal Eigen value

n is number of parameters

RI is random consistency Index

CI is consistency index

3.2.6. Estimation of electricity potential

Identifying ideal sites by combining different suitability layers is the first step of the current study; the next is determining how much electricity can be generated in the area. During this calculation, the annual solar radiation, the area of available land, area factor and the efficiency of the solar modules are taken into account. Various PV systems have different efficiencies. So for the current study, the efficiency value was taken by averaging efficiencies of different solar panels that are used in the tropics. The calculation was done using the formula used by (Charabi and Gastli, 2010, and Gerbo *et al.*, 2020).

$$EGP = SR * CA * AF * \eta \dots\dots\dots (1)$$

Where, EGP is annual electric power generation (GWh/year), SR is annual average radiation gigawatt hour per square meter per year (GWh/m²/year), CA is total suitable area in square kilometer (km²), AF is area factor which indicates the fraction suitable area which could be covered by solar panels in percentage (%), and η is panels efficiency.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Spatio-temporal distribution of solar radiation

The design and planning of solar farms must consider the insolation that reaches the earth's surface. Unfortunately, as mentioned in previous chapter, site specific measurement of solar data is not available in most places, or it is spread over a wide distance. As a result, it's difficult to identify the exact insolation value at the local level.

The solar irradiance received by a particular location depends on the elevation above sea level, the angle of the sun (due to latitude, season, and time of day) and scattering elements such as clouds (Fondriest Environmental, 2014; Fu and Rich, 1999). For this study the solar radiation data was downloaded from global solar atlas and masked to the extent of the study area boundary in ArcGIS environment.

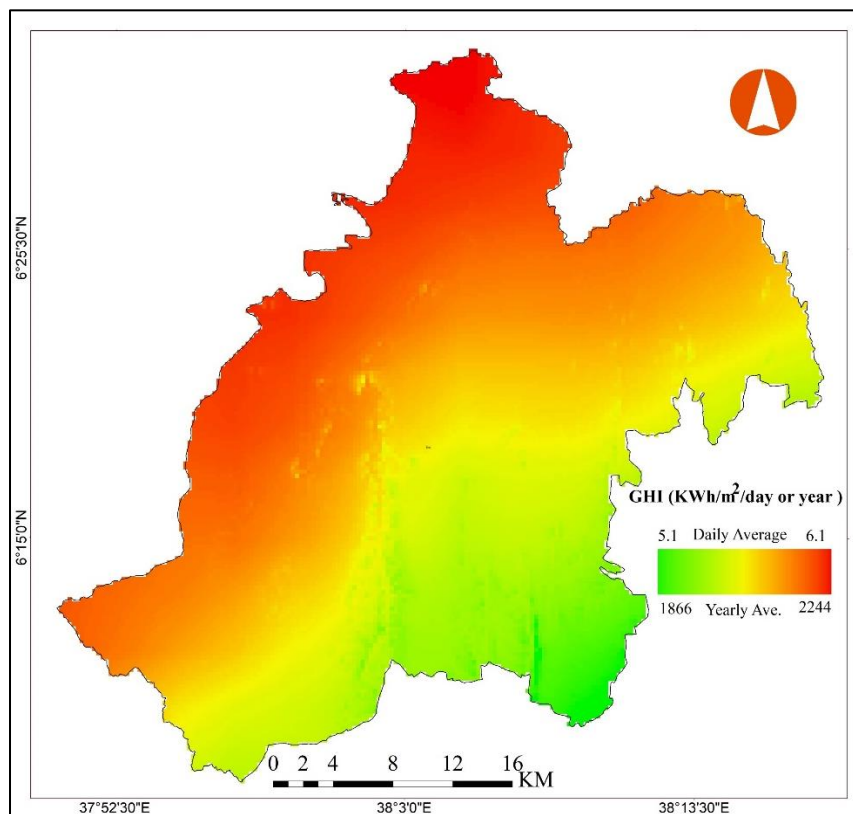


Figure 11. Spatial distribution of daily and annual GHI (1994 – 2018 Average)

The above figure shows that almost all parts of the woreda receive relatively good amount of Global Horizontal insolation. The more populated parts of the woreda, including the north-eastern, eastern, and southern areas, enjoy relatively low levels of Global Horizontal Insolation, which reach up to 1866 kwh/m²/year. However, most parts of the area have an annual average insolation of up to 2244 kwh/m²/year. Topography could be responsible for the variation. In terms of agro-ecology the low elevation areas like the edge of Abaya Lake receives high insolation. Additionally, the above map shows that, the mid land areas experience medium GHI. The areas with relatively low amount of insolation are located along the boundary of Guji Gedeo border. Despite the lower value in the upper borders of study area, the amount is by far enough to electrify the area if harnessed properly. The GHI, which is the sum of the DNI and the DI, is extremely suitable for generating power using solar panels. In general, the spatial distribution of GHI in Abaya woreda is sufficient to generate the household's electricity needs.

The knowledge of solar insolation temporal distribution in addition to its spatial distribution is essential for proposing any solar insolation related project. Like spatial data, long-term temporal data of insolation at the local level is found rarely. Having an accurate and site-specific better temporal resolution of solar insolation requires the installation and regular calibration of measuring instruments. In this study the temporal data obtained from global solar atlas was visualized in origin pro (Figure 12). Like spatial variation solar irradiance shows temporal variation. Solar irradiation shows fluctuation within a day and also there is a variation in different seasons. The rotation of the Earth is responsible for hourly variations in sunlight. According to (Christoph *et al.*, 2013) in the early morning and late afternoon, the sun is low in the sky. This is responsible for the low insolation in the morning and high at noon. Beyond hourly variations, solar radiation also shows a variation in different seasons of the year.

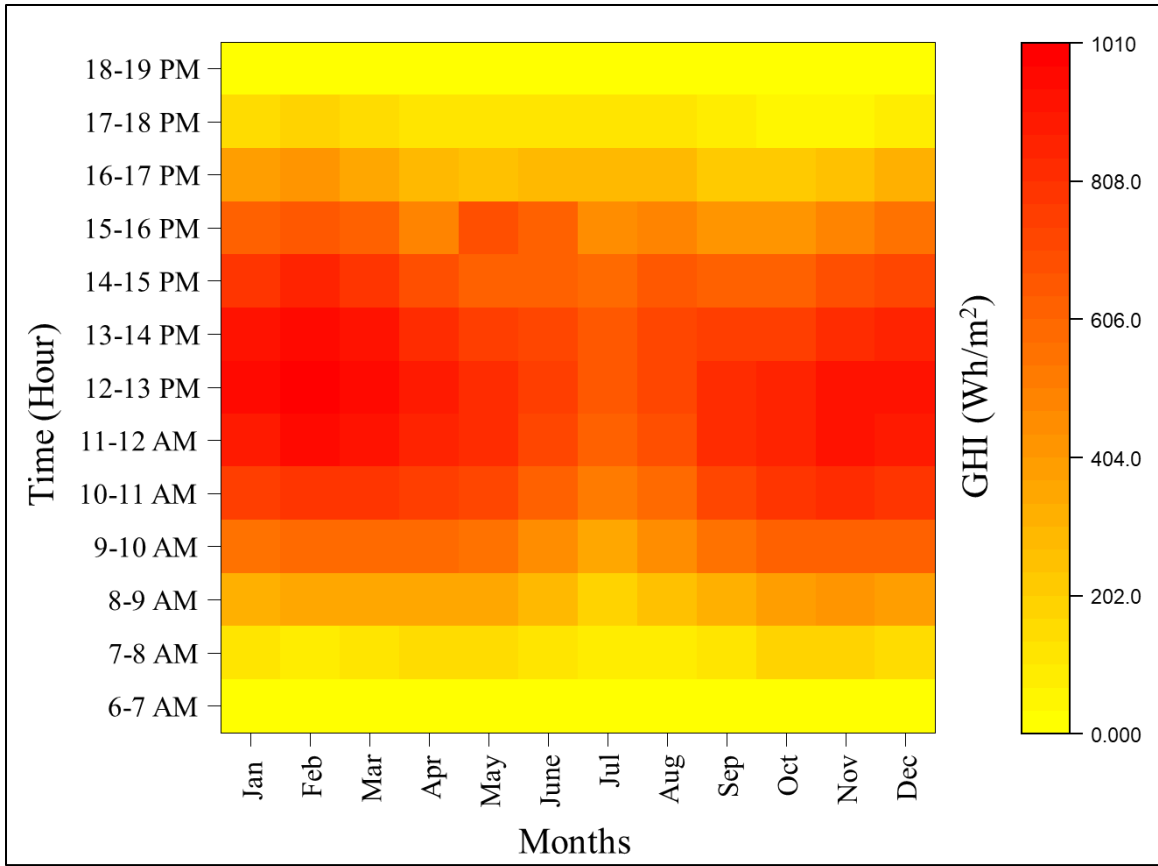


Figure 12. Heat map showing hourly insolation for all months (Source: SolarGIS,2020)

The above heat map illustrates the hourly estimated solar insolation for each month of the year in Wh/m^2 . According to the above map, the maximum hourly average recorded solar insolation is 109 Wh/m^2 in the month of March. Throughout all months, the insolation is very low in the morning due to the sun's very slanted angle of illumination. In addition, most parts of the area receive very little incoming sunlight in the morning because of the topography, which casts a shadow over the lower regions. From sunrise towards mid noon, the insolation continuously increases and reaches its peak between 11:00 AM and 14:00 PM. Basically, the insolation intensity drops as the time approaches sunset and disappears after sunset. This daily variation of solar insolation is attributed to the position of the sun in the sky. Besides the daily variations, the heat map above shows variations in solar irradiance among months as well.

In January, February, March, April, May, October, November, and December, there is intense solar radiation throughout the day. This is resulted from the clearness of the sky

during these months especially in the lowlands of the woreda as there are low clouds. Tesema. (2014) reported the similar result while doing an assessment of solar insolation for hybrid energy generation in rural Ethiopia. In contrast, June, July, August, and September, have relatively lower insolation. This is due to the fact that these months are characterised by more cloudy sky and rainy days. The availability of clouds in the sky hinders the penetration of solar radiation to the surface of the Earth. (Mahmud *et al.* (2014) found the same result while conducting solar resources assessment in Geba catchment of Northern Ethiopia. In most parts of Ethiopia these months are known by their heavy rain.

4.2. Suitability factors reclassification

Site suitability analysis using GIS for a particular purpose is a process that evaluates a target area based on the consideration of multiple factors to determine its suitability for a specific use. In this study, responsible factors are determined based on different literature and national and international standards, as well as expert opinions. For any type of suitability analysis to be effective, the suitability of each factor must be determined before the development of a combined map. Various studies have been conducted throughout the world to determine the best places to install solar panels using geospatial technology (Charabi & Gastli, 2011, Noorollahi *et al.*, 2016, Nebey *et al.*, 2020). Although the studies have used different factors to determine the suitable area, they all have the following parameters in common: land use, land cover, solar insolation, slope, aspect (slope direction), proximity to infrastructure, like roads, and proximity to densely populated areas. The following section describes the suitability of all parameters by identifying a suitability layer for each factor. All the criteria were reclassified into four suitability layers. The suitability layers are defined as: 4 = highly suitable, 3 = suitable, 2 = marginally suitable and 1 = least suitable.

4.2.1. Reclassified Global Horizontal Insolation

In choosing the optimal PV system location, solar radiation is one of the most important factors associated with how much sunlight will be available throughout the year at the site. Generally, PV systems are more efficient with GHI than both DNI and DI. Annually,

the area experiences global horizontal insolation between 1866 and 2244 Kwh/m²/year. According to these guidelines, these amounts are sufficient to develop solar farms, as they can generate enough electricity with PV systems. Accordingly, the GHI was reclassified into four suitability layers following (Mokarram *et al.*, 2020; Brewer *et al.*, 2015; Noorollahi *et al.*, 2016) recommendations. Therefore the areas having GHI greater than 2030Kwh/m²/year was assigned highly suitable class. GHI values between 1970 and 2030 Kwh/m²/year assigned suitable value, 1925 to 1970 Kwh/m²/year was assigned marginally suitable value. Finally the lowest values between less than 1925Kwh/m²/year was assigned the least suitable class.

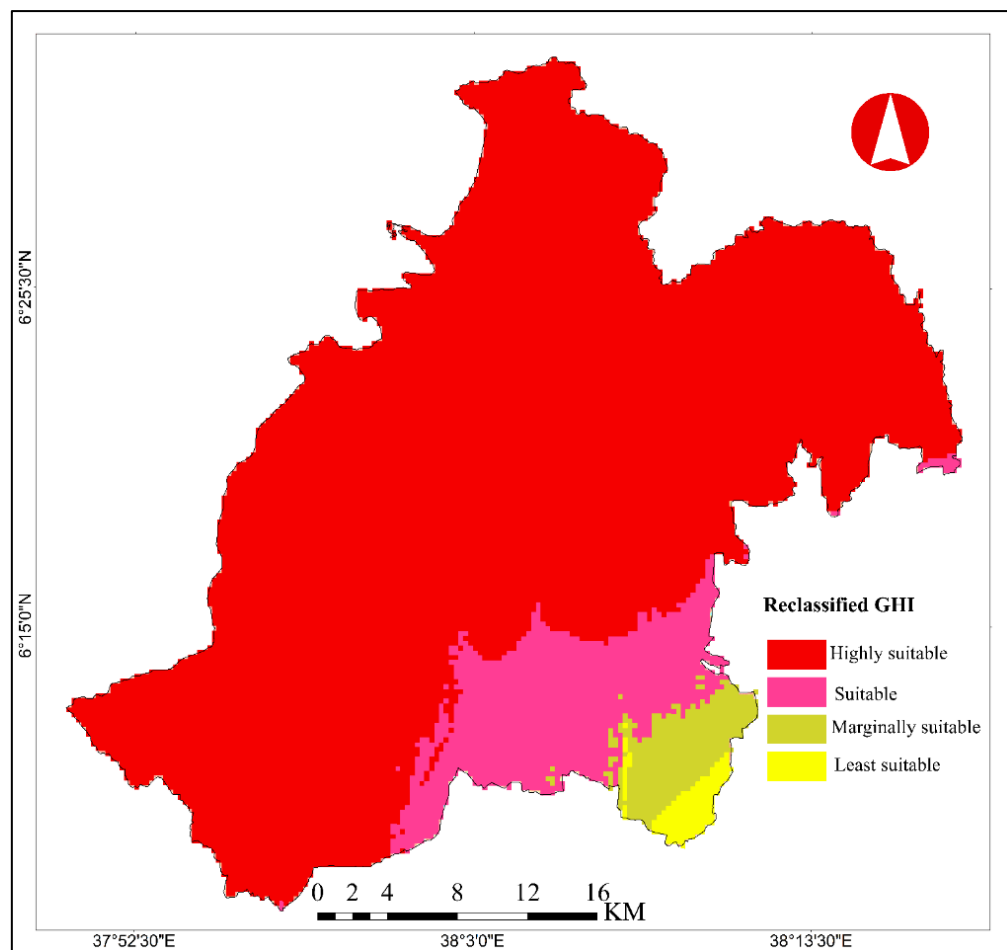


Figure 13. Reclassified Global Horizontal Irradiance (GHI)

As shown in the above figure, most parts of the woreda, which accounts for about 86%, are highly suitable. These areas receive yearly insolation of up to 2244Kwh/m²/year. The northern, central, and southwestern parts of the woreda are covered under this suitability

class. The suitable category is mostly found in the populated south-eastern part of the woreda. Approximately 11% of the area is devoted to the suitable class. The remaining parts of the woreda, which account for 3%, show the marginally suitable class. Only 1% of the woreda is included in the least suitable area according to the GHI suitability class. In this way, almost all parts of the woreda are suitable for the development of solar farms without considering other parameters

4.2.2. Reclassified Land use/cover

Land use/ cover plays a key role in choosing the best site for a solar farm (Sánchez-Lozano *et al.*, 2014; EROĞLU, 2018). Availability of suitable open area land is a key to successful development and utilization of solar farm. Land use land cover of the area was processed from Landsat 8 (OLI) image. The accuracy assessment was done by using the independently collected Ground control points. The overall accuracy of the classification is found to be 83.5% with kappa Statistics 0.81. By doing so eight land use land covers were identified in the study area. The land use/cover identified includes: agricultural land (18591.12 ha), shrub/bush land (49172.67 ha), wood land (21305.13 ha), agroforestry (12290.31 ha), bare land (6085.53 ha), water body (2999.7ha), built up area (3184.92 ha), and wetland (6838.83 ha). Land use/covers, like bare land, agricultural land, as the top suitable, whereas land use/covers like; water bodies, wetlands, forest/plantation areas, wooded areas, and orchards are not suitable for solar panel installations (Gerbo *et al.*, 2020). The land use/cover of the study area was reclassified into four suitability classes. The bare land and agricultural lands were given the top priority and assigned a highly suitable suitability class. Shrub/bush lands are assigned suitable class, agroforestry and wood lands were deemed marginally suitable category, and finally wetlands, water bodies and built-up areas were given the least suitable class.

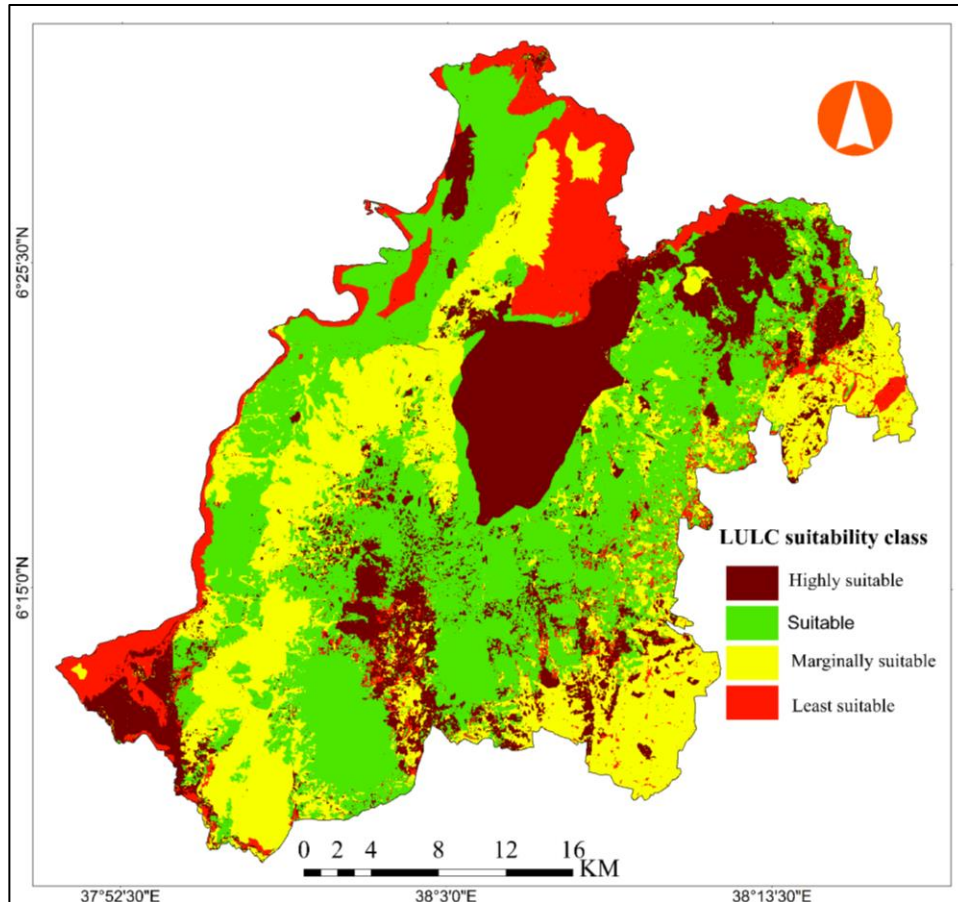


Figure 14. Reclassified Land use/cover

The above map illustrates the four suitability categories. Accordingly, the whole map was reclassified into four suitability categories, namely: highly suitable, suitable, marginally suitable, and least suitable. According to the result of the reclassification, 21% (25603.11 ha) of the area is found to be highly suitable, this class includes bare land and agricultural land, land use/covers. Bare land and open agricultural lands are considered the best sites for the installation of solar panels. It is common for bare land and agricultural lands to have very little vegetation and no other cover that can block the incoming solar insolation. The suitable class accounts for 39.8% (47899.71ha), this includes shrub/bush lands which dominates huge parts of the woreda including margins of Abaya Lake). With solar panels, there is a possibility that 50-80% of power lose if 5% of the photovoltaic solar panels are in shade. For these reasons, it is highly recommended that, the solar PV system should remain out of shade or shade casting land use/cover throughout the day (Michael, 2012). Additionally, the figure shows 27.8% (372862 ha) as marginally suitable area in terms

land use/cover. Shade causes a much greater loss of power than the area of the panel that is shaded. Solar panels system doesn't allow shadow-casting erect materials to be part of its system due to the nature its design. Due to these reasons wooded lands and agroforestry areas are given marginally suitable. They have the capacity of casting shades during the day time. Only 11.1% shows the least suitable area. This category includes wetlands and water bodies. Waterbodies and wetlands are not recommended for sitting solar arrays ((Nebey et al., 2020). To develop solar farms on such land use/covers, one should use sophisticated technologies, which are impractical in many cases.

4.2.3. Reclassified Slope

Slope is the most important topographic factors to take into consideration when deciding which location to develop solar farms. The slope map of the area was generated from 30m spatial resolution elevation data in ArcGIS spatial analyst tool. The value ranges from flat to 71° which is steep slope. In most cases, it is difficult to install solar panels on steep slopes. It is imperative to give priority to gentle slopes. Charabi and Gastli, (2010); Guaita-Pradas *et al.* (2019) recommend slopes not exceeding 4° facing south if the proposed area is found in the northern hemisphere for effective solar farm development. It is generally not practical to construct a solar farm on slopes exceeding 12°. Depending on the above recommendations, for this study, the slope was categorized into four suitability classes. In this case, slopes of less than 3° were assigned to the highly suitable category, slopes of 3°-7° to the suitable category, slopes of 7°-12° to the marginally suitable category, and slopes greater than 12° to the least suitable category.

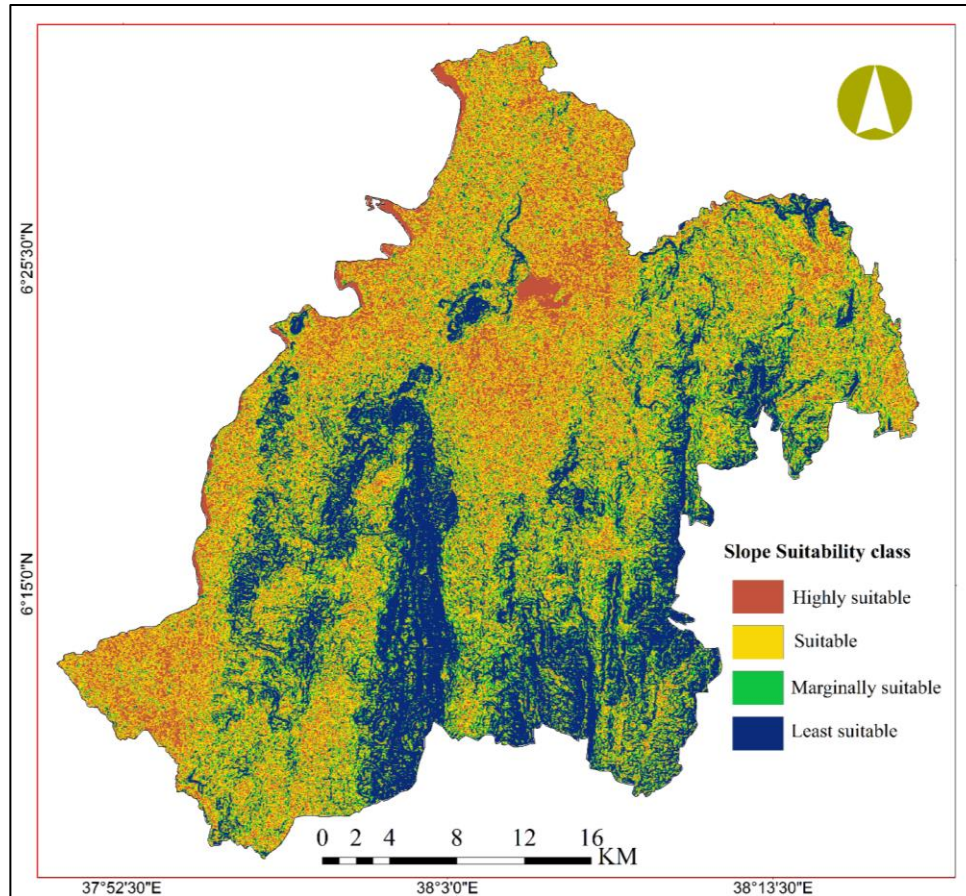


Figure 15. Reclassified Slope

As a result of the recommendations and standards, the slope was classified into four suitability classes. The above map shows the suitability class of the slope. The area has a slope ranging from flat to very steep, which reaches up to 71° . Following the reclassification, 20% (24011.55 ha) resulted in a highly suitable class. These ranges of slopes need minimal earthwork and can be directly utilized for the construction of either large-scale or small-scale solar farms. Gerbo *et al.* (2020); EROĞLU (2018) confirms that, slopes of less than 3° are the best for construction of either PV or CSP solar farms. About 38.54 (46197.81 ha) resulted in a suitable class. Even though it is suitable for solar farm development, such slopes require minimal to medium earthwork before construction. Beyond the requirements of earthwork, if panels are constructed on such slopes, they cast shade on the consecutive panels, which could result in an efficiency drop. 16.7% (20007.8 ha) was categorized as a marginally suitable slope, and the rest, which is 24.73% (29642.04 ha), was in the least suitable category. This result is in line

with Ruiz et al (2020). It is unlikely that steep slopes will be economically viable, since a lot of technical work, such as earthworks, will be required. In addition, if the panels are installed on a steep slope, they might cast long shadows on one another.

4.2.4. Reclassified Aspect

The aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors (ESRI, 2019). Most of the time, the aspect is related to the best direction the solar panels should face in order to collect the maximum amount of solar energy. Aspect of the area was generated from elevation data, using ArcGIS surface analyst tool aspect. The generated aspect contains nine classes (eight directions) and flat which is represented by -1. The aspect map was reclassified into four suitability layers. To have the same meaning with other thematic layers the numbers indicating suitability class was assigned. By this way the highly suitable aspect was assigned number 4, suitable number 3, and marginally suitable number 2 and least suitable is assigned number 1.

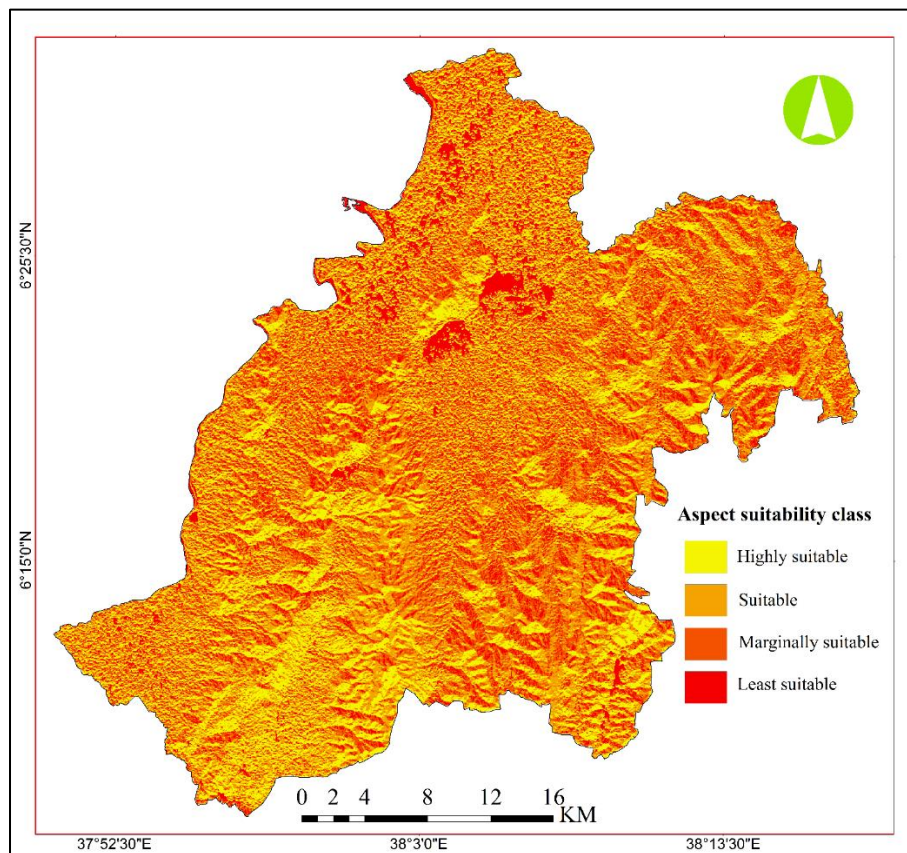


Figure 16. Reclassified Aspect (slope direction)

Solar radiation availability alone does not determine the best location for a solar farm. For optimum energy production, the insolation originated from the surface of the sun must hit the surface of the panels at an appropriate angle. In this way, different directions of the earth receive different amounts of insolation. The above map illustrates the reclassified direction of slope (aspect). Based on the results, we can see that 27.66% of the area (33124.32 ha) is classified as highly suitable. These include the directions facing south, southeast, and southwest. In the northern hemisphere, the exact direction the solar panels face should be in the south direction. But since this is always not practical, other directions also need to be chosen. But finding directions other than south will cost us some sort of energy loss. Yassine (2014) and Michael (2012) reported that in the northern hemisphere there is about 1.1% efficiency drop in panels for each 5° change of direction from south. Nearly the same area of land falls under the suitable category. The east and west directions are assigned to the marginally suitable class. The two directions can be best utilized by solar trackers, but for fixed solar panels they give half day of enough radiation in each direction. About 27.9% (33519.78 ha) and 17.29% (20724.84 ha) show marginally suitable and least suitable directions respectively. In normal situations, these directions are not recommended for solar farms.

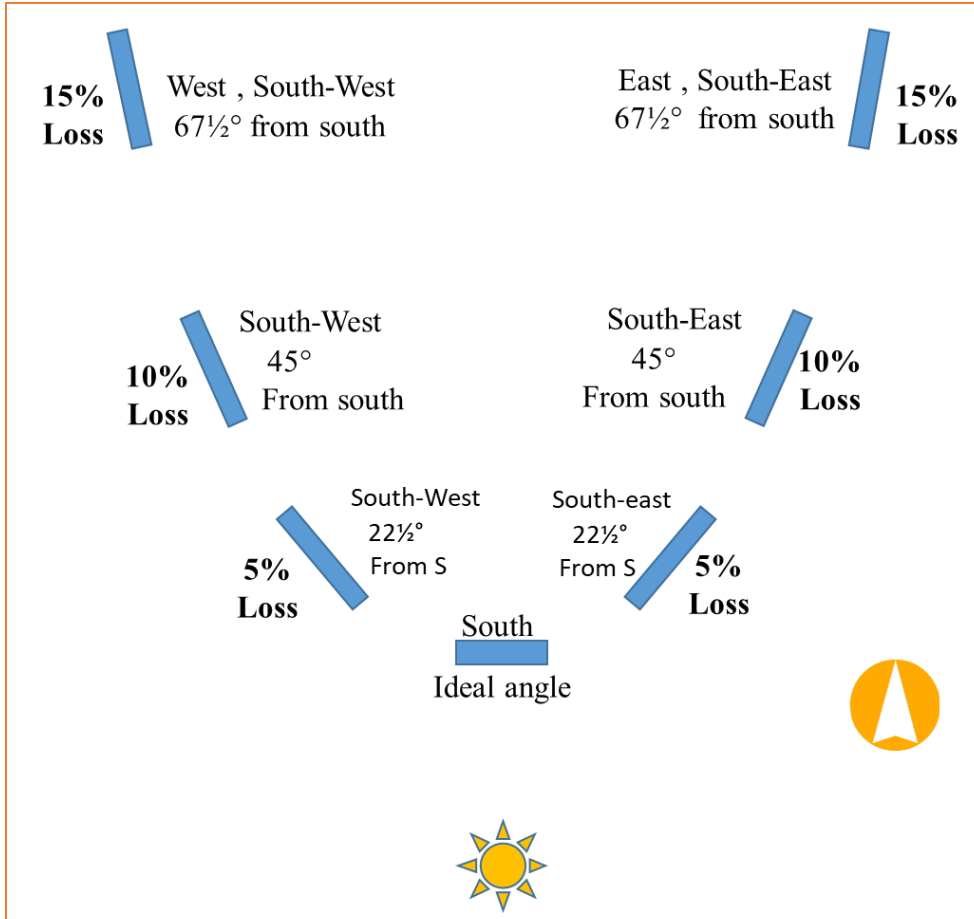


Figure 17. Approximate efficiency loss by not facing solar panels directly south.

The above figure shows the approximate efficiency loss of solar panels by not facing directly south. As it is clear from the figure, there is up to a 15% loss of efficiency by facing the panels in the wrong direction. Accordingly, even by rotating the face of the panels 22½° to the southeast or southwest, we lose up to 5% of the efficiency of the panels. As the direction inclines away by half from the ideal direction, the loss also doubles.

4.2.5. Reclassified distance Proximity to roads

Roads are an important infrastructure for determining where solar panels can be placed. Roads are very important from the beginning of construction to the operation time. Construction of new access roads for transporting goods and equipment is expensive and it is one of the unavoidable factors involved with solar plant construction. Certainly, the easier access to the plant, the lower the cost of plant construction will be (Brewer et al.,

2015). Gerbo et al. (2020), recommends that, for effective utilization, the potential site should not be greater than seven kilometers. As stated in the methods section, the road of the area is digitized on screen in ArcGIS from topographic maps. The digitized polyline features were converted into raster format and the Euclidean distance was calculated from the center of each cell. The distances from each cell is expressed in meters.

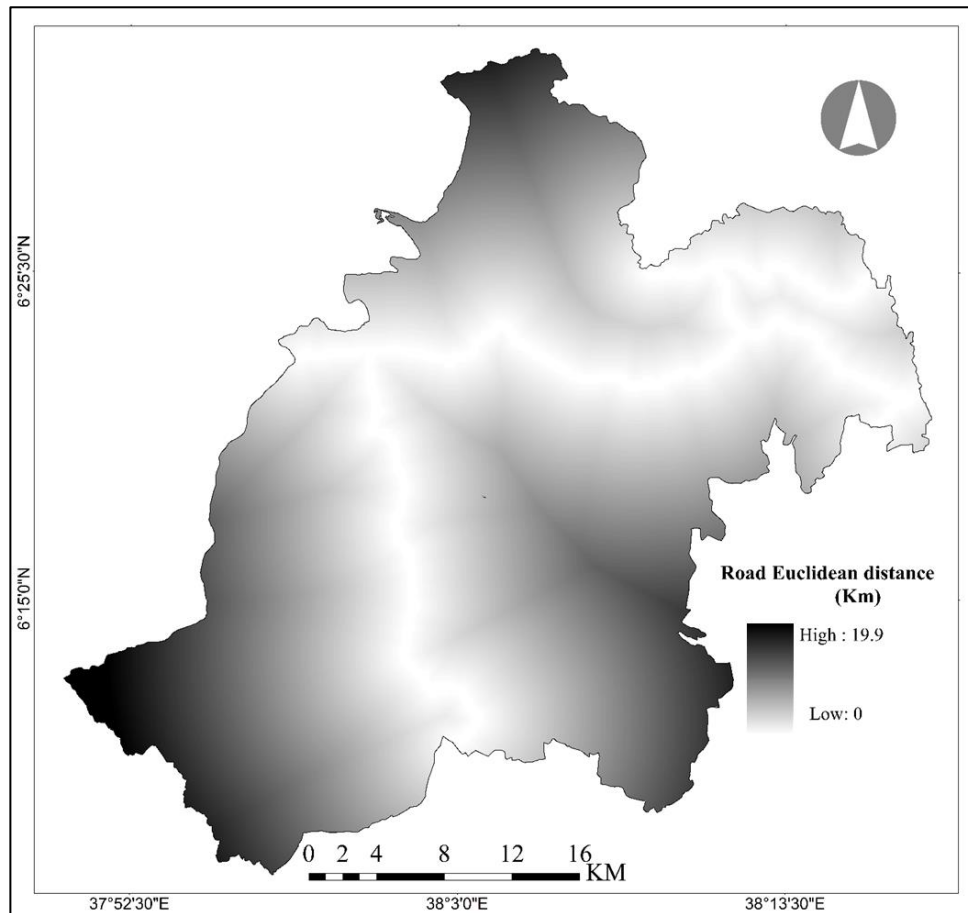


Figure 18. Road Euclidean Distance

For effective transportation of construction materials and for quick maintenance of the PV systems, distances to roads play an important role (Kırçalı & Selim, 2021). Noorollahi *et al.*, (2016) in their research conducted in Iran, concludes that solar farms should be as near to potential consumers as possible. For this study, after the calculation of Euclidean distances, the distances were categorized into four suitability classes. The distances of less than 2500 meters to the roads were given the highly suitable class. Distances ranging from 2500 to 5000 meters were assigned to the suitable class. Furthermore, distances

from 5000 to 7000 meters were reclassified as marginally suitable. Finally, the areas that are greater than 7000 meters from the roads were given the least suitable category (Figure 19)

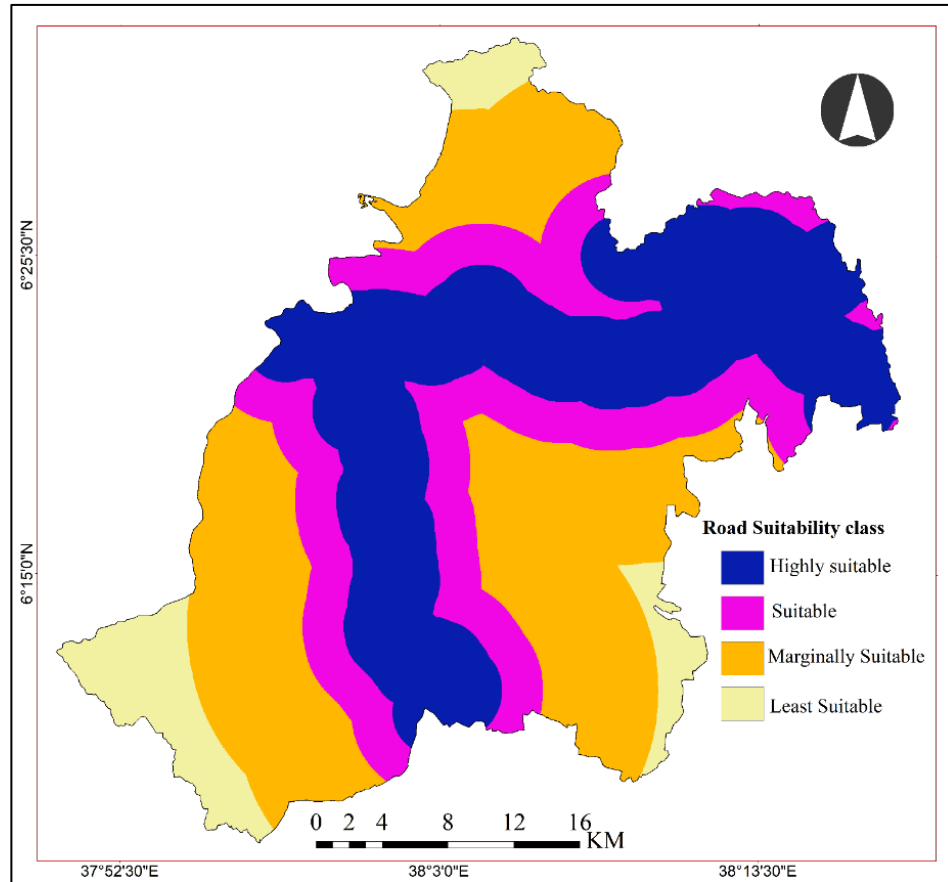


Figure 19. Reclassified proximity to roads

The above map shows the suitability class for proximity to roads. As stated above, accordingly, from this map, it is clear that 34.03% of parcels lie within 2500 meters of the main roads, making them ideal parcels in terms of distance to roads. About 21.39% of the areas are located within 2500-5000 meters of main roads. 35% of the woreda is found to be 5000 to 12000 meters from the roads. Only 8.9% is found at a distance of greater than 12000 meters from the roads.

4.2.6. Reclassified Proximity to settlement

As much as possible, the solar farm should be located near areas where people live in large numbers. At the same time, the area should not be inside of towns where buildings,

hedges and fences are present. The settlement data was acquired by hand held GPS and digitized from Google Earth. The collected data was converted into polygons in ArcGIS and converted to raster data format for ease of analysis. The Euclidean distance from the center of each cell was calculated using Euclidean distance tool in ArcGIS environment and the distances were in meters. The distances shows maximum of 19,800 meters from the settlement areas.

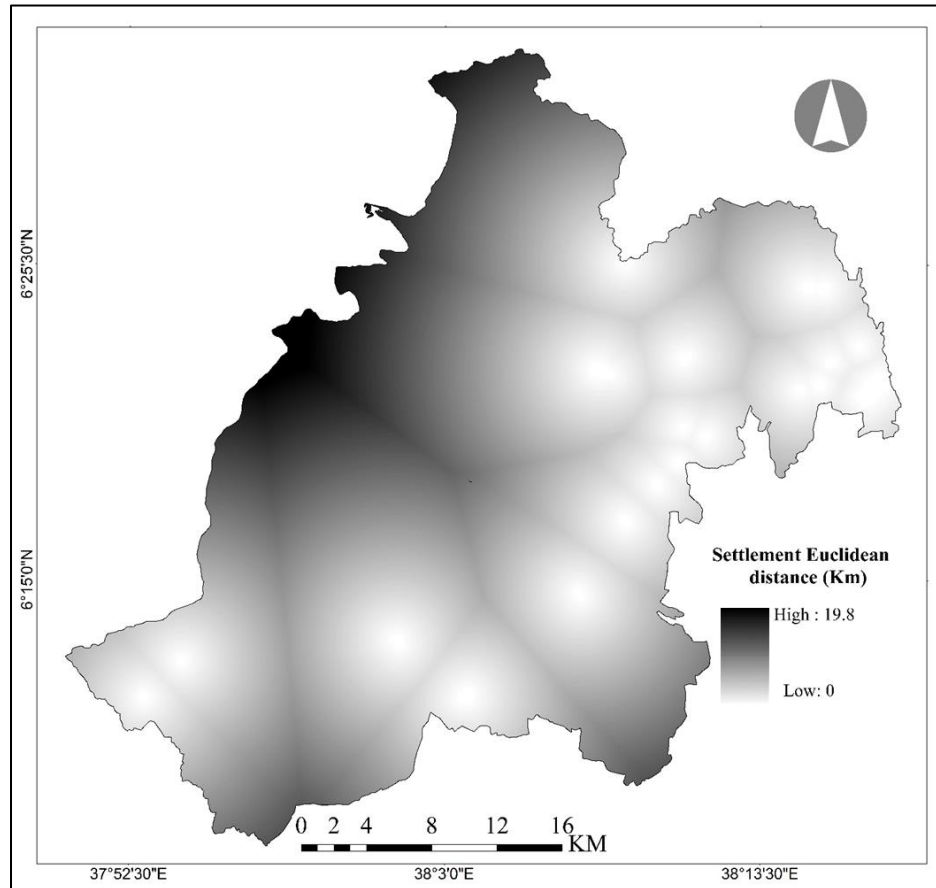


Figure 20. Settlement Euclidean distance

The reclassification was made on the calculated Euclidean distance raster. Thus, distances from 1500 - 3500 meters were assigned a highly suitable class. Distances between 3500 and 5500 meters were assigned a suitable class. Distances between 5500 and 7000 were classified as marginally suitable. Solar farms are less suitable to be developed at distances greater than 7000 meters from populated areas (Figure 21) because they are difficult to build at such distances. So, distances greater than 7000m from the populated area is given the least suitable class. Additionally, the distances less than 1500 meters from the

populated areas were considered as least suitable considering the unlikely development of solar farm at such distances to the populated areas.

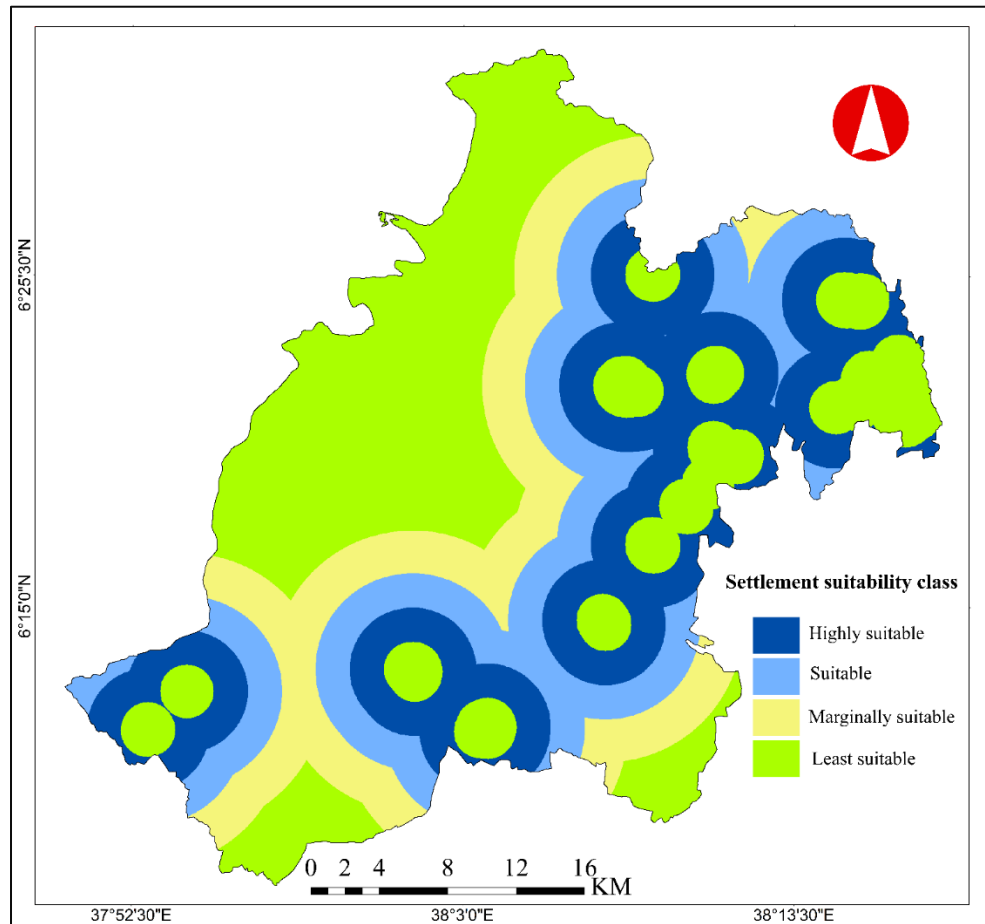


Figure 21. Reclassified proximity to populated areas

As seen from the above map 23.38 % (28184.31 ha) of the area is found within 1500 to 3500 meters from the populated areas. This suitability class is very convenient for establishment of solar farm, the households can easily be connected to the energy sources through mini-grid systems. Sánchez-Lozano *et al.*, (2014) recommends the distances of less than 4 kilometers as a highly suitable category as far as the distance to settlements is considered. When the projects are far from densely populated areas, the developers must pay for the installation of long-distance extension lines to reach the project site (Pivot Energy, 2019). These factors can add a significant cost to a project, and, in turn, make it impossible for a site to be suitable for a project. The generally accepted principle is that sustainable energy production and consumption should be as close as possible. About

18.1% (21838.32 ha) of the areas are found at the distances of 3500 to 5500 meters from the populated areas. The developments of solar PV at such distances is possible, but it could add additional costs for the installation of long distances distribution wires. 17.48 % (21079.71 ha) of the study area is found at the distance of 5500 to 7000 meters from the populated areas. About 41% (49427.46 ha) of the area is found at the distance of greater than 7000 meters from the populated areas. At these distances PV development could not be feasible economically. Additionally, the distances less than 1500 meter from the populated areas were treated as least suitable. This is done considering the shades from hedges and fences of homes. The exclusion also considers the future expansion of the settlement.

4.3. Deriving factors weight by AHP

The AHP method is a relative evaluating mathematical method. This method includes both people's subjective judgement and objective criteria. Its judgement is easy, and its mathematical dealing is convenient. It is suitable for the comparison of several systems to find out their selecting order (Yan, 2016). The AHP was applied to compute the significance of weightings for the selected criteria in the current study using a matrix of pair-wise comparisons.

This method breaks the problem into different levels of hierarchy. The first level is called the target level, whereas the second level is called the criteria level. In the current study, AHP was applied to compute weightings for the selected criteria using a matrix of pair-wise comparisons. Following the steps of the AHP hierarchy, the top target level of the hierarchy is to find the best sites for sitting solar panels or establishing energy-generating solar farms. The second, or criteria level, deals with the factors responsible for selecting the best sites for solar panel installation. Here the criteria are used to evaluate alternatives. However, not all criteria are equally important for the decision-making process. So, to evaluate the importance of one criterion over the other, the intensity scale developed for this purpose, ranging from 1 (equal importance) to 9 (extreme importance), was used (Table 2.). The evaluation was made based on the opinions collected from experts.

Table 2. Saaty’s scale for pairwise comparison

Saaty's scale	1	2	3	4	5	6	7	8	9
Definition (Importance)	Equal	Weak	moderate	Moderate +	Strong	Strong +	v. strong	v.v. strong	Extremely strong

4.3.1. The Derived criterion weights

Weights/influences of the parameters were determined using the AHP ArcGIS tool. The procedures undertaken and the scales given for each parameter are present in the figure below (Figure 22) Unlike other types of pairwise comparison methods, this method doesn't require normalization of the values. Values were normalized and weights are calculated using an algorithm built into the software. It gives weights in percentages for the parameters, which add up to 100% when totaled up.

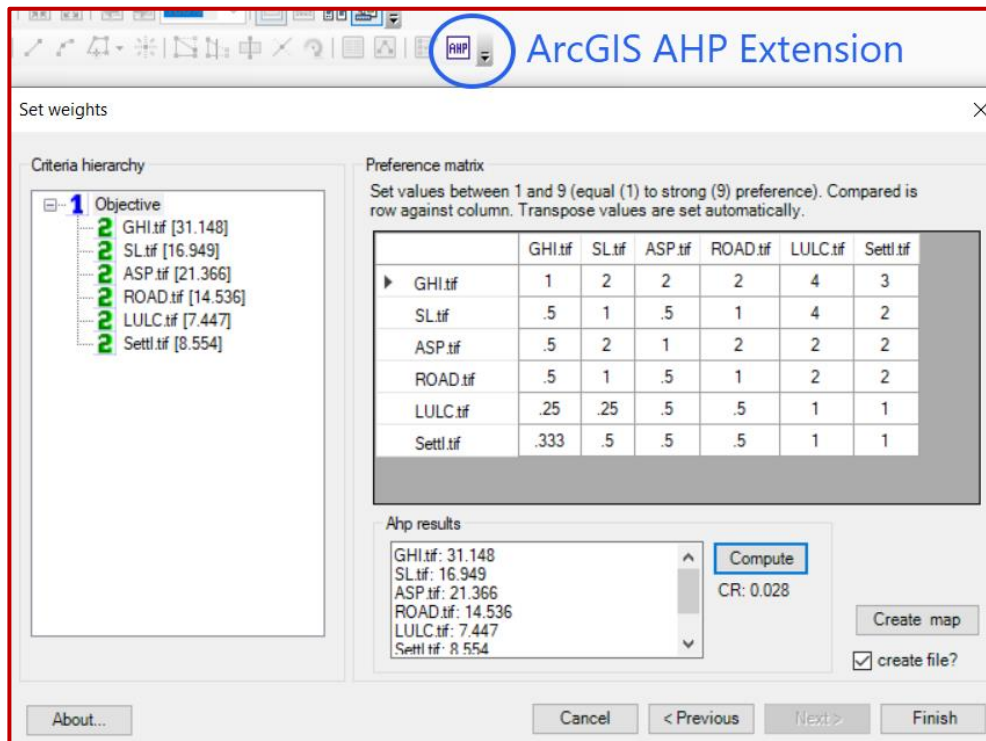


Figure 22. Pair wise comparison result

The result of the weights calculation revealed that the higher weight is assigned to Global Horizontal Irradiance. By this way, the GHI weighted at 31.14%. This implies that GHI is considered as the leading factor in the making of decisions process. This result is almost similar to (Nebey *et al.*, 2020). According to the AHP results, the second largest weight was given to the aspect, which is 21.366%. The third largest weight, 16.94%, was given for slope. Proximity to roads, proximity to populated areas, and land use land cover were assigned weights of 14%, 8.55%, and 7.44% respectively. These results are in accordance with the values reported by (Azmi *et al.*, 2017). The overall consistency ratio is 0.028 (2.8%). Consistency ration less than 0.1 (10%) is permissible and further analysis can be made using the calculated weights. Since consistency ratio meets the minimum requirement there is no need of repeating the pairwise comparison. The values for criteria weights were in decimal digits. Since the weighted overlay tool doesn't support the decimal numbers, the values were rounded to the nearest whole number for ease of analysis.

Table 3. Summary of suitability classes and criteria weights

Criteria	Sub-criteria	Suitability	Weight (%)
GHI (Kwh/m ² /year)	>2030	Highly suitable	31.14%
	1970 – 2030	Suitable	
	1925 – 1970	Marginally suitable	
	< 1925	Least suitable	
Aspect (Direction)	South , southeast & southwest	Highly suitable	21.36%
	East & west	Suitable	
	Northeast & Northwest	Marginally suitable	
	North & Flat	Least suitable	
Slope (Degree)	0 – 3	Highly suitable	16.94%
	3 – 7	Suitable	
	7 – 12	Marginally suitable	
	>12	Least suitable	
Land use/cover	Bare land & Agriculture land	Highly suitable	7.44%
	Shrub/bush land	Suitable	
	Agroforestry & woodland	Marginally suitable	
	Built-up, wetland & waterbody	Least suitable	
Prox. to roads(meter)	0 – 2500	Highly suitable	14%
	2500 – 5000	Suitable	
	5000 – 7000	Marginally suitable	
	>7000	Least suitable	
Prox. to populated area(meter)	1500 – 3500	Highly suitable	8.55%
	3500 – 5500	Suitable	
	5500 – 7000	Marginally suitable	
	0 - 1500 , & > 7000	Least suitable	

4.4. Overlay analysis and validation

The Weighted Overlay tool applies one of the most used approaches for overlay analysis to solve multicriteria problems such as site selection and suitability models. To prepare for the weighted overlay analysis, the parameters were broken into sub models and assigned new values to give the same meaning in the overlay analysis. Since all criteria do not have the same influence on site selection, their weights were calculated in AHP by comparing the influence of one criterion with the other. This means, the final output is governed by criteria weights. Before combining the criteria using a weighted overlay, the reclassified input datasets were assigned a weight value (Table 3), which indicates the influence of each criterion in relation to another. The output weight of the criteria contains decimal digits. But the weighted overlay analysis tool doesn't support decimal numbers

for analysis. So, to make the weights convenient for the weighted overlay tool, the decimal digits were rounded to the nearest whole number.

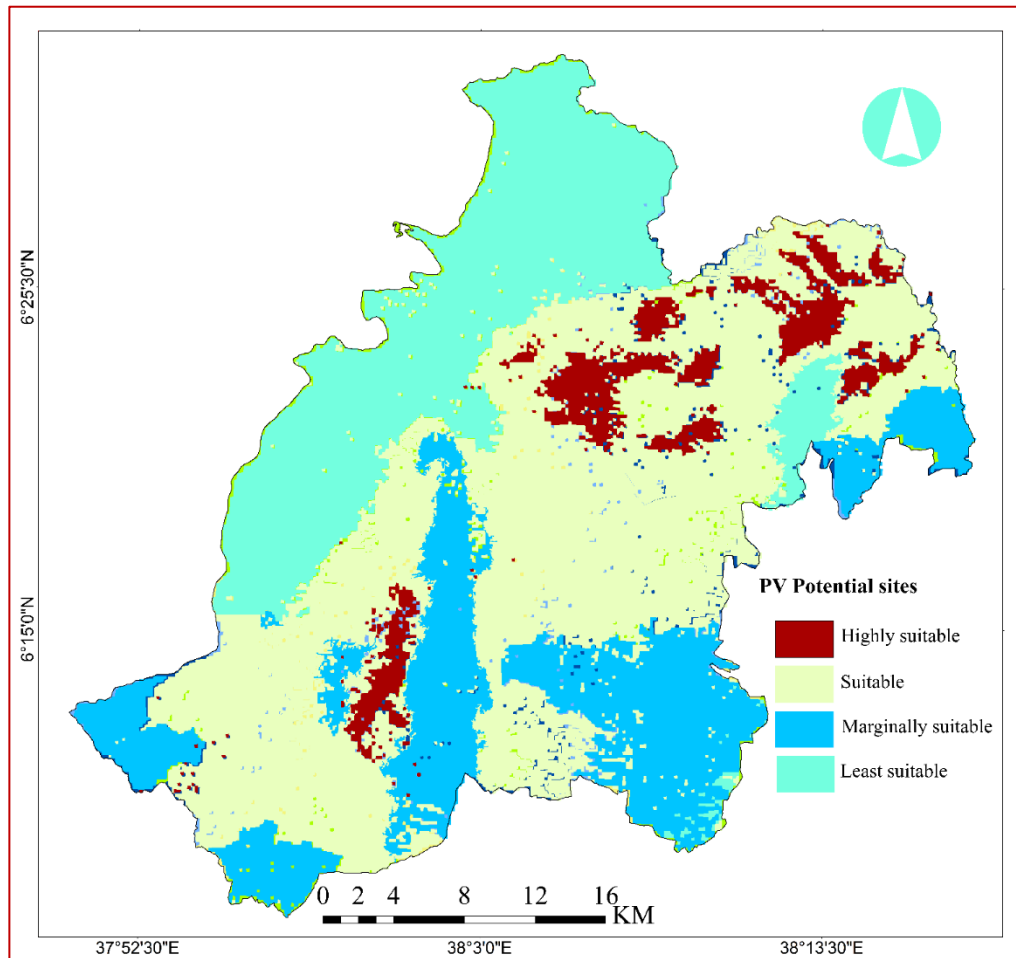


Figure 23. PV potential sites

The above map shows the final suitability map. The result was a raster layer that indicates suitability scores between 1 and 4. Pixel values of 4 are highly suitable and pixel values of 1 indicate the least suitable. The result of the weighted overlay contains tiny polygons that are found between two suitability classes. For the ease of interpretation and visualization, the small, non-significant cells were filtered out by the majority filter tool.

In this case, about 6.26% (7306 ha) of the area resulted in a highly suitable class. This result is located in areas with low slopes, in the south, southwest and southeast directions, and less than 2.5 kilometres from the roads and relatively near to the populated areas. Moreover, the highly suitable sites have high solar radiation, and are mostly found on

lands covered with nothing and agricultural lands. Nebey et al. (2020) conducted a site suitability analysis in northern Gonder and concluded that the highly suitable sites for solar panels comprise slopes less than 4°, south, southeast, and southwest facing aspect, and GHI greater than 2000Kwh/m2/year. Similarly, the study which was conducted by Tesema (2014) indicated suitable sites for solar farms comprise GHI of 2000Kwh/m2/year. The highly suitable areas are found in Gelo, Wedeyi Ture, Dibicha, Bunata and Semero Gambella kebeles.

Validation is a key step during analysis of site suitability for any purpose. This can be done by direct observation, by locating previously developed similar projects or by using available technology like Google Earth. In the current study, there are no previously developed solar farms. This makes it difficult to validate using predesigned solar farms. So the validation was done by observation and with the aid of Google Earth. The validation confirms that most parts of the highly suitable sites have lower slopes, are near infrastructure like roads, and are relatively close to places where people live in mass.

Table 4 PV potential summary.

Suitability Class	Area (Ha)	Percentage
Highly suitable	7306.29	6.26
Suitable	55806.48	47.82
Marginally suitable	24296.94	20.82
Least suitable	29283.84	25.09

4.5. Estimated energy potential

Finding only suitable areas for solar farm developments is not enough. The energy output of the sites should be estimated considering different factors. These factors range from available solar insolation, solar panel efficiency, and available parcel of land. Solar panel efficiency is considered as the main input for the calculation, since different panels have different efficiencies. Usually, most solar panels' peak output is tested at 25°C. But if the temperature of the solar panels increases, the voltage output decreases in direct correlation and linearly. This has significant effects on the output of solar panels, especially in the case of Ethiopia, which features areas with high levels of solar irradiation > 2000 kWh/m2 per year (Energypedia, 2019).

Here, the power generation capacity of the area is estimated only using a highly suitable site (Figure 24). Other areas other than highly suitable are excluded for different reasons. The first reason is that the suitable and marginally suitable areas require additional earthwork, especially for the levelling of steep slopes. Additionally, the least suitable area by no means meets even the minimum requirements. For this reason, and others, all suitability classes other than the highly suitable sites were excluded and the calculation was done on the area considered as highly suitable or feasible.

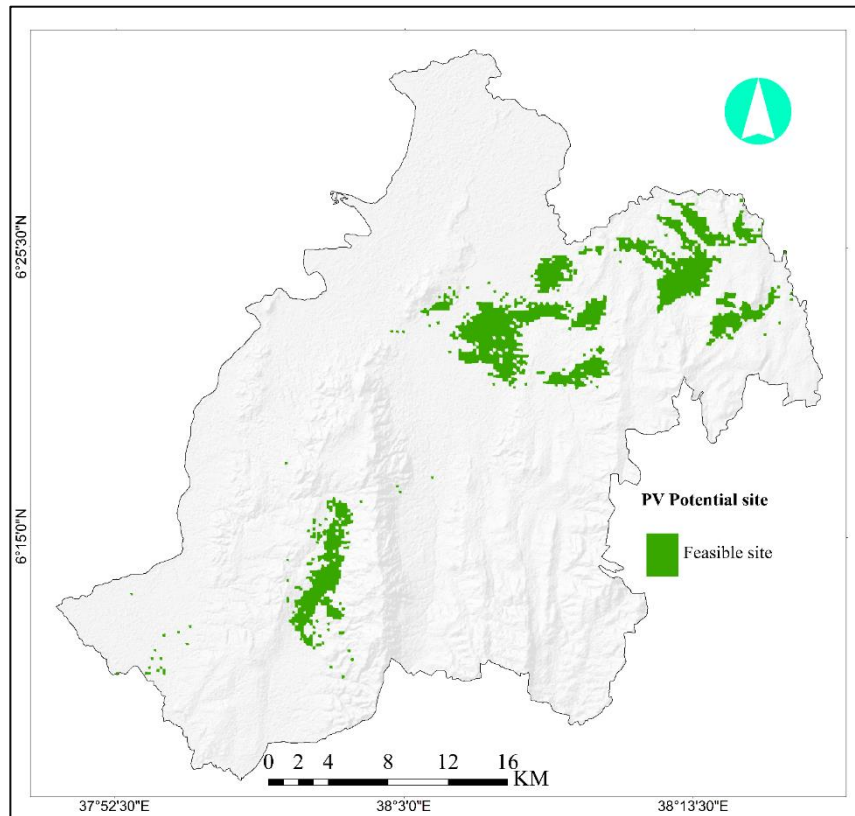


Figure 24. Identified Photovoltaics potential sites

Besides available land, estimation of energy potential considers the efficiency of solar panels. Currently, most of the commercially available solar panels' efficiency is below 20%. This means a solar panel with an efficiency of 20% has the capability of converting only 1/5th of the solar radiation it received into usable energy form. Even though efficiency is the primary criteria for selecting solar panels, other issues, such as the capacity to perform well in tropical areas, need to be considered. In this study, the top

five efficient solar panels that are found on the market are used as samples for power generation capacity calculation. Besides better efficiency, these panels have the capability of withstanding temperature increments by maintaining their efficiency.

Table 5. High efficiency solar panels

Manufacturer	Efficiency %	Wattage range
Jinko Solar Tiger Pro	21.2 – 21.4	535 – 585
SunPower® A-series	20.9 – 22.8	410 – 425
Panasonic EverVolt	20 – 21.7	360 - 370
LG NeON® 2 Series	19.6 – 21	340 – 440
Hanwha Q CELLS	19.5 – 20.6	335 – 360

The power generation capacity of the area is calculated by the commonly used formula which considers; SR: daily/annual Global Horizontal irradiation in Kwh/m²/day or Kwh/m²/year; C: available suitable area in m², η: efficiency of the solar panels, which is described in percentage; SF: shading factor, which is an indicative measure of what fraction of the calculated areas is exploitable for PV panels.

$$EPG = CA * SF * \eta * SR$$

In this case, the identified highly suitable area, which is 7306 ha, is used for calculation. The efficiency of the panels was taken by averaging the high-rated and low-rated solar panels. The average efficiency used was 19.5 %. Additionally the shading factor was taken as 0.5 thinking, as if half of the area could be utilized. Instead of daily Global Horizontal Irradiance, the yearly GHI was used. The average yearly GHI used in the calculation is 2055 Kwha/m²/year.

$$PG = 7306 \text{ ha} * 0.5 * 19.5 * 2055 \frac{\text{Kwh}}{\text{m}^2} / \text{year}$$

$$PG = 7306 * 10000\text{m}^2 * 0.5 * 19.5 * 2055 \frac{\text{Kwh}}{\text{m}^2} / \text{year}$$

$$\underline{\underline{PG = 146390 \text{ MWh/Year}}}$$

The above is a value indicating how much electricity can be generated in the area identified as suitable for power production. It is possible to generate this much electricity only by using 50% of the land available in the area. If all the available land is utilized, the value could change. Additionally, various panels with different efficiency levels could alter the annual power generation in the area.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study assesses solar suitability analysis for solar photovoltaics in Abaya Woreda. The study used several spatial data that are responsible for the selection of the best sites for PV. The analysis is done by overlaying different layers of criteria with different suitability levels. The result identified potential sites for future development of solar photovoltaics. The result shows that there is a very high potential for power generation in the study area. Most parts of the woreda are characterized by large amounts of daily and yearly solar insolation. On average, the yearly insolation reaches up to 2055 KWH per year. Using geospatial technology, about nine sites with high potential for photovoltaics were identified. In total, an area of 7306 ha was identified as a potential site. The currently identified sites have the potential to electrify the whole woreda if utilized properly. If the selected sites could be exploited properly, they could generate more than 146390MWh of electricity per year using half of the potential sites with 19.5% efficiency panels, which is enough to provide clean and secure energy for the people of the woreda.

5.2. Recommendations

Based on the findings of the present study the following recommendations are forwarded:

- ❖ The Ethiopian Meteorological Agency should work on availing solar radiation at the local level by installing insolation measuring instruments.
- ❖ Using GIS based assessment for photovoltaic site selection can bring a promising result if supported by accurate and site-specific data.
- ❖ The decision makers, including developers and funders, should use GIS based multi criteria analysis for assessment of potential sites for renewable energy developments by adding more criteria and constraints.
- ❖ This current study made good progress using the available data, but for more accurate and comprehensive results, researchers can use accurate insolation data that has been recorded on the site for long periods of time.

- ❖ If the identified area is utilised for solar farm establishments, it has the capacity of electrifying the households of the area.

CHAPTER SIX

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APPENDIX

Annex 1: Satellite image information

Path and Row	Specific object ID
168/056	LC08_L1TP_168056_20200119_20200128_01_T1
169/056	LC08_L1TP_169056_20200110_20200114_01_T1

Annex 2: Global Horizontal Irradiance (GHI) information

Temporal /Spatial Resolution	Specific Object Id
Yearly Average Total / 250m	Ethiopia_GISdata_LTAY_YearlyMonthlyTotals_GlobalSolarAtlas-v2_GEOTIFF
Daily Average / 250m	Ethiopia_GISdata_LTAY_AvgDailyTotals_GlobalSolarAtlas-v2_GEOTIFF

Annex 3: The average hourly Global horizontal irradiation data for all Months

Global horizontal irradiation Wh/m ²												
	Jan	Feb	March	April	May	Jun	July	Aug	Sep	Oct	Nov	Dec
0-1	0	0	0	0	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0	0	0	0	0
2-3		0	0	0	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0	0	0	0	0	0
6-7	1	1	1	8	22	11	6	6	5	16	12	6
7-8	101	100	116	138	157	112	78	87	127	169	181	149
8-9	335	338	348	347	354	273	199	237	336	384	415	382
9-10	572	583	591	586	564	463	368	464	563	610	639	606
10-11	774	798	803	755	722	629	521	597	723	777	810	784
11-12	905	946	934	871	816	722	623	694	811	862	912	897
12-13	957	1009	973	889	838	760	671	732	817	852	918	931
13-14	915	973	915	813	767	723	653	714	756	760	835	872
14-15	789	850	782	676	634	622	591	646	614	609	682	736
15-16	613	660	618	474	676	634	460	491	426	412	482	545
16-17	382	420	366	271	254	276	288	290	220	212	267	324
17-18	148	175	146	106	101	114	131	119	78	54	61	97
18-19	5	11	8	7	7	11	21	10	3	0	0	0
19-20	0	0	0	0	0	0	0	0	0	0	0	0
20-21	0	0	0	0	0	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0	0	0	0	0	0

Annex 4: Classification Accuracy Assessment report

CLASSIFICATION ACCURACY ASSESSMENT REPORT

ERROR MATRIX

Classified Data	Unclassifi	Reference Data		
		Agricultur	Agroforest	Builtup Ar
Unclassified	0	0	0	0
Agricultural La	0	22	1	0
Agroforestry	0	0	20	6
Builtup Area	0	1	0	20
Wood Land	0	0	0	0
Bareland	0	0	0	0
Water Body	0	0	0	0
Wetland	0	0	0	0
Bush/Shrub	0	2	2	1

Column Total	0	25	23	27
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Reference Data

Classified Data	Wood Land	Bareland	Water Body	Wetland
Unclassified	0	0	0	0
Agricultural La	0	2	0	0
Agroforestry	0	0	0	0
Builtup Area	0	1	0	0
Wood Land	19	0	0	0
Bareland	0	20	0	0
Water Body	0	0	22	3
Wetland	0	0	3	18
Bush/Shrub	5	2	2	0
Column Total	24	25	27	21

Reference Data

Classified Data	Bush/Shrub	Row Total
Unclassified	0	0
Agricultural La	1	26
Agroforestry	0	26
Builtup Area	0	22
Wood Land	1	20
Bareland	0	20
Water Body	0	25
Wetland	0	21
Bush/Shrub	26	40
Column Total	28	200

----- End of Error Matrix -----

ACCURACY TOTALS

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Unclassified	0	0	0	---	---
Agricultural La	25	26	22	88.00%	84.62%
Agroforestry	23	26	20	86.96%	76.92%
Builtup Area	27	22	20	74.07%	90.91%
Wood Land	24	20	19	79.17%	95.00%
Bareland	25	20	20	80.00%	100.00%
Water Body	27	25	22	81.48%	88.00%
Wetland	21	21	18	85.71%	85.71%
Bush/Shrub	28	40	26	92.86%	65.00%
Totals	200	200	167		

Overall Classification Accuracy = 83.50%

----- End of Accuracy Totals -----

KAPPA (K[^]) STATISTICS

Overall Kappa Statistics = 0.8111

Conditional Kappa for each Category.

Class Name	Kappa
Unclassified	0.0000
Agricultural Land	0.8242
Agroforestry	0.7392
Builtup Area	0.8949
Wood Land	0.9432
Bareland	1.0000
Water Body	0.8613
Wetland	0.8404
Bush/Shrub	0.5930

----- End of Kappa Statistics -----