GIS-Based Assessment of Solar Energy Harvesting Sites and Electricity Generation Potential in Zambia

Mabvuto Mwanza and Koray Ulgen

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Abstract

Land and environment are some of limited nature resource for any particular country and requires best use. Therefore, for sustainable energy generation it is often important to maximize land use and avoid or minimize environmental and social impact when selecting the potential locations for solar energy harvesting. This chapter presents an approach for identifying and determining the potential sites and available land areas for solar energy harvesting. Hence, the restricting and enhancing parameters that influence sites selection based on international

M. Mwanza (✉)
Department of Electrical & Electronic Engineering, School of Engineering, University of Zambia, Lusaka, Zambia

K. Ulgen
Ege University, Solar Energy Institute, Bornova/Izmir, Turkey
e-mail: koray.ulgen@ege.edu.tr

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regulation have been imposed to the Laws of Zambia on environmental protection and pollution control legislative framework. Thus, both international regulations and local environmental protection and pollution control legislative have been used for identifying the potential sites and evaluating solar PV electricity generation potential in these potential sites. The restricting parameters were applied to reduce territory areas to feasible potential sites and available areas that are suitable for solar energy harvesting. The assessment involved two different models: firstly the assessment of potential sites and mapping using GIS, and secondly, evaluation of the available suitable land areas and feasible solar PV electricity generation potential in each provinces using analytical methods. The total available suitable area of the potential sites is estimated at 82,564.601 km^2 representing 10.97% of Zambia's total surface area. This potential is equivalent to 10,240.73 TWh annual electricity generation potential with potential to reduce CO_2 emissions in the nation and achieve SDGs. The identification of potential sites and solar energy will help improve the understanding of the potential solar energy can contribute to achieving sustainable national energy mix in Zambia. Furthermore, it will help the government in setting up tangible energy targets and effective integration of solar PV systems into national energy mix.

Keywords

Sustainable systems · Potential sites · Solar energy harvesting · Renewable energy · Zambia

Introduction

The purpose of meeting human basic needs and curbing climate change by reducing greenhouse gas emissions both at local and global levels has led to search for and establishment of energy policies for promoting renewable energy (Samuel and Owusu 2016; Sanchez-Lozano and García-Cascales 2014). The energy policies not only emphasized on promoting renewable energies but also on protecting natural resources and supporting natural environmental sustainability (Ivan 2015). Electricity generation from solar energy is in constant increase across the globe, but its share in the total energy production locally and globally still remains low as compared to fossil fuels. However, due to continual PV price decrease, increase in efficiency and maturity of technology in the last decades, feed-in tariffs including other incentives in many countries, has led to remarkable boom in photovoltaic (PV) technologies deployment and development both at utility-scale and residential levels across the globe (Robert 2014). According to International Energy Agency (IEA), the production of electricity from solar energy is expected to continue growing up to between 20% and 25% by 2050 (SEFI/UNEP 2009; Yassine 2011; Yassine and Adel 2012).

Despite of the remarkable boom in the application of solar PV technologies across the world, the application of these technologies in the electricity production in many developing countries like Zambia is still very negligible (Bowa 2017). However, there are only a few examples of small isolated solar systems used by communities, schools, companies, private households, hospitals, and health centers. These systems are often used to meet the daily energy needs and to cover up energy needs during load-shedding period (MMWED 2008; Bowa 2017). One of the largest solar systems installed by government so far through Rural Electrification Authorities (REA) was built in 2010 in Samfya district Northern Province (installed capacity of 60 kW) (Bowa 2017). According to Bowa (2017), the estimated total installed capacity of solar photovoltaic-based power plants as of 2016 was more than 2 MW (small off-grid systems). Hence, despite of the country being located in most favorable solar belt (MMWED 2008) and receiving significant higher solar irradiation than most of world's largest solar energy utilizing countries, solar energy application for electricity generation has remained negligible. According to Meteorological Department of Zambia, the country has monthly average solar radiation incident rate of 5.5 kWh/m^2-day (Gauri 2013; MMWED 2008; Walimwipi 2012; IRENA 2013). The solar radiation intensity across the country varies with western part of country having the highest annual average of approximately 5.86 kWh/m^2-day and the eastern part with the lowest of 5.68 kWh/m^2-day as shown in Fig. 1. Therefore, Zambia has a favorable climate conditions for utilization of solar energy for both production of electricity and thermal use. The total annual average global solar radiation ranges from 1981 kWh/m^2 in parts of North-Western, Eastern, Northern, Central, and Southern provinces to 2281 kWh/m^2 in parts of Luapula, Northern, and Western provinces of Zambia as illustrated in Fig. 2.

In order to increase access to electricity for all, the Government of Republic of Zambia has set targets and plans to encourage deployment and development of renewable energy facilities across the country, with hydropower and solar energy based on photovoltaic technologies expected to experience the greatest growth. However, despite of several tools being available across the globe for estimating the solar energy potential for particular location, these tools do not fully take into consideration the environmental and social issues. In addition, the surface land areas and the natural environment are some of the world scarce natural resources that require selection of the best use of these rare resources (Ronald 2016). Therefore, in order to safeguard the natural environment and consider best use of available surface land areas, energy planning and site selection for promotion and deployment of renewable energy technologies in individual countries has become one of the most challenging aspect more especially in developing countries like Zambia.

In addition, unified planning and poor site selection for intermitted renewable energy source based power plant have resulted in mismatch between the grid capacity and PV power plant output during peak time in some parts of the world (Siheng et al. 2016; Ming 2015). On the other hand, arbitrary site selection and neglecting the transmission line available reserve margin in the procedure have resulted in some PV power plant exceeding the local transmission line reserve margin and grid unable to transmit the energy to the load centers during peak hours (Chinairn 2013; Aly Sanoh 2014; Quansah 2016). Therefore, preliminary estimation and mapping of potential sites, available areas, and technical energy yield potential for intermitted renewable energy source based power plant

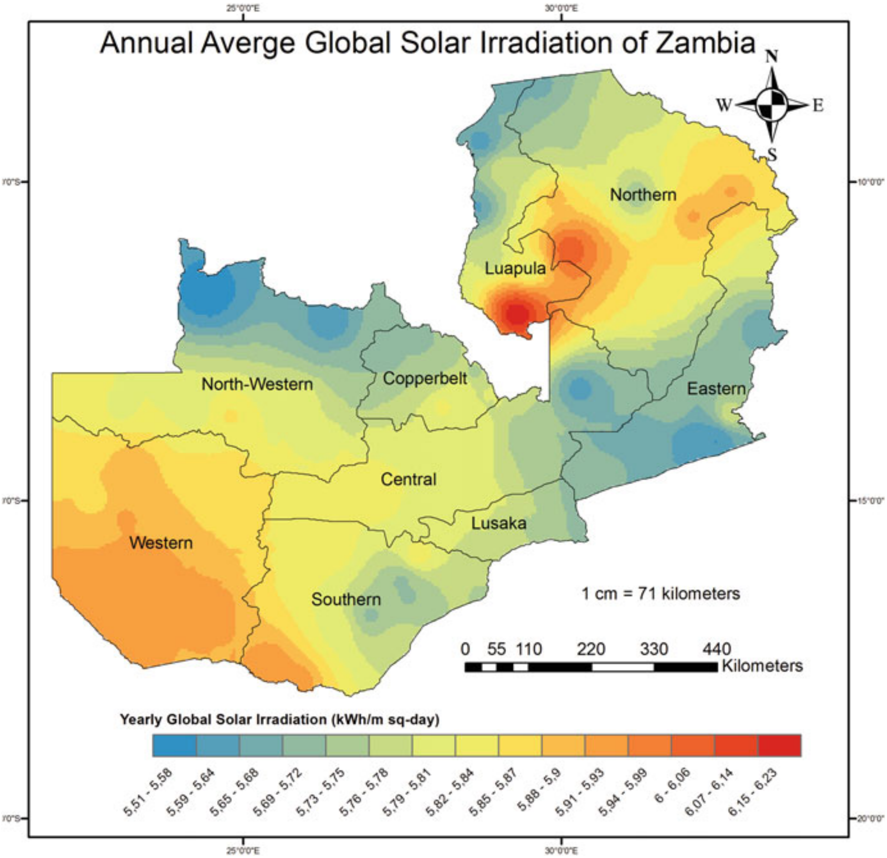


Fig. 1 Annual average horizontal solar irradiation

deployment while considering social acceptability and supporting natural environmental sustainability can be helpful to overcome these problems (Siheng et al. 2016). Doing so also helps to avoid and minimize potential negative environmental and social impacts associated with deployment of these technologies. The preliminary estimates and mapping of potential sites and technical energy yield potential for solar photovoltaic power plant development, however, have not been made in most developing countries like Zambia due to various reasons.

However, selection of potential site and evaluation of technical electricity generation potential requires a number of finer spatial resolution data, since not all locations of any particular country are suitable for deployment of these technologies due to local landscape terrain, climate, and environmental regulations (Suri 2005).

This chapter aims at providing a method for identifying and mapping a series of the potential sites and the available land areas suitable for solar energy harvesting in Zambia. The chapter further provides a method for assessing the electricity generation potential from solar energy based on commercially available solar photovoltaic

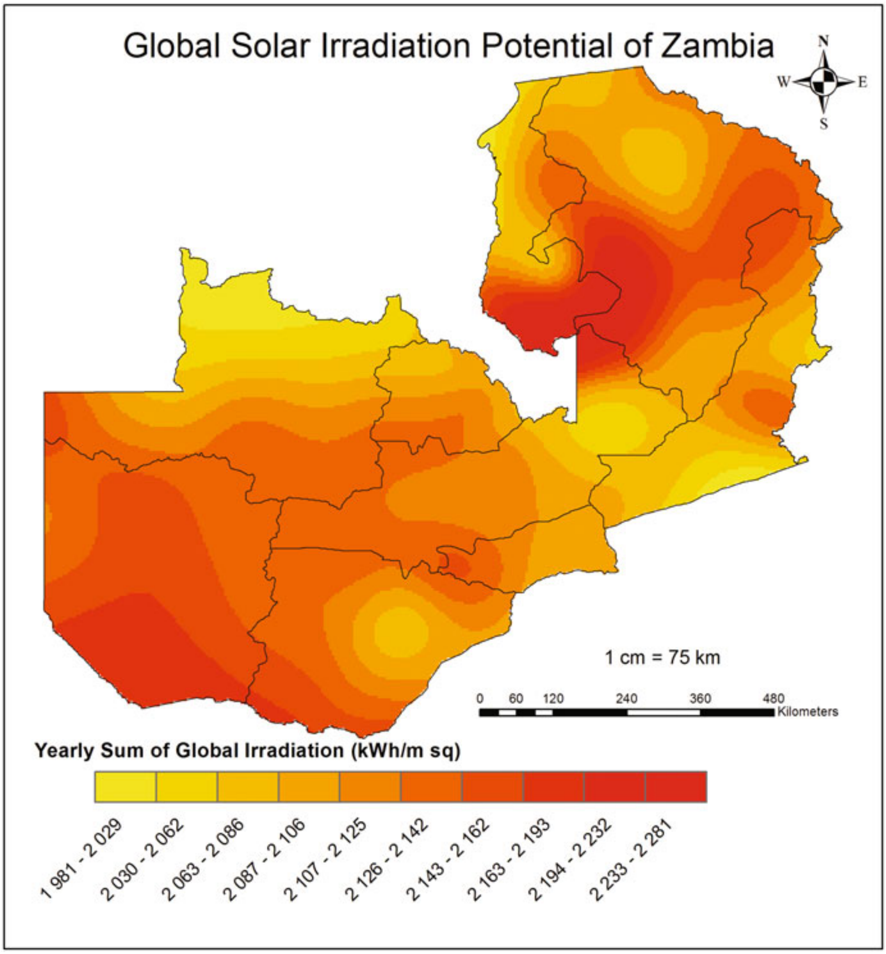


Fig. 2 Annual total global solar radiation intensity (Mwanza et al. 2016a)

technologies and available land areas. The evaluations in this chapter considered the modules of the solar PV systems mounted at optimal tilt position to the ground. The analysis focused on solar radiation, available areas, and typical energy that can be generated from the PV system considering the solar PV module characteristics and available solar radiation of the potential sites. The results of this study are important as it provides summarized information with regard to suitable potential sites, available land area, and technical electricity generation potential that can be attained from using solar photovoltaic technologies across Zambia.

Geographical Description

Zambia is unique country endowed with variety and abundant nature resources, such as wildlife resources, watercourse resources, forests resources, minerals resources, and renewable energy resources. Its abundant renewable energy resources such as solar energy are heavily untapped. The country is also blessed with unique climate and geography of flatland in most part of the country. It is situated between latitudes 8^0 and 18^0 south of the equator and longitudes 22^0 and 34^0 east of prime meridian. The country is landlocked by eight countries, Zimbabwe and Botswana to the South, Angola to the West, Democratic Republic of Congo and Tanzania to the North, Malawi and Mozambique to the East, and Namibia to the Southwest (Mwanza et al. 2016a).

Solar Photovoltaic Power Plant Sitting Considerations

Environmental and Social Issues

Solar energy is clean, free, and unlimited renewable energy sources that can be used for variety of purposes including pumping water for irrigations, drying and preparing food, and most importantly for electricity generation. However, just like any other alternative energy supply option, solar photovoltaic technology deployments at utility-scale are not free from imposing negative effects on both the environment and society (www.energy.gov) (Wang and Prinn 2010; Union of Concerned Scientists 2015). Most of these effects depend on development size, site, and the type of technology deployed and also site selection and environmental guidance procedure. The envıronmental and socıal impacts associated with renewable energy technology development are mainly grouped as listed in Table 1 (Ahmed Aly 2017; Turlough 2017; Shifeng and Sicong 2015; Kaoshan et al. 2015; Fylladitakis 2015; Saidur et al. 2011; Gipe 1995; Interior Department 2010; Damon and Vasilis 2011; U.S 2016; Geoffrey and Tidwell 2013; England 2011; Tsoutsos 2005, 2009).

Restricting Issues

The potential impacts associated with utilization of renewable energy technology have potential to hinder or delay deployment and development of solar photovoltaic technologies or facilities in potential sites. Table 2 and Figs.3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 list solar PV systems deployment restricting issues that have, among others, been considered for inclusion, as appropriate, in the available land area, technical electricity generation potential, and potential sites assessment for sustainable solar photovoltaic facilities development in Zambia based on highlighted environmental and social impacts (www.energy.gov; Abdolvahhab Fetanat 2015; Alami et al. 2014; Ahmed et al. 2017; Arthur Bossavy 2016; Addisu and Mekonnen 2015; Marcos Rodriques 2010; Anthony Lopez 2012). Restricting criteria data are features that

Table 1 Summarized environmental and social impacts induced by solar photovoltaic power Plants

Type of impact	Causes	Factors contributing	Effects
Noise pollution	Inverter noise due to internal electronics, transformer noise, construction noise	Air temperature, humidity, ground surface material, background noise, heavy machinery, human activity	Sleep disturbance, hearing losses, headaches, irritability, fatigue, constrict arteries, weaken immune systems, annoyance, or dissatisfaction
Air and water pollution	PV module: Toxic materials, heavy machinery & transformers: Oil, switchgear breaker gas SF_6, ground clearing and grading	Fire, module cracking, leaking machinery due to poor maintenance, leakages in switchgear, transformers, & machinery, access roads & ground preparing	Death, injuries, loss of ecosystem, contamination of soil, water, and air
Water use	Periodic maintenance: PV module surface cleaning, construction activity, dust abatement activities	Dust, wind, location, size of facility, system performance, unpaved roads	Reduced underground water recharge, reduced surface water flow, agriculture water problem, wildlife water problem, human water problem
Climate Change & Greenhouse gas (GHG) emissions	Concrete and steel for PV array mounting foundations	Size of PV array, location of facility	CO_2 emission; global warming
Wildlife & Habitat loss	Excavation, grading, ground clearing, road & electrical grid construction	Location, landscape topography, size of facility, distance to road and electrical grid	Loss of feeding, nesting or roosting grounds for animals, birds, ecosystem disturbance, wildlife reduction
Visual impact	Distance to residential areas, size of facility, night lights at power plant, human perception	Scenic backgrounds, local landscape topography, local landscape between solar plant and viewers, location of solar farm, color of PV panels, layout of solar farm; irregular or regular, clear skies	Aesthetic effects, public health, negative perception of solar energy technologies, visual effect

(continued)

Table 1 (continued)

Type of impact	Causes	Factors contributing	Effects
Land use/ Soil & Land Degradation, fugitives dust	Power grid & access road construction, PV array foundation excavation, removal of surface plants, wastewater and oil from construction machinery, excess wastes from construction: Plastics, metal, glues, & inks	Layout of solar PV farms, location of solar PV farm, landscape topography, type of PV technology, tilt angle of modules, distance to access road and electrical grid, office wastes	Deforestation, soil erosion, loss of habitat, landslide, floods, air and water pollution, ecosystem disturbance, fugitive dust

Table 2 Restricting issue datasets

Type of impact eliminated, minimized or avoided	Site descriptions	Detail nature of sites descriptions
Water use, Wildlife & Habitat Loss	Wildlife sites	National parks and game reserves
Visual impact, Noise Pollution & Land use/degradation, fugitives dust	Community interest sites	Airfields, historical sites, archaeological sites, traditional and cultural heritage sites, national monuments sites and tourism sites, religious significance sites
Water use, land use/degradation	Agriculture sites	Crop areas and potential agriculture areas
Fugitive dust, water use, air/Noise Pollution & Visual Impact, land use	Settlement sites	Rural/urban and residential areas: Towns, cities, villages, and areas used extensively for recreation and aesthetic reasons
Water pollution, Wildlife & Habitat Loss, land degradation	Surface water bodies and surrounding sites	Rivers, lakes, streams, waterfalls, and wetlands
Land degradation, Wildlife & Habitat Loss	Landscape	Land elevation and slope (>5degrees), areas prone to flooding and natural hazards, zones prone to erosion or desertification, zones of high biological diversity, areas supporting populations of rare and endangered species,
Land use, Wildlife & Habitat Loss, fugitive dust, water, air and soil pollution, visual impact	Right of way	Transmission, roads and railroads network right of way
Wildlife & Habitat Loss, climate Change & Greenhouse gas (GHG) emissions, land degradation	Forest and surrounding sites	Forests: Low need-leaved deciduous forest and moderate evergreen deciduous forest, shrub-lands: Closed to open shrub-land and open shrub-land, grassland: Sparse grassland, indigenous forest

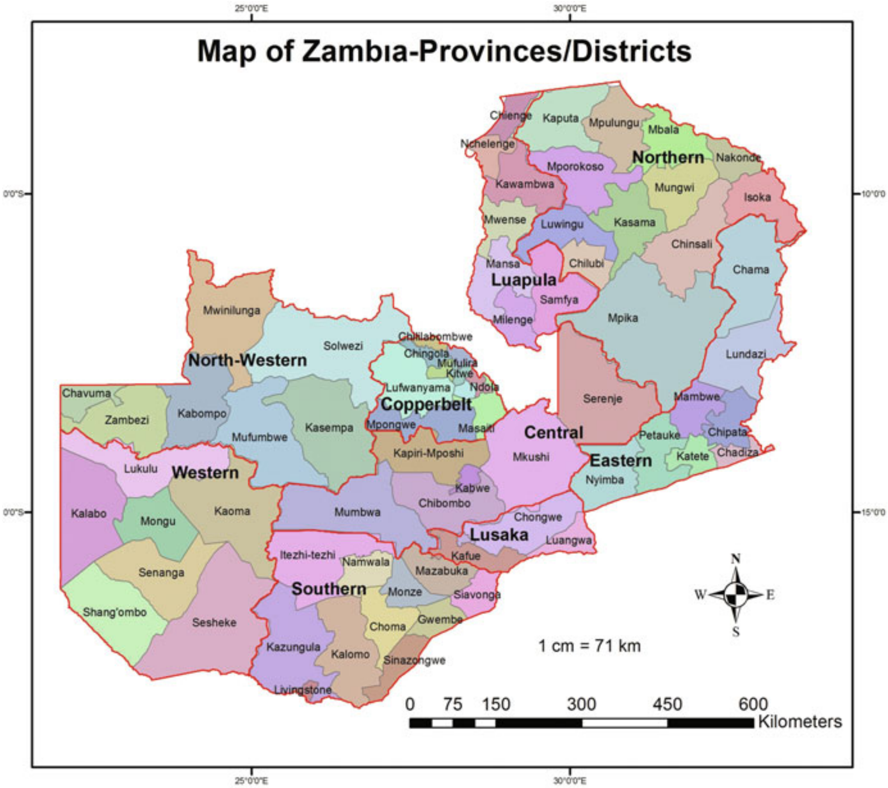


Fig. 3 Administrative boundary map

pose restrictions or limitations, that is, unsuitable or not preferred areas based on legislative laws of the country and nature.

Potential Site Identification and Mapping

Solar PV Potential Site Identification and Mapping

In order to assess the potential sites suitable for utility-scale solar photovoltaic deployment based on literatures surveyed and the laws of Zambia on environmental for development of any industry or plant on a particular site and restrictions datasets summarized in Table 2. Thus, the following environmental and social impacts and issues illustrated in Table 3, among others, are considered for inclusion, as appropriate, in the selection of suitable sites for solar energy facilities (ECZ 1994).

These maps included land elevation map (DEM), land use/cover layer map, town and village location map, community interest sites map, national parks map, surface water bodies map, roads and railway map, study area boundaries, and transmission

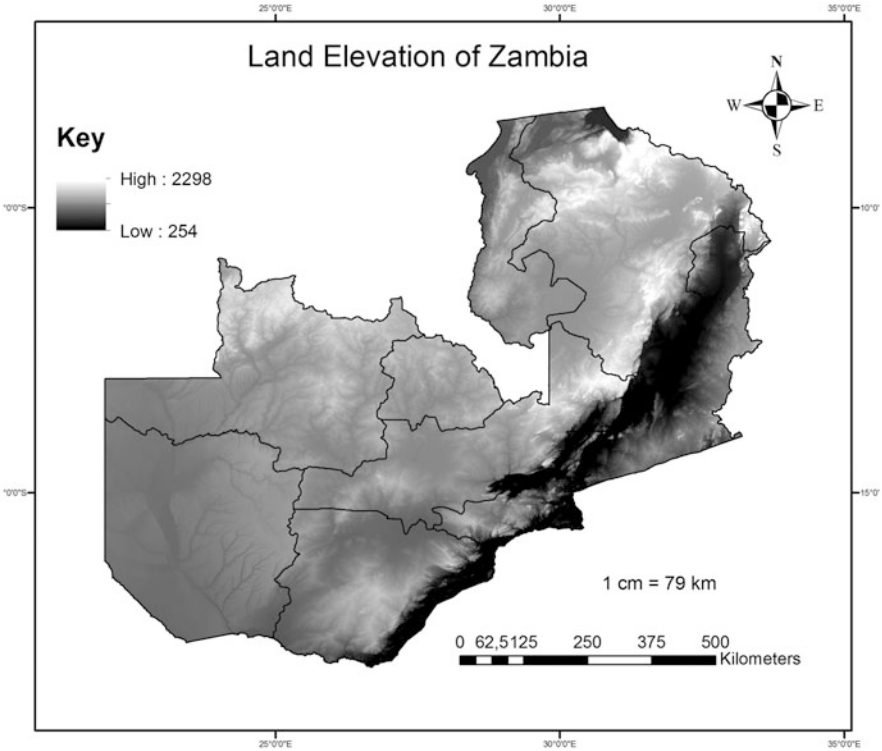


Fig. 4 Land digital elevation map

line maps (Nazli Yonca 2010; Sanchez Lozano et al. 2013, Brewer 2014, Chao-Rong Chen 2014, Charabi and Gastli 2011, Lopez 2012, Janke 2010; Uyan 2013). The rationale used for each restrictions are as follows:

- ***Land Use/Cover (C6, C9):*** This dataset has 10 classes including bare land, closed to open shrubland, open shrubland, sparse grassland, croplands, urban settlement, water courses, wetland, and forest sites; low need-leaved deciduous forest and moderate evergreen forest. For deployment of solar PV power plants only bare lands, sparse grassland and open shrubland were considered suitable due to easy accessibility considering an emerging economy and also to reduce land clearing costs.
- ***Wildlife Sites (C2):*** this dataset considers areas such as national parks, game reserves, and other natural resources since development in these sites will have adverse impact on birds, animals, and ecology, thus any construction in these areas may face public and international resistance. Therefore, these areas and the surrounding areas within the buffer of 2 km were considered not suitable (Nazli Yonca 2010).

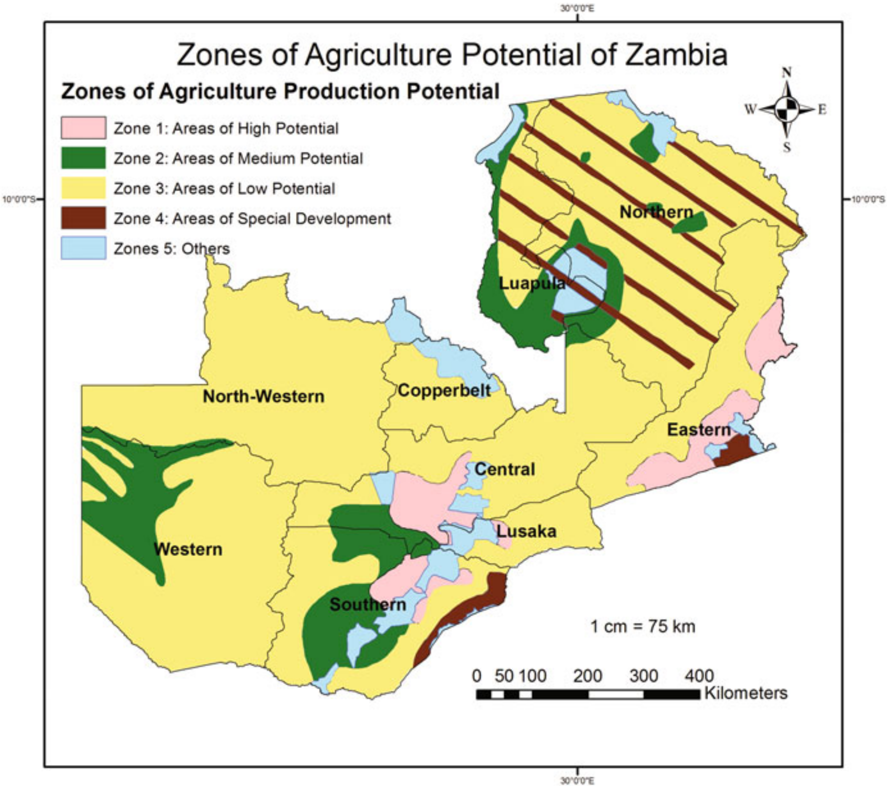


Fig. 5 Zones of agriculture production potential

- ***Settlement and Community Interest Sites (C4, C1):*** The dataset consists of settlement areas for both rural and urban such as airfields, airports, towns, villages, and other dwelling areas and community interest sites. Here a buffer of 3 km is considered to avoid aforementioned impacts and increase public safety and acceptance. All areas outside the buffer were considered suitable (Joss and Watson 2015).
- ***Land Elevation (C7):*** As it is expected that no one will install solar PV power plants in gorges or higher elevation due to construction costs. Thus, this dataset considered all higher and lower elevations such as mountains and gorges with steeper slopes above 5^0 as unsuitable areas.
- ***Surface Water Bodies (C8):*** In this dataset all surface water bodies such as rivers, streams, lakes, including waterfalls, and wetlands were considered as protected areas in order to avoid water pollution. Thus, a buffer of 2 km was considered with all areas outside buffer being suitable.
- ***Roads and Railways Network (C3):*** The dataset considers roads and railway network to be restriction since no one is supposed to build on roads or railway and also for the safety of the public. Hence, a 0.5 km buffer has been considered in

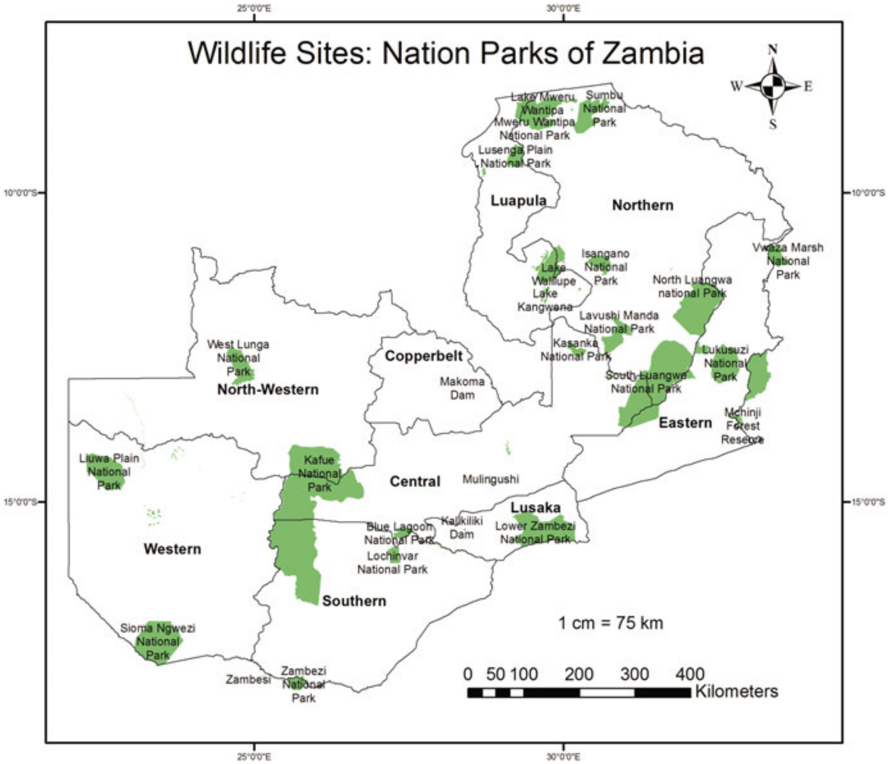


Fig. 6 Wildlife areas: national parks

order to increase public safety and also reduce cost of constructing access road which usually leads to land use/degradation, wildlife and habitat loss, fugitive dust, and air and soil pollution to the site and surrounding areas. Thus, the areas outside the buffer are considered suitable.

- ***Transmission Line Network (C5):*** In this dataset the right of way for transmission line were considered as unsuitable area for solar PV power plants, thus a 0.5 km buffer was used. Any areas within the buffer were considered unsuitable. The 0.5 km buffer were considered so that the cost of constructing new transmission lines is reduced, but at the same time to avoid conflict with right of way for transmission lines and avoid land use/degradation, wildlife and habitat loss, fugitive dust, water, and air and soil pollution to the site and surrounding areas.

After creating buffers, and changing some features from vector to raster, in order to evaluate available areas and identify/map feasible potential sites, the created buffers for the restricting layers were overlaid on each other using GIS spatial analysis. Figure 13 below shows the summarized analysis procedure.

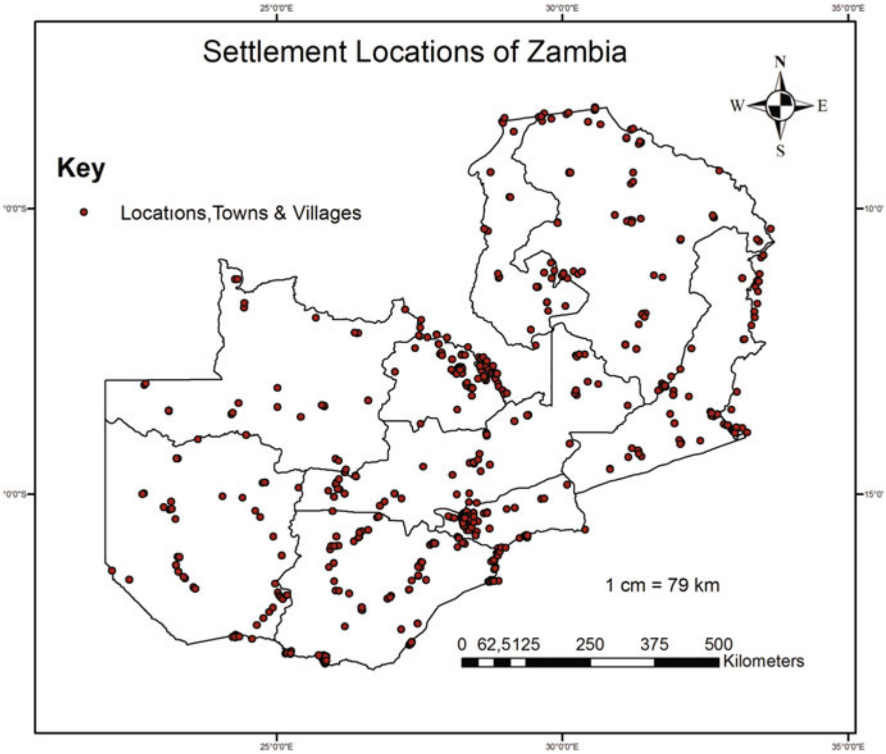


Fig. 7 Settlement and community interest sites

Available Land Area

In order to estimate the available suitable areas for solar photovoltaic power plant development based on aforementioned restrictions issues, a new factor called Area Suitability factor f_{SF} was introduced. It is defined as the ratio of total grid cells of suitable surface area to the total cells of the study surface area. The factor is estimated based on study area grid cells; here the total grid cells for study surface area are evaluated considering the sum of restricted and suitable surface areas' cells. Hence the factor depends on the ratio of available suitable area and surface area of the study area and it is calculated using the expression below.

$$f_{SF} = \left(\frac{C_{CSA}}{C_{CSA} + C_{CRA}} \right) = \frac{C_{CSA}}{C_{TSSA}} \quad (1)$$

where C_{CSA} is the total number of cells of suitable areas, C_{CRA} is the total number of cells of restricted areas, and C_{TSSA} is total number of cells of study area.

Therefore, the total available suitable land areas for each district and for Zambia were evaluated using expression 2 given below

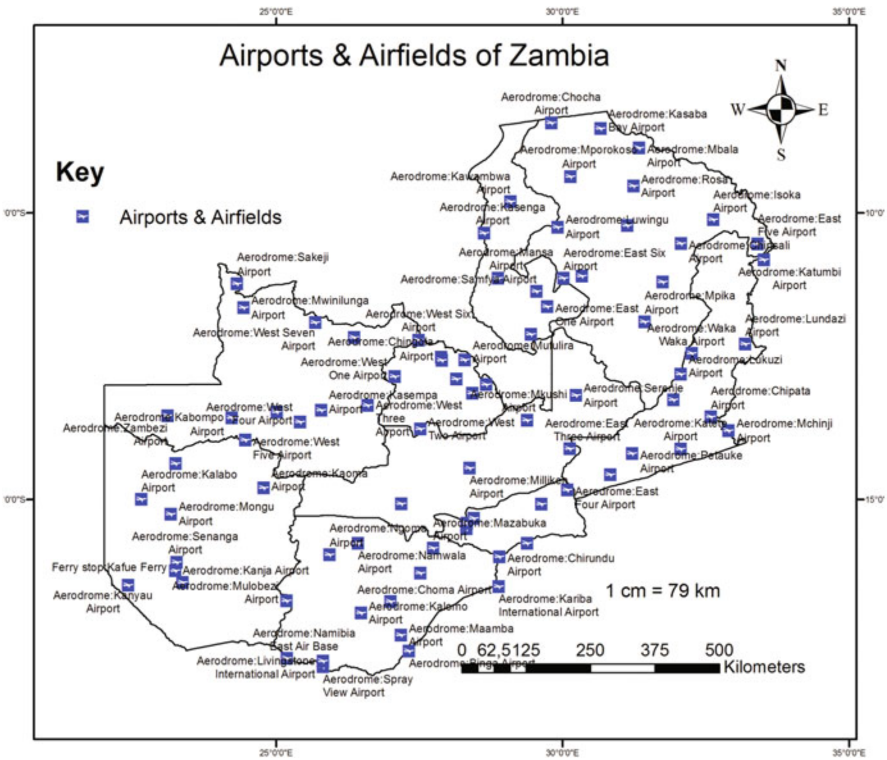


Fig. 8 Airports and airfield

$$A_{ADS} = f_{SF} \cdot A_{TSA} \tag{2}$$

where A_{ADS} is total available suitable areas (km^2), and A_{TSA} is total surface area of the study area (km^2).

Electricity Generation Potential

Solar Energy Potential in Zambia

According to the literature and data undertaken by Meteorological Department of Zambia, the country has a significant potential of solar energy for both electrical power production and thermal from solar energy technologies. The country has average peak sunshine of about 6–8 hours per day and monthly average solar radiation of 5.5 kWh/m^2-day throughout the year (MMWED 2008; Walimwipi 2012). According to International Renewable Energy Agency (IRENA 2012), the country has the highest total yearly solar radiation of 2,750 kWh/m^2-year with the highest average temperature of 30 °C, which presents good opportunity for solar systems deployment (IRENA 2012).

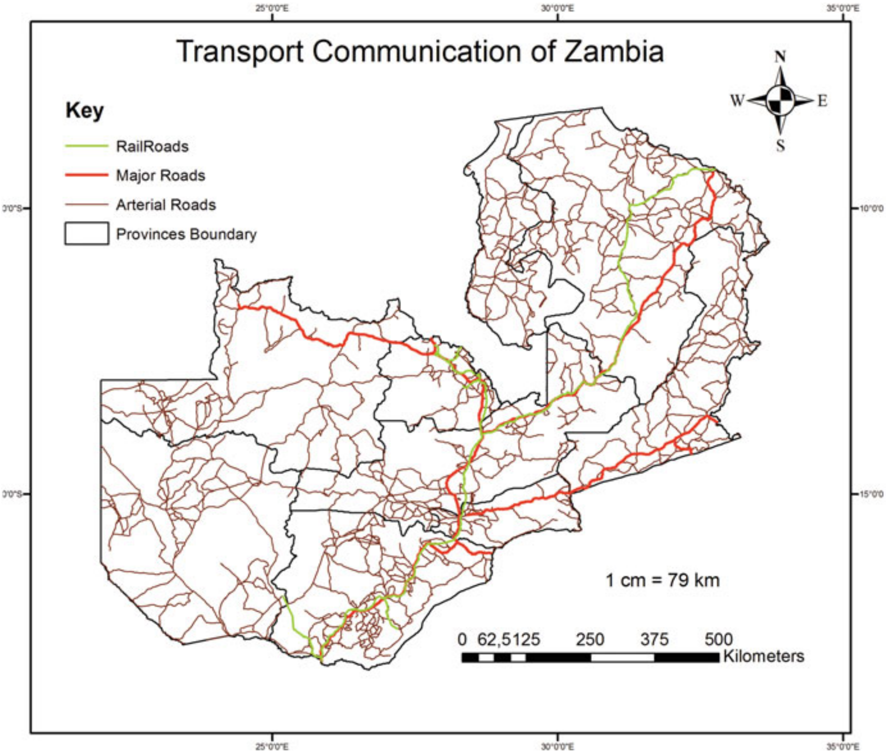


Fig. 9 Road and railroad networks

Performance of PV System

In order to evaluate the performance of grid connected PV power plants, the following performance indices are normally used: yields, normalized losses, and system efficiencies, performance ratio, and capacity factor – (British Standard 1998). However, in this chapter final yield, performance ratio and capacity factor have been adopted for analyzing the PV system performance of the various types of PV technologies commercially available on the market (Table 3) considering Zambia's weather condition. In addition, several PV technologies have been considered in the evaluation of technical electricity generation and power potential: firstly, because the energy generation by PV power plants with same peak power and receiving same amount of solar irradiation differs depending on the type of technology employed in the power plants, and secondly, the amount of peak power that can be installed at a given land area differ with PV technologies as shown in Table 4. Hence, it can be concluded that the type of cell technology has greater influence in the amount of land area needed for a peak power installation, the higher the efficiency the lower the land requirements for the peak power capacity installation (Martin-Chivelet 2016).

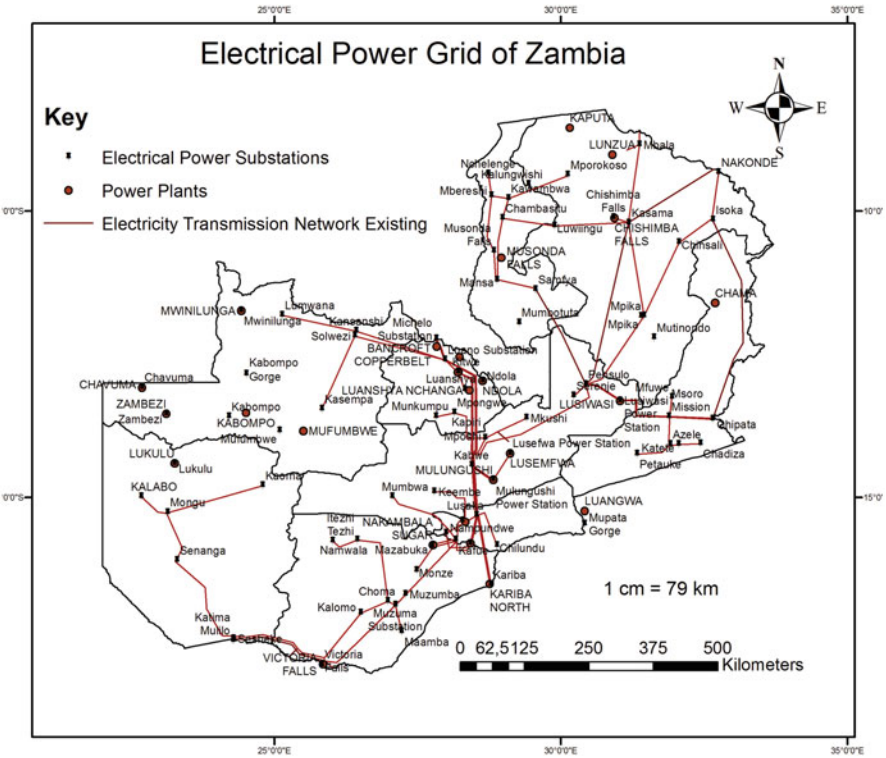


Fig. 10 Existing electrical network

Energy Model of PV Array

The solar energy resources are the key determinants of PV system electricity generation (IRENA 2012). The higher the solar energy resources, the more output yield of a PV systems per kilowatt. However, higher temperatures, dust, shading, balance of system inefficiencies, and PV technology characteristics have negative impact on the PV system energy yield (Didler 2012). Therefore, the electricity generated and supplied to grid by PV system considering these negative impacts has been estimated using Eq. 3:

$$E_A = A_{PV} \cdot H_R \cdot \eta_P \left(1 - \lambda_p\right)\left(1 - \lambda_C\right) \qquad (3)$$

where E_A is energy output of PV system (MWh/year), H_R is solar radiation on the surface of module (kWh/m^2-day), A_{PV} is PV system active area (m^2), η_P is module efficiency under STC condition, λ_p is miscellaneous module losses due to dusty covering, and λ_C is losses due to power conditioning unit and cable losses. Module efficiency is a function of its nominal efficiency, η_r, which is measured at STC $T_r = 25$ °C (Didler 2012). İt has been calculated as:

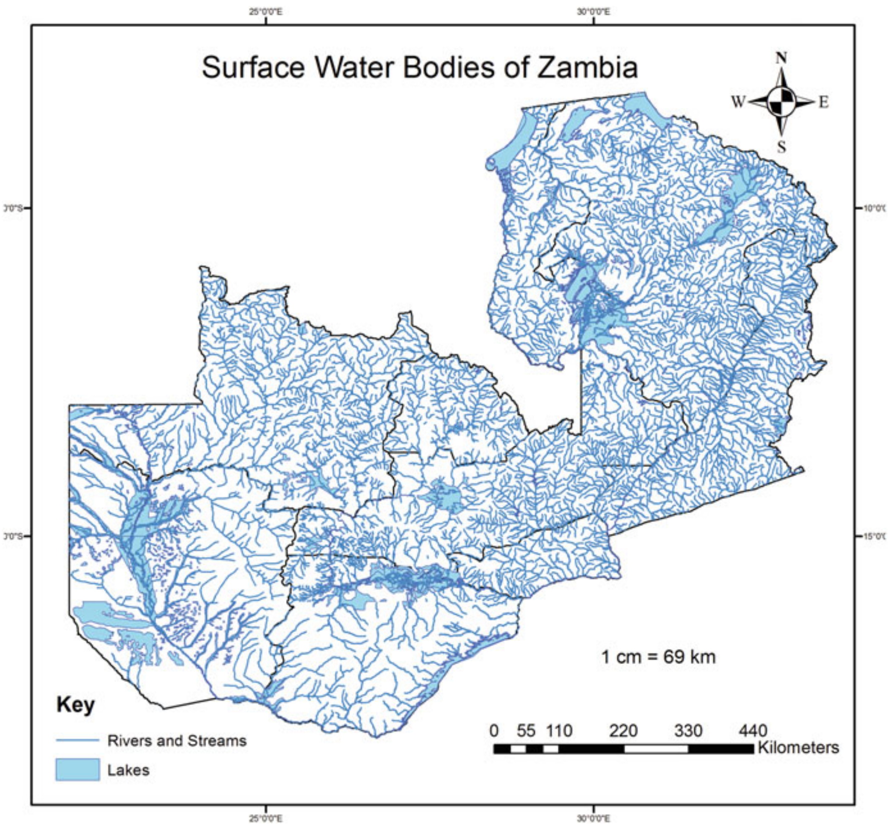


Fig. 11 Surface watercourses and streams

$$\eta_p = \eta_r \cdot [1 - \beta(T_c - T_r)] \tag{4}$$

where β is a temperature coefficient for module efficiency, T_c is a module temperature due to air temperature, and T_r is STC reference temperature.

Module temperature is related to the average monthly ambient air temperature, Ta, for a local condition has been calculated using Eq. 5 (Didler 2012).

$$T_c; = T_a + \frac{G_T}{G_{T.NOCT}} \left(\frac{9.5}{5.7 + 3.8V_W} \right) (T_{c,NOCT} - 20)(1 - \eta_m) \tag{5}$$

where G_T is solar irradiance (W/m^2), T_a is ambient air temperature (°C), and V_W is wind speed(m/s) for the location, $T_{c,NOCT}$ is nominal operating cell temperature (Table 3), it depends on type of PV technology, η_m is the factor less than 1 and normally neglected and $G_{T,NOCT}$ is 800 W/m^2.

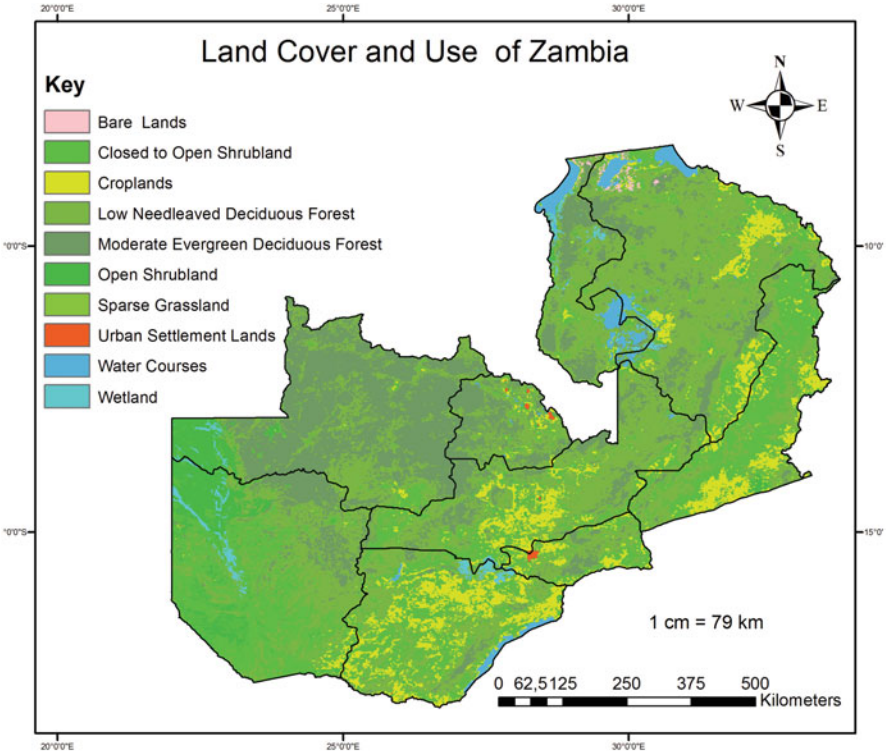


Fig. 12 Land aspects

Performance Ratio Model

Performance ratio is denoted by PR, this factor is important as it shows the overall effect of losses on the PV array's rated output power due to the PV array temperature, incomplete use of the solar irradiation, and PV system component inefficiencies or failures. It is calculated as (British Standard 1998).

$$PR_{.} = \frac{Y_F}{Y_R} = \frac{E_{AC}}{G\eta_{STC}} \quad (6)$$

where G-standard test condition solar radiance (1 kW/m^2) and η_{STC}-array efficiency at standard test condition given as.

$$\eta_{STC} = \frac{P_{PV}}{GA_{PV.A}} \quad (7)$$

where $A_{PV,A}$-Active array area (m^2) and $P_{PV,A}$- array rated power (kW_P).

Table 3 Environmental and social consideration for site selection in Zambia (ECZ 1994)

Issues	Considerations	Effect description
Ecological	(a) *Biological diversity.*	• Effect on number, diversity, breeding sites, etc. of flora and fauna • Effect on the gene pools of domesticated and wild sustainable yield
	(b) *Sustainable use including:*	• Effect of soil fertility • Breeding populations of fish and wildlife (game) • Natural regeneration of woodland and sustainable yield
	(c) *Ecosystem maintenance including:*	• Effects of proposal on food chains • Nutrient cycles • Aquifer recharge, water run-off rates, etc. • Aerial extent of habitats • Biogeographical processes
Social, economic, and cultural	• Effects of generation or reduction of employment in the area • Social cohesion or disruption (resettlement) • Immigration (including induced development when people are attracted to a development site because of possible enhanced economic opportunities) • Communication-roads opened up, closed, re-routed • Local economic impacts	
Land scope	• Views opened up or closed • Visual impacts (features, removal of vegetation, etc.) • Compatibility with surrounding areas • Amenity opened up or closed, e.g., recreation facilities	
Land use	• Effects on land uses and land potential in the project area and in the surrounding areas • Possibility of multiple use	
Water	• Effects on surface water quality and quantity • Effects on underground water quality and quantity • Effect on the flow regime the water course	
Air quality	• Effects on the quality of the ambient air of the area • Type and amount of possible emissions (pollutants)	

Capacity Factor Model

This is a model used to show the amount of energy delivered to the grid by an electric power generation system (Ayompe 2014). It is defined as the ratio of the output actual annual energy generated by PV system to the amount of energy the PV system would generate if it is operated continuously at full rated power for 8,760 hours in a year and it is expressed as (Ayompe 2014; Kynakis 2009; British Standard 1998).

$$CF_{.} = \frac{E_{AC}}{8760 \times P_{PV}} = \frac{PR \times H_t}{8760 \times P_{PV}} \tag{8}$$

where CF is capacity factor (%), E_{AC} is Actual annual energy output (kWh/year), and P_{PV} is Full rated PV power (kW_p).

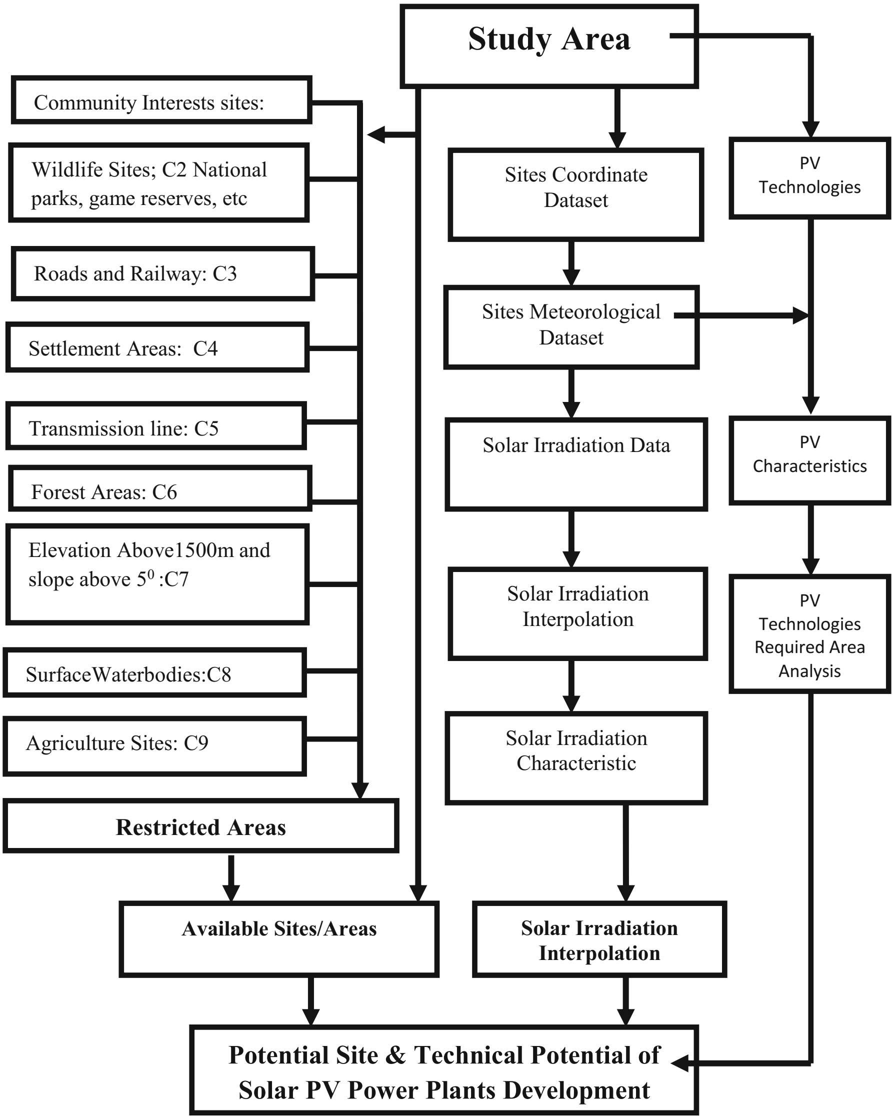


Fig. 13 Analysis Procedure

Solar Energy Potential Model

Theoretical Solar Energy Potential Model

Theoretical solar energy potential involves the assessment of the total solar energy that is received at the surface of the study area. This potential involves identifying the study area boundary and the size of the study land area, including total annual

Table 4 PV technology parameters

PV technology parameters	PV technologies					
	mc-Si	Pc-Si	a-Si	CIS	CdTe	Reference
Efficiency (%)	23	16	7–10	12.1	11.2	IRENA 2012
Temp. Coeff. β (%/^{0}C)	0.41	0.43	0.27	0.26	0.25	Suprava and Pradip 2015
Active PV area needed (m^2/kW)	7	8	15	10	11	IRENA 2012
Total PV system area needed (m^2/MW)	14,000	16,000	30,000	20,000	220,000	Estimated
NOCT (°C)	47	45	40.3	45.6	45	Suprava and Pradip 2015
Max. PV module (W)	320	320	300	120	120	IRENA 2012
BOS losses (%)	8	8	8.13	11.33	11.33	Various sources
Dust factor (%)	5	5	5	5	5	Various sources

average solar radiation magnitude. The theoretical potential has been calculated using Eq. 9:

$$E_{TH} = A_S \cdot H_P \tag{9}$$

where E_{TH} is theoretical solar energy potential (MWh/year), A_s is study area active surface area (km^2), and H_R is total annual average solar irradiance (MWh/km^2-year).

Geographical Solar Energy Potential Model

Geographical solar energy potential involves assessing the solar energy that is received on the available and suitable land area of the active surface land area of study area (Lopez 2012). Hence, the process of assessing this potential involved firstly excluding all the protected and restricted areas from the active surface area of the study area under consideration (Yan-wei 2013; Lopez 2012).

Therefore, the remaining surface land area is taken as the most suitable land area of the total study area surface land area for solar energy technologies development. In this study, the geographical solar energy potential has been estimated using Eq. 10 given below:

$$E_G = A_{AOS}.H_R. \tag{10}$$

where E_G is geographical solar energy potential (kWh/year), A_{ADS} is Available Suitable Area (m^2), and H_R is total annual average solar radiation (kWh/m^2-year).

Solar PV Technical Power Potential Model

The process of assessing the feasible solar PV technical potential, that is, the maximum power capacity that can be installed for any country without environmental and social impacts involves firstly by excluding restricted areas and areas not suitable for utility-scale PV systems development within the defined boundaries. Furthermore, considering technical characteristics of solar PV technologies (Table 3) to convert the solar energy to electrical energy, the total solar energy that is received at the surface of the solar PV module and the area required by the PV system and its supporting infrastructures. Hence, the technical solar PV potential has been estimated using Eq. 11 (Yan-wei 2013; Lopez 2012):

$$P_{TP} = \left(\frac{A_{ADS}}{A_{PVSA}}\right). = P_{PD}A_{PV} \quad (11)$$

where P_{TP} is Solar PV Power Potential (MW), A_{PVSA} is Solar PV system and Supporting Infrastructure Occupied Area per MW (km^2/MW), A_{ADS} is Available Suitable Area for Study Area (km^2), A_{PV} is total geographıcal occupied area by PV system and supporting infrastructure (km^2), and P_{PD} is solar power density of the area (MW/km^2).

Solar PV Systems Electricity Generation Technical Potential Model

The total AC electricity generated by the PV system is the sum of the electricity produced by all array in the PV power plant measured at the point where the system fed to utility grid. The total daily $E_{AC,DP}$ and monthly $E_{AC,mP}$ AC energy generated by plant are expressed as (Ali et al. 2016; Tripathi et al. 2014; Siyasankari and Babu 2015):

$$E_{AC,DP} = \sum_{t-1}^{24} E_{AC,t} \quad (12)$$

$$E_{AC,mP} = \sum_{d-1}^{N} E_{AC,DP} \quad (13)$$

where N is number of days in the month, and $E_{AC,t}$ is energy produced by PV power plant per hour (kWh).

Utility-scale photovoltaic are large-scale solar PV power plant that can be deployed within the boundaries of the country on an open space land area (Lopez 2012). Several studies have considered that the modules covers the available suitable areas on horizontal; however, the method proposed in this study seeks to consider the active area of PV arrays only and also the supporting infrastructures in the evaluation of technical potential. The process of assessing the extractable electricity generation potential from the sun for any country involves firstly by excluding areas not suitable for utility-scale PV systems within the defined boundaries, and secondly, considering technical characteristics of PV systems to convert the solar energy to electrical energy and the area required by the PV system and its supporting infrastructures. In this study the technical solar energy potential was estimated using Eq. 14 (Yan-wei 2013; Lopez 2012):

$$E_T = P_{TP}.CF.T_{TSH} \tag{14}$$

where E_T is Solar PV Electricity Generation Potential (MWh/year), P_{TP} is the technical power potential (MW), CF is Study Area Capacity factor (%), and T_{TSH} is the hours of the whole year (8,760 hours/year).

Potential Site and Electricity Generation Potential

Solar PV Potential Sites and Mapping

Figure 14 presents the map of solar PV potential suitable sites evaluated for Zambia, which indicates that the country has large land areas suitable for solar PV power plant development both at district and provincial levels. The aim of this case was focused on mapping the potential sites suitable for PV power plant installation with minimized or no environmental and social impacts. Therefore, all limiting factors considered not suitable for PV systems and those areas likely to have environmental and social issues were eliminated in the analysis using GIS spatial analysis. Hence, the Solar PV Potential Sites atlas shows that the country has the largest suitable site for solar PV power plant development in the Southern Province with Lusaka Province having the least. However, it can be observed that the available suitable areas are distributed throughout the country, hence providing opportunity for wide deployment of the solar PV technologies across the country. In addition, the atlas also shows that regions near to the national power grid contain suitable sites for easy integration of these technologies into the national energy mix and national power grid. The atlas provides essential information for sites close to villages and towns far from the grid offering opportunity for mini off-grid systems. Therefore, the atlas offers vital information for setting targets for electrification of both rural and urban areas of the country.

Available Suitable Land Area

Table 5 shows the annual average solar irradiation, total surface area and the available suitable areas for each district of Zambia. This reveals significant differences in suitable available areas within the 75 districts and 9 provinces across the country due to the availability of the aforementioned restricting factors considered in the evaluation. It can be observed that the districts in Eastern Province have lowest ratios of suitable area to surface areas in the ranges of 1.57 to 11.61% mainly due to the availability of restricting factors such as escapement, protected areas (e.g., National Parks, Zones of higher Agriculture Potential), and agriculture activities.

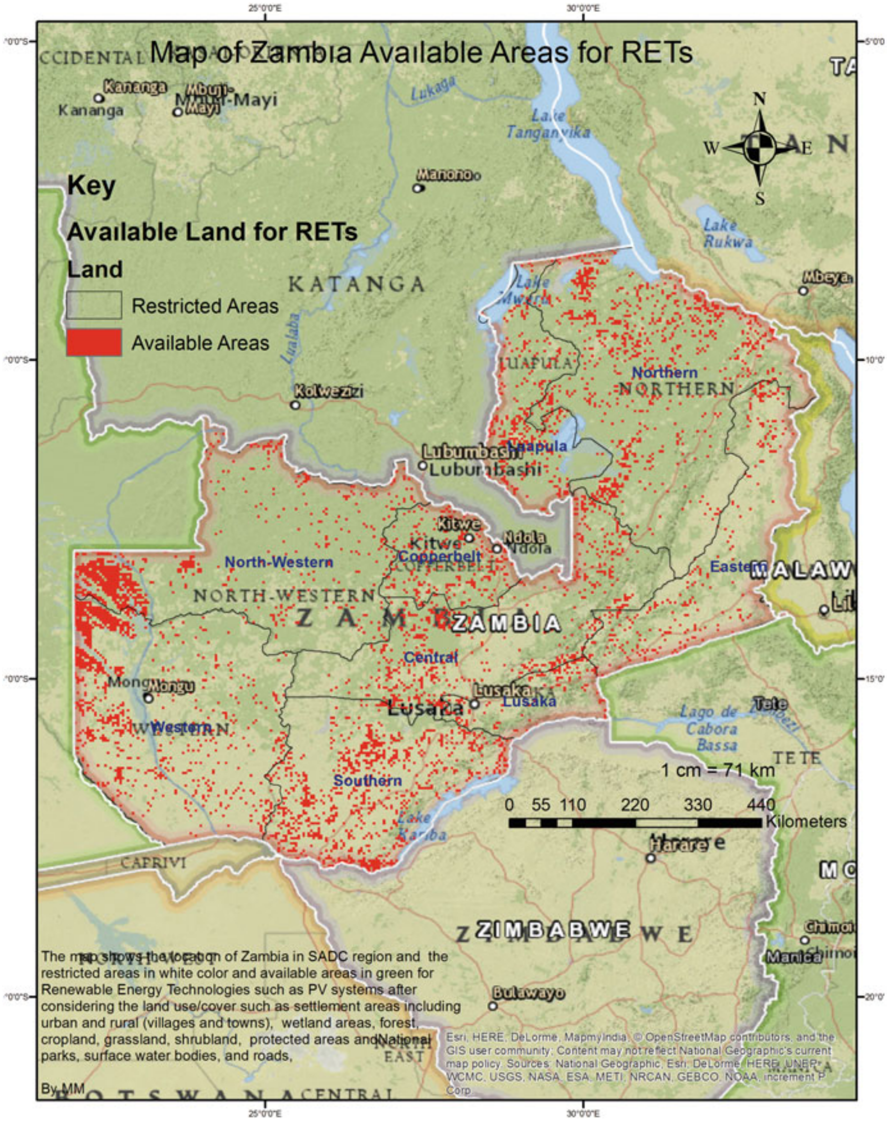


Fig. 14 Potential suitable sites for utility-scale solar PV power plant deployment

The provincial total suitable areas available for utility-scale solar photovoltaic power plants development as shown in Table 6 ranged from 2,151.70 km^2 (Lusaka) to 16,593.56 km^2 (Southern). As earlier stated, Eastern Province has the lowest annual average solar irradiation and also the overall percent suitable area (6.61%) whereas Southern Province has the largest (19.33%). However, Lusaka Province due to its size and population has the lowest overall suitable area (2,151.70 km^2) followed by Copperbelt (4,475.66 km^2) and highest being the Southern Province

Table 5 Available suitable areas in the districts of Zambia

Province	Districts	Coordinates		Annual solar irradiation	Total surface area	Percentage suitable area	Total suitable area
Eastern	Sites	S (^{0})	E (^{o})	(kWh/m^2-day)	(km^2)	(%)	(km^2)
	Chama	11.216	33.162	5.79	18,152	8.07	1,464.8664
	Chipata	13.641	32.646	5.78	6,172	1.71	105.5412
	Chadiza	14.061	32.417	5.58	2,541	4.72	119.9352
	Petauke	14.248	31.322	5.65	8,495	11.61	986.2695
	Katete	14.051	32.047	5.59	3,969	6.86	272.2734
	Lundazi	12.281	33.173	5.65	13,517	1.57	212.2169
	Nyimba	14.557	30.822	5.69	10,444	10.41	1,087.2204
	Mambwe	13.550	31.756	5.71	5,918	5.47	323.7146
Total	-	-	-	-	**69,208**	**6.61**	**4,572.0376**
Lusaka	Chongwe	15.336	28.670	5.72	11,728	11.45	1,342.856
	Kafue	15.765	28.181	5.72	5,658	10.39	587.8662
	Luangwa	15.305	30.037	5.64	4,062	5.00	203.1000
	Lusaka	15.403	28.287	5.72	447	4.00	17.8800
Total	-	-	-	-	**21,896**	**9.83**	**2,151.7022**
Southern	Choma	16.805	27.004	5.71	7,010	18.54	1,299.654
	Gwembwe	16.494	27.598	5.71	4,048	11.81	478.0688
	Itezhi-tezhi	15.734	26.054	5.83	16,310	23.78	3,878.518
	Kalomo	17.025	26.477	5.80	13,808	22.71	3,135.7968
	Kazungula	17.550	25.425	5.92	18,375	23.78	4,369.575
	Livingstone	17.843	25.840	5.92	755	12.16	91.8080
	Mazabuka	15.856	27.751	5.83	6,432	17.30	1,112.736
	Monze	16.278	27.488	5.71	4,685	14.47	677.9195
	Namwala	15.739	26.455	5.83	5,216	5.16	269.1456
	Siavonga	16.502	28.746	5.75	4,284	17.31	741.5604
	Sinazongwe	17.220	27.477	5.77	4,898	11.00	538.7800

(continued)

Table 5 (continued)

Province	Districts	Coordinates		Annual solar irradiation	Total surface area	Percentage suitable area	Total suitable area
Total	-	-	-	-	**85,823**	**19.33**	**16,593.5621**
Luapula	Chienge	8.653	29.166	5.67	3,391	5.77	195.6607
	Kawambwa	9.800	29.078	5.78	9,651	8.67	836.7417
	Mansa	11.197	28.893	5.76	10,096	23.77	2,399.8192
	Milenge	12.082	29.295	6.23	5,930	9.64	571.6520
	Mwense	10.392	28.666	5.63	6,654	11.80	785.1720
	Nchelenge	9.361	28.742	5.62	3,632	7.46	270.9472
	Samfya	11.353	29.491	5.80	11,213	8.98	1,006.9274
Total	-	-	-	-	**50,567**	**11.998**	**6,066.9202**
North Western	Chavuma	13.079	22.681	5.81	4,434	47.17	2,091.5178
	Kabompo	13.593	24.203	5.79	14,295	6.15	879.1425
	Kasempa	13.459	25.840	5.80	22,061	4.28	944.2108
	Mufumbwe	13.678	24.796	5.84	19,734	4.12	813.0408
	Mwinilunga	11.738	24.428	5.51	21,191	4.26	902.7366
	Solwezi	12.168	26.384	5.60	30,232	6.44	1,946.9408
	Zambezi	13.539	23.115	5.80	13,879	28.37	3,937.4723
Total	-	-	-	-	**125,826**	**9.15**	**11,515.0616**
Available suitable areas in the districts of Zambia							
Province	Districts	Coordinates		Solar irradiation	Total surface area	Percentage suitable area	Total suitable area
Northern	-	S(0)	E(0)	(kWh/m^2-day)	(km^2)	(%)	(km^2)
	Chinsali	10.542	32.080	5.90	14,939	4.12	615.4868
	Chilubi	11.073	30.130	6.04	5,187	3.58	185.6946
	Isoka	10.150	32.660	5.90	9,344	5.05	471.8720
	Kaputa	8.472	29.662	5.67	12,843	16.16	2,075.4288
	Kasama	10.201	31.193	5.88	10,590	10.86	1,150.0740
	Luwingu	10.250	29.916	5.73	8,721	11.96	1,043.0316

	Mbala	8.847	31.371	5.77	8,662	11.37	984.8694
	Mpika	11.824	31.440	5.83	40,025	6.38	2,553.5950
	Mporokoso	9.373	30.125	5.75	12,028	12.44	1,496.2832
	Mpulungu	8.771	31.124	5.77	10,351	7.53	779.4303
	Mungwi	9.609	32.212	5.84	10,051	8.37	841.2687
	Nakonde	9.354	32.723	5.84	4,445	18.45	820.1025
Total	-	-	-	-	**147,186**	**8.84**	**13,017.1369**
Central	Chibombo	14.703	28.106	5.80	13,298	10.50	1,396.2900
	Kabwe	14.435	28.435	5.80	1,594	5.95	94.8430
	Kapiri-Mposhi	13.955	28.674	5.80	12,120	13.11	1,588.9320
	Mkushi	13.995	29.474	5.72	22,552	8.06	1,817.6912
	Mumbwa	15.006	27.059	5.83	21,755	10.59	2,303.8545
	Serenje	13.253	30.284	5.62	23,075	12.35	2,849.7625
Total	-	-	-	-	**94,394**	**10.65**	**10,051.3732**
Copperbelt	Chililabombwe	12.353	27.834	5.70	938	15.00	140.7000
	Chingola	12.538	27.837	5.70	1,766	13.95	246.3570
	Kalulushi	12.844	28.026	5.74	1,121	16.00	179.3600
	Kitwe	12.809	28.216	5.74	889	21.67	192.6463
	Luanshya	13.152	28.413	5.80	950	16.22	154.0900
	Lufwanyama	12.678	27.279	5.70	11,316	11.05	1,250.4180
	Masaiti	13.280	28.408	5.80	3,703	19.73	730.6019
	Mpongwe	13.529	28.144	5.82	8,465	14.71	1,245.2015
	Mufulira	12.557	28.240	5.74	1,145	15.91	182.1695
	Ndola	12.980	28.628	5.74	1,035	14.89	154.1115

(continued)

Table 5 (continued)

Province	Districts	Coordinates		Annual solar irradiation	Total surface area	Percentage suitable area	Total suitable area
Total	-	-	-	–	**31,328**	**14.29**	**4,475.6557**
Western	Kalabo	14.998	22.681	5.86	18,065	23.49	4,243.4685
	Kaoma	14.817	24.807	5.85	22,099	4.90	1,082.8510
	Lukulu	14.408	23.258	5.89	15,589	21.09	3,287.7201
	Mongu	15.274	23.148	5.90	10,125	4.00	405.0000
	Senanga	16.120	23.303	5.93	15,205	9.53	1,449.0365
	Sesheke	16.747	24.549	5.91	29,423	6.97	2,050.7831
	Shang'ombo	16.317	22.264	5.92	15,880	10.09	1,602.2920
Total	-	-	-	-	**126,386**	**11.17**	**14,121.1512**

Table 6 Provincial total suitable areas for utility-scale solar photovoltaic power plants

Province	Annual solar irradiation (kWh/m^2-day)	Total area (km^2)	Suitable area (km^2)	Percent suitable area (%)
Lusaka	5.70	21,896	2,151.7022	9.82
Luapula	5.78	50,567	6,066.9202	12.00
Central	5.76	94,394	10,051.3732	10.65
Copperbelt	5.75	31,328	4,475.6557	14.29
Northern	5.83	147,186	13,017.1369	8.84
N/Western	5.74	125,826	11,515.0616	9.15
Western	5.89	126,386	14,121.1512	11.17
Southern	5.80	85,823	16,593.5621	19.33
Eastern	5.68	69,208	4,572.0376	6.61
Zambia	**5.78**	**752,614**	**82,564.6007**	**10.97**

(16,593.56 km^2) (Fig. 15a, b). In short, comparing only available suitable areas where installation of PV system is suitable, Southern province has about 7.71 times more suitable area than Lusaka Province. However, there are large differences in surface area size between the two provinces, with Lusaka having 3.92 times less surface area than Southern Province. The country has approximately 10.97% equivalent to 82,564.60 km^2 of the total suitable surface land area for development of utility-scale solar PV power plant (Table 6).

Electrical Power and Electricity Generation Potential

Table 7 shows district solar energy theoretical and geographical energy potential. Since these potentials depend on the solar irradiation and available surface area and available geographical suitable areas. Hence areas with larger surfaces and receiving the higher solar irradiation such as Northern, Western, and North-Western have the highest overall theoretical potential whereas areas with larger suitable areas such as Southern, Western, Northern, North-Western, and Central Provinces have higher geographical solar energy potential (Table 8 and Fig. 16).

The district-based solar PV technical power potential by technology (Table 9) shows that crystalline silicon based solar PV technologies possess large potential due to less land requirements for installation, with monocrystalline-silicon technology having the largest technical power potential of 5,897.46 GW whereas amorphous-silicon having the lowest potential of 2,752.16 GW due to huge land requirements. The variation in power potential per district is highly depended on the available suitable areas in each district which is as a result of local geographical and terrain features.

The provincial solar PV technical power potential per technology (Table 10 and Fig. 17) shows that Southern Province, followed by Western have the highest potential and Lusaka Province being the lowest. Figure 18 shows the comparison

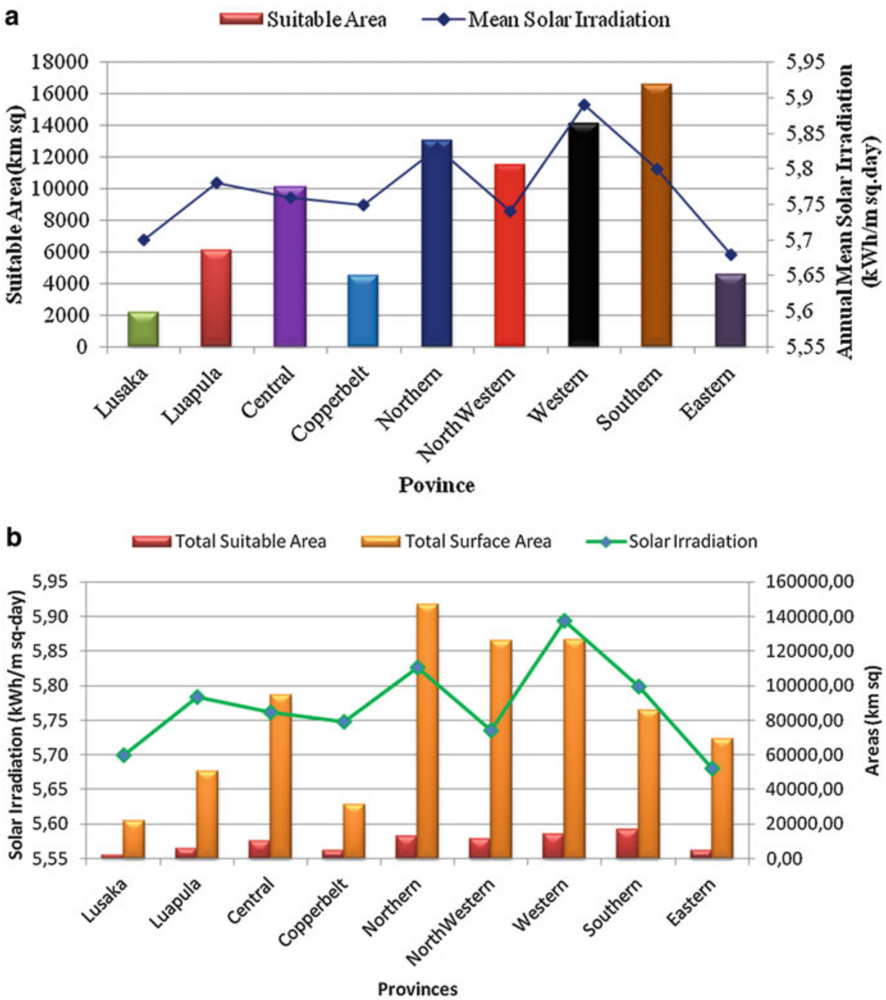


Fig. 15 (**a**) Provincial total suitable areas for utility-scale solar photovoltaic power plants. (**b**) Comparison of provincial total surface areas and suitable areas for utility-scale solar photovoltaic power plants

of solar PV technologies peak power potential for Zambia, with monocrystalline silicon having the largest whereas amorphous silicon having the lowest potential.

In absolute numbers, the highest electricity generation can be generated in the Southern, Western, Northern, North-Western, and Central Provinces due to large available suitable land areas for utility-scale solar PV system development (Table 12 and Fig. 19). Table 11 illustrates the district solar PV technical electricity generation potential by technology. Just like technical power potential it can be observed that districts with large suitable areas have the largest electricity generation potential.

Table 7 District solar energy theoretical and geographical potential

Province	Districts	Annual solar irradiation	Total surface area	Total suitable area	Theoretical potential	Geographical potential
Eastern	Sites	(kWh/m^2-day)	(km^2)	(km^2)	(TWh/year)	(TWh/year)
	Chama	5.79	18,152	1,464.8664	38,361.53	3,095.78
	Chipata	5.78	6,172	105.5412	13,021.07	222.66
	Chadiza	5.58	2,541	119.9352	5,175.25	244.27
	Petauke	5.65	8,495	986.2695	17,518.81	2033.93
	Katete	5.59	3,969	272.2734	8,098.15	555.53
	Lundazi	5.65	13,517	212.2169	27,875.43	437.64
	Nyimba	5.69	10,444	1,087.2204	21,690.62	2,257.99
	Mambwe	5.71	5,918	323.7146	12,334.00	674.67
Total			**69,208**	**4,572.0376**	**143,482.03**	**9,478.75**
Lusaka	Chongwe	5.72	11,728	1,342.856	24,485.72	2,803.61
	Kafue	5.72	5,658	587.8662	11,812.77	1,227.35
	Luangwa	5.64	4,062	203.1000	8,362.03	418.10
	Lusaka	5.72	447	17.8800	933,25	37,33
Total			**21,896**	**2,151.7022**	**45,554.63**	**4,476.62**
Southern	Choma	5.71	7,010	1,299.654	14,609.89	2,708.67
	Gwembwe	5.71	4,048	478.0688	8436,64	996.37
	Itezhi-tezhi	5.83	16,310	3,878.518	34,706.86	8,253.29
	Kalomo	5.80	13,808	3,135.7968	29,231.54	6,638.48
	Kazungula	5.92	18,375	4,369.575	39,704.70	9,441.78
	Livingstone	5.92	755	91.8080	1,631.40	198.38
	Mazabuka	5.83	6,432	1,112.736	13,686.97	2,367.85
	Monze	5.71	4,685	677.9195	9,764.24	1,412.89
	Namwala	5.83	5,216	269.1456	11,099.39	572.73
	Siavonga	5.75	4,284	741.5604	8,991.05	1,556.35
	Sinazongwe	5.77	4,898	538.7800	10,315.43	1,134.70

(continued)

Table 7 (continued)

Province	Districts	Annual solar irradiation	Total surface area	Total suitable area	Theoretical potential	Geographical potential
Total			**85,823**	**16,593.5621**	**181,630.34**	**35,117.56**
Luapula	Chienge	5.67	3,391	195.6607	7,017.84	404.93
	Kawambwa	5.78	9,651	836.7417	20,360.71	1,765.27
	Mansa	5.76	10,096	2,399.8192	21,225.83	5,045.38
	Milenge	6.23	5,930	571.6520	13,484.52	1,299.91
	Mwense	5.63	6,654	785.1720	13,673.64	1,613.49
	Nchelenge	5.62	3,632	270.9472	7,450.32	555.79
	Samfya	5.80	11,213	1,006.9274	23,737.92	2,131.67
Total			**50,567**	**6,066.9202**	**106,760.30**	**12,808.87**
North Western	Chavuma	5.81	4,434	2,091.5178	9,402.96	4,435.38
	Kabompo	5.79	14,295	879.1425	30,210.34	1,857.94
	Kasempa	5.80	22,061	944.2108	46,703.14	1,998.89
	Mufumbwe	5.84	19,734	813.0408	42,064.99	1,733.08
	Mwinilunga	5.51	21,191	902.7366	42,618.28	1,815.54
	Solwezi	5.60	30,232	1,946.9408	61,794.21	3,979.55
	Zambezi	5.80	13,879	3,937.4723	29,381.84	8,335.63
Total			**125,826**	**11,515.0616**	**263,421.22**	**24,107.19**
Province	Districts	Solar irradiation	Total surface area	Total suitable area	Theoretical potential	Geographical potential
Northern		(kWh/m^2-day)	(km^2)	(km^2)	(TWh/year)	(TWh/year)
	Chinsali	5.90	14,939	615.4868	32,171.14	1,325.45
	Chilubi	6.04	5,187	185.6946	11,435.26	409.38
	Isoka	5.90	9,344	471.8720	20,122.30	1,016.18
	Kaputa	5.67	12,843	2,075.4288	26,579.23	4,295.20
	Kasama	5.88	10,590	1,150.0740	22,728.26	2,468.29
	Luwingu	5.73	8,721	1,043.0316	18,239.54	2,181.45
	Mbala	5.77	8,662	984.8694	18,242.61	2,074.18

	Mpika	5.83	40,025	2,553.5950	85,171.20	5,433.92
	Mporokoso	5.75	12,028	1,496.2832	25,243.77	3,140.32
	Mpulungu	5.77	10,351	779.4303	21,799,72	1,641.52
	Mungwi	5.84	10,051	841.2687	21,424,71	1,793.25
	Nakonde	5.84	4,445	820.1025	9,474.96	1,748.13
Total			**147,186**	**13,017.1369**	**313,025.37**	**27,683.98**
Central	Chibombo	5.80	13,298	1,396.2900	28,151.87	2,955.95
	Kabwe	5.80	1,594	94.8430	3,374.50	200.78
	Kapiri-Mposhi	5.80	12,120	1,588.9320	25,658.04	3,363.77
	Mkushi	5.72	22,552	1,817.6912	47,084.07	3,794.98
	Mumbwa	5.83	21,755	2,303.8545	46,293.55	4,902.49
	Serenje	5.62	23,075	2,849.7625	47,333.75	5,845.72
Total			**94,394**	**10,051.3732**	**198,511.37**	**21,138.12**
Copperbelt	Chililabombwe	5.70	938	140.7000	1,951.51	292.73
	Chingola	5.70	1,766	246.3570	3,674.16	512.55
	Kalulushi	5.74	1,121	179.3600	2,348.61	375.78
	Kitwe	5.74	889	192.6463	1,862.54	403.61
	Luanshya	5.80	950	154.0900	2,011.15	326.21
	Lufwanyama	5.70	11,316	1,250.4180	23,542.94	2,601.49
	Masaiti	5.80	3,703	730.6019	7,839.25	1,546.68
	Mpongwe	5.82	8,465	1,245.2015	17,982.20	2,645.18
	Mufulira	5.74	1,145	182.1695	2,398.89	381.66
	Ndola	5.74	1,035	154.1115	2,168.43	322.88

(continued)

Table 7 (continued)

Province	Districts	Annual solar irradiation	Total surface area	Total suitable area	Theoretical potential	Geographical potential
Total			**31,328**	**4,475.6557**	**65,726.77**	**9,390.02**
Western	Kalabo	5.86	18,065	4,243.4685	38,639.23	9,076.35
	Kaoma	5.85	22,099	1,082.8510	47,186,89	2,312.16
	Lukulu	5.89	15,589	3,287.7201	33,514.01	7,068.11
	Mongu	5.90	10,125	405.0000	21,804.19	872.17
	Senanga	5.93	15,205	1,449.0365	32,910.46	3,136.37
	Sesheke	5.91	29,423	2,050.7831	63,469.82	4,423.85
	Shang'ombo	5.92	15,880	1,602.2920	34,313.50	3,462.23
Total			**126,386**	**14,121.1512**	**271,908.65**	**30,380.45**

Table 8 Provincial solar energy theoretical and geographical potential

Province	Annual average solar irradiation	Total surface area	Total suitable area	Theoretical energy potential	Geographical energy potential
	(kWh/m^2-day)	(km$^)$)	(km^2)	(TWh/year)	(TWh/year)
Lusaka	5.70	21,896.00	2,151.70	45,554.63	4,476.62
Luapula	5.78	50,567.00	6,066.92	106,760.30	12,808.87
Central	5.76	94,394.00	10,051.37	198,511.37	21,138.12
Copperbelt	5.75	31,328.00	4,475.66	65,726.77	9,390.02
Northern	5.83	147,186.00	13,017.14	313,025.37	27,683.98
Northwestern	5.74	125,826.00	11,515.06	263,421.22	24,107.19
Western	5.89	126,386.00	14,121.15	271,908.65	30,380.45
Southern	5.80	85,823.00	16,593.56	181,630.34	35,117.56
Eastern	5.68	69,208.00	45,72,0.38	143,482.03	9,478.75
Zambia	5.77	752,614.00	82,564.60	1,590,020.67	174,581.55

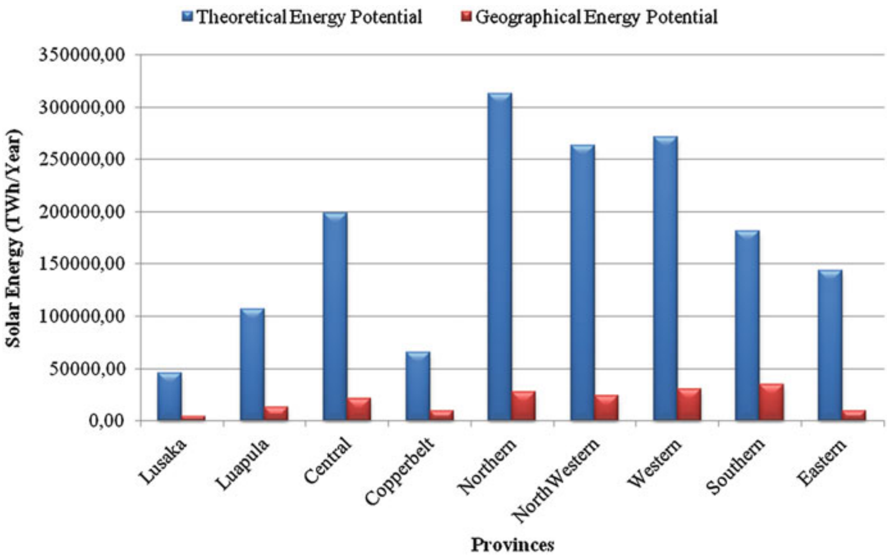


Fig. 16 Provincial solar energy theoretical and geographical potential

Table 12 and Fig. 19 show that Southern Province, followed by Western Province have the highest potential while Lusaka province has the lowest potential for electricity generation from solar PV based technologies due to aforementioned issues. Figure 20 shows a comparison of the provincial theoretical and geographical solar energy potential and the technical solar electricity potential. It is worth noting that due to technical characteristic of the solar cell technologies and land requirements the technical solar electricity generation potential is lower as compared to the solar energy received on these potential sites. Hence, this presents the need to select

Table 9 District solar PV technical power potential by technology

Province	Districts	Technical power potential (GW)				
		mc-Si	pc-Si	a-Si	CIS	CdTe
Eastern	Chama	104.63	91.55	48.83	73.24	66.58
	Chipata	7.54	6.60	3.52	5.28	4.80
	Chadiza	8.57	7.50	4.00	6.00	5.45
	Petauke	70.45	61.64	32.88	49.31	44.83
	Katete	19.45	17.02	9.08	13.61	12.38
	Lundazi	15.16	13.26	7.07	10.61	9.65
	Nyimba	77.66	67.95	36.24	54.36	49.42
	Mambwe	23.12	20.23	10.79	16.19	14.71
Total	-	**326.57**	**285.75**	**152.40**	**228.60**	**207.82**
Lusaka	Chongwe	95.92	83.93	44.76	67.14	61.04
	Kafue	41.99	36.74	19.60	29.39	26.72
	Luangwa	14.51	12.69	6.77	10.16	9.23
	Lusaka	1.28	1.12	0.60	0.89	0.81
Total	-	**153.69**	**134.48**	**71.72**	**107.59**	**97.80**
Southern	Choma	92.83	81.23	43.32	64.98	59.08
	Gwembwe	34.15	29.88	15.94	23.90	21.73
	Itezhi-tezhi	277.04	242.41	129.28	193.93	176.30
	Kalomo	223.99	195.99	104.53	156.79	142.54
	Kazungula	312.11	273.10	145.65	218.48	198.62
	Livingstone	6.56	5.74	3.06	4.59	4.17
	Mazabuka	79.48	69.55	37.09	55.64	50.58
	Monze	48.42	42.37	22.60	33.90	30.81
	Namwala	19.22	16.82	8.97	13.46	12.23
	Siavonga	52.97	46.35	24.72	37.08	33.71
	Sinazongwe	38.48	33.67	17.96	26.94	24.49
Total	-	**1,185.25**	**1,037.10**	**553.12**	**829.68**	**754.25**
Luapula	Chienge	13.98	12.23	6.52	9.78	8.89
	Kawambwa	59.77	52.30	27.89	41.84	38.03
	Mansa	171.42	149.99	79.99	119.99	109.08
	Milenge	40.83	35.73	19.06	28.58	25.98
	Mwense	56.08	49.07	26.17	39.26	35.69
	Nchelenge	19.35	16.93	9.03	13.55	12.32
	Samfya	71.92	62.93	33.56	50.35	45.77
Total	-	**433.35**	**379.18**	**202.23**	**303.35**	**275.77**
North Western	Chavuma	149.39	130.72	69.72	104.58	95.07
	Kabompo	62.80	54.95	29.30	43.96	39.96
	Kasempa	67.44	59.01	31.47	47.21	42.92
	Mufumbwe	58.07	50.82	27.10	40.65	36.96
	Mwinilunga	64.48	56.42	30.09	45.14	41.03
	Solwezi	139.07	121.68	64.90	97.35	88.50
	Zambezi	281.25	246.09	131.25	196.87	178.98
Total	-	**822.50**	**719.69**	**383.84**	**575.75**	**523.41**

(continued)

Table 9 (continued)

Province	Districts	Technical power potential (GW)				
		mc-Si	pc-Si	a-Si	CIS	CdTe
Province	Districts	Technical power potential (GW)				
		Mc-Si	Pc-Si	a-Si	CIS	CdTe
Northern	Chinsali	43.96	38.47	20.52	30.77	27.98
	Chilubi	13.26	11.61	6.19	9.28	8.44
	Isoka	33.71	29.49	15.73	23.59	21.45
	Kaputa	148.24	129.71	69.18	103.77	94.34
	Kasama	82.15	71.88	38.34	57.50	52.28
	Luwingu	74.50	65.19	34.77	52.15	47.41
	Mbala	70.35	61.55	32.83	49.24	44.77
	Mpika	182.40	159.60	85.12	127.68	116.07
	Mporokoso	106.88	93.52	49.88	74.81	68.01
	Mpulungu	55.67	48.71	25.98	38.97	35.43
	Mungwi	60.09	52.58	28.04	42.06	38.24
	Nakonde	58.58	51.26	27.34	41.01	37.28
Total	**-**	**929.80**	**813.57**	**433.90**	**650.86**	**591.69**
Central	Chibombo	99.74	87.27	46.54	69.81	63.47
	Kabwe	6.77	5.93	3.16	4.74	4.31
	Kapiri-Mposhi	113.50	99.31	52.96	79.45	72.22
	Mkushi	129.84	113.61	60.59	90.88	82.62
	Mumbwa	164.56	143.99	76.80	115.19	104.72
	Serenje	203.55	178.11	94.99	142.49	129.53
Total	**-**	**717.96**	**628.21**	**335.05**	**502.57**	**456.88**
Copperbelt	Chililabombwe	10.05	8.79	4.69	7.04	6.40
	Chingola	17.60	15.40	8.21	12.32	11.20
	Kalulushi	12.81	11.21	5.98	8.97	8.15
	Kitwe	13.76	12.04	6.42	9.63	8.76
	Luanshya	11.01	9.63	5.14	7.70	7.00
	Lufwanyama	89.32	78.15	41.68	62.52	56.84
	Masaiti	52.19	45.66	24.35	36.53	33.21
	Mpongwe	88.94	77.83	41.51	62.26	56.60
	Mufulira	13.01	11.39	6.07	9.11	8.28
	Ndola	11.01	9.63	5.14	7.71	7.01
Total	**-**	**319.69**	**279.73**	**149.19**	**223.78**	**203.44**
Western	Kalabo	303.10	265.22	141.45	212.17	192.88
	Kaoma	77.35	67.68	36.10	54.14	49.22
	Lukulu	234.84	205.48	109.59	164.39	149.44
	Mongu	28.93	25.31	13.50	20.25	18.41
	Senanga	103.50	90.56	48.30	72.45	65.87
	Sesheke	146.48	128.17	68.36	102.54	93.22
	Shang'ombo	114.45	100.14	53.41	80.11	72.83
Total	**-**	**1,008.65**	**882.57**	**470.71**	**706.06**	**641.87**

Table 10 Provincial solar PV technical power potential per technology

Province	Technical Power Potential (GW)				
	mc-Si	pc-Si	a-Si	CIS	CdTe
Lusaka	153.69	134.48	71.72	107.59	97.80
Luapula	433.35	379.18	202.23	303.35	275.77
Central	717.96	628.21	335.05	502.57	456.88
Copperbelt	319.69	279.73	149.19	223.78	203.44
Northern	929.80	813.57	433.90	650.86	591.69
North-Western	822.50	719.69	383.84	575.75	523.41
Western	1,008.65	882.57	470.71	706.06	641.87
Southern	1,185.25	1,037.10	553.12	829.68	754.25
Eastern	326.57	285.75	152.40	228.60	207.82
Zambia	**5,897.46**	**5,160.28**	**2,752.16**	**4,128.24**	**3,752.93**

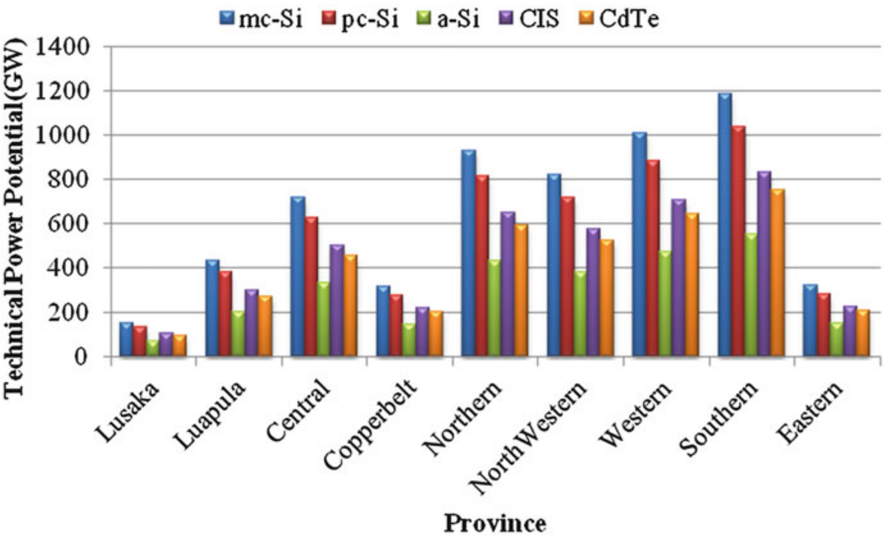


Fig. 17 Provincial solar PV technical power potential per technology

suitable solar cell technology for application in the solar energy harvesting systems for optimal solar energy utilization.

Figure 21 shows the comparison of solar PV technologies for electricity generation potential for Zambia considering the available suitable areas and the technology characteristics. İt is observed that monocrystalline provides the highest electricity generation potential followed by polycrystalline and least amorphous. This is mainly due to the differences in amount of land area requirements for the same peak power and the ability of the technology to convert the solar energy into electrical energy (efficiency).

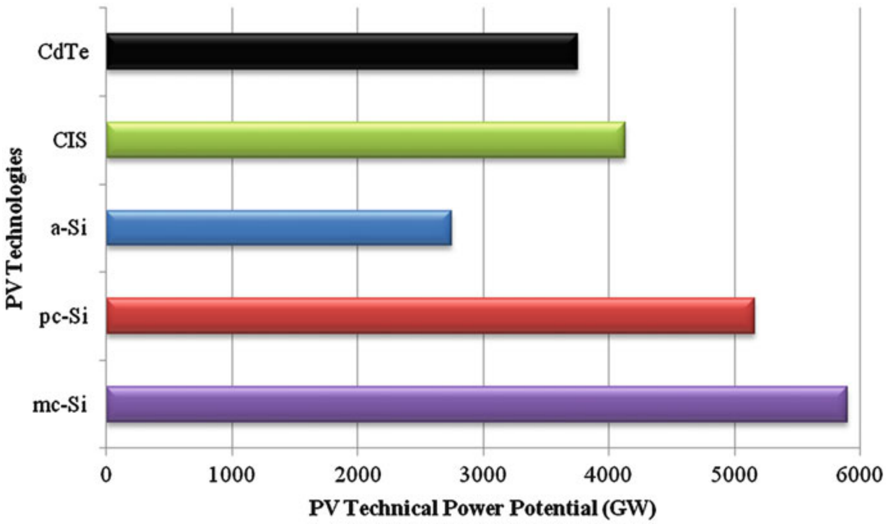
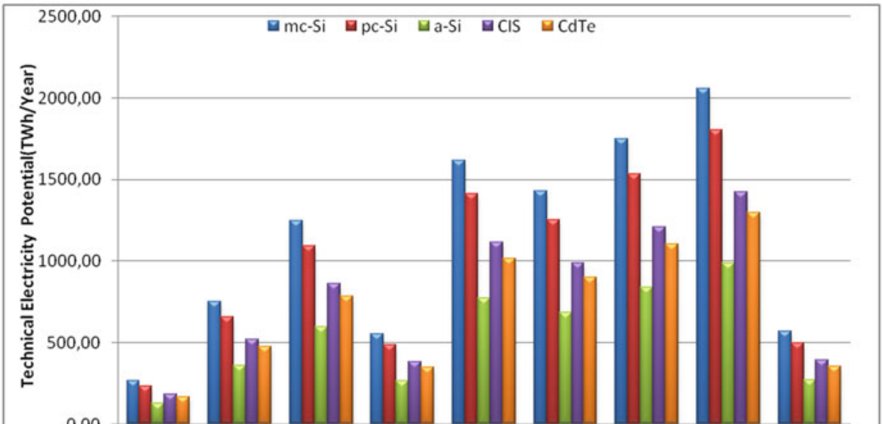


Fig. 18 Comparison of solar PV technical power potential per technology of Zambia



	Lusaka	Luapula	Central	Copperbelt	Northern	NorthWestern	Western	Southern	Eastern
mc-Si	266,88	752,50	1246,70	555,13	1614,55	1428,25	1751,49	2058,15	567,08
pc-Si	233,86	659,39	1092,45	486,44	1414,79	1251,53	1534,78	1803,50	496,92
a-Si	128,19	361,43	598,80	266,63	775,49	686,00	841,26	988,55	272,38
CIS	184,50	520,20	861,85	383,76	1116,14	987,35	1210,81	1422,80	392,03
CdTe	168,09	473,94	785,20	349,63	1016,89	899,54	1103,13	1296,27	357,16

Fig. 19 Provincial solar PV technical electricity generation potential

Table 11 District solar PV technical electricity generation potential by technology

Province	Districts sites	Technical electricity generation potential (TWh/Year) Solar PV technologies mc-Si	pc-Si	a-Si	CIS	CdTe
Eastern	Chama	181.69	159.21	87.27	125.60	114.43
	Chipata	13.09	11.47	6.29	9.05	8.24
	Chadiza	14.88	13.04	7.15	10.28	9.37
	Petauke	122.33	107.19	58.76	84.57	77.05
	Katete	33.77	29.59	16.22	23.35	21.27
	Lundazi	26.32	23.07	12.64	18.20	16.58
	Nyimba	134.85	118.17	64.77	93.22	84.93
	Mambwe	40.15	35.18	19.29	27.76	25.29
Total	-	**567.08**	**496.92**	**272.38**	**392.03**	**357.16**
Lusaka	Chongwe	166.56	145.95	80.00	115.14	104.90
	Kafue	72.91	63.89	35.02	50.41	45.92
	Luangwa	25.19	22.07	12.10	17.41	15.87
	Lusaka	2.22	1.94	1.07	1.53	1.40
Total	-	**266.88**	**233.86**	**128.19**	**184.50**	**168.09**
Southern	Choma	161.20	141.25	77.43	111.44	101.53
	Gwembwe	59.30	51.96	28.48	40.99	37.35
	Itezhi-tezhi	481.06	421.54	231.06	332.56	302.99
	Kalomo	388.94	340.82	186.81	268.88	244.97
	Kazungula	541.97	474.91	260.31	374.67	341.35
	Livingstone	11.39	9.98	5.47	7.87	7.17
	Mazabuka	138.02	120.94	66.29	95.41	86.93
	Monze	84.08	73.68	40.39	58.13	52.96
	Namwala	33.38	29.25	16.03	23.08	21.03
	Siavonga	91.98	80.60	44.18	63.58	57.93
	Sinazongwe	66.83	58.56	32.10	46.20	42.09
Total	-	**2,058.15**	**1,803.50**	**988.55**	**1,422.80**	**1,296.27**
Luapula	Chienge	24.27	21.27	11.66	16.78	15.28
	Kawambwa	103.78	90.94	49.85	71.75	65.37
	Mansa	297.66	260.83	142.97	205.77	187.47
	Milenge	70.90	62.13	34.06	49.02	44.66
	Mwense	97.39	85.34	46.78	67.32	61.34
	Nchelenge	33.61	29.45	16.14	23.23	21.17
	Samfya	124.89	109.44	59.99	86.34	78.66
Total	-	**752.50**	**659.39**	**361.43**	**520.20**	**473.94**
Northwestern	Chavuma	259.42	227.32	124.60	179.34	163.39
	Kabompo	109.04	95.55	52.37	75.38	68.68
	Kasempa	117.11	102.62	56.25	80.96	73.76
	Mufumbwe	100.84	88.37	48.44	69.71	63.51
	Mwinilunga	111.97	98.12	53.78	77.40	70.52
	Solwezi	241.48	211.61	115.99	166.94	152.09
	Zambezi	488.38	427.95	234.57	337.62	307.59
Total	-	**1,428.25**	**1,251.53**	**686.00**	**987.35**	**899.54**

(continued)

Table 11 (continued)

Province	Districts sites	Technical electricity generation potential (TWh/Year) Solar PV technologies mc-Si	pc-Si	a-Si	CIS	CdTe
Northern	Chinsali	76.34	66.90	36.67	52.77	48.08
	Chilubi	23.03	20.18	11.06	15.92	14.51
	Isoka	58.53	51.29	28.11	40.46	36.86
	Kaputa	257.42	225.57	123.64	177.96	162.13
	Kasama	142.65	125.00	68.51	98.61	89.84
	Luwingu	129.37	113.36	62.14	89.43	81.48
	Mbala	122.116	107.04	58.67	84.45	76.94
	Mpika	316.173	277.54	152.13	218.96	199.48
	Mporokoso	1851.59	162.63	89.14	128.30	116.89
	Mpulungu	96.168	84.71	46.43	66.83	60.89
	Mungwi	104.35	91.43	50.12	72.13	65.72
	Nakonde	101.72	89.13	48.86	70.32	64.07
Total	-	**1,614.55**	**1,414.79**	**775.49**	**1,116.14**	**1,016.89**
Province	Districts	Technical electricity generation potential (TWh/year)				
		Solar PV technologies				
	Sites	Mc-Si	Pc-Si	a-Si	CIS	CdTe
Central	Chibombo	173.19	151.76	83.18	119.72	109.08
	Kabwe	11.76	10.31	5.65	8.13	7.41
	Kapiri-Mposhi	197.08	172.70	94.66	136.24	124.13
	Mkushi	225.45	197.56	108.29	155.86	142.00
	Mumbwa	285.75	250.40	137.25	197.54	179.97
	Serenje	353.46	309.73	169.77	244.35	222.62
Total	-	**1,246.70**	**1,092.45**	**598.80**	**861.85**	**785.20**
Copperbelt	Chililabombwe	17.45	15.29	8.38	12.06	10.99
	Chingola	30.56	26.78	14.68	21.12	19.25
	Kalulushi	22.25	19.49	10.69	15.38	14.01
	Kitwe	23.89	20.94	11.48	16.52	15.05
	Luanshya	19.11	16.75	9.18	13.21	12.04
	Lufwanyama	155.09	135.90	74.49	107.22	97.68
	Masaiti	90.62	79.41	43.53	62.64	57.07
	Mpongwe	154.45	135.34	74.18	106.77	97.27
	Mufulira	22.60	19.80	10.85	15.62	14.23
	Ndola	19.11	16.75	9.18	13.21	12.04
Total	-	**555.13**	**486.44**	**266.63**	**383.76**	**349.63**
Western	Kalabo	526.33	461.21	252.80	363.85	331.50
	Kaoma	134.31	117.69	64.51	92.85	84.59
	Lukulu	407.79	357.33	195.86	281.90	256.83
	Mongu	50.23	44.02	24.13	34.73	31.64
	Senanga	179.73	157.49	86.33	124.25	113.20
	Sesheke	254.36	222.89	122.17	175.84	160.21
	Shang'ombo	198.74	174.15	95.46	137.39	125.17
	-	**1,751.49**	**1,534.78**	**841.26**	**1,210.81**	**1,103.13**
Zambia	-	**10,240.73**	**8,973.66**	**4,918.72**	**7,079.44**	**6,449.86**

Table 12 Provincial solar PV technical electricity generation potential by technology

	Technical Electricity Generation Potential (TWh/Year)				
	Solar PV technologies				
Provinces	mc-Si	pc-Si	a-Si	CIS	CdTe
Lusaka	266.88	233.86	128.19	184.50	168.09
Luapula	752.50	659.39	361.43	520.20	473.94
Central	1,246.70	1,092.45	598.80	861.85	785.20
Copperbelt	555.13	486.44	266.63	383.76	349.63
Northern	1,614.55	1,414.79	775.49	1,116.14	1,016.89
Northwestern	1,428.25	1,251.53	686.00	987.35	899.54
Western	1,751.49	1,534.78	841.26	1,210.81	1,103.13
Southern	2,058.15	1,803.50	988.55	1,422.80	1,296.27
Eastern	567.08	496.92	272.38	392.03	357.16
Zambia	**10,240.73**	**8,973.66**	**4,918.72**	**7,079.44**	**6,449.86**

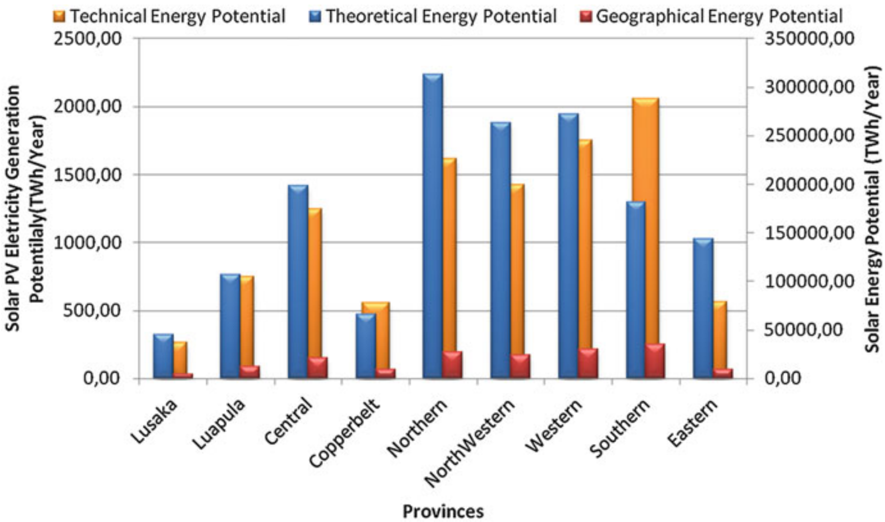


Fig. 20 Comparison of theoretical, geographical, and technical solar energy potential

While Zambia has abundance suitable areas (Fig. 14) and almost evenly distributed sunlight (Figs. 1 and 2) across the country, the focus on surface and suitable areas in the nine provinces and solar irradiation levels, the following can be identified. These factors however should be considered in the planning of national energy mix and also for management of electricity in the national grid once the penetration of solar PV technologies increases and becomes a significant part in the national electricity generation.

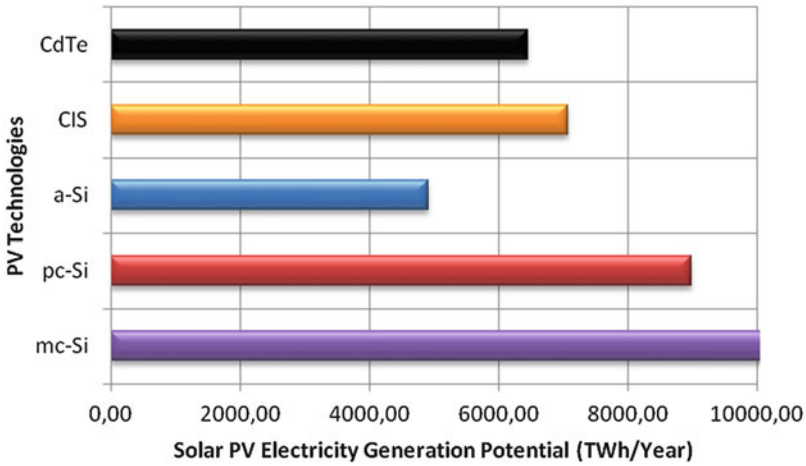


Fig. 21 Comparison of solar PV cell technologies electricity generation potential

- The highest theoretical solar energy potential is in Northern Province (313,025.37TWh/year) due to large surface areas of the province.
- However, the highest geographical and technical solar energy potential for solar electricity generation is in Southern Province (35,117.56TWh/year) due to large available suitable areas.
- From highest yield point of view, due to abundance of sunlight received by Western province (5.89kWh/m^2-day), the annual yields per installed solar PV systems peak are expected in Western province as compared to the rest of the country.
- Comparing the PV technologies, large electricity generation differences can be observed not only at district level but also at provincial levels. Table 13 indicates crystalline silicon based PV technologies have higher electricity generation potential as compared to thin film per square kilometer.

Table 13 summarizes the estimated solar PV technical electricity generation and solar PV power capacity potential in Zambia for each nine (9) provinces investigated in this chapter.

Conclusion

This chapter provides an approach for identifying and mapping the potential sites for sustainable development of solar PV technologies based power plants using GIS spatial analysis. The chapter has integrated the geographical and technological factors as well as the Laws of Zambia on environmental protection and pollution control legislative framework for evaluating the electricity generation potential and feasible sites suitable for sustainable PV systems deployment across Zambia.

Table 13 National solar PV technical electricity generation potential

Provinces	Annual average solar irradiation (kWh/m^2-day)	Total surface area (km^2)	Total suitable area (km^2)	Theoretical energy potential (TWh/Year)	Geographical energy potential (TWh/year)	Technical Power Potential (GWp) – Solar PV technologies: mc-Si	pc-Si	a-Si	CIS	CdTe	Technical electricity generation potential (TWh/Year) – Solar PV technologies: mc-Si	pc-Si	a-Si	CIS	CdTe
Lusaka	5.70	21,896	2,152.70	45,554.63	4,476.62	153.69	134.48	71.72	107.59	97.80	266.88	233.86	128.19	184.50	168.09
Luapula	5.78	50,567	6,066.92	106,760.30	12,808.87	433.35	379.18	202.23	303.35	275.77	752.50	659.39	361.43	520.20	473.94
Central	5.76	94,394	10,051.37	198,511.37	21,138.12	717.96	628.21	335.05	502.57	456.88	1,246.70	1,092.45	598.80	861.85	785.20
Copperbelt	5.75	31,328	4,475.66	65,726.77	9,390.02	319.69	279.73	149.19	223.78	203.44	555.13	486.44	266.63	383.76	349.63
Northern	5.83	147,186	13,017.14	313,025.37	27,683.98	929.80	813.57	433.90	650.86	591.69	1,614.55	1,414.79	775.49	1,116.14	1,016.89
Northwestern	5.74	125,826	11,515.06	263,421.22	24,107.19	822.50	719.69	383.84	575.75	523.41	1,428.25	1,251.53	686.00	987.35	899.54
Western	5.89	126,386	14,121.15	271,908.65	30,380.45	1,008.65	882.57	470.71	706.06	641.87	1,751.49	1,534.78	841.26	1,210.81	1,103.13
Southern	5.80	85,823	16,593.56	181,630.34	35,117.56	1,185.25	1,037.10	553.12	829.68	754.25	2,058.15	1,803.50	988.55	1,422.80	1,296.27
Eastern	5.68	69,208	4,572.038	143,482.03	9,478.75	326.57	285.75	152.40	228.60	207.82	567.08	496.92	272.38	392.03	357.16
Zambia	**5.77**	**752,614**	**82,564.60**	**1,590,020.67**	**174,581.55**	**5,897.46**	**5,160.28**	**2,752.16**	**4,128.24**	**3,752.93**	**10,240.73**	**8,973.66**	**4,918.72**	**7,079.44**	**6,449.86**

Thus, this chapter shows that Zambia has vast available solar energy technical potential for PV electricity generation. The larger PV electricity generation potential variability at district and provincial level is highly linked with the local geographical features and terrain which affect the availability of suitable area and also local solar energy resource. Therefore, integration and generation of electricity from PV systems has greater potential to mitigate the current energy shortage and increase access to energy for all in Zambia. Furthermore, the suitable land areas in almost all districts and provinces is large enough for solar energy harvesting at utility-scale PV system capable of covering the present and future total electricity demands for Zambia. The identified potential sites have a total of available suitable area of 82,564.601 km^2 representing 10.97% of Zambia's total surface area equivalent to 5,897.46 GW technical power potential. This translates to 10,240.73TWh/year electricity generation potential considering annual average solar irradiation of 5.78 kWh/m^2-day and monocrystalline silicon solar PV technology mounted at optimal tilt angle. This potential has capacity to reduce CO_2 emission and contribute to achieve energy access for all and Sustainable Development Goals (SDGs).

The identification of potential sites and solar energy potential analysis will help improve the understanding of the potential solar energy, and PV technology can contribute to achieving sustainable national energy mix and increasing energy access for all in Zambia. Furthermore, it will help the government in setting up tangible energy targets and effective integration of solar PV systems into national energy mix. Hence, it is hoped that the suitability map established and the technical potential evaluated will help guide the decision makers and also the investors for planning future electricity generation targets and investment across the country and achieve the 2030 development goals.

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