NAGESSO BEKER HADJI

EVALUATION OF SOLAR ENERGY POTENTIAL IN ETHIOPIA AS POWER GENERATION SOURCE: A CASE STUDY AT 100 SELECTED CITIES

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
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In Partial Fulfilment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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Approval of Director of Graduate School of Applied Sciences

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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To my parents and myself…

ABSTRACT

Ethiopian energy sector development is at a very low level. The largest share of the population dwells in rural areas using kerosene for lighting and solid bioenergy for cooking and heating facing indoor air pollution. This study evaluates grid-connected solar energy potential using two simulation software PVGIS and PVWatt. The first three scenarios examine household roof-parallel PV system with an installed capacity of 1kW, 3kW and 5kW and the fourth scenario consider a 45kW PV power plant. The study investigates the capacity factor using PVGIS software is much greater than PVWatt. Ethiopian annual solar radiation ranges from 1730kWh/m^2 in Chencha city to 2481kWh/m^2 in Asaita city. The annual PV energy was found to be 1686.579 kWh, 5059.95 kWh, and 83832 kWh respectively. Capacity factor and annual PV energy for 45 kW is 19.14% and 75447kWh respectively. Additionally, an economic feasibility study was conducted using RETScreen depending on the living standard of the household and 100 locations in Ethiopia were selected for the study. The average annual energy production cost is 0.167$/kWh and a maximum payback period of the roof-parallel systems is 6 year while for a 45kW system the average cost is 0.186$/kWh and a maximum payback period of 18 years. The study will help both government and actors investing in rural energy development.

Keywords: Roof-parallel PV system; power plant; grid-connected; clean energy; Ethiopia, economic analysis

ÖZET

Etiyopya enerji sektörü gelişimi çok düşük düzeydedir. Nüfusun en büyük payı, kırsal alanlarda, aydınlatma için gazyağı ve iç mekan hava kirliliğine bakan yemek pişirmek ve ısıtmak için katı biyoenerji kullanarak yaşamaktadır. Bu çalışma iki simülasyon yazılımı PVGIS ve PVWatt kullanarak şebekeye bağlı güneş enerjisi potansiyelini değerlendirmektedir. Sistemin finansal analizi, RETScreen adlı bir simülasyon yazılımı kullanılarak yapıldı. Çalışma için hanehalkının yaşam standardına bağlı olarak dört senaryo ve Etiyopya'da 100 yerleşim yeri seçilmiştir. İlk üç senaryo, 1kW, 3kW ve 5kW kurulu kapasiteye sahip ev tipi çatı paralel PV sistemini inceler ve dördüncü senaryo 45kW PV santralini göz önünde bulundurur. Çalışma PVGIS yazılımı kullanan kapasite faktörünü PVWatt'tan çok daha fazla araştırıyor. Etiyopya yıllık güneş ışınımı Chencha kentinde 1730kWh / m2'den Asaita kentinde 2481kWh / m2'ye kadar değişmektedir. Yıllık PV enerjisi sırasıyla 1686.579 kWh, 5059.95 kWh ve 83832 kWh olarak bulunmuştur. Kapasite faktörü ve yıllık 45 kW için PV enerjisi sırasıyla% 19.14 ve 75447kWh'dir. Ek olarak, her şehirdeki her senaryo için ekonomik bir fizibilite çalışması düşünülmüştür. Yıllık ortalama enerji üretim maliyeti 0,167 $ / kWh ve çatı paralel sistemlerin maksimum geri ödeme süresi 6 yıldır, 45kW sistem için ortalama maliyet 0,188 $ / kWh ve maksimum geri ödeme süresi 18 yıldır. Çalışma hem hükümete hem de kırsal enerji gelişimine yatırım yapan aktörlere yardımcı olacaktır.

Anahtar Kelimeler: *Çatı-paralel PV sistemi*; enerji santrali; şebekeye bağlı; temiz enerji; Etiyopya, ekonomik analiz

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LIST OF ABBREVIATIONS

DIF:	Diffuse Horizontal Irradiation
DNI:	Direct Normal Irradiation
EEPCo:	Ethiopian Electric Power Corporation
FT	Feet
GEOS:	Goddard Earth Observing System
GHI:	Global Horizontal Irradiation
GMAO:	Global Modelling and Analysis Office
GTI:	Global Tilted Irradiation
GW:	Giga Watt
GWh:	Giga Watt hour
KW:	Kilo Watt
KWh:	Kilo Watt hour
KWp:	Kilo Watt power
MW:	Mega Watt
MWh:	Mega Watt hour
NASA:	National Aeronautics and Space Administration
NRCan:	Natural Resources Canada
NREL:	National Renewable Energy Laboratory
PV:	Photovoltaic
PVGIS:	Photovoltaic Geographical Information System
PVOUT:	Photovoltaic Electricity Output
SEE:	Space Environments and Effects
SWERA:	Solar and Wind Energy Assessment Resource program
TW:	Terra Watt
TWh:	Terra Watt hour

CHAPTER 1
INTRODUCTION

1.1 Background

Energy fosters economic growth and essential in human welfare (Tucho, Weesie, & Nonhebel, 2014). Worlds demand for energy is raising prodigiously due to rapid growth in population, economic development and industrial evolution (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018). Energy resources are categorized into Nuclear, Fossil fuel, and Renewable energy sources. Fossil fuels cover the majority of the world's energy sources. However, fossil fuels are an exhaustible type of non-renewable energy source, which has a negative environmental effect and are the causes of global warming (Adams & Nsiah, 2019). To meet these rising energy demand and to bypass the energy crises in the future it is very important to consider different clean, environmentally friendly and renewable Energy sources (Kannan & Vakeesan, 2016).

Renewable energy is a non-pollutant environmentally friendly energy source that replaces itself by nature (Gorjian, 2018; Herzog, Lipman, & Kammen, 2001). Renewable energy can be categorized as traditional and modern or new. Traditional renewable energies are large-scale hydropower and traditional biomass, whereas the modern ones are small-scale hydro-power, solar, wind, geothermal, biomass and ocean energy. Renewable energy sources are eco-friendly and clean. Challenges that arise from environment and energy demand can be fulfilled by the most common and promising renewable energy sources. However, solar energy sources are the most promising energy option for the future world (Kannan & Vakeesan, 2016).

Solar energy is an abundant, inexhaustible and freely available source of energy derived from the sun (Kannan & Vakeesan, 2016). Solar energy reaches the earth in the form of heat and light. This is a likely energy source in the world because exploitation does not affect the ecosystem, it is non-exhaustible and provides an increased output efficiencies compared to the other types of energy sources (Stutenbäumer, Negash, & Abdi, 1999).

Theoretically, it is claimed that if technologies for harvesting and supplying were efficient and readily available solar energy can satisfy the world's energy demand (Blaschke, Biberacher, Gadocha, & Schardinger, 2012).

Solar energy is harnessed by using different technologies (Kabir et al., 2018). This technologies can be grouped into two. First, technologies that convert sunlight to electricity and second, technologies that convert sunlight to heat. Photovoltaic (PV) solar energy technology is the most common sunlight to electricity conversion technology used for present estimation of solar energy (Kabir et al., 2018). This Photovoltaic technology has the largest output from lower input.

The adoption of solar technologies would substantially mitigate and alleviate problems related with electricity security, Unemployment, climate change. For example, in California, USA 696,544 metric tons of CO2 emissions have been reduced by installing 113,533 household photovoltaic systems (Kabir et al., 2018). Approximately 40% of the world's population energy source is dependent on solid fuels such as fuelwood, animal dung, charcoal, plant residue, and coal (FDRE, 2012). The majority of this type of energy source in rural areas of Latin America, Asia, and Africa is used for lightning and direct heating where the access to clean, modern and affordable energy sources are limited. Different researches show that indoor air pollution produced by this practice is responsible for premature deaths an also responsible for world's climate change (Downward et al., 2018; Fullerton, Bruce, & Gordon, 2008; "Indoor Air Pollution in Developing Countries and Acute Respiratory Infection in Children," 1989). The World health organization report in 2014 shows that household air pollution from inefficient use of solid fuel is the main causes for premature deaths of four million people and more in 2012.

1.2 Electricity in Ethiopia

Ethiopia is located in the tropical zone lying above the equator and below the tropic of cancer where renewable energy sources like solar, thermal and wind energy sources are available with high potential (Ethiopian Economics Association, 2007). Unfortunately, the country shows a negligible amount of exploiting the opportunity.

Ethiopian modern power generation for electricity at a glance level almost all depend on hydropower (van der Zwaan, Boccalon, & Dalla Longa, 2018).The power generated from these hydropower plants is estimated to be 45 GW. The Grand Ethiopian Renaissance Dam under construction with the installed capacity of 6000MW is the largest hydropower plant in the country (Kebede, 2015). Other than hydropower the country endowed with the most common renewable energy sources with an estimated potential of 10 GW of wind and 5 GW of geothermal where solar radiation ranges from 4.5 kWh//m2 day to 7.5 kWh/day (Ethiopian Economics Association, 2007). Even though, the majority of the population remains un-electrified (Tessema, Mainali, & Silveira, 2014). Among others, the solar energy potential of the country has got little attention, and poor efforts of exploitation of this potential have been done. Adoption of solar photovoltaic (PV) technologies remained so sluggish and only a few studies have attempted to assess the renewable energy potentials of Ethiopia (Teferra, 1986).

Around 80% of the population in the country lives in the rural areas without access to grid electricity and uses biomass energy sources (fuelwood, animal dung, charcoal, plant residues) for cooking and kerosene for lightening at the national level (Gabisa & Gheewala, 2018). In 2016 around 96% of the population in Ethiopia were affected by household air pollution. Nearly 98% of households in rural areas use biomass as the main energy source for cooking and heating (Gezahegn, Gebregiorgis, Gebrehiwet, & Tesfamariam, 2018). Different gas emissions like hydrocarbons, carbon dioxide, and particulate matter are produced from in-efficient burning of biomass fuel and particulate matter (Mondal, Bryan, Ringler, Mekonnen, & Rosegrant, 2018).

Energy has a substantial effect on the country's economic and social development (Teferra, 2002). The electricity demand raises by 11.5 % per year. In 2006 it was 2,400 GWh and 11,000 GWh will be expected in 2020 (Ethiopian Economics Association, 2007). As the economy of the country increases the energy demand also increases significantly and this will cause the country's energy scarcity due to the energy sector's low growth (Mondal et al., 2018).

1.3 Administrative Division

Ethiopia is a land-locked country in eastern Africa (Horn of Africa) covering a total area of 1,104,300 km2 and has a mean elevation of 1,330m above sea level with geographic coordinates of 8 00 N latitude and 38 00E longitudes. Ethiopia is a home for about 108,386,391 (July 2018 est.) of the population ("The world fact book," n.d.). The country is divided into 9 regional states namely Somali, Gambela, Afar, Benishangul gumuz, Amhara, Southern nations, nationalities and people (SNNP), Oromiya, Tigray, and Harari as shown in Figure 1.1. These regional states are further subdivided into weredas and kebele. The country has two administrative states, Addis Ababa city administrative and Dire Dawa city council (DPADM, 2004; Proposed New Ethiopian Government Administrative Boundary System for Unified Nation Building, 2018).

Figure 1.1: Administrative divisions of Ethiopia

1.4 Aim of the Study

The aim of the study was to evaluate solar energy potential as a power generation and financial feasibility for selected locations in rural areas of the country. The objective of this paper was to identify the strategy that minimizes the critical factors that affect energy sector development issues like:

- Heavy economic burden on oil fuel imports
- Consumption biomass energy at high level and its environmental and health effect
- Shortage of electricity generation capacity
- Low level of access to electricity supply
- Inefficient energy utilization in all sectors
- Low growth in the renewable power industry in addition to the growth of large-scale hydropower

1.5 Thesis Outline

In this section contents of the thesis were briefly described

- **Chapter 1:** gave an introduction and background about world's energy situation, development of renewable energy sources and solar energy potential. This section also describes electricity problem, demand and consumption in Ethiopia. It also described the aim of the thesis and administrative division of regions in Ethiopia.
- **Chapter2:** described different literatures so far done on solar energy assessment and technologies. It also described important literatures on Ethiopian solar potential and its applications.
- **Chapter 3:** described about selected locations, methodology and scenarios used in the study.
- **Chapter 4:** presented the result and discussion of the analysis
- **Chapter 5:** described conclusion and recommendations based on the findings

CHAPTER 2
LITERATURE REVIEW

2.1 Ethiopian Energy Sector

Ethiopian energy sector with the growing economy and energy demand have faced two major problems of highly dependent on biomass fuels and access to modern energy resources are limited (Tessema et al., 2014). Ethiopian power generation is dependent almost entirely on hydropower. The majority portion of the population (i.e. 83%) inhabit in rural areas of the country without access to electricity. In the urban areas, the access to electricity is 87% whereas in the rural side only 5% of the population has access to electricity. The energy source in the areas without access to electricity (i.e, mostly in the rural area) is highly dependent on poor biomass energy sources for cooking and lighting (Kebede & Mitsufuji, 2014). Ethiopian per capita electricity consumption has increased from 23kwh in 2000 to 70kwh in 2014. To provide electricity access by 2025, the nation is initiating a domestic electrification program called ‘’ Light to all’’. The government of Ethiopia aimed at improving economic development at an annual rate of over 10%. The electricity supply must increase by 14 percent or more per year to accomplish this objective (Ethiopian Economics Association, 2007).

2.2 Ethiopian Energy Consumption by Fuel Types

This chapter reviewed various types of gas consumed by Ethiopia based on data from various literature sources, Ethiopian Electric Power Corporation (EEPCo) and Ethiopian Ministry of Water and Energy. EEPCo owns, produces and distributes electricity in Ethiopia.

2.2.1 Biomass

The vast majority of the population of Ethiopia (i.e., around 80%) dwells in the rural area without access to grid electricity and uses traditional energy sources such as Biomass fuels (firewood, animal dung, and agricultural residues) at the national level which accounts 334TWh out of 365TWh of the total primary energy consumption per year (Tucho et al., 2014).

In 2016 around 96% of the population in Ethiopia were exposed to household air pollution from an in-efficient burning of biomass fuels and results in the premature death of infants. CO_2 emission in Ethiopia is increasing from 0.06 tons in 2005 to 0.19 tons in 20014 per capita basis (Ethiopian Economics Association, 2007).

2.2.2 Petroleum

Ethiopian petroleum consumption is 100% imported since the country is non-oil producing. In 2009, domestic oil consumption was 25TWh. Out of this 81% is used in the transportation sector, 13% in the residential sector and 6% in the industrial sector. Kerosene is used by 64% of the rural and 8% of the rural population for lightning and 0.2% of the rural and 5% of the urban population for cooking.

2.2.3 Electricity

Ethiopian electricity production is almost all depends on renewable energy sources. The electricity sector accounts for only 2% of the overall primary energy consumption. The main consumers of these fuel type are industry and households. Wind, hydro and geothermal are the main energy sources of electricity (Tucho et al., 2014).

A. Hydropower

Ethiopian electricity generation is almost entirely dependent on a hydropower energy source with an estimated potential of 45GW (van der Zwaan et al., 2018). From the overall estimated potential about 2GW of hydropower is in operation (Tucho et al., 2014). EEPCo is developing large scale hydroelectric projects including the new under-construction mega project which is anticipated to be the largest output from all hydropower projects with the installed capacity of 6000MW (Kebede, 2015). One of the drawbacks of this source of energy is during drought time (Ethiopian Economics Association, 2007). When the dam is lack of enough water mostly from April to June there is power- cut.

B. Solar energy

Ethiopia has estimated solar radiation ranges between 4.5kwh/m^2/day to 7.5kwh/m^2/day. Solar energy in the country is not yet exploited and as some research papers and data shows only 150,000 solar home systems are scheduled for implementation in rural areas and organizations (Bekele & Palm, 2010).

2.3 Recent Studies on Solar Energy Potential and Application in Ethiopia

An investigation conducted on the feasibility of a 5MW grid-connected solar photovoltaic system of 35 places across Ethiopia (Kebede, 2015). The study considers only the capital city Addis Ababa for the feasibility study and the rest locations were selected to show the capacity of grid-connected farms across the country. RETScreen software was used to analyse and compare the potential of selected locations. The study used NASA's worldwide database on solar radiation. For each location, the researcher used a fixed slope facing south and zero azimuth angle was assumed for all locations. The study showed that Tepi has a minimum grid electrical feed (7730.8MWh / year) and that Debre-Tabor has the largest annual output of electricity (9331.2MWh). The study concluded that Ethiopian solar energy capacity for on-grid and off-grid potential consumption is very high and the detailed feasibility study in Addis Ababa shows that the investment on the system is financially viable but still not appealing to business investors.

A study conducted using a logit model of analysis to assess the factors that affect the implementation of solar energy technology in Ethiopia. The analysis was conducted in two kebeles found in Weliso town, in central Ethiopia and these locations were considering the lack of connection the power grid, the accessibility of solar energy and the drop in the price of the technology (Guta et al., 2017). Households live in this location use kerosene for lighting and solid bioenergy sources which causes indoor air pollution that led to health risk and environmental impact. To come up with this problem introducing renewable energies, especially solar energy source is the more likely way. Research results indicate that well-educated and rich families are more likely to adopt solar technologies.The outcome also illustrates that households that are headed by women adopt technology than households that are headed by men. The outcome states that the adoption of photovoltaic technology will also increase as the country's economy rises. The finding of the research showed the direction to the government and non-government organizations working in the rural energy access to address solution towards the energy access problem of the area.

A study conducted by Mahmud et al., (2014) in Geba catchment of northern Ethiopia (i.e,) has undertaken using a different measurement at the selected sites of the area that include Dera, Hagereselam, Mayderu and Mekele University campus. Pyranometer sensor was used to measure solar irradiance and global radiation. Measurement was conducted from 2010 and the analysis was for 1 year from June 2011 to May 2012. The highest value (>6.5kwh/m^2/day) of average daily solar radiation was recorded in February where the lowest average daily solar radiation was measured in July. The finding of the study showed that Geba catchment has the substantial potential of average horizontal solar radiation of 5.59kwh/m^2/day and this potential could be an alternative energy source for the rural population.

A study aimed at the techno-economic analysis of electrifying a district called Werder with a hybrid renewable energy system. The district is located in the Somali region of Ethiopia far from the national grid and extension is not economically feasible. The study considers different hybrid energy alternatives PV/wind/diesel hybrid system has been considered and to calculate the technical and economic feasibility of the systems HOMER simulation software was applied. The hybrid system was regarded to be based on lower annual diesel consumption, lower unmet load, high renewable penetration, lower capacity shortages, and low Levelized energy costs. The findings showed that PV/wind/diesel generator hybrid power systems are feasible (Tesema, 2015) .

A survey aimed at investigating issues affecting the spread of solar technology in Ethiopia using the Innovation System Framework to investigate the variables. The findings indicate that the critical variables for the slow pace of diffusion are the absence of inclusion between the solar actors and the economic issue that both parties of the supply chain are facing (Kebede & Mitsufuji, 2014).

In addition to this study, a report by Ethiopian ministry of water and energy in 2012 showed that some most important constraints of energy development in Ethiopia included a low level of socio-economic and infrastructure development, insufficient assessment of biomass energy resources and technologies, lack of information and under-developed rural energy markets.

A study aimed at investigating the possibility of electricity supply from the solar-wind hybrid system to households dwelling far away from the electricity grid in Ethiopia. Wind and solar energy potential for the selected four locations were assessed and the results were taken from previous studies of the author. Feasibility study concentrating on the supply of electricity generated from the hybrid system to 200 families was carried out using a simulation tool called HOMMER. The findings from the feasibility study showed that the most cost-effective system was the generator-battery-convertor setup with $201,609 net present cost. The finding also recommended that if the hybrid system was implemented it would benefit the country through minimizing deforestation, improving the quality of life in the area and others (Bekele & Palm, 2010).

A study conducted on testing the economics, performance and potential of a small-scale photovoltaic system in Addis Ababa Ethiopia. Climate datas were collected from the stations located in the rift valley. The finding showed that implementation of the small-scale photovoltaic systems are cost-effective for Ethiopia (Stutenbäumer et al., 1999).

A brief study was conducted on different renewable energies (i.e solar, wind and hydro) potential for large-scale and standalone application and energy consumption in Ethiopia. Solar energy potential assessment was carried out in 19 selected locations based on annual solar radiation and land resource data from FAO statistics. The findings showed that there is a large difference between the urban and the rural energy consumption and the energy share in the country is composed of biomass, petroleum, and electricity where biomass accounts for the leading share. The findings also showed that the country has a huge amount of exploitable electricity potential of 0.2PWh from hydroelectric, 4PWh from wind energy and 7.5PWh from solar energy. The finding also showed that biomass energy was the most dominant energy source in Ethiopia (Tucho et al., 2014).

A study aimed at designing a hybrid power generation system for Ethiopian remote area was conducted by Bekelea & Boneya, (2012). The hybrid system was comprised of Photovoltaic arrays, wind turbines, and diesel generator with battery banks and power condition units for a standalone system. The datas were gathered from the National Meteorological Agency (NMA) for the years 2003 up to 2005 and analysed using HOMMER simulation tool. The finding showed that huge utilizable solar energy potential was available at the site. The findings also showed that there were several alternatives of feasible hybrid systems with different levels of renewable energy sources by changing the net present cost for each setup.

Some of the researches conducted on the application of solar energy; solar energy application using a solar box cooker (Weldu et al., 2019). Solar powered heat storage for Injera (i.e, the national food of Ethiopia) baking (Tesfay, Kahsay, & Nydal, 2014).

CHAPTER 3
METHODOLOGY

3.1 Material and Method

In this chapter financial analysis and the solar energy potential in the selected 100 cities throughout the country was analysed. The analysis was based on 3 simulation software and four scenarios. Figure 3.1 shows the flow chart that describes the analysis procedure.

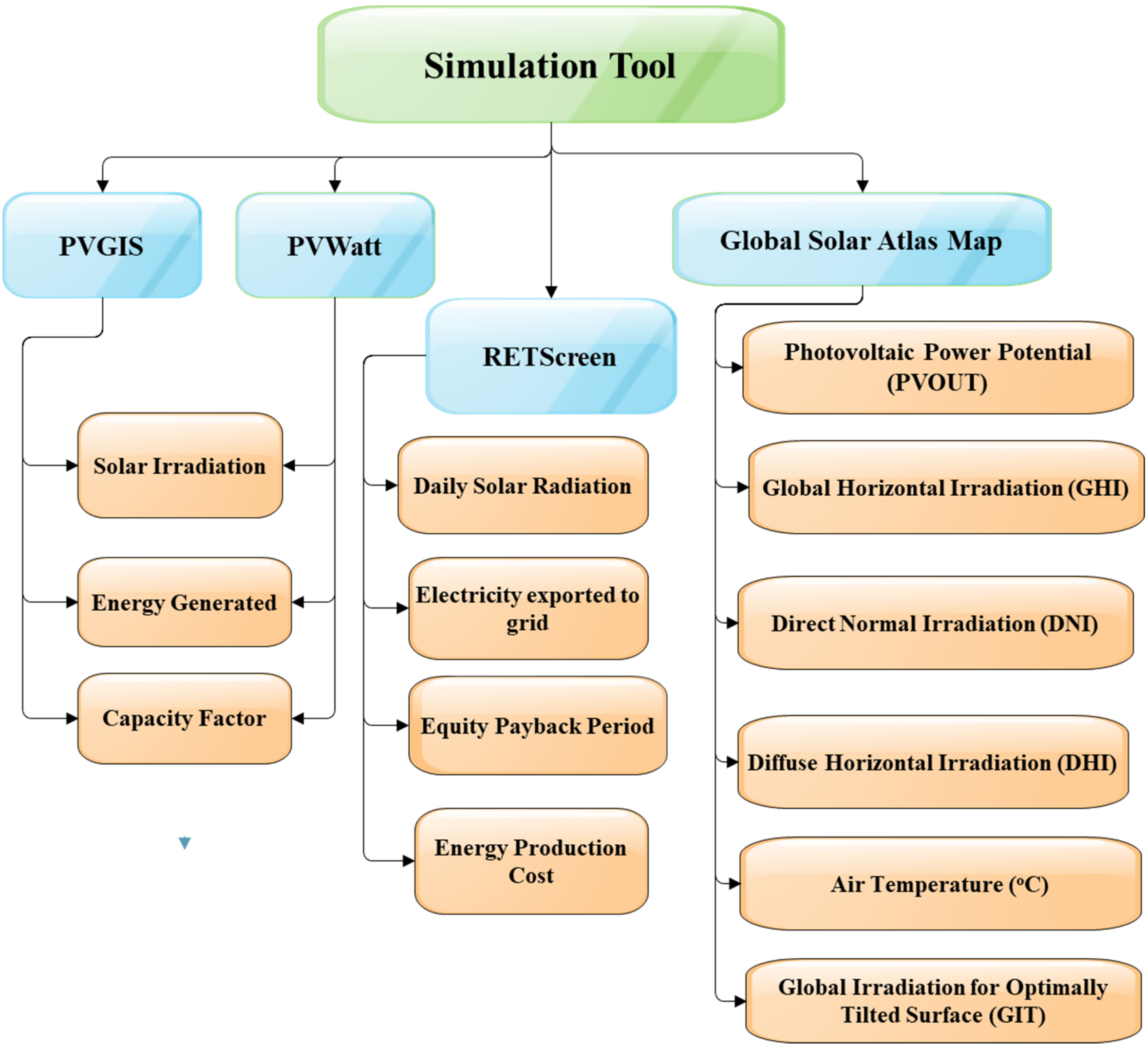


Figure 3.1: Flowchart describing analysis of study

3.2 Scenarios

In this study four scenarios in the selected locations were considered. This scenarios were considered based on household PV system and as a power plant.

A. First Scenario

A roof parallel solar PV system with 1kW installed capacity and system cost of 1430 USD were considered in this scenario. There were three mono-crystalline fixed mounting modules with an area of 100ft^2.

Table 3.1: A 1kW solar PV system for a household

First System	
Installed power	1 kWp
Installation type	Roof Parallel
Type of modules	Mono Crystalline, Efficiency 14.9%
No. of Module (340 Wp)	3 Module
Mounting system	Fixed mounting, free standing
1 Panel dimension	Length – 6.2 ft, width – 3.2 ft
Space required	100 ft^2
Life	25 years
Cost of the system	1430USD

B. Second Scenario

A roof parallel solar PV system with 3 kW installed capacity and system cost of 3932USD were considered in this scenario. There were nine mono-crystalline fixed mounting modules with an area of 300ft^2.

Table 3.2: A 3 kW solar PV system for a household

Second System	
Installed power	3 kWp
Installation type	Roof Parallel
Type of modules	Mono Crystalline, Efficiency 14.9%
No. of Module (340 Wp)	9 Module
Mounting system	Fixed mounting, free standing
1 Panel dimension	Length – 6.2 ft, width – 3.2 ft
Space required	300 ft^2
Life	25 years
Cost of the system	3932USD

C. Third Scenario

A roof parallel solar PV system with 5 kW installed capacity and system cost of 6792 USD were considered in this scenario. There were fifteen mono-crystalline fixed mounting modules with an area of 500ft^2.

Table 3.3: A 5 kW solar PV system for a household

Third System	
Installed power	5 kWp
Installation type	Roof Parallel
Type of modules	Mono Crystalline, Efficiency 14.9%
No. of Module (340 Wp)	15 Module
Mounting system	Fixed mounting, free standing
1 Panel dimension	Length – 6.2 ft, width – 3.2 ft
Space required	500 ft^2
Life	25 years
Cost of the system	6792 USD

D. Fourth Scenario

A solar farm with 45 kW installed capacity and system cost of 145357 USD were considered in this scenario. There were 150 mono-crystalline fixed mounting modules with an area of 4500ft^2. The analysis has gone through the evaluation of solar energy potential and financial analysis in the selected locations.

Table 3.4: A 45 kW PV system description

Forth System	
Installed power	45 kWp
Installation type	Power Plant
Type of modules	Mono Crystalline, Efficiency 14.9%
No. of Module (340 Wp)	150 Module
Mounting system	Fixed mounting, free standing
1 Panel dimension	Length – 6.2 ft, width – 3.2 ft
Space required	4500 ft^2
Life	25 years
Cost of the system	145357 USD

3.3 Feasibility Study

A clean energy management software called RETScreen was applied for the feasibility analysis of the PV system considered in all scenarios. The equity payback period and the cost of energy generation for each location were determined in this study. Some financial parameters considered in the study were tabulated in Table 3.5.

Table 3.5: Financial considerations for the PV system

Financial Parameters	**Value**
Inflation rate	8%
Discount rate	6%
Reinvestment rate	18%
Project life	25 Years
Electricity export escalation rate	5%

3.4 Global Solar Atlas

Global solar atlas is provided by International Finance Corporation and World Bank. Solar resource information on maps offers an excellent opportunity for site exploration and pre-assessment of solar energy potential in different countries and areas. It also provides an online simulation tool and different map layers ("Global Solar Atlas," n.d.). This Atlas offers average annual long-term solar resource and PV potential values defined below.

- **Global Horizontal Irradiation (GHI):** is the quantity of solar irradiation that falls horizontally on the surface of the earth. It is the sum of standard direct irradiance and horizontal diffusive irradiation. As a measuring instrument, a pyranometer is used.
- **Direct Normal Irradiation** (**DNI):** is a part of directly reaching the surface of the solar radiation. It's often measured by absolute cavity radiometer and pyrheliometer.
- **Diffuse Horizontal Irradiation** (**DIF**): is the earth's irradiance of a horizontal surface dispersed or diffused by the atmosphere. As a measuring instrument, a pyranometer is used.
- **Global Tilted Irradiation** (**GTI**): is the quantity of solar irradiation that falls on a tilted photovoltaic surface. It is the sum of standard direct irradiance and horizontal diffusive irradiation. The inclined surface also gets a tiny quantity of ground-reflected solar radiation compared to the horizontal surface.

- **PV Electricity output (**PVOUT**):** is the quantity of energy, converted via a PV system into electricity [kWh / kWp] to be produced in accordance with the geographical circumstances of the site and the PV system setup.
- **Air Temperature (**TEMP**):** The air temperature [^{O}C or ^{O}F] determines the temperature of PV cells and modules and has a direct impact on the efficiency of PV energy conversion and consequent loss of energy. A significant aspect of each solar energy project evaluation is air temperature and some other meteorological parameters as they determine the solar power plant's working circumstances and operating efficiency.

3.5 Selected Cities

Ethiopia is divided in regions zones and districts (Divisions, 2017). Accessibility of data, low attention paid to the country's solar energy potential, and poor efforts to exploit this potential are some of the site selection factors. Among others, Adoption of solar photovoltaic (PV) technologies remained so sluggish and only few studies have attempted to assess the renewable energy potentials of Ethiopia. Traditional use of biomass fuels in this areas is very high, which is the cause of both health and environmental impacts. Geographical location and elevation of selected cities is tabulated in Table 3.6 and presented in Figure 3.3. In this study PVGIS and PVWatt software's were used to analyse and compare the solar potential of the selected locations and RETScreen was used to analyse the financial feasibility of the proposed systems in each site.

Table 3.6: Geographical locations and elevation of selected cities

City	Latitude	Longitude	Elevation (m)	City	Latitude	Longitude	Elevation (m)
Abiy Adi	14.442	39.080	1856	Gore	8.344	36.087	2042
Adaba	7.006	39.394	2420	Gorgora	12.257	37.260	1819
Addis Alem	10.817	37.055	2364	Goro	6.991	40.480	1062
Addis Zemen	12.125	37.778	1942	Gouder	8.977	37.766	2355
Adet	11.233	39.383	2211	Harbu	10.923	39.785	2464
Adwa	14.165	38.895	1885	Haromaya	9.395	42.013	1146
Agarfa	7.269	39.823	2469	Hossa'ina	7.548	37.855	1652
Agaro	7.857	36.590	1685	Humera	14.288	36.609	603
Alaba	7.388	38.029	1963	Huruta	8.183	39.283	2008
Alamat'a	12.418	39.558	1864	Hyke	11.313	39.677	1864
Alem Ketema	10.057	38.987	2242	Injibara	10.959	36.935	1820
Aleta Wondo	6.603	38.422	1921	jinka	5.786	36.565	1676
Ankober	9.591	39.734	2887	kemise	10.716	39.867	1864
Asaita	11.565	41.439	355	Konso	5.340	37.442	1652
Azezo	12.549	37.427	2070	Lailibela	12.036	39.046	1864
Babile	9.226	42.332	1649	Logiya	11.723	40.976	1864
Bati	11.192	40.020	1640	Maychew	12.784	39.540	2432
Bedele	8.456	36.353	2018	Mechara	8.600	40.324	1062
Berhale	13.863	40.022	1864	Meki	8.152	38.821	2355
Bichena	10.452	38.202	2538	Mendi	9.800	35.100	1661
Boditi	6.950	37.857	1652	Metehara	8.903	39.918	1062
Bonga	7.265	36.248	1712	Metema	12.958	36.153	718
Burie	10.717	37.062	2066	Metu	8.301	35.581	1725
Butajira	8.117	38.381	2355	Mieso	9.233	40.755	1062
Chelenko	9.397	41.560	2172	Mille	11.350	39.633	1864
Chencha	6.251	37.573	2704	Mojo	9.767	36.667	1780

Table 3.6 Continued

City	Latitude	Longitude	Elevation (m)	City	Latitude	Longitude	Elevation (m)
Dhera	8.334	39.318	1062	Sodo	6.864	37.763	2026
Chiro	10.953	39.231	1779	Mota	11.081	37.881	2433
Dabat	13.017	37.767	2581	Moyale	7.504	36.070	1951
Dalocha	7.790	38.246	1956	Nejo	9.505	35.502	1676
DebreMarkos	10.340	37.729	2420	Nekemte	9.088	36.547	1676
Debre Tabor	11.857	38.008	2669	sekota	12.626	39.035	2250
Debre Werk	6.867	35.517	2500	Sendafa	9.156	39.024	2355
Dejen	10.164	38.150	2470	Shakiso	5.775	38.903	1652
Delgi	12.196	37.051	1807	Shambu	9.566	37.100	2476
Dembi	8.081	36.463	1931	Sheno	9.316	38.272	2355
Deneba	9.762	39.192	2680	Shire	14.102	38.283	1921
Dil Yibza	13.115	38.441	3236	Sokoru	7.926	37.418	1922
Dinsho	7.108	39.780	1652	Tefki	8.848	38.499	2075
Dodola	6.975	39.181	2477	Tenta	11.317	39.250	2915
Durame	7.244	37.905	1652	Tulu Milki	9.908	38.347	2578
Fiche	9.772	38.739	2355	Weldiya	11.829	39.596	1864
Finote Selam	10.680	37.261	1864	Weliso	8.539	37.976	2043
Gasera	7.368	40.199	2369	Welkite	8.286	37.782	1676
Gelemso	8.813	40.522	1818	Wereta	11.924	37.696	1858
Gewane	10.159	40.662	1864	Wonji	8.407	39.272	1062
Ghimbi	9.172	35.838	1922	Wukro	13.787	39.603	2005
Gidole	5.650	37.367	1652	Yabelo	4.893	38.095	1097
Goba	7.007	39.969	2710	Yirga Alem	6.747	38.405	1768
Gololcha	9.545	41.768	1649	Ziway	7.929	38.719	1649

Figure 3.2: Geographical location of selected cities on Ethiopian map

3.6 Simulation Analysis

3.6.1 PVGIS

PVGIS (Photovoltaic Geographical Information System) is a freely available web-based calculation tool with bulky and comprehensive database that is comparatively simple to use and accurate (Huld, Müller, & Gambardella, 2012). The software was developed by the European Commission to predict solar power generation of a photovoltaic technologies for stand-alone or grid-connected PV (Sharma, Verma, & Sing, 2014). PVGIS provides enormous and precise solar radiation free database (Paper & Sciences, 2014). The software was applied to estimate stand-alone photovoltaic installations output.

PVGIS software was used in targeted locations to analyse and compare the grid connected solar PV energy potential. Solar radiation database, crystalline PV technology, 14% system loss and a fixed free standing mounting option were considered for different scenarios ("PVGIS (Photovoltaic Geographical Information System)," n.d.). The key steps involved in the software are given bellow.

Step 1

Start with http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html for online simulation and enter the location name.

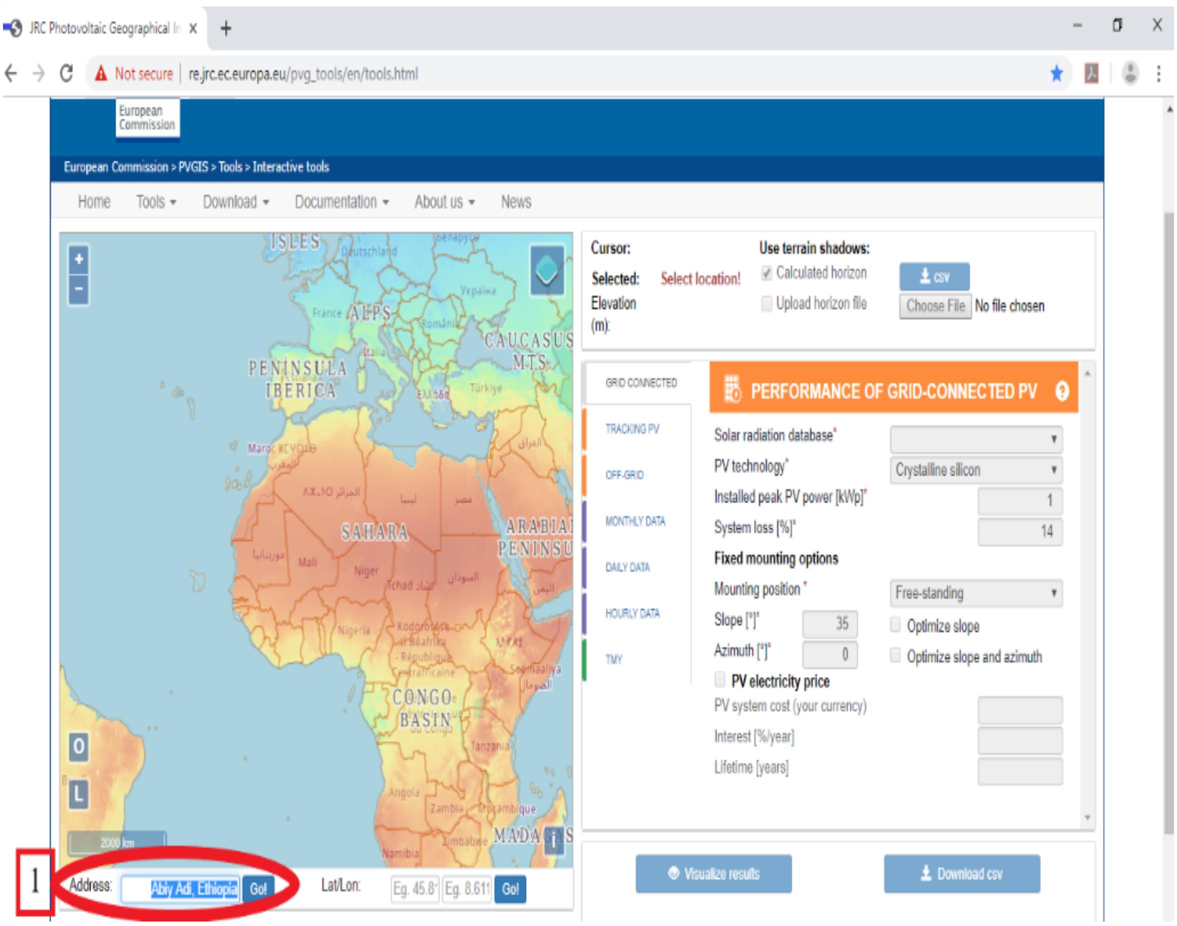


Figure 3.3: PVGIS Software interactive tool page

Step 2

Select the solar radiation database (PVGIS-CMASAF used by default), PV technology, installed peak PV power in kW, system loss (14% by default) and fill the fixed mounting options as your system.

Step 3

Click on ''visualize results'' to see the system output

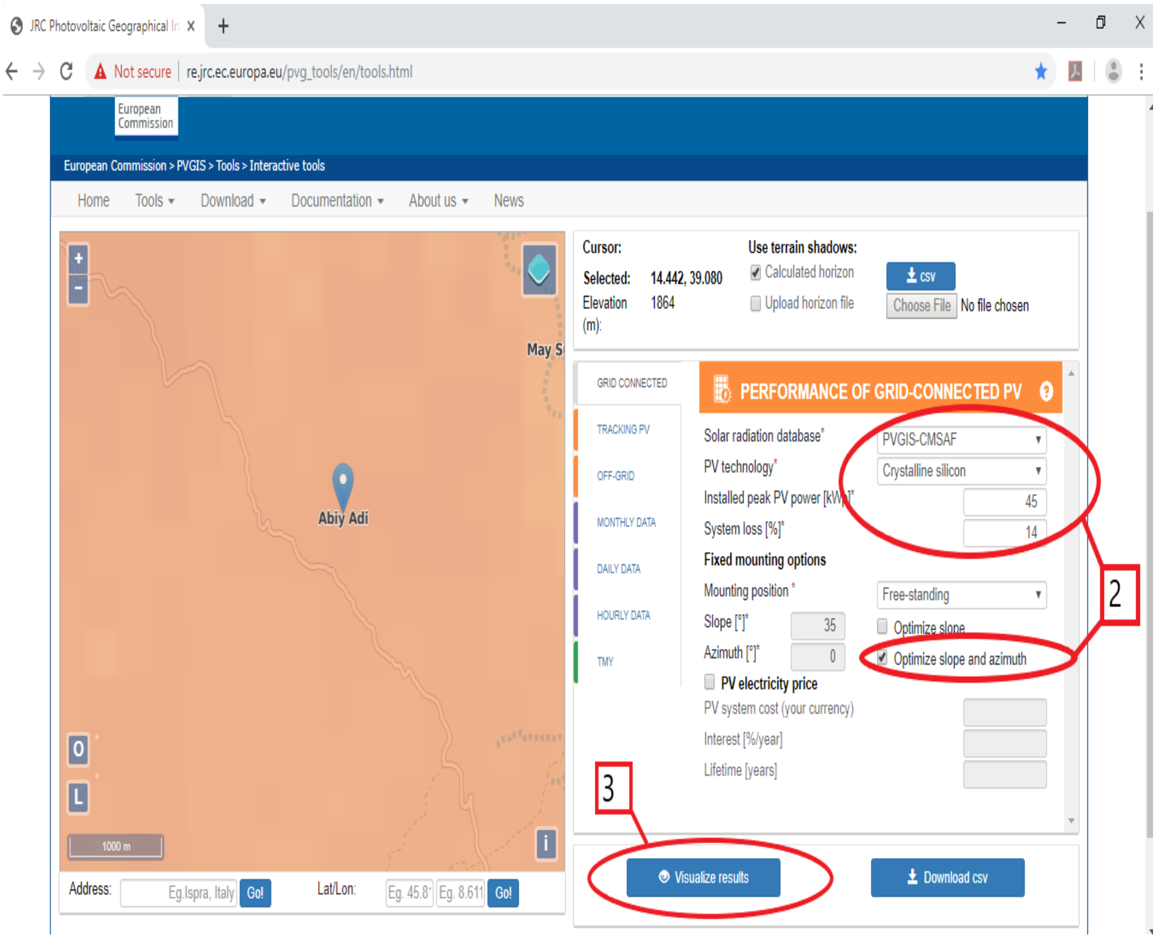


Figure 3.4: PVGIS Software performance of grid connected PV data logging page

Step 4

Click on ‘’pdf’’ to download the pdf file of the results

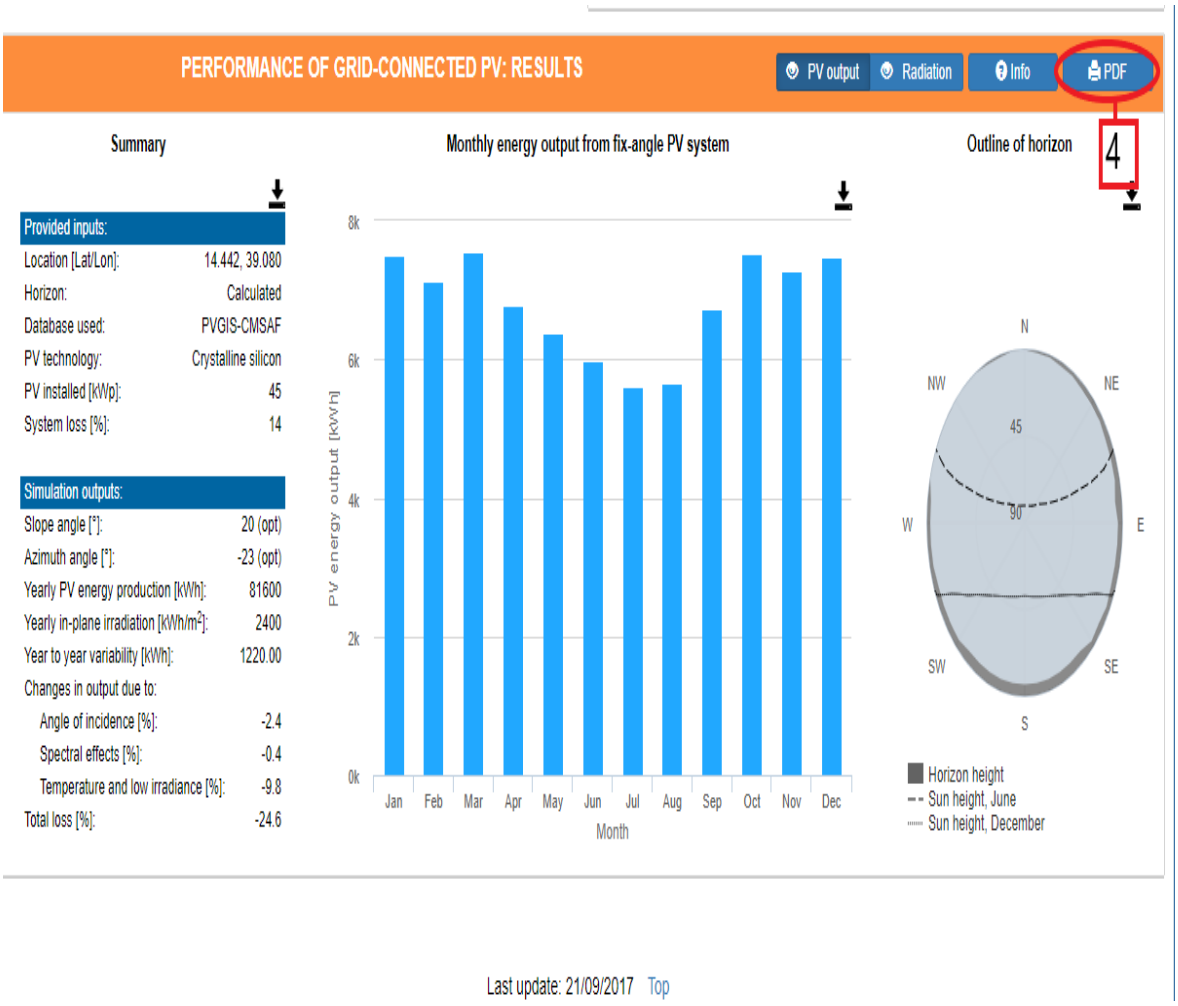


Figure 3.5: PVGIS Software output download page

Step 5

Once you get the pdf file then copy the useful data's like slope and azimuth angle, Yearly PV energy production, yearly in-plane irradiation and Monthly PV energy and solar irradiation and then paste to excel file for further analysis.

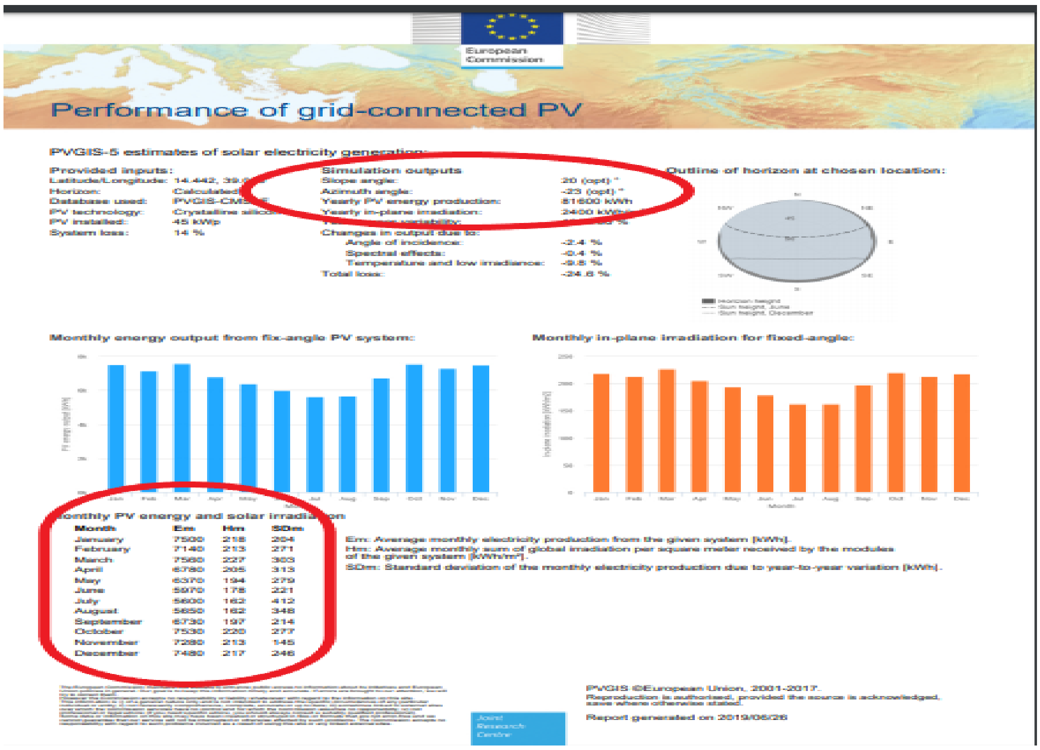


Figure 3.6: PVGIS Software output in pdf format

3.6.2 PVWatt calculator

PVWatt is a freely accessible web-based, comparatively easy to use and precise software created by the U.S. National Renewable Energy Laboratory (NREL). This software calculated the energy generation of a photovoltaic (PV) grid-connected system (Sharma et al., 2014). Depending on the location, PVWatt reads solar resource data from various databases: the Solar and Wind Resource Assessment Program (SWERA) (Dobos, 2014; Paper & Sciences, 2014).

PVWatt Calculator was used to estimate and compare grid-connected PV systems for energy production ("National Renewable Energy Laboratory (NREL).," n.d.) (Paper & Sciences, 2014). The key steps involved in the software were given bellow.

Step 1

Start with https://pvwatts.nrel.gov/ for online simulation enter selected location name

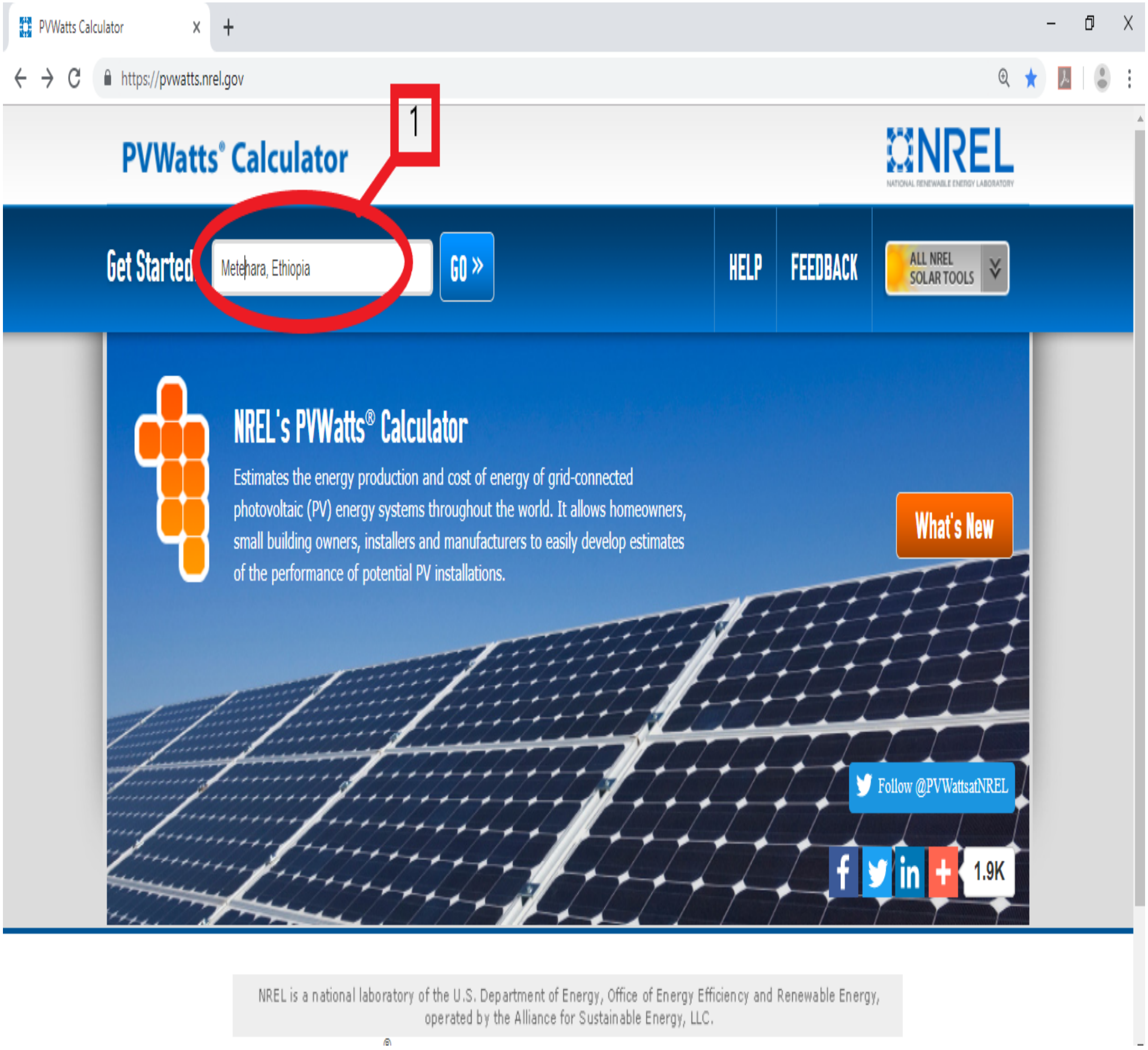


Figure 3.7: PVWatt software interactive tool page

Step 2

Confirm location of the solar resource data site and verify the place chosen on the map.

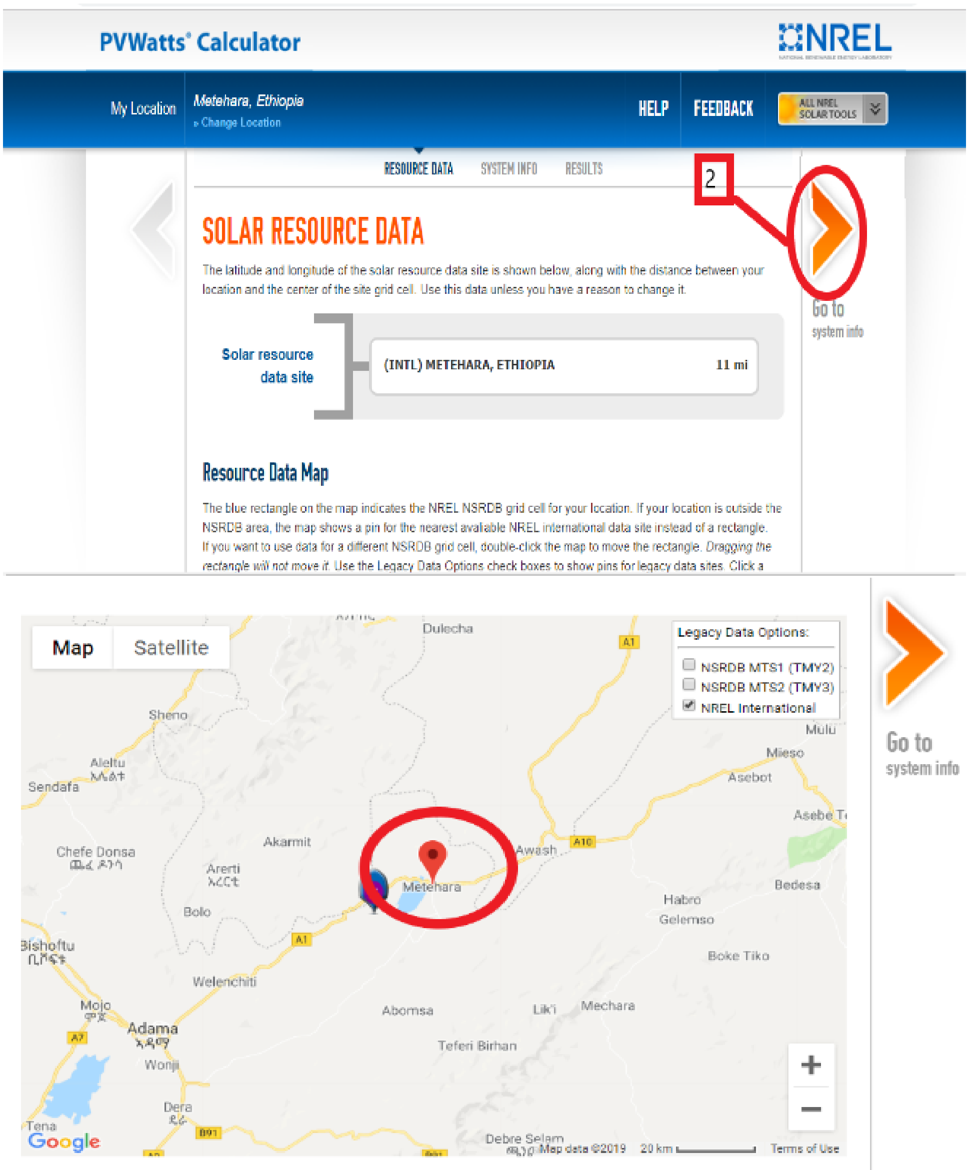


Figure 3.8: PVWatt software showing solar resource data site and site location map

Step 3

Fill out the system information like, installed capacity, array type, and tilt and azimuth angle.

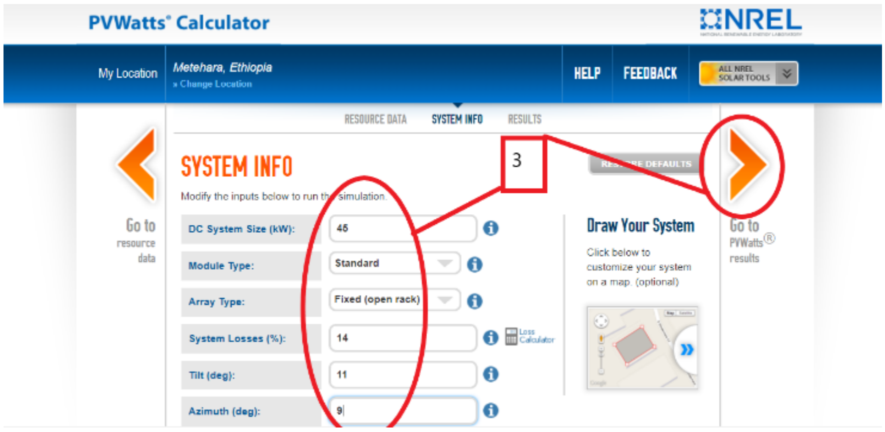


Figure 3. 9: PVWatt software system information filling page

Step 4

From the results download monthly output and the results are in excel format

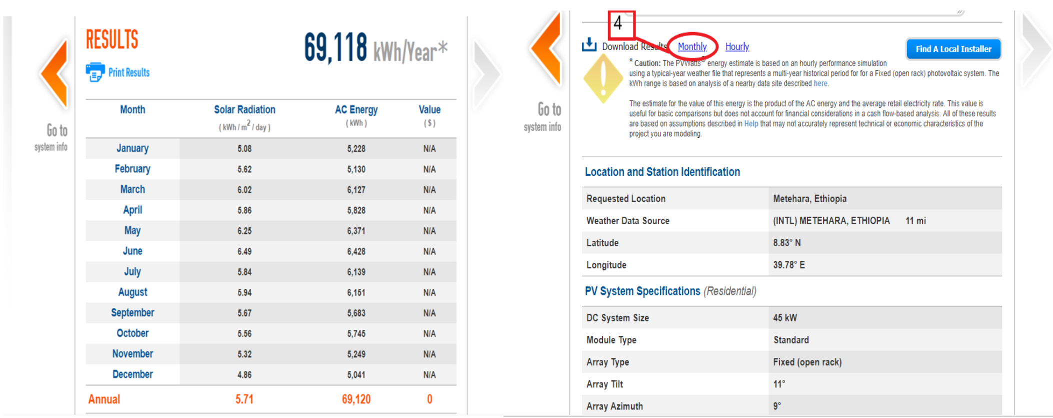


Figure 3.10: PVWatt Software showing annual and monthly results

Parameters used in the performance assessment of solar energy using PVGIS and PVWatt simulation tools were discussed below:

- **Solar irradiation:** is an integrated solar irradiance in which solar irradiance is the power per unit area (W/m^2), received from the Sun in the form of electromagnetic radiation as shown in the measuring instrument's wavelength range. In order to report the radiant energy emitted into the surrounding area (J/m) during this period, solar irradiance is often incorporated over a specified time period.
- **Energy generated*:*** is the entire electricity produced for each month by the photovoltaic system. The values are based on typical year solar resource data, represent the typical monthly generation of the system over a period of many years, not the monthly generation for a given year's months.
- **Capacity factor:** is the proportion of the real electrical yield to the maximum electrical output feasible over that period of time (*U.S.Energy Information Administration*, n.d.).

$$\textit{Annual Capacity Factor} = \left(\frac{\textit{Actual annual energy generation}}{\textit{Maximum plant rating} * 8760}\right) * 100\% \quad (3.1)$$

3.6.3 RETScreen

RETScreen is a software for the analysis of a clean energy project. It was previously developed for the analysis of renewable energy technologies by Natural Resources Canada NRCan) CANMET Energy Technology Centre (Sharma et al., 2014). RETScreen can be used globally to calculate power output and investment, expenses, reductions in emissions, economic sustainability and risk for various kinds of renewable energy and energy efficient systems. Meteorological parameters (e.g. temperature, moisture, etc.) are derived from the NASA Global Modeling and Analysis Office (GMAO) meteorological evaluation of the Goddard Earth observation scheme (GEOS v. 4.0.3) (Pan, Liu, Zhu, Zhang, & Zhang, 2017; Sharma et al., 2014).

In this study RETScreen software was applied to analyse and compare the potential and financial feasibility of the selected locations. For each location a fixed solar tracking mode was considered. Solar tracking mode one-axis and two-axis have not been considered as it needs due maintenance after seasonal variation. Azimuth and slope angle were taken from PVGIS software. The key steps used in the simulation software were described below.

Step 1: RETScreen Expert simulation software from the getting started options listed choose virtual energy analyser.

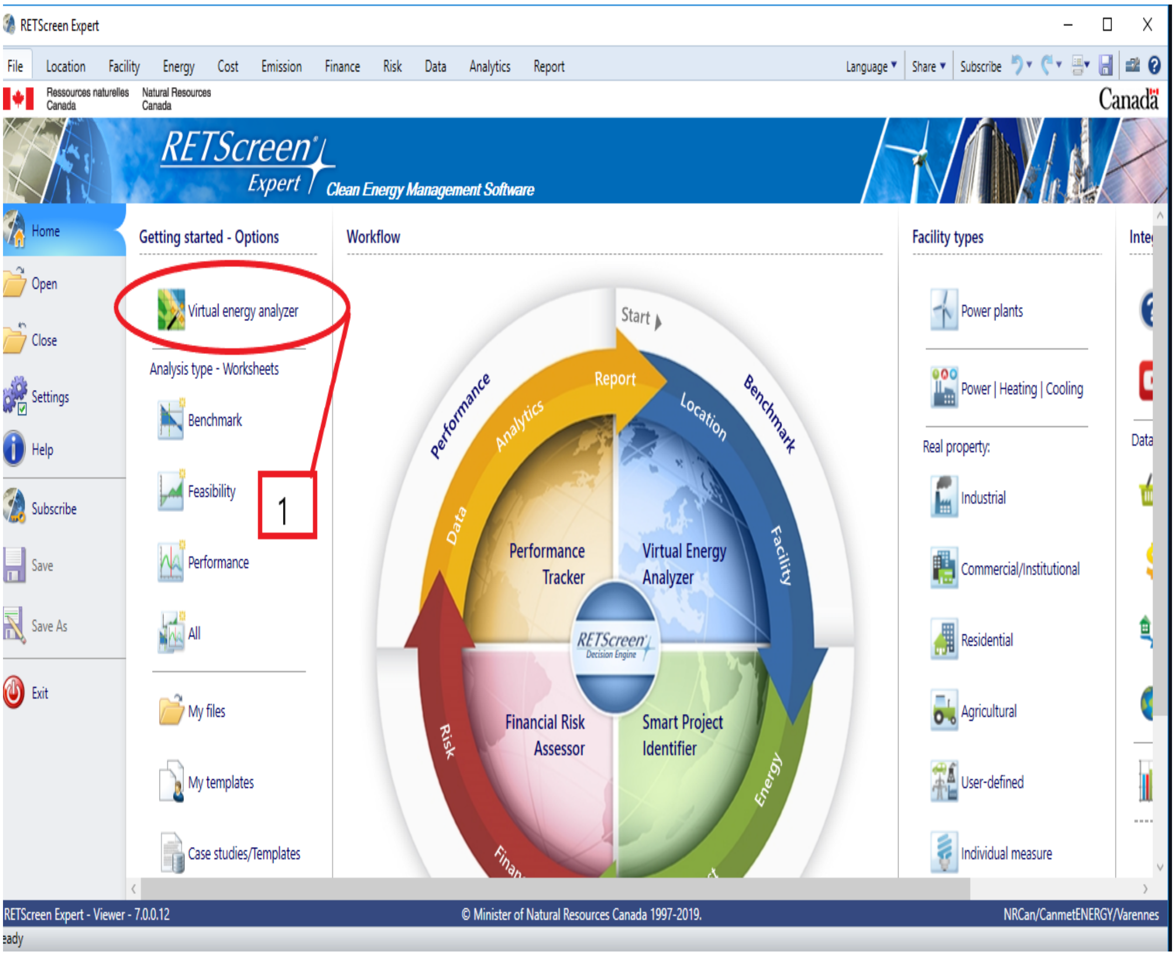


Figure 3.11: RETScreen expert software front end

Step 2 choose the facility information and location of your system

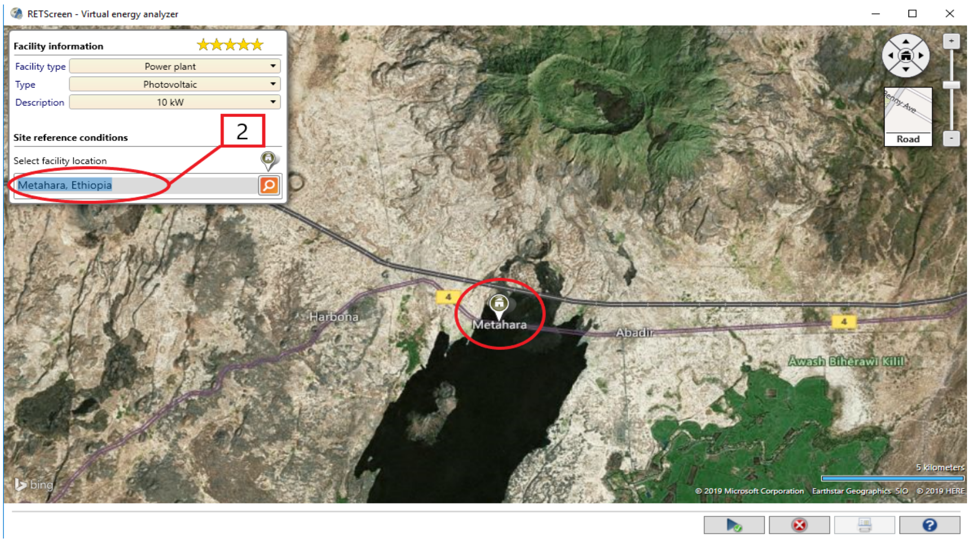


Figure 3.12: RETScreen expert software facility information and location setting page

Step 3: click on energy tab and fill the azimuth and slope angle data you get from PVGIS software and the system information.

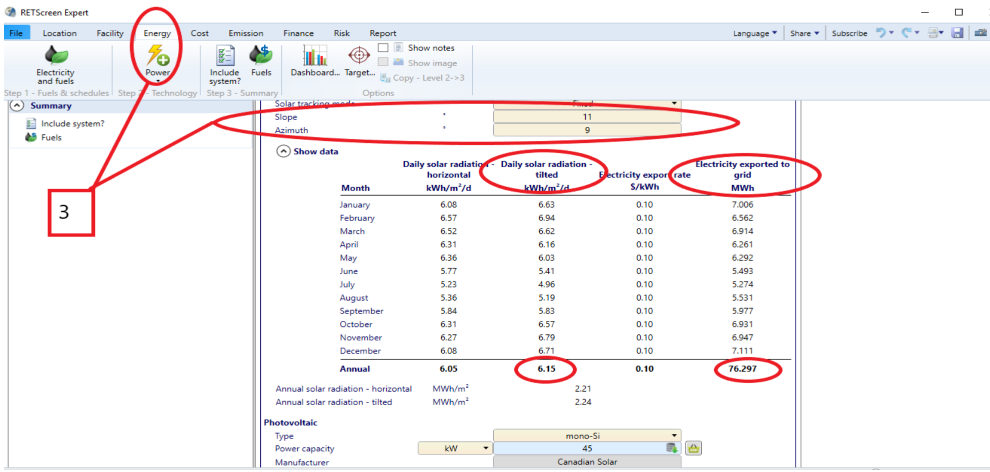


Figure 3.13: RETScreen expert showing Data generated from the energy analysis

Step 4: Click on the finance tab and input financial parameters for the analysis

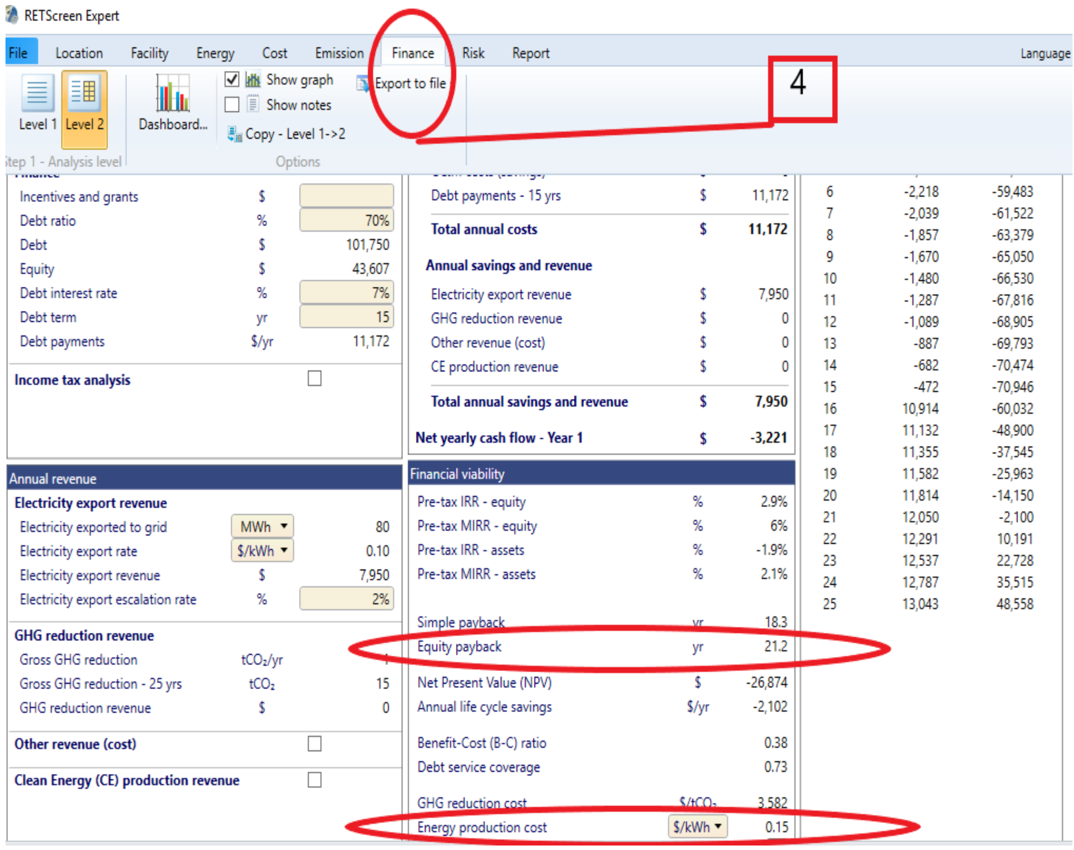


Figure 3.14: RETScreen expert software showing financial analysis

Parameters used in the financial assessment of solar energy using RETScreen simulation software discussed below:

- **Daily solar radiation – tilted:** The incident of energy on a PV module relies on the energy from sunlight and the angle of the module to the sun. The quantity of solar radiation incident on a tilted surface of the module is the element of the solar radiation incident perpendicular to the surface of the module. The RETScreen simulation tool calculates the average quantity of solar radiation on a tilted surface at the site during one day. Model range of typical values from 0 to 10 kWh /m^2/d.

- **Electricity exported to grid:** it is the amount of surplus energy exported to the grid. A grid-tied PV system's operating principle is to synchronize the installation with the voltage, frequency, and phase of the electrical utility, which essentially transforms the PV system into part of the grid. If the system output exceeds the owner's demand at any given time and there is no energy storage available, the surplus production is automatically exported and metered to the electric utility grid.
- **Equity payback:** RETScreen simulation software calculates the equity payback, which shows how long it takes a facility owner to recover their own initial investment (equity) from the project's cash flows. The equity payback takes into account the project's cash flows from its inception including the project's leverage (debt level), which makes it a better time indicator of project merits than simple payback. To calculate this value, the model uses the year number and the cumulative after-tax cash flows.
- **Energy production cost:** RETScreen simuation software calculates the energy (electricity) production cost per kWh (or MWh). This value (also known as the Levelized Electricity Cost or LCOE) reflects the export rate of electricity needed to have a Net Present Value (NPV) of 0. The GHG reduction revenue, the customer premium income (rebate), the other revenue (cost) and the Clean Energy (CE) production revenue are not included in this calculation.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Solar Irradiation

Solar irradiation data obtained using the online software PVGIS and PVWatts are tabulated in Table 4.1. PVGIS showed that the annual in-plane normal irradiation data in the selected cities varies from 1730 to 2481 kWh/m^2. The maximum annual solar irradiation was recorded in Asaita city located in east Ethiopia and the lowest in-plane normal irradiation was recorded in chencha city located in north Ethiopia. PVWatt showed that the Annual in-plane normal irradiation data in the selected cities varied from 1794.112 to 2236.804 kWh/m^2. The maximum in-plane normal irradiation was recorded in Chelenko city located in east Ethiopia and the lowest annual solar irradiation is recorded in yabelo city located in south west Ethiopia. PVGIS and PVWatt result for 1 kW system was shown in the Figures 4.1 – 4.5.

Table 4.1: Annual solar irradiation (kWh/m^2)

No	City	PVGIS	PVWatt	No	City	PVGIS	PVWatt
1	Abiy Adi	2406	1874.42	51	Gore	2368	1840.18
2	Adaba	2216	1970.23	52	Gorgora	2369	1936.12
3	Addis Alem	2033	1902.45	53	Goro	2324	2146.07
4	Addis Zemen	2373	1936.09	54	Gouder	2160	1986.54
5	Adet	2335	1998.31	55	Harbu	2317	1888.14
6	Adwa	2355	1875.78	56	Haromaya	2369	2150.82
7	Agarfa	2108	2117.36	57	Hossa'ina	2163	1948.57
8	Agaro	2084	1849.71	58	Humera	2409	1921.35
9	Alaba Qulito	2247	1959.03	59	Huruta	2248	2093.94
10	Alamat’A	2299	1947.26	60	Hyke	2265	2075.67

Table 4.1 Continued

No	City	PVGIS	PVWatt	No	City	PVGIS	PVWatt
11	Alem Ketema	2317	1897.93	61	Injibara	1896	1999.79
12	Aleta Wendo	1963	1940.70	62	Jinka	1832	1876.70
13	Ankober	2135	2083.43	63	Kemse	2338	2035.98
14	Asaita	2481	2034.64	64	Konso	2210	1982.87
15	Azezo	2153	1940.90	65	Lailibela	2287	1975.34
16	Baille	2352	2147.37	66	Logiya	2454	2032.42
17	Bati	2388	2063.20	67	Maychew	2251	1968.98
18	Bedele	2177	1841.51	68	Mechara	2016	2088.63
19	Berhale	2440	2002.27	69	Meki	2393	1945.57
20	Bichena	2298	1864.25	70	Mendi	2058	1864.54
21	Boditi	2103	1951.38	71	Metehara	2434	2084.04
22	Bonga	1819	1849.87	72	Metema	2331	1936.96
23	Burie	2165	1829.49	73	Metu	2031	1840.55
24	Butajira	2245	1946.16	74	Mieso	2323	2140.97
25	Chelenko	2183	2236.80	75	Mille	2476	2042.98
26	Chencha	1730	1968.94	76	Mojo	2399	1949.96
27	Chiro	2044	2082.83	77	Mota	2343	1989.08
28	Dabat	2182	1925.41	78	Moyale	2056	1796.80
29	Dalocha	2247	1950.06	79	Nejo	2036	1829.55
30	Debre Markos	2145	1842.00	80	Nekemte	2018	1809.90
31	Debre Tabor	2095	2074.04	81	Sekota	2334	1907.65
32	Debre Werk	2250	1865.87	82	Sendafa	2144	1899.51
33	Dejen	2385	1880.00	83	Shakiso	1999	1988.71
34	Delgi	2270	1921.74	84	Shambu	1996	1855.35
35	Dembi	2141	1850.24	85	Sheno	2028	1941.94
36	Deneba	2217	1827.73	86	Shire	2310	1875.08
37	Dhera	2366	2181.02	87	Sodo	2086	1951.38
38	Dil Yibza	2280	1910.40	88	Sokoru	2176	1850.72
39	Dinsho	1941	1968.68	89	Tefki	2308	1910.04

Table 4.1 Continued

No	City	PVGIS	PVWatt	No	City	PVGIS	PVWatt
40	Dodola	2189	1972.03	90	Tenta	2369	2001.27
41	Durame	2129	1942.75	91	Tulu Milki	2251	1888.15
42	Fiche	2202	1912.23	92	Weldiya	2263	2012.12
43	Finote Selem	2250	1840.88	93	Weliso	2202	1910.04
44	Gasera	2187	1928.67	94	Welkite	2234	1841.00
45	Gelemso	2267	2106.76	95	Wereta	2379	1973.90
46	Gewane	2463	2072.05	96	Wonji	2369	2084.70
47	Ghimbi	2057	1829.55	97	Wukro	2380	1887.74
48	Gidole	1919	1966.99	98	Yabelo	2045	1794.11
49	Goba	1898	2112.78	99	Yirgalem	2049	1950.12
50	Gololcha	2368	2137.35	100	Ziway	2403	1944.85

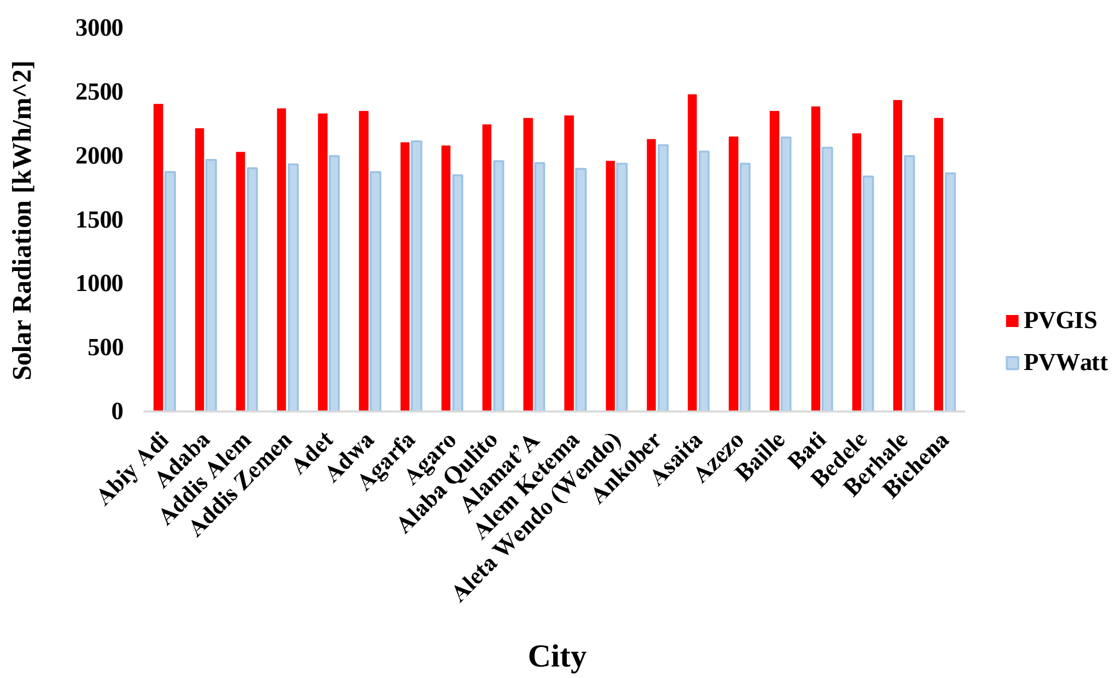


Figure 4.1: Annual solar irradiation using PVGIS and PVWatt in 20 locations for 1kW

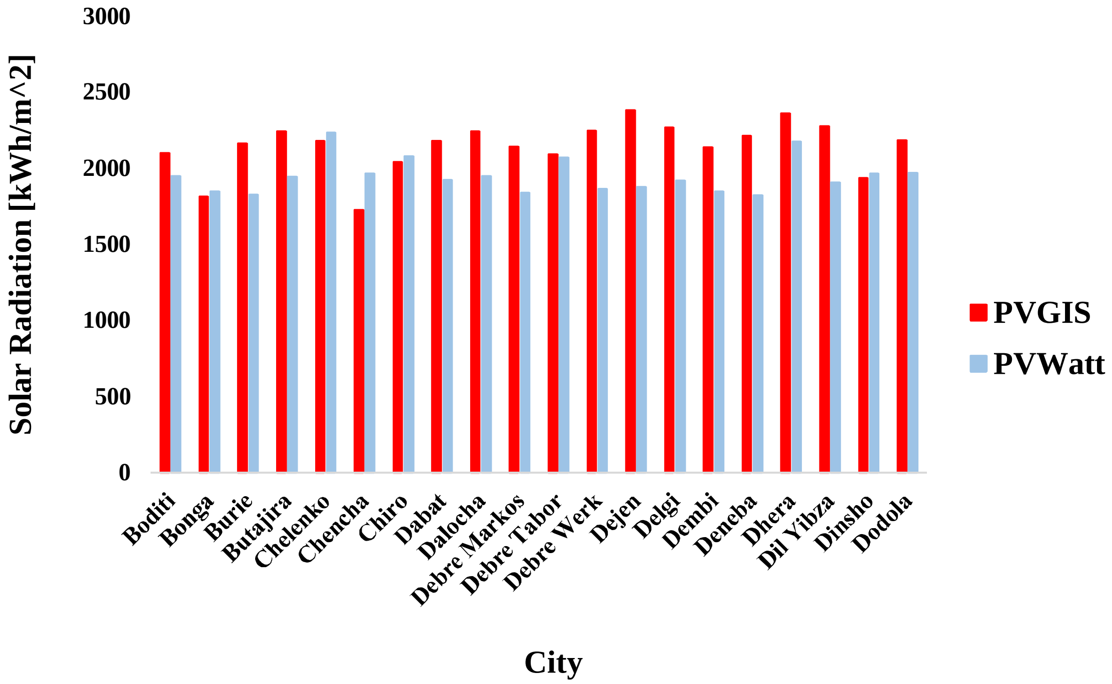


Figure 4.2: Annual solar irradiation using PVGIS and PVWatts in 20 locations for 1kW

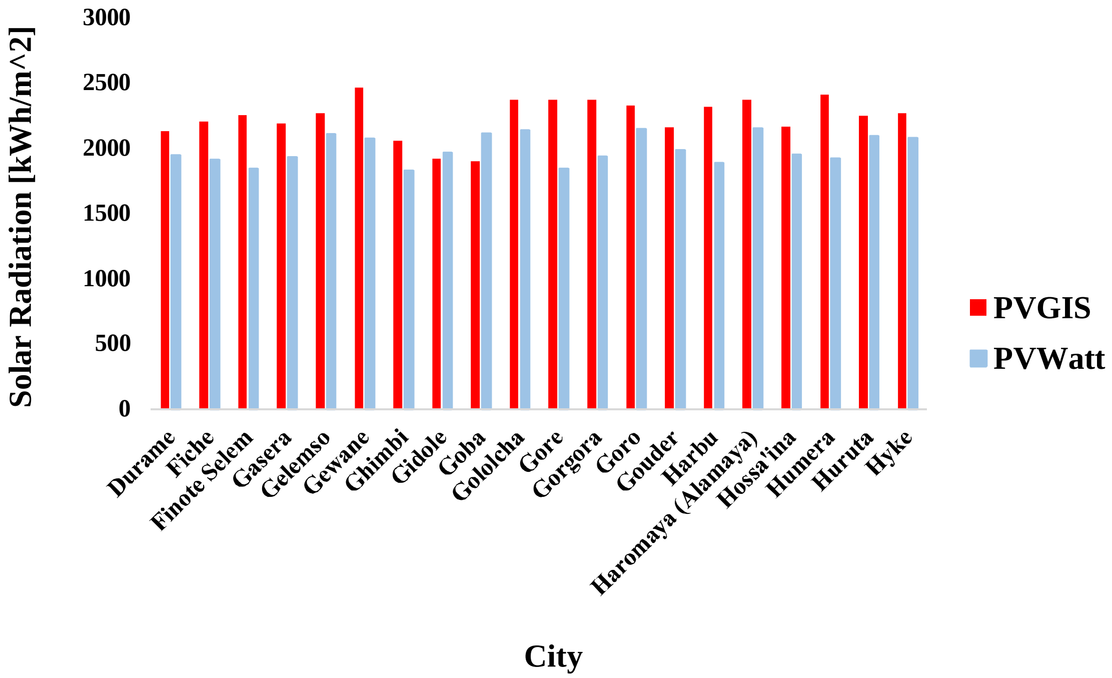


Figure 4.3: Annual solar irradiation using PVGIS and PVWatts in 20 locations for 1kW

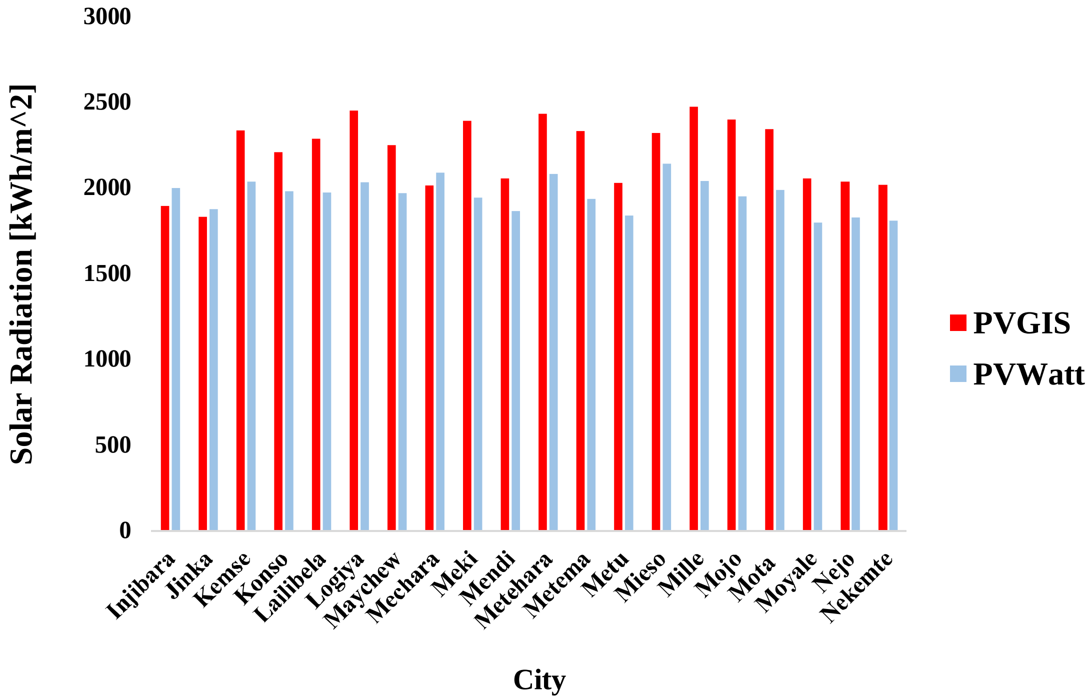


Figure 4.4: Annual solar irradiation using PVGIS and PVWatts in 20 locations for 1kW

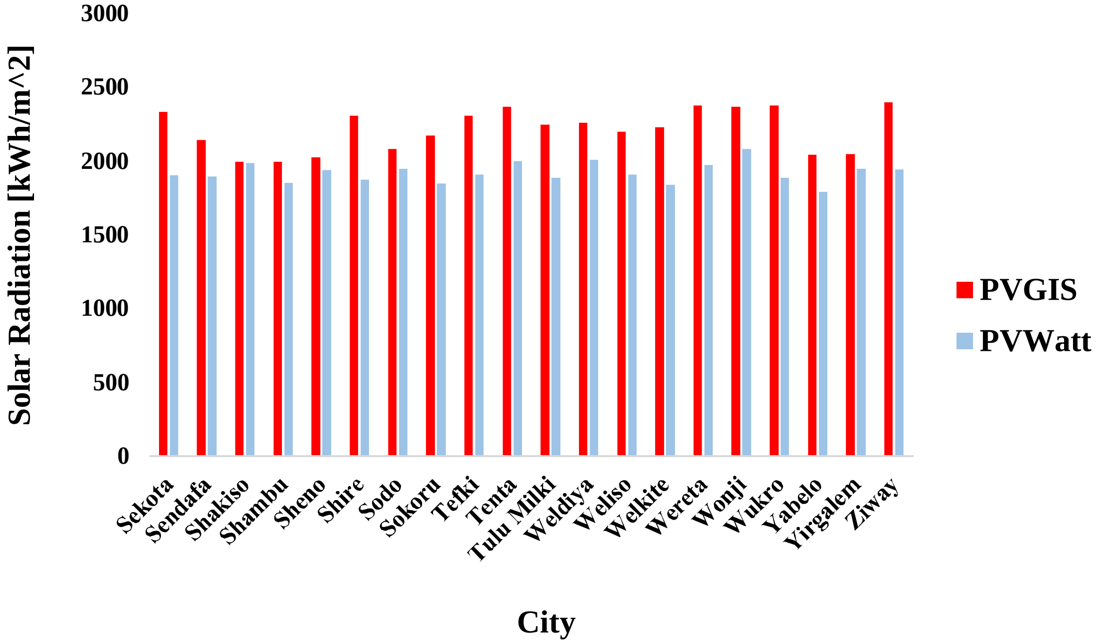


Figure 4.5: Annual solar irradiation using PVGIS and PVWatts in 20 locations for 1kW

4.2 Energy Generation and Capacity Factor

Annual photovoltaic energy generated for each scenario and location was calculated using a simulation software PVGIS and PVWatt. Specific annual yield and capacity factor were calculated using annual photovoltaic energy result. As the result showed the capacity factor obtained by PVGIS simulation software is much higher than PVWatt software.

A. First Scenario: 1 kW PV System

Energy generation data obtained using the online software PVGIS and PVWatts were tabulated in Table 4.2 and presented in Figure 4.6 – 4.5. PVGIS showed that the annual Photovoltaic energy generation in the selected cities varies from 1838 to 1369 kWh/m^2 and the average capacity factor is 19.25%. The maximum energy generation was recorded in Tenta city located in south Ethiopia and the lowest energy generation was recorded in Chencha city located in north Ethiopia.

PVWatt showed that the annual energy generation in the selected cities varied from 1663.112 to 1354.767 kWh/m^2 and the average capacity factor is 16.89%. The maximum energy generation was recorded in Dil Yibza city located in North Amhara Ethiopia and the lowest energy generation was recorded in Nekemte city located in west Ethiopia.

Table 4.2: Annual energy generated data in the selected 100 cities for 1kW system.

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**	**Annual PV energy [kWh]**	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**
1	Abiy Adi	1815	1815	20.72	1403.15	1403.15	16.02
2	Adaba	1728	1728	19.73	1484.30	1484.30	16.94
3	Addis Alem	1566.7	1566.7	17.88	1494.23	1494.23	17.06
4	Addis Zemen	1779	1779	20.31	1449.36	1449.36	16.55
5	Adet	1808	1808	20.64	1496.17	1496.17	17.08
6	Adwa	1778	1778	20.30	1404.31	1404.31	16.03
7	Agarfa	1633	1633	18.64	1559.45	1559.45	17.80
8	Agaro	1558	1558	17.79	1383.87	1383.87	15.80
9	Alaba Qulito	1700	1700	19.41	1477.50	1477.50	16.87
10	Alamat’A	1712	1712	19.54	1468.53	1468.53	16.76
11	Alem Ketema	1724	1724	19.68	1489.96	1489.96	17.01
12	Aleta Wendo	1508.2	1508.2	17.22	1462.48	1462.48	16.69
13	Ankober	1709	1709	19.51	1535.36	1535.36	17.53
14	Asaita	1799	1799	20.54	1536.17	1536.17	17.54
15	Azezo	1621	1621	18.50	1452.65	1452.65	16.58
16	Baille	1784	1784	20.37	1592.82	1592.82	18.18
17	Bati	1792	1792	20.46	1557.86	1557.86	17.78
18	Bedele	1663	1663	18.98	1378.07	1378.07	15.73
19	Berhale	1781	1781	20.33	1510.73	1510.73	17.25
20	Bichena	1774	1774	20.25	1446.76	1446.76	16.52
21	Boditi	1616.9	1616.9	18.46	1472.01	1472.01	16.80
22	Bonga	1382.8	1382.8	15.79	1384.00	1384.00	15.80
23	Burie	1649	1649	18.82	1419.51	1419.51	16.20

Table 4.2 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
24	Butajira	1705	1705	19.46	1528.59	1528.59	17.45
25	Chelenko	1695	1695	19.35	1661.53	1661.53	18.97
26	Chencha	1369	1369	15.63	1485.64	1485.64	16.96
27	Chiro	1629	1629	18.60	1533.98	1533.98	17.51
28	Dabat	1698	1698	19.38	1441.10	1441.10	16.45
29	Dalocha	1711	1711	19.53	1470.90	1470.90	16.79
30	Debre Markos	1648	1648	18.81	1429.32	1429.32	16.32
31	Debre Tabor	1629	1629	18.60	1542.65	1542.65	17.61
32	Debre Werk	1727	1727	19.71	1448.05	1448.05	16.53
33	Dejen	1804	1804	20.59	1459.15	1459.15	16.66
34	Delgi	1736	1736	19.82	1438.43	1438.43	16.42
35	Dembi	1621	1621	18.50	1384.31	1384.31	15.80
36	Deneba	1732	1732	19.77	1367.51	1367.51	15.61
37	Dhera	1772	1772	20.23	1663.11	1663.11	18.99
38	Dil Yibza	1778	1778	20.30	1430.39	1430.39	16.33
39	Dinsho	1563	1563	17.84	1483.27	1483.27	16.93
40	Dodola	1703	1703	19.44	1485.50	1485.50	16.96
41	Durame	1635.6	1635.6	18.67	1465.72	1465.72	16.73
42	Fiche	1714	1714	19.57	1501.63	1501.63	17.14
43	Finote Selem	1680	1680	19.18	1428.45	1428.45	16.31
44	Gasera	1695	1695	19.35	1419.83	1419.83	16.21
45	Gelemso	1731	1731	19.76	1551.59	1551.59	17.71
46	Gewane	1794	1794	20.48	1564.45	1564.45	17.86

Table 4.2 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
47	Ghimbi	1570.9	1570.9	17.93	1369.11	1369.11	15.63
48	Gidole	1492.8	1492.8	17.04	1484.07	1484.07	16.94
49	Goba	1506.7	1506.7	17.20	1556.01	1556.01	17.76
50	Gololcha	1785	1785	20.38	1573.99	1573.99	17.97
51	Gore	1785	1785	20.38	1376.78	1376.78	15.72
52	Gorgora	1814	1814	20.71	1449.26	1449.26	16.54
53	Goro	1821	1821	20.79	1580.45	1580.45	18.04
54	Gouder	1642	1642	18.74	1560.60	1560.60	17.82
55	Harbu	1721	1721	19.65	1465.33	1465.33	16.73
56	Haromaya	1824	1824	20.82	1595.41	1595.41	18.21
57	Hossa'ina	1692	1692	19.32	1469.62	1469.62	16.78
58	Humera	1740	1740	19.86	1436.79	1436.79	16.40
59	Huruta	1728	1728	19.73	1541.24	1541.24	17.59
60	Hyke	1731	1731	19.76	1566.49	1566.49	17.88
61	Injibara	1471.7	1471.7	16.80	1487.53	1487.53	16.98
62	Jinka	1383	1383	15.79	1403.13	1403.13	16.02
63	Kemse	1730	1730	19.75	1535.86	1535.86	17.53
64	Konso	1651	1651	18.85	1494.88	1494.88	17.06
65	Lailibela	1722	1722	19.66	1490.11	1490.11	17.01
66	Logiya	1787	1787	20.40	1534.44	1534.44	17.52
67	Maychew	1755	1755	20.03	1485.63	1485.63	16.96
68	Mechara	1524	1524	17.40	1538.17	1538.17	17.56
69	Meki	1799	1799	20.54	1528.07	1528.07	17.44

Table 4.2 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
70	Mendi	1552.6	1552.6	17.72	1446.97	1446.97	16.52
71	Metehara	1778	1778	20.30	1535.95	1535.95	17.53
72	Metema	1704	1704	19.45	1449.86	1449.86	16.55
73	Metu	1532.2	1532.2	17.49	1377.04	1377.04	15.72
74	Mieso	1727	1727	19.71	1576.78	1576.78	18.00
75	Mille	1803	1803	20.58	1542.39	1542.39	17.61
76	Mojo	1821	1821	20.79	1531.92	1531.92	17.49
77	Mota	1792	1792	20.46	1479.75	1479.75	16.89
78	Moyale	1568	1568	17.90	1379.80	1379.80	15.75
79	Nejo	1548.4	1548.4	17.68	1369.15	1369.15	15.63
80	Nekemte	1540.4	1540.4	17.58	1354.77	1354.77	15.47
81	Sekota	1786	1786	20.39	1428.15	1428.15	16.30
82	Sendafa	1669	1669	19.05	1491.43	1491.43	17.03
83	Shakiso	1542.3	1542.3	17.61	1501.09	1501.09	17.14
84	Shambu	1545.8	1545.8	17.65	1439.77	1439.77	16.44
85	Sheno	1595.1	1595.1	18.21	1525.72	1525.72	17.42
86	Shire	1750	1750	19.98	1403.71	1403.71	16.02
87	Sodo	1603.2	1603.2	18.30	1472.01	1472.01	16.80
88	Sokoru	1647	1647	18.80	1384.37	1384.37	15.80
89	Tefki	1762	1762	20.11	1499.55	1499.55	17.12
90	Tenta	1838	1838	20.98	1509.89	1509.89	17.24
91	Tulu Milki	1733	1733	19.78	1465.29	1465.29	16.73
92	Weldiya	1711	1711	19.53	1517.83	1517.83	17.33

Table 4.2 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
93	Weliso	1676	1676	19.13	1499.55	1499.55	17.12
94	Welkite	1691	1691	19.30	1377.36	1377.36	15.72
95	Wereta	1778	1778	20.30	1468.43	1468.43	16.76
96	Wonji	1838	1838	20.98	1536.56	1536.56	17.54
97	Wukro	1832	1832	20.91	1412.82	1412.82	16.13
98	Yabelo	1595.6	1595.6	18.21	1377.71	1377.71	15.73
99	Yirgalem	1560	1560	17.81	1469.53	1469.53	16.78
100	Ziway	1811	1811	20.67	1527.44	1527.44	17.44
	max	1838	1838	20.98	1663.11	1663.11	18.99
	min	1369	1369	15.63	1354.77	1354.77	15.47
	Average	1686.579	1686.579	19.25	1479.20	1479.20	16.89

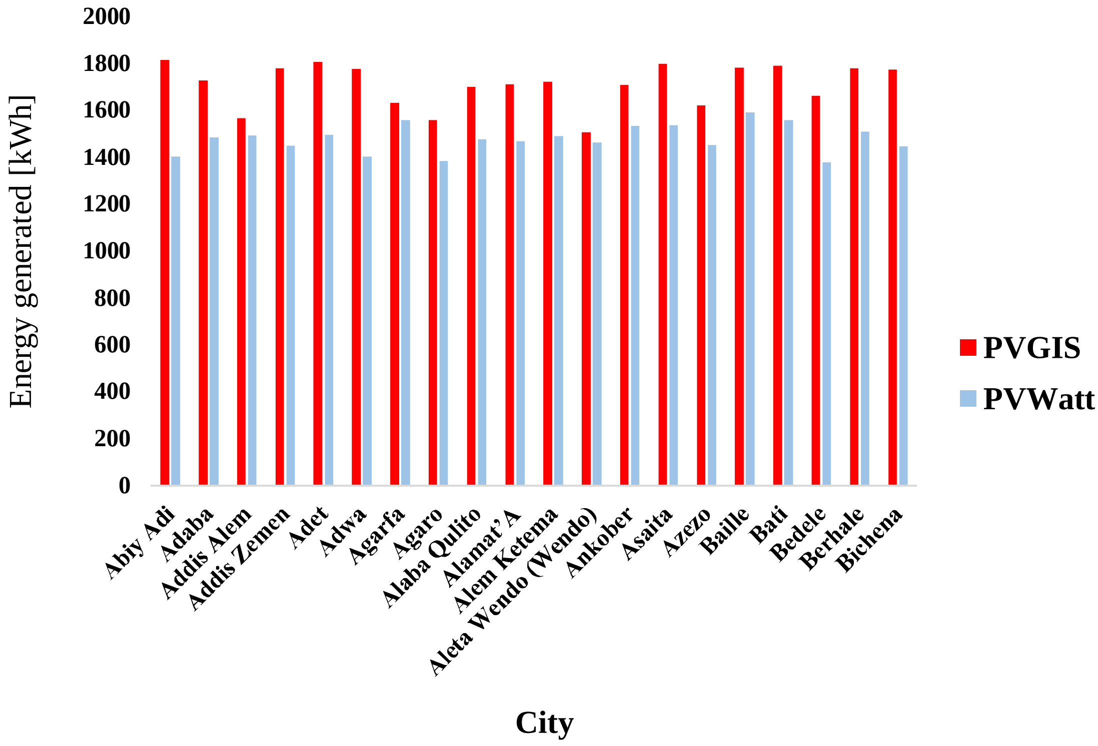


Figure 4.6: Annual energy generated using PVGIS and PVWatts in 20 locations

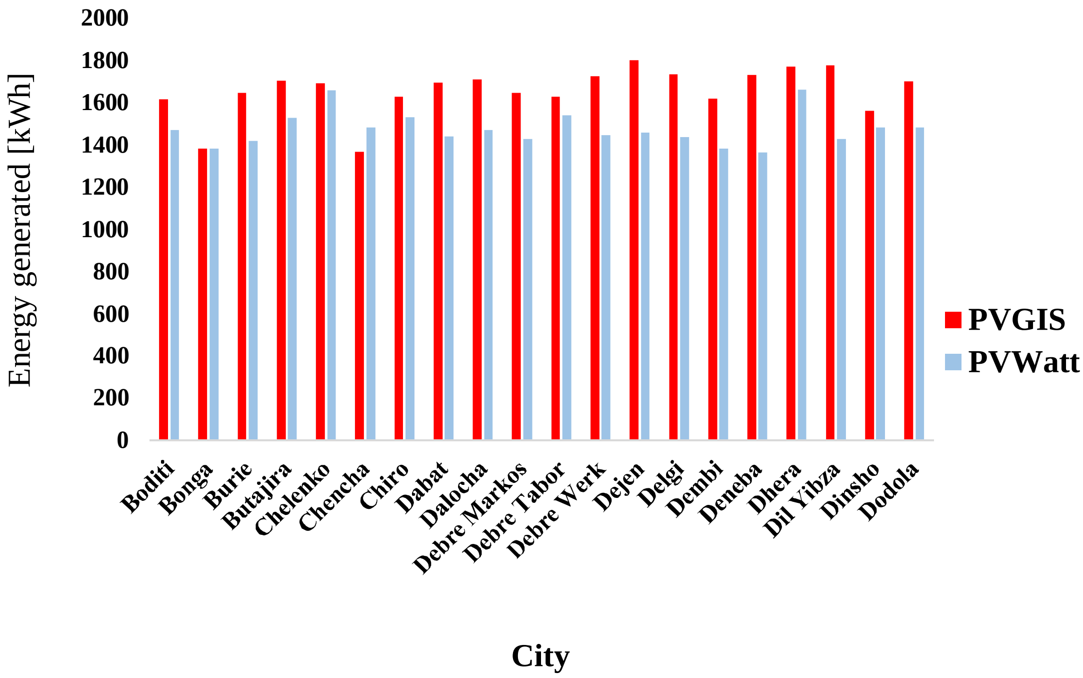


Figure 4.7: Annual energy generated using PVGIS and PVWatts in 20 locations

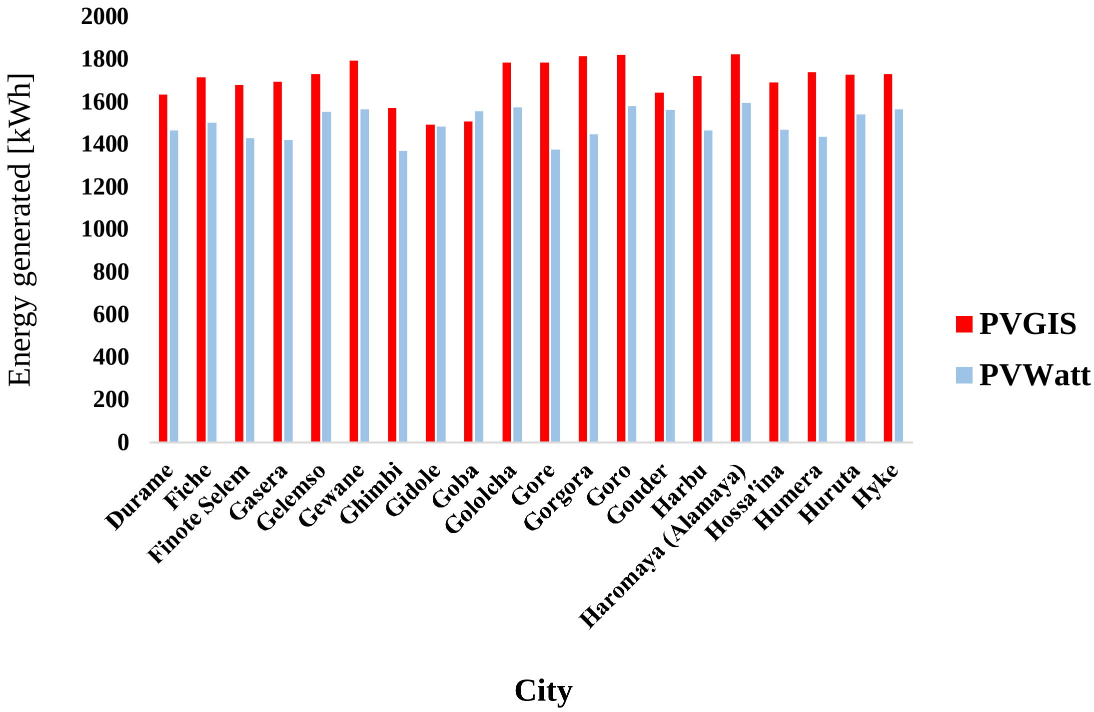


Figure 4.8: Annual energy generated using PVGIS and PVWatts in 20 locations

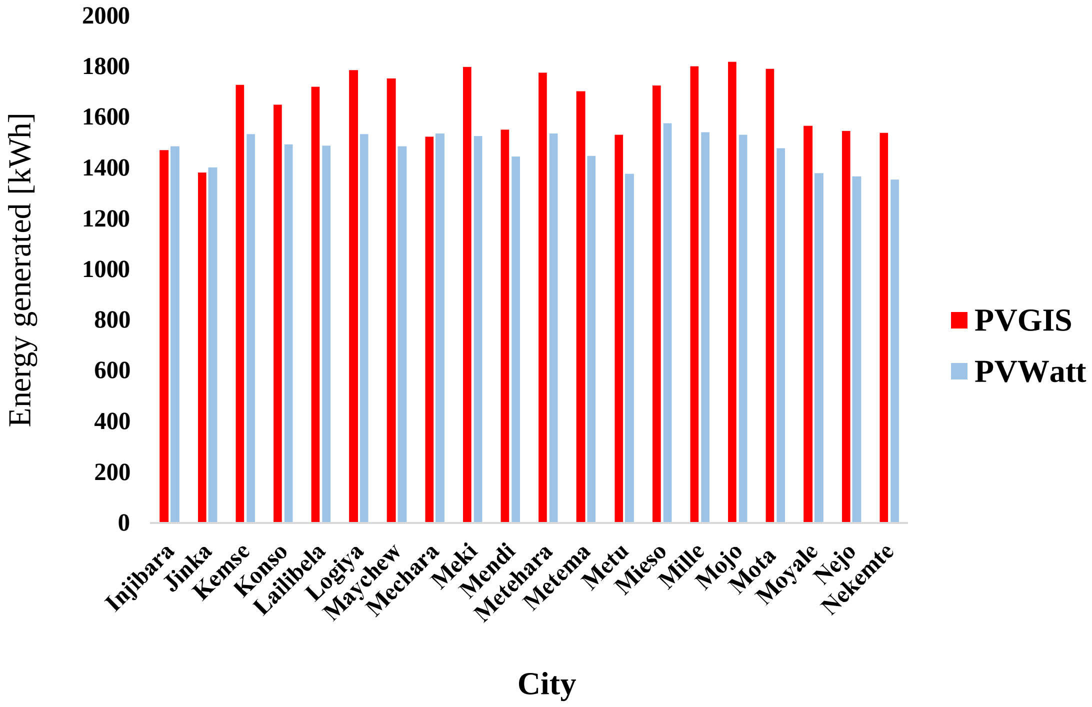


Figure 4.9: Annual energy generated using PVGIS and PVWatts in 20 locations

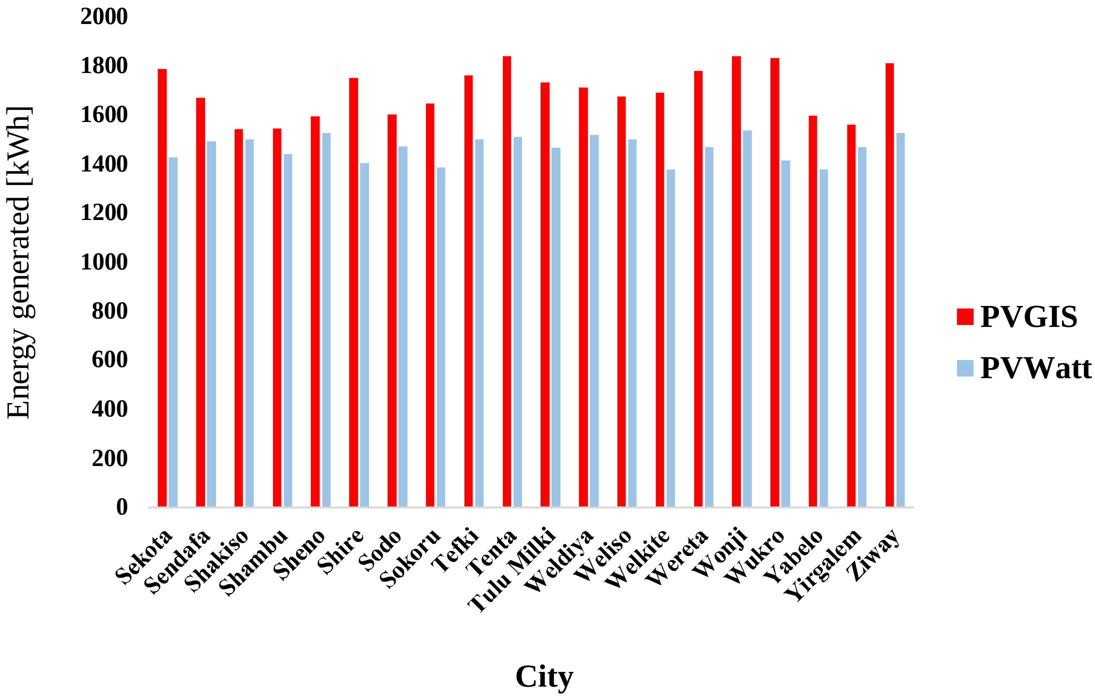


Figure 4.10: Annual energy generated using PVGIS and PVWatts in 20 locations

B. Second Scenario: 3 kW PV System

Energy generation data obtained using the online software PVGIS and PVWatts are tabulated in Table 4.3 and presented in Figure 4.11 – 4.15. PVGIS showed that the annual energy generation in the selected cities varies from 5515 to 4107 kWh/m^2 and the average capacity factor is 18.96%. The maximum energy generation is recorded in Tenta city located in south Ethiopia and the lowest energy generation was recorded in Chencha city located in north Ethiopia. PVWatt shows that the annual energy generation in the selected cities varies from 5909.994 to 4064.302 kWh/m^2 and the average capacity factor is 16.80%. The maximum energy generation was recorded in Dil Yibza city located in North Ethiopia and the lowest energy generation was recorded in Nekemte city located in West Ethiopia.

Table 4.3: Annual energy generated data in the selected 100 cities for 3kW system.

		PVGIS			PVWatt		
No	**City**	**Annual PV energy [kWh]**	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**	**Annual PV energy [kWh]**	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**
1	Abiy Adi	5440	1813.33	20.70	4209.46	1403.15	16.02
2	Adaba	5184	1728.00	19.73	4452.90	1484.30	16.94
3	Addis Alem	5339	1779.67	20.32	4348.07	1449.36	16.55
4	Addis Zemen	5399	522.23	5.96	4348.07	1494.23	17.06
5	Adet	5428	1809.33	20.65	4488.51	1496.17	17.08
6	Adwa	5334	1778.00	20.30	4212.94	1404.31	16.03
7	Agarfa	4899	1633.00	18.64	4678.36	1559.45	17.80
8	Agaro	4678	1559.33	17.80	4151.61	1383.87	15.80
9	Alaba Qulito	5101	1700.33	19.41	5909.99	1970.00	22.49
10	Alamat'A	5137	1712.33	19.55	4405.60	1468.53	16.76
11	Alem Ketema	5169	1723.00	19.67	4469.87	1489.96	17.01
12	Aleta Wendo	4523	1507.67	17.21	4387.44	1462.48	16.69
13	Ankober	5129	1709.67	19.52	4604.79	1534.93	17.52
14	Asaita	5398	1799.33	20.54	4608.52	1536.17	17.54
15	Azezo	5354	1784.67	20.37	4357.95	1452.65	16.58
16	Baille	5354	1784.67	20.37	4778.45	1592.82	18.18
17	Bati	5378	1792.67	20.46	4673.59	1557.86	17.78
18	Bedele	4991	1663.67	18.99	4134.20	1378.07	15.73
19	Berhale	5342	1780.67	20.33	4573.04	1524.35	17.40
20	Bichena	5319	1773.00	20.24	4343.94	1447.98	16.53
21	Boditi	4850	1616.67	18.46	4416.03	1472.01	16.80
22	Bonga	4148	1382.67	15.78	4152.00	1384.00	15.80
23	Burie	4945	1648.33	18.82	4258.54	1419.51	16.20
24	Butajira	5120	1706.67	19.48	4585.77	1528.59	17.45
25	Chelenko	5082	1694.00	19.34	4984.60	1661.53	18.97

Table 4.3 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
26	Chencha	4107	1369.00	15.63	4456.91	1485.64	16.96
27	Chiro	4889	1629.67	18.60	4601.95	1533.98	17.51
28	Dabat	5093	1697.67	19.38	4323.31	1441.10	16.45
29	Dalocha	5136	1712.00	19.54	4412.70	1470.90	16.79
30	Debre Markos	4944	1648.00	18.81	4287.95	1429.32	16.32
31	Debre Tabor	4882	1627.33	18.58	4627.95	1542.65	17.61
32	Debre Werk	5177	1725.67	19.70	4344.16	1448.05	16.53
33	Dejen	5416	1805.33	20.61	4377.46	1459.15	16.66
34	Delgi	5204	1734.67	19.80	4315.28	1438.43	16.42
35	Dembi	4857	1619.00	18.48	4152.92	1384.31	15.80
36	Deneba	5198	1732.67	19.78	4102.53	1367.51	15.61
37	Dhera	5317	1772.33	20.23	4605.45	1535.15	17.52
38	Dil Yibza	5335	1778.33	20.30	4291.18	1430.39	16.33
39	Dinsho	4691	1563.67	17.85	4442.72	1480.91	16.91
40	Dodola	5114	1704.67	19.46	4456.51	1485.50	16.96
41	Durame	4911	1637.00	18.69	4397.15	1465.72	16.73
42	Fiche	5145	1715.00	19.58	4504.88	1501.63	17.14
43	Finote Selem	5039	1679.67	19.17	4285.36	1428.45	16.31
44	Gasera	5085	1695.00	19.35	4259.48	1419.83	16.21
45	Gelemso	5193	1731.00	19.76	4654.78	1551.59	17.71
46	Gewane	5379	1793.00	20.47	4693.34	1564.45	17.86
47	Ghimbi	4714	1571.33	17.94	4107.32	1369.11	15.63
48	Gidole	4481	1493.67	17.05	4452.21	1484.07	16.94
49	Goba	4518	1506.00	17.19	4668.02	1556.01	17.76

Table 4.3 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
50	Gololcha	5358	1786.00	20.39	4721.97	1573.99	17.97
51	Gore	4492	1497.33	17.09	4130.33	1376.78	15.72
52	Gorgora	5444	1814.67	20.72	4347.78	1449.26	16.54
53	Goro	5460	1820.00	20.78	4741.34	1580.45	18.04
54	Gouder	4930	1643.33	18.76	4681.81	1560.60	17.82
55	Harbu	5166	1722.00	19.66	4395.99	1465.33	16.73
56	Haromaya	5468	1822.67	20.81	4786.23	1595.41	18.21
57	Hossa'ina	5080	1693.33	19.33	4408.86	1469.62	16.78
58	Humera	5218	1739.33	19.86	4314.43	1438.14	16.42
59	Huruta	5188	1729.33	19.74	4628.06	1542.69	17.61
60	Hyke	5189	1729.67	19.75	4699.46	1566.49	17.88
61	Injibara	4420	1473.33	16.82	4462.60	1487.53	16.98
62	Jinka	4150	1383.33	15.79	4209.38	1403.13	16.02
63	Kemse	5188	1729.33	19.74	4607.58	1535.86	17.53
64	Konso	4952	1650.67	18.84	4484.64	1494.88	17.06
65	Lailibela	5163	1721.00	19.65	4470.32	1490.11	17.01
66	Logiya	5360	1786.67	20.40	4603.31	1534.44	17.52
67	Maychew	5265	1755.00	20.03	4456.88	1485.63	16.96
68	Mechara	4572	1524.00	17.40	4614.50	1538.17	17.56
69	Meki	5394	1798.00	20.53	4584.20	1528.07	17.44
70	Mendi	4659	1553.00	17.73	4340.90	1446.97	16.52
71	Metehara	5334	1778.00	20.30	4607.84	1535.95	17.53
72	Metema	5108	1702.67	19.44	4349.57	1449.86	16.55
73	Metu	4603	1534.33	17.52	4131.11	1377.04	15.72
74	Mieso	5184	1728.00	19.73	4730.33	1576.78	18.00

Table 4.3 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
75	Mille	5162	1720.67	19.64	4569.38	1523.13	17.39
76	Mojo	5467	1822.33	20.80	4595.75	1531.92	17.49
77	Mota	5373	1791.00	20.45	4439.25	1479.75	16.89
78	Moyale	4708	1569.33	17.91	4139.39	1379.80	15.75
79	Nejo	4643	1547.67	17.67	4103.61	1367.87	15.61
80	Nekemte	4622	513.47	5.86	4064.30	451.59	5.16
81	Sekota	5354	1540.67	17.59	4284.44	1354.77	15.47
82	Sendafa	5011	1784.67	20.37	4474.30	1428.15	16.30
83	Shakiso	4622	1670.33	19.07	4503.26	1491.43	17.03
84	Shambu	4636	1540.67	17.59	4319.31	1501.09	17.14
85	Sheno	4787	1545.33	17.64	4577.15	1439.77	16.44
86	Shire	5249	1595.67	18.22	4207.18	1525.72	17.42
87	Sodo	4805	1749.67	19.97	4416.03	1402.39	16.01
88	Sokoru	4939	1601.67	18.28	4153.12	1472.01	16.80
89	Tefki	5281	1646.33	18.79	4498.64	1384.37	15.80
90	Tenta	5515	1760.33	20.10	4529.66	1499.55	17.12
91	Tulu Milki	5202	1838.33	20.99	4395.88	1509.89	17.24
92	Weldiya	5133	1734.00	19.79	4553.48	1465.29	16.73
93	Weliso	5026	1711.00	19.53	4498.64	1517.83	17.33
94	Welkite	5080	1675.33	19.12	4132.08	1499.55	17.12
95	Wereta	5338	1693.33	19.33	4405.29	1377.36	15.72
96	Wonji	5442	1779.33	20.31	4609.68	1468.43	16.76
97	Wukro	5493	1814.00	20.71	4238.47	1536.56	17.54
98	Yabelo	4787	1831.00	20.90	4133.12	1412.82	16.13

Table 4.3 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
99	Yirgalem	4675	1595.67	18.22	4408.60	1377.71	15.73
100	Ziway	5434	1558.33	17.79	4582.31	1469.53	16.78
	Max	5515	1838.33	20.99	5909.99	1970.00	22.49
	Min	4107	513.47	5.86	4064.30	451.59	5.16
	Average	5059.95	1660.90	18.96	4446.97	1472.02	16.80

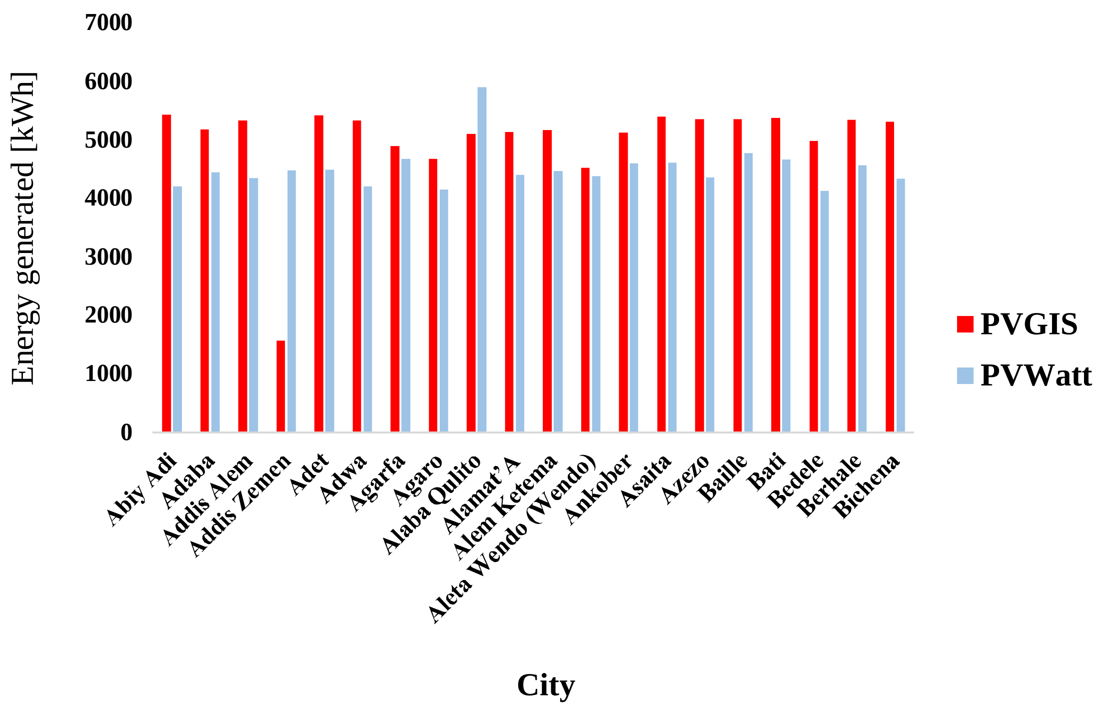


Figure 4.11: Annual energy generated using PVGIS and PVWatts in 20 locations

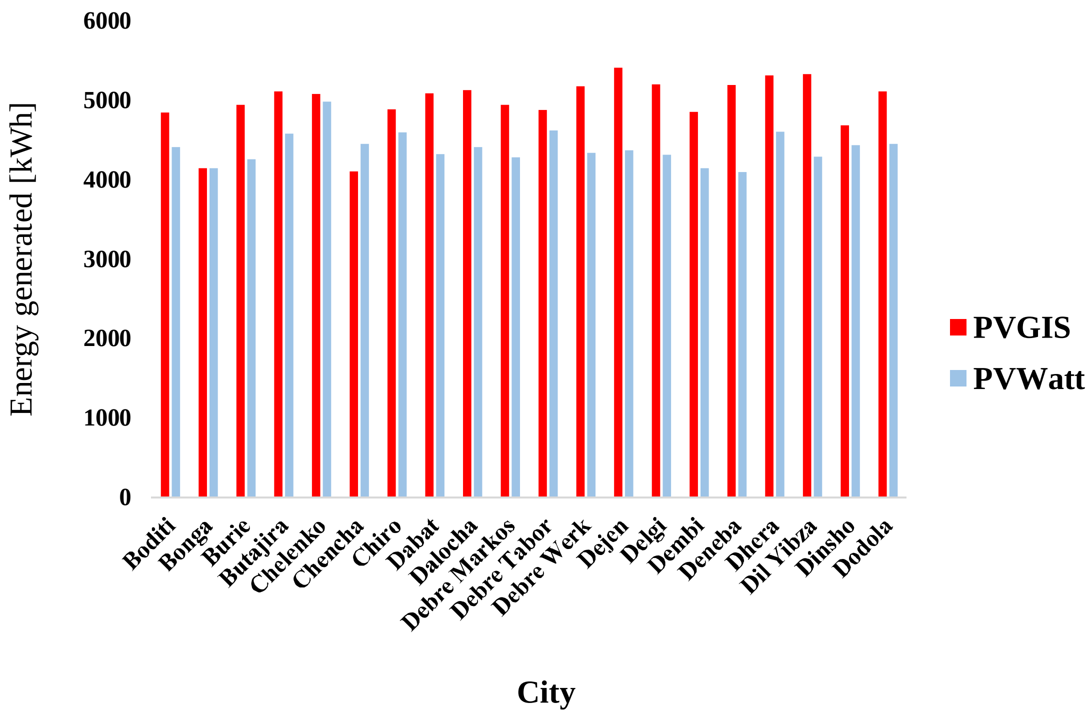


Figure 4.12: Annual energy generated using PVGIS and PVWatts in 20 locations

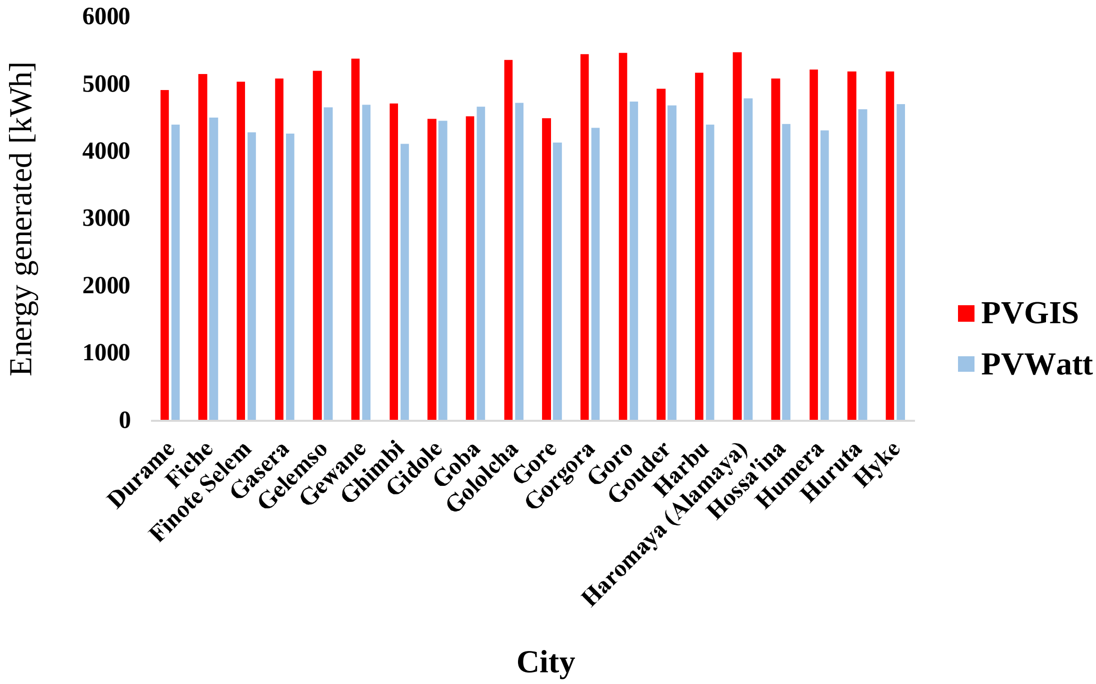


Figure 4.13: Annual energy generated using PVGIS and PVWatts in 20 locations

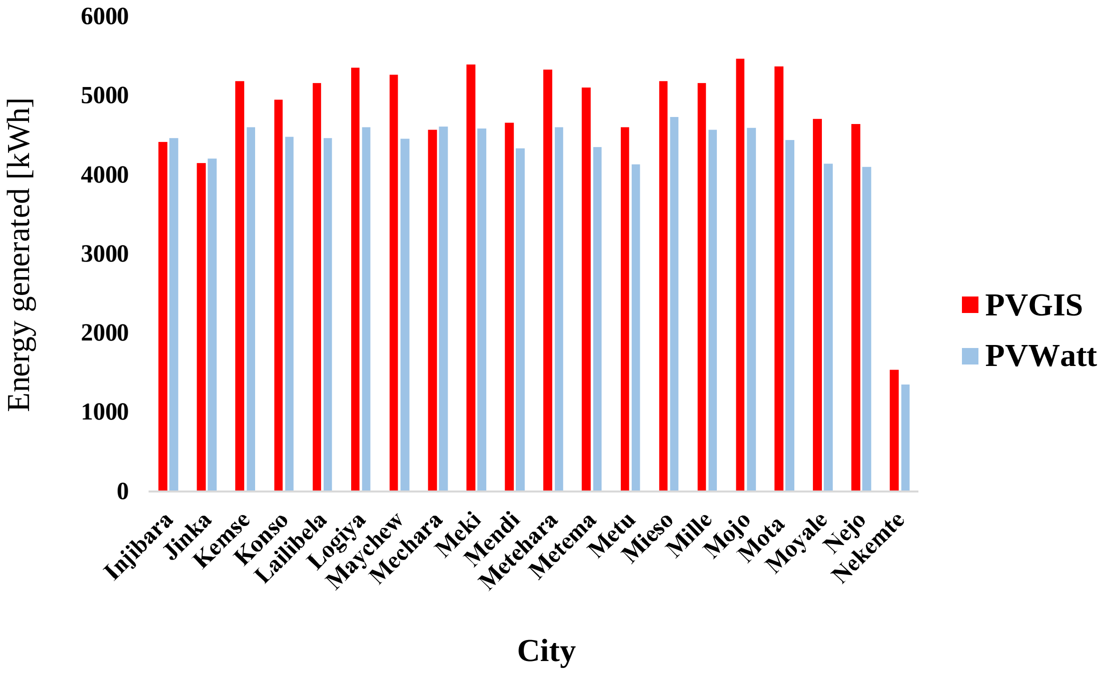


Figure 4.14: Annual energy generated using PVGIS and PVWatts in 20 locations

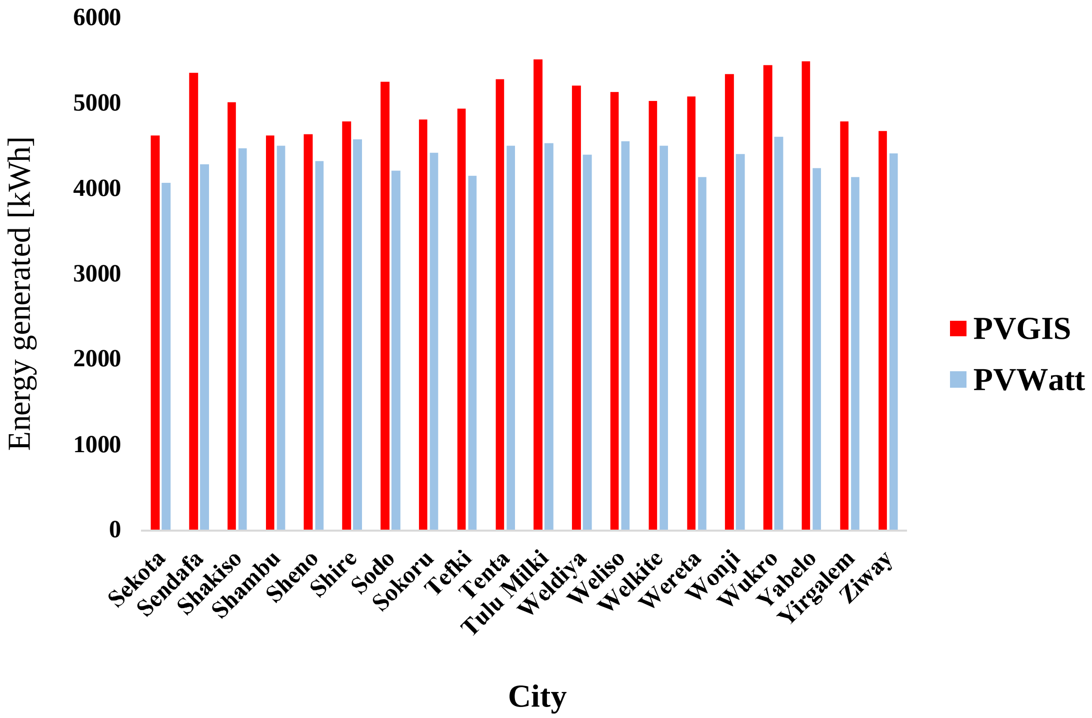


Figure 4.15: Annual energy generated using PVGIS and PVWatts in 20 locations

C. Third Scenario: 5 kW PV System

Energy generation data obtained using the online software PVGIS and PVWatts are tabulated in Table 4.4 and presented in Figure 4.16 – 4.20. PVGIS showed that the annual energy generation in the selected cities varies from 9193 to 4572 kWh/m^2 and the average capacity factor is 19.14%. The maximum energy generation is recorded in Tenta city located in south Ethiopia and the lowest energy generation was recorded in Chencha city located in north Ethiopia. PVWatt showed that the annual energy generation in the selected cities varied from 8307.67 to 4614.503 kWh/m^2 and the average capacity factor was 16.70%. The maximum energy generation was recorded in Dil Yibza city located in North Ethiopia and the lowest energy generation as recorded in Nekemte city located in west Ethiopia.

Table 4.4: Annual energy generated data in the selected 100 cities for 5kW system.

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**	**Annual PV energy [kWh]**	**Specific annual Yield [kWh/kWp]**	**Capacity Factor [%]**
1	Abiy Adi	9067	1813.4	20.70	7015.76	1403.15	16.02
2	Adaba	8643	1728.6	19.73	7421.51	1484.30	16.94
3	Addis Alem	8898	1779.6	20.32	7246.78	1449.36	16.55
4	Addis Zemen	7834	1566.8	17.89	7471.14	1494.23	17.06
5	Adet	9044	1808.8	20.65	7480.85	1496.17	17.08
6	Adwa	8888	1777.6	20.29	7021.56	1404.31	16.03
7	Agarfa	8165	1633	18.64	7797.27	1559.45	17.80
8	Agaro	7795	1559	17.80	6919.34	1383.87	15.80
9	Alaba Qulito	8498	1699.6	19.40	7387.49	1477.50	16.87
10	Alamat’A	8562	1712.4	19.55	7551.48	1510.30	17.24
11	Alem Ketema	8617	1723.4	19.67	7449.79	1489.96	17.01
12	Aleta Wendo	7540	1508	17.21	7312.40	1462.48	16.69

Table 4.4 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
13	Ankober	8550	1710	19.52	7676.78	1535.36	17.53
14	Asaita	8996	1799.2	20.54	7680.86	1536.17	17.54
15	Azezo	8113	1622.6	18.52	7263.25	1452.65	16.58
16	Baille	8922	1784.4	20.37	7964.08	1592.82	18.18
17	Bati	8965	1793	20.47	7789.32	1557.86	17.78
18	Bedele	8318	1663.6	18.99	6890.33	1378.07	15.73
19	Berhale	8904	1780.8	20.33	7553.67	1510.73	17.25
20	Bichena	8868	1773.6	20.25	7233.82	1446.76	16.52
21	Boditi	8083	1616.6	18.45	7360.05	1472.01	16.80
22	Bonga	6917	1383.4	15.79	6920.00	1384.00	15.80
23	Burie	8241	1648.2	18.82	7097.57	1419.51	16.20
24	Butajira	8532	1706.4	19.48	7642.96	1528.59	17.45
25	Chelenko	8471	1694.2	19.34	8307.67	1661.53	18.97
26	Chencha	6845	1369	15.63	7428.18	1485.64	16.96
27	Chiro	8147	1629.4	18.60	7669.91	1533.98	17.51
28	Dabat	8487	1697.4	19.38	7205.52	1441.10	16.45
29	Dalocha	8560	1712	19.54	7354.49	1470.90	16.79
30	Debre Markos	8240	1648	18.81	7146.59	1429.32	16.32
31	Debre Tabor	8137	1627.4	18.58	7713.25	1542.65	17.61
32	Debre Werk	8627	1725.4	19.70	7240.26	1448.05	16.53
33	Dejen	9025	1805	20.61	7295.77	1459.15	16.66
34	Delgi	8675	1735	19.81	7192.13	1438.43	16.42
35	Dembi	8091	1618.2	18.47	6921.54	1384.31	15.80
36	Deneba	8664	1732.8	19.78	6837.54	1367.51	15.61
37	Dhera	8864	1772.8	20.24	7675.75	1535.15	17.52

Table 4.4 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
38	Dil Yibza	8891	1778.2	20.30	7151.96	1430.39	16.33
39	Dinsho	7821	1564.2	17.86	7416.37	1483.27	16.93
40	Dodola	8525	1705	19.46	7427.52	1485.50	16.96
41	Durame	8182	1636.4	18.68	5862.86	1172.57	13.39
42	Fiche	8576	1715.2	19.58	7508.13	1501.63	17.14
43	Finote Selem	8398	1679.6	19.17	7142.26	1428.45	16.31
44	Gasera	8478	1695.6	19.36	7099.13	1419.83	16.21
45	Gelemso	8656	1731.2	19.76	7757.97	1551.59	17.71
46	Gewane	8966	1793.2	20.47	7822.23	1564.45	17.86
47	Ghimbi	7857	1571.4	17.94	6845.53	1369.11	15.63
48	Gidole	7470	1494	17.05	7420.34	1484.07	16.94
49	Goba	7527	1505.4	17.18	7780.04	1556.01	17.76
50	Gololcha	8930	1786	20.39	7869.95	1573.99	17.97
51	Gore	7487	1497.4	17.09	6883.89	1376.78	15.72
52	Gorgora	9072	1814.4	20.71	7246.30	1449.26	16.54
53	Goro	9099	1819.8	20.77	7902.23	1580.45	18.04
54	Gouder	8217	1643.4	18.76	7803.01	1560.60	17.82
55	Harbu	8612	1722.4	19.66	7326.64	1465.33	16.73
56	Haromaya	9115	1823	20.81	7977.05	1595.41	18.21
57	Hossa'ina	8466	1693.2	19.33	7348.10	1469.62	16.78
58	Humera	8700	1740	19.86	7190.71	1438.14	16.42
59	Huruta	8648	1729.6	19.74	7713.43	1542.69	17.61
60	Hyke	8648	1729.6	19.74	7832.43	1566.49	17.88
61	Injibara	7366	1473.2	16.82	7437.67	1487.53	16.98

Table 4.4 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
62	Jinka	6914	1382.8	15.79	7015.64	1403.13	16.02
63	Kemse	8644	1728.8	19.74	7679.30	1535.86	17.53
64	Konso	8255	1651	18.85	7474.41	1494.88	17.06
65	Lailibela	8605	1721	19.65	7450.54	1490.11	17.01
66	Logiya	8931	1786.2	20.39	7672.18	1534.44	17.52
67	Maychw	8774	1754.8	20.03	7428.14	1485.63	16.96
68	Mechara	4572	914.4	10.44	4614.50	922.90	10.54
69	Meki	8992	1798.4	20.53	6112.27	1222.45	13.95
70	Mendi	7766	1553.2	17.73	7234.83	1446.97	16.52
71	Metehara	8890	1778	20.30	7679.74	1535.95	17.53
72	Metema	8513	1702.6	19.44	7249.28	1449.86	16.55
73	Metu	7671	1534.2	17.51	6885.18	1377.04	15.72
74	Mieso	8640	1728	19.73	7883.89	1576.78	18.00
75	Mille	8603	1720.6	19.64	7615.63	1523.13	17.39
76	Mojo	9111	1822.2	20.80	7657.35	1531.47	17.48
77	Mota	8957	1791.4	20.45	7398.76	1479.75	16.89
78	Moyale	7848	1569.6	17.92	6898.98	1379.80	15.75
79	Nejo	7740	1548	17.67	6845.77	1369.15	15.63
80	Nekemte	7702	1540.4	17.58	5419.07	1083.81	12.37
81	Sekota	8926	1785.2	20.38	7140.73	1428.15	16.30
82	Sendafa	8354	1670.8	19.07	7457.16	1491.43	17.03
83	Shakiso	7700	1540	17.58	7505.44	1501.09	17.14
84	Shambu	7726	1545.2	17.64	7198.85	1439.77	16.44
85	Sheno	7977	1595.4	18.21	7628.58	1525.72	17.42

Table 4.4 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
86	Shire	8750	1750	19.98	7018.54	1403.71	16.02
87	Sodo	8005	1601	18.28	7360.05	1472.01	16.80
88	Sokoru	8233	1646.6	18.80	6921.87	1384.37	15.80
89	Tefki	8803	1760.6	20.10	7497.74	1499.55	17.12
90	Tenta	9193	1838.6	20.99	7549.43	1509.89	17.24
91	Tulu Milki	8671	1734.2	19.80	7326.47	1465.29	16.73
92	Weldiya	8554	1710.8	19.53	7589.14	1517.83	17.33
93	Weliso	8377	1675.4	19.13	7497.74	1499.55	17.12
94	Welkite	8467	1693.4	19.33	6886.81	1377.36	15.72
95	Wereta	8897	1779.4	20.31	7342.14	1468.43	16.76
96	Wonji	9069	1813.8	20.71	7682.80	1536.56	17.54
97	Wukro	9158	1831.6	20.91	7064.12	1412.82	16.13
98	Yabelo	7977	1595.4	18.21	6833.56	1366.71	15.60
99	Yirgalem	7793	1558.6	17.79	7347.66	1469.53	16.78
100	Ziway	9058	1811.6	20.68	7637.18	1527.44	17.44
	max	9193	1838.6	20.99	8307.67	1661.53	18.97
	min	4572	914.4	10.44	4614.50	922.90	10.54
	Average	8383.2	1676.6	19.14	7316.04	1463.21	16.70

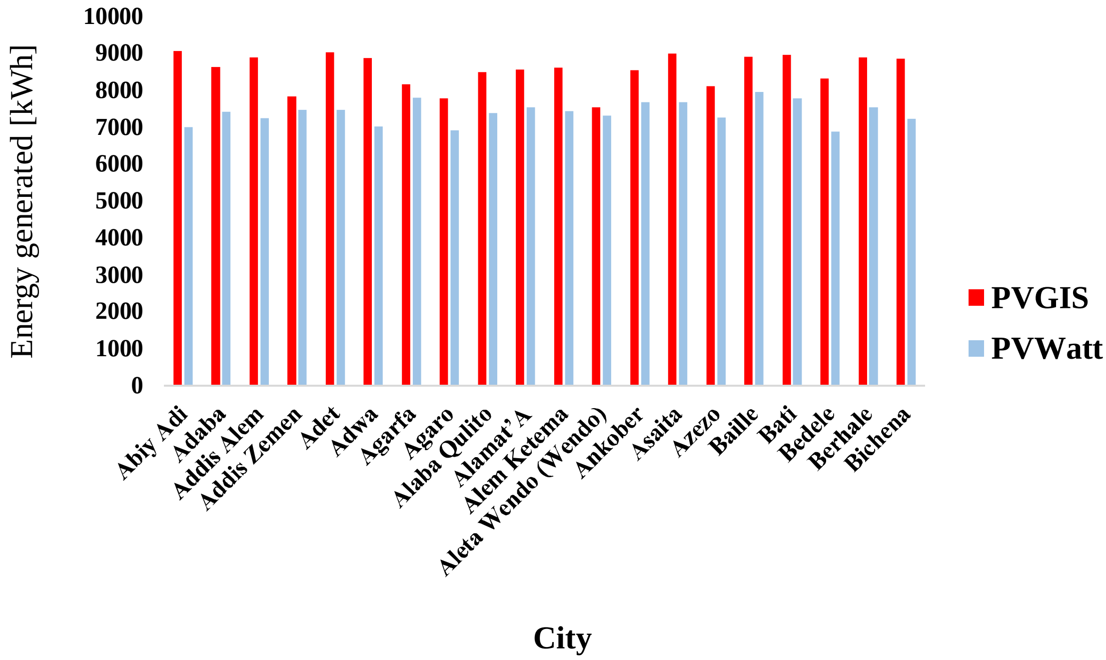


Figure 4.16: Annual energy generated using PVGIS and PVWatts in 20 locations

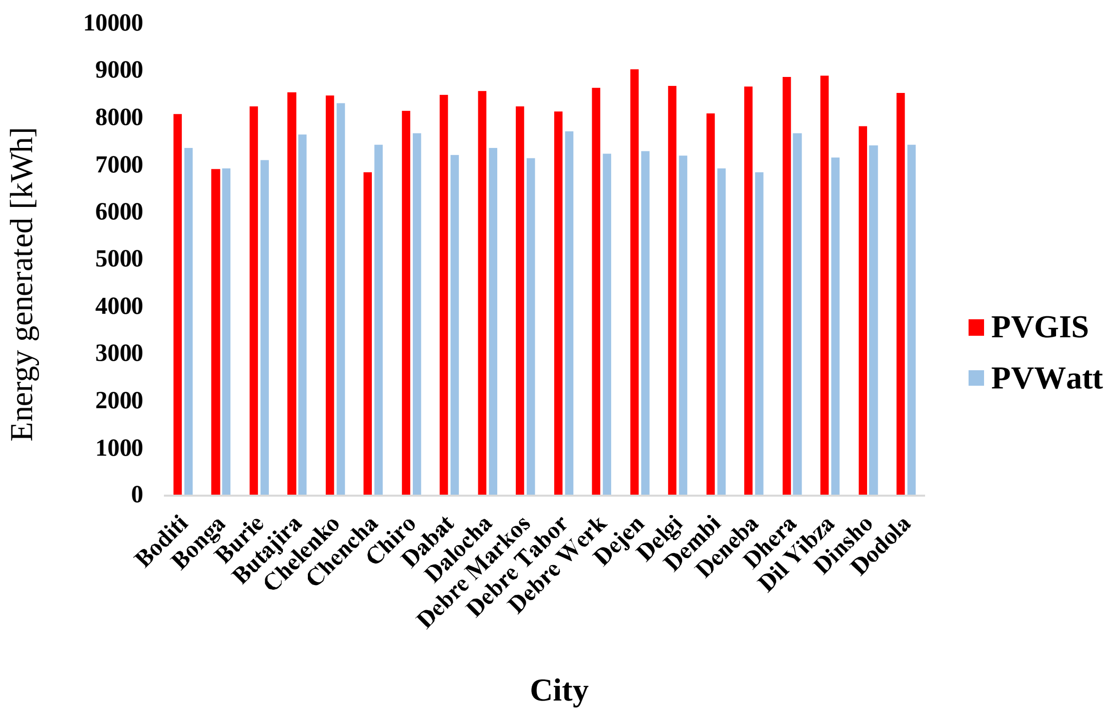


Figure 4.17: Annual energy generated using PVGIS and PVWatts in 20 locations

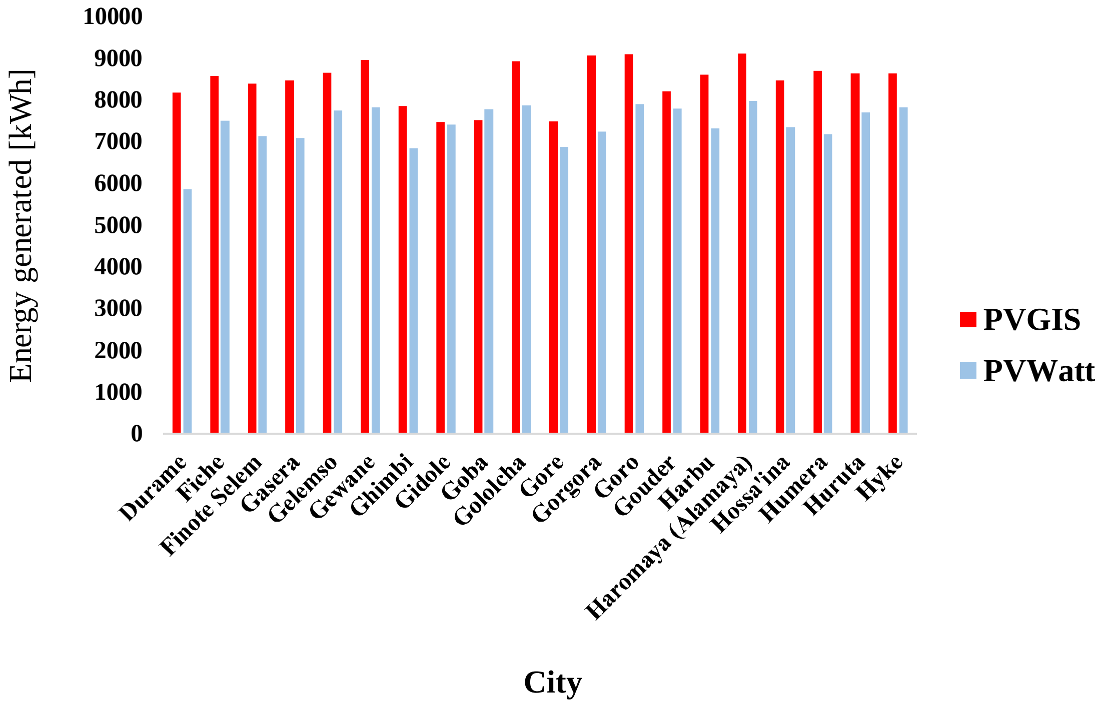


Figure 4.18: Annual energy generated using PVGIS and PVWatts in 20 locations

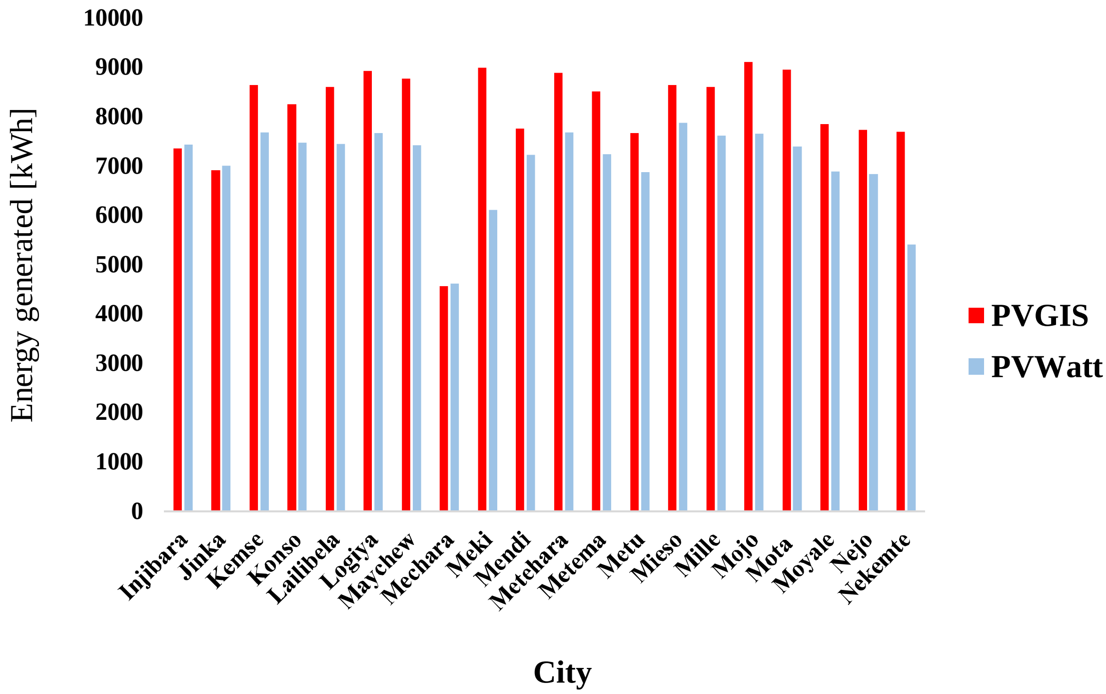


Figure 4.19: Annual energy generated using PVGIS and PVWatts in 20 locations

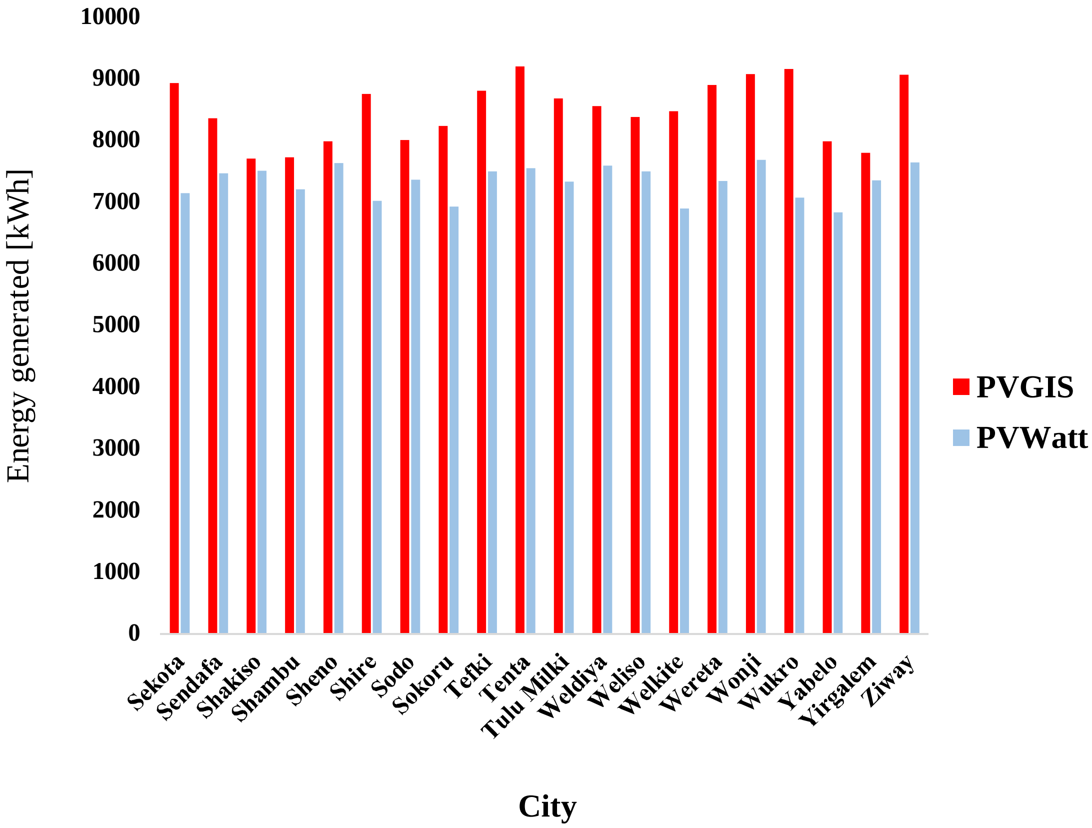


Figure 4.20: Annual energy generated using PVGIS and PVWatts in 20 locations

D. Forth Scenario: 45 kW PV System

Energy generation data obtained using the online software PVGIS and PVWatts are tabulated in Table 4.5 and presented in Figure 4.21 – 4.25. PVGIS showed that the annual energy generation in the selected cities varied from 82740 to 61600 kWh/m^2 and the average capacity factor was 19.14%. The maximum energy generation ws recorded in Tenta city located in south Ethiopia and the lowest energy generation was recorded in Chencha city located in north Ethiopia. PVWatt showed that the annual energy generation in the selected cities varied from 74769.035 to 5721.568 kWh/m^2 and the average capacity factor was 16.61%. The maximum energy generation was recorded in Dil Yibza city located in North Ethiopia and the lowest energy generation was recorded in Nekemte city located in west Ethiopia.

Table 4.5: Annual energy generated data in the selected 100 cities for 45kW system.

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
1	Abiy Adi	81590	1813.111	20.70	63141.88	1403.15	16.02
2	Adaba	77770	1728.222	19.73	66793.57	1484.30	16.94
3	Addis Alem	70520	1567.111	17.89	67240.21	1494.23	17.06
4	Addis Zemen	80050	1778.889	20.31	66626.16	1480.58	16.90
5	Adet	81390	1808.667	20.65	67327.63	1496.17	17.08
6	Adwa	80000	1777.778	20.29	64885.26	1441.89	16.46
7	Agarfa	72110	1602.444	18.29	68851.00	1530.02	17.47
8	Agaro	70180	1559.556	17.80	62274.09	1383.87	15.80
9	Alaba	74380	1652.889	18.87	66277.12	1472.82	16.81
10	Alamat'a	77060	1712.444	19.55	67963.33	1510.30	17.24
11	Alem Ketema	77550	1723.333	19.67	67048.09	1489.96	17.01
12	Aleta Wondo	67870	1508.222	17.22	65811.63	1462.48	16.69
13	Ankober	76950	1710	19.52	69091.01	1535.36	17.53
14	Asaita	80970	1799.333	20.54	69127.73	1536.17	17.54
15	Azezo	73060	1623.556	18.53	65369.23	1452.65	16.58
16	Babile	74520	1656	18.90	69588.30	1546.41	17.65
17	Bati	80670	1792.667	20.46	70038.31	1556.41	17.77
18	Bedele	74870	1663.778	18.99	62012.97	1378.07	15.73
19	Berhale	80120	1780.444	20.32	68595.58	1524.35	17.40
20	Bichena	79800	1773.333	20.24	65104.35	1446.76	16.52
21	Boditi	72740	1616.444	18.45	66240.47	1472.01	16.80
22	Bonga	62260	1383.556	15.79	62280.02	1384.00	15.80
23	Burie	74160	1648	18.81	63878.14	1419.51	16.20

Table 4.5 Continued

No	City	PVGIS Annual PV energy [kWh]	PVGIS Specific annual Yield [kWh/kWp]	PVGIS Capacity Factor [%]	PVWatt Annual PV energy [kWh]	PVWatt Specific annual Yield [kWh/kWp]	PVWatt Capacity Factor [%]
24	Butajira	76790	1706.444	19.48	68786.59	1528.59	17.45
25	Chelenko	76230	1694	19.34	74769.03	1661.53	18.97
26	Chencha	61600	1368.889	15.63	66853.66	1485.64	16.96
27	Chiro	73320	1629.333	18.60	71156.44	1581.25	18.05
28	Dabat	76370	1697.111	19.37	64849.65	1441.10	16.45
29	Dalocha	77040	1712	19.54	66190.45	1470.90	16.79
30	Debre Markos	74170	1648.222	18.82	64319.30	1429.32	16.32
31	Debre Tabor	73220	1627.111	18.57	69419.26	1542.65	17.61
32	Debre Werk	61700	1371.111	15.65	67467.98	1499.29	17.12
33	Dejen	81230	1805.111	20.61	5836.62	129.70	1.48
34	Delgi	78070	1734.889	19.80	64729.15	1438.43	16.42
35	Dembi	72800	1617.778	18.47	62293.83	1384.31	15.80
36	Deneba	76290	1695.333	19.35	67028.78	1489.53	17.00
37	Dhera	79800	1773.333	20.24	69081.77	1535.15	17.52
38	Dil Yibza	79990	1777.556	20.29	5721.57	127.15	1.45
39	Dinsho	70400	1564.444	17.86	66747.33	1483.27	16.93
40	Dodola	76730	1705.111	19.46	66847.64	1485.50	16.96
41	Durame	79630	1769.556	20.20	65957.22	1465.72	16.73
42	Fiche	77190	1715.333	19.58	67573.14	1501.63	17.14
43	Finote Selam	75600	1680	19.18	64280.34	1428.45	16.31
44	Gasera	79260	1761.333	20.11	69193.06	1537.62	17.55
45	Gelemso	77910	1731.333	19.76	69821.72	1551.59	17.71
46	Gewane	80680	1792.889	20.47	70400.03	1564.45	17.86
47	Ghimbi	70710	1571.333	17.94	61609.80	1369.11	15.63

Table 4.5 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
48	Gidole	67220	1493.778	17.05	66783.11	1484.07	16.94
49	Goba	67730	1505.111	17.18	70020.32	1556.01	17.76
50	Gololcha	80330	1785.111	20.38	70829.55	1573.99	17.97
51	Gore	67370	1497.111	17.09	61954.99	1376.78	15.72
52	Gorgora	81660	1814.667	20.72	65216.75	1449.26	16.54
53	Goro	81910	1820.222	20.78	71120.11	1580.45	18.04
54	Gouder	73960	1643.556	18.76	70227.09	1560.60	17.82
55	Harbu	75770	1683.778	19.22	65135.15	1447.45	16.52
56	Haromaya	82010	1822.444	20.80	71793.46	1595.41	18.21
57	Hossaina	76210	1693.556	19.33	66132.94	1469.62	16.78
58	Humera	78280	1739.556	19.86	64716.38	1438.14	16.42
59	Huruta	77850	1730	19.75	69420.84	1542.69	17.61
60	Hyke	77830	1729.556	19.74	70491.89	1566.49	17.88
61	Injibara	66300	1473.333	16.82	66938.98	1487.53	16.98
62	Jinka	62250	1383.333	15.79	63140.75	1403.13	16.02
63	Kemse	77810	1729.111	19.74	69113.74	1535.86	17.53
64	Konso	74280	1650.667	18.84	69507.64	1544.61	17.63
65	Laibela	77430	1720.667	19.64	67054.86	1490.11	17.01
66	Logiya	80390	1786.444	20.39	69049.63	1534.44	17.52
67	Maychew	78960	1754.667	20.03	66853.26	1485.63	16.96
68	Mechara	68610	1524.667	17.40	69217.54	1538.17	17.56
69	Meki	80910	1798	20.53	68763.06	1528.07	17.44
70	Mendi	69890	1553.111	17.73	65113.46	1446.97	16.52
71	Metehara	80010	1778	20.30	69117.61	1535.95	17.53

Table 4.5 Continued

No	City	PVGIS			PVWatt		
		Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]	Annual PV energy [kWh]	Specific annual Yield [kWh/kWp]	Capacity Factor [%]
73	Metu	69040	1534.222	17.51	61966.65	1377.04	15.72
74	Mieso	77780	1728.444	19.73	70955.03	1576.78	18.00
75	Mille	77420	1720.444	19.64	68540.68	1523.13	17.39
76	Mojo	81990	1822	20.80	68936.27	1531.92	17.49
77	Mota	79080	1757.333	20.06	66098.05	1468.85	16.77
78	Moyale	70650	1570	17.92	62090.86	1379.80	15.75
79	Nejo	69690	1548.667	17.68	61611.92	1369.15	15.63
80	Nekemte	70460	1565.778	17.87	61267.83	1361.51	15.54
81	sekota	79870	1774.889	20.26	64152.69	1425.62	16.27
82	Sendafa	75180	1670.667	19.07	67114.48	1491.43	17.03
83	Shakiso	69290	1539.778	17.58	67548.95	1501.09	17.14
84	shambu	69530	1545.111	17.64	64789.65	1439.77	16.44
85	Sheno	71800	1595.556	18.21	68657.27	1525.72	17.42
86	Shire	79860	1774.667	20.26	63045.96	1401.02	15.99
87	Sodo	72830	1618.444	18.48	66369.43	1474.88	16.84
88	Sokoru	69970	1554.889	17.75	61950.20	1376.67	15.72
89	Tefki	76690	1704.222	19.45	67534.45	1500.77	17.13
90	Tenta	82740	1838.667	20.99	67944.87	1509.89	17.24
91	Tulu Milki	78920	1753.778	20.02	65323.75	1451.64	16.57
92	Weldiya	76980	1710.667	19.53	68302.24	1517.83	17.33
93	Weliso	74380	1652.889	18.87	67486.81	1499.71	17.12
94	Welkite	76180	1692.889	19.33	61981.25	1377.36	15.72
95	Wereta	79990	1777.556	20.29	65688.18	1459.74	16.66

Table 4.5 Continued

No	City	PVGIS Annual PV energy [kWh]	PVGIS Specific annual Yield [kWh/kWp]	PVGIS Capacity Factor [%]	PVWatt Annual PV energy [kWh]	PVWatt Specific annual Yield [kWh/kWp]	PVWatt Capacity Factor [%]
96	Wonji	81610	1813.556	20.70	69145.19	1536.56	17.54
97	Wukro	81740	1816.444	20.74	63820.88	1418.24	16.19
98	Yabelo	71790	1595.333	18.21	61502.02	1366.71	15.60
99	Yirga Alem	68790	1528.667	17.45	64964.96	1443.67	16.48
100	Ziway	81530	1811.778	20.68	68734.59	1527.44	17.44
	max	82740	1838.667	20.99	74769.03	1661.53	18.97
	min	61600	1368.889	15.63	5721.57	127.15	1.45
	Average	75447	1676.6	19.14	65469.82	1454.88	16.61

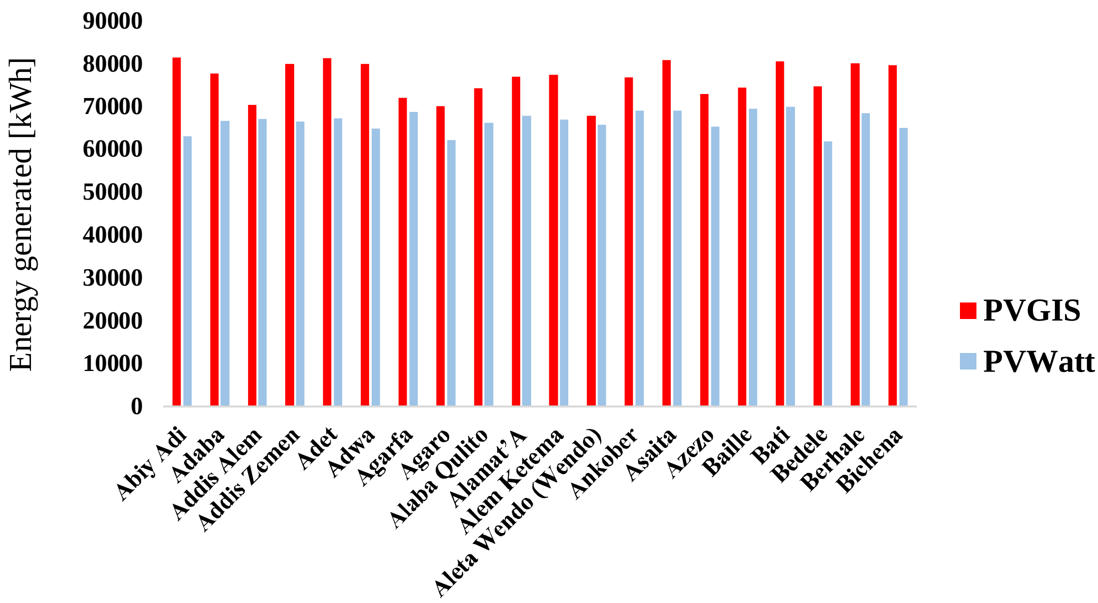


Figure 4.21: Annual energy generated using PVGIS and PVWatts in 20 locations

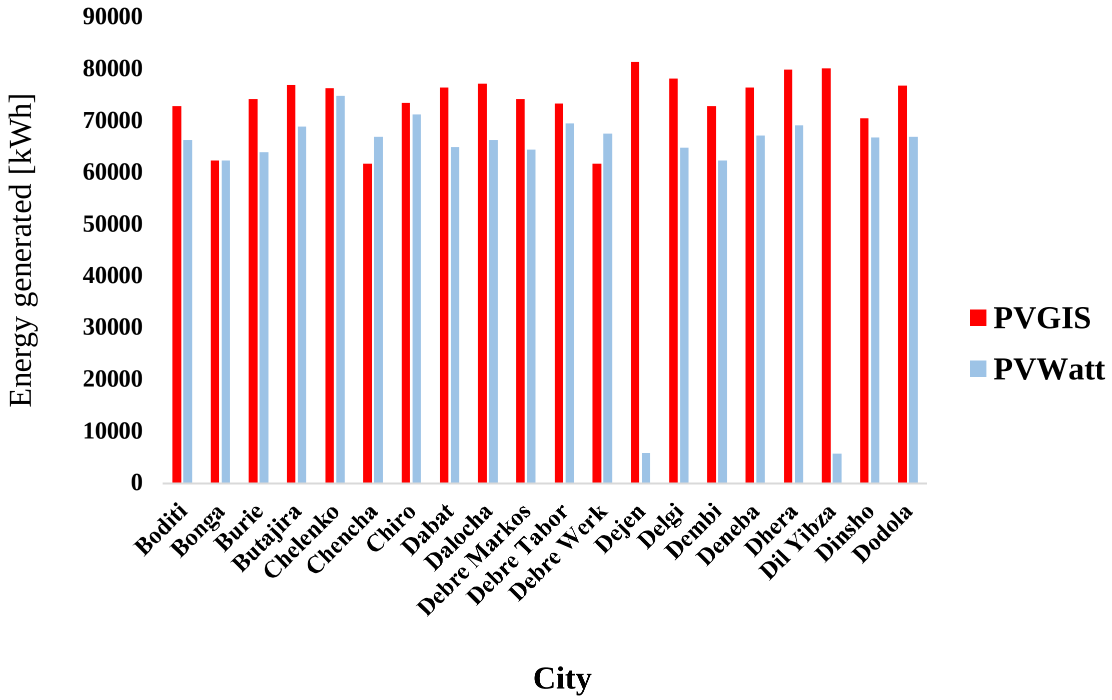


Figure 4.22: Annual energy generated using PVGIS and PVWatts in 20 locations

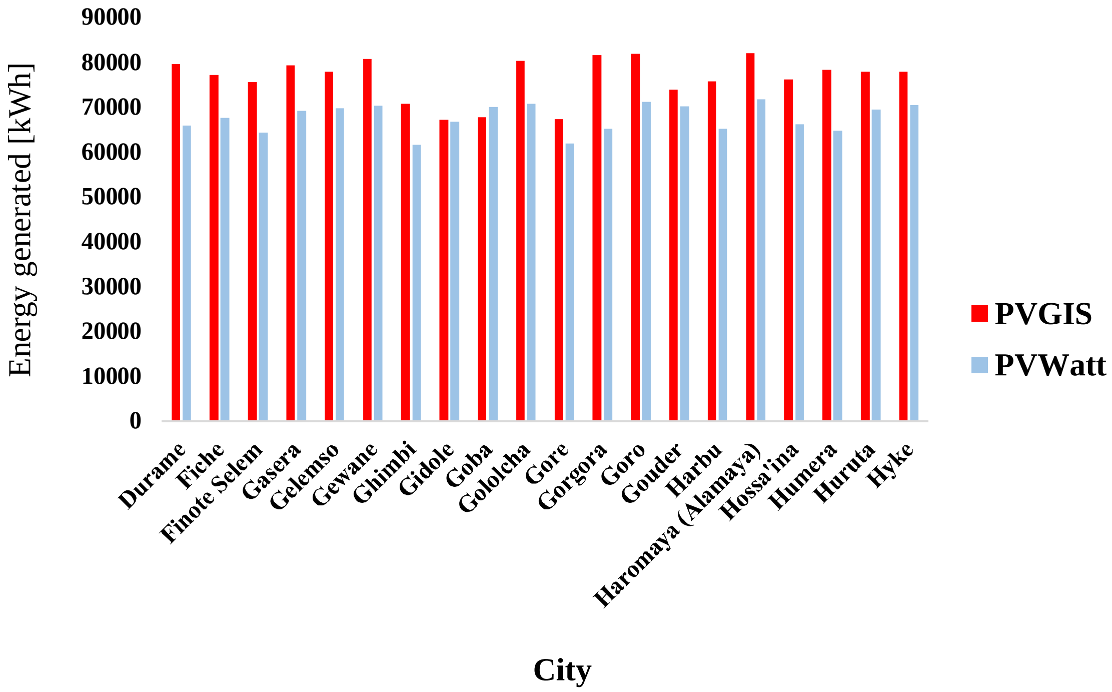


Figure 4.23: Annual energy generated using PVGIS and PVWatts in 20 locations

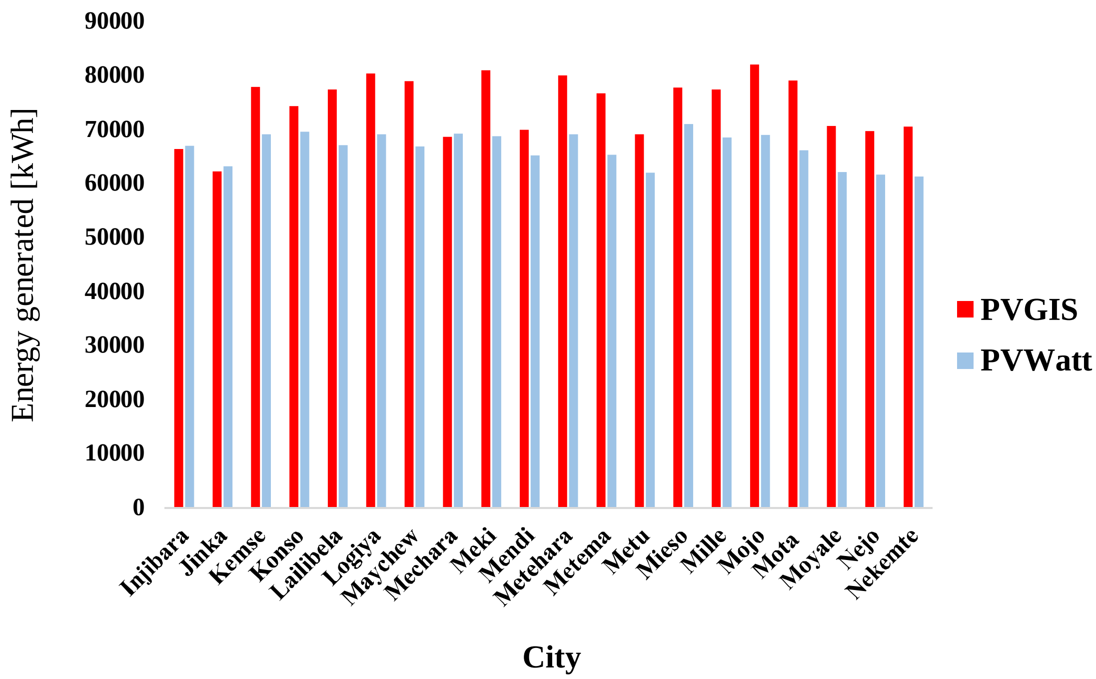


Figure 4.24: Annual energy generated using PVGIS and PVWatts in 20 locations

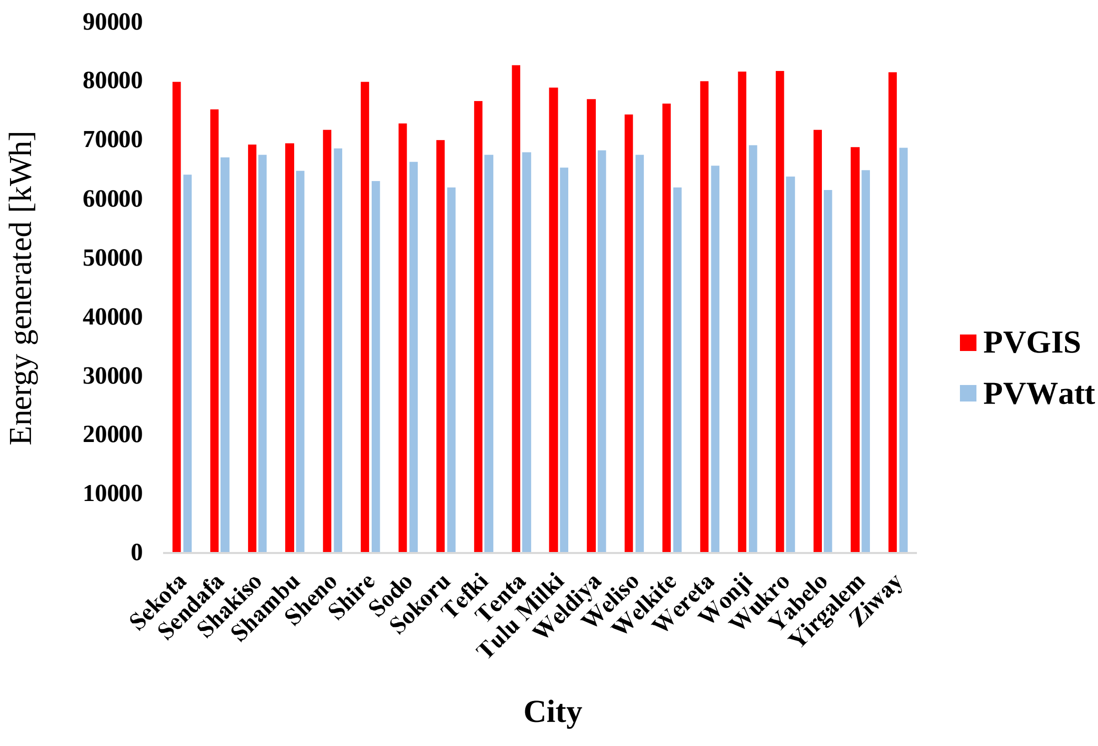


Figure 4.25: Annual energy generated using PVGIS and PVWatts in 20 locations

4.3 Performance Comparison of PVGIS and PVWatt

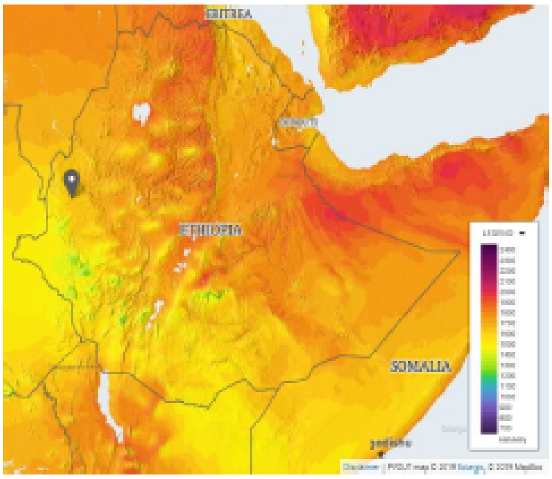
PVGIS software provides the maximum annual output compared to PVWatt. The value of capacity factor and performance ratio for PVGIS are significantly much higher than PVWatt. Table 4.2 shows the maximum energy output, capacity factor, and solar irradiation for each scenario. Comparing the two simulation software PVGIS is found to be the most widley used and effective tool. PVGIS is able to perform various analyzes.

Table 4.6: Average results of performance parameters for PVGIS and PVWatt

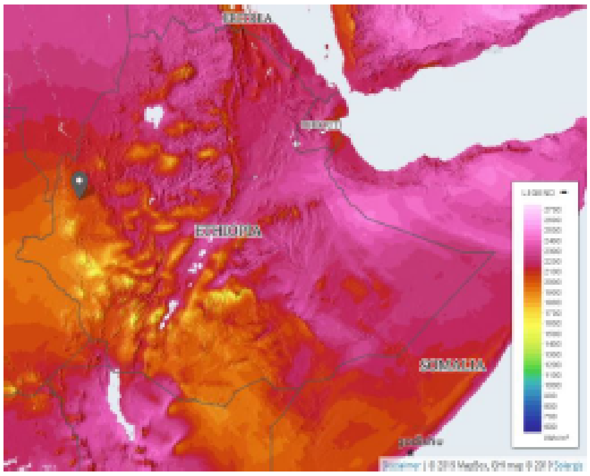
Scenario	Average Annual PV Energy [kWh]		Average Capacity Factor [%]		Average Annual Solar Irradiation [kWh/m^2]	
	PVGIS	PVWatt	PVGIS	PVWatt	PVGIS	PVWatt
1kW	1686.579	1479.20	19.25	16.89	2208.43	1956.96
3kW	5059.95	4446.97	18.96	16.80		
5kW	8383.2	7316.04	19.14	16.70		
45kW	75447	65469.82	19.14	16.61		

4.4 Solar Energy Potential and Radiation Characteristics

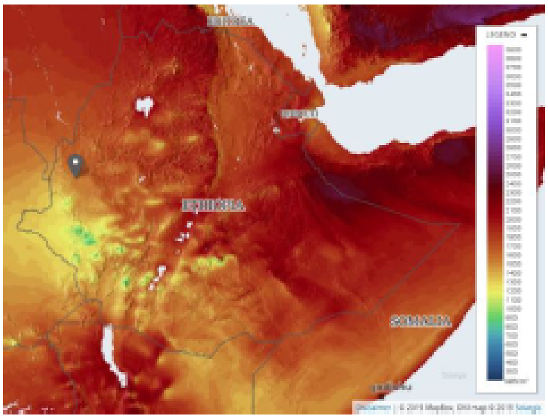
Primary Climate Spectacles that governs solar power generation were presented in the Figure 4.26. It can be realized that PVOUT of the country ranges between 1500 and 2000 kWh/kWp, the maximum values detected in the east of Tigray, east Amara, central and east of Oromiya and north Somali regions. GHI, GTI and DNI of the country ranges between 1900 and 2700 Kwh/m^2 and 1200 and 2300 kWh/ m^2 respectively, the highest values recorded in Somali, Afar, Tigray, Amhara and east Oromiya regions. DIF of the country ranges between 800 and 1000 Kwh/m^2, the highest values recorded in Afar, Gambela, SNNP, west Amhara and south Oromiya regions. Air Temperature of the country ranges between 12 and 32 ^{o}C, the highest values recorded in Afar, Gambela, east Oromiya and Somali regions.



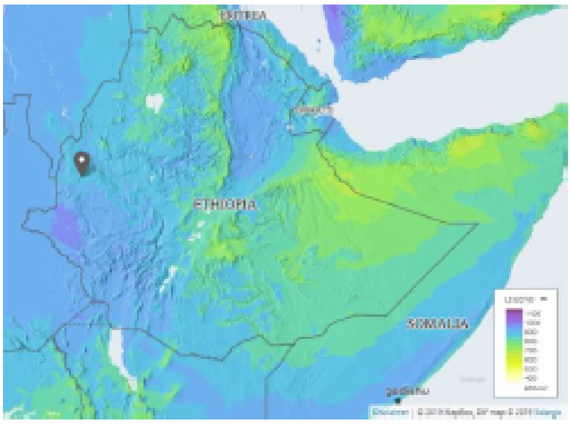
Photovoltaic power potential [kWh/kWp] – PVOUT



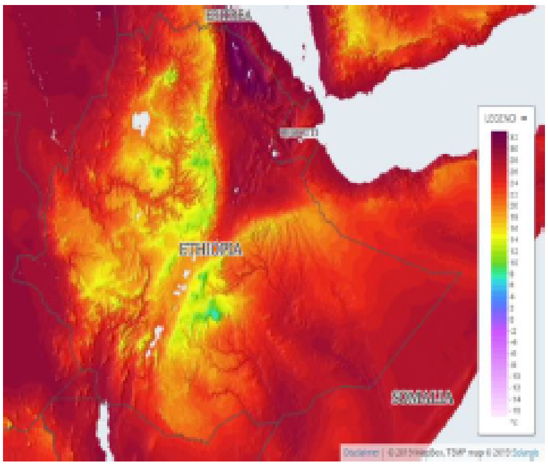
Global horizontal irradiation [kWh/m2] – GHI



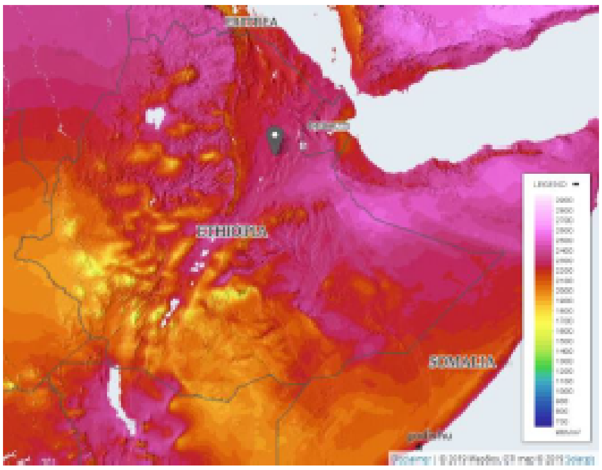
Direct normal irradiation [kWh/m2] - DNI



Diffuse horizontal irradiation [kWh/m2] – DHI



Air Temperature (°C) - TEMP



Global irradiation for optimally tilted surface [kWh/m2] - GIT

Figure 4.26: Ethiopia's long-term average solar resource

4.5 Financial Analysis

RETScreen expert software was implemented to evaluate the economic viability of the proposed systems. The first three scenarios were for roof-parallel house hold. These scenarios were classified based on the living standard or income of the household. This study classified as low, medium and high income level.

A. First Scenario: 1kW system

Table 4.6 illustrated the results of equity payback period, energy production cost, electricity exported to grid and daily solar radiation tilted for 1 kW household rooftop solar PV system for all selected cities. The average energy production cost for 1 kW system was 0.08$/kWh. Energy production cost for Tenta city where annual energy generation was recorded maximum costs 0.067$/kWh and Chencha city where annual energy generation was minimum costs 0.071$/kWh. The equity payback period for both location was 5 years.

Table 4.7: Economic analysis results for 1kW system

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
1	Abiy Adi	6.23	1.794	5	0.065
2	Adaba	5.56	1.636	5	0.08
3	Addis Alem	5.03	1.478	6	0.079
4	Addis Zemen	6.30	1.81	4	0.065
5	Adet	6.07	1.733	5	0.068
6	Adwa	6.08	1.751	5	0.067
7	Agarfa	5.80	1.695	5	0.069
8	Agaro	5.34	1.555	6	0.075
9	Alaba	5.77	1.675	6	0.07
10	Alamat'a	6.18	1.753	5	0.067

Table 4.7 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
11	Alem Ketema	6.00	1.721	5	0.068
12	Aleta Wonde	5.85	1.683	5	0.07
13	Ankober	6.00	1.722	5	0.068
14	Asaita	6.15	1.688	5	0.069
15	Azezo	6.11	1.601	6	0.073
16	Babile	6.15	1.754	6	0.067
17	Bati	5.99	1.678	5	0.07
18	Bedele	5.66	1.645	5	0.071
19	Berhale	6.20	1.785	5	0.066
20	Bichena	6.15	1.767	5	0.066
21	Boditi	5.76	1.672	5	0.07
22	Bonga	5.33	1.553	6	0.075
23	Burie	6.04	1.73	5	0.068
24	Butajira	5.79	1.679	5	0.07
25	Chelenko	6.14	1.735	5	0.068
26	Chencha	5.75	1.644	5	0.071
27	Chiro	6.17	1.738	5	0.067
28	Dabat	6.33	1.779	5	0.066
29	Dalocha	5.78	1.678	5	0.07
30	Debre Markos	6.09	1.748	5	0.67
31	Debre Tabor	6.24	1.795	5	0.065
32	Debre Werk	6.17	1.771	5	0.066
33	Dejen	6.17	1.772	5	0.066
34	Delgi	6.29	1.778	5	0.066
35	Dembi	5.66	1.645	5	0.071

Table 4.7 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
36	Deneba	5.75	1.668	5	0.07
37	Dhera	6.14	1.764	5	0.066
38	Dil Yibza	6.14	1.736	5	0.067
39	Dinsho	5.57	1.638	5	0.072
40	Dodola	5.55	1.634	5	0.072
41	Durame	5.90	1.7	6	0.069
42	Fiche	6.18	1.786	5	0.066
43	Finote Selam	6.05	1.733	5	0.068
44	Gasera	5.88	1.678	5	0.07
45	Gelemso	6.11	1.738	5	0.067
46	Gewane	6.06	1.674	5	0.07
47	Ghimbi	5.68	1.628	5	0.072
48	Gidole	5.79	1.64	6	0.071
49	Goba	5.56	1.635	5	0.072
50	Gololcha	6.09	1.734	5	0.068
51	Gore	5.52	1.597	6	0.073
52	Gorgora	6.29	1.778	5	0.066
53	Goro	5.95	1.699	5	0.069
54	Gouder	5.97	1.729	5	0.068
55	Harbu	6.06	1.629	5	0.072
56	Haromaya	6.06	1.705	5	0.069
57	Hossaina	5.77	1.675	5	0.07
58	Humera	6.33	1.749	5	0.067
59	Huruta	6.13	1.763	5	0.066

Table 4.7 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
60	Hyke	6.13	1.74	5	0.067
61	Injibara	6.01	1.723	5	0.068
62	Jinka	5.81	1.631	5	0.072
63	Kemse	6.27	1.801	5	0.065
64	Konso	5.79	1.642	5	0.071
65	Lalibela	6.15	1.746	5	0.067
66	Logiya	6.16	1.691	5	0.069
67	Maychew	6.16	1.748	5	0.067
68	Mechara	6.11	1.736	5	0.067
69	Meki	5.85	1.708	5	0.069
70	Mendi	5.77	1.618	6	0.072
71	Metehara	6.15	1.767	6	0.066
72	Metema	6.26	1.726	5	0.068
73	Metu	5.52	1.597	6	0.073
74	Mieso	6.15	1.735	5	0.068
75	Mille	6.01	1.682	5	0.07
76	Mojo	6.14	1.763	5	0.066
77	Mota	6.12	1.748	5	0.067
78	Moyale	5.38	1.534	6	0.076
79	Nejo	5.69	1.63	5	0.072
80	Nekemte	6.02	1.723	5	0.068
81	sekota	6.17	1.752	5	0.067
82	Sendafa	5.07	1.488	6	0.079
83	Shakiso	5.67	1.636	5	0.072
84	Shambu	6.03	1.727	5	0.068

Table 4.7 Continued

No	City	Daily Solar Radiation Titled [kWh/m²/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
85	Sheno	5.94	1.704	5	0.069
86	Shire	6.29	1.768	5	0.066
87	Sodo	5.85	1.709	5	0.069
88	Sokoru	5.78	1.677	5	0.07
89	Tefki	5.07	1.489	6	0.079
90	Tenta	6.17	1.759	5	0.067
91	Tulu Milki	6.16	1.77	5	0.066
92	Weldiya	6.17	1.752	5	0.067
93	Weliso	5.99	1.733	5	0.068
94	Welkite	5.99	1.732	5	0.068
95	Wereta	6.14	1.754	5	0.067
96	Wonji	6.12	1.757	5	0.067
97	Wukro	6.26	1.801	4	0.065
98	Yabelo	5.77	1.646	5	0.071
99	Yirga Alem	5.86	1.685	5	0.07
100	Ziway	5.84	1.707	5	0.076
	Max	6.33	1.81	6.00	0.67
	Min	5.03	1.48	4.00	0.07
	Average	5.95	1.70	5.13	0.08

B. Second Scenario: 3kW System

Table 4.7 illustrates the results of equity payback period, energy production cost, electricity exported to grid and daily solar radiation tilted for 3 kW household rooftop solar PV system for all selected cities. The average energy production cost for 3 kW system is 0.063$/kWh. Energy production cost for Tenta city where annual energy generation is recorded maximum costs 0.061$/kWh and Chencha city where annual energy generation is minimum costs 0.065$/kWh and the equity payback period is 4 and 5 years respectively.

Table 4.8: Economic analysis results for 3kW system

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
1	Abiy Adi	6.23	5.367	4	0.060
2	Adaba	5.56	4.908	5	0.066
3	Addis Alem	5.03	4.433	6	0.073
4	Addis Zemen	6.30	5.429	4	0.059
5	Adet	6.07	5.200	4	0.062
6	Adwa	6.08	5.252	4	0.061
7	Agarfa	5.80	5.086	4	0.063
8	Agaro	5.34	4.666	5	0.069
9	Alaba	5.77	5.025	4	0.064
10	Alamat'a	6.18	5.258	4	0.061
11	Alem Ketema	6.00	5.163	4	0.062
12	Aleta Wonde	5.85	5.050	4	0.064
13	Ankober	6.00	5.167	4	0.062
14	Asaita	6.15	5.064	4	0.064
15	Azezo	6.11	5.338	4	0.060
16	Babile	6.15	5.261	4	0.061

Table 4.8 Continued

No	City	Daily Solar Raduation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
17	Bati	5.99	5.035	4	0.064
18	Bedele	5.66	4.935	5	0.065
19	Berhale	6.20	5.354	4	0.060
20	Bichena	6.15	5.302	4	0.061
21	Boditi	5.76	5.016	4	0.064
22	Bonga	5.33	4.658	5	0.069
23	Burie	6.04	5.190	4	0.062
24	Butajira	5.79	5.026	4	0.064
25	Chelenko	6.14	5.253	4	0.061
26	Chencha	5.75	4.993	5	0.065
27	Chiro	6.17	5.213	4	0.062
28	Dabat	6.33	5.338	4	0.060
29	Dalocha	5.78	5.035	4	0.064
30	Debre Markos	6.09	5.244	4	0.061
31	Debre Tabor	6.24	5.384	4	0.060
32	Debre Werk	6.17	5.312	4	0.061
33	Dejen	6.17	5.315	4	0.061
34	Delgi	6.29	5.334	4	0.060
35	Dembi	5.66	4.934	5	0.065
36	Deneba	5.75	5.004	5	0.064
37	Dhera	6.14	5.292	4	0.061
38	Dil Yibza	6.14	5.394	4	0.060
39	Dinsho	5.57	4.914	5	0.066
40	Dodola	5.55	4.902	5	0.066
41	Durame	5.90	5.101	4	0.063

Table 4.8 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
42	Fiche	6.18	5.358	4	0.060
43	Finote Selam	6.05	5.199	4	0.062
44	Gasera	5.88	5.035	4	0.064
45	Gelemso	6.11	5.213	4	0.062
46	Gewane	6.06	5.021	4	0.064
47	Ghimbi	5.68	4.884	5	0.066
48	Gidole	5.79	4.920	5	0.065
49	Goba	5.56	4.906	4	0.066
50	Gololcha	6.09	5.202	4	0.062
51	Gore	5.52	4.791	5	0.067
52	Gorgora	6.29	5.333	4	0.060
53	Goro	5.95	5.098	4	0.063
54	Gouder	5.97	5.188	4	0.062
55	Harbu	6.06	5.092	4	0.063
56	Haromaya	6.06	5.116	4	0.063
57	Hossaina	5.77	5.025	4	0.064
58	Humera	6.33	5.246	4	0.061
59	Huruta	6.13	5.288	4	0.061
60	Hyke	6.13	5.221	4	0.062
61	Injibara	6.01	5.163	4	0.062
62	Jinka	5.81	4.894	5	0.066
63	Kemse	6.27	5.030	4	0.060
64	Konso	5.79	4.926	5	0.065
65	Lalibela	6.15	5.237	4	0.062

Table 4.8 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
66	Logiya	6.16	5.074	4	0.063
67	Maychew	6.16	5.243	4	0.061
68	Mechara	6.11	5.209	4	0.062
69	Meki	5.85	5.125	4	0.063
70	Mendi	5.77	4.853	5	0.066
71	Metehara	6.15	5.300	4	0.061
72	Metema	6.26	5.177	4	0.062
73	Metu	5.52	4.792	5	0.067
74	Mieso	6.15	5.206	4	0.062
75	Mille	6.01	5.065	4	0.064
76	Mojo	6.14	5.290	4	0.061
77	Mota	6.12	5.244	4	0.061
78	Moyale	5.38	4.601	5	0.070
79	Nejo	5.69	4.890	5	0.066
80	Nekemte	6.02	5.168	4	0.062
81	sekota	6.17	5.251	4	0.061
82	Sendafa	5.07	4.465	5	0.072
83	Shakiso	5.67	4.907	5	0.066
84	Shambu	6.03	5.181	4	0.062
85	Sheno	5.94	5.112	4	0.063
86	Shire	6.29	5.303	4	0.061
87	Sodo	5.85	5.126	4	0.063
88	Sokoru	5.78	5.030	4	0.064
89	Tefki	5.07	4.468	5	0.072
90	Tenta	6.17	5.277	4	0.061

Table 4.8 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
91	Tulu Milki	6.16	5.310	4	0.061
92	Weldiya	6.17	5.255	4	0.061
93	Weliso	5.99	5.200	4	0.062
94	Welkite	5.99	5.197	4	0.062
95	Wereta	6.14	5.262	4	0.061
96	Wonji	6.12	5.291	4	0.061
97	Wukro	6.26	5.403	4	0.060
98	Yabelo	5.77	4.936	5	0.065
99	Yirga Alem	5.86	5.054	4	0.064
100	Ziway	5.84	5.122	4	0.063
	max	6.33	5.43	6.00	0.073
	min	5.03	4.43	4.00	0.059
	Average	5.95	5.11	4.24	0.063

C. Third Scenario: 5kW system

Table 4.8 illustrates the results of equity payback period, energy production cost, electricity exported to grid and daily solar radiation tilted for 5 kW household rooftop solar PV system for all selected cities. The average energy production cost for 5 kW system was 0.066$/kWh. Energy production cost for Tenta city where annual energy generation was recorded maximum costs 0.063$/kWh and Chencha city where annual energy generation was minimum costs 0.064$/kWh. The equity payback period was 4 and 6 years respectively.

Table 4.9: Economic analysis results for 5kW system

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
1	Abiy Adi	6.23	8.946	4	0.062
2	Adaba	5.56	8.181	5	0.068
3	Addis Alem	5.03	7.389	6	0.075
4	Addis Zemen	6.30	9.049	4	0.061
5	Adet	6.07	8.667	4	0.064
6	Adwa	6.08	8.753	4	0.064
7	Agarfa	5.80	8.477	5	0.066
8	Agaro	5.34	7.777	5	0.072
9	Alaba	5.77	8.375	5	0.066
10	Alamat'a	6.18	8.764	4	0.063
11	Alem Ketema	6.00	8.606	5	0.065
12	Aleta Wonde	5.85	8.416	5	0.066
13	Ankober	6.00	8.612	5	0.065
14	Asaita	6.15	8.441	5	0.066
15	Azezo	6.11	8.896	4	0.063
16	Babile	6.15	8.769	4	0.063
17	Bati	5.99	8.388	5	0.066
18	Bedele	5.66	8.224	5	0.068
19	Berhale	6.20	8.923	4	0.062
20	Bichena	6.15	8.836	4	0.063
21	Boditi	5.76	8.36	5	0.067
22	Bonga	5.33	7.45	6	0.075
23	Burie	6.04	8.651	5	0.064
24	Butajira	5.79	8.394	5	0.066
25	Chelenko	6.14	8.755	4	0.064

Table 4.9 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
26	Chencha	5.75	8.221	5	0.068
27	Chiro	6.17	8.689	4	0.064
28	Dabat	6.33	8.896	4	0.063
29	Dalocha	5.78	8.392	5	0.066
30	Debre Markos	6.09	8.74	4	0.064
31	Debre Tabor	6.24	8.973	4	0.062
32	Debre Werk	6.17	8.853	4	0.063
33	Dejen	6.17	8.859	4	0.063
34	Delgi	6.29	8.891	4	0.063
35	Dembi	5.66	8.221	5	0.068
36	Deneba	5.75	8.34	5	0.067
37	Dhera	6.14	8.766	4	0.063
38	Dil Yibza	6.14	8.678	4	0.064
39	Dinsho	5.57	8.191	5	0.068
40	Dodola	5.55	8.17	5	0.068
41	Durame	5.90	8.502	5	0.065
42	Fiche	6.18	8.931	4	0.062
43	Finote Selam	6.05	8.666	4	0.064
44	Gasera	5.88	8.392	5	0.066
45	Gelemso	6.11	8.689	4	0.064
46	Gewane	6.06	8364	5	0.067
47	Ghimbi	5.68	8.141	5	0.068
48	Gidole	5.79	8.2	5	0.068
49	Goba	5.56	8.177	5	0.068
50	Gololcha	6.09	8.67	4	0.064

Table 4.9 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
51	Gore	5.52	7.985	5	0.07
52	Gorgora	6.29	8.888	4	0.063
53	Goro	5.95	8.496	5	0.065
54	Gouder	5.97	8.646	5	0.064
55	Harbu	6.06	8.487	5	0.066
56	Haromaya	6.06	8.526	5	0.065
57	Hossaina	5.77	8.375	5	0.066
58	Humera	6.33	8.743	4	0.064
59	Huruta	6.13	8.814	4	0.063
60	Hyke	6.13	8.701	4	0.064
61	Injibara	6.01	8.605	5	0.065
62	Jinka	5.81	8.157	5	0.068
63	Kemse	6.27	9.004	4	0.069
64	Konso	5.79	8.21	5	0.068
65	Lalibela	6.15	8.729	4	0.064
66	Logiya	6.16	8.457	5	0.066
67	Maychew	6.16	8.738	4	0.064
68	Mechara	6.11	8.681	4	0.064
69	Meki	5.85	8.542	5	0.065
70	Mendi	5.77	8.088	5	0.069
71	Metehara	6.15	8.834	4	0.063
72	Metema	6.26	8.628	5	0.064
73	Metu	5.52	7.986	5	0.07
74	Mieso	6.15	8.677	4	0.064

Table 4.9 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
75	Mille	6.01	8.441	5	0.066
76	Mojo	6.14	8.817	4	0.063
77	Mota	6.12	8.74	4	0.064
78	Moyale	5.38	7.668	6	0.073
79	Nejo	5.69	8.15	5	0.068
80	Nekemte	6.02	8.614	5	0.065
81	sekota	6.17	8.759	4	0.064
82	Sendafa	5.07	7.441	6	0.075
83	Shakiso	5.67	8.178	5	0.068
84	Shambu	6.03	8.634	5	0.064
85	Sheno	5.94	8.52	5	0.065
86	Shire	6.29	8.839	4	0.063
87	Sodo	5.85	8.357	5	0.067
88	Sokoru	5.78	8.384	5	0.066
89	Tefki	5.07	7.446	6	0.075
90	Tenta	6.17	8.795	4	0.063
91	Tulu Milki	6.16	8.85	5	0.063
92	Weldiya	6.17	8.758	4	0.064
93	Weliso	5.99	8.667	4	0.064
94	Welkite	5.99	8.662	5	0.064
95	Wereta	6.14	8.769	5	0.063
96	Wonji	6.12	8.995	4	0.062
97	Wukro	6.26	9.004	4	0.062

Table 4.9 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
98	Yabelo	5.77	8.229	5	0.068
99	Yirga Alem	5.86	8.423	5	0.066
100	Ziway	5.84	8.537	5	0.065
101	max	6.33	8364.00	6.00	0.075
	min	5.03	7.39	4.00	0.061
	Average	5.95	92.07	4.63	0.066

D. Fourth Scenario: 45kW system

Table 4.9 illustrates the results of equity payback period, energy production cost, electricity exported to grid and daily solar radiation tilted for 45 kW solar farm PV system for all selected cities. The average energy production cost for 45 kW system is 0.186$/kWh. Energy production cost for Tenta city where annual energy generation is recorded maximum costs 0.15$/kWh and Chencha city where annual energy generation is minimum costs 0.161$/kWh. The equity payback period is 17 and 18 years respectively.

Table 4.10: Economic analysis results for 45kW system

No	City	Daily Solar Radiation Titled [kWh/m²/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
1	Abiy Adi	6.22	80.512	17	0.148
2	Adaba	5.56	73.625	18	0.162
3	Addis Alem	5.03	66.499	19	0.179
4	Addis Zemen	6.30	81.442	17	0.146
5	Adet	6.07	78.003	17	0.153
6	Adwa	6.08	78.774	17	0.151
7	Agarfa	5.80	76.295	17	0.156
8	Agaro	5.34	69.996	18	0.17
9	Alaba	5.77	75.359	17	0.158
10	Alamat'a	6.18	78.872	17	0.151
11	Alem Ketema	6.00	77.451	17	0.154
12	Aleta Wonde	5.86	75.746	17	0.157
13	Ankober	6.00	77.507	17	0.154
14	Asaita	6.17	75.967	17	0.157
15	Azezo	6.30	80.065	17	0.149
16	Babile	6.15	78.92	18	0.159
17	Bati	5.99	75.519	17	0.158
18	Bedele	5.66	74.018	18	0.161
19	Berhale	6.20	80.305	17	0.148
20	Bichena	6.15	79.525	17	0.151
21	Boditi	5.76	75.243	18	0.158
22	Bonga	5.33	69.866	18	0.17
23	Burie	6.04	77.856	17	0.153
24	Butajira	5.79	75.347	18	0.158
25	Chelenko	6.14	78.07	17	0.152
26	Chencha	5.75	73.993	18	0.161

Table 4.10 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
27	Chiro	6.17	78.2	17	0.152
28	Dabat	6.33	80.066	17	0.149
29	Dalocha	5.78	75.527	17	0.158
30	Debre Markos	6.09	78.66	17	0.154
31	Debre Tabor	6.24	80.76	17	0.147
32	Debre Werk	6.05	79.542	17	0.15
33	Dejen	6.17	79.729	17	0.149
34	Delgi	6.29	80.015	17	0.149
35	Dembi	5.66	74.007	18	0.161
36	Deneba	5.77	75.328	17	0.158
37	Dhera	6.14	79.379	17	0.15
38	Dil Yibza	6.16	78.102	17	0.152
39	Dinsho	5.57	73.713	18	0.161
40	Dodola	5.55	73.532	18	0.162
41	Durame	5.89	76.456	17	0.156
42	Fiche	6.18	80.376	17	0.148
43	Finote Selam	6.05	77.99	17	0.151
44	Gasera	6.00	77.057	17	0.154
45	Gelemso	6.11	78.199	17	0.152
46	Gewane	6.06	75.321	18	0.158
47	Ghimbi	5.68	73.26	18	0.162
48	Gidole	5.79	73.799	18	0.161
49	Goba	5.56	73.596	18	0.162
50	Gololcha	6.09	78.033	17	0.153
51	Gore	5.52	71.864	18	0.166

Table 4.10 Continued

No	City	Daily Solar Radiation Titled [kWh/m^2/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
52	Gorgora	6.29	79.992	17	0.149
53	Goro	5.95	76.466	18	0.156
54	Gouder	6.21	79.146	17	0.15
55	Harbu	6.06	76.392	17	0.155
56	Haromaya	6.06	76.735	18	0.155
57	Hossaina	5.77	75.377	18	0.158
58	Humera	6.33	78.676	17	0.151
59	Huruta	6.13	79.322	17	0.15
60	Hyke	6.13	78.312	17	0.152
61	Injibara	6.01	77.445	17	0.154
62	Jinka	5.81	73.412	18	3.162
63	Kemse	6.27	81.037	17	0.147
64	Konso	5.79	73.89	18	0.161
65	Lalibela	6.15	78.559	17	0.152
66	Logiya	6.16	76.112	17	0.156
67	Maychew	6.16	78.642	17	0.151
68	Mechara	6.11	78.13	17	0.152
69	Meki	5.85	76.882	17	0.155
70	Mendi	5.77	72.796	18	0.164
71	Metehara	6.15	79.502	17	0.155
72	Metema	6.26	77.649	17	0.153
73	Metu	5.52	71.878	18	0.166
74	Mieso	6.15	78.097	17	0.152
75	Mille	6.03	75.969	17	0.157
76	Mojo	6.14	79.351	17	0.15
77	Mota	6.13	78.749	17	0.151

Table 4.10 Continued

No	City	Daily Solar Radiation Titled [kWh/m²/d]	Electricity Exported to grid [MWh]	Equity Payback [Yr]	Energy Production Cost [$/kWh]
78	Moyale	5.38	69.008	19	0.172
79	Nejo	5.69	73.349	18	0.162
80	Nekemte	6.03	76.764	17	0.155
81	sekota	6.20	79.194	17	0.15
82	Sendafa	5.07	66.968	19	0.178
83	Shakiso	5.67	73.601	18	0.162
84	Shambu	6.05	77.853	17	0.153
85	Sheno	5.94	76.676	17	0.153
86	Shire	6.32	79.918	17	0.149
87	Sodo	5.84	76.744	17	0.159
88	Sokoru	5.78	75.478	17	0.158
89	Tefki	5.08	67.082	19	0.177
90	Tenta	6.14	79.156	17	0.15
91	Tulu Milki	6.16	79.626	17	0.149
92	Weldiya	6.17	78.822	17	0.151
93	Weliso	6.00	78.072	17	0.152
94	Welkite	5.99	77.958	17	0.153
95	Wereta	6.15	79	17	0.146
96	Wonji	6.14	79.365	17	0.15
97	Wukro	6.27	81.163	17	0.147
98	Yabelo	5.77	74.06	18	0.161
99	Yirga Alem	5.87	75.925	17	0.157
100	Ziway	5.84	76.829	17	0.155
	max	6.33	81.44	19.00	3.16
	min	5.03	66.50	17.00	0.15
	Average	5.95	76.68	17.34	0.186

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The greater number of inhabitants in Ethiopia still remains an electrified residing in the rural part of the country. Households in this rural area uses kerosene and solid fuels as the primary energy source facing the indoor air pollution which is the cause for environmental and health risk that lead to premature death. The shift towards clean energy sources is paramount to improve the quality and life standard of the community. In this study three scenarios;1kW, 3kW and 5kW on grid connected rooftop PV system for household and one scenario on a 45 kW solar farm PV power generation potential of 100 selected locations throughout Ethiopia were examined. Three simulation software namely; PVGIS, PVWatt and RETScreen were applied for the evaluation of PV potential throughout the country. PVGIS and PVWatt are web based simulation softwares. Based on the simulation results the capacity actor obtained by PVGIS is much high greater than PVWatt. Since PVGIS software gives better capacity factor it is recommended for the PV energy assessment. RETScreen Expert simulation software is a renewable energy software developed by natural resource Canada. These simulation software was used for financial analysis of the scenarios considered in all cities. Solar radiation potential with in the country is very high ranging from 1730 to 2481 kWh/m^2. From PVGIS Asaita, located in Afar region and Chelenko located in Oromiya region were cities found to have the maximum and minimum solar irradiation potential. Economic feasibility study was considered for each scenario in each city. The average annual energy production cost is 0.167$/kWh and a maximum payback period of the roof-parallel systems was 6 year while for a 45kW system the average cost was 0.186$/kWh and a maximum payback period of 18 years.

Application of the proposed systems improve human wealth, reduce environmental and health risks arise from household air pollution, reduce the expenditure on kerosene, improve the access to electric supply, improve electricity generation capacity, improve development towards renewable energy. The findings of this research will help government and actors participating in the rural energy development sector. The financial evaluation shows the system is economically feasible.

5.2 Recommendations

Applying feed in tariff law within the country will improve the investors interest of investing on rural energy development market. The financial growth of the population is very essential in improving solar energy technology adoption and increasing the installed capacity. Ethiopian rural electrification program must appreciate and support researches based on alternative energy adoption and assessment. Further studies for all districts will give the country and the government to implement cost effective and generate high capacity of electricity.

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