Design and Performance Analysis of 125 MW Floating Photovoltaic Power Plant in Ethiopia: Metema vs Lake Tana

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Abstract. Floating solar PV power plants are currently emerging form of photovoltaic technologies that uses the surface of water bodies such as irrigation, canals, water reservoirs, lakes and failing ponds, ocean, water treatment plants, etc. Uses of man-made reservoirs for floating solar PV have significant advantages over land-based and other water body's installation. Ethiopian power authority planned to install 125 MWp grid connected battery-less land-based PV solar systems at Metema in Amhara region. In this paper, output performance of the solar PV plant at Metema and on Lake Tana is compared. Factors that affect the PV power plant efficiency such as wind speed and temperature are modelled and simulated in MATLAB/ SIMULINK. Panels and inverters are selected and the system components are configured to generate 125 MW. The system is modeled by MATLAB/SIMULINK to show the efficiency variations of solar PV. Due to high temperature and wind speed, solar PV efficiency drops. The efficiency of solar PV on water surface is improved by 2.88%, 3.6 MW from 125 MW plant, over the land surface. This indicates that temperature and wind speed are the major factors that affects the output performance of solar PV generation systems.

Keywords: Floating solar PV · PV power plant · Wind and temperature effects

1 Introduction

In the last few years, renewable energy capacity installed from sun has increasing and in 2017 the PV market practiced a further worldwide growth with an installed capacity over 400GW [1]. The promising alternative energy technology, solar photovoltaic system, is now becomes a very reasonable choice for harnessing the resource by utilizing obtainable water surface [2].

Though premium, loss of efficiency at high operating PV cell temperature and during tracking 50–60% increase in land occupancy are some of the factors that limits the growth of PV penetration around the world [2, 3]. Thus, the combination of solar PV and floating technology on water surface is best solution to overcome the above-mentioned problems [4].

Japan was the first to install floating PV system in 2007 in Achi, followed by France, Italy, South Korea, Spain and USA, all of which have tested small scale for research and development. Recently, China takes the lead with plant capacity of 73%

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of the world (around 1752 MW). The world solar generation plant capacity could reach up to 1.2 TW by the end of 2020, according to solar power Europe reports [1].

Floating solar PV power plants are currently emerging form of photovoltaic technologies that uses the surface of water bodies such as irrigation, canals or remediation, water reservoirs, lakes and tailing ponds, ocean, water treatment plants [2, 5]. Floating PV system has lower ambient temperature in virtue to the cooling effect of water and thus reduces cell temperature of the PV panel. Consequently, efficiency of floating solar PV panel is 11% higher than the land based solar panels [5, 6].

In addition to improving generation efficiency, the systems provide other environmental benefits such as reducing evaporation by up to 70% and improve water quality. It also reduces the growth of algae by shading the water from sun [7].

Uses of dam reservoir for floating solar PV have significant advantages over land based and other water body's installation. Water conservation, PV variability compensation, peak load demand support and facilitation of black start for hydropower are the main advantages of integrating floating PV on existing infrastructure of hydroelectric dam [8, 9].

A countrylike Ethiopia, where agriculture leads the economy and food insecurity is critical issues. Floating solar power plant technology on the surface water bodies is not a choice. Therefore, the aim of this paper is to show the floating solar PV at Lake Tana has better performance over land-based systems at Metema.

2 Methodology

Detail sizing and configuration of the various components of the floating PV power plant is carried out. ABB central inverter and HCP78X9-400W PV module specification are used to show the effect of temperature performance in energy production of the plant [10, 11]. MATLAB/SIMULINK is used to simulate the model the overall system. Finally, the floating solar panel performance is compared with land-based installation.

2.1 Study Area

Metema is a city in the Amhara region in Ethiopia. Metema is located at 12°58′0″ N and 36°12′0″ E. The temperature ranges between 36 to 45 °C. The area intensively used to farm peanut, cotton, incense and sesame [12]. They are the major export products of the country. To preserve this precious land and improve energy production due to high ambient temperature, the design is proposed on the surface of Lake Tana.

Lake Tana is the largest and one of the tourist destinations in Ethiopia, which is found in Amhara regional state nearby the capital city Bahir Dar, located at 11.5742°N latitude and 37.3614°E longitude [13]. The location map of Metema and Lake Tana is shown in (Fig. 1).

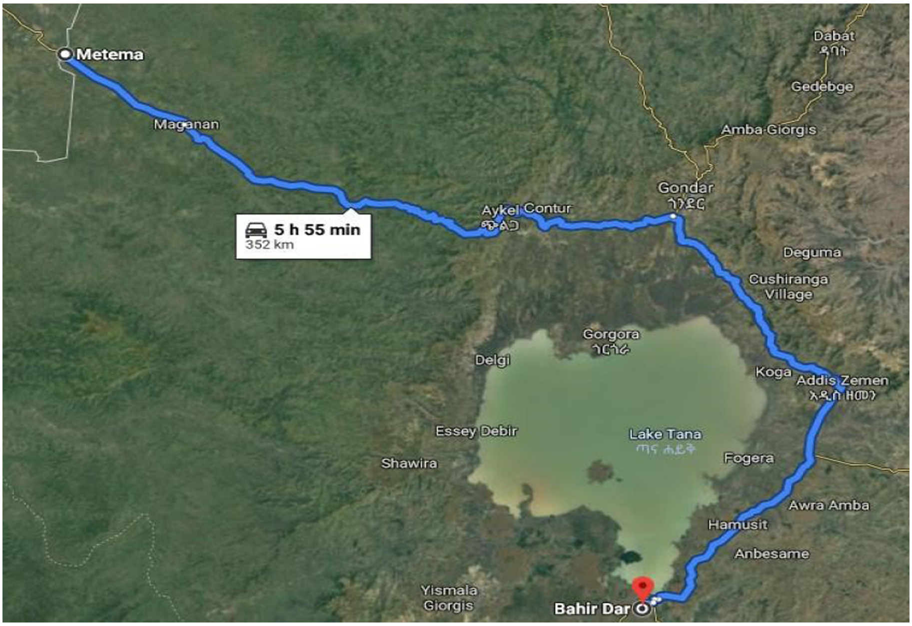

Fig. 1. Location map of Metema and Lake Tana

2.2 Study Area

The average solar radiation (Table 1) and maximum ambient air temperature (Table 2) for the last 20 years for the Bahir Dar city and Metema are taken from NASA surface meteorology and solar energy data base [14, 15]. Temperature and wind speed are corrected to fit surface temperature of the water.

Table 1. Monthly average daily insolation incident on horizontal surface (KWh/m^2/day) of Bahir Dar/Metema

Lat & Lon	Jan	Feb	Mar	Apr	May	Jun
Bahir Dar						
Lat 11.5742°N						
Lon 37.3614°E	6.4	6.7	7.0	6.9	6.6	5.6
Metema						
Lat 12.9545°N						
Lon 36.1573°E	7.0	7.2	6.73	7.3	6.9	7.5

Table 2. Maximum daily temperature (°C) of Bahir Dar/Metema

Lat & Lon	Jan	Feb	Mar	Apr	May	Jun
Bahir Dar						
Lat 11.5742°N						
Lon 37.3614°E	29	31	32	32	32	29
Metema						
Lat 12.9545°N						
Lon 36.1573°E	35.7	39.5	40.3	40.3	39	36

2.3 Components of Floating Photovoltaic Power Plant

To improve efficiency of the plant and preserve the land for agriculture, the solar PV generation structural modification is required to install the plant over the water surface [3, 6]. This installation of PV plant over treasurable land is replaced by using floating system.

2.3.1 Solar Module and Associated Components

It is common to use standard crystalline PV module with aluminum frame. However, on the salty environment specially fabricated module and polymer made frame are applied to resist corrosion. Other associated elements in a system such as inverters, DC disconnect and protection equipment's are the same as it is applied in land-based installation [16–18].

Floating

A floating body with effective buoyancy to the safe weight ratio that allows installation of PV module can be used. It is usually made from steel, aluminum, HDPE or glass reinforced plastic. Low cost, good durability in wet and salty as well as humid environment, low weight and good strength per unit of weight make HDPE and glass reinforced plastic a preferred choice [18, 19].

Mooring

Floating PV technology requires the technical capability to secure structural stability and durability on the water. The mooring system keeps the panel structure fixed in the same position to adapt the change to water level using nylon wire rope slings to be tied to bollards on bank or bottom [3, 6, 20].

Underwater Cable and Connection System

Extremely robust resistance, high mechanical load and abrasion, high temperature resistance and excellent weather proof cables are used to transfer generated power from water bodies to the substation. The weatherproof IP67 junction boxes and high current capacity connectors are used for power plant cable connection if available under water [3, 16, 18, 21].

2.4 Mathematical Modeling of Temperature and Wind Effect

The efficiency of solar PV power plant is highly dependent on temperature and wind speed. For silicon modules, a typical reduction of efficiency with temperature is 0.4–0.5%/°C. Therefore, estimation of the temperature of the PV panel to assess the efficiency of the system due to temperature rise is important [22–24]. The efficiency of PV panel, η_{PV} is given by

$$\eta_{PV} = \eta_{STC}\left[1 + \beta\left(T_{panel} - 25\,^{\circ}\mathrm{C}\right)\right]\left[1 + \gamma \ln\left(\frac{G_T}{G_o}\right)\right] \quad (1)$$

Where:

$\eta_{STC}-$ Module/panel efficiency at STC.
$T_{panel}-$ Module temperature.
G_T- Irradiance received by a module.
G_o- Reference solar irradiance taken as 1000 W/m^2.
$\beta-$ Temperature coefficient at maximum power point.
$\gamma-$ Azimuth angle ($\gamma = 0$ for surface facing to south).

In this study, it is assumed that the PV module are fixed with tilting angle 11.5742° and 12.9545° facing south for Bahir Dar and Metema respectively and the efficiency is [17].

$$\eta_{PV} = \eta_{STC}\left[1 + \beta\left(T_{panel} - 25^{\circ}\mathrm{C}\right)\right] \quad (2)$$

But the operating cells temperature *Tpanel*, of the PV panel is determined by

$$T_{panel} = T_{amb} + \frac{(N_{OCT} - 20^{\circ})}{0.8\,\mathrm{KW/m^2}} * G_o \quad (3)$$

In this study, it is assumed that the PV module are fixed with tilting angle 11.5742° and 12.9545° facing south for Bahir Dar and Metema respectively and the efficiency is [17].

Where N_OCT is nominal operating cell temperature defined by the manufacturer for the exploitation condition for each PV panel, it is usually set to 45 °C.

Floating PV module were situated in a boundary air layer and the lake surface, whose surface temperature >20 °C [17, 18]. In this paper the ambient temperature is assumed *a* $T_{amb} = T_{lakearea}$. High wind location, is not considered in this work, the precise temperature estimation formula for free standing mounting type is given by

$$T_{Panel} = T_{amb}\left(\frac{0.32}{8.91 + 2V_f}\right)G_T \quad (4)$$

Where V_f- free steam wind speed.

Wind speed value can be adjusted at the required height according to the measured height using power law formula [17].

$$\frac{V_f}{V_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^n \tag{5}$$

$$n = \frac{0.37 - 0.0881\ln(V_{ref})}{1 - 0.0881\ln(\frac{Z_{ref}}{10})} \tag{6}$$

Where:

Z_{ref}- Reference height measured from ground.
Z- Required height in meter.
V_{ref}- Known wind speed at the reference height.

The sea temperature T_w is given in relation to the air (land) temperature T_a, air-water regression model based on daily and weekly water temperature data resulted [25, 26].

$$T_w = 5 + 0.75T_{amb} \tag{7}$$

Due to the thermal inertia of the water, response of water temperature is damped and delayed, which is depicted in coefficients in a given formula. As shown in the formula above, the water temperature will be warmer than the temperature if the air temperature is below 20 °C [26].

Annual average temperature (Table 2) is 28.75 °C

$$T_w = 5 + 0.75 * 28.75 = 26.56\,°\mathrm{C}$$

The velocity of wind in the sea is always higher than that of the land. The wind on sea V_{ws} in terms of land wind speed V_{wl} [17] is given by

$$V_{ws} = 1.62 + 1.17 * V_{wl} \tag{8}$$

$$V_{ws} = 1.62 + 1.17 * 6.14 = 8.8\,\mathrm{m/s}$$

Energy production (E) at any time of hour using floating PV panel can be defined by the following equation [17, 19].

$$E = G_T * A * \eta \tag{9}$$

Where:
A- is surface area (m^2) of the solar array

$$\eta = \eta_{mod} * \eta_{Pv} * \eta_{inv} \tag{10}$$

Where:

η_{mod}- Module efficiency (15–18% recommended or can be taken from module specification).

η_{inv}- Inverter efficiency (>95% recommended for solar application or can be taken from inverter specification).

The power generated by the PV panels is given by [17, 19].

$$P_{PVout} = P_{R.PV} * \frac{G_T}{G_o} * \left[1 + \beta_T \left(T_{panel} - 25\,^{\circ}\mathrm{C}\right)\right] * \eta_{inv} * \eta_{mod} \tag{11}$$

Where $P_{R.PV}$- PV rated power at required condition.

2.5 Panel and Inverter Specification

Mono crystalline silicon module HCP78X9-400W made in China with 400 Wp per panel capacity and ABB central inverter of PVS 980–58.5.0 VA (10 MW) is selected for this research [6, 27, 28] (Tables 3 and 4).

Table 3. Solar photovoltaic specification

Module type	HCP78X9-400W
Maximum power *Pmax*	400 W
Open-circuit voltage *Voc*	51.6 V
Maximum power voltage *Vmp*	42.0 V
Short-circuit current *Isc*	9.95 A
Maximum power current *Imp*	9.53 A
Module efficiency (%)	18.38%
Power tolerance	0 ~+ 5 W
Temperature coefficient of *Isc*	0.05%/°C
Temperature coefficient of *Voc*	−0.31%/°C
Temperature coefficient of *Pmax*	−0.38%/°C
Standard test environment	Irradiance 1000 W/m^2, cell temperature 25 °C, Spectrum AM 1.5

Table 4. Inverter specification

Inverter type	PSV980-58-4348-5000 KVA
Max power input	10 MWp
Voltage range	978–1250 V
Max DC voltage	1500 V
Max DC current	5700 A
Nominal AC power output	5000 KVA
Nominal AC current	3700 A
Nominal AC voltage output	690 V
Efficiency	98.5%

2.6 Design of 125 MWp Floating Solar PV

Ethiopian power authority planned to install, 125 MWp grid connected battery-less land-based at Metema. 125 MW power was estimated by Ethiopian electric power to electrify Metema and surrounding community. This estimated power is used in the paper.

2.6.1 System Sizing

Required number of modules to generate 10 MW peak power

$$Number\ of\ PV\ modules = \frac{Pinverter}{Pmodule} = \frac{10\,\mathrm{MW}}{400\,\mathrm{W}} = 25,000\,modules \tag{12}$$

Number of modules in series

$$N_{ms} = \frac{V_{inverter}}{V_{mp}} = \frac{1250}{42} = 29.76 \approx 30\,modules \tag{13}$$

Number of modules in parallel

$$N_{mp} = \frac{N_m}{N_{ms}} = \frac{25,000}{30} = 833.33 \approx 834\,modules \tag{14}$$

The total number of modules for 10 MW inverter = 834 * 30 = 25,020 modules. To generate 125 MW power, 312,750 modules are required. Thus, system components are arranged so as to generate 125 MW power.

2.6.2 String and Component Arrangement

The configuration shown in Fig. 2 indicates that 834 strings are clustered in to 13 inverters to be coupled with 1.25/15 KVA distribution transformer.

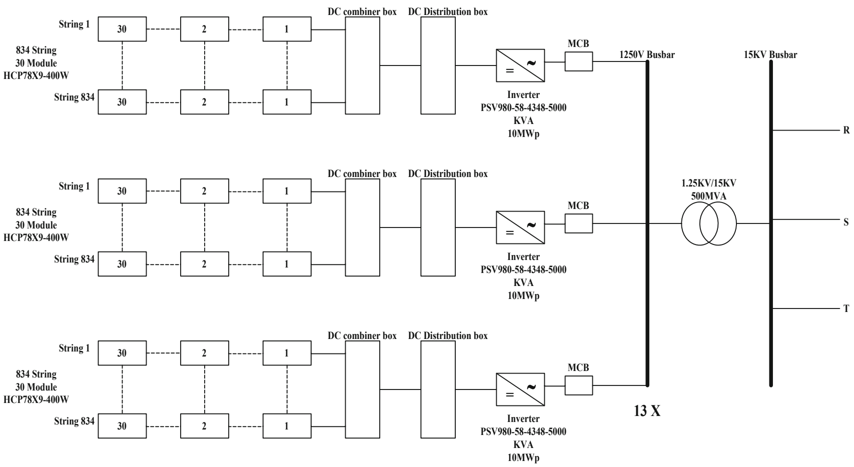

Fig. 2. String and system component arrangement

2.7 MATLAB Modeling Solar PV

Solar PV is modeled for Metema at an average temperature of 36.7 °C and Lake Tana at an average temperature of 26.56 °C. MATALAB/Simulink is used to model the system in both cases (Fig. 3).

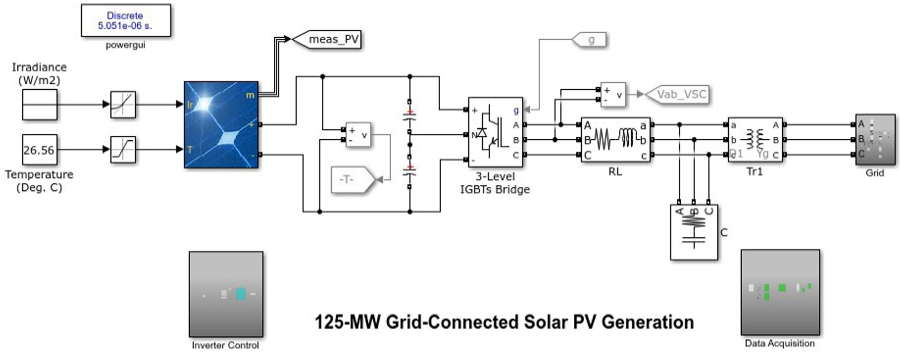

Fig. 3. MATLAB/Simulink model of 125 MW Solar PV system

3 Result and Discussion

To generate 125 MW power at Metema and Lake Tana, 312,750 modules of HCP78X9-400W and 13 number of 10 MW, ABB - PSV980-58-4348-5000 KVA are required. The generated power at Metema with 36.7 °C is 116.4 MW (Fig. 4) and at Lake Tana with 26.56 °C is 120 MW (Fig. 5). Therefore, generated power using a floating solar PV system is improved by 2.88%, which is 3.6 MW more compared with Metema (Table 5).

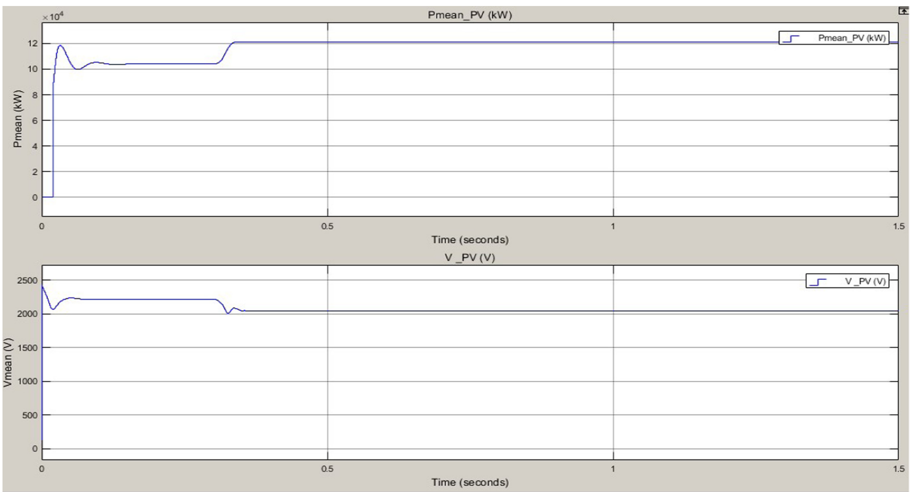

Fig. 4. Mean power and Voltage simulation result at 36.7 °C

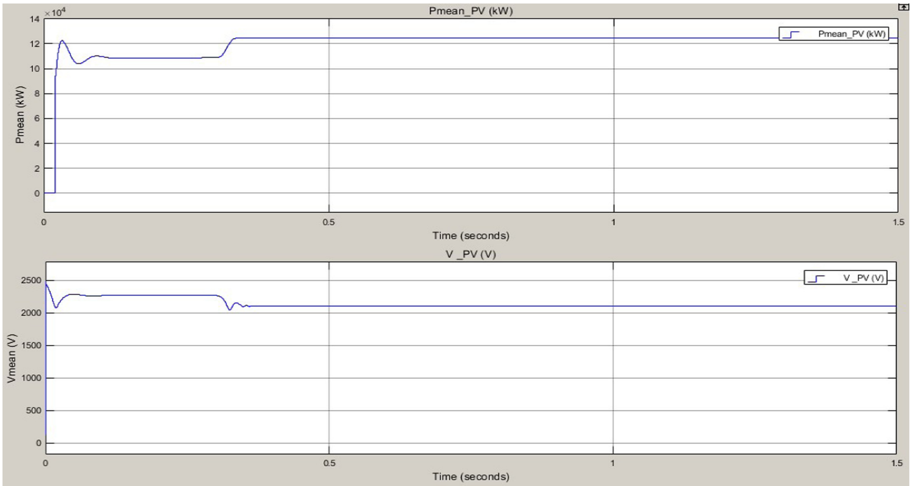

Fig. 5. Mean power and voltage simulation result at 26.56 °C

Table 5: Comparison of 125 MW solar photovoltaic generation at Metema and Lake Tana

Place	Ta (°C)	Pmean (MW)	Vmean (V)	Performance ratio (%)
Metema	36.7	116.4	2079	93.12
Lake Tana	26.56	120	2138	96

4 Conclusion

Ethiopian government proposed to install land-based solar power plants in selected areas. This leads to loss of fertile land and solar PV plants efficiency drops. Temperature and wind speed effects are the dominant factor for efficiency drops. Thus, installing solar photovoltaic systems at Lake Tana instead of Metema, improves the efficiency of power generation, reduces evaporation of water, more economical and saves the fertile land for agriculture. The performance ratio of power generation at Metema and Lake Tana to the proposed power generation is 93.12% and 96% respectively at different temperature.

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