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Determination of Optimum Tilt Angle for Rooftop Solar Photovoltaic System Installation for KikuKinderhaus in Kumasi

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Abstract: The population growth in the Ghanaian urban areas and the high energy consumption per unit area compared to the low solar energy capture by Photovoltaic (PV) systems makes solar PV energy systems investment an unattractive venture for most urban settlers. Because building architectures mostly do not incorporate solar PV systems in facility planning, most building roofs pose challenges for solar PV array installation leading to lower PV energy output. The effects of tilt angle on the output of Solar Photovoltaic Systems were analyzed in this study using RETScreen 4. The optimum tilt angle and the corresponding PV output were estimated annually for three different PV systems. It was found that, the optimum tilt angle for all the systems that would give better yield and allow self-cleaning is 10°. The information presented in this study can serve as inputs for the development of grid-tied PV system without battery storage, grid-tied PV system with battery storage and stand-alone systems in Kumasi, Ghana.

Keywords: Solar Photovoltaic, Tilt Angle, Orientation, Optimum, Energy Output

1. Introduction

Solar Photovoltaic (PV) technology has the ability to convert solar energy into electricity consuming no fossil fuels, using no moving parts, creating no pollution and noise, and lasting for years with little maintenance. The environmental reliability and power availability benefits of the solar Photovoltaic (PV) system make it a justifiable option among all renewable energy systems. Different geographical regions experience different weather patterns, so the site where we live is a major factor that affects the photovoltaic system design from many ways; determination of the orientation of the panels, finding the number of days of autonomy when the sun does not shine in the skies, and choosing the best tilt angle of the solar panels.

The population growth in the Ghanaian urban areas and the high energy consumption per unit area compared to the low solar energy capture by PV systems makes solar PV energy systems investment an unattractive venture for most urban settlers. The social aspect plays a significant role in the design, planning, implementation and management of a PV plant [13]. Since building architectures mostly do not incorporate solar PV systems into building designs, most building roofs pose challenges for maximum solar energy capture due to wrong PV array orientation and tilt angle. To design a Solar Photovoltaic system with optimal power output, professional contractors need to consider a number of factors. Khatib, Mohamed and Sopian, presented a review of the PV system optimization techniques for PV systems [15]. They revealed that; orientation, tilt and shading on the PV array must be of special importance, as they all have a major impact on the amount of sunlight that reaches the photovoltaic panels. The optimum tilt angle is generally the angle that would make the sun's ray perpendicular to the solar module at noon. However this tilt angle is never constant throughout the year, that is, seasonal variation of the modules tilt angle has to be ensured, hence posing a major challenge for the optimum operation of the system.

A study by Micheal Hartner, on "The optimal tilt angle and orientation of photovoltaic panels from electricity system perspective in Australia and Germany" revealed that adjustment of installation angles can increase PV output and in effect reduce installation costs. The year fixed tilt angle is approximately equal to the location latitude but it is not suitable for some location [3, 5]. The tilt angle of the panels varies in different locations and they differ monthly, seasonally and annually [11, 12]. Figure 1shows the monthly variation of declination and tilt angles for Kumasi metropolis.

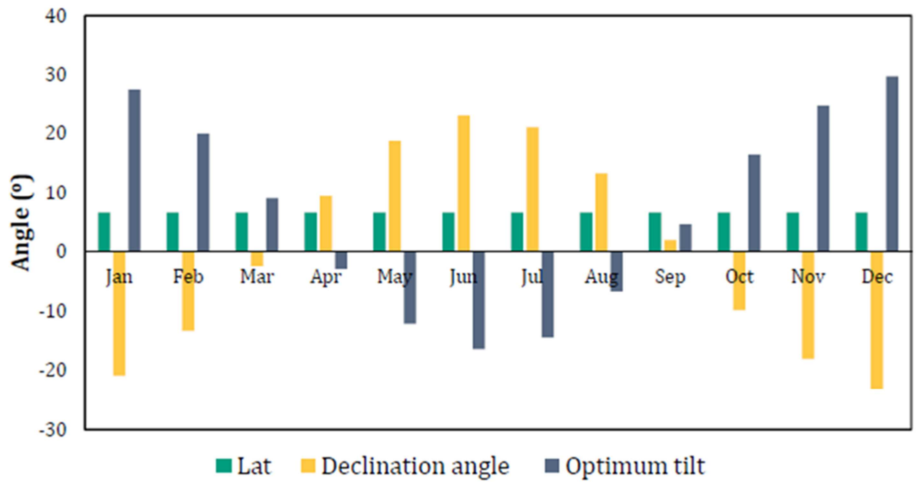


Figure 1. *Monthly variation of tilt angles for Kumasi metropolis.*

It appears that; on average, orienting a solar module toward the equator and tilting it up at an angle closer to the local latitude is a good rule-of-thumb for annual performance.

A study on "The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system" by Norton concludes that the monthly optimum collection angle for a south-facing surface maximizing incident irradiation varied from 10° in June to 70° in December and seasonally from 20° in summer to 60° in winter. The annual incident irradiation on horizontal and vertical surfaces with orientations of 90° East or West from due south were 9.0% and 42.5% lower, respectively, than the maximum annual irradiation, and annual PV outputs were 9.9% and 54.4% lower, respectively than the annual maximum total PV output [6].

A study by *T. Pavlovic* on the "Determining optimum tilt angles and orientations of photovoltaic panels in niš, Serbia" revealed that solar module oriented towards the South gives the greatest values of electrical energy for all the chosen angles. Solar module oriented towards the South gives the greatest value of electrical energy for the angle of 30°, the optimum fixed position for latitude 13°. Generated electrical energy output for solar module oriented towards the South 30° and East (West) for the angle 30° differ by 0.54%. And also the generated electricity for solar module oriented towards the East, South and West for angle 0° is the same [7].

Another study by K. Vickery on "Solar Photovoltaic energy production comparison of East, West, South- facing and tracking arrays in Vermilion, Alberta" where the East and West PV modules were tilted at 17.5° versus 68° for South facing modules revealed that South oriented solar modules produced approximately 30% more energy annually than the East or West modules. However, the East/West orientation modules produce more power during the summer months when the relatively high Sun elevation favors the tilt angle of the East/West oriented modules than the South oriented modules [10].

The main aim of this research study is un-earth the optimum tilt angle for roof top solar PV system installation (fixed tilts and orientations) and the extent to which deviation from the optimum affects the output of the PV system. The study seeks obtain the best Photovoltaic module tilt angle that can reduce the installation cost of PV system installation. This study applied to the technical assessment for rooftop Solar Photovoltaic system installation KikuKinderhause in Kumasi. The effects of tilt angle on the output of Solar Photovoltaic Systems for the Ghanaian setting would be analyzed using RETScreen 4. The optimum tilt angle and the corresponding PV output would be estimated annually for three different PV systems.

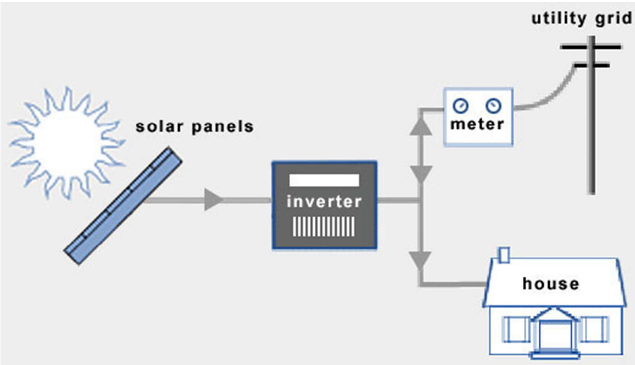
2. Methodology

The methods and data used to evaluate the optimal PV array tilt angle for the three different PV systems are described in this section. The section is organised under; theoryconsiderations of PV systems, case study, design methodology and implementation.

2.1. Theoretical Considerations of PV Systems

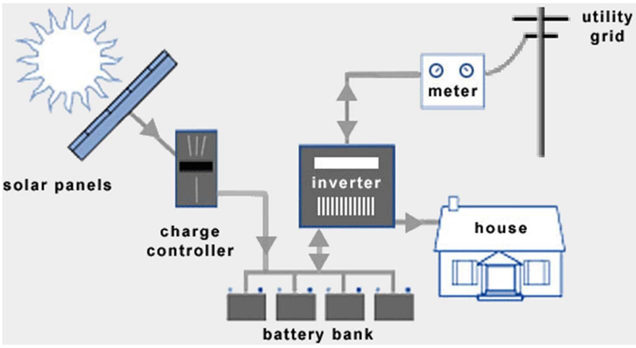
The reference diagrams for the Grid tied solar PV system, Grid tied Solar PV-Battery energy storage system and

Standalone Solar PV system including the energy flow is represented in figure 2, figure 3, and figure 4 respectively. The system comprises of the PV array, the battery bank, charge controller, inverter, the grid source and the load. The battery energy storage are generally used to compensate the gap between the energy availability and the energy demand [14].



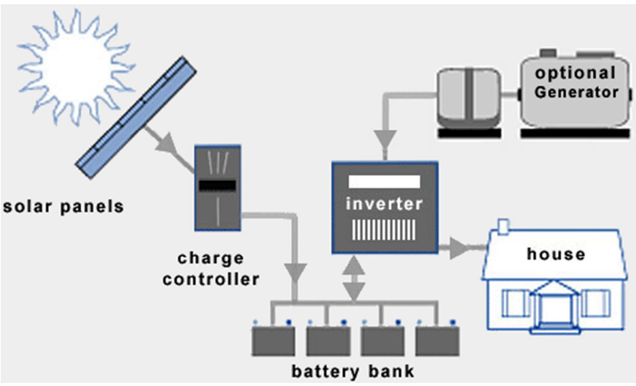
(Source: Energy informative, 2017).

Figure 2. *Grid tied PV system without battery storage.*



(Source: Energy informative, 2017).

Figure 3. *Grid tied System with battery energy storage.*



(Source: Energy informative, 2017).

Figure 4. *Stand-alone PV system.*

In the grid-tied system without battery storage the daily energy demand is satisfied by the PV array while the grid connection works as a backup energy source if the PV is not able to fully satisfy the energy demand. Equation (1) demonstrates the daily energy balance of this system.

$$E_{Ld} = E_{Ad} + E_{Gd} \tag{1}$$

In the grid-tied PV with battery energy storage system, and the stand-alone PV systems a charge controller with maximum power point tracking charges and protects the batteries from overcharging and excess discharge levels. The DC/AC inverter provides the conversion of the input current, coming PV array and the battery system, to alternating current required by the load in all the three systems. In the Grid tied system with battery energy systems the PV system operates to meet the energy demand, while the energy surplus, if there is, is first directed to the Battery energy system until it is fully charged, where the excess is sent to the grid. On the other hand, in case of low irradiation and during the night-time hours, the battery energy system supplies the energy deficit until the battery's state of charge gets to its minimum level. Therefore, the daily energy balance is satisfied by the PV plant, $E_{A,d}$, the battery energy storage system, $E_{B,d}$ and the grid backup, $E_{G,d}$ as defined in the Eq. (2).

$$E_{Ld} = E_{Ad} + E_{Bd} + E_{Gd} \tag{2}$$

In the stand-alone system the systems aim to supply the daily energy demand through the energy produced by the PV array or that stored in the battery system. Equation (3) demonstrates the daily energy balance of this system.

$$E_{Ld} = E_{Ad} + E_{Bd} \tag{3}$$

Performance assessment

The performance of a PV system is examined using selected performance indices such as energy output and capacity factor.

Energy output is the amount of alternating current, (AC) energy by the system over a given period, demonstrated by equation 4.

$$E_{AC} = \sum_{t=1}^{N} E_{AC}, t \tag{4}$$

Capacity factor, C_f is defined as the ratio of AC energy produced by the PV system over a given period of time to the energy output that would have been generated if the system were operating at full capacity for the entire period.

$$C_f = \frac{E_{ac}}{P_{pv,rated} * A_m} \tag{5}$$

2.2. Case Study

The study is applied to the optimum tilt angle and orientation for the design of an effective system for the installation of Solar PV System to meet the energy demand of KiKu-Kinderhaus Children's Home, a residential building in a remote community known as Ekyem a subbed of EjisuJuaben district in the Ashanti region of Ghana (Latitude 6.67N, Longitude 1.65W). The location is of high irradiation level, an average of 4.34kWh/m^2/day, an average ambient temperature of 26.1°C and an average sunshine hours of 5.3 hours per day [2]. The home already depends on the national grid for its electricity needs. Table 1 shows the roof characteristics, including the angle of inclination, the available useful area as per the orientation (N-S-E-W facing) as well as the possible shading Figure 5 is the picture of the main building at KiKu-Kinderhaus Children's Home considered for the solar PV installation.

Table 1. *Available roof-space and inclination in various directions.*

Roof Orientation	Area/m^2	Inclination (angle/0)	Possible shading
North	81.78	22.2	Poly tank
South	99.52	22.2	N/A
Inner (West/East)	66.46W /54.76 E	24.1	N/A
Outer (West/East)	54.76W/66.46E	24.6	Assembly Hall

Figure 5. *Main Building of the facility.*

Roof Characteristics and Estimations

A compass, level meter (android application) and a tape measure were used to measure, the North-South-East-West facing roof orientations, angle of inclination and area of the roof respectively. The roof is U-shaped with the East facing and West facing at the winds whiles the South and North facing at the middle front and middle back respectively when viewed from the entrance. Figure 6 shows the 2D rooftop view of the main building considered for the solar PV installation.

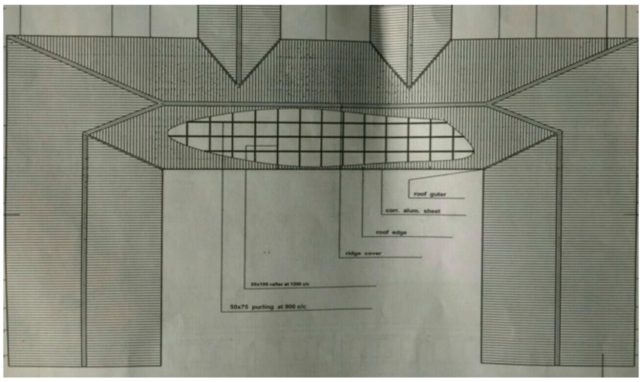


Figure 6. *Thetwo dimensional (2D) architectural drawing of the main building of Kiku residence.*

Load profile

The hourly load profile of the Kikukinderhause residence is illustrated in figure 7. They show an average load of about 40.8kWh/day in the rainy season and 29.9kWh/day in the dry season, and a yearly daily average request of about 35.35kWh/day. The main electrical load in the house consist of microwave oven, refrigerator, blender, hand iron, television, computer, ceiling fan, water pump and security light. Out of this average daily consumption, 30% represent consumptions from the premises street light (security light) which would be replaced by solar street light sets. Av average total with 10% load growth on the remaining daily consumption of 24.72kWh/day was used in the component sizing.

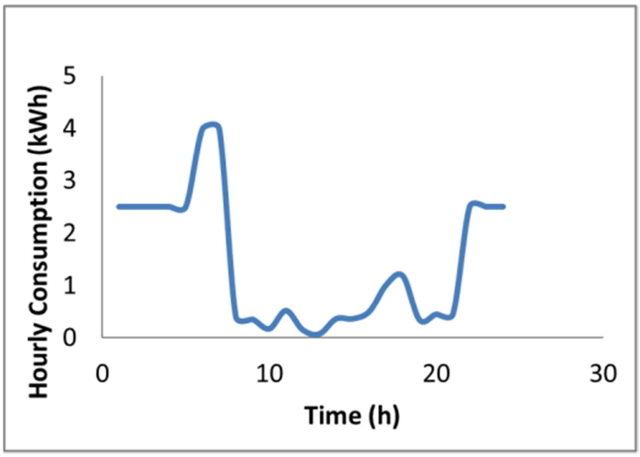


Figure 7. *Hourly Load profile.*

2.3. Design Methodology

This section deals with the design procedures used in sizing and specifications for all the PV system components within each solar PV system scenario under consideration. The general methodological steps include;

Assumptions for System Design

The average monthly daily solar irradiation would be used for the design of the Grid tied systems, while the lowest monthly daily solar irradiation (critical design analysis) would be used for the Stand- alone system.

Two days of autonomy is chosen for the Stand-alone system while one day of autonomy is chosen for the Grid tied PV-Battery energy system due to the relative stability of grid supply.

The monthly daily solar radiation for Kumasi varies throughout the year with an average of 4.344kWh/m^2 per day. The critical design month chosen is August because of its lowest average daily solar irradiation. Figure 8 below is the monthly average daily solar irradiation for Kumasi obtained from NASA data available on RETScreen.

System design procedures

The design procedures are common to all the PV systems since they are all designed to meet a specific load. An inverter with a combined rated power output of 25% or more of the array power rating at STC. All the PV systems considered were designed to meet the load. For each PV system scenario the system components were sized and selected according to the daily irradiation and system component efficiencies that would meet the required AC demand.

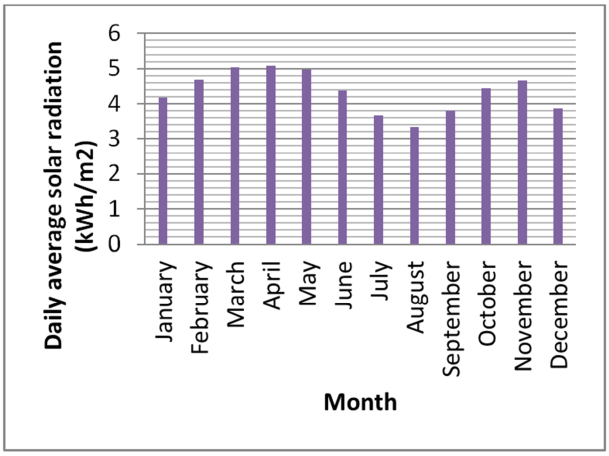


Figure 8. *The Average monthly daily horizontal solar irradiation for Kumasi.*

Scenario 1; Grid Tied Photovoltaic System (without battery Storage)

The daily electric load demand of the facility is 28.1 kWh/day with peak AC power of 8785.7W.

The corresponding PV array, P_{array} is *7.785kW*. Hence 30 modules of YL260P-35b solar panels would be selected.

For the system with peak AC power of 8785.7W. Thus inverter with nominal power of 11kW and a surge power of 17kW would be suitable. Fronius USA-Primo 11-4-1-240inverter would be selected.

Scenario 2; Grid Tied Photovoltaic System (with battery Storage)

Lithium Ion battery was selected based on its numerous economic and environmental advantage [1]. Lithium Ion Battery with a battery size of 200Ah, a nominal voltage of 12V, 80% depth of discharge of and 94% efficiency was selected. A battery bank size of 1000Ah and a system voltage of 48V were selected (a total of 20 batteries).

The corresponding PV array, P_{array} is 10400Wp (rounded). Hence 40 modules of YL260P-35b solar panels were selected.

For the system with peak AC power of 8785.7W. Thus inverter with nominal power of 11kW and a surge power of 17kW would be suitable. FroniusUSA-Primo 11-4-1-240inverter was selected. The selected MPPT Charge Controller is Vario String- 48V- 7000W-120A- MPPT solar controller.

Scenario 3; Grid Tied Photovoltaic System (with battery Storage)

Lithium Ion Battery with a battery size of 200Ah, a nominal voltage of 12V, 80% depth of discharge of and 94% efficiency was selected. A battery bank size of 1800Ah and a system voltage of 48V were selected (a total of 36 batteries). The corresponding PV array, P_{array} is 11440Wp (rounded). Hence 44 modules of YL260P-35b solar panels would be selected.

Two off grid string inverters with a combined capacity of 12kW would be required. Thus two 6kW string inverters would be would be used. A TBB 6000W (CSI6000S) off grid inverter would be appropriate for the battery size.

The selected MPPT Charge Controller is Vario String-48V- 7000W-120A- MPPT solar controller.

3. Results and Discussion

System simulation with RETScreen 4

The optimum tilt angle would be used to estimate the annual per watt energy yield for all the PV systems. In order to identify the optimum tilt angle, all the systems were simulated with different tilt angles. Table 3 presents the effect of tilt angle on per watt annual energy generated for all the three PV systems. Figure 9 presents graphical comparison of the effect of tilt angle on per watt annual energy generated for all the three PV systems. The systems energy output for the various orientations (South facing, East (West) facing and North facing orientations respectively). The results obtained from simulating the systems with all loss consideration are presented below in table 2. Table 3 presents the comparison annual per watt energy yield for all the orientations considered for the three PV systems. Figure 9 presents graphical comparison of per watt energy yield for all the orientations considered for the three PV systems with South orientation as reference.

The Grid-Tied system without battery, the grid tied with battery storage and the stand-alone system are identified in the tables with superscripts [1], [2] and [3] respectively for all orientations.

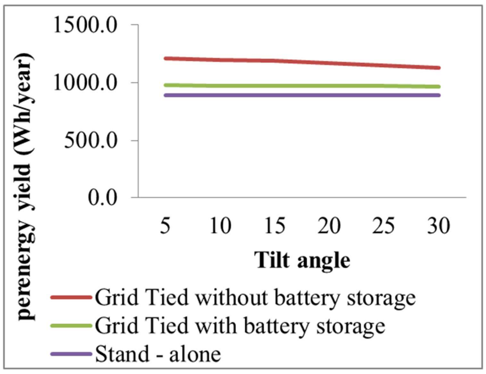


Figure 9. *Comparison of the per watt Energy yield of the systems.*

Table 2. *Effects of tilt angle on per watt energy yield.*

Tilt angle (°)	Per watt yearly energy yield (Wh)		
	Grid Tied without battery storage	Grid Tied with battery storage	Stand-alone
5	1208.5	976.4	894.4
*10	1200.4	975.5	894.2

Tilt angle (°)	Per watt yearly energy yield (Wh)		
	Grid Tied without battery storage	Grid Tied with battery storage	Stand-alone
15	1188.3	974.5	893.7
20	1170.9	972.6	893.4
25	1150.8	970.7	892.8
30	1127.9	966.8	892.0

From figure 9, the per watt energy yield of the PV systems decreases as the tilt angle increases. The Grid tied without battery storage is highly affected by the tilt angle while the systems with battery storage are marginally affected by the tilt angle. Karafil and Ozbey have said that environmental factors such as dust and dirt have significant effects on the efficiency of solar panels and should be considered when determining the optimum tilt angle for maximum solar PV performance [4]. Therefore the optimum tilt angle for all the systems that would give better yield and allow self-cleaning is 10°. Deviation from this optimum tilt angle would cause a reduction of 0.01% or more depending on how far the tilt is from the equator [8]. The generated electrical energy output by solar module at the optimum tilt angle (10°) was estimated for all the orientation for the three systems as presented by table 3.

Table 3. *Systems annual Energy production for the various orientation.*

Orientation	Installed capacity (kW)	E_{AC} produced (kWh/yr 1)	Capacity factor (%)
[1]South	8.32	10108	13.9
[1]East	8.32	9987	13.7
[1]West	8.32	9987	14.7
[1]East/West	8.32	9987	13.7
[2]South	10.40	10145.16	14.3
[2]East	10.40	10145.16	14.1
[2]West	10.40	10145.16	14.1
[2]East/West	10.40	10145.16	14.1
[3]South	11.44	10234.88	14.3
[3]East	11.44	10234.68	14.1
[3]West	11.44	10234.68	14.1
[3]East/West	11.44	10234.68	14.1

Comparison of the annual per watt energy yield of the various systems for all orientations is presented in table 4.

Table 4. *Comparison of annual per watt energy yield for all the orientations with South orientation as reference.*

Orientation	Yearly Energy produced per watt (Wh/yr)	Percentage reduction (%)
[1]South	1214.9	-
[1]East	1200.4	1.2
[1]West	1200.4	1.2
[1]East &West	1200.4	1.2
[2]South	975.5	-
[2]East	975.5	0.0
[2]West	975.5	0.0
[2]East&West	975.5	0.0
[3]South	894.7	-
[3]East	894.7	0.0
[3]West	894.7	0.0
[3]East &West	894.7	0.0

The yearly energy yield per watt is maximum for the Grid tied without battery storage followed by the Grid tied with battery storage with the stand – alone system giving the minimum due to storage losses. The East or West, East & West combined orientation give the same average annual energy yield for all the PV systems. For the Grid tied system without battery storage, the South orientation gives about 1.2% higher annual energy yield than all the other orientations which corroborates with the findings of [6] and [9].

4. Conclusion and Recommendation

4.1. Conclusion

This study investigates the optimum tilt angle for rooftop Solar Photovoltaic System installation KikuKinderhause in Kumasi. The technical performance of 8.32kW grid-tied without battery system, 10.40kW grid-tied with battery energy storage system and 11.44kW stand-alone system for four different orientations were investigated.

It was found that the optimum tilt angle for all the systems that would give better yield and allow self-cleaning is 10°. Deviation from this optimum tilt angle (away from the equator) would cause a reduction of 0.01% or more depending on how far the tilt is from the equator. The South orientation gives about 1.2% higher annual energy yield than the East or West orientation at the optimum tilt angle.

Again the yearly energy yield per watt is maximum for the Grid tied without battery storage followed by the Grid tied with battery storage with the stand – alone system giving the minimum due to storage losses. The East or West, East & West combined orientation give the same average annual energy yield for all the PV systems.

The information presented in this thesis can serve as inputs to the development of grid-tied PV system without battery, grid-tied PV system with battery storage and Stand-alone systems in Ghana.

4.2. Recommendation

1. The economic effect of tilt angle and orientation on the PV system with the aim to define the system tilt angle configuration that minimizes the LCOE is another interesting area.
2. Building architectures must incorporate solar PV systems in facility planning to enhance solar PV system energy output.
3. Also determination of Optimum tilt angle for Ground Solar Photovoltaic System installation could be considered for economic impact.

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