ORIGINAL RESEARCH ARTICLE

Effect of tilt angle on the performance of a thin-film photovoltaic system

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ABSTRACT
Solar energy is among the cleanest and most sustainable ways to enhance electrical supply's resiliency and reliability for domestic and industrial use. A Photovoltaic (PV) system is the most effective way of capturing solar energy. Long-term warranty, low-cost maintenance, and vast resource availability, solar power generation has an advantage over other approaches. Thin-film technology PV cells are a new kind of solar cell that offers an efficient technique of generating electricity from sunlight. The thin-film PV technology (FFMAT-10, Renovagen, UK) used in this study can supply 0.9 to 1.6 kW of energy to the fast-fold energy hub. The hub's system status and configuration display battery power input, battery's state of charge, thin-film PV power and AC power output. Two fast-fold mats (with a surface area of 25.3 m^2) were connected to the energy hub. Increasing energy demand coupled with frequent power outages, and inaccessibility of electricity in rural areas necessitates the usage of PV systems at their best performance level. The study objective, therefore, sought to assess the effect of tilt angle on the performance of the thin-film PV system. The study was conducted at Kimicha in Kirinyaga County Kenya, and Juja, Kenya at tilt angles between 0^o to 30^o. The results indicated that the mean peak PV power for Kimicha was 347.8±231.9 W at 5^o and 517.7± 131.3 W at 15^{o}for Juja. The maximum solar radiation during the study period was 1086.4 ±211.4 W/m^2 for Juja and 973.5±219.93 W/m^{2}for Kimicha. From the study, it was realized that an optimal tilt angle yields optimum solar radiation that translates to maximum power production. Even though the study was conducted in two different regions, it may be applied to any other geographical location. The outcome of the study aids in acquiring self-sustaining power in the most remote locations where electricity is scarce as well as improving energy security.

Keywords; Energy hub, Performance, Thin-film PV-system, Tilt angle, Solar radiation.

1.0 Introduction

Solar energy is one of the renewable energy sources that has been thoroughly explored as a means of supplying society's demands once fossil fuels have been depleted. Solar energy is, at

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its foundation, nuclear energy. Hydrogen is fusing into helium at a rate of around 7×10^{11} kg of hydrogen per second in the sun's inner 25%, but there is enough hydrogen in the core to keep this rate going for another five billion years. Every second, the sun emits 3.85×10^{26} joules of energy, which is greater than the total energy that man has ever utilized since creation (Miller, 2012). Although some of this energy is wasted in the atmosphere, the amount reaching the earth's surface every second is likely enough to meet the world's energy requirement if adequately harnessed.

Solar energy's only limitations are weather and time of day, which means it is not always available on Earth. As a result, a storage device is required to keep a solar power system running during the night when the sun is obscured by local weather circumstances(Babatunde, 2012). Solar energy can be transformed directly into electricity using a photovoltaic (PV) solar module, which uses the photoelectric effect to convert sunlight into electricity. The performance of the PV module, on the other hand, is dependent on the sun's light intensity, which is dependent on the weather and the solar panel's orientation. In addition to the two criteria discussed above, the performance of a solar panel is also influenced by a crucial component known as the ideal tilt angle. This is the angle at which the solar panel should be placed in relation to the horizontal plane to generate the most energy (Figure 1). The angle is determined by the latitude of the installation site and the season in which the solar panel is installed(Ajao et al., 2013).

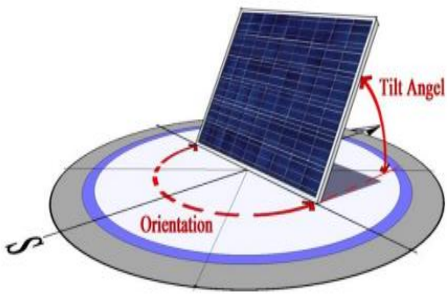

*Figure 1: Tilt angle of a solar panel (Al-Ghamdi & Alshaibani, 2018)***.**

Photovoltaic is a process of converting sunlight into electricity. This is achieved through the use of solar cells which absorb solar energy and convert it to electrical energy through the production of electron-hole pairs. Several factors determine the output from the solar panel such as air pollution, orientation, cloud movement as well as other factors (Salih & Kadim, 2014). The tilt angle of a PV system is defined as the size of the angle in degrees from the horizontal plane or the position in which a solar panel is positioned to face the sun (Sado et al., 2021). The tilt angle has a significant impact on the efficiency of PV (photovoltaic) panels. Therefore, to generate optimal power output, it is important to align the PV panels at a tilt angle for each given site. Solar PV generation climbed by 23% (+131 TWh) in 2019 (Figure 2), placing it second among all renewable technologies in terms of absolute generation growth, after only wind but ahead of hydropower. This indicates that solar PV generation has huge potential to solve the global energy demand. As the level of competition continues to rise, solar PV is on track to meet the Sustainable Development Scenario (SDS) targets, which call for average annual growth of 15% between 2019 and 2030.

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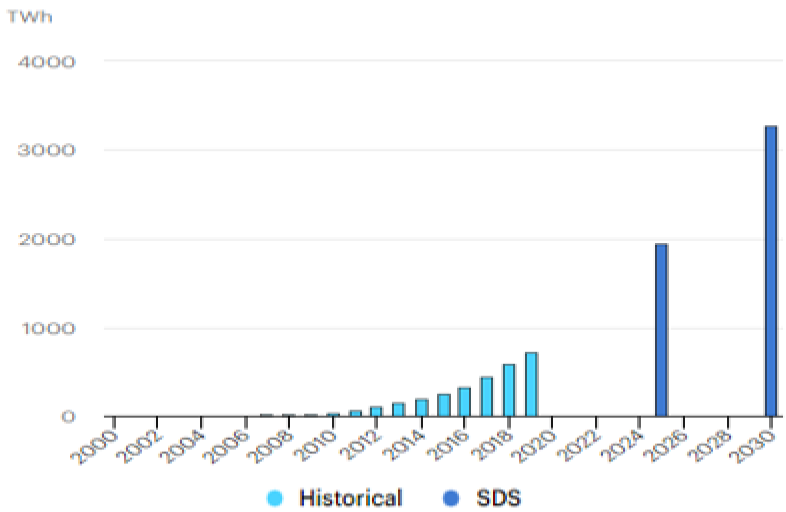

Figure 2: Solar PV power generation in the Sustainable Development Scenario (IEA, 2021).

The effect of tilt angle on the performance of the photovoltaic system has been widely studied. Shareef (2017) studied the impact of tilt angle on the PV panel output by varying angles from 0° to 90° in 1° step and found out that maximum power output occurred at an optimum angle of 45° angle but decreased significantly when the tilt angle is far from the optimum. Suman (2015) studied the effect of tilt angle and azimuth angle on solar output and optimum tilt and azimuth angles for Chandigarh, India by varying tilt angle from 8° to 36° with 2° step and azimuth angle from 120° to 240° with 20° step and concluded that an annual fixed angle of 20° and the annual azimuth of 180° produces an optimum output. A study conducted by Sharma et al. (2020) on determining the optimal tilt angle by use of real-time data acquisition of PV panels showed that the output of the PV panel is affected by inclination angle. They realized that optimal output was achieved between 26° and 28° which agreed with the results obtained through simulation. The magnitude of power generated by a PV is directly affected by the fixed tilt angle, hence, angles must be determined accurately to enhance the amount of incident solar radiation at the surface of the panel

According to Teske & Masson (2011), thin-film photovoltaic technology is a PV technology made through the deposition of thin layers of photosensitive material on a low-cost material like glass and plastic. A laser is then used to cut the attached photosensitive material on the backing. The commercially available thin-film modules are; Amorphous silicon (a-Si) (1 µm thick semiconductor material, low flow of electrons resulting in the efficiency of 4-8%), multi-junction thin silicon film (a-Si/µc-Si) (the µc-Si layer utilize red and infrared light raising efficiency to 10%). The other available modules are; cadmium telluride (CdTe) (has a module efficiency of 11%), copper, indium, gallium, (di)selenide/ (di)sulphide and copper, indium, (di)selenide/(di)sulphide (CIS) (has module efficiency in the range of 7-12%).

Thin films have a wide range of thicknesses, ranging from a few nanometers to tens of micrometers, and are thus best defined in terms of their generation and not thickness (Chopra et al., 2004). Thin-film solar cells traditionally have lower power conversion efficiency than bulk

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technology due to their amorphous or polycrystalline nature. Several intrinsic advantages of thin-film technology were, and continue to be, outweighed by this disadvantage (Kirchartz et al., 2016). In the field of thin film deposition, nanotechnology has a global reputation, and it also prepares the way for revolutionary techniques in large-scale applications. Advanced thin-film technology has progressed into an advanced method of improving performance and aesthetic value in the creation of new device applications. One such use is the hunt for novel materials for thin-film solar cells, which offers a solution to current energy (Senthi & Kalaiselvi, 2019). The study seeks to determine the optimal tilt angle of the thin-film PV system (a new generation of cells) which is different from the conventional crystalline silicon cells which have been widely studied.

2.0 Materials and methods

2.1 System description

A fast fold energy hub (Figure 3) that was used in this study had a weatherproof case which houses 10kWh capacity battery, an inverter, a battery management system and a charge controller. It is capable of supplying a maximum of 3 kW power. The system status screen displays the battery state of charge, power generated by fast fold mats and power output. It was also fitted with an emergency off button, circuit protection devices and a low battery alarm indicator. Fast fold energy hub can be supplied by a maximum of two fast fold mats.

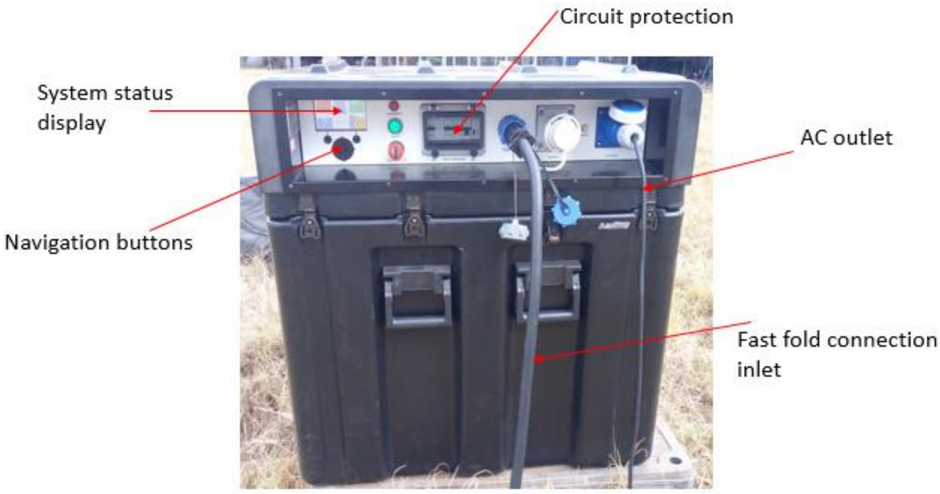

Figure 3. Fast fold energy hub

2.2 Study area and system set up

The experiment was conducted in Kimicha, Kirinyaga County, Kenya (37.294° E longitude, 0.594° S latitude and 1258 m altitude) and Juja, Kiambu County, Kenya (37.014°E longitude, 1.093°S latitude, and 1532.5 m altitude). A 1kW rated thin-film PV technology (FFMAT-10, Renovagen, UK) was mounted using strings to a double fabricated frame joined using three hinges (to facilitate adjustment of angles) fixed at 1.8 m interval(Figure 4a). The dimensions of the frame were 5.5 m long by 2.3 m wide. The thin-film PV was connected to an energy hub (FFENERGYHUB-10, Renovagen, UK) with a display.

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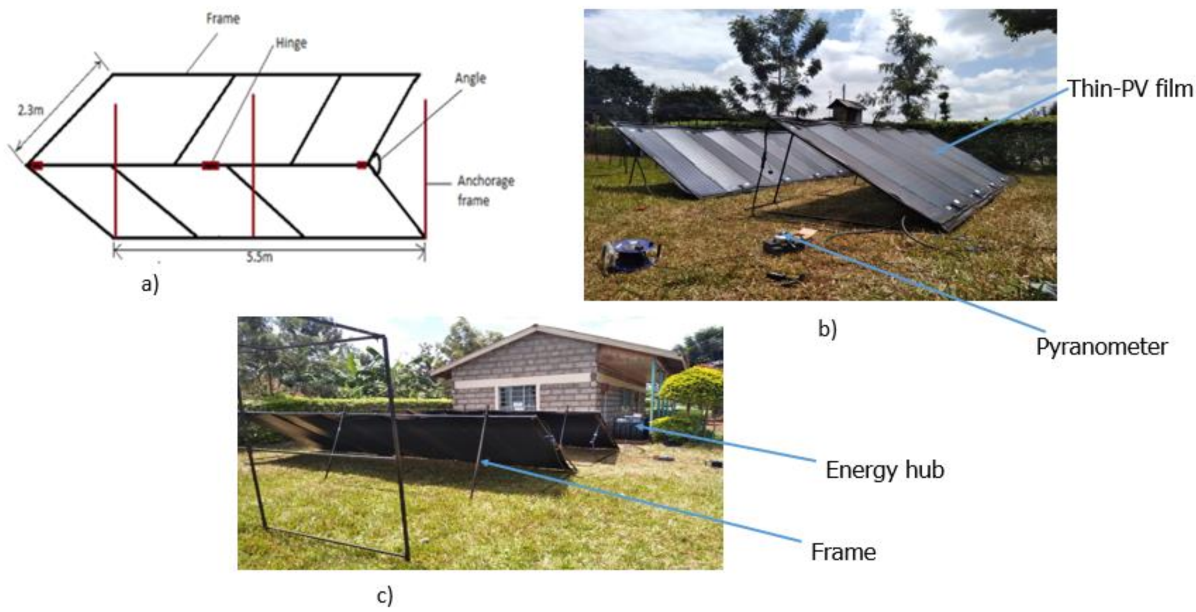

Figure 4: Thin-film PV system tilt angle set-up.

A pyranometer (SPN1, UK) was used to measure solar radiation. The thin-film PV system was first mounted at 0^o to the horizontal and repeated for the same at a succession of 5^o until a maximum of 30^o. A maximum of 30^o was selected based on the fact that pitched roofs have a slope of more than 10 degrees from the horizontal (Republic of Kenya, 2009). The maximum different angles were achieved by hooking the frame using anchorage bars with holes drilled at different distances representing different angles which were determined through the SOHCATOA rule. This process was repeated on an hourly basis from 5^o to 30^{o}under varying conditions. The optimal tilt angle of a thin-film PV system was then determined by analyzing the collected data of the angle that produced the maximum PV power charge data during the measuring period.

2.3 Data analysis

Analysis of variance (ANOVA) was conducted using R 4.1.2 for Windows (Vienna, Austria) to analyze the difference between the means of PV power and solar radiation at 5% level. In addition, the standard deviation was carried out to check the variability of the data about the mean.

3.0 Results

3.1 PV power

The maximum average PV power obtained in Kimicha (Figure 5) was 347.8±231.9 W which corresponds to 5^o and the minimum average power was 248.1±175.3W corresponding to 30^o. The results obtained from Juja (Figure 6) showed that the maximum average PV power was 517.7±131.3W and the average minimum was 367.9±146.7W corresponding to 15^o and 30^o, respectively. The results obtained can be attributed to the fact that a PV module must constantly face the sun for the incident light to be perpendicular to the module to capture the

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maximum amount of solar energy (Vidyanandan, 2017). However, when the sun moves from east to west across the sky, the angle of incidence changes dramatically, resulting in a drop in solar energy falling on the PV panel as more of the light bounces off the glass rather than being absorbed by the Photovoltaic panels (Asowata et al., 2014). It can be concluded that the optimal tilt angle for Kimicha is 5° and 15° for Juja. There was a significant difference ($p < 0.05$) between the means of PV power from the two study sites.

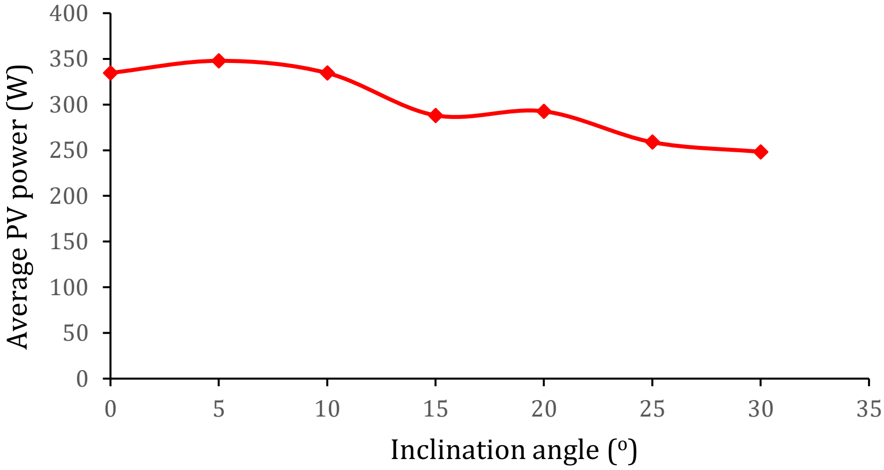

Figure 5: Average PV power output (Kimicha).

The ideal tilt angle can sometimes be greater than the latitude, and sometimes it is less. This occurrence is dependent on the day and month in consideration (Adama et al., 2021). The results from the two experiments are important because a wrong orientation of the thin-film PV system leads to a considerable loss of expected solar energy. As a general rule, the tilt angle is fixed at ±15°, where "+" represents the winter latitude angle and "-" summer latitude angle (Vidyanandan, 2017). This rule was not considered in this case because first; the relation does not factor in the different altitudes above sea level and cloud patterns (Mamun et al., 2018), Secondly, the regions under investigation are close to the equator. The results of the relationship between PV power output and the tilt angle is in agreement with (Mamun et al., 2022).

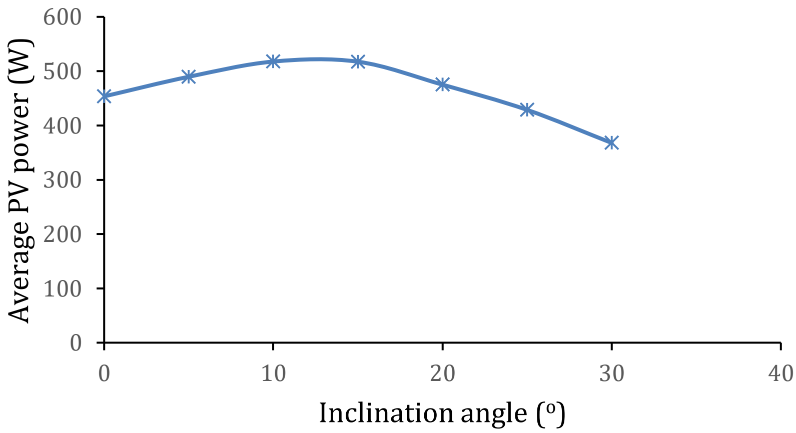

Figure 6: Mean PV power output at Juja

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3.2 Solar radiation

Solar radiation values for both Kimicha and Juja were also recorded. Results indicate that the maximum solar radiations were 973.5±219.9 W/m^2 and 1086.4±211.4W/m^2 for Kimicha and Juja both at time 14:00 hours (Figure 7) and (Figure 8), respectively. The minimum solar radiations were 230±219.9W/m^2 and 319.0±211.4W/m^2 for Kimicha and Juja, respectively. The results are attributed to the fact that the sun's radiation striking the earth is most powerful during solar noon (when the Sun is at its highest elevation in the sky) however, the radiation strikes at a lower angle during other times. As a result of the energy being dispersed over a broader surface area, its intensity is reduced (Vidyanandan, 2017). The maximum solar radiation values obtained indicated that the thin-film PV system at the right tilt angle can convert solar radiation to produce maximum power. There was a significant difference ($p< 0.05$) between the means of solar radiation at the two study sites.

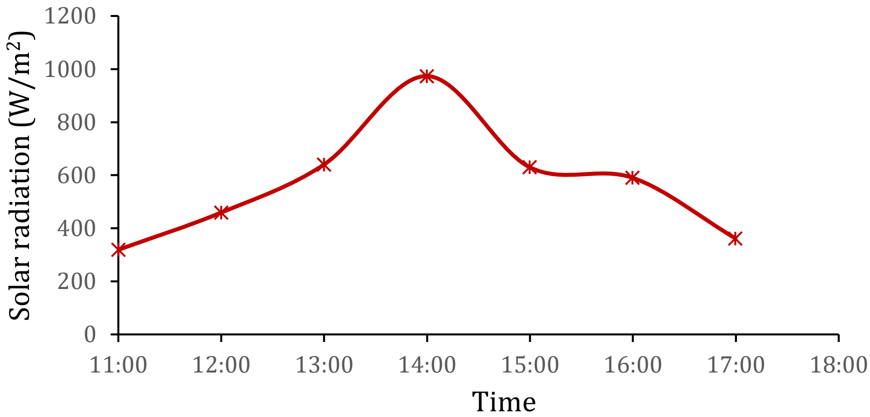

Figure 7: Meansolar radiation at Kimicha

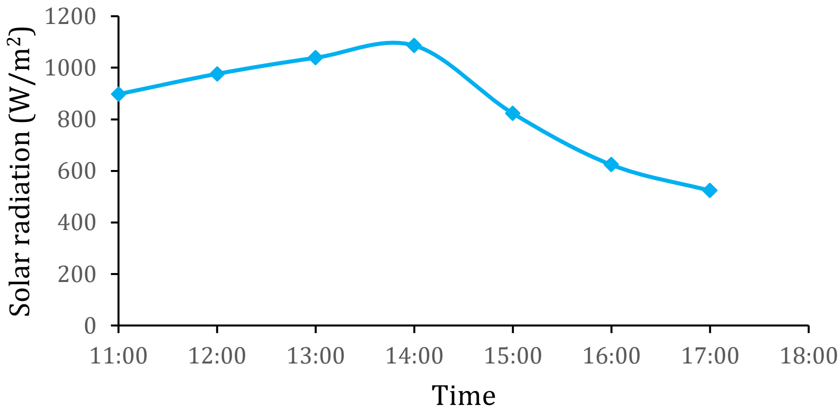

Figure 8: Mean solar radiation at Juja

4.0 Conclusion

The results from the two study sites indicated that the optimum tilt angles at which the solar panel generated the most PV power were 5° and 15° for Kimicha and Juja, respectively. The mean solar radiation of 567.8 W/$m^2$for Kimicha and 852.8 W/m^2 for Juja produced the average PV power of 347.9 W and 517.7 W for Kimicha and Juja, respectively. These results indicate that the PV system outperformed in Juja compared to Kimicha and this can be attributed to

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the different altitudes and climatic conditions of the two regions. Improper solar panel orientation results in power loss and eventually a low return on investment. As a result, determining the optimum tilt angle for a PV system is critical to generating maximum energy from a solar PV system. In addition, orienting the PV system at the right tilt angle ensures that energy security and sustainable development are achieved. Although the fact that the study was conducted in two different regions, it may be applied to any other geographical location.

5.0 Acknowledgement

5.1 Funding

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5.2 Presentation of the study, findings, and a portion of the work

A portion of the work done was presented in the 16th JKUAT Scientific, Technological and Industrialization Conference held on 24th - 25th March 2022, (venue-Council Room, JKUAT & Virtually under subtheme: Engineering technologies, ICT, built environment and infrastructure.

5.3 Declaration of interests

There were none declared. The current project fulfills the requirements for a Master's degree in Agricultural and Processing Engineering. The manuscript studies were organized in a chosen manner based on their relevance to the subject matter and predicted work quality, rather than being exhaustive. This article's opinions, assessments, knowledge, and conclusions are exclusively those of the author. The funders were not involved in the study design, data collection, or analysis, or in the decision to write or publish the report.

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