



Impact of the optimal tilt angle on the sizing parameters of solar photovoltaic powered pumping system

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Abstract: In this paper, comparative study of the effect of the yearly-fixed optimal tilt angle and the monthly adjusted optimal tilt angle were studied for a location in Imo State. The optimal tilt angle for each month and for the yearly-fixed optimal tilt angles were used to determine the water flow rate, pump hydraulic power, required solar photovoltaic (PV) array power, number of modules, area, and cost for the two scenarios. The results showed that for a sample numerical case of 50000 liters /day water demand there was a yearly average of 3.8% reduction in water flow rate and 3.8% reduction in the required hydraulic power when the monthly adjusted tilt angle is adopted. The month of December had the highest reduction of 9.9 % in the required flow rate and hydraulic power whereas the month of September had the lowest reduction of 0.3 % . Also, there was an increase in the PV power, number of modules, area and cost when the yearly-fixed optimal tilt angle was used as compared to the case where the monthly adjusted optimal tilt angles were used. In all, with respect to the cost of PV array, when the monthly adjusted optimal tilt angle was adopted, there was a saving of about 4 % of the total amount of money that would have been spent if the yearly-fixed tilt angle was used.

Keywords: Tilt Angle, Solar Power, Water Pump, Photovoltaic, Renewable Energy, Optimal Tilt, Hydraulic Power

I. Introduction

As the years go by, the adoption of renewable energy increases [1,2,3,4,5]. Also, in the developing countries where the national power grid have failed to provide the much-needed electricity to the vast majority of the population, the citizens and institutions have turned to diverse alternative sources of electricity to meet their daily energy demand [6,7,8,9,10,11]. Solar-powered water pumping system is among the popular applications of solar energy in the developing countries. However, the investment cost of such projects always make it difficult for many users to afford the solar pumping facility [12,13,14].

In this paper, the focus is to demonstrate one simple idea that can be used to improve on the efficiency of the solar pumping system and hence reduce the investment cost. Generally, the common practice has been to use the yearly-fixed optimal tilt angle to ensure yearly optimal solar radiation captured by the solar modules [15,16,17]. Furthermore, the use of an automated sun tracking mechanism has been advocated but the heavy cost of acquisition, installation and maintenance of such facility has made it not common in the developing countries. Rather than automated sun tracking adjustment of the solar panel tilt angle, manual adjustment can also provide significant gain if properly done [18, 19,20]. In this case, if the optimal tilt angle of the solar module is known for each month, the solar modules' tilt angle can be adjusted manually once every month.

In this paper, the impact and expected improvement in the solar pumping system facility specification requirement and cost for monthly adjusted optimal tilt angle are presented. The requisite analytical expressions are presented along with sample numerical example based on a solar-powered pumping system with 50000 liters/day water demand.

II. Methodology

The location is Faculty of Engineering Imo State University with the longitude 5.5082 and latitude of 7.0421 respectively. The optimal tilt angle for each month and the yearly-fixed optimal tilt angle of the location is obtained using PVSyst software. For the location with peak sun hour (PSH) and daily water demand, Q in liters/day, the water flow rate, r_f in m^3/s is given as;

$$r_f = \frac{\left(\frac{Q}{1000}\right)}{PSH(60)(60)} = \frac{Q}{PSH(3600000)} \quad (1)$$

Total Dynamic Head (TDH) in meters is given as;

$$TDH = \text{Vertical lift} + \text{Friction head} + \text{other losses} \quad (2)$$

Pump hydraulic power (W) requirement, P_{hyppwr} is given as

$$P_{hyppwr} = \rho(g)(r_f)(THD) \quad (3)$$

Where r_f is the flow rate in m^3/s ; ρ =density of fluid (kg/m^3) which for water is $1000 (kg/m^3)$
 $G = 9.81 \text{ in } m/s^2$ and TDH is the Total Dynamic Head (TDH) in meters. The pump efficiency is η_{pump} and the DC motor efficiency is η_{motor} , then the electrical power (P_{elpwr}) in W/day required to provide the given hydraulic power (P_{hypwr}) is given as;

$$P_{elpwr} = \frac{P_{hypwr}}{(\eta_{pump})(\eta_{motor})} \quad (4)$$

Assuming the pump will run for hpd hours per day, then the electrical energy (E_{elen}) in Wh/day required to the given electrical power is given as;

$$E_{elen} = P_{elpwr}(hpd) \quad (5)$$

In practice , about loss or safety factor value of 30% is applied to the PV array and its associated accessories. Hence, let efficiency the PV array and its associated accessories be denoted as $\eta_{pv\&a} = 77\%$; so the PV array energy (E_{PVAen}) required to provide the needed electrical energy (E_{elen}) for the pumping system is given as;

$$E_{PVAen} = \frac{E_{elen}}{\eta_{pv\&a}} = \frac{E_{elen}}{0.77} = 1.3(E_{elen}) \quad (6)$$

The PV array power (E_{PVApwr}) required to provide the needed PV array electrical energy (E_{PVAen}) is given as

$$E_{PVApwr} = \frac{E_{PVAen}}{PSH} = \frac{E_{elen}}{PSH(\eta_{pv\&a})} = \frac{1.3(E_{elen})}{PSH} \quad (7)$$

The required number of solar module is N_{PV} where ;

$$N_{PV} = \frac{E_{PVApwr}}{P_{pv}} = \quad (8)$$

Where P_{pv} is the power rating of a single PV panel. Let A_{pv} be the area of a single PV panel, then the total area (A_{AR}) of the PV area is given as;

$$A_{AR} = (A_{pv}) N_{PV} = (A_{pv}) \left(\frac{E_{PVApwr}}{P_{pv}} \right) \quad (9)$$

Let C_{pv} be the cost of a single PV panel, then the total cost (C_{AR}) of the PV area is given as;

$$C_{AR} = (C_{pv}) N_{PV} = (C_{pv}) \left(\frac{E_{PVApwr}}{P_{pv}} \right) \quad (10)$$

III. Results and Discussion

The computation was done for a daily water demand of 50000 liters/day or $50 m^3/day$, Total Dynamic Head (TDH) of 30 meters, Pump Efficiency (%) of 45%, DC Motor Efficiency (%) of 55%, PV array safety factor of 30 % which is equivalent to efficiency of 77% for the PV array and its associated accessories, the daily pumping hours is equal to the PSH of the month, per unit PV power is 50 watts , per unit PV area is $0.57m^2$ and per unit PV cost is ₦ 12,500. The result for the pump flow rate and hydraulic power for the yearly-fixed optimal tilt angle and monthly adjusted optimal tilt angle are given in Figure 1 and Figure 2. The results show that there is a yearly average of 3.8% reduction in water flow rate and 3.8% reduction in the required hydraulic power when the monthly adjusted tilt angle is adopted. The month of December has the highest reduction of 9.9 % in the required flow rate and hydraulic power whereas the month of September has the lowest reduction of 0.3 % .

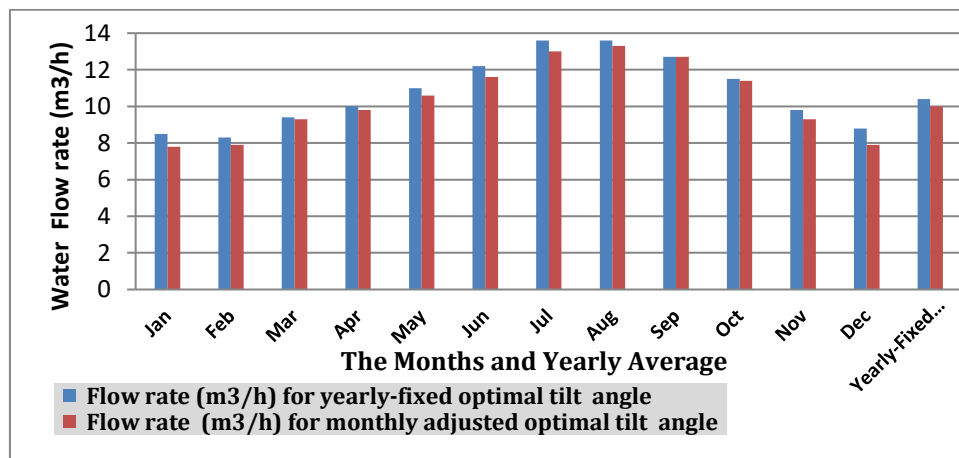


Figure 1 The water flow rate for the yearly-fixed optimal tilt angle and monthly adjusted optimal tilt angle

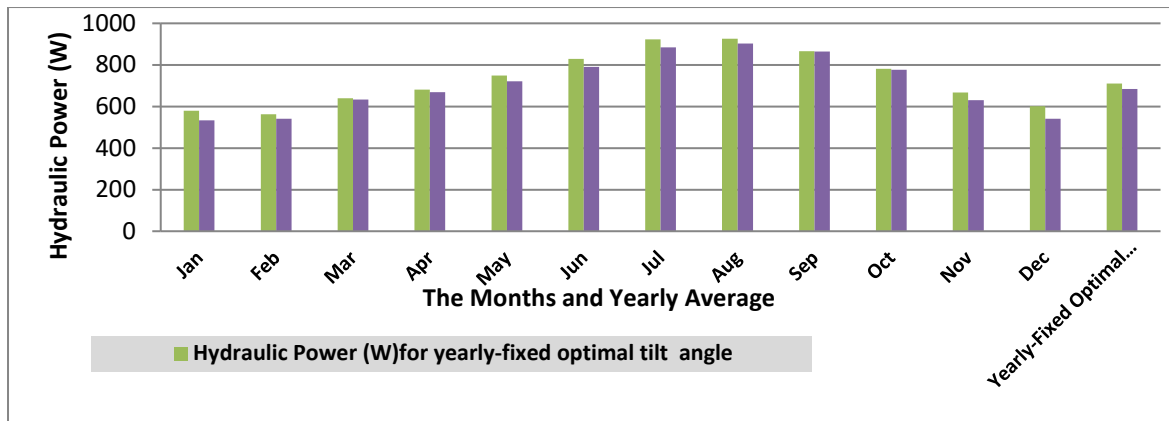


Figure 2 The hydraulic power for the yearly-fixed optimal tilt angle and monthly adjusted optimal tilt angle

The results for the PV array power, the number of modules, area and cost for the yearly-fixed optimal tilt angle and monthly adjusted optimal tilt angle are given in Table 1. There is an increase in the PV power, the number of modules, area and cost when the yearly-fixed optimal tilt angle is used as compared to the case where the monthly adjusted optimal tilt angles are used.

Table 1 The PV Array power, number of modules, area and cost for the yearly-fixed optimal tilt angle and monthly adjusted optimal tilt angle

Month	PV Array Power (W) for yearly-fixed optimal tilt angle	PV Array Power (W) for monthly adjusted optimal tilt angle	Number of PV Modules for yearly-fixed optimal tilt angle	Number of PV Modules for monthly adjusted optimal tilt angle	PV Array Area (m ²) for yearly-fixed optimal tilt angle	PV array Area (m ²) for monthly adjusted optimal tilt angle	PV array Cost (N) for yearly-fixed optimal tilt angle	PV array Cost (N) for monthly adjusted optimal tilt angle
Jan	3651.3	3365.2	74	68	42.2	65.3	925,000	850,000
Feb	3548.7	3413.3	71	69	40.5	66.2	505,875	828,000
Mar	4035.7	3990.6	81	80	46.2	76.8	577,125	960,000
Apr	4293.9	4218.0	86	85	49.0	81.6	612,750	1,020,000
May	4718.6	4548.7	95	91	54.2	87.4	676,875	1,092,000
Jun	5223.8	4981.4	105	100	59.9	96.0	748,125	1,200,000
Jul	5818.3	5576.5	117	112	66.7	107.5	833,625	1,344,000
Aug	5834.2	5694.9	117	114	66.7	109.4	833,625	1,368,000
Sep	5463.0	5449.2	110	109	62.7	104.6	783,750	1,308,000
Oct	4924.2	4890.6	99	98	56.4	94.1	705,375	1,176,000
Nov	4209.7	3975.9	85	80	48.5	76.8	605,625	960,000
Dec	3786.5	3413.3	76	69	43.3	66.2	541,500	828,000
Year Fixed Optimal Tilt Angle	4482.2	4311.2	90	87	51.3	83.5	641,250	1,044,000

In all, with respect to the cost of PV array, when the monthly adjusted optimal tilt angle is adopted, there is a saving of about 4 % of the total amount of money that would have been spent if the yearly-fixed tilt angle is used. In addition, an extra number of PV modules required for the case of the yearly-fixed tilt angle will also attract extra accessories such as wires as well as extra installation and maintenance cost. Furthermore, the higher water flow rate and higher required pump hydraulic power means that larger capacity and hence higher cost water pump will be required for the case of yearly-fixed optimal tilt angle.

IV. Conclusion

The effect of adjusting the tilt angle of the solar panels optimally on monthly bases was studied and compared to the usual practice of yearly-fixed optimal tilt angle. The relevant mathematical analysis for the comparative study was presented. The analysis is based on the yearly fixed optimal tilt angle and the monthly optimal tilt angle for a case study site in Imo State. The results showed that the monthly adjusted optimal tilt angle will reduce the required water flow rate and pump hydraulic power as well as the number, area and cost of the PV array needed to meet the daily water demand.

V. References

1. He, Z. X., Xu, S. C., Li, Q. B., & Zhao, B. (2018). Factors That Influence Renewable Energy Technological Innovation in China: A Dynamic Panel Approach. *Sustainability*, 10(1), 124.

2. da Silva, P. P., Cerqueira, P. A., & Ogbe, W. (2018). Determinants of renewable energy growth in Sub-Saharan Africa: Evidence from panel ARDL. *Energy*, 156, 45-54. Rahman, Z. A., & Elinda, E. (2016, March). The drivers to adopt renewable energy among residential users. In *IOP Conference Series: Earth and Environmental Science* (Vol. 32, No. 1, p. 012041). IOP Publishing.
3. Timmons, D., Harris, J. M., & Roach, B. (2014). The economics of renewable energy. *Global Development And Environment Institute, Tufts University*, 52.
4. Doner, J. (2007). Barriers to adoption of renewable energy technology. *Institute for Regulatory Policy Studies*.
5. Eswaralal, V. K., Dey, P. K., & Shankar, R. (2011). Enhanced renewable energy adoption for sustainable development in India: Interpretive structural modeling approach.
6. Oyedepo, S. O. (2012). Energy and sustainable development in Nigeria: the way forward. *Energy, Sustainability and Society*, 2(1), 15.
7. Ahuja, D., & Tatsutani, M. (2009). Sustainable energy for developing countries. *SAPI EN. S. Surveys and Perspectives Integrating Environment and Society*, (2.1).
8. Rapu, C. S., Adenuga, A. O., Kanya, W. J., Abeng, M. O., Golit, P. D., Hilili, M. J., ... & Ochu, E. R. (2015). Analysis of Energy Market Conditions in Nigeria. *Central Bank of Nigeria Occasional Paper*, 55.
9. Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, 47, 74-82.
10. Avila, N., Carvallo, J. P., Shaw, B., & Kammen, D. M. (2017). *The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers*. Technical report, OXFAM.
11. Kabir, E., Kim, K. H., & Szulejko, J. E. (2017). Social Impacts of Solar Home Systems in Rural Areas: A Case Study in Bangladesh. *Energies*, 10(10), 1615.
12. Bao, Q., Honda, T., El Ferik, S., Shaukat, M. M., & Yang, M. C. (2017). Understanding the role of visual appeal in consumer preference for residential solar panels. *Renewable Energy*, 113, 1569-1579.
13. Alexander, B. R., & Briesemeister, J. (2016). Solar Power on the Roof and in the Neighborhood: Recommendations for Consumer Protection Policies. *Consultant*.
14. Avila, N., Carvallo, J. P., Shaw, B., & Kammen, D. M. (2017). *The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers*. Technical report, OXFAM.
15. Zang, H., Guo, M., Wei, Z., & Sun, G. (2016). Determination of the optimal tilt angle of solar collectors for different climates of china. *Sustainability*, 8(7), 654.
16. Ekanem, O. D., & Onojo, J. O. (2017). Determination of Yearly Fixed Optimal Tilt Angle for Flat-Plate Photovoltaic Modules Based on Perez Transposition Model. *American Journal of Software Engineering and Applications*, 6(3), 80-84.
17. Karafil, A., Ozbay, H., Kesler, M., & Parmaksiz, H. (2015, November). Calculation of optimum fixed tilt angle of PV panels depending on solar angles and comparison of the results with experimental study conducted in summer in Bilecik, Turkey. In *Electrical and Electronics Engineering (ELECO), 2015 9th International Conference on* (pp. 971-976). IEEE.
18. Guo, M., Zang, H., Gao, S., Chen, T., Xiao, J., Cheng, L., ... & Sun, G. (2017). Optimal tilt angle and orientation of photovoltaic modules using HS algorithm in different climates of China. *Applied Sciences*, 7(10), 1028.
19. Koussa, M., Haddadi, M., Saheb, D., Malek, A., & Hadji, S. (2012). Sun tracking mechanism effects on flat plate photovoltaic system performances for different step time and main parameters affecting the obtained gains: case of North Africa and Mediterranean site. *Energy Procedia*, 18, 817-838.
20. Anyaka, B. O., Ahiabuike, D. C., & Mbunwe, M. J. (2013). Improvement of PV Systems Power Output Using Sun-Tracking Techniques. *International Journal of Computational Engineering Research*, 3(9), 80-98.