Design and Performance of a 1.5 axis Sun tracking Concentrated Photovoltaic System

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Abstract. This paper reports the design and testing of a concentrated solar photovoltaic thermal (CSPVT) system. The system consists of the PV panel, its cooling system, the parabolic concentrator, and the sun tracking mechanism. Photo Voltaic Thermal (PVT) systems are already a promising technique for improving energy yields and efficiencies of PV panels. The current work adds a concentration effect to make further improvements, especially on yields. Unlike the case of other research which uses plane mirrors along the sides of PV panels, this work employs a single parabolic reflector of concentration ratio 1.3, integrated with the panel mounting. A cooling system is also integrated with the mounting, so that the specially designed sun tracking mechanism turns the entire assembly, keeping both panel and reflector facing the sun without affecting the coolant flow in the adjoining pipes. This is one of the novelties of this work. We use vertical axis tracking but with seasonal adjustment of tilt. Hence the 1.5 axis in the title of this paper. Southern hemisphere spring tests in Cape Town showed a 60.2\% electric power gain when compared with yields from an identical fixed panel. We also develop and test a MATLAB program using actual weather data for the experimentation period, and do a TRNSYS simulation using the software’s embedded TMY (typical meteorological year) weather data for the period. We find MATLAB results to be closer to experimental ones, while TRNSYS ones are not far out on totals. We conclude that CSPVT has much potential to increase both yields and efficiencies. In addition, we suggest that TRNSYS simulation would probably be most useful in cases where actual weather data is not available.

1. Introduction

The continued rise of solar energy has induced researchers to look at solar panels as one of the quick and effective ways to resolve Africa’s energy crisis. Sub-Sahara Africa is known for its poor electricity grid. An on-going project published by the university of Cape Town [1], shows that more than 600 million of Africans have no access to electrical power, with over a half of them in rural areas with no access to the grid at all. According to Raguraman [2], Africa is a continent blessed with so much sunshine, which makes it suitable for solar energy harvesting. However, solar power usage in Africa is still relatively low when compared to other continents [3]. Solar panels are known for converting solar radiation directly into usable electricity, which makes them convenient for independent power generation.

Despite their convenience, solar panels’ ability to convert sunlight to electricity is very low which makes them less attractive to some homeowners. Their efficiencies are known to vary between 10 and 15\% [4]. Mono-crystalline silicon panels are considered to be the most efficient panels with efficiency ratings of 15\% to 22\% [4]. A number of factors affect a solar panel’s efficiency. Some of these are: the
fill factor (FF), the quantum efficiency [4]; type of solar cell, orientation to the sun, intensity of sunlight, temperature [5]; maintenance and lifetime, etc. Ref [6] gives 25°C as the temperature of testing solar cell efficiency. This is way below the expected cell’s operational temperature. Under normal operating conditions, the efficiency of the panel drops rapidly once the temperature goes beyond the cell’s nominal operating temperature (NOCT). Another crucial factor is the panel’s orientation to the sun as it enables the panel to receive a huge percentage of beam radiation from the sun. Manuel, [7] states that “most PV panels are less efficient because they are motionless and have no concentration of sunlight on them”.

This paper presents a suitable solution to the above. The methodology used was of ‘design, construction and experimentation’ type. Two systems were tested simultaneously, and results therefrom, compared. In the process, MATLAB and TRNSYS software simulation aided in calculating some of the variables used.

2. Theoretical framework and literature review
Several researches show that solar trackers can improve the efficiency of PV panel by allowing a big percentage of direct radiation to reach the glazing surface of the panel [8]. Kanyarusoke and Gryzagoridis, [9] report a 34.1% gain from tracking alone, without concentration. Irrespective of the tracking mode used, Vermaak, [10] experimental results displayed an additional gain of energy of between 33% and 37% compared to the static system. Although solar tracking is seen as a boost to PV panel energy yields, it can cause over-heating of the cells, which might adversely affect the efficiency and deliver undesirable and unexpected results when no cooling system is included.

Solar cells are made of different materials - namely: mono-crystalline silicon, polycrystalline and thin film. Every cell has distinct temperature coefficient from the manufacture. Mono-crystalline cells are considered to be the most efficient panels, with a temperature coefficient of -0.446%/°C[11]. However, their efficiency hardly surpasses 15%, due to excessive heat. Solar cells standard testing conditions are at 25°C, with a NOCT (nominal operating cell temperature) of 43°C. This means that, if operated at temperatures beyond 25°C, the outputs will be lower than the manufacturer’s recommendations even under similar radiation incidence conditions. Researchers around the globe combined the principles of PV panel with solar collectors, naming it, PV-T hybrid collector [12, 13]. The aim of the PV-T is to prevent the cell from overheating while also producing water and electricity simultaneously.

During experimental work conducted in Cape Town by Assembe [14], 18.89% increase in electrical efficiency was recorded and a thermal efficiency of 61.65% was achieved. The experiment was done using a 20 W multi-crystalline solar panel, which had no tracking or concentration on it. With that system, the researcher only resolved the temperature issue by using water to cool the panel. Unfortunately, his research does not address all issues mentioned previously. Above all, the PV panel used for his experiment was a small-scale panel, which is not suitable for a home.

A study by Salem et al. [15] on PV-T system shows an average increase of electrical efficiency of 17.7% - 38.4% relative to uncooled PV panel and a thermal efficiency range of between 31.1% - 57.9%. Three poly-crystalline 50 W non-tracking panels were tested and compared. The results obtained were quite impressive. However, it would have been better with a sun tracking and concentrated PV. Ramos et al. [16] back up the great potential for PV-T collectors. In their recent publication, they show that PV-Ts can reach overall efficiencies of over 70%, with electrical efficiency between 15%-20% or more in some cases. These figures are estimated for non-concentrated, non-tracking PV panels. Higher efficiencies could be obtained with the CSPVT.

Different researchers have already used reflectors to aid in efficiency of PV panels. For example, a study conducted in Saudi Arabia showed that by applying cooling alone, the power of the PV-T panel can be increased by 22.8% and for the concentrated PV-T by 31.5% relative to a simple PV [17]. Their experimental set-up consisted of a SunPower 230 W module and two rectangular glass mirrors with a reflectivity of 79%.

Results of a two-year pilot phase research conducted for a Germany company PlusAmpere Gmbh on PV panels, finds that using reflectors near PV panels can increase power generation by at least 14% [18]. Although, these results look appealing, the use of reflectors alone without any cooling system is not advisable for high temperature regions. Mar et al. [19] presented two studies conducted on a domestic solar PV in the United Kingdom and Nigeria. The results of the study revealed a drop of 1.1%
of power output for every increase in degrees Celsius once the cells reached temperatures of 42°C - 44°C.

The PV-T alone, does not improve the orientation nor does it increase the intensity of sunlight onto the panel; concentrated PV-T presents a better potential. However, it requires a tracking mechanism for better performance. Therefore, the present paper introduces a system that will target three of the most prominent factors affecting the conversion efficiency of solar panels. By using a sun-tracking concentrated solar photovoltaic thermal (CSPVT), the temperature of the cells is controlled and more energy is added to the panel (due to concentration of sunlight onto the panel and sun tracking).

3. Methodology

3.1. Design and Construction

The CSPVT used consisted of a 90Wp mono-crystalline solar panel, a 24L thermal water storage tank, a concentrating collector and a tracking mechanism. The design of a vertical axis sun tracking system, used ray-tracing approaches and sun-earth relative motions throughout the year to maximize ray concentration onto the panel. A water heating subsystem, which also acted as a panel cooling system was part of the tracking assembly. This element - of a sun-tracking tank, is one of the most important innovations of the project. Suffice to mention at this stage that the tracking design work involved time programming of a microcontroller. Figure 1 represents the 3D model of the CSPVT.

3.1.1 Testing and Experimentation. After construction, testing was done against suitable controls. Testing days were between the months of September and October 2018 in Cape Town, South Africa. The experiments were done on top of the roof of the Mechanical Engineering department at CPUT, where a first class weather station and two identical 90Wp mono-crystalline PV panels are installed from a previous research by Kanyarusoke [20]. The simple PV is inclined at 30° to the horizontal while the CSPVT is inclined at 25°. Figure 2 shows an overview of the experimental set-up. On the left is the conventional PV and on the right hand side is the CSPVT.
In testing, solar radiation arriving on site was measured using the mentioned weather station and electric energy harvest was monitored by logging 15 minute PV generated voltages and currents in the weather station data logger shown in figure 3. Thermal energy was monitored half hourly by direct readings of thermometers inserted at the bottom and top of the solar syphon tank. In addition, temperatures of the PV panel glazing and back plate were monitored to be able to give an indication of the cell temperatures through the King model as used in Kanyarusoke et al., [21] and Kanyarusoke & Gryzagoridis [10]. These data helped compute total energy yield and system energy efficiencies. The same was done on a standalone, non-tracking, and non-concentrating identical PV unit and comparisons made.

Due to academic deadlines, the experiments were limited to 10 days, as extending the duration would result in a year delay on the completion of the program. Nevertheless, the ten days were good enough to estimate the performance of the CSPVT. The variation of the meteorological conditions during the period of the experimental analysis was able to show performances resulting from different weather conditions except those for extreme winter.

The following equations were used compute the electrical and thermal efficiency of the systems:

- **Instantaneous efficiency:**
  \[ \eta_{\text{inst}} = \frac{\text{Total energy collected}}{\text{Total incident energy}} = \frac{VI}{AG_{gl}} \]  
  \[ (1) \]

  In which, \( V \) is the voltage in Volts; \( I \), is the current in amps; \( G_{gl} \) is the total radiation reaching the glazing surface of the panel, W/m\(^2\) and \( A \), is the area of the PV module in m\(^2\).

- **Electrical efficiency**
\[ \eta_{\text{elec}} = \frac{E_{\text{elec}}}{A \times \int_{\text{day}} G_{\text{gl}} \, dt} \]  

(2)

Where, \( E_{\text{elec}} \) is the total energy collected in Joules, and \( t \), is time in seconds.

\[ E_{\text{elec}} = \int_{\text{day}} V \, dt \]  

(3)

- **Thermal efficiency**:

\[ \eta_{\text{thermal}} = \frac{Q_{\text{collected}}}{\int_{\text{day}} A G_{\text{gl}} - E_{\text{elec}}} \]  

(4)

\[ Q_{\text{collected}} = m_{\text{water}}(h_{\text{out}} - h_{\text{in}}) \]  

(5)

In which \( Q_{\text{collected}} \) is the thermal energy collected in the water from cooling the PV panel; \( m_{\text{water}} \) is mass of water, kg/s, \( h_{\text{in}} \) and \( h_{\text{out}} \) are specific enthalpies water (inlet and outlet).

- **CSPVT efficiency**

\[ \eta_{\text{total}} = \frac{Q_{\text{collected}} + E_{\text{elec}}}{\int_{\text{day}} A g_{\text{gl}}} \]  

(6)

- **Optical efficiency**

\[ \eta = \frac{G_{\text{in}}}{G_{\text{gl}}} \]  

(7)

Where: \( G_{\text{in}} \) is the solar radiation through the glazing. Both \( G_{\text{gl}} \) and \( G_{\text{in}} \) are calculated as described by Duffie & Beckman, [22] by using MATLAB.

- **Heat loss**

\[ U_{c} = \left[ \frac{N_{u} \times k_{a}}{L_{1}} + \left( \frac{1}{\varepsilon_{p}} + \frac{1}{\varepsilon_{g}} - 1 \right) \left( \frac{T_{p}^{2} + T_{g}^{2}}{T_{p} + T_{g}} \right)^{-1} \right] \left( h_{w} + \sigma \varepsilon_{g} \left( \frac{T_{g}^{4} - T_{a}^{4}}{T_{g} - T_{a}} \right) \right)^{-1} + \frac{\delta_{g}}{k_{g}} + \frac{L_{1}}{k_{1}} \]  

(8)

Where: \( k_{a}, k_{g} \) is the thermal conductivity of air and glass; \( N_{u} \): Nusselt number, calculated as in a modification of a method recommended by Duffie and Beckmann [22]. \( \varepsilon_{p}, \varepsilon_{g} \): emissivity of the plate and glass; \( L_{1} \): distance between the glass and the absorber plate; \( T_{p} \) & \( T_{g} \): temperature of the plate and glazing; \( \sigma \): Stefan-Boltzmann value; \( h_{w} \): convection heat coefficient; \( \delta_{g} \): glass thickness.

### 3.1.2 TRNSYS Simulation

Transient system simulation, TRNSYS, is a simulation software used in the fields of renewable energy, construction, solar thermal processes, etc. [23]. The program uses typical meteorological data to estimate the yearly performance of the system being analysed. For present research, the simulation was necessary to estimate the energy gain from concentrating PV collectors relative to conventional PV module. Figure 4 shows basic model of TRNSYS used in predicting the total energy yield from the CSPVT module.

![Figure 4: TRNSYS simulation for Cape Town](image-url)
Weather data reading: the simulation used a corresponding standard weather format for Cape Town, type 15-2, TMY2, as listed in the software. The modeller selected all other parameters such as the slope, the tracking mode and radiation.

- **kJ/h convertor**: to convert Watts to kJ/h.
- **CSPVT**: Concentrating PVT collector.
- **Integration**: is used to compute the daily and yearly performance of the PV module
- **Graph plots**: used to display the graphical results
- **Daily and annual results**: used to record the results obtained

4. **Results and discussion**

The performance of CSPVT was determined from the thermal and electrical efficiency of the same. The sum of the two characteristics is the overall or total efficiency of the CSPVT. Figure 5 shows the daily energy generated from both PV modules. The power produced from PV modules is given in watts ($V \times I$), which was converted to energy in kWh. The sum of the daily energy produced by the CSPVT during ten experimental days came to 8.134kWh, which is 60.2% greater than the energy produced by its counterpart. The conventional PV generated 5.08kWh of energy. Assembe [14] reported an efficiency increase of 18.89% by cooling alone. Whereas Kanyarutsoke [21] showed a 34.1% gain in electrical power when tracking alone. TRNSYS simulation displayed in figures 9 & 10 shows a 27% boost on energy generated by the tracking CPV without cooling. This seems to suggest that the reflector makes a contribution of 7-14% on the overall efficiency.

![Energy Yield By Both PV Modules](image)

**Figure 5.** Daily energy yield in kWh

Figure 6 gives a representation of the overall energy collected from the CSPVT. Total thermal energy collected was 96.32 MJ, while the electrical energy was 29.3MJ; totaling 125.62MJ which is 62% of the total incident energy as presented in figure 7. For the conventional PV, over 80% of the energy incident was lost as revealed in figure 7.
Figures 8 and figure 9 are a representation of the total irradiance on the surface of the PV module. The total irradiance on the CSPVT, $G_{CSPVT}$, was 278.75 MJ while on the conventional PV it amounted to 169.56 MJ. These results show an increase of 64.4% of energy reaching the panel. TRNSYS simulation shows 54.6% increase in kWh of energy available on the panel relative to the conventional PV. Table 1 highlights a typical day’s energy yield from both panels.

| Hour of year | daypanel kWh | dayelec kWh | daythermal kWh | Eta-day | thermal η |
|--------------|--------------|-------------|----------------|---------|-----------|
| 6048         | 3.57         | 0.57        | 2.40           | 0.16    | 0.67      |
| 6072         | 4.50         | 0.72        | 2.89           | 0.16    | 0.64      |
| 6096         | 5.04         | 0.81        | 3.39           | 0.16    | 0.67      |
| 6312         | 4.53         | 0.68        | 3.18           | 0.15    | 0.70      |
| 6360         | 5.58         | 0.84        | 3.87           | 0.15    | 0.69      |
| 6408         | 5.58         | 0.84        | 3.73           | 0.15    | 0.67      |
| 6672         | 3.88         | 0.58        | 2.37           | 0.15    | 0.61      |
| 6696         | 3.21         | 0.48        | 2.07           | 0.15    | 0.64      |
| 6720         | 6.13         | 0.92        | 4.12           | 0.15    | 0.67      |
| 6744         | 4.53         | 0.68        | 3.08           | 0.15    | 0.68      |
Figure 8. Solar irradiance, $G_{gl}$ on CSPVT

Figure 9. Solar irradiance on conventional PV

TRNSYS simulation helped to estimate the fraction of energy added due to the concentrating effect. Figures 10 and figure 11 are the representations of the electrical and thermal yields from the CSPVT. The simulations predicted a total energy yield of 38.2 kWh. That represents an overall (electrical and thermal) efficiency of 82%. Where, 16% derives from the electric performance. The experimental results show 34.89 kWh of energy yield (thermal plus electrical).

Figure 10. TRNSYS graphical results for energy yield
Figure 11. TRNSYS graphical results for thermal yield

Figure 12 compares the experimental results to TRNSYS. It shows the typical results extracted from simulations against the actual ones. According to simulations, the CSPVT would generate a total of 7.1kWh of energy. However, from the experiments, the CSPVT generated 8.134kWh. The discrepancy between the results is to be expected due to many factors discussed in the author’s next article “validation of TRNSYS modelling for a CSPVT” to be published in Nov. 2019. The results obtained thus far, show that CSPVTs have a great potential of increasing the efficiency of PV panels from as little as 14% to over 60%.

Figure 12. Comparison of experimental results vs TRNSYS

Figure 13 highlights the temperature of the panels versus the solar radiation. The temperature of the CSPVT glazing was between 18°C-50°C due to water-cooling, giving better performance on the electric yield.
5. Conclusions
This research work has introduced a new improved design, the concentrated solar photovoltaic thermal (CSPVT) cooled system for domestic use. The system’s main purpose was to improve the energy yield from solar panels and consequently its efficiency. The experiments conducted led to the following conclusions:

- CSPVTs can improve the electrical efficiencies of solar panels by over 60%. When designed well, the heat recovery system achieved by cooling the panels can exceed 80% efficiency.
- Tracking itself improves the performance of PV panels by at least 30%, while cooling and reflecting can add 20 and 15% respectively.
- CSPVT systems can recover over 50% of the energy dissipated from PV panel cells.
- Depending on the quality and type, reflectors can increase the incident radiation and the optical efficiency of the panel by at least 34%.

Acknowledgement
The authors would like to thank the national research foundation, NRF, for funding this research work.

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