Light Filtered Concentrated Photovoltaic Thermal System

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Abstract

PV cells generate electricity, but the electrical output is only one component of the total energy produced by a photovoltaic array. A typical PV module has an ideal conversion efficiency of around ±15%, with the remaining energy generated as heat. This heat can raise the temperature by as much as 50°C above ambient temperature, resulting in two concerns: possible structural damage; and PV cell efficiency decreases as temperature increases. Crystalline cells are affected by temperature and their performance drops as cell temperature rises. In the case of combined photovoltaic thermal cells it has been shown that for each 1°C increase in temperature, the power output drops by approximately 0.5% which results in limiting the harvested energy

This article aims to introduce the concept of a concentrated Photovoltaic thermal system using an optical filtering technique. To this end concentrated sunlight is filtered into its major components and then utilised in a more appropriate way. The visible light is directed onto a standard PV surface while infrared is filtered before striking the PV surface and directed to a water column for heating purposes.

Keywords: Photovoltaic; Solar heating, light filtration; Photovoltaic thermal.

1. Introduction

The Earth's surface receives between 0.5 and 1 kW/m2 energy from sun in the form of solar irradiation. This varies from one location to another and even varies within the same location as the solar density varies in the course of seasons. However energy production is positively affected by light density.

Solar irradiance striking the earth's surface is divided based on wavelength and energy content into three ranges: ultraviolet (UV) 5-10% energy content (wavelength below 400nm), visible light (VL) around 40% energy content (wavelength from 400 to 700 nm) and infrared (IR) 50% of the energy content (wavelength above 700nm) [1].

Generally, energy production from solar irradiance takes two forms: thermal energy collection and direct electricity production. The IR range is considered as the major source of heat in the solar spectrum and is most useful for the thermal energy collection. Commercial single layer PV cells are predominantly designed to operate in the VL range. To this end, the appropriate utilization of incident solar energy should be governed by the ability to collect the energy across the total incident spectrum.

2. Solar Energy harvesting

Traditionally solar energy has been harvested in two forms:

2.1. Electricity Production

Photovoltaic (PV) cells present a source of clean renewable energy that should be used widely, but is still limited as a result of the relatively low conversion efficiency of the PV cell. [2, 3].

PV cell modules generate electricity, but the electrical output is only one component of the total energy produced by a photovoltaic array. A typical PV module has an ideal conversion efficiency in the range of 10 - 18%, with the remaining energy generated as heat. This heat can raise the temperature by as much as 50°C above ambient temperature, resulting in two concerns: the first is the possible structural damage if panels are not vented properly or if the heat is not recovered via a heat exchange process; the second issue is that the PV cell efficiency decreases as temperature increases. Crystalline cells are affected by temperature and their performance drops as cell temperature rises. It has been shown that for each 1°C increase in temperature, the power output drops by approximately 0.5% [4].

Commercial PV Cells (single layer PV cells) responds to light in different ways (see fig 1). While it reaches its highest efficiency at the VL range, their reaction to IR is unstable. Further the IR component is responsible for the undesired heat buildup in the PV cell. The principle behind the PV reaction to light is that the PV cell reflects the high energy photons (UV), and does not absorb the low energy photons (IR). In fact PV only makes use of the moderate energy photons in the VL range [5]. More precisely, Poly-Si cells shows around 80% External Quantum efficiency on VL range while sharply drops over IR rang. This besides the builded up heat under PV surface as operation continues due to the absorption of the IR portion of light [6].

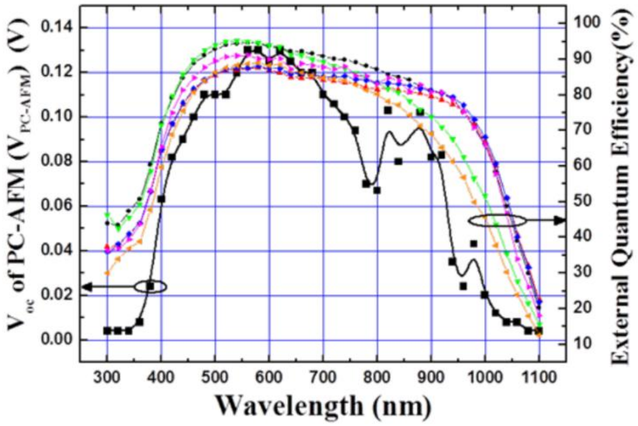

Fig. 1. External quantum efficiency (EQE) curve and VPC-AFM value with light wavelength of poly-Si solar cell devices [6]

2.2. *Photovoltaic and thermal (PVT) systems*

The harmful heat buildup in a PV cell could be transformed into a useful energy mainly by capturing it in the form of thermal energy. It has been confirmed that it is possible to capture four times the thermal energy than the electrical energy produced from the same surface area [7]. This fact has motivated the development of the photovoltaic thermal cells (PVT).

Although PVT systems produce thermal energy the fact that the heat is generated by cooling down the PV cell surface (the cooling fluid leaves at 5 to 10^{o}C lower than the PV cell surface temperature) this in turn limits the harvested thermal energy temperature due to PV efficiency and structural concerns. In other words, the increase in the thermal output may also result in a decrease in the electrical output [8]. Therefore, the most mature and affordable PVT systems are limited to non-concentration systems.

2.3. Solar thermal energy

Several applications have been developed and optimized in order to maximize the harvested thermal energy. One of the most common applications is the concentrated solar thermal collector (CSC). CSC systems generate only thermal energy, mostly at a high temperature but with sacrificing a considerable portion of the VL. There are different forms of CSC design taking into account various factors but most importantly driven by the required output temperature. Single point collectors (dishes, Fresnel lens collectors and helio towers) have the highest output temperature ever achieved [9].

Using a solar collector that suits buildings footprint is one of the most critical factors to overcome today`s challenge of energy decentralization. Fresnel lens collector presents a viable option for miniature concentrator that suits building`s foot print. Such concentrator is capable to produce a significantly high temperature from a relatively small area. For instance, a commercial Fresnel lens could easily provide more than 100 suns concentration.

2.4. Multilayer Photovoltaic

The recent development of the multilayer PV cell has achieved two important breakthroughs: first the significantly higher efficiency due to the wider operating solar spectrum and secondly a higher operating temperature which can reach to 100^{o}C. This presents the opportunity to apply low or mid factor concentration techniques to harvest thermal energy in a relatively high temperature space.

This technology might be limited due to some major disadvantages such as: the material cost and the complicated fabrication required are some of the concerns [8, 10]. Moreover, around half of the energy striking these PV models is transformed into heat as reported by a manufacturer of a sophisticated multi-layer PV cell (32% efficiency) Solar Cell Central [11]. Also, the PV structure is only capable of tolerating temperatures up to 100°C (212°F) (in the case of the most recent multi-layer PV cells [12]

2.5. Solar thermal collection fluid

In order to maximize the thermal output, most of the absorption chamber in CSC are black painted to trap most of the Solar spectrum into the absorption fluid. This allows several fluids to be used based on their thermal conductivity. One of the most affordable and widely used fluid is the water. However, water is one of the most studied fluids and almost all its properties have been overlooked. Still no or little research addresses the behavior of water in the solar thermal collectors in terms of its absorption of the solar array.

Several studies have been performed to investigate the absorption of solar irradiance by water in different fields (space, ocean, swimming pool, etc.). Most studies agreed that water absorbs predominantly the IR spectral components and very little of the VL components [13, 14, 15]. Figure 2 demonstrates this phenomenon as it shows that the water’s lowest absorption coefficient occurs in the VL range. Richard [16] carried out a detailed study on a swimming pool to assess the water absorption behavior towards solar irradiance. According to his findings, 24% of the solar spectrum is absorbed within the first inch of the water.

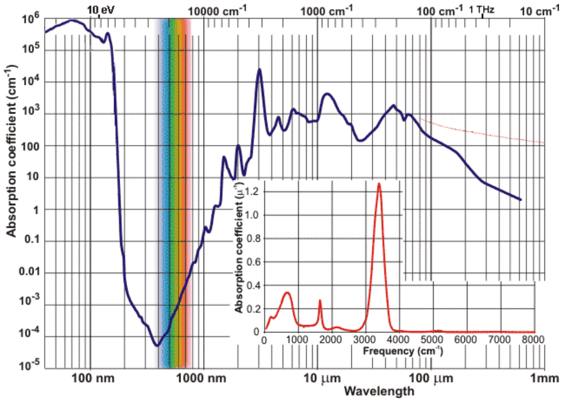

Fig.2. Water absorption coefficient across sun spectrum [14]

3. Conceptual design

This article introduces a concept of an ongoing project at the University of Johannesburg it is aimed at developing a higher energy density system that produces both forms of solar energy (electricity and heat) using the same projected area. The proposed system is designed to be an affordable small scale system that most importantly uses the solar spectrum in the most efficient manner possible.

In order to maximize the harvested energy from the sun, it is important to utilize each part of the spectrum in the most appropriate way. In this manner we deduced that the VL components are best used in the PV cell (for electrical generation), while the IR components are most appropriately used for the thermal energy collection and use. Furthermore by applying a simple concentration technique the effective usage of the incident solar energy can be even more efficiently. And also, split between the various components since the input energy can be more accurately matched to the various collection elements (PV cell and thermal collector).

To this end, a feasibility study has been conducted in order to develop a system that satisfy the band matching aim. As such, below are some commercially available technologies that would shape the system design:

3.1. Concentrator lens

A commercial, flexible square Fresnel lens, with a 90% transmission efficiency, that has a 100 times concentration power from a 1100 x 1100 mm^2 area onto an area with a diameter of approximately 70mm. This lens operates across the total spectrum with a transmission performance as shown in figure 3. The lens has the following specifications:

- Size: 1100 x 1100 mm
- Focal length: 1300 mm
- Focal point diameter: ±70 mm
- Material: Polymethyl Methacrylate (PMMA)
- Weight: 10 kg

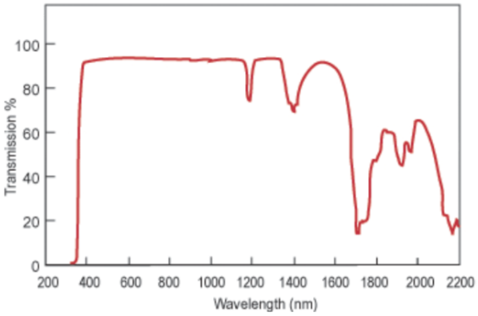

Fig. 3. Fresnel lens transmission used in the solar concentrator [17]

3.2 Filtering element

The filter implemented to split the VL from the IR parts of the spectrum is a so-called “Hot mirror” that has a transmission and reflection characteristic as given in figure 4(a) – it reflects almost 95% of the IR light and transmits almost 90% of the visible light [17].

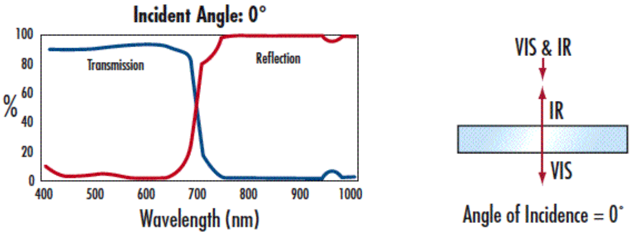

Fig. 4. (a) Hot mirrior trasmission and reflection, (b) hot mirror incident angle [18]

3.3. Heat collection fluid

Water has been selected as the thermal energy collection medium due to:

- high thermal conductivity;
- high absorption of the IR spectrum;
- high transmission of the VL spectrum.

Water light absorption and transmission are best described by Beer's law using the following equations [14]:

$$A = -\log10(I/I_o) = \alpha l. \qquad (1)$$

$$I/I_o = 10^{\alpha L} \qquad (2)$$

where

- A: absorbance in optical density

- I: density of light transmitted through the substance W/m2
- Io: density of light striking a substance W/m2
- α: absorption coefficient of the substance
- L: is the distance the light travels through the substance

3.4. Electricity Generation PV

Removing the IR light and thus; its associated heat from the surface of the PV cell allows the usage of the single layer commercial PV which is much more affordable compared to the multilayer PV. The selected commercial cell made by ENERSOL gives ±15% efficiency and 30W power on normal conditions.

Although, Light striking the surface of the PV is limited to VL, still increasing the amount of light high above PV maximum efficiency may lead some of the VL light to be transformed into heat. Therefore, PV has been decided to be matching the reaching light amount which lays around 300W then the targeted area is $0.25m^2$.

3.5. Solar Tracker

In order to achieve high concentration (+100 sun) it is mandatory to use a dual axis solar tracker. The selected tracker consists of 3 major parts as illustrated in figure 5:

1. sun sensors on the four directions,
2. control which receives the sensor signal and transfers it to the actuators
3. two actuators 1500N each, one for north-south and one for East- West

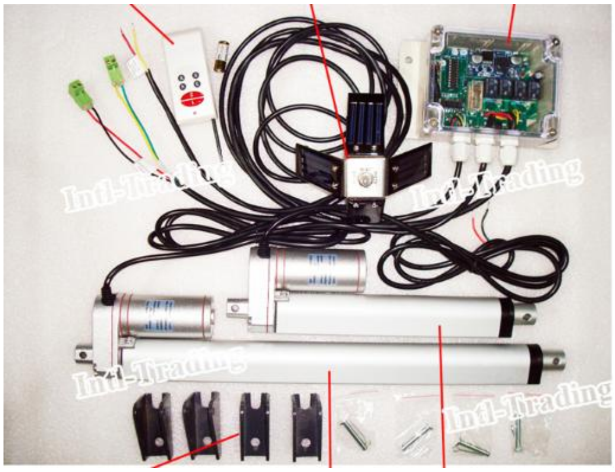

Fig. 5. Solar tracker kit [19]

4. System Operation

The proposed system was designed to operate in the following manner:

4.1. Concentration

- Light strikes the lens surface at a 0^o incident angle (due to the usage of a dual axis solar tracker).
- The lens concentrates the sun light at a distance of 1300mm away from the lens surface into a focal point of 70mm diameter.

4.2. Thermal energy collection

- A water container designed for a pressure of 69 kPa (10 PSIa) and temperature of 200^oC has been placed at the focal point [20]
- A water container covered with an uncoated window glass that has very high transparency also in line with the temperature and pressure requirements .
- 1kg of water with a depth of 100 mm absorbs ±50% of the incident IR.
- At the bottom of the water container is a hot mirror that reflects 98% of the incident IR which on reflection is again available for absorption by the water.
- A thermocouple and controlled water pump to circulate the water based on the required hot water temperature.

4.3. Electricity production

- VL light passes through the water and the top and bottom glass cover to impinge onto the PV cell.
- The PV cell receives the net of a 300W band matching light which is available for electricity generation.

4.3. Harvested energy

CPVT system is designed to produce electricity and thermal energy simultaneously from the same projected area as following:

- Thermal energy: The water column absorbs around ±400W IR light which increases water temperature from ±20oC to the desired temperature of 120oC this process takes around 10 minutes.
- Electrical output: poly-Si cell size $0.25m^2$ is placed to receive around 300W VL light which will be transformed into electricity at 15% efficiency to deliver 45W which is +15W higher than this size PV power (30W)

5. Conclusion

The design of an innovative, small scale CPVT system is presented based on an analysis of the solar spectrum and the manner in which the various components can best be used in conjunction with standard elements. The design is based on the concept of using a simple concentrator and mirror type splitter to more efficiently drive parallel PV cell and thermal collection units. The proposed system is expected to deliver the following outputs:

- Hot water at over 120°C
- Approximately 45W of electrical energy from a 0.25m^2 single layer PV cell.

This system has been design to best suits southern African conditions as Southern Africa is known for its cold, clear sunny winter, season with large energy demand, which in turn makes it suitable for solar energy harvesting. Such a CPVT system produces both forms of energy namely: water heated to a high temperature accompanied by a free electrical output. This design is likely to be more cost effective than more expensive concentrator designs due to the use of standard solar energy elements and the improved utilization of the solar spectrum. The system has also been designed to be smaller than many solar concentrator systems so that it may be applied in areas with limited space for solar system implementation. .

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