Hybrid Photovoltaic Thermal Cells: A Viable Solution to the Problem of Renewable Energy

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Hybrid photovoltaic thermal (PVT) cells represent a current frontier in renewable energy. These cells can harness both thermal and electrical energy from the sun resulting in large increases in net efficiency over traditional photovoltaic (PV) or solar thermal cells. High net efficiency PVT cells have already been demonstrated. However, the PV elements in these cells show poor electrical efficiencies when compared with traditional PV cells. The same can be said for the the thermal element. Further optimisation is needed. The current state of research in the field of PVT cells is presented, as well as potential avenues for future improvements. These avenues include the physical geometry of the cell, the material composition of both the PV cell and the heat exchanger and the coolant fluid. Current research is being conducted into nanofluids as an alternative to water or air cooling in PVT cells, which shows substantial increases in efficiencies of the cells. It is suggested in the literature that PVT cells could provide a viable alternative to centralised power generation by placing these cells on buildings. PVT cells may allow progress towards net zero energy buildings (nZEB).

Introduction

The scientific community, and indeed the global community, has turned its attention towards alternatives to fossil fuels in the generation of electricity. Photovoltaic (PV) cells are of particular interest. This clean and renewable source of energy has come to prominence in recent years as PV cells have become more popular among the general public. There are many clear advantages to PV cells: they provide power without the need for fossil fuels, they can be retrofitted for home use in attempts to reach an energy equilibrium or an nZEB. These are buildings where the power demands of the building are met entirely by power produced on site (Sartori *et al.*, 2012). They can also be scaled up to large scale photovoltaic plants such as the potential 10 MW power plant in Abu Dhabi discussed by Harder and Gibson (2011). Power plants producing greater than an order of magnitude more power have been discussed theoretically and have been installed in practice, such as the Solar Star I and II plants in California, USA.

There are some considerable drawbacks and limits to the effectiveness of PV cells. The Shockley-Quiesser limit is a fundamental limitation to the efficiency of traditional photovoltaic cells (Shockley and Quiesser, 1961). Most traditional PV cells consist of a p-n junction produced with either monocrystalline or polycrystalline silicon. The Shockley-Quiesser limit determines that the maximum possible efficiency for an ideal silicon p-n junction PV cell with a band gap of 1.1 eV is 30%. The experimental upper limit was predicted by Shockley and Quiesser to be in the region 27%. The primary reasoning behind the inefficiency of the PV cell is that the cell cannot efficiently absorb at all wavelengths as photons with energy less than the band gap will not excite electrons to the conduction band. The excess energy from photons with energy greater than the band gap will be converted into heat. There is, as a result, a large generation of heat in the cells. This problem is compounded by the fact that PV cells become less efficient at higher temperatures resulting in even lower efficiency (Skoplaki and Palyvos, 2008). Steps have been taken to increase the efficiency of the photovoltaic cells by increasing the number of terminals and the variety of materials to increment the range over which the cell will absorb efficiently. Steiner *et al.* (2015) produced a large-scale four-junction PV module with an efficiency of 36.7%. Efficiencies can be increased further by concentrating the light incident onto the cell (Guter *et al.*, 2009).

However, the problem of waste heat generated still remains and the cells have to be cooled to maintain optimal efficiency. Hybrid photovoltaic thermal (PVT) cells aim to harvest both the electrical energy and the thermal energy produced in the cells. These cells combine a photovoltaic cell and a solar thermal cell to produce solar electricity as well as either thermal electricity or usable heat. PVT cells have the potential to vastly increase overall efficiencies of the traditional PV cell. The research on this innovative technology is still in relative infancy although very high total efficiencies have already been reported (Dupeyrat *et al.*, 2011).

Basic Principles of PVT Cells

The most common form of PVT cell is the flat-plate PVT cell. The flat plate PVT cell consists of a PV element that is placed in thermal contact with a thermal collector. The methods of mounting the PV element onto the thermal collector can considerably effect the net efficiency of the cell (Dupeyrat *et al.*, 2011). The thermal collector is simply a material with a high absorbance with a cooling fluid passing through it to transfer heat from the cell. The cooling fluid, the most common being either water or air, is pumped through the system for active cooling of the cell and heat transport. Natural air convection can instead be used for passive cooling in some circumstances. There are several popular configurations as outlined by Chow (2010). The main competitor to the flat plate PVT cell is the concentrator type PVT (c-PVT). In this type of cell, light is concentrated onto the cell using an optical system, either reflectors or lenses, in order to increase the radiation intensity incident upon each cell. The specific designs of the systems vary depending on the cooling fluid but their basic structures are similar. The recent research in the area can be split into three main categories: air cooled PVT cells (PVTa), water cooled PVT cells (PVTw) and c-PVT cells.

PVTa Cells

The path a coolant takes through the thermal collector can drastically effect the performance of the cell. Hegazy (2000) compared four types of PVTa configurations. The 4 configurations involved were as follows:

1. Air flowing over the heat absorber.
2. Air flowing under the heat absorber.
3. Air flowing both over and under the heat absorber in a single pass.
4. Air flowing first over and then under the heat absorber in a double pass.

Hegazy (2000) found that the thermal efficiency (η_T) for configuration 1 was considerably lower than the others, showing η_T values 3-5% lower than the other configurations, at flow rates of air ranging from 0.005 to 0.04 kg s^{-1} m^{-2}. The electrical efficiency (η_e) was found to be very similar in all four cases, ranging from 0.068 to 0.081. A point Hegazy (2000) makes is that the power required to circulate the air with fans should be factored into any calculations regarding net power produced. It was found that the third configuration required the least amount of fan power and, as a result, produced the largest net available electrical energy of the four configurations. The net calculations for the configuration 3 PVTa cell show a net efficiency (η) of 0.55 at a mass flow rate of 0.03 kg s^{-1} m^{-2}.

Tripanagnostopoulos *et al.* (2002) tested both PVTa and PVTw cells outdoors under a variety of configurations. The bulk of the tests were carried out using polycrystalline Silicon (pc-Si) PV cells. The most notable inclusions are additional glazing in order to increase η_T of the cell and the inclusion of reflectors between cells, which increase the incident power onto the cells. It was found in both cases that the highest η_T was achieved when both the additional glazing and the reflectors were in place. At a cell coolant temperature equal to ambient temperature, η_T of 0.8 for the PVTw cell and 0.75 for the PVTa cell were observed. η_e for both cases were similar, between 0.1 and 0.15 respectively. The inclusion of the glazing notably lowered η_e, however the inclusion of the reflector effectively reversed this decrease. The maximum electrical efficiencies were found with reflectors without glazing.

Bambrook and Sproul (2012) attempted to optimise a PVTa system integrated into a home for use as an air heater. Building-integrated PVT (biPVT) cells are becoming of increasing interest in the attempt to reach a nZEB (Good *et al.*, 2015). Of particular relevance to this paper is the optimisation of the fans providing the cooling to the cell. It is noted in the paper that there is a delicate trade-off between increased fan speed and η. Although an increased mass flow rate of air will increase both η_T and η_e, the increased fan speed will, itself, require more power. At mass flow rates from 0.02-0.055 kg s^{-1} m^{-2}, the electricity gained from increased efficiency of the PV cell outweighs the power required to drive the fans. At higher flow rates, the fans power consumption outweighs the benefit provided. The maximum observed thermal efficiency was between 0.55-0.60 at a mass flow rate of 0.082 kg s^{-1} m^{-2}. The air was found, at these elevated flow rates, to only deviate from ambient temperature by 3-4 K. This temperature gradient is insufficient for effective heating of a household. Such issues lead the authors to suggest a moderate airflow of 0.04-0.05 kg s^{-1} m^{-2}.

Pathak *et al.* (2012) take a different approach to the PVT cell. They suggest that rather than trying to lower the temperature of the cell to increase η_e, operating at a higher cell temperature will increase η_T. This could also have benefits for biPVT cells used for heating purposes. They note that the η_e of amorphous silicon PV cells has a much lower dependence on temperature. Thus, operating at an increased temperature would result in minor decreases in η_e but would result in considerable increases of the η_T of the cell.

Parametric Optimisation of a PVTw System

Dupeyrat *et al.* (2011) discuss an optimisation process for a glazed flat plate biPVT used for hot water systems (biPVTw). The first point considered is the reflection of incident light by the glass coating. It is found that glass used in conventional PV cells has a global normal transmission coefficient of approximately 0.91. With the use of double-sided anti-reflective coated low iron glass, this coefficient is increased above 0.94. Single crystalline silicon (c-Si) is found to have a higher η_e than polycrystalline silicon (pc-Si). Dupeyrat *et al.* (2011) investigated η_T of pc-Si to determine its viability in comparison to c-Si. c-Si proved superior in this regard, showing an absorption coefficient of 0.90 compared with pc-Si of 0.85, resulting in higher η_e values for c-Si. The discrepancy is explained by the uniform surface texturing of c-Si compared to the pc-Si. The rough surface of pc-Si results in higher reflection of incident radiation compared to c-Si.

The PV packing factor, defined as the ratio of the surface area of the PV cells to the total surface area, was then investigated to determine a packing factor that produced optimum η. It was found that increasing the packing factor increased η_e and decreased η_T values (Dupeyrat *et al.*, 2011). The material composing the heat exchanger to which the PV cells are bonded generally has a correspondingly higher absorption coefficient than the cell itself, and this leads to the decrease in η_T. A packing factor of 0.8 was used by Dupeyrat *et al.* (2011). It was found that the method of adhering the PV elements to the heat exchanger can effect η_T. Early investigations by Zondag *et al.* (2003) and Ji *et al.* (2007) used epoxy glue and silicon adhesive respectively. Dupeyrat *et al.* (2011) used a lamination process which increased the thermal conductivity between the PV cell and the heat exchanger, with improvements in η_T of between 4-8% and improvements in η_e of roughly 1% compared to that used by Zondag *et al.* Combining the anti-reflective coating, c-Si PV cells, 0.8 packing factor and laminated adhesion of the cells to the heat exchanger produced a highly efficient cell. The cell with coolant at ambient temperature produced an η_e of 0.087 and a η_T of 0.790 for an overall η of 0.877. This result shows a marked improvement in efficiency over conventional PV cells as governed by the Shockley-Quiesser limit (Shockley and Quiesser, 1961). The coolant remaining at ambient temperature is an ideal case. However, the more realistic measurements provided show only minor decreases in performance over small temperature ranges. It should be noted that the η_e of this optimised cell is considerably lower than traditional PV cells which commercially show values of η_e of between 0.15-0.18 (Saga, 2010). Further work is needed to improve η_e. Changing the material composition of the PV cells could provide a solution.

Nanoparticle Suspensions as Coolant for Increased net PVT Efficiencies

The thermal conductivity of the coolant fluid can effect η of a PVT, as a coolant with higher thermal conductivity than the water coolants currently used will allow the PV cells to operate at lower temperatures, resulting in higher η_e. One of the most promising advances in the field is the use of nanofluids. These are fluids, most commonly water, which have a suspension of nanoparticles within them. It has long been known that the thermal conductivity of a suspension of nanoparticles is considerably higher than that of the original fluid (Choi and Eastman, 1995). Water has a thermal conductivity of 0.6155 W kg s^{-1} m^{-2} at 303K (Bashirnezhad *et* *al.*, 2015). Suspensions of 80 nm Cu nanoparticles at 3% volume were reported by Bashirnezhad *et al.* to increase the thermal conductivity of water by up to 33%. Similar values for other nanoparticles such as Al2O3 were also reported.

Selective Absorption of Radiation by MgO Nanoparticles

The optical properties of nanoparticles change with their size (Cui and Zhu, 2012). A suspension of MgO nanoparticles was used as a coolant in a PVT cell in an attempt to improve η. One of the key advantages of nanoparticles is the fact that their optical properties can be easily tuned. In the configuration used by the group, the nanofluid flowed between the PV cells and the source of radiation, rather than in a pipe underneath the PV cells. The ideal coolant in this instance would be one that is totally transparent in the region relevant to the band gap of silicon and absorbing all infrared (IR) radiation beyond the band gap of silicon (Cui and Zhu, 2012). In theory, the optical properties of the nanoparticles can be tuned to maximise the heat absorbed by these, ensuring high η_T while still allowing a large portion of the radiation to be harnessed by the PV cells to generate photocurrent. A film of MgO suspension of 0.02% by weight with thickness 10 mm showed transmittance in the region of 40-70% in the wavelength range of 400-1300 nm, corresponding well with the 1.1 eV band gap of silicon. The nanofluid was shown to be virtually opaque outside of this range. Increases in the concentration of the particles produced large decreases in the transmittance of the nanofluid. The thickness of the film was also varied. Thicknesses of 2mm showed marked improvements in overall transmittance, including in the 1500-1900 nm range which would result in excess heat being absorbed by the PV cell and not the coolant. The reported η of the solar cell is above 0.6 (Cui and Zhu, 2012). These particles, which can be tuned to absorb light across various regions of the spectrum, show promise. Nonetheless, further work must be done to increase the transmittance over the region of the spectrum corresponding to the band gap while maintaining opacity over other regions of the spectrum.

Increased η_T and System Control Through use of Nano Ferrofluids as Coolant

Other promising options for coolants include magnetic nanofluids, or nano ferrofluids. These are fluids in which the suspended nanoparticle is super paramagnetic. This is a property of nanoscale particles of ferromagnetic and ferrimagnetic materials in which the overall dipole moment of the particle undergoes random and rapid reversals over time (Papaefthymiou, 2009). Ferrofluids show increased thermal conductivity in agreement with other nanofluids, but their viscosity and thermal conductive properties can be changed by applying an external field (Papaefthymiou, 2009). Ghadiri *et al.* (2015) used a suspension of Fe_3O_4 particles in a more traditional configuration where the coolant flows through pipes in thermal contact with the heat exchanger beneath the PV cell. They tested at both 1% weight and 3% weight concentrations of the ferrofluid and under a variety of magnetic conditions: firstly with no external field applied, then with a constant field applied of 0.03 T and finally with a field of 0.03 T alternating at 50Hz.

Under conditions of no magnetic field, η_T of 0.68 was reported for the cell containing the 3% weight ferrofluid, marginally higher than the 1% weight ferrofluid. The thermal efficiencies under a constant magnetic field are effectively unchanged. However, a field oscillating at 50Hz produced a marked improvement, particularly in the case of the 3% weight ferrofluid, increasing its η_T to 0.73. Ghadiri *et al.* (2015) suggest the reason for this increase in thermal performance lies in the tendency of the particles to form clusters in suspension. The clusters align in chainlike morphologies which increases their overall thermal conductivity. Ghofrani *et al.* (2013) suggest that the increase in thermal conductivity may be caused by convection of the nanoparticles due to the alternating magnetic field. The convection of the nanoparticles disturbs thermal boundary layers, which they highlight as being an important mechanism for heat transfer. A stark difference in efficiency is observed when a comparison is made with the same system cooled with deionised water. Efficiencies when the coolant is cooled with water are below 0.5. Ghadiri *et al.* (2015) note that the η_T of the system increased by 45% in the absence of a magnetic field and by 50% in the case of an alternating magnetic field when cooled with the ferrofluid instead of the water. One must question how much the benefit in thermal performance is offset by the electrical cost to power the alternating magnets. However, the notable η_T increase of the ferrofluid compared to water, even in the absence of an external field, is substantial.

Conclusions

Although work has been done on the subject of hybrid PVT systems since the 1970s, it is only recently that large scale attention has been turned towards this technology. As a result, the technology is still in its infancy. The electrical efficiency η_e of these hybrid cells is currently lower than that of the current PV cells. Additionally, their thermal efficiency η_T is lower than that of traditional thermal cells. However, net efficiencies of PVT cells are very high, such as the 0.877 net efficiency cell produced by Dupeyrat *et al.* (2011). The potential for large increases in the efficiency of solar component of the PVT cells is very promising. Current PVT cells tend to operate between 0.08 and 0.15 solar efficiency, whereas readily available commercial c-Si PV cells with solar efficiencies above 0.2 are widespread. Incorporating these more advanced technologies into the PVT cells is a potential next step in the field of PVT optimisation. The work on nanofluid coolants is extremely promising. Parametric analysis in the vein of Dupeyrat *et al.* (2011) is essential to combine the current advances into more efficient PVT cells.

The primary future application for PVT cells will most likely lie in distributed home use, rather than in large power plants. Much of the current research, including Bambrook and Sproul (2012) and Dupeyrat *et al.* (2011), is involved in home-integrated cells for combined heating and power use. Comparisons between solar thermal, PV and PVT regarding net usable power have been shown in recent literature (Good *et al.*, 2015). The analysis suggests that at present, a total PV array or a total solar thermal array may currently provide a greater overall benefit than a PVT in attempts to produce nZEB. PVT cells are not up to par with current PV and thermal technologies, however, there appears to be a considerable scope for improvement as this technology continues to mature.

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