Development and Field Testing of a Novel Hybrid PV-Thermal Solar Collector

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Abstract

This paper presents laboratory and field data of the new Virtu hybrid PV-thermal solar collector developed by Naked Energy Ltd. By mounting PV cells on a novel phase-change thermo-syphon heat plate contained within an evacuated tube, Virtu can deliver hot water in the temperature range that is required for domestic hot water and space heating, whilst providing simultaneous electrical power. Laboratory tests show excellent performance at high output temperatures, and field data collected in Malta show that 40-60°C hot water can be delivered all year round. A transmissive low-emissivity coating has been developed and tested leading to further enhancement of the thermal performance.

Keywords: hybrid PV-T, solar thermal, emissivity, heating

1. Introduction

One effective approach to increase total solar conversion efficiency is to combine photovoltaic and solar thermal into a hydrid PV-T module(Zondag, 2008). By mounting the PV cells on a water cooled substrate, both heat and electrical power can extracted from the same area, increasing the overall power density and maximizing the energy that can be produced from a limited mounting area(Good et al., 2015). Active control of the module temperature can also offer advantages in PV output and long-term reliability. However, combining two technologies into a single module creates some technical challenges, especially as the largest solar thermal application markets require efficient operation in the temperature range 40-80°C(Fox et al., 2011; Ramos et al., 2017) (Figure 1), necessitating specific measures to avoid thermal losses to the environment (Mellor et al., 2018).

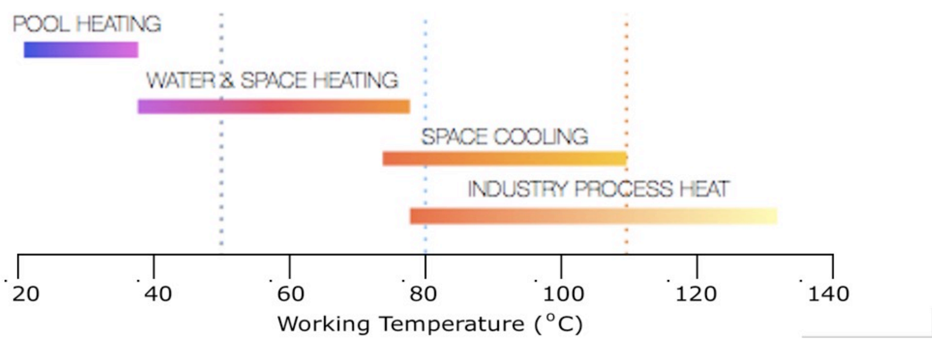

Figure 1. Typical working temperatures of different heat demands

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2. Technology Elements

This paper describes a new hybrid PV-T collector called Virtu, in which the PV cells are mounted in a vacuum tube and operated at temperatures up to 90°C. A novel heat exchanger has been developed that contains a phase change thermo-syphon and delivers highly uniform temperature (+/-2°C) across the front absorber surface. Mono-crystalline silicon PERC cells have been bonded to the heat exchange plate, but this bond has required careful materials selection to achieve the required vacuum performance and avoid thermal stresses. Vacuum levels within the tube have been optimized as a trade-off between thermal performance and manufacturing cost. A photo of a Virtu tube is shown in Figure 2 (a). Novel low emissivity coatings have also been deposited on to the PV cells, to control radiative losses at the higher operating temperatures. The collector is mounted with the tube horizontal (parallel to the east-west axis) and the absorber tilted, making roof installation easier than conventional rack mounted panels and also achieving a very low profile on flat roofs (Figure 2 (c)). Self-shading between tubes is accommodated by an optimized spacing, with a linear reflector between each tube maximizing annual sun hour capture. This reflector delivers a peak 30% boost in both PV and thermal performance at very low incremental cost.

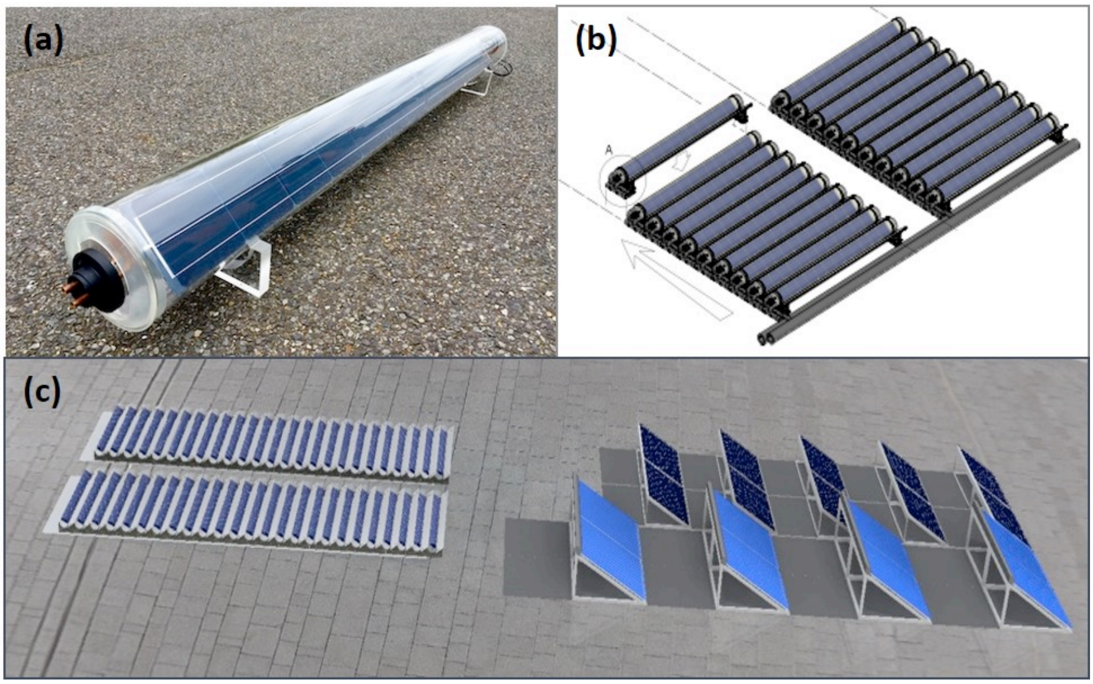

Figure 2. (a) Photo of a Virtu collector tube. (b) Schematic of Virtu's modular assembly. (c) Low profile and compactness of flat-roof-mounted Virtu tube array compared to that of flat-plate collectors.

3. Indoor Performance

Lab testing and optimization of the collector design was carried out in-house using a bespoke designed 2.3 x 0.8 m solar simulator (Figure 3 (a)). The irradiance of the simulator is monitored using both a silicon reference cell and a pyrometer, and is close to 1000 Wm-2 during measurements. Both the thermal and electrical power output were measured simultaneously under a steady flow rate. The total absorber efficiency plotted in Figure 3 (b) is the sum of the electrical and thermal outputs relative to the radiant power incident on the absorber area. The collector is designed to be operated under vacuum, but we show also results for the same collector filled with air and with Argon for comparison.

The vacuum clearly has a marked effect on the collector performance at higher water temperatures, close-to doubling the total efficiency when delivering hot water at 60°C above ambient, as compared to the air- and Argon-filled configurations. The total efficiency of the evacuated Virtu collector is on a par with the higher-end of evacuated-tube solar-thermal collectors, and well above that of commercially available PV-T collectors. This demonstrates the efficacy of Virtu‘s thermal management and heat-plate performance.

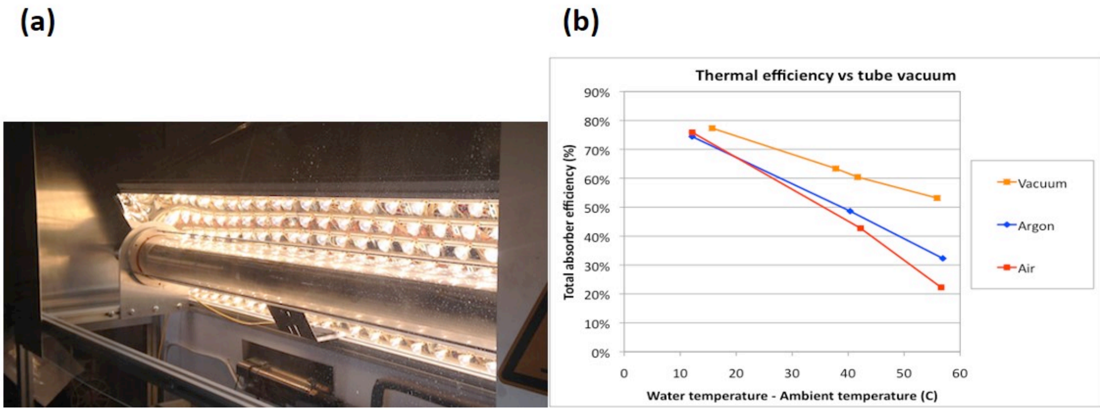

Figure 3 (a) A Virtu tube mounted in the solar simulator used for lab testing. (b) Thermal performance of an evacuated Virtu tube. Also shown is the performance of Virtu tubes when un-evacuated and containing air and Argon.

4. Field Performance

Outdoor testing of a manifold of 8 Virtu tubes was performed on the roof of the Dolmen Resort Hotel on the island of Malta over the course of a year. A photo of the array is shown in Fig 4 (a). Fig 4 (b) shows the maximum daily temperature averaged over each month, showing that the array is capable of delivering domestic hot water throughout the year. The daily average thermal and electrical energy output per collector tube is shown for each month in Fig 4 (c) and (d) respectively. The thermal-to-PV ratio reaches 3.8 at the height of summer, but falls to 2.5 in winter due to increased thermal losses when the ambient temperature is low. The thermal output in winter can be improved using transmissive low-emissivity coatings as described in the following section.

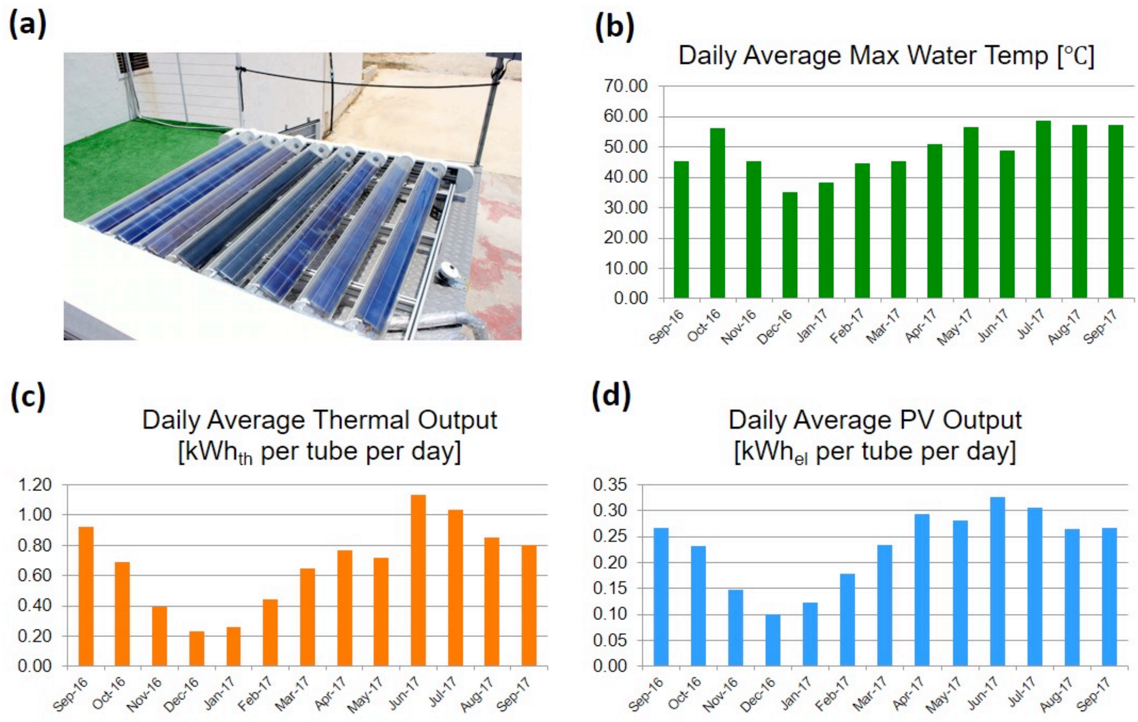

Figure 4. (a) Photo of the tube array used for outdoor testing in Malta. (b) Averaged maximum daily temperature each month over the course of the year. (c) Averaged daily thermal output each month over the course of the year. (d) Averaged daily electrical (PV) output each month over the course of the year.

5. Future Directions – Low Emissivity Coatings

To further control thermal losses, ITO-based low emissivity coatings have been developed in collaboration with Imperial College London (Alonso-Álvarez et al., 2017). The coatings are transmissive at solar wavelengths, allowing sunlight to reach the underlying PV cells, but are reflective in the near-infrared, reducing the thermal emissivity. The concept is shown schematically in Figure 5 (a) and a scanning-electron-microscopy (SEM) image of the ITO coating on a silicon PV cell is shown in Figure 5 (b).

The spectral absorptivity of ITO-coated and uncoated silicon PV cells was measured in the 300 nm to 16 µm range by taking hemispherical reflectance and transmission measurements using an FTIR spectrometer with and integrating sphere, and is shown in Figure 5 (c). The spectral absorptivity and spectral emissivity are equal close to thermal equilibrium, and so the curves in Figure 5 (c) also represent the spectral emissivity of the coated and uncoated cells. Also shown for reference are the AM1.5G solar spectrum and a thermal blackbody spectrum at 60 °C. The ITO coating reduces the emissivity from 80% to 50% at the peak wavelength of radiative thermal emission, but have only a small effect on the absorptivity at solar wavelengths. Figure 5 (d) shows light-IV curves of ITO-coated and uncoated PV cells. The presence of the ITO film leads to a small reduction in open circuit voltage, due to reduced light transmission into the cell, but the ITO deposition process does not reduce the open circuit or fill factor of the underlying solar cell.

Indoor tests were performed on two equivalent Virtu collector tubes using ITO-coated and uncoated PV cells. The electrical and thermal efficiencies are shown in Figure 5 (e) and (f) respectively. The ITO coatings cause a slight decrease in electrical efficiency, which is consistent with the aforementioned short-circuit-current drop (Figure 5 (d)). However, the benefit of the ITO coatings can be seen in Figure 5 (f), where 10-percentage-point improvement in thermal efficiency is observed at a reduced temperature of 0.06 Km^2W^{-1}.

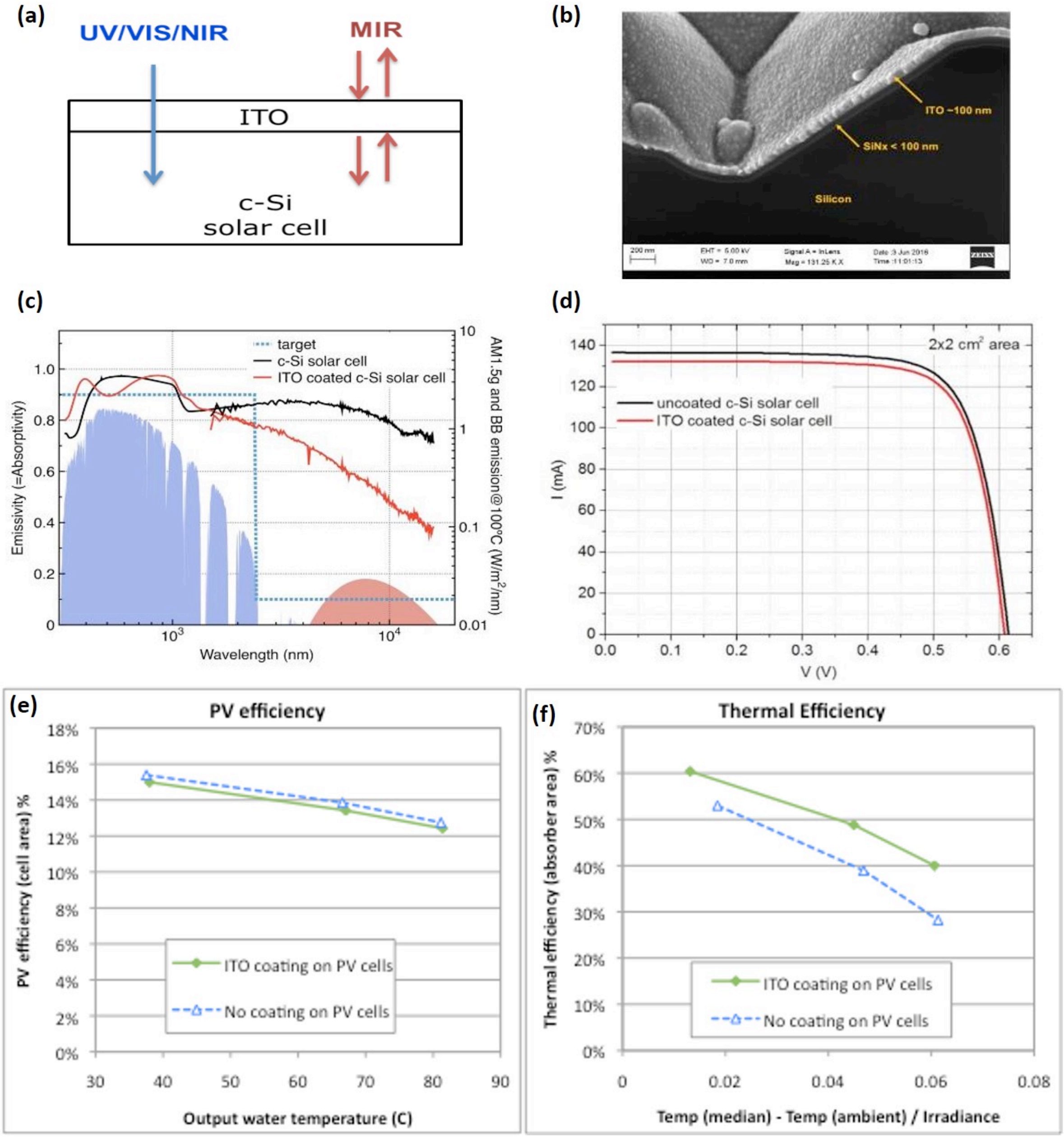

Figure 5. (a) Schematic of transmissive low-emissivity coating concept. (b) SEM image of ITO coating on Silicon PV cell. (c) Spectral emissivity (= absorptivity) of ITO-coated (red curve) and uncoated (black curve) silicon PV cells over the UV, visible and near infra-red ranges. Also shown are the AM1.5 solar spectrum (blue shaded area – right axis), and a 60 °C thermal black-body spectrum (red shaded area – right axis). (d) light IV curves of ITO coated and uncoated silicon PV cells. (e) PV efficiency of Virtu collector tubes containing uncoated and ITO-coated cells. (f) Thermal efficiency of Virtu collector tubes containing uncoated and ITO-coated cells.

6. Conclusions

Virtu is a new hybrid PV-T collector in which the PV cells are mounted in a vacuum tube on phase-change thermo-syphon heat plate, and operated at temperatures up to 90°C. Lab testing under a solar simulator has shown that the total efficiency of the Virtu collector is similar to that of high-performing solar thermal collectors, and well above that of other commercially available PVT collectors, particularly when delivering water in the 40-80°C temperature range required for domestic hot water and space heating. Field tests in Malta have shown that the tubes can deliver the temperatures required for domestic hot water all year round. Finally, a transmissive low-emissivity coating has been developed and tested leading to enhanced thermal efficiency with minimal electrical efficiency loss. Further improvements can be expected by continued optimization of the coating.

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