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Determining the value of cooling in photovoltaics for enhanced energy yield

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ABSTRACT

Methods for cooling photovoltaic (PV) modules to increase their output have been proposed several times in the literature. Most of these reports describe the increase in power output achieved, but they rarely comment on the economic cost-benefit proposition. Where the economics have been considered, this has been based on measurements for the authors' specific PV system at a specific site. This means the economics are not easily interpreted for other systems at other sites.

We derive a theoretical formulation for quantifying the economic value of artificial cooling of PV modules. The formulation is not specific to any particular method of cooling. It takes as input the rate of heat removal that a cooling method can provide (in Wm^{-2} or $Wm^{-2}K^{-1}$) and determines the economic value of this cooling rate, based on variables including local solar conditions, capital cost of the system, system ventilation, plus the temperature coefficient and efficiency of the modules.

We find that the economic value of cooling PV depends strongly on the system design and local conditions, with favourable circumstances leading to a viable cost of potentially over $\$40/m^2$, however unfavourable circumstances are many times less attractive at less than $\$1/m^2$. The equations presented can be used to optimise the design of a cooling feature that is applied to a PV module or system, provided the above parameters of the cooling feature and PV system are established.

1. Introduction

An opportunity for improvement in photovoltaics that has been largely untapped, at least commercially to date, is to reduce the operating temperature of PV panels in the field. Most PV technology types, and certainly the dominant type made from crystalline silicon, experience a linear reduction in power output as the junction temperature increases. This is the result of two compounding effects; thermal broadening of the electron energy distribution, and a lowering of the effective bandgap due to thermal expansion of the atomic lattice. These effects fundamentally reduce the ability of the PV device to produce voltage, and hence are parasitic to the power output. The reduction in power output is approximately linear with temperature and hence is most commonly described in terms of a relative temperature coefficient, γ, for the maximum output power, P_{max}. The value of γ for crystalline silicon PV is typically in the range 0.40–0.45 % for every °C change above or below 25 °C.

A cooler-running PV module or system would have marketable economic value, due to an increase in power and energy output for a given nominal capacity, hence is able to attract a higher price. In this paper we present a method for determining the value of that increase in output, hence the maximum cost that should be incurred in manufacturing and incorporating the technology to produce that cooling.

Artificial cooling for photovoltaics has been studied extensively in relation to (i) concentrating PV systems, for which cooling is essential for operation, see reviews by Bahaidarah et al. (2016) and Royne et al. (2005); and also in relation to (ii) photovoltaic/thermal (PV/T) designs, where the economics include the energy collected from the heat removal system, see review by Chow (2010). In recent years a number of articles have proposed methods to cool conventional (non-concentrating) PV for the sole purpose of improving power output. Examples include radiative cooling (Habiballahi et al., 2016; Safi and Munday, 2015), spray-cooling systems (Moharram et al., 2013; Nizetic et al., 2016; Zsiboracs et al., 2016), evaporative cooling (Alami, 2014), forced air flow (Rahimi et al., 2014; Teo et al., 2012), heat pipes (Zhang et al., 2016), "sprinkling" (Bai et al., 2016) and "natural vaporization" (Ebrahimi et al., 2015). Some of these articles, particularly (Bai et al., 2016) have included some economic evaluation of the proposed

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method. To date however, all published economic analyses have been specific to the cooling design being presented, and also to the site at which it has been tested. No published work to date has described a general method to determine the economic potential of applying a certain rate of cooling to a PV module deployed at an arbitrary site.

It may at first seem trivial to determine the economic benefit of a device that provides cooling for a PV system. It is indeed true that a fixed reduction in operating temperature will result in a constant and easily calculable improvement in output, however it is by no means easy to predict what that temperature reduction will be at a given time, for an arbitrary PV device in an arbitrary installation and environment. The key parameter linking the specific and general cases is the *cooling capacity*, which describes the ability of the cooling device to remove heat per unit area, measured in Wm^{-2}, or $Wm^{-2}K^{-1}$ where appropriate. The cooling capacity is a property of the cooling device that can be refined at the design stage and then mathematically linked to its effectiveness in the field. Here we work through such a calculation to determine the cost requirements for any cooling device or technology that might be designed for non-concentrating PV power applications.

The calculation framework we propose is independent of the method used to achieve the cooling. Future technologies for PV cooling might include for example, special photonic layers for infrared reflection or enhanced radiative cooling, fixtures that increase surface area for improved convective cooling, plasmonic absorbers that capture the energy in hot carriers before it thermalises into heat, or methods that we cannot yet even conceive. Our calculation only requires that the heat removal capacity of the cooling method is known, or is calculable. That information is then used to determine the cost requirement for that method of cooling to provide a net economic benefit.

We start with the idealised "refrigeration case", so named because it is akin to attaching a perfect refrigeration element to the rear of each solar module. For this scenario (albeit unlikely to be economically feasible), any cooling capacity can be provided, regardless of the local environment. We later extend the analysis to include two more realistic scenarios, where the cooling is proportional to the temperature difference between (i) the cell and ambient – the "ambient limited case", and (ii) the cell and an arbitrary temperature – the "reservoir limited case". These two cases represent more realistic types of cooling that might be proposed.

2. Methodology

In this section we build our calculation using, as a starting point, the well-known linear relationship between the PV module temperature and the prevailing solar irradiance. To aid the reader's interpretation, the key steps are summarised as follows:

- Measure the relationship between the irradiance and the module temperature (actually, the difference between module and ambient temperatures) for PV modules of different types in the field;
- Modify this relationship in recognition that not all of the incident irradiance is absorbed by the module as heat (some heat is reflected by the module), hence introduce the term *solar heat loading*;
- Recognise that at thermal equilibrium (which applies to the PV modules in the field for most of the time), any artificial cooling applied to a module has the same effect as an equivalent reduction in the solar heat loading;
- Apply the above to determine a relationship between the rate of artificial cooling and the decrease in module temperature;
- Hence determine a relationship between the artificial cooling rate and the economic value of the energy gained – note that this depends on the solar resource and climate at the point of use of the system;
- Determine the "break-even cost" at which it becomes economically sensible to apply a given rate of artificial cooling to a given system in a given location;
- Explore the dependence of the break-even cost on the relevant input parameters.

2.1. Experimental

In order to confirm the relationship between the temperature of a PV module and the prevailing environmental conditions, measurements were made using the outdoor research facility for photovoltaics (PVORF) at the CSIRO Energy Centre in Newcastle, Australia. Specific information on that facility and this particular measurement is given in the Supplementary Information.

2.2. Determining native cooling from experimental data

In order to calculate the influence of a cooling device or technology in an arbitrary location it is necessary to identify a model that can predict the temperature of a PV module in the field. A number of such models are available, ranging from simple empirical expressions (Faiman, 2008; Ross, 1976) to rigorous thermodynamic treatments that individually account for the various heat flows that occur (Fuentes, 1987; Jones and Underwood, 2001). An excellent summary of the pertinent correlations is given in Skoplaki and Palyvos (Skoplaki and Palyvos, 2009). For the cost calculations presented here we find that a simple model, with parameters determined from careful measurements, is easily adequate. The model is based on the Ross relationship (Ross, 1976) which links the difference between module temperature, T_{mod}, and ambient temperature, T_{amb}, to the plane-of-array irradiance, G_{POA} as shown in (1). The value of the Ross coefficient k carries information about the ability of the PV module to cool naturally in its installed configuration. The typical range of k values for different PV installation types is discussed in Section 3.2.

$$T_{mod} = T_{amb} + kG_{POA} \tag{1}$$

The reader may observe that k is akin to an effective thermal resistance for the system, however that analogy is complicated by the fact that not all of the incident irradiance produces heat in the module. In order to make the model more physically meaningful, we consider only the fraction of the incident irradiance that contributes to heating the PV module, G_{heat}, and we call this the *solar heat loading*. The solar heat loading can be determined by factoring out (removing) the portion of the irradiance that is either reflected, transmitted or used in the performance of electrical work (Silva et al., 2010). The relationship between the solar heat loading and G_{POA} is therefore given in (2), where R is the AM1.5 reflectance of the PV module (transmittance is assumed to be zero) and η is the module power conversion efficiency.

$$G_{heat} = G_{POA}(1-R-\eta) \tag{2}$$

Working with the solar heat loading, rather then the irradiance, allows us to directly relate any applied cooling power to a change in the module's observed temperature. Since for most of the time the PV module is in approximate thermal equilibrium with its environment, the relationship between G_{heat} and T_{mod} can now be used to account for any additional artificial cooling, by simply subtracting the artificial cooling power from G_{heat} and determining the new (lower) value for T_{mod}. The use of G_{heat} instead of G_{POA} means the k parameter is no longer exactly the Ross coefficient, hence from this point we will use the term k_{th} instead, see (3).

$$T_{mod} = T_{amb} + k_{th}G_{heat}-T_0 \tag{3}$$

The model in (3) contains one further modification over the previously published form in (1), with the inclusion of an offset parameter, T_0. The value of T_0 does not dominate the final result but is a potentially important correction to include, since it leads to a more consistent value for k_{th}. Including T_0 results in a more accurate linear fit to the relationship between irradiance and module temperature derived from measured data. Although neither the Ross model (Ross, 1976) nor the