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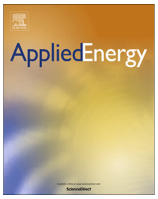

Optimization of annealing cycles for electric output in outdoor conditions for amorphous silicon photovoltaic–thermal systems

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HIGHLIGHTS

- Hybrid solar photovoltaic thermal (PVT) have high exergy efficiencies.
- Solar thermal operates at high temperature needs PV with small temp. coefficients.
- Amorphous silicon PV good candidates that benefit from PVT annealing.
- Studied a-Si:H PVT dispatch strategies with outdoor temperatures.
- Found improved electrical performance in a range of geographic locations.

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ABSTRACT

Previous studies with fixed operating temperatures have shown that hydrogenated amorphous silicon (a-Si:H) was a promising absorber layer for solar photovoltaic–thermal (PVT) systems because of (a) a low temperature coefficient and (b) the opportunity to reverse light induced degradation with thermal annealing. This study further refined the simulation of the optimal dispatch strategy for a-Si:H based PVT by studying annealing cycles and analysis of the degradation at other operating temperatures controlled by the varying ambient temperatures. Four representative case studies were evaluated for the combinations of high and low solar flux and high and low average ambient temperature. Electrically-optimized dispatch strategies are found for a range of PVT thermal insulating effectivenesses. The results showed significantly more electricity generation in all the case study representative regions except for areas dominated by low temperatures and low solar fluxes. These results indicate that a-Si:H PV performance can be improved in most populated regions in the world by integrating it into a PVT device and using spike annealing to reverse light-induced degradation effects. The model presented in this paper uses publicly-available data to implement suitable dispatch strategies and execute virtual performance analysis of PVT for any geographic location in the world.

1. Introduction

Crystalline silicon (c-Si) solar photovoltaic (PV) cells with commercialized conversion efficiencies in the range of high teens to low twenties are the most widely used on the market, representing about 80–90% of the world total PV cell production [1]. High-efficiency c-Si PV cells have advantages in performance and area-requirements and are thus normally used as the absorber in hybrid solar photovoltaic thermal (PVT) systems [2]. PVT systems combine a photovoltaic cell with a solar thermal collector and perform dual operation: (1) converts light energy directly into electricity and (2) captures the remaining energy normally considered waste heat from the PV module for domestic hot water or other heating needs. The combined capture of both heat and electricity allow these devices to have higher exergy and thus be more overall spatially energy efficient than either stand-alone solar photovoltaic or solar thermal systems [3]. This dual use enables PVT technology to provide benefits in terms of energy, exergy efficiency, and in some cases cost [3–12].

However, there is a inherent technical contradiction with the operating temperature of PVT devices. Photovoltaic cell efficiency falls with the rise in temperature and as c-Si has a large thermal coefficient (−0.45%/K) [13] using it at acceptable operating temperatures as a PVT absorber material leads to poor performance

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of the thermal component and thus the whole system non-optimized [14–18]. This is because the conventional PVT system is designed to carry heat away from the modules thereby cooling the cells and thus improving their electricity conversion efficiency by lowering resistance [9]. Although this is beneficial for the PV, it causes the thermal component to under-perform compared to a stand-alone solar thermal collector allowed to operate at higher temperatures. However, thin film hydrogenated amorphous silicon (a-Si:H) PV have a thermal coefficient of only −0.13%/K [13], making it acceptably functional at higher temperatures. PV materials with low temperature coefficients such as a-Si:H PV allow the PVT to be operated at high temperatures, promoting a more unified and potentially optimized PVT system [19–21].

The two primary challenges to widespread commercialization of a-Si:H PV in general are relatively low efficiencies (∼10%) and light-induced degradation of performance known as the Staebler–Wronski effect (SWE) [22]. SWE is associated with increased defect state density in the mobility gap of the material when exposed to sunlight, which cause a drop in power generation/conversions efficiency with light exposure time until a steady state (degraded steady state or DSS) is reached [22–27]. SWE is reversible with annealing at elevated temperatures [22–27]. Recent, experiments have shown that PVT operating temperatures can be used to provide regular high temperature spike thermal annealing (e.g. 1 h at 100 °C on a 12 h cycle) is adequate to reduce the number of defect states and provide a significantly higher electricity output [20]. In order to improve the performance of the PVT system further a previous study investigated the impact of annealing cycles in different geographic locations with real solar flux data and showed that at standard and sustained PV operating temperatures one anneal pulse per day provided the largest electrical output through the year [28]. Overall the results showed additional electricity generation is possible over the year with an appropriate dispatch strategy of spike thermal annealing cycles. With operating temperatures for standard testing conditions (25 °C), PV operational (50 °C) and PVT operational (90 °C as this is the operational temperature of solar thermal systems) provided 23%, 10%, and 1.2% additional electricity generation over a year, respectively. Although it is possible to sometimes fix the operating temperature of the PVT the ambient temperature that the system operates in can fluctuate widely. To take this real-world consideration this paper further refines the simulation of the optimal dispatch strategy for a-Si:H based PVT by studying annealing cycles and analysis of the degradation at other operating temperatures controlled by the ambient temperature. Four case studies are evaluated for the combinations of high and low solar flux and high and low average ambient temperature. Optimal dispatch strategies are found for a range of PVT thermal insulating effectivenesses. The results are discussed and conclusions are drawn about the optimal dispatch strategy for PVT devices in any geographic region.

2. Background SWE degradation associated parameters

Previous work has introduced the a-Si:H PV SWE degradation kinetics associated parameters k_{dss} and u_{dss} [28], which quantify the SWE degradation rates and magnitude of reduced PV performance under illumination. The parameter k_{dss} is associated with the magnitude of the DSS and u_{dss} is associated with the degradation rate. These parameters were introduced in the PV max power generation equation in order to modify the equation for PVT and incorporate the effect of SWE into it [28]. Exponential fits [28] to experimental data [27] showing SWE to the DSS were obtained at sustained operating temperatures 25 °C, 50 °C, and 90 °C for a-Si:H PV cell active layer thickness of 630 nm under 1 sun illumination were used to derive k_{dss} and u_{dss}.

When the irradiance is constant, it is notable that the exponential degradation rate and the DSS power generation both depend on the operating temperature. To take into account the effect of operating temperature outside of these fixed values, the degradation rate and the steady state power generation is required to make a function of temperature. This is accomplished in this paper to expand the geographic validity of the PVT spike annealing dispatch strategy to any location.

3. Methods

3.1. Derivation of temperature dependent k_{dss} and u_{dss}

The degradation associated parameters k_{dss} and u_{dss} are represented as a function of temperature in order to extrapolate PVT performance in any region (ambient temperature dependent operation). These parameters both have unique relationship with temperature. It has also been experimentally determined that k_{dss} decreases and u_{dss} increases with increasing temperature. In addition as the temperature is increased the power generation reaches steady state with a faster degradation rate (requires less time) and this DSS is higher at higher temperatures. As a first approximation the changes in the parameter values have been considered to be changing linearly in the range between the experimentally measured temperatures. Eqs. (1) and (2) linearly calculate the values of k_{dss} and u_{dss} in the intermediate regions between 25 °C to 50 °C and 50 °C to 90 °C [28] and Figs. 1 and 2 shows the corresponding graphs.

$$k_{dssx} = k_{dss1} + \frac{k_{dss2} - k_{dss1}}{T_2 - T_1} \times (T_x - T_1) \tag{1}$$

$$u_{dssx} = u_{dss1} + \frac{u_{dss2} - u_{dss1}}{T_2 - T_1} \times (T_x - T_1) \tag{2}$$

The values of the parameters at temperature x outside the range of 25–90 °C are again calculated by extending the lines linearly. Temperature 1 and 2 are the known (measured temperatures).

3.2. Geographic expansion and simulation mechanism updates

Previous simulations were confined to four specific cities in United States [28]. In order to expand the optimization maps for the performance of the PVT it is required to expand the modeling range by including more solar and weather data collected from worldwide solar resources and satellites. As a primary approach in the present work the solar data for regions all over U.S. (including Alaska and Hawaii) and Canada has been included in the simulation. Specifically the hourly solar irradiance and temperature data from the U.S. Air Force weather stations has been used [29,30], National Renewable Energy Lab (NREL)'s Solar Prospector

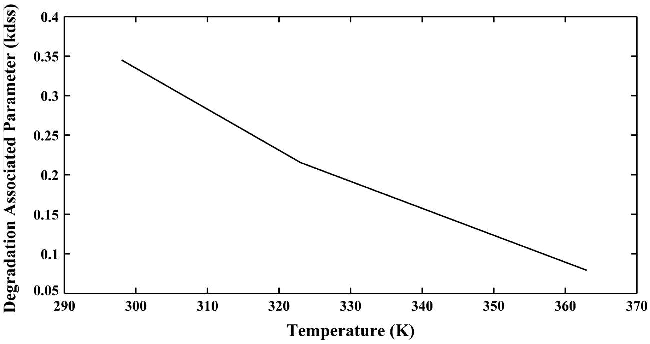

Fig. 1. Degradation associated parameter k_{dss} against temperature.