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The effects of dispatch strategy on electrical performance of amorphous silicon-based solar photovoltaic-thermal systems

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ABSTRACT

Previous work has shown that high-temperature short-term spike thermal annealing of hydrogenated amorphous silicon (a-Si:H) photovoltaic thermal (PVT) systems results in higher electrical energy output. The relationship between temperature and performance of a-Si:H PVT is not simple as high temperatures during thermal annealing improves the immediate electrical performance following an anneal, but during the anneal it creates a marked drop in electrical performance. In addition, the power generation of a-Si:H PVT depends on both the environmental conditions and the Staebler–Wronski Effect kinetics. In order to improve the performance of a-Si:H PVT systems further, this paper reports on the effect of various dispatch strategies on system electrical performance. Utilizing experimental results from thermal annealing, an annealing model simulation for a-Si:H-based PVT was developed and applied to different cities in the U.S. to investigate potential geographic effects on the dispatch optimization of the overall electrical PVT systems performance and annual electrical yield. The results showed that spike thermal annealing once per day maximized the improved electrical energy generation.

1. Introduction

Despite improvements in solar photovoltaic (PV) efficiency, which reduces the cost of PV generated electricity to competitive levels in some markets [1], in conventional cells much of the radiation above the bandgap does not contribute to electrical energy generation and instead is wasted as heat. On the other hand, solar thermal systems, which have the potential for high efficiencies, have low exergy values [2]. Thus, developing photovoltaic solar thermal (PVT) systems offer a distinct advantage over simple PV or low exergy solar thermal systems by utilizing this waste thermal energy from the PV absorber for heating applications [2]. PVT offers advantages in overall exergy, energy and cost [2–9]. Historically, most of the PVT systems were developed using crystalline silicon (c-Si) PV, which have a thermal coefficient of −0.45%/K [10]. Because of this relatively large thermal coefficient c-Si-based PVT systems are designed to cool the c-Si PV modules in order to maximize the electrical output and extracted thermal energy is considered as secondary benefit. This results in non-optimization of c-Si-based PVT systems because the thermal component under-performs when compared to standard solar thermal collectors [11–15].

Thin-film hydrogenated amorphous silicon (a-Si:H) solar cells, however, have a thermal coefficient of only 0.13%/K [10], which makes it suitable for high temperature applications that are not possible with c-Si PV due to what would be significant electrical output losses at high operating temperatures. The biggest technical challenge confronting a-Si:H PV is a light-induced degradation of performance known as the Staebler–Wronski effect (SWE) [16–20]. This effect is associated with the creation of defect states in the a-Si:H material when exposed to sunlight, which causes a reduction in efficiency of the solar cells with exposure time [17]. These defects states tend to saturate after an extended exposure to sunlight (approximately 100 h under continuous 1 sun illumination) and this stabilized state is refereed as degraded steady-state (DSS) [21,22]. However, it has been found that SWE is reversible in nature and the performance (efficiency) of a-Si:H solar cell can be returned to its initial state if the cell is heated to 150 °C for 4 h as the defect states are annealed [17,21,23,24] although the defect states can anneal at lower temperatures over more extended time periods [21].

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Reducing SWE is viewed as so important, that Pola et al. have even suggested removing entire PV arrays and annealing the modules in a hot air oven at lower temperatures (e.g. at 80 °C) over extended times [25]. Additionally, because of this effect it has been reported that a-Si:H PV performs better at high temperatures in view of the fact that optoelectronic properties of a-Si:H materials [16,26,27] stabilize at a higher efficiency at higher temperatures [22,28]. Operating at elevated temperatures is highly desirable for PVT hybrid systems as the solar thermal efficiency increases with temperature. For a solar thermal flat plate collector a temperature of 100 °C can be easily achieved and if the system is stagnated it can even climb higher than 200 °C [29]. Therefore, direct deposition of a-Si:H PV over flat plate solar collectors can facilitate high-temperature operation where the PV panel could be in-situ annealed and simultaneously increasing overall system exergy [30–32]. It has also been experimentally demonstrated that high temperature operation and regular high temperature spike thermal annealing for 1 h at 100 °C on a 12 h cycle can result in higher energy and exergy output [33]. However, a dispatch strategy is required to optimize the usage of available resources to meet the electrical and thermal demand and to maximize the overall system efficiency. Although spike thermal annealing of a-Si:H PV panels with short thermal spikes can improve the immediate electrical performance following an anneal, the annealing process at high temperatures creates a marked drop in electrical performance over the annealing period (it can also deteriorate the overall thermal performance of the system as the thermal energy required for spike annealing is not being extracted). It has also been observed that, the degraded steady state is obtained more rapidly at higher temperature at a higher power [33]. Therefore a dispatch strategy is required to optimize the number of required spike thermal annealing cycles in order to maximize the overall system performance including the thermal and electrical output.

This paper reports on the effects of various dispatch strategies on the first of these outputs – the electrical system performance. Utilizing experimental results from thermal annealing, an annealing model simulation for a-Si:H-based PVT was developed and applied to different cities (Goldendale, San Antonio, Reno and Las Vegas) in U.S. to investigate the effects of geographic optimization on the overall electrical PVT systems performance.

2. Methods

The PVT system shown schematically in Fig. 1 was used for modeling and simulation in this paper. The a-Si:H PV is connected to an inverter that powers the AC load and the heat generated by the PVT is transferred to thermal load by a heat exchanger. A temperature controller is used to control both this heat flow and the regular thermal annealing, which is provided by the heat generated from the PVT itself. High temperature spike thermal annealing for 1 h at 100 °C at regular cycles is carried in order to reverse SWE.

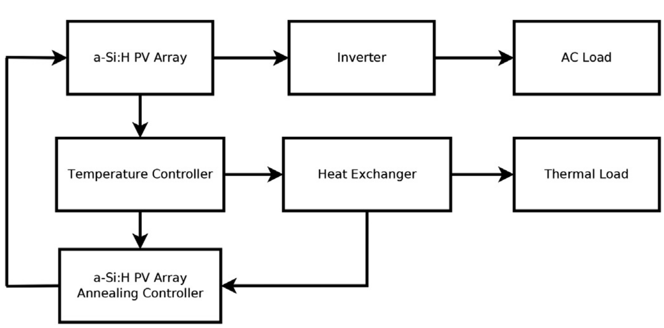

Fig. 1. Schematic of a-Si:H-based PVT system.

Usually a-Si:H-based PV exhibit power degradation due to 1) the temperature effect, exhibited by all solar cells and 2) SWE, which is a long-term light exposure effect, which is a unique characteristic of a-Si:H-based solar cells. The total energy generated by the PV of power, P, for a year is given by:

$$E = \sum_{n=1}^{365\times24} P_n \cdot t \tag{1}$$

where P_n is the power produced in the nth hour and t is time, which is 1 h is this case. The maximum power, $P_{\max(T)}$, at a temperature T from reference temperature (T_{ref}) having a temperature coefficient of γ is given by [34]:

$$P_{\max(T)} = \frac{P_{\max(\text{ref})}}{\left(1+\gamma\left(T_{\text{ref}}-T\right)\right)} \cdot \frac{S}{S_{\text{ref}}} \cdot \frac{1}{\left(1+\delta \ln\left(\frac{S}{S_{\text{ref}}}\right)\right)} \tag{2}$$

where S and S_{ref} are the irradiance and reference irradiance level respectively, $P_{\max(\text{ref})}$ is the maximum power at a reference temperature T_{ref}, which is 25 °C, S_{ref} is equal to 1000 W/m^2, γ is -0.0020/°C, δ is $+0.063$ [34]. Eq. (2) is used to calculate the power with no thermal annealing and universally applicable to any solar cells.

Eq. (2) does not take SWE into account and must therefore be modified with an exponential term that is governed by the aggregate exposure to solar flux from the annealed state and the operating temperature. The exponential terms were determined by curve fitting the experimental results of Pathak et al. [33] as shown in Fig. 2.

Fig. 2 shows the experimentally obtained data for degenerated steady states at different temperatures for a-Si:H based PV/T with i-layer thickness of 630 nm under 1 sun (1000 W/m^2 irradiance) for 600 h. For a-Si:H PVT the modified form of Eq. (2) is altered to be:

$$P_{\max(T)} = \left(\frac{P_{\max(\text{ref})}}{\left(1+\gamma\left(T_{\text{ref}}-T\right)\right)} - k_{\text{dss}} P_{\max(\text{ref})} \cdot \left(1-e^{-u_{\text{dss}}\cdot t}\right)\right) \cdot \times \frac{S}{S_{\text{ref}}} \cdot \frac{1}{\left(1+\delta \ln\left(\frac{S_{\text{ref}}}{S}\right)\right)} \tag{3}$$

The values of the parameters k_{dss} and u_{dss} were obtained by analyzing the experimental data and their values vary with temperature. For the temperatures 25 °C, 50 °C, and 90 °C, k_{dss} has the

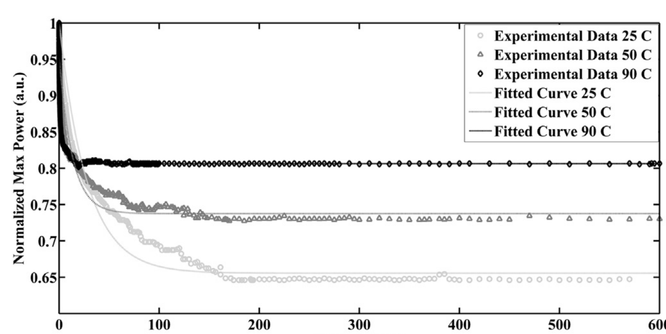

Fig. 2. Experimental data showing degenerated steady state obtained at temperatures 25 °C, 50 °C, and 90 °C respectively for a-Si:H PV cell active layer thickness of 630 nm under 1 sun [33] and exponential fits using Eq. (3).