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Assessing high-temperature photovoltaic performance for solar hybrid power plants

Joya Zeitouny[a,b], Noémie Lalau[a], Jeffrey M. Gordon[c], Eugene A. Katz[c], Gilles Flamant[a], Alain Dollet[a], Alexis Vossier[a,*]

[a] Laboratoire Procédés, Matériaux et Energie Solaire (PROMES) – CNRS, 7 Rue du Four Solaire, 66120 Odeillo, France
[b] Université de Perpignan Via Domitia (UPVD), 52 Avenue Paul Alduy, 66100 Perpignan, France
[c] Department of Solar Energy and Environmental Physics, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990, Israel

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ABSTRACT

Hybrid solar photovoltaic/thermal power systems offer the possibility of dispatchable, low-cost, efficient and reliable solar electricity production. A key design strategy capable of fully exploiting the heat generation stemming from both solar cell thermalization and sub-bandgap photons involves an integrated photovoltaic/thermal absorber operated under concentrated sunlight, at temperatures conducive to efficient turbine operation, to wit, hundreds of degrees C. A pivotal aim is attaining the highest efficiency possible while ensuring a substantial fraction of the total power derives from the turbines, with gas-fired backup heating and/or thermal storage mitigating the ephemeral character of solar availability. However, the performance of solar cells at unprecedented elevated temperatures remains an open question. Key issues include (a) whether the efficiency loss stemming from high-temperature solar cell operation can be maintained acceptably small, as well as how optical concentration affects it, and (b) whether the solar thermal contribution can constitute a significant fraction of total electricity production. Here, we try to establish upper bounds on photovoltaic and system performance, covering a broad range of cell temperature and concentration levels, for single- and multi-junction cells operating at the radiative limit. We demonstrate that (1) the use of highly concentrated sunlight markedly diminishes photovoltaic - as well as thermal - efficiency losses at high temperature, and (2) the extent to which high operating temperature affects cell efficiency strongly depends on cell architecture. The implications for future generations of high-temperature/high-concentration solar cells are also addressed.

1. Introduction

A sizable fraction of solar radiation cannot be converted into electricity by photovoltaics (PVs) because of (1) sub-bandgap photons, and (2) thermalization losses [1]. This claim is especially valid for the single-junction cells that dominate current solar cell technology, and is less pronounced but still germane for today's best commercial multi-junction (MJ) cells. Invariably, these losses are dissipated as heat. Prior studies have explored how to exploit that heat for purely thermal applications, albeit at temperatures well below those required to drive heat engines at respectable efficiencies.

Recently, attention has shifted to utilizing part or all of these nominal losses toward generating the high temperatures needed to generate electricity in conventional turbines [2,3] (e.g., 600–1000 K) with heat-to-electricity conversion efficiencies exceeding 30%. A large part of the motivation is having a solar power plant that is far less susceptible to the intermittency of sunlight - for example, that can offer capacity credit to a utility - because the thermal sub-system can generate multi-hour uninterrupted electricity due to standard gas-fired backup heating and/or high-temperature thermal storage (e.g., in molten salts).

Some of these proposals are predicated on spectral splitting in solar concentrators, with sub-bandgap photons reflected to a high-temperature thermal receiver [2,4,5]. But this strategy does not diminish thermalization losses in the solar cells.

A challenging alternative is solar concentration onto a single integrated receiver the top layer of which comprises PVs that are thermally bonded to a thermal receiver below them. Optical concentration (C) values of hundreds to thousands of suns are envisioned (with 1 sun defined as the typical maximum terrestrial solar beam irradiance of 1 mW/mm^2). This amalgamated absorber would operate at the temperatures required for efficient turbine conversion (*vide supra*), but

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* Corresponding author.
E-mail address: alexis.vossier@promes.cnrs.fr (A. Vossier).

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engenders the intrinsic reduction of PV efficiency with temperature. This disadvantage may be mitigated by the combination of (1) the increase in the efficiency of high-quality (low-series-resistance) solar cells with optical concentration, (2) the decrease in the magnitude of the temperature coefficient of PV efficiency with temperature [6,7], and (3) consideration of PV materials that may not have been deemed suitable candidates for solo PV power stations due to an excessive degree of sub-bandgap solar radiation (which in this instance is converted to useful heat to drive a turbine).

While such studies are in their infancy, it is often valuable to establish upper bounds on power conversion efficiency when PVs would be deployed at high temperatures, including the division between the PV and thermal sub-systems. PV performance at high temperatures has likely not been investigated due to the perceived pronounced lowering of efficiency, along with the absence of applications. The revival of the solar hybrid power plant concept prompts revisiting this subject.

We begin by evaluating PV performance in the fundamental radiative limit (i.e., in the absence of non-radiative and series resistance losses) [8] as a function of both cell temperature and cell irradiance. Whereas this is an idealized limit, it should be noted that the best commercial single- and multi-junction cells have already reached more than 70% of their respective maximum efficiencies near ambient temperature [9,10], with further improvements on the horizon. This PV evaluation is followed by an analysis of hybrid PV/thermal solar power generation as a function of absorber temperature, at the high cell irradiance values that are readily achievable with available solar concentrators.

The high-temperature heat produced by such hybrid PV/thermal plants could equally be used for inherently thermal applications such as industrial process heat and absorption chillers (rather than for electricity generation), typically with the required delivery temperatures being noticeably lower than those for efficient turbine operation. But in the absence of a *bona fide* electricity demand, and given the high solar-to-*thermal* conversion efficiency of current solar concentrators, such purely thermal applications have been delegated to purely thermal (as opposed to hybrid) solar concentrators.

Also, other electricity storage options are available, e.g., batteries and pumped hydro. To date, the former has proven far too expensive and short-lived to enjoy significant impact at the utility scale. Being highly location-dependent, pumped hydro may be a viable option, but is not universally applicable, and, in any event, is an autonomous option completely detached from the solar power plant.

2. Methodology

2.1. Photovoltaics in the radiative limit

The basic upper bound for PV efficiency corresponds to the idealized radiative limit [8,11], for which the governing relation between current density J and voltage V is:

$$J = J_{ph} - J_0\left(\exp\left(\frac{qV}{nkT}\right) - 1\right) \tag{1}$$

where J_{ph} and J_0 are the photo-generated and the dark current densities, respectively, and n is the diode ideality factor. q, k and T are the elementary charge, Boltzmann's constant, and cell temperature, respectively. In this limit, the short-circuit current density J_{sc} is equal to J_{ph}, with the latter described by:

$$J_{ph} = Cq\int_{E_g}^{\infty} f(E)dE \tag{2}$$

where $f(E)$ is the spectral photon flux density of incident solar beam radiation, and the external quantum efficiency is implicitly taken to be a step function: perfect absorption for above-bandgap photons, and no absorption of sub-bandgap photons. For example, for blackbody radiative input (often used as an approximation for extraterrestrial solar radiation), $f(E)$ in Eq. (2) is:

$$f(E) = \frac{2\pi}{h^3c^2}\frac{E^2}{\exp\left(\frac{E-qV}{kT}\right) - 1} \tag{3}$$

where h and c are Planck's constant and the speed of light, respectively. E denotes photon energy, E_g is the bandgap energy, and μ is chemical potential. However, the spectrum of solar beam radiation AM1.5D [12] was used in the computations below, toward more closely accounting for the effect of atmospheric attenuation on the terrestrial spectrum.

PV efficiency η_{PV} is the ratio of the maximum power density (per absorber area) produced by the solar cells P_{PV} to cell irradiance:

$$\eta_{PV} = \frac{P_{PV}}{CI_{solar}} = \frac{J_{sc}V_{oc}FF}{CI_{solar}} \tag{4}$$

where V_{oc} and FF denote open-circuit voltage and fill factor, respectively, and I_{solar} is the collectible incident solar irradiance. From Eq. (1),

$$V_{oc} = \frac{kT}{q} \times \ln\left(\frac{J_{sc}}{J_0}\right). \tag{5}$$

2.2. Temperature dependence of photovoltaic performance

The temperature dependence of η_{PV} stems mainly from that of J_o, which can be expressed as:

$$J_0 = \frac{q}{k} \times \frac{15\sigma}{\pi^4} \times T^3 \times \int_u^{\infty}\frac{x^2}{e^x - 1}dx \tag{6}$$

with $x = E/(kT)$, $u = E_g/(kT)$, and σ being the Stefan-Boltzmann constant. In addition, a knowledge of the bandgap's temperature dependence is required. E_g for semiconductors, in general, decreases with temperature, leading to increased photocurrent. In the absence of a general theory for $E_g(T)$, we adopt the measured linear dependence for GaAs [6,13] and a number of III-V semiconductors that are also candidates for efficient concentrator cells (see Supplementary material A):

$$E_g(T) = E_g(0) - 0.5 \times 10^{-3} \times T \tag{7}$$

with T in K, E_g in eV, and $E_g(0)$ denoting the bandgap at $T = 0$ K.

For current-matched MJ cells, one sums the voltage of each sub-cell at the current density of the lowest-J sub-cell. Using a genetic algorithm [14], we computed the combination of sub-cell E_g values leading to the highest PV efficiency, which we call the energetically optimal bandgaps (this computation can guide cell manufacturers in identifying candidate semiconductor materials for these cell architectures). This method uses a set of E_g values as an initial population, and applies various genetic operations (namely, mutation, cross-over and breeding) toward minimizing an objective function, taken here as 1-η_{PV}. The optimal E_g values at a given temperature are thus defined as the outcome of successive generations selected for their ability to minimize the objective function. In addition, we note at the outset that the nominally optimal E_g values at high temperature differ noticeably from the familiar published values for 1, 2 and 3-junction cells at temperatures far closer to ambient conditions.

We then calculated the T and C dependence of the principal cell parameters V_{oc}, J_{sc}, FF and η_{PV} for single, double and triple-junction cells. The nominal optimization for bandgap values depends on T. Although performance predictions are presented below across wide ranges of T and C, the cell bandgaps were determined at $T = 773$ K as a reasonable compromise between the opposing temperature trends of turbine and PV efficiency (also keeping in mind the inordinate computational time for calculating the full sets of optimal E_g values at each pair of T and C values, for 1, 2 and 3-junction cells). That notwithstanding, there is only a weak sensitivity of the optimal bandgaps to T over the range of practical interest (600–1000 K). For example, the introduction of this approximation leads to overall hybrid system efficiency changes up to only ± 4% over this range (see Supplementary