# Systematic Operating Temperature Differences Between Al-BSF, PERC, and PERT-With-Optimized-Rear-Reflector Solar Mini-Modules Due to Rear Reflectance

Jonathan L. Bryan, Timothy J. Silverman, Michael G. Deceglie, Mason Mahaffey, Peter Firth, and Zachary C. Holman

***Abstract*—Reflecting sub-bandgap light from photovoltaic modules has the potential to improve lifetime energy generation of fielded systems by reducing operating temperature. In this article, the temperature of fielded aluminum back-surface field (Al-BSF) and passivated emitter and rear contact (PERC) mini-modules was monitored every 5 minutes for 75 days along with corresponding meteorological data. Additionally, passivated emitter rear totally diffused (PERT) mini-modules with high-performance sub-bandgap rear reflectors were tested and compared to the state-of-the-art industrial modules. These reflectors consisted of a >300-nm-thick silicon dioxide nanoparticle film with a low refractive index. The impact of reflectance on measured operating temperature was isolated with a previously developed thermal model and quantified as the reflectance-induced median temperature difference between each tested module at representative outdoor conditions (1000 W·m$^{-2}$, 25 °C ambient temperature, and 1.43 m·s$^{-1}$ wind speed). We found that, because of their reflectance differences, PERC modules ran systematically cooler than Al-BSF modules by 1.0 °C, whereas the PERT-with-optimized-rear-reflector systematically operated 1.4 °C cooler than the Al-BSF module and 0.4 °C than the PERC module. We also found that the rear reflector provided the greatest temperature benefit during periods of highest irradiance.**

***Index Terms*—Optics, photovoltaic cells, photovoltaic systems, solar panels, thermal management.**

Manuscript received August 26, 2021; revised October 26, 2021; accepted November 8, 2021. Date of publication December 13, 2021; date of current version December 23, 2021. This work was supported in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract DE-AC36-08GO28308 and in part by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office under Agreement 30312.
*(Corresponding author: Jonathan L. Bryan.)*

Jonathan L. Bryan and Mason Mahaffey are with the School of Electrical Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287 USA (e-mail: jlbryan5@asu.edu; mpmahaff@asu.edu).

Timothy J. Silverman and Michael G. Deceglie are with the National Renewable Energy Laboratory, Golden, CO 80401 USA (e-mail: timothy.silverman@nrel.gov; michael.deceglie@nrel.gov).

Peter Firth and Zachary C. Holman are with the School of Electrical Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287 USA, and also with Swift Coat Inc., Tempe, AZ 85284 USA (e-mail: peter@swiftcoat.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JPHOTOV.2021.3127447.

Digital Object Identifier 10.1109/JPHOTOV.2021.3127447

## I. Introduction

PHOTOVOLTAIC (PV) cells are typically characterized at standard test conditions (STC) of 25 °C and AM1.5G irradiance. When installed in the field, however, cells are encapsulated in module materials and operate at meteorological and irradiance conditions different than STC [1], [2]. This leads to operating temperatures higher than 25 °C, and even exceeding 70 °C in some cases [3], [4]. The waste heat generated in the module has a large impact on the energy yield of an outdoor system. The power output of the module decreases as its operating temperature increases; this loss is commonly described by a temperature coefficient [5]. For commercial silicon PV technology, the temperature coefficient of efficiency ranges from approximately −0.38%/°C for high-quality monocrystalline passivated emitter rear totally diffused (PERT) to −0.4%/°C for passivated emitter and rear contact (PERC) modules to −0.43%/°C for traditional aluminum back-surface field modules (Al-BSF) [6]. Higher module temperature not only reduces instantaneous operating efficiency but also accelerates nearly every type of module degradation [7]. For instance, rates of encapsulant browning were higher during accelerated testing of field-aged silicon modules when they were held at 85 °C compared to 60 °C; this resulted in a relative short-circuit current ($I_{sc}$) drop of 3.26% for the warmer module and 1.37% for the cooler one [8]. Thus, reducing operating temperature in the field results in higher power conversion efficiency and longer system lifetime, manifesting as lower levelized cost of electricity and greater value for the end user [9]. As a result, a broad range of thermal mitigation strategies has been investigated [10].

The waste heat in the module originates from two sources: losses in the process of converting radiative energy to electrical energy (thermalization, nonradiative recombination, transport, Carnot, etc.) and parasitic absorption of light in the module that does not lead to electrical energy generation [11]. The former are fundamental limitations in the PV energy conversion process and minimizing their degree through efficiency enhancement has long been the focus of PV research; the single-junction silicon efficiency record is currently 26.7%, just short of the approximate 29% intrinsic limit [12]. A particularly insidious form of the latter heating mechanism is the parasitic absorption of light that