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Full Length Article

Smart Control and Power Optimization of Solar Photovoltaic Systems for Improved Energy Efficiency

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Abstract
Photovoltaic (PV) energy yield depends on how closely the converter keeps the array at its maximum power point as irradiance and temperature change. This paper develops a fuzzy-logic maximum power point tracking (MPPT) controller for a PV module feeding a boost converter, and compares it with fixed-duty operation, perturb and observe (P&O) and incremental conductance (INC). The fuzzy controller takes the power–voltage slope and its change as inputs and produces a variable duty-ratio step, so that large corrections are made far from the maximum power point and almost none near it. The system comprises a 60-cell single-diode module model (221.7 W at standard conditions) and an averaged boost converter, solved numerically in Python in a block-diagram form. Two scenarios are used: an irradiance staircase between 1000 and 400 W/m², and a 350 W/m² per second ramp with a simultaneous 15 °C temperature rise. Over the staircase, the fuzzy controller reached a tracking efficiency of 96.8 % against 90.8 % for P&O and INC, mostly because of faster start-up; after start-up the efficiencies were 99.5 % and 99.3 %, so the steady advantage is small. During the ramp, the fuzzy controller reached 98.9 % against 96.8 %. Steady-state power ripple fell from 0.4 to 0.7 % of the available power to below 0.01 %. Fixed-duty operation reached only 75.1 % after start-up. The results are simulation-based, assume uniform irradiance and noise-free measurements, and do not address partial shading.

Keywords: *photovoltaic systems; maximum power point tracking; fuzzy logic control; boost converter; energy efficiency; power optimization*

Introduction

Solar photovoltaic (PV) generation is attractive because it converts solar energy into electricity without emissions [1]. The output of a PV module, however, is nonlinear and shifts continuously with irradiance, temperature and shading. A maximum power point tracking (MPPT) controller acting on a DC–DC converter keeps the module at its optimum operating point, and the task becomes harder when temperature, irradiation and partial shadowing change [1].

Conventional methods such as perturb and observe (P&O) are simple to implement, but they suffer from slow tracking, poor convergence and steady-state oscillation [2]. Soft computing and intelligent methods have been proposed to reduce these problems [2], [3]. A fixed-step method forces a compromise: a large step tracks quickly but oscillates around the optimum, while a small step reduces oscillation but responds slowly. This compromise directly reduces the energy delivered.

The objectives of this paper are (i) to design a fuzzy-logic MPPT controller with a variable duty-ratio step for a boost converter, (ii) to build a numerical model of a PV module and converter in which fixed-duty operation, P&O, INC and the fuzzy controller can be compared under identical conditions, and (iii) to quantify tracking efficiency, convergence and steady-state ripple during irradiance steps and a fast ramp with temperature change.

The paper is organized as follows. Section 2 reviews related work, Section 3 describes the models and controllers, Section 4 reports and discusses the results, and Section 5 concludes and indicates future work.

Literature Review

Recent reviews organize the MPPT field from several angles. Derbeli et al. reviewed essential control techniques for MPPT, with emphasis on nonlinear control and boost converters, and noted that the maximum power point becomes more complex as temperature, irradiation and partial shadowing vary [1]. Worku et al. classified MPPT methods as conventional, soft computing and hybrid, and compared tracking speed, complexity and dynamic behavior under partial shading; they stated that conventional methods work under uniform irradiation but fail under partial shading, with slow tracking, poor convergence and high steady-state oscillation [2]. Bhukya et al. reached a

similar conclusion for P&O, hill climbing and incremental conductance, and reported that intelligent techniques offer better tracking accuracy and efficiency with less steady-state oscillation than offline and online methods [3].

Intelligent controllers have been explored in many forms. Hayder et al. combined an improved particle swarm optimization with a neural-network-assisted P&O method for a standalone PV system with a boost converter and DC load under shading and varying atmospheric conditions [4]. Attoui et al. proposed an adaptive fuzzy backstepping sliding-mode controller that approximates the switching function with fuzzy systems in order to avoid chattering, and verified it in Simulink under different operating conditions [5].

Model predictive control (MPC) forms another line of work. Ahmed et al. compared MPPT techniques based on MPC, separating fixed-switching methods, which use a digital observer of the PV model, from finite-set MPC [6]. Yang et al. unified bus-voltage regulation and MPPT for several PV sources in an islanded DC microgrid using a modified MPC, motivated by the robustness, transient behavior and constraint handling of MPC in power electronics [7]. Bhagwan et al. applied MPC-based MPPT to a high-gain DC–DC converter that raises the voltage tenfold, and reported a better transient response than incremental conductance [8]. Heguig et al. used a predictive current controller for a shunt active power filter combined with fuzzy MPPT of the PV generator, tested in MATLAB/Simulink [9]. Joshal and Gupta placed MPC in a wider context, from converter-level control to energy management in microgrids [10].

The reviewed works expose a trade-off. P&O and INC are simple but oscillate and converge slowly, while model-based and hybrid methods improve transient behavior at the price of more modelling, sensing or computation. A rule-based fuzzy controller with a variable step lies between these options: it needs no converter model and only voltage and current measurements. Its benefit relative to fixed-step P&O and INC is quantified in this paper under identical conditions, including a case with a fast ramp in irradiance and temperature.

Materials and Methods

Materials

The system of Fig. 1 consists of a 60-cell PV module, an averaged boost converter, a resistive load and four selectable duty-ratio generators. No measured data were used. The module parameters are representative values chosen for the study and are not taken from a specific datasheet; with them the model delivers 221.7 W at 29.36 V and 7.55 A under standard conditions (1000 W/m², 25 °C). The converter and controller parameters are also given The model was solved in Python 3 with NumPy using a 40 µs semi-implicit Euler step, and the controllers update the duty ratio every 10 ms. The block diagrams in Fig. 1 and Fig. 2 use a Simulink-style layout.

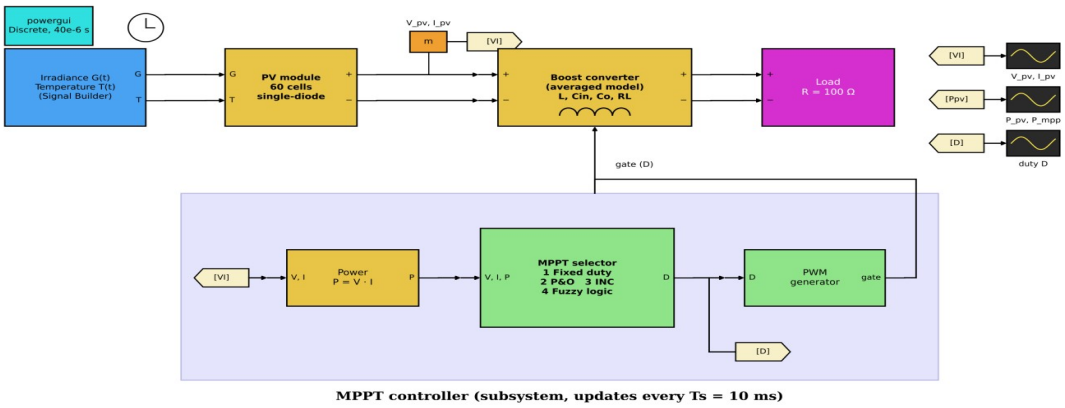

Fig. 1. Simulink-style block diagram of the PV module, boost converter and selectable MPPT controllers.

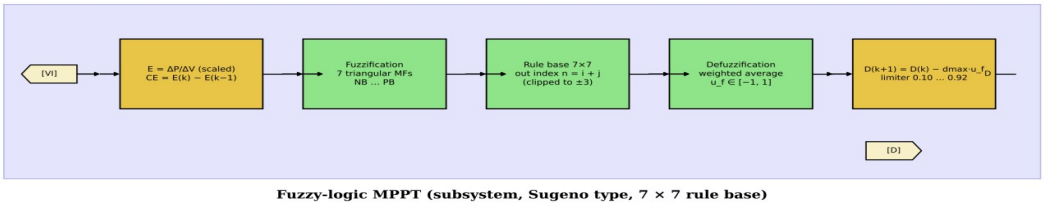

Fig. 2. Structure of the Sugeno-type fuzzy MPPT controller.

Procedures

Step 1: PV module. The terminal current is obtained from the single-diode equation, solved by Newton iteration at every step:

$$I = I_{ph} - I_0\cdot[\exp((V + I\cdot R_s)/(a\cdot N_s\cdot V_t)) - 1] - (V + I\cdot R_s)/R_{sh} \quad (1)$$

$$I_{ph} = I_{sc}\cdot(G/1000)\cdot[1 + \alpha\cdot(T - 25)] \quad (2)$$

where V is the module voltage, I_{ph} the photocurrent, I_0 the diode saturation current (scaled with temperature using the band gap), V_t the thermal voltage, G the irradiance in W/m², T the cell temperature in °C and α the current temperature coefficient.

Step 2: boost converter. The averaged model with duty ratio D is:

$$L\cdot di_L/dt = V_{pv} - (1 - D)\cdot V_o - R_L\cdot i_L \quad (3)$$

$$C_{in}\cdot dV_{pv}/dt = I_{pv} - i_L; \quad C_o\cdot dV_o/dt = (1 - D)\cdot i_L - V_o/R \quad (4)$$

Raising D lowers the voltage seen at the PV terminals, which is why all controllers move D in the direction opposite to the desired voltage change.

Step 3: controllers. P&O and INC adjust D by a fixed step of 0.004 every 10 ms. The fuzzy controller computes the slope E = ΔP/ΔV, normalized by 10 W/V, and its change CE = E(k) − E(k−1). Each input is fuzzified with seven triangular membership functions (NB to PB). A 7 × 7 additive rule base assigns the output index n = i + j (clipped to ±3), defuzzified by weighted average to u_f in [−1, 1]:

$$D(k+1) = D(k) - d_{max}\cdot u_f(E, CE), \quad d_{max} = 0.012 \quad (5)$$

Far from the maximum power point the slope is large and the step approaches d_{max}; close to it the slope vanishes and the step shrinks toward zero. The fixed-duty reference uses D = 0.80, the value that is optimal at standard conditions.

Analysis

Two scenarios are simulated from an initial duty of 0.5. In S1 the irradiance is 1000, 600, 800 and 400 W/m² for 1.5 s each at 25 °C. In S2 the irradiance rises from 300 to 1000 W/m² in 2 s (350 W/m² per second) while the cell temperature rises from 25 to 40 °C, followed by 2 s of constant conditions. The instantaneous maximum power P_{mpp} is computed numerically from the same module model. The main indicators are:

$$\eta_{MPPT} = 100\cdot\sum P_{pv}(k) / \sum P_{mpp}(k) \quad (6)$$

together with the settling time within 2 % of P_{mpp} after each step and the steady-state ripple, defined as the peak-to-peak variation of P_{pv}/P_{mpp} during the last 0.5 s of a plateau. The efficiency is also reported after the first 1.5 s to separate start-up from step response. The P&O and INC step was chosen as a moderate value; a different step would shift the speed and ripple balance of these two methods.

Results and Discussion

Fig. 3 shows the model characteristics. The maximum power point lies near 29 V for all irradiance levels used (221.7, 176.9, 131.4 and 85.7 W at 1000, 800, 600 and 400 W/m²), and it moves to lower voltage as temperature rises. Because the optimal operating voltage is almost constant while current scales with irradiance, the optimal duty ratio changes only moderately (0.80 at 1000 W/m² to about 0.69 at 400 W/m² in Fig. 4).

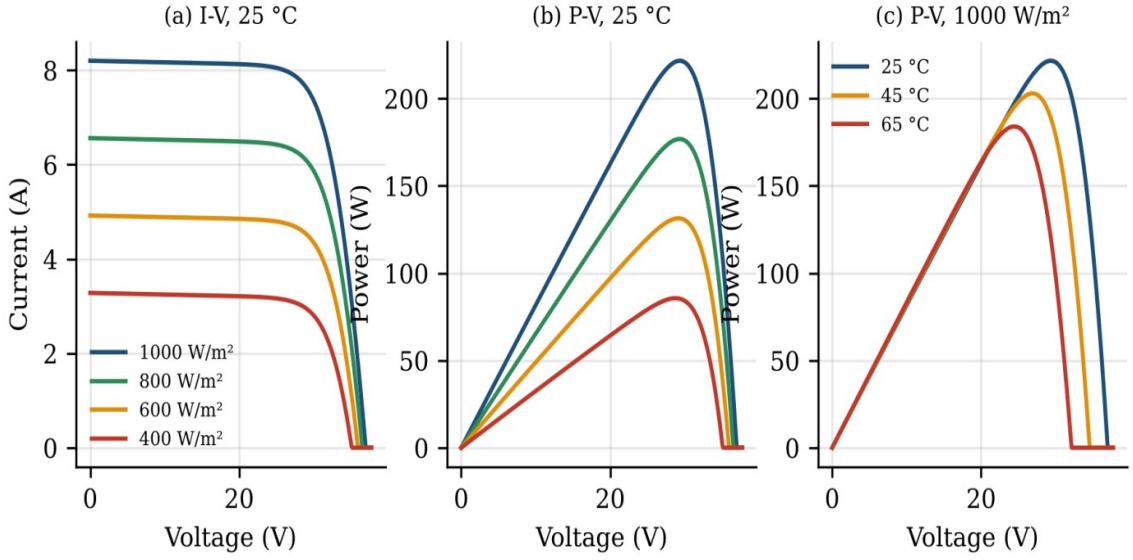

Fig. 3. Simulated characteristics of the 60-cell module: (a) I–V and (b) P–V curves at 25 °C for several irradiance levels, and (c) P–V curves at 1000 W/m² for several temperatures.

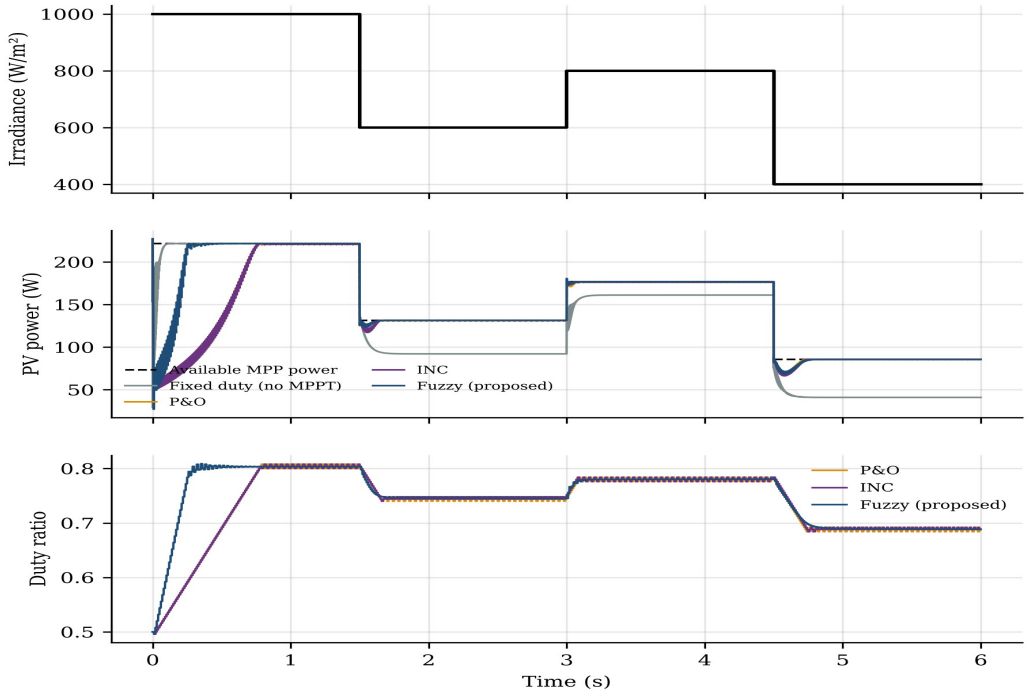

Fig. 4. Scenario S1: irradiance, PV power versus available power, and duty ratio for each controller.

Fig. 4 give the results for S1. The whole-run efficiency of the fuzzy controller (96.77 %) exceeds that of P&O and INC (about 90.75 %) by roughly six points, but this difference comes almost entirely from the first second: starting from D = 0.5, the fixed 0.004 step needs about 0.8 s to reach the optimum, whereas the fuzzy step reaches it in about 0.3 s. After the first 1.5 s the efficiencies are 99.51 %, 99.31 % and 99.30 %, so the steady advantage of the fuzzy controller is about 0.2 points. Its larger benefit lies in the steady-state ripple, which falls below 0.01 % of the available power against 0.35 to 0.57 % for INC and P&O (Fig. 5b). The settling time after the three irradiance steps is similar for all three methods (0.115 to 0.128 s on average); the fuzzy controller is fastest after the 1000 → 600 W/m² step (0.10 s against 0.13 s) but slightly slower after the 800 → 400 W/m² step (0.23 s against 0.21 s), which shows that the benefit is not uniform. Fixed-duty operation is optimal only at the condition it was tuned for and delivers 75.1 % of the available power after start-up.

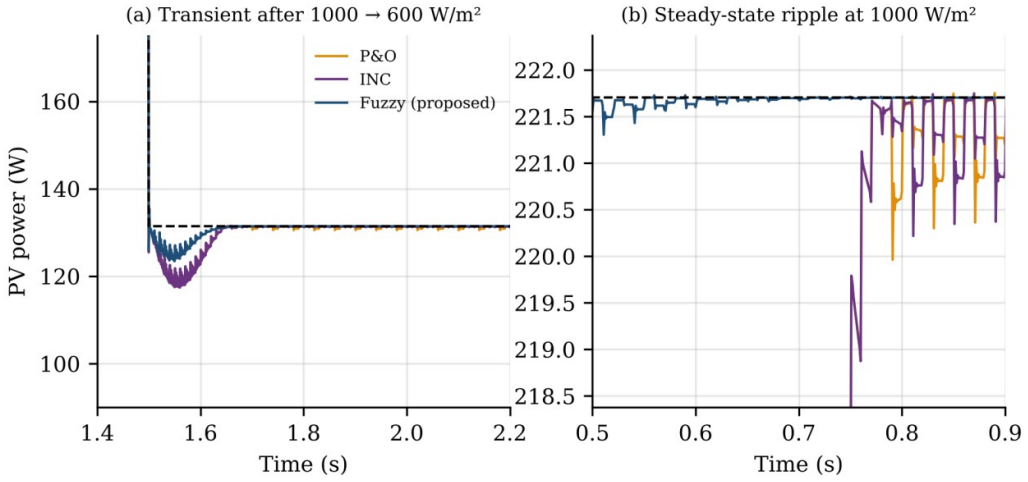

Fig. 5. Zoomed views: (a) transient after the 1000 to 600 W/m² step and (b) steady-state ripple at 1000 W/m².

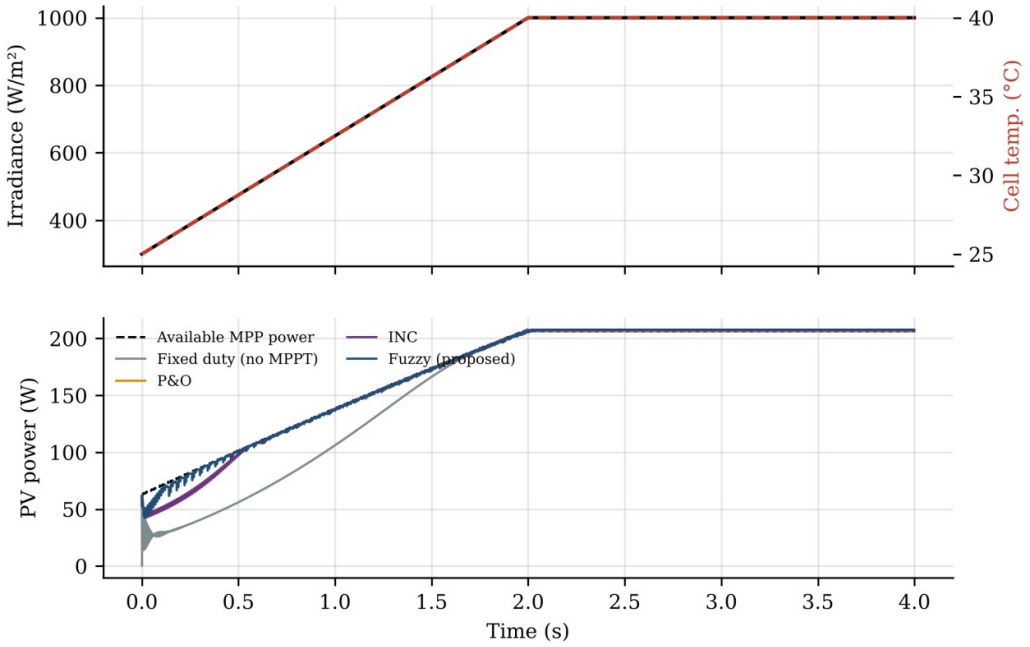

Fig. 6. Scenario S2: irradiance and temperature ramp, and PV power versus available power.

The ramp in S2 Fig. 6, is more discriminating. While the irradiance and temperature change continuously, the fuzzy controller keeps 98.88 % of the available power against 96.76 % for P&O and 96.77 % for INC, because its larger step lets it follow the moving optimum without a permanent lag. Fixed-duty operation falls to 80.7 % during the ramp. Over the full 4 s the efficiencies are 99.55 % (fuzzy), 98.60 % (INC), 98.59 % (P&O) and 91.90 % (fixed duty).

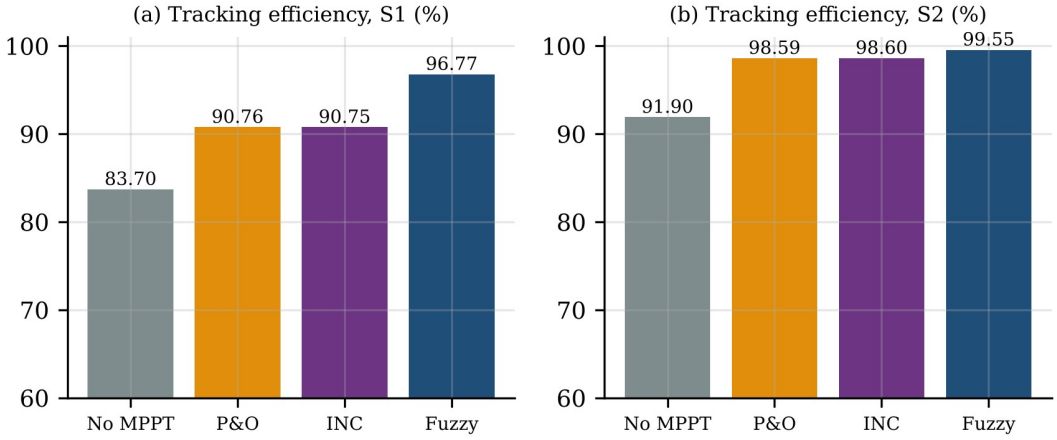

Fig. 7. Tracking efficiency in (a) scenario S1 and (b) scenario S2.

These findings are consistent with the qualitative statements in the literature that intelligent techniques reduce steady-state oscillation and raise tracking efficiency relative to P&O, HC and INC [3], [2], and with the reported advantage of predictive MPPT during transients [8]. The results are not directly comparable in magnitude, because the plants, scenarios and step sizes differ, and the fuzzy controller here is rule-based, without a converter model, unlike the MPC methods of Ahmed et al. and Yang et al. [6], [7]. Two limitations should be emphasized. The measurements are noise-free, which favors the slope-based fuzzy input; sensor noise would require filtering or a dead zone. In addition, a uniformly illuminated module has a single power peak; the partial-shading failure of local-search methods described in the reviews [2], [1] was not tested, and the local-search behavior of the fuzzy controller would not solve it.

Conclusion and Future Work

A fuzzy-logic MPPT controller with a variable duty-ratio step was designed for a PV module and boost converter and compared with fixed-duty operation, P&O and INC in a numerical block-diagram model. In an irradiance staircase the fuzzy controller reached 96.8 % tracking efficiency against 90.8 % for P&O and INC, but the gap was almost entirely due to faster start-up; after start-up the difference was 0.2 points. During a 350 W/m² per second ramp with a temperature rise, it retained 98.9 % of the available power against 96.8 %. Steady-state ripple fell from 0.35 to 0.66 % to below 0.01 %.

The contribution is a transparent comparison under identical conditions that separates start-up, step response, ramp tracking and ripple. The conclusions are limited to the assumed module and converter parameters, to simulation, to ideal measurements and to uniform irradiance. Future work should add sensor noise and a dead-zone design, test partial shading with a global search stage, tune the P&O and INC steps by optimization for a fairer comparison, include converter switching and losses, and validate the controller on hardware or with measured irradiance data.

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