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UNCERTAINTY QUANTIFICATION AND CARRIER-COLLECTION ROBUSTNESS UNDER PHYSICAL TOLERANCES IN A SERIES VERTICAL-JUNCTION SILICON SOLAR CELL

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ABSTRACT

This work investigates the propagation of uncertainties in physical parameters to carrier collection in a series vertical-junction silicon solar cell. Starting from an exact dimensionless collection law, uncertainties are introduced in the base thickness H , diffusion coefficient D , carrier lifetime τ , and interface recombination velocities S_f and S_b . For each realization, the diffusion length and the reduced parameters h , f , and b are recalculated, thereby preserving the dependencies induced by the physical transformation. Twenty-seven nominal regimes and four controlled uncertainty amplitudes, from $\pm 5\%$ to $\pm 30\%$, are investigated using a Monte Carlo campaign of 120,000 realizations per scenario. Robustness is characterized by the coefficient of variation of collection and by $R_{90} = P(C \geq 0.9 C_0)$. The median coefficient of variation increases from approximately 3.13% at $\pm 5\%$ to 18.94% at $\pm 30\%$, while the maximum value reaches 37.14%. Over the same range, the median R_{90} decreases from 100% to approximately 68.12%. At $\pm 30\%$, some regimes retain R_{90} close to unity, whereas the least robust regime in the grid reaches approximately 60.17%. The regime of maximum statistical dispersion does not exactly coincide with that of minimum R_{90} . These results show that nominal performance, statistical dispersion, and probabilistic robustness are distinct properties and establish a regime-dependent map for assessing collection robustness under controlled physical uncertainty.

Keywords: Series Vertical-Junction Silicon Solar Cell; Uncertainty Quantification; Carrier Collection; Parametric Variability; Probabilistic Robustness; Monte Carlo Simulation.

1 INTRODUCTION

The performance of a photovoltaic cell depends simultaneously on its geometry, carrier-transport properties, and recombination mechanisms. A deterministic description generally represents these quantities by nominal values. In a real device, however, they exhibit dispersions related to the material, technological process, metrology, and operating

conditions. A design that is satisfactory at the nominal point may therefore exhibit a different response when the parameters fluctuate.

Uncertainty propagation is already used in photovoltaics. Tolić et al. studied the propagation of measurement uncertainty through several cell models and evaluated it using Monte Carlo simulation [1]. Zhang et al. subsequently quantified the effect of random parameters on photovoltaic-cell performance, stability, and reliability using quasi-Monte Carlo methods [2], and then formulated a functional-failure analysis based on the probability of remaining within an admissible operating region [3]. Global sensitivity analyses [4] and robust-design formulations [5] have also been proposed. The uncertainty associated with estimating the electrical parameters of a cell was also investigated by Attivissimo et al. [6].

Within the family of series vertical-junction silicon solar cells, available studies have mainly addressed diffusion capacitance [7], optimum thickness [8], spectral response [9], efficiency and recombination [10], as well as the effects of magnetic field and thickness [11]. These studies confirm the major roles of geometry, transport, and interfaces, but they do not directly answer the question considered here: how do dispersions in physical parameters propagate to normalized carrier collection, and does this propagation depend on the nominal regime?

The present study introduces uncertainties at the level of the five physical parameters (H , D , τ , S_f , S_b) and then propagates them to the diffusion length and reduced parameters. The objective is to quantify collection variability, identify robust and fragile regions of the nominal space, and distinguish nominal performance from probabilistic robustness. The amplitudes $\pm 5\%$, $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ are used as controlled uncertainty scenarios; they are not interpreted as measured industrial tolerances.

2 PHYSICAL MODEL AND PROBABILISTIC FORMULATION

Minority-electron transport in the p-type base of the $n^+/p/p^+$ structure is described, in the reference diffusion model, by a diffusion length L defined by

$$L = \sqrt{D\tau} \quad (1)$$

The dimensionless geometry and recombination parameters are

$$h = \frac{H}{L}, \quad f = \frac{S_f L}{D}, \quad b = \frac{S_b L}{D} \quad (2)$$

The normalized collection considered in this work is

$$C(h, f, b) = \frac{f[\sinh(h) + b(\cosh(h) - 1)]}{(1 + bf)\sinh(h) + (f + b)\cosh(h)} \quad (3)$$

The physical parameters are then treated as uncertain:

$$X = (H, D, \tau, S_f, S_b) \quad (4)$$

For each nominal parameter $X_{i,0}$, an independent uniform relative perturbation is applied:

$$X_i = X_{i,0}(1 + \varepsilon_i), \quad \varepsilon_i \sim U(-a, a) \quad (5)$$

with $a \in \{0.05, 0.10, 0.20, 0.30\}$. For each realization, L , h , f , and b are recalculated from the five physical parameters. The induced dependencies among h , f , and b are therefore preserved by construction.

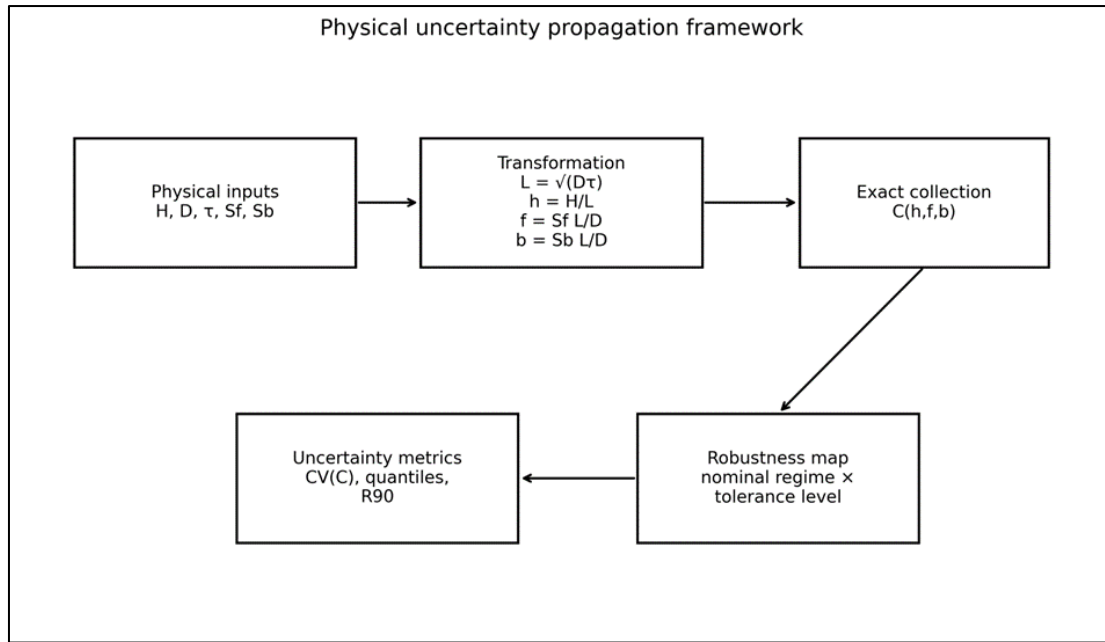


Figure 1: Framework for propagating physical uncertainties to collection and robustness metrics.

2.1 Variability and robustness metrics

$$CV_C = \frac{\sigma_C}{\langle C \rangle} \quad (6)$$

$$R_{90} = P(C \geq 0.9 C_0) \quad (7)$$

CV_C measures the relative dispersion of collection, whereas R90 measures the probability of retaining at least 90% of the nominal collection C₀. The Q05, Q50, and Q95 quantiles are also recorded to describe the distribution without assuming normality.

3 NUMERICAL PROTOCOL

The nominal space is defined by $h_0 \in \{0.2, 1, 5\}$, $f_0 \in \{0.1, 1, 10\}$, and $b_0 \in \{0.1, 1, 10\}$, giving 27 nominal regimes. Four uncertainty levels are applied to the five physical parameters, resulting in 108 scenarios. The materialized campaign uses 120,000 Monte Carlo realizations per scenario, corresponding to 12,960,000 probabilistic evaluations of the collection law. A fixed pseudorandom seed is used to make the campaign reproducible.

The uncertainty levels are deliberately common to all five parameters in order to investigate the structure of the model under controlled perturbation. They do not constitute an experimental estimate of the dispersions of an industrial process.

4 RESULTS

4.1 Variability amplification

Table 1: Summary of variability and robustness over the 27 nominal regimes.

Uncertainty	Median CV (%)	Maximum CV (%)	Median R90 (%)	Minimum R90 (%)
±5	3.13	6.05	100.00	95.91
±10	6.23	12.11	95.03	79.78
±20	12.54	24.43	76.84	66.27
±30	18.94	37.14	68.12	60.17

Collection dispersion increases steadily with uncertainty amplitude. Table 1 summarizes the results over the 27 nominal regimes.

The median CV_C increases from 3.13% for $\pm 5\%$ to 18.94% for $\pm 30\%$, while the maximum value increases from 6.05% to 37.14%. The same amplitude of physical uncertainty can therefore produce very different dispersion levels depending on the nominal regime.

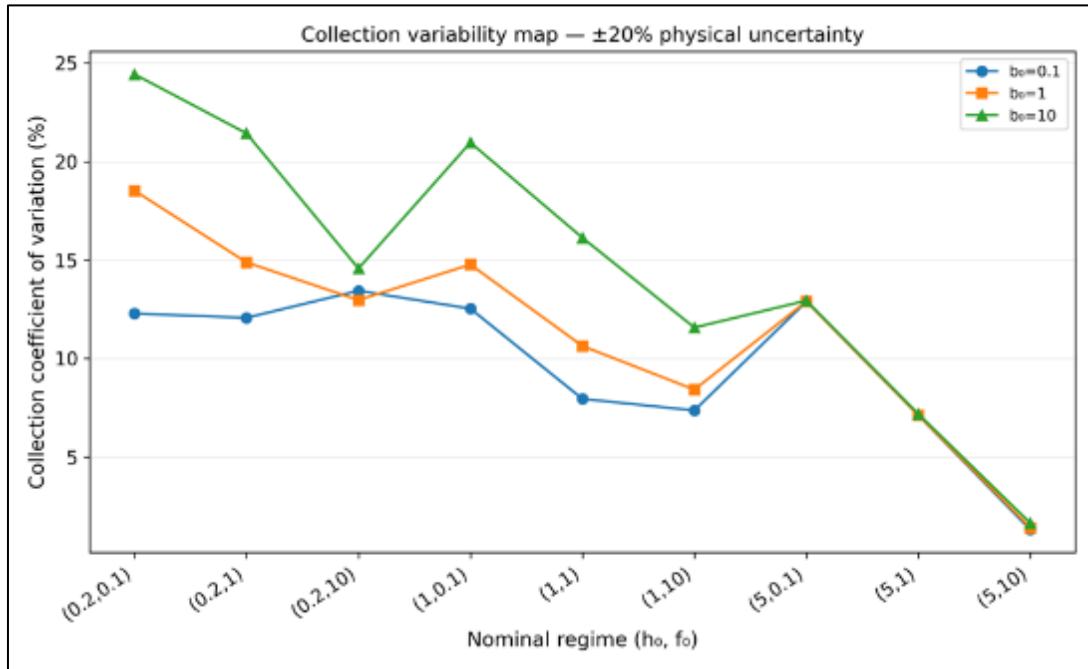


Figure 2: Collection-variability map for $\pm 20\%$ physical uncertainty. The nine (h_0, f_0) pairs are compared for three values of b_0 .

4.2 Probabilistic robustness map

The R90 metric reveals a progressive degradation in performance retention. Its median is 100% at $\pm 5\%$, 95.03% at $\pm 10\%$, 76.84% at $\pm 20\%$, and 68.12% at $\pm 30\%$. The observed minimum decreases from 95.91% to 60.17%.

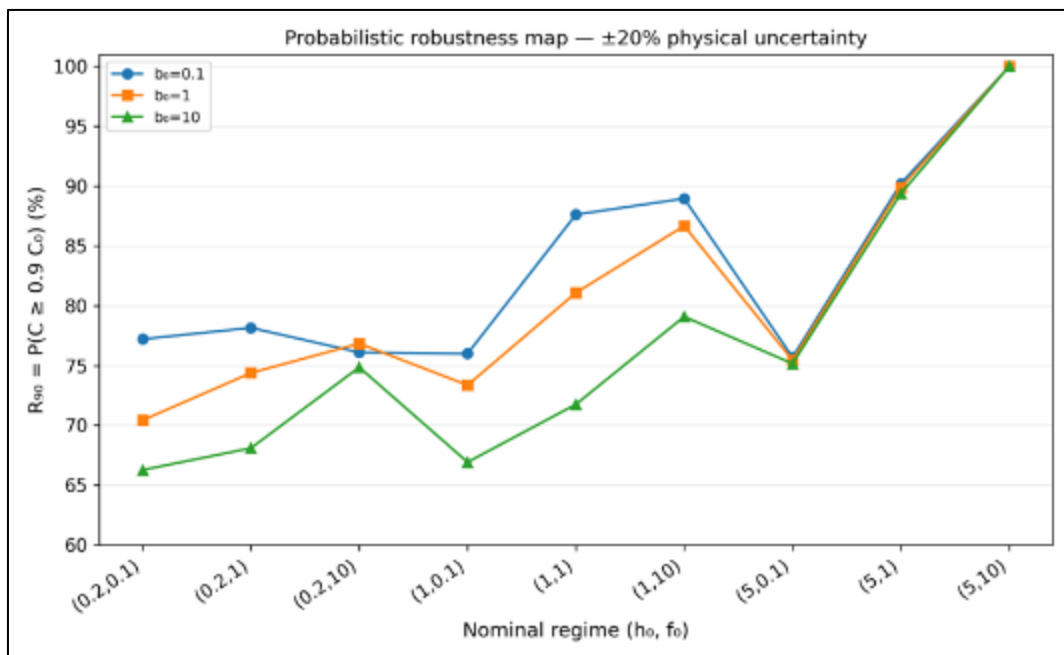


Figure 3: Probabilistic robustness map R90 for $\pm 20\%$ physical uncertainty.

4.3 Fragile and robust regimes

At $\pm 20\%$, the regime $(h_0, f_0, b_0) = (0.2, 0.1, 10)$ has $C_0 = 3.755 \times 10^{-3}$, $CV_C = 24.43\%$, and $R_{90} = 66.27\%$. At $\pm 30\%$, its CV_C reaches 37.14% and $R_{90} = 61.02\%$. The absolute minimum R_{90} at $\pm 30\%$ nevertheless occurs for $(1, 0.1, 10)$, with $R_{90} = 60.17\%$. The regime of maximum dispersion is therefore not exactly the regime of minimum robustness.

At the other extreme, the regimes $(5, 10, 0.1)$, $(5, 10, 1)$, and $(5, 10, 10)$ remain highly robust at $\pm 30\%$: their CV_C values are approximately 2.05% , 2.26% , and 2.71% , respectively, and their R_{90} values are 100% , 100% , and 99.80% . The investigated space therefore contains clearly fragile regions and other regions that are highly tolerant to the same physical perturbations.

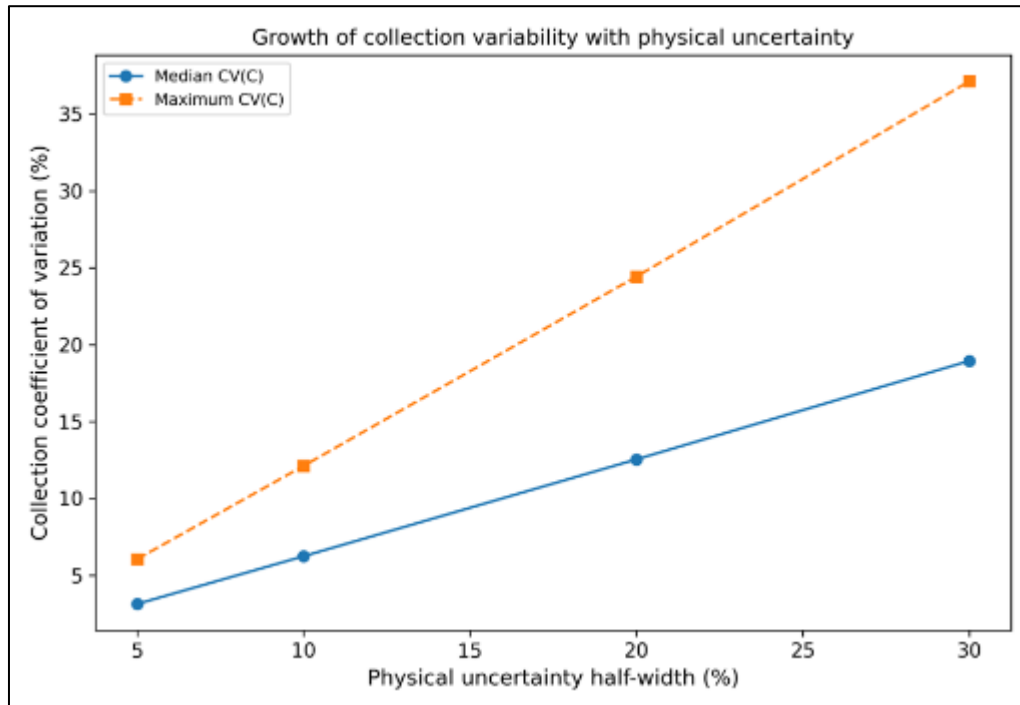


Figure 4: Evolution of the median and maximum coefficient of variation of collection with physical-uncertainty amplitude.

4.4 Nominal performance and robustness

The nominal collection C_0 and R_{90} answer two different questions: the former describes performance at the nominal point, whereas the latter describes the probability of remaining close to that performance under perturbation. Their comparison shows that a high nominal value alone is insufficient to characterize robustness.

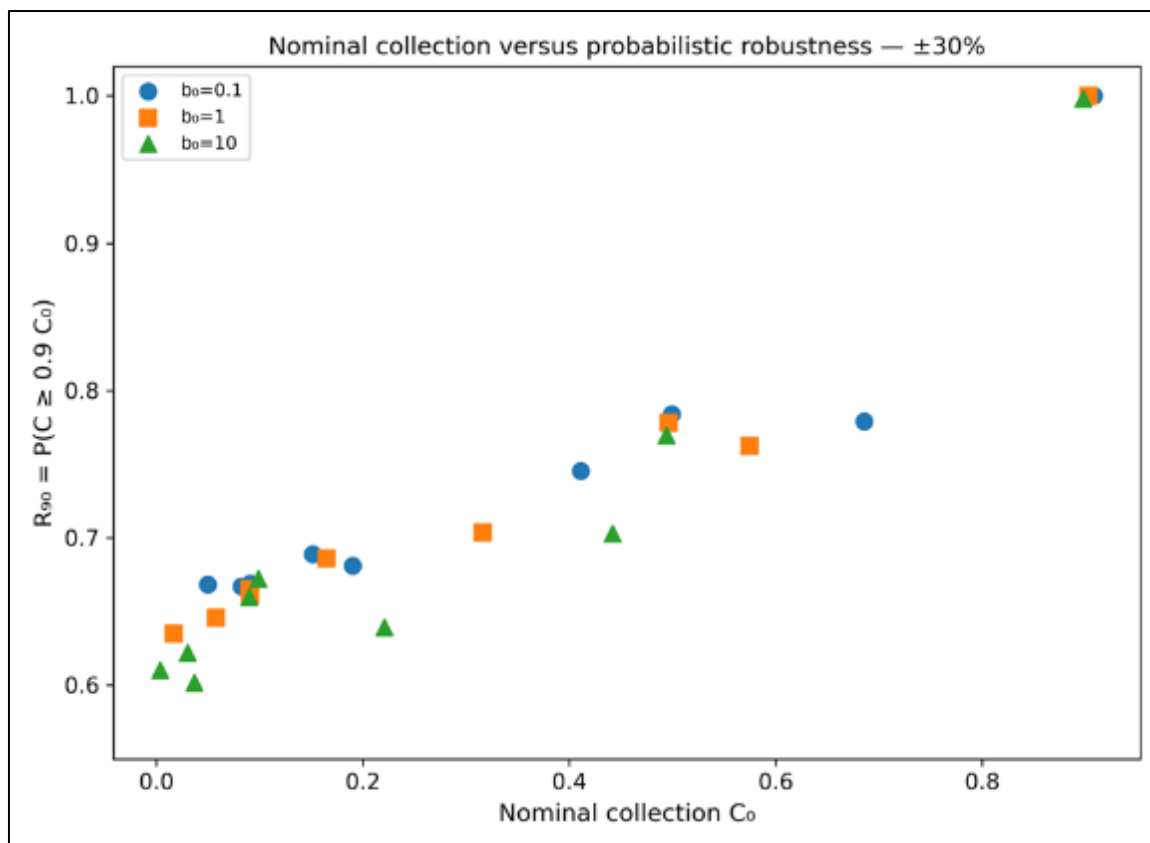


Figure 5: Nominal collection and probabilistic robustness for $\pm 30\%$ physical uncertainty.

5 DISCUSSION

The main result is not simply the increase in variance as perturbations increase. Rather, it lies in the strongly regime-dependent character of this amplification. For the same amplitude applied to H , D , τ , S_f , and S_b , the responses may remain highly concentrated or become widely dispersed. Collection robustness therefore results from an interaction between the precision of the physical parameters and the selected nominal point.

This interpretation complements uncertainty approaches already used in photovoltaics. Studies [1–6] have established the relevance of Monte Carlo methods, global sensitivity, failure probabilities, and robust design for outputs such as power, fill factor, efficiency, or parameters of electrical models. The present work operates at a different level: the propagated quantity is the normalized collection derived from an analytical transport model for a series vertical-junction silicon solar cell.

CV_C and R_{90} are complementary. The former quantifies the relative spread of the distribution, whereas the latter introduces a performance-retention requirement. The fact that their most unfavorable regimes do not exactly coincide shows that a single statistical metric is insufficient to characterize robustness.

The regions $(h_0, f_0, b_0) = (5, 10, b_0)$ appear particularly robust within the investigated grid. This finding does not, however, constitute a technological optimization: the study addresses neither cost, maximum power, overall efficiency, nor manufacturing constraints. It is therefore more appropriate to refer to robust collection regions rather than a robust optimum.

The $\pm 5\text{--}30\%$ amplitudes are controlled scenarios. Their purpose is to test the propagation structure of the model over an increasing range, not to represent measured industrial statistics. Future technological validation should replace these uniform distributions with distributions derived from process measurements and, where necessary, introduce correlations among physical parameters.

Finally, the study is limited to 27 nominal regimes and to normalized collection. A natural extension is to compare the map with experimental dispersions and then propagate uncertainties to complete photovoltaic quantities such as J_{sc} , V_{oc} , P_{max} , and efficiency.

6 CONCLUSION

A probabilistic analysis of carrier collection in a series vertical-junction silicon solar cell was developed by introducing uncertainties directly into H , D , τ , S_f , and S_b before transforming them into reduced parameters. The campaign of 108 scenarios shows that increasing uncertainty generally increases dispersion, but that this amplification strongly depends on the nominal regime. Between $\pm 5\%$ and $\pm 30\%$, the median CV_C increases from approximately 3.13% to 18.94%, whereas the median R_{90} decreases from 100% to approximately 68.12%. At $\pm 30\%$, some regimes remain almost perfectly robust, whereas the minimum R_{90} reaches approximately 60.17%. The point of maximum dispersion does not exactly coincide with the point of minimum robustness. These results therefore establish that nominal performance, statistical dispersion, and probabilistic robustness are three distinct properties. The proposed map provides a framework for identifying collection regimes that are most tolerant to controlled physical uncertainties, while leaving validation against measured technological distributions open.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The author declares that there is no conflict of interest.

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