# TropicalField-Tandem: A Paired Indoor-Outdoor Dataset and Proposed Physics-Informed Framework for Perovskite-Silicon Tandem Mini-Module Reliability in Tropical Climates

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## Abstract

Perovskite-silicon (Pvk-Si) tandem solar modules are a leading route to push past the single-junction efficiency limit, but the path to commercialisation is held back by poor stability in real operating conditions. We introduce TropicalField-Tandem, a paired indoor-outdoor dataset from 2T monolithic Pvk-Si tandem mini-modules deployed in the field in Singapore. After about 3 months outdoors, our modules show Voc losses up to -21.5% and FF losses up to -16.6%, while a co-deployed silicon heterojunction (HJT) reference module remains fully stable throughout, pointing to perovskite-specific failure mechanisms. Alongside the dataset, we propose Tropical-Translator, a physics-informed probabilistic framework that aims to turn short indoor MPPT measurement sequences, together with local climate data, into long-horizon field reliability predictions with quantified uncertainty, with the goal of supporting go/no-go decisions in encapsulation qualification. No model results are reported in this paper; the contribution is the dataset and the framework design, put forward as an open benchmark for the community.

*Keywords: perovskite-silicon tandem; tropical outdoor stability; physics-informed machine learning; uncertainty quantification; degradation forecasting; MPPT*

## 1. Introduction & Motivation

Indoor stability protocols such as ISOS-L and ISOS-D are widely used because they are fast and reproducible [1], but they often miss what happens under tropical outdoor conditions, where heat, humidity, and daily temperature swings can trigger failure mechanisms that barely appear in the lab. For 2T monolithic tandems this is a particular problem, since field conditions shift the current-matching point between sub-cells and can drive irreversible recombination losses at interfaces [3,4]. Our measurements make this gap concrete: modules that look perfectly stable through hundreds of hours of indoor MPPT can lose more than 20% of their open-circuit voltage within a few months in Singapore. Getting on top of this requires models grounded in the device physics, that can account for local climate, and that give honest uncertainty estimates so that qualification decisions are actually trustworthy [2].

## 2. Dataset & Experimental Setup

Devices. The tandem modules are 2T monolithic Pvk-Si devices built on M2-format silicon HJT bottom cells. A silicon HJT reference module was co-deployed throughout all campaigns to separate perovskite and interface losses from any drift in the silicon baseline.

Indoor MPPT. We collected 124.63 h of indoor MPPT data across two measurement campaigns, totalling around 519,520 data points at roughly 1 Hz. A 96 h uninterrupted window gives a coefficient of variation of 0.73% and a power drift of -1.36%, and the time series covers both the early conditioning transient and the later steady-state drift under controlled conditions.

Outdoor tropical operation and IV follow-up. Modules were deployed outdoors in Singapore for 25 days of continuous MPPT tracking, followed by periodic IV measurements over roughly 3 months. Across the tandem modules we see Voc losses up to -21.5% and FF losses up to -16.6%. The HJT reference shows no measurable change in either parameter, which confirms that the degradation is perovskite-related rather than a general environmental effect. Together, the indoor and outdoor data form a paired dataset where the task is to predict field performance from lab measurements.

## 3. Proposed Framework: Tropical-Translator

Tropical-Translator is a framework we are developing to take short indoor MPPT records and local climate data as inputs and produce probabilistic forecasts of how a module will degrade over months in the field. The planned inputs are indoor MPPT features (drift rate, variability, change-points in the time series), sparse IV measurements (Voc, FF, and recombination proxies), and outdoor climate data (temperature and relative humidity statistics, diurnal cycling estimates, and UV exposure where available).

The key design choice is to build physical knowledge into the model rather than treating it as a black box. Predictions of ΔVoc(t) and ΔFF(t) will be constrained by a diode-equation surrogate so the model cannot produce physically implausible combinations, such as FF recovery while recombination is increasing [6]. Temperature dependence will be regularised with an Arrhenius prior on the latent degradation rate; a simple fit to our field data gives an activation energy of roughly 0.45 eV, which we plan to use as the prior centre. Cumulative moisture exposure will be tracked through a latent damage variable that integrates temperature-weighted RH history, to capture the gradual and partially irreversible nature of moisture ingress [3,4]. The output will be a predictive distribution over ΔVoc(t), ΔFF(t), and ΔPmpp(t), produced by either a Bayesian state-space approach or an ensemble method [5], and assessed with coverage and proper scoring rules alongside standard regression metrics. We have not yet trained or evaluated the model.

## 4. Dataset Findings & Benchmark Definition

What the data show. Under controlled indoor conditions, the modules are reassuringly stable: CV of 0.73% and a power drift of just -1.36% over 96 h. Outdoors in Singapore the picture changes sharply. Tandem modules lose up to -21.5% in Voc and -16.6% in FF within 3 months, while the HJT reference sits at 0% change throughout. The contrast makes it clear that the degradation is tandem-specific, and gives a well-defined target for supervised modelling.

We propose three benchmark tasks for the community:

- T1 - Translation: given indoor MPPT features and climate data, predict Voc and FF change over 30 to 90 days outdoors.
- T2 - Forecasting: predict how Voc and FF evolve during continuous outdoor operation (autoregressive setting).
- T3 - Early warning: using only the first N days of outdoor data together with indoor measurements, flag modules at high risk of degradation.

The primary output we have in mind is a risk score: the probability that Voc loss will cross a given threshold by day 30, 60, or 90.

## 5. Contributions & Outlook

- A paired indoor-outdoor dataset from real 2T Pvk-Si tandem mini-modules, measured at high sampling rate indoors and tracked in a tropical climate for several months. The co-deployed HJT reference provides a stable internal baseline, which is unusual in the published literature and makes the dataset well-suited to learning degradation signatures rather than correlations.
- The Tropical-Translator framework design: a physics-constrained probabilistic model with Arrhenius temperature priors, diode-based output constraints, and a latent moisture damage variable, aimed at producing well-calibrated uncertainty estimates for encapsulation qualification decisions. The model itself is work in progress.
- A defined benchmark with three tasks (T1-T3), evaluation metrics, and a standardised data schema (MPPT + IV + environment) that we plan to release openly, so that others can train and compare approaches on the same data.

All measurements in this paper come from a single site in Singapore, so we cannot yet separate the contributions of temperature, humidity, and UV. EL/PL imaging, impedance spectroscopy, and UV dose logs are not part of this dataset. The next steps are expanding to additional climate zones and using the

framework to figure out which indoor tests are actually needed to bound field-risk uncertainty for a given deployment context.

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