Global-Scale Non-Linear Modelling of Photovoltaic Module Degradation

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Introduction

Photovoltaic (PV) systems are the fastest growing [1] and most preferred sources of renewable energy resources worldwide. In recent years, PV installations have contributed to approximately 60% increase in the renewable capacity worldwide [1]. The installed capacity of PV technology is expected to increase further to meet energy demand and achieve renewable energy targets [1,2]. However, long-term exposure to outdoor weather conditions can induce severe stress on the PV modules, resulting in module degradation over time.

Manufacturers consider a module to be degraded when the power generation capacity of the module falls below 80% of its rated power during its lifetime (25-30 years) [3]. Several meteorological parameters like solar radiation, temperature, wind speed, and moisture affect a PV module's performance and yield. Extreme weather conditions and diurnal weather changes induce severe environmental stress on the PV modules, resulting in accelerated degradation and reduced lifetime [4].

Hydrolysis, thermo-mechanical and photodegradation are the most common degradation mechanisms for silicon modules [5,6]. These mechanisms are initiated due to the influence of meteorological variables: temperature, relative humidity and UV irradiance. According to an extensive field inspection report for the modules deployed in the US, hotspots (33%) followed by ribbon discoloration (20%), glass breakage (12%), encapsulant discoloration (10%), cell breakage (9%), and potential induced degradation (PID, 8%) were found to be the most common degradation modes in silicon modules over the last ten years [7].

In the past, researchers have looked at these individual degradation modes and studied their influence on power. Studies have reported that cell cracks alone can reduce power output by 3% [8,9]. They interrupt electrical conductivity in the cell and lead to reduction in the short-circuit current and increase in series resistance, which reduces power output. Cell cracks can also increase the chances of PID, which leads to power losses of up to 5% [10]. Hot spots create localized temperature differences due to thermal expansion and can result in cell cracking or delamination. Delamination increases the light reflection and water penetration inside the module structure, thereby triggering corrosion of metal contacts. Furthermore, moisture ingress and high module temperature can lead to encapsulant discoloration that can lead to 6-13% reduction in the short-circuit current [11,12]. Hence, it is evident that module degradation is non-linear, and there can be interactions among the different modes that affect the lifetime of the modules.

However, there is a huge gap in modelling the PV module degradation modes, their frequency of occurrence, speed of evolution and degree of impact on module lifetime and reliability. A recent study has highlighted the need for a holistic framework of integrating degradation modelling components to predict more accurate degradation rates [13] (figure 1). In this study, we aim to develop a modelling framework that considers the weather parameters responsible for module degradation and their non-linear interactions.

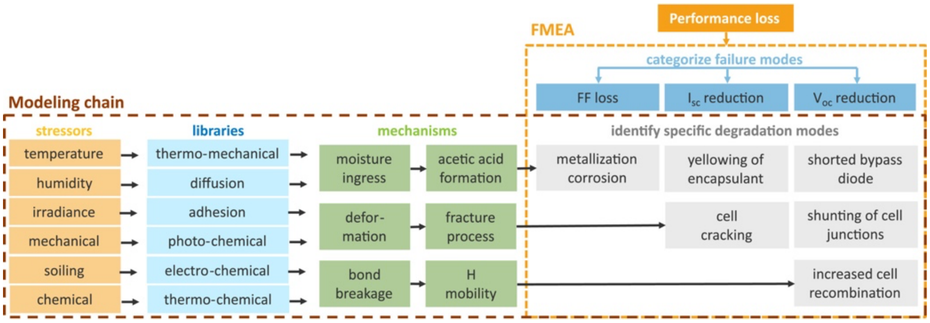

Figure 1. Individual modelling blocks required for developing a unifying degradation modelling framework [13].

Modelling Approach

Currently, under the modelling framework, we identify the stressors and individually model the degradation mechanisms: hydrolysis, thermal degradation, and photodegradation. We empirically model the degradation caused by temperature and humidity induced stress on modules [14]:

$$r_{h-t} = A(rh)^n \exp\left(-\frac{E_{TH}}{k_B \times T_m}\right) \qquad eq\ [1]$$

where E_{TH} is the thermal activation energy of the degradation process, k_B is the Boltzmann constant, T_m is the module temperature, rh is the relative humidity. A and n are constants dependent on the failure mode. Similarly, we model thermal and photodegradation following the equations [15]:

$$r_t = A_{Tm}(\Delta T)^{\theta} C_N \exp\left(-\frac{E_{Tm}}{k_B \times T_U}\right) \qquad eq\ [2]$$

$$r_P = A_P(UV)^X\left(1 + rh_{eff}{}^X\right) \exp\left(-\frac{E_P}{k_B \times T_m}\right) \qquad eq[3]$$

where T_U represents the module maximum temperature, C_N is the cycling rate. θ denotes the effect of temperature difference on degradation, A_{Tm}, A_P are the pre-exponential constant. E_{Tm}, E_P is the activation energy for degradation. X is a model parameter that denotes the impact of UV radiation on degradation. rh_{eff} represents effective module relative humidity. We obtain the module temperature of crystalline silicon modules using PVWatts model [16]. We use meteorological data from the weather station in Alice Springs, Australia to validate and test our model. We use ERA5 reanalysis data and climate model data from the CMCC-CM2 projections [a CMIP6 (sixth Coupled Model Intercomparison Project) model] to analyse degradation rates globally.

The next step in this framework would be to model individual degradation modes. Modelling degradation modes has been challenging due to their non-linear interactions and difficulty in isolating their effect on power when modules are exposed to environmental conditions [5]. Traditionally, degradation is measured and modelled on the PV system level without modelling each mode [17–19]. Instead of modelling total degradation as the top-down total system DC output degradation, our framework proposes a novel approach to construct degradation as an aggregate of the component degradation and failure modes for a given system. We achieve this by mapping the effects of degradation and failure modes to their quantified change on inputs to the single-diode equation:

$$I = I_L - I_0\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \frac{V + IR_S}{R_{sh}} \qquad eq[4]$$

where I, I_L, I_0 are operating current, photocurrent and reverse saturation current. V denotes operating voltage; n is the diode ideality factor; q is the charge of an electron; k is the Boltzmann constant; T denotes the cell temperature; and R_s and R_{sh} are series resistance and shunt resistance, respectively.

For example, discoloration of the encapsulant material will reduce photocurrent, while corrosion of contacts will increase series resistance. In our implementation, which extends the PVLib simulation package [20] for increased flexibility and computational performance, the degraded system output at a given time-step is produced by solving the single-diode equation using the degraded inputs for all modules in the system. The resulting IV curves for all modules are subsequently processed using standard methods for current/voltage matching to estimate the maximum power point.

Results and Future Scope

Preliminary results show that during the historical period, degradation due to temperature and humidity stress is dominant for the regions with a tropical climate (~1.2-1.5%) (figure 2). As expected, the rates are relatively lower for regions with drier climates having relatively lower temperatures, like northern USA, Europe and southern Australia (up to 0.4%). The regions with high temperature and low relative humidity or vice-versa have low to moderate degradation rates. We will include subsequent analysis for other degradation mechanisms in the future.

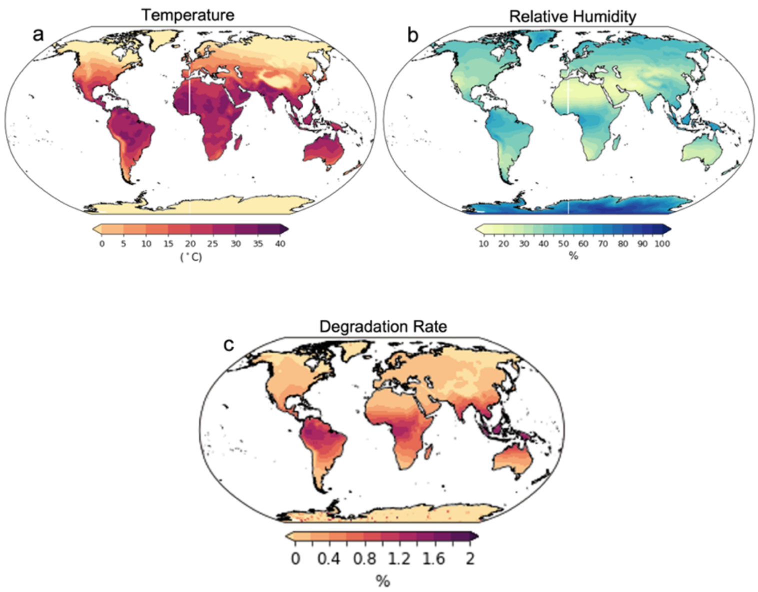

Figure 2. Temperature, relative humidity and degradation rate of crystalline-silicon due to humidity and temperature interaction on modules. The maps show historical mean (1985-2014).

A framework has been created to model degradation modes in unprecedented detail, allowing us to understand and predict the non-linear interaction of degradation modes in modules. The next step is to apply and validate this approach for specific effects, like EVA discoloration, light-induced degradation (LID) and corrosion. To achieve this, we will utilize both accelerated laboratory-based testing and publicly accessible datasets. The model will also be extended to perform string and plant-level simulations to capture the full impact on output. Furthermore, with this framework we will be able to model module mismatch due to differences in manufacturing batches, spatial effects, interactions, and feedback effects. This approach will be useful to model the nonlinear degradation effects that depend on current climate and operating conditions (figure 3). Figure 3 shows the non-linear degradation of the module over time due to its dependence on the weather as opposed to the traditional estimates. In the past, the degradation rates have been considered as linear as shown in the orange line.

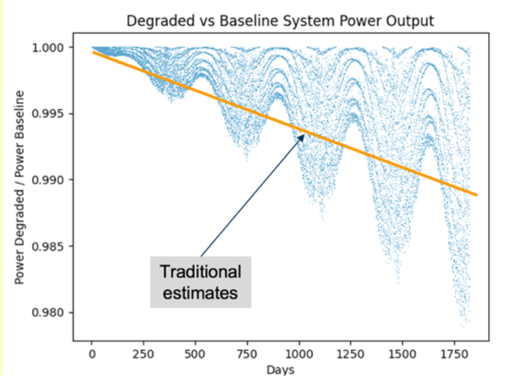

Figure 3. Model-produced ratio of degraded power output to non-degraded power output for a hypothetical system over a 5-year period using irradiance data. Traditional linear degradation estimates in orange.

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