Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science

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1 Abstract

A better understanding of the degradation modes and rates for photovoltaic PV modules is necessary to optimize and extend the lifetime of modules. Lifetime and degradation science (L&DS) is used to better understand degradation modes, mechanisms and rates of materials, components and systems in order to predict lifetime of PV modules. Statistical analysis was used to explore the relationship of various module performance and degradation pathways. A PV module lifetime and degradation science (PVM L&DS) model is an essential component to predict lifetime and mitigate degradation of PV modules. Previously published accelerated testing data from Underwriter Labs on PV modules with TPE backsheets which included eight modules were exposed to 4000 hours of damp heat (85% relative humidity at 85°C) and eight exposed to 4000 hours of ultraviolet light (80 W/m^2 of TUV at 60°C) . There were 15 different variables that related to experiments on system performance, degradation mechanisms, component metrics and time. Modules were analyzed for three system performance metrics (fill factor, peak power and wet installation). In addition, 11 unit experiments, six of which are directly related to degradation mechanisms and five of which are component performance experiments, were performed. The results from these experiments were statistically analyzed to identify variable transformations, statistically significant relationships and to develop a PVM L&DS model using structural equation modeling. The statistically signification relationships and significant model coefficients were then combined with domain analytics incorporating materials science, chemistry and physics expertise to produce a system of equations that model system performance based on unit degradation processes at the materials, component and system level. This exemplifies the development of a methodology to determine lifetime and degradation pathways present in modules and their effects on module performance over lifetime.

2 Introduction

Lifetime and degradation science (L&DS) can be used to help understand degradation modes, mechanisms and rates for PV materials, components and systems their overall contribution to power loss in PV modules. This understanding can help companies to mitigate degradation from the major contributor to power loss and not focus on modes that are related to small amounts of power loss [1] (Figure 1). Domain and statistical analytics are used to develop a PV module L&DS (PVM L&DS) model that can predict service lifetime and guide new technology insertion.

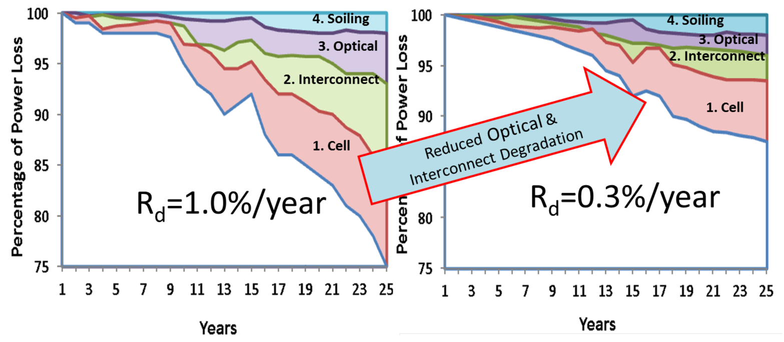

Figure 1: A simulated example of possible contributors to power loss in different modules.

3 UL Data

The data used for the statistically modeling was published by E. Wang et. al.. [2] Twenty commercially available polycrystalline 60-cell solar PV modules made with TPE backsheets were fabricated at the same time by DelSolar.[3] Eight PV modules were subjected to damp heat (DH) aging and eight modules were exposed to UV and two modules were not exposed and used as control samples.There were no explicit variations in the PV modules used by using the same PV modules under two exposures conditions for the statistical analysis. Damp heat exposure consisted of 85°C ambient temperature and 85% relative humidity and is described in the test 10.13 of IEC 61215 Ed.2..[4] The UV exposure was similar to test 10.10 of IEC 61215 Ed.2, [4] for UV preconditioning but with higher light intensity, approximately 80 W/m^2 UV irradiance plus an additional 15% of the total irradiance at the back of the PV modules. The module temperature was controlled at 60°C, but the relative humidity was uncontrolled.Fifteen experiments were measured on the harvested modules (Figure 3(a) and Figure 3(b)) and several measured variables were performed on each module (Figure 2).

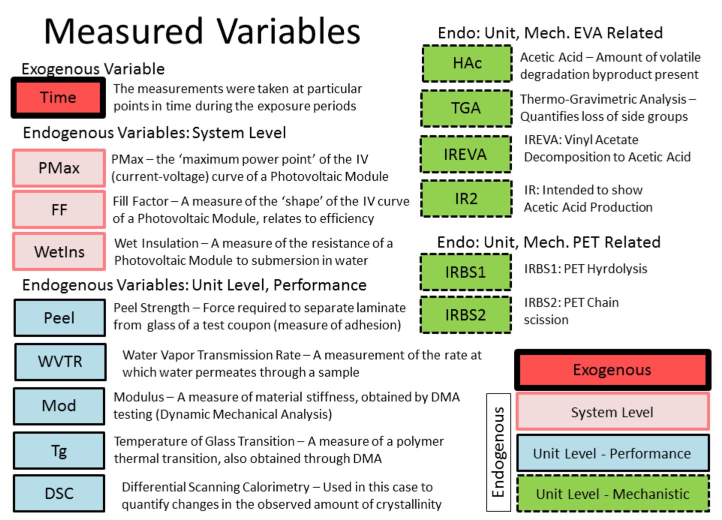

Figure 2: Measured variables used in the model development

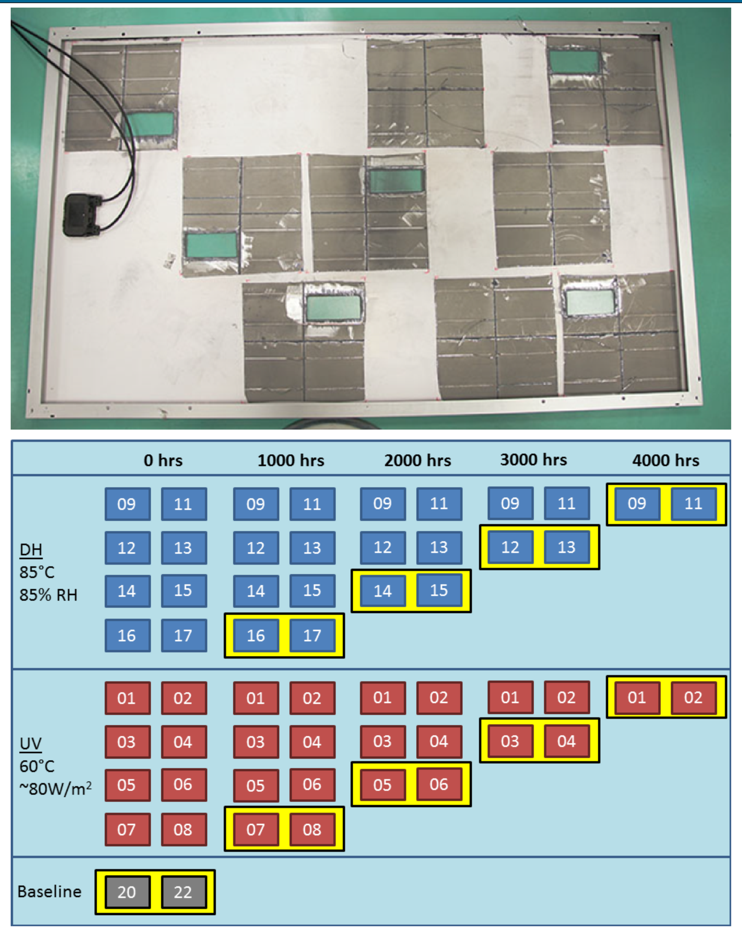

Figure 3: (a): Example of a harvested module (left) (b): Modules harvested at each time point for analysis and destructive testing (right)

4 PVM L&DS Model Development

The PVM L&DS model will be iteratively developed with both real-world and accelerated testing information. This model will be guided by domain knowledge from literature and statistics. Better informed study protocols can be elucidated from the statistics and improved domain knowledge will be available. The model development continually checks with domain knowledge to ensure the validity of the models from knowledge of chemistry and physics and will be guided by good statistics (Figure 4).

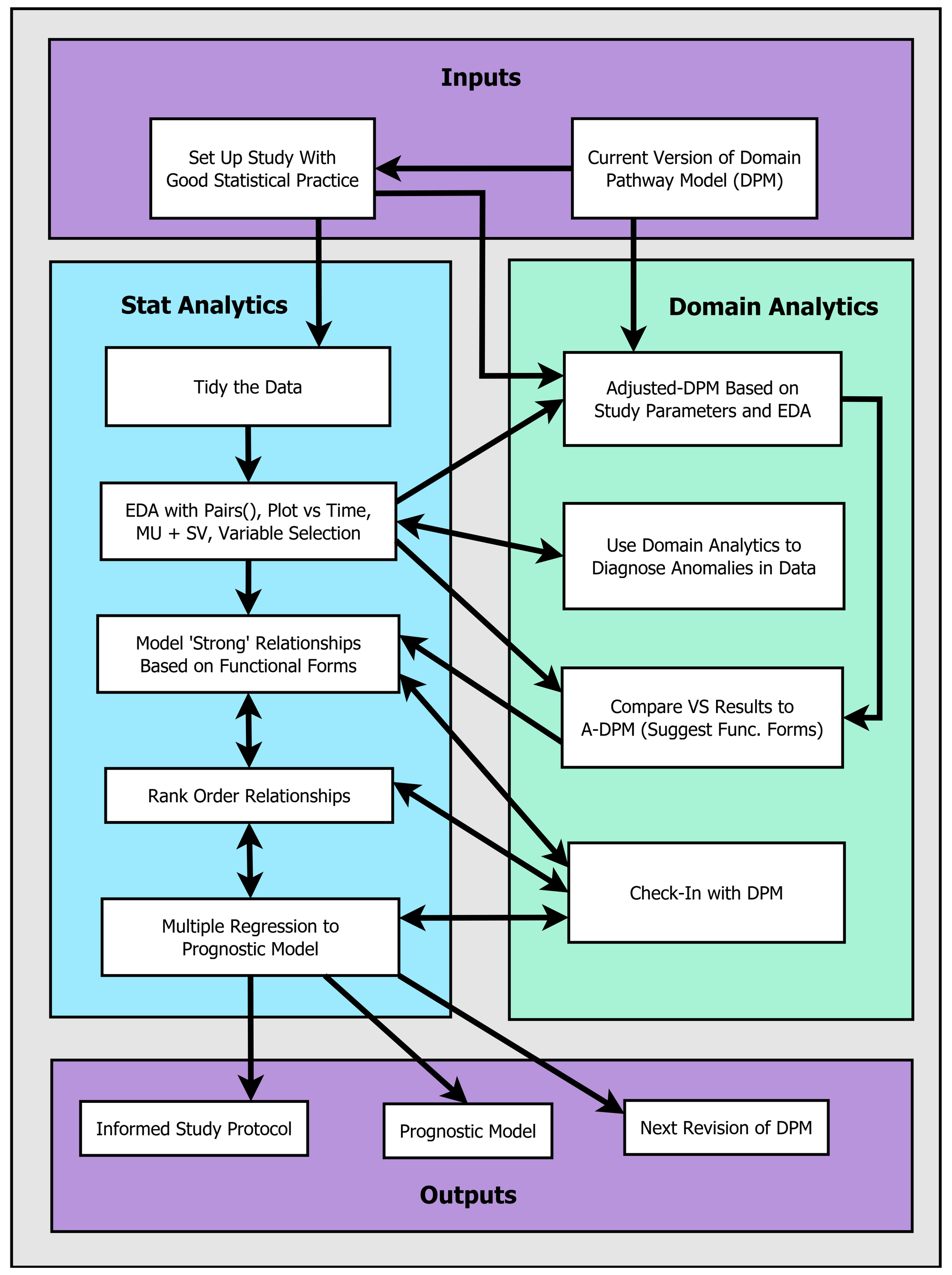

Figure 4: Iterative PVM L&DS model development

5 Domain Analytics

An initial domain pathway diagram was developed from literature that includes both real-world and accelerated testing insights [5, 6, 7, 8, 9, 10] (Figure 5(a)). Modes that were not analyzed in this study are considered latent variables appear as ovals in Figure 5(b). The final domain pathway model used to inform the statistical analysis is shown in Figure 5(c), which includes only measured variables from the UL study.

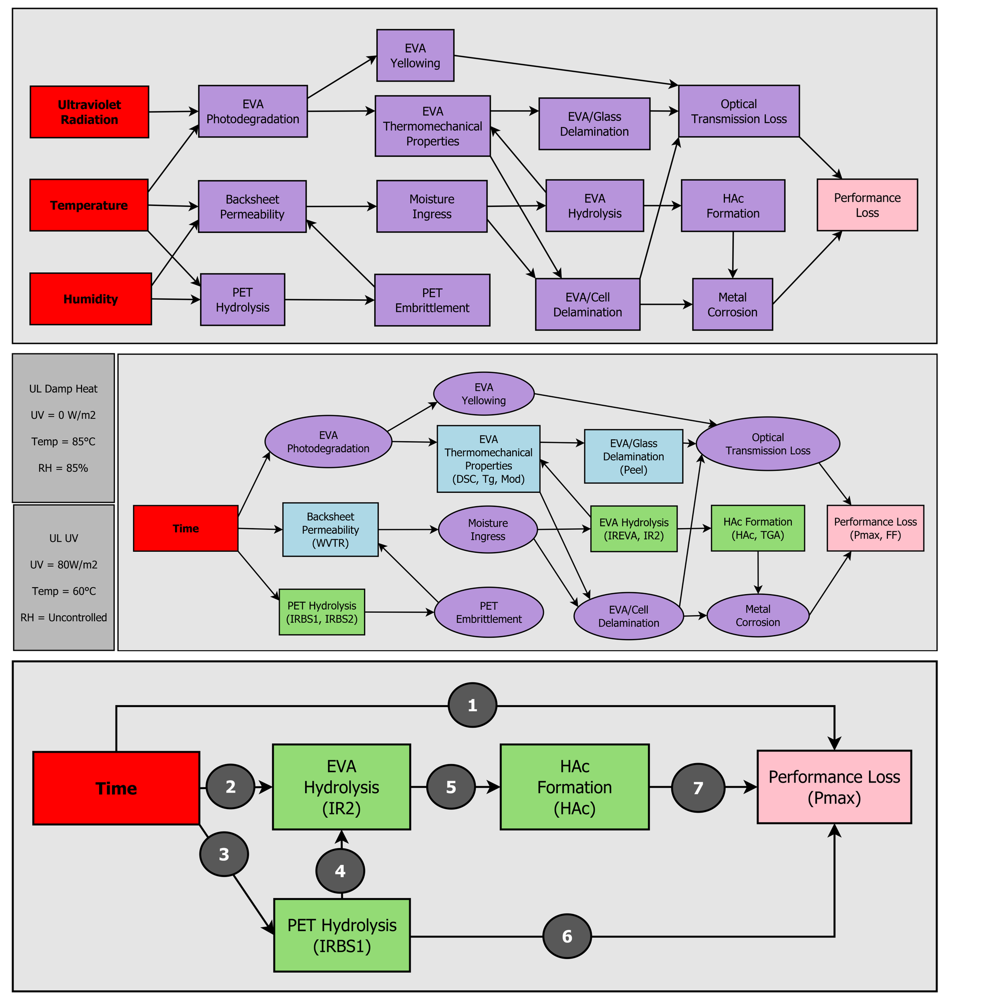

Figure 5: (a):Literature informed degradation pathway model (top) (b): Pathway model showing the latent (not measured) variables as ovals (middle) (c): Possible pathway model that includes the measured variables in this study (bottom)

6 Statistical Analytics

For a statistically valid model, only n-2 variables can be included in a model where n is the number of coincident observations; therefore, only 6 variables including time were used in the stepwise variable selection using the AIC statistic as the criterion value as statistical significant for variables to one another. In order to include more variables in the model, there needed to be more coincident samples by increasing sampling rate or exposure time. [11] Statistical analysis was performed with R and RStudio. [12]

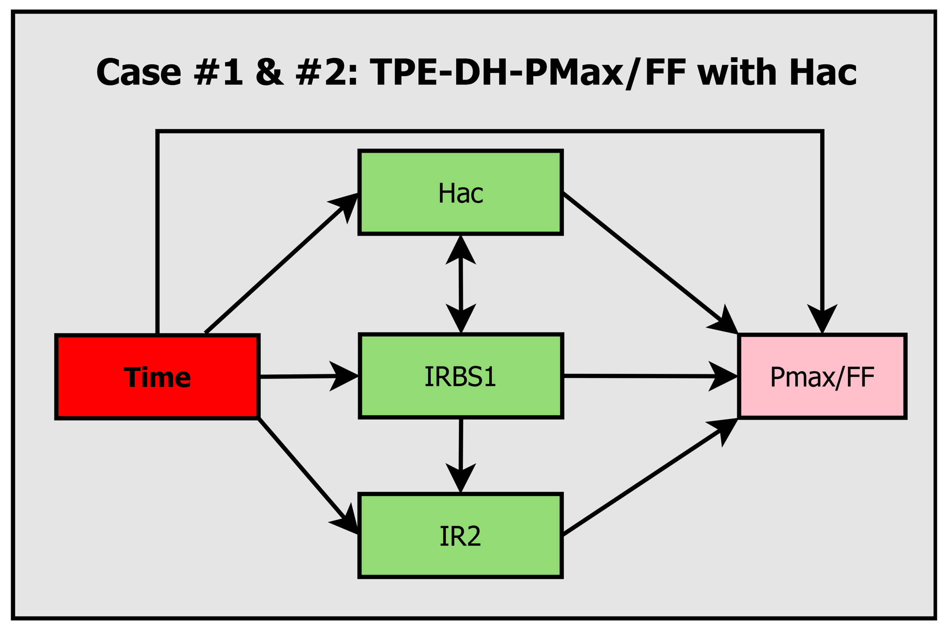

Figure 6: Statistical pathway diagram for the damp heat exposure modules for Pmax and FF system responses including the HAc variable.

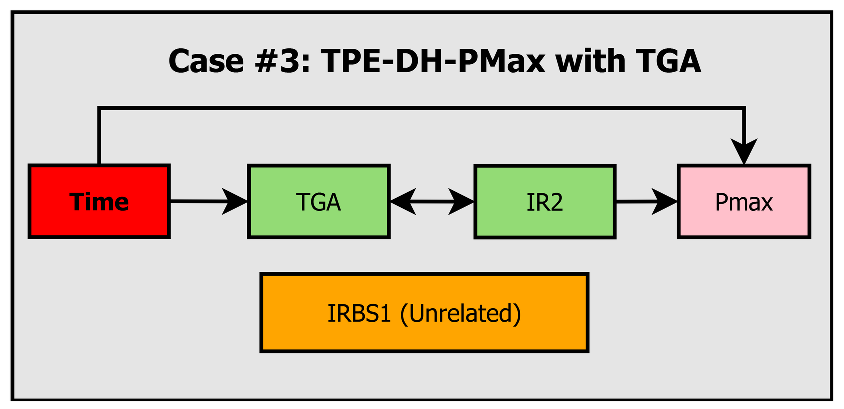

Figure 7: Statistical pathway diagram for the damp heat exposure modules for the Pmax system response including TGA

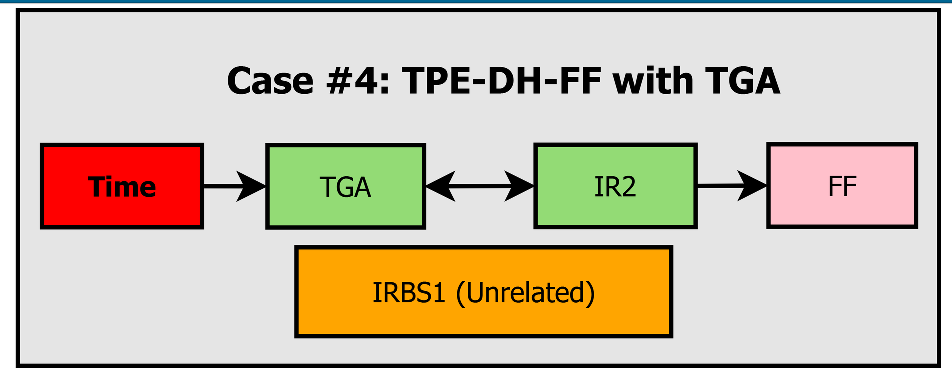

Figure 8: Statistical pathway diagram for the damp heat exposure modules for the FF system response including TGA

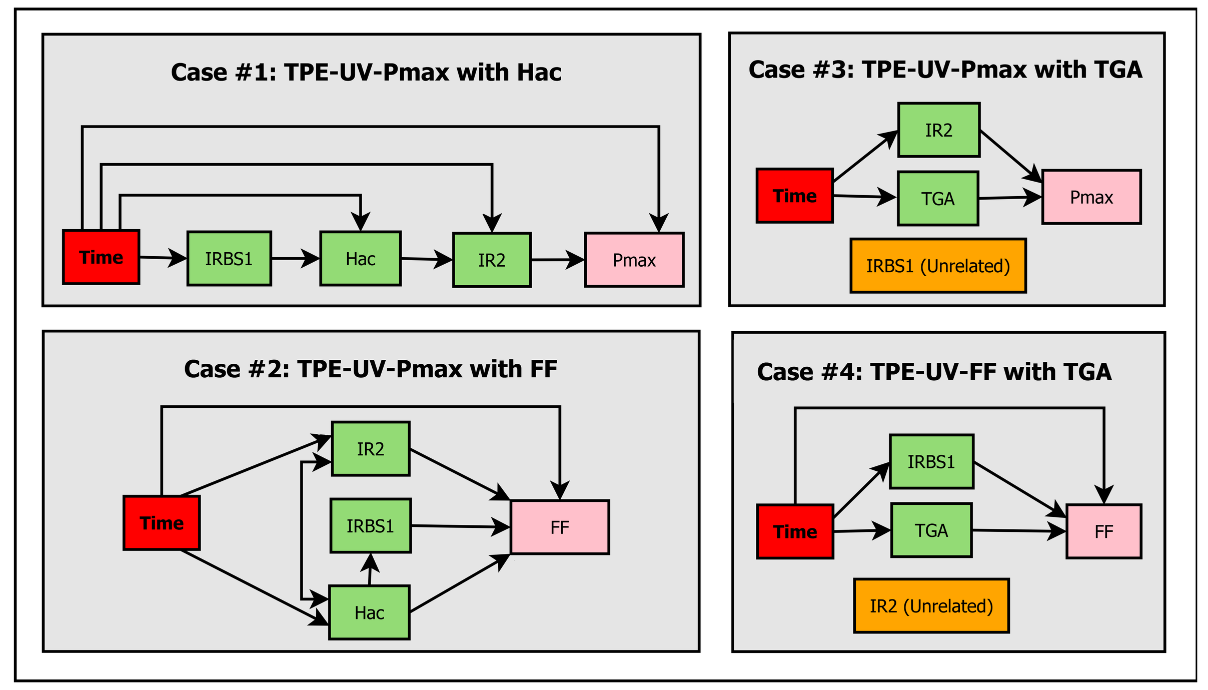

Figure 9: Statistical pathway diagram for the modified UV preconditioning exposures: for Pmax including the HAc variable (top left), for FF including the HAc variable (top right), for Pmax including the TGA variable (bottom left), for FF including the TGA variable (bottom right)

7 Conclusion

A PV module lifetime and degradation science modeling approach is being developed as an essential component to predict lifetime and mitigate degradation of PV modules. Through the combination of domain analytics and statistical analytics, a degradation pathway model can be developed that encompasses both domain knowledge of degradation modes and mechanisms and statistical measures of relationships and rates. The results from diverse experiments can be statistically analyzed to identify statistically significant relationships between the variables and develop and improve the PVM L&DS model of the system. The model is then further refined by combining these statistical insights with domain analytics incorporating materials science, chemistry and physics expertise to produce a system of equations that model system performance based on unit degradation processes at the material, component and system levels. This process exemplifies the development of a methodology to determine lifetime and degradation pathways present in modules and their effects on module performance over lifetime.

8 Acknowledgments

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