

CHALLENGES IN PREDICTING PV MODULE DEGRADATION FROM ACCELERATED AGING TESTS

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ABSTRACT: Predicting photovoltaic (PV) module degradation before market introduction is important for lifetime-yield assessment, product comparison, and the proposed EU Energy Label, yet long-term outdoor data are rarely available within current product-development cycles. This study examines whether accelerated-aging results can be converted into location-specific performance trajectories using MAPLE_TCM, an in-house developed open source modeling framework that parametrizes mechanism-specific literature models from accelerated aging test data, evaluates them with climate data, and combines their contributions over a 30-year service life. Simulations for representative module types show that degradation assumptions materially affect degradation and the resulting Energy Label category. The modeled trajectories are generally non-linear, and a worked example demonstrates that, in contrast to the designated Transitional Method by the EU, precision of measured post-test power loss can change the calculated energy-efficiency index significantly. The analysis exposes further fundamental limitations: sparse and uncertain input data, incomplete and technology-dependent model coverage, uncertain transferability of parameters, bill-of-materials dependence, unresolved interactions among degradation mechanisms, and the substantial effort required to maintain an extensive standardized model library. We therefore conclude that accelerated-test-based simulations are currently valuable for comparative assessment, design optimization, test interpretation, and climate-specific risk analysis, but are not sufficiently mature to serve as warranties, exact product-level predictions, or the sole basis of a mandatory label. Improving comparability of warranty conditions or simpler reliability categories linked to stricter accelerated-test criteria are introduced as more practical near-term alternatives.

Keywords: photovoltaic modules; degradation modeling; accelerated aging; reliability; EU Energy Label;

1 INTRODUCTION

Quantification of the reliability of photovoltaic (PV) modules is an important factor for the evaluation of bankability and economic viability. The determination and quantification of the expected degradation for a given module type before it enters the market is highly relevant for improved bankability and O&M planning. This topic has gained traction recently due to the planned introduction of an EU Energy Label for PV modules [1], [2], for whose calculation the PV module degradation would be a relevant factor.

There is currently no generally accepted method to quantitatively forecast the degradation of PV modules. Amongst the reasons are the high number and complexity of degradation processes, and the questionable validity of existing degradation models due to continuously changing solar cell and module technologies.

The currently designated “Transitional Method” [3] by the EU to determine the degradation rate is not able to differentiate between different module types, as it applies the same constant degradation rate to all products. The only designated allowed alternative for a more differentiated assessment is an elaborate outdoor exposure campaign over five years, at two locations per considered climate zone, and including different mounting situations. For this data, modeling approaches for determining the degradation rate exist, e.g. frameworks such as RdTools [4]. However, this approach is impractical, given the time requirement; Realistically, only a few months are available to determine the degradation for any given module product type, because of the short development cycle of PV modules.

This means that the analysis mainly has to rely on results from characterization and accelerated aging tests. An exciting and promising approach is present in NREL’s PVDeg degradation model collection [5]. However, to the best of our understanding, only LeTID models cover the

required scope from accelerated testing to performance loss. This gap resulted in research projects funded by the European commission [2], amongst others, which are currently ongoing.

This paper addresses the approach of is about simulating the degradation of PV modules from accelerated aging test results. The overall task can be described as modeling degradation observed in standardized accelerated tests and extrapolating it to the operating conditions of arbitrary outdoor locations. We present the modeling approach tool MAPLE_TCM [6], evaluate the suitability of the approach in the context of the proposed EU Energy Label and other applications, and discuss where it can generate genuine value and where limits are reached.

The EU Energy Label for PV modules is currently at the proposal/draft stage. Generally, its definition is based on the so-called “energy efficiency index”, defined as: “*the ratio of output of performance, service, goods or energy to input of energy*” [7]. This definition somewhat challenges its application for PV modules since, in contrast to most electrical consumer products, PV modules consume basically no energy during use. The current proposal by Polverini et al. [8], without considering any degradation, is therefore based on the energy *generated* per area EEI_m :

$$EEI_m = \frac{EY_m (kWh)}{A_m (m^2)} = \frac{CSER \cdot P_{STC} (W) \cdot H_p \left(\frac{kWh}{m^2} \right)}{1000 \left(\frac{W}{m^2} \right) \cdot A_m (m^2)} \quad (1)$$

With the expected lifetime energy yield EY_m per module area A_m . EY_m is thereby calculated based on a climate specific energy rating (CSER) as defined in IEC 61853 for the three relevant climate zones for Europe: Subtropical arid, Temperate coastal and Temperate continental; with the nominal module power P_{STC} and the total in-plane irradiance H_p .

The reference PV module installation for the CSER calculation is ground-mounted, fixed open-rack, South-facing, at 20° inclination for a duration of 30 years, all of which were used as input parameters for the simulation accordingly.

Due to the lack of another procedure, the currently designated "Transitional Method" to determine the degradation rate is not able to differentiate between different module types, as it applies a fixed degradation rate of 0.7 %/year to mono- or polycrystalline Si modules and 1.0 %/year for all other technologies, including silicon heterojunction and "innovative materials" [3]. The only designated possibility for a module manufacturer to use different values for the calculation is an elaborate outdoor exposure campaign. However, with requirements including over five years of data from two locations per considered climate zone and different mounting situations, this approach seems impractical, especially considering the rapid pace of technological advancement.

This gap motivates the investigation of whether degradation can instead be simulated from accelerated aging test results.

2 METHODS

2.1 Simulating PV Module Degradation from Accelerated Aging Tests

To incorporate module degradation into the above-mentioned approach for Energy Label calculation, we propose applying a degradation function $D(t)$ (preferably over a linear rate) to EEL_m at each time step t_i over the assumed module lifetime of 30 years:

$$EEL_{m,d} = EEL_m \frac{1}{t} \int_0^t D(t_i) dt$$

The degradation function thereby is converted so that the initial non-degraded value is $D(0) = 1$. In contrast, the visualizations of the calculations in this paper (Fig. 2 - Fig. 4) represent the degradation in values from 0 to -100 % as is more common in reporting of degradation testing.

Our recently developed PV module degradation framework [9] currently implements a library of mechanism-specific degradation models. In general, previously published degradation models can be used and combined in this approach if the following requirements are met:

- It must address specific, physically identifiable degradation mechanisms rather than a single lumped rate.
- The model input should consist of results from accelerated aging tests
- The model output must be a time series of the module performance (e.g. P_{MPP}) or a comparable property over time under a defined outdoor climate.
- Because input data consists only of a few datapoints per applied stress test, the models should not contain too many free parameters.
- Those parameters must be fittable from accelerated aging test results.
- Most existing modeling approaches do not fulfil these requirements without adaptation.

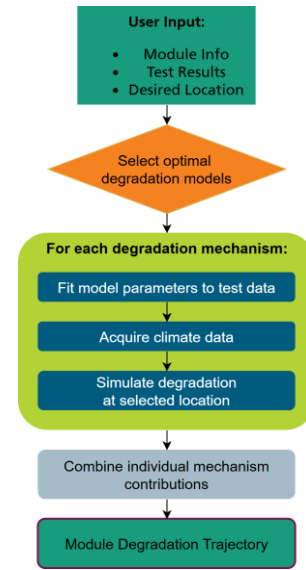


Fig. 1: Scheme of MAPLE_TCM working principle

2.2 Working Principle of MAPLE_TCM

The working principle of MAPLE_TCM is as follows (see **Fehler! Verweisquelle konnte nicht gefunden werden.**):

- The available test results and information on the particular model type (e.g. information from the module datasheet) are collected, currently in the form of an excel sheet. This step also allows a selection of particular degradation models, where multiple models for a certain degradation mechanism are available.
- The optimal degradation models are selected per degradation mechanism category, e.g. Moisture-induced corrosion, encapsulant discoloration, PID, UVID, LeTID, etc. based on user input, or, where the user has not selected specific models, based on the provided information, e.g. module technology.
- Each degradation mechanism, which is represented by a parametrized model from literature, is treated one by one in the following fashion:
 - The model parameters are fitted based on the user input, e.g. results of accelerated aging tests. In case the authors of the respective publication provide different parameter datasets for different module/cell technologies, these are applied accordingly. If insufficient test data is available, only some model parameters are fitted and the others are used as initially reported.
 - The climate data is being acquired from PVGIS [10] or open-meteo [11] (fallback, depending on the location) for the location of interest, as specified by the user.
 - The parameters are then used to simulate the degradation at the selected location.
- Finally, the individual mechanism contributions are combined to yield a module performance trajectory.
- In this publication, the following failure mechanisms are exemplarily combined: Moisture corrosion [12], encapsulant yellowing [13], UV-induced degradation (UVID), Potential-induced degradation (PID) [14], Light- and elevated temperature-induced degradation [5], [15].

2.3 Energy Label Calculation

The calculation of the energy label category (i.e. Letters A-G) was done for the temperate continental climate zone using values proportional to those proposed by Polverini et al. [8]. Since these previous suggestions need to be adjusted to account for degradation, a proportionality factor of 0.56 was chosen to result in a 'B' label for the highest scoring example and thereby allow some room for improvement for future technologies. The scaled thresholds used here serve exclusively as an illustrative scenario and must not be interpreted as a regulatory recommendation.

Tab. 1: Adjusted thresholds for the temperate continental climate. Values signify the minimum EEI a module must reach to obtain the respective label category.

Label	A	B	C	D	E	F	G
EEI	185	163	141	119	102	85	0

For the calculation, modules with 600 or 550 W, denoted as TOPCon and PERC, respectively and the same area of 2.6 m², and a third dataset with 280 W on 1.63 m², named Al-BSF were used. Identical values for CSER = 0.98 were used for all modules were used in order to not obscure the effect of degradation on the energy label calculation.

3 RESULTS AND DISCUSSION

3.1 Comparing Linear Degradation Rates

To estimate the general effect of the degradation rate on an Energy Label, the different degradation rates provided by the Transitional Method, namely annual rates of -0.7 % and -1 % were compared with a currently common warranty (-1 % in the first year, followed by -0.4 % annually). The different linear degradation trajectories (Fig. 2) were applied to the calculation as detailed in the Method Section. As can be seen, already small changes in module degradation can significantly affect the energy yield and Energy Label category. Assuming the same degradation behavior for all modules of a certain technology or generation therefore seems like a too strong oversimplification.

Tab. 2: EEI kWh/m² calculated for different module types with different assumed annual degradation rates. The colors correspond to the resulting Energy Label according to the thresholds in Tab. 1.

EEI (kWh/m ²) Module Type	Annual Degradation / %			
	None	1/0.4	0.7	1.0
TOPCon	180	168	160	152
PERC	165	154	147	139
Al-BSF	133	124	119	112

3.2 Simulating PV Module Degradation from Accelerated Aging Tests: example case

The degradation of a specific module type was simulated based on results of accelerated aging tests using MAPLE_TCM with the input parameters (i.e. test results) listed in Tab. 3.

The individual degradation curves in Fig. 3 represent the applied degradation models. Notably, their

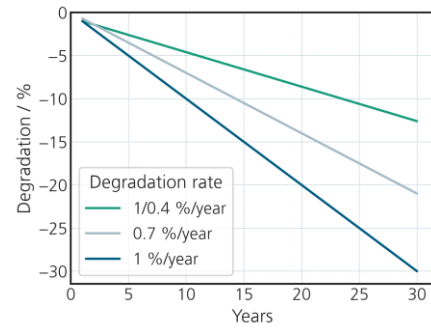


Fig. 2: Linear degradation rates according to a current warranty example and the Transitional Method

development is typically non-linear, with a wide variety of shapes being observed. As will be discussed in more detail below, each of the individual degradation models used required various simplifications and assumptions, which is why they could be contested. The overall degradation is calculated as the product of the relative performance trajectories of the individual mechanisms.

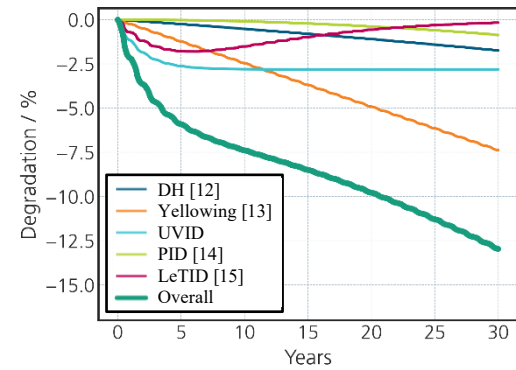


Fig. 3: Simulated degradation using MAPLE_TCM based on the testing results from Example 1 (Tab. 3)

Tab. 3: Synthetic dataset as input parameters for degradation simulation. All values of Example 2 show 0.5 % stronger power loss, which could happen in a testing scenario due to measurement uncertainties, even if the module degradation of examples 1 and 2 are identical.

		Example 1		Example 2	
Damp Heat	DH / h	P_{MPP} / %	I_{SC} / %	P_{MPP} / %	I_{SC} / %
	1000	-1.8	-0.2	-2.3	-0.7
	2000	-2	-0.7	-2.5	-1.2
	3000	-2.5	-1.2	-3	-1.7
UV	UV Dose	P_{MPP} / %	I_{SC} / %	P_{MPP} / %	I_{SC} / %
	60 kWh/m ²	-1.5	-0.5	-2	-1
	120 kWh/m ²	-2.2	-0.7	-2.7	-1.2
PID	PID / h	P_{MPP} / %		P_{MPP} / %	
	96	-4		-4.5	
	192	-9		-9.5	
LeTID	LeTID / h	P_{MPP} / %		P_{MPP} / %	
	162	-0.75		-1.25	
	324	-1.2		-1.7	
	648	-1.45		-1.95	
Energy Label		164 A		154 B	

3.3 Limitations

The following issues and limitations have to be considered when using the modeling approach discussed in this publication.

3.3.1 Input Uncertainty

To illustrate the model's sensitivity to measurement precision, all power losses from Example 1 were shifted by -0.5 percentage points in Example 2. This is not a probabilistic uncertainty analysis, but a scenario within a plausible range of deviation caused by measurement imprecision, assuming the actual degradation of the PV module is identical in both Examples 1 and 2 (**Tab. 3**).

Comparing the respective simulations (**Fig. 4**) with Example 1 (**Fig. 3**), the differences are only small for some mechanisms, e.g. PID, the trajectory of the LeTID failure mode is significantly altered, as it shows almost no recovery in this example. The 30-year performance loss changes from 13.0 % to 15.8 %, and the EEI changes from 168 to 143 kWh/m², corresponding to two Energy Label classes from A to C.

This underlines the general sentiment that the extrapolation from roughly half a year of testing to 30 years of operation, based on 1–2 modules per test, with a measurement precision of around 0.5 % is an ambitious endeavor.

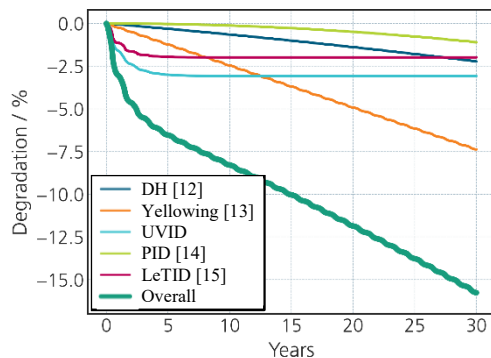


Fig. 4: Simulated degradation using MAPLE_TCM based on testing results from Example 2 (**Tab. 3**), i.e. with 0.5 % stronger degradation compared with Example 1 (**Fig. 3**)

3.3.2 Limited model availability.

Out of the large variety of degradation mechanisms, that can in principle be relevant for PV modules [16], only a few of them can reasonably be described by degradation models that meet the requirements listed above. For example, many degradation models have output parameters describing a changing material property (e.g. defect density, mechanical properties, encapsulant crosslinking, leakage current) instead of the module performance.

Further Reasons for an absent model for a given mechanisms could be its recent discovery, i.e. incomplete understanding of the exact underlying mechanism, while development is still ongoing.

Notably, mechanisms driven by the interaction of several stressors – most prominently UV combined with humidity and temperature for polymer degradation and discoloration – are hard to test in a standardized way, which might be the reason why the corresponding degradation modes, like encapsulant discoloration or backsheet embrittlement, are often underrepresented in model libraries.

For complex mechanistic interactions, how the individual mechanism contributions should be combined is unresolved. A multiplication of the relative performance trajectories per mechanism, as used here, implicitly assumes their independence. In reality, however, mechanisms often interact and compete. For example, moisture ingress can cause discoloration, which in turn reduces the irradiance that drives UVID. In this example, temperature additionally affects both discoloration and UVID independently. This issue is on a fundamental level, because even the physical principles of mechanism interaction are often not completely understood.

Regardless of the reasons, any framework that omits mechanisms is systematically optimistic, and it favors module designs that fail by the omitted or unknown mechanisms.

3.3.3 Selection bias in model development.

Those models that actually exist for certain degradation mechanisms are, by necessity, developed on module types that clearly exhibit the mechanism in question. In reality, this often leads to the use of historic or deliberately poor module designs. Parameters derived from such datasets are not necessarily transferable to modern modules. Because of the necessity to use default parameters when fitting the degradation from a small dataset of reliability testing, the strong degradation can be transferred to the DUT and therefore lead to stronger simulated degradation.

3.3.4 No fair comparison across technologies.

Following from the two previous points, the set of available models is not equally complete for all technologies. A technology whose dominant degradation mode has a well-parametrized model has a good chance to appear worse than a technology whose dominant mode is not modelled at all. In a label context, this creates an incentive structure that rewards being unmodelled rather than being reliable. This issue is aggravated by the pace of technological change, because, in fact, most published models predate current mainstream, i.e. TOPCon, HJT, back-contact and bifacial glass-glass designs.

3.3.5 Bill of materials dependence.

A PV module's degradation behavior is determined to a large extent by its BOM. Since a commercial module type typically covers a range of approved BOMs, and since certification requires retesting for BOM changes [17], a simulation is strictly valid only for the exact BOM that was tested. We can also assume that different BOMs cause variations strong enough to result in different Energy Label classifications, at least in some cases. It would therefore have to be clarified how a label can be applied to a certain module type, which in reality consists of a whole family of BOMs with a large variety of label classes.

3.3.6 Complexity in a standardization context

Independently of its final form, the herein discussed modeling approach requires a decision for every single degradation mode, for example:

- Which degradation mechanism shall be considered based on the test results?
- Which model per mechanism?
- Which parameters for which technology?
- Which modifications to make published models parametrizable from accelerated tests?
- Which temperature model to use/which climate

dataset?

Each of these decisions has to be maintained and updated as technologies evolve. As with other, already existing norms, this would require a permanent effort, including input from testing houses, module manufacturers, EPCs and end users, and standardization is inherently slow relative to the product development cycles that it is supposed to represent.

Considering the timelines of major degradation modes' (like for example PID, LeTID, UVID) past discoveries, to test and model development, there is a realistic risk that a standardized method would never reach the maturity to mirror the most critical degradation modes of the current mainstream technology.

3.4 Sensible Use Cases for Simulation

The limitations above do not invalidate the modeling approach in general; they merely define where it needs further enhancement for a policy instrument, and where it can be applied currently. It is essential to be explicit about what the simulated trajectory is *not*: it is not an exact prediction of the behavior of an individual module or plant, and it is not a warranty. What it does provide is a physically motivated, quantitative, and reproducible conversion of accelerated test results into energy-relevant units. Thereby it is a large increase in informative value compared to a simple pass/fail statement against a 5 % threshold, which is based on approximately the same data. We see the following applications as well supported:

- **Comparative assessment rather than absolute prediction.** Comparing two module types or two BOMs under identical assumptions cancels much of the systematic model bias mentioned above. Ranking and relative differences are more robust than absolute end-of-life values.
- **Informing design and material decisions.** For module developers, the framework can help quantifying the consequences and sensibility of a material choice: a PID-resistant encapsulant, a UV-blocking encapsulant or front glass, or the trade-off between a slightly lower initial cell efficiency and a lower susceptibility to UVID.
- **Interpretation of reliability test results.** For EPCs and investors, the model approach can transform the results of stress tests into an estimated yield impact for the actual project location/climate, instead of being compared to a generic pass/fail criterion. This might help in concrete decisions, for example when ranking modules that are affected by different failure modes.
- **Climate sensitivity of degradation.** Because the same parametrized module is evaluated against site-specific climate data, the framework estimates which mechanism dominates at which site, and can support decisions on where a given product should or should not be deployed; E.g. corrosion-driven risks in coastal/tropical climates vs. UV-driven risks in high-irradiance arid climates.

3.5 Alternative Approaches

Considering that the fully model-based route is not yet mature for determining an Energy Label, two alternative options present itself, both of which would improve on the situation of the current Transitional Method, i.e. a fixed degradation of 0.7 %/a.

3.5.1 Warranty-based degradation rates

PV modules are unusual among electrical products in that manufacturers publish an explicit performance

warranty, typically as a maximum degradation per year after the first year. Using these values would be simple, would require no additional testing, and would tie the declared rate to a financial commitment.

The practical obstacles are, however, substantial: Warranty rates are currently very similar across manufacturers and reflect historic industry expectations rather than the actual technological specifics of certain module types; and are therefore weakly differentiating.

Experience with actual field failures shows that the conditions attached to the warranty – measurement procedure, uncertainty allowance, exclusions, proof obligations and a large variety in remedies (repair, replacement or reimbursement) are often more important to determine whether a claim should or can be enforced. A viable variant would therefore require a way to harmonize the different warranty conditions, making warranties comparable across manufacturers and projects.

Whether this is achievable within the Energy Label framework is an open question, but it would create value independently of the label.

3.5.2 Reliability categories

A more pragmatic compromise would be to keep the current linear degradation values as a default baseline, but to define alternative reliability classes with associated degradation rates for the label calculation. A better rating than the default would be awarded if the module type passes stricter accelerated aging criteria – for example extended test durations or tighter power-loss limits – or if it uses materials/designs with established beneficial properties.

This approach preserves the differentiation between module types and the incentive to invest in reliability, while explicitly not claiming to predict the exact outdoor degradation of an individual product. It would be less complicated to standardize and update rules for this approach than a complete reliability model library. However, this approach is also significantly more arbitrary in nature.

4 SUMMARY AND CONCLUSION

The determination of degradation of specific PV module products is a prerequisite for the introduction of an EU Energy Label for PV modules for which no method currently exists. We have examined whether this gap can be closed by simulating degradation from accelerated aging test results, using the MAPLE_TCM framework, which combines mechanism-specific literature models parametrized from test data and evaluated against site-specific climate data.

The approach is technically feasible and produces results that are more informative than a single rate or a simple pass/fail criterion: the simulated trajectories are markedly non-linear, and the spread between module constructions exceeds the difference between the default values of the Transitional Method.

At the same time, our analysis shows significant limitations of this approach when used for a policy instrument as the EU Energy Label: A high influence of measurement precision; missing models for relevant mechanisms, selection bias from models developed on poorly performing legacy modules; the unresolved question of how mechanism contributions should be combined; BOM-level validity; and a standardization

effort that would have to be maintained continuously against a rapidly moving technology base. We therefore consider the use of these simulations as a warranty basis, as a guaranteed performance prediction for an individual product, or as the quantitative input to a mandatory label, to be premature at the current state of model availability and validation.

For an Energy Label, harmonized warranty conditions or a small number of reliability categories tied to stricter accelerated test criteria appear to be more robust intermediate steps.

We therefore conclude that model-based degradation prediction should currently be used for comparative and diagnostic purposes, where it can serve as a helpful tool increasing the informative value of accelerated aging tests. Sensible applications span from comparing designs, materials, BOMs, test results and locations, and accordingly prioritizing module/material selection as well as application location.

An important consideration for a policy instrument: as soon as a modelled number carries financial value, there is an incentive to optimize for the model rather than for field reliability. This could, for example, bear the risk of optimizing modules against older, well known degradation mechanisms rather than the currently most critical ones, if the latter are not covered by the standardized model library.

On the other hand, one could argue that this general issue, in part, also applies for other benchmarks, e.g. the CSER (forming the basis for the Energy Label) and performance measurements at standard conditions, with the argument for the latter case being that standard conditions are very rarely met under realistic outdoor conditions. Nevertheless, the industry relies heavily on these established performance metrics, as it brings clear benefits for all stakeholders. Optimizing for a non-perfect benchmark might be preferable to not optimizing at all.

In conclusion, the modeling approach is well worth developing further: it extracts substantially more value from test results that are (in large part) performed already during module certification. For future development of MAPLE_TCM, the inclusion of further degradation modes and alternative models for the existing modes are planned. Additionally, future publications on regulations for the evaluation of PV modules will be considered and incorporated into the framework. The source code of the framework will be released under a BSD license [6].

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REFERENCES

- [1] N. Dodd, Espinosa, Martinez Maria De Las Nieves, P. van Tichelen, K. Peeters, and A. Soares, "Preparatory study for solar photovoltaic modules, inverters and systems," JRC and VITO, 2020, doi: 10.2760/852637. [Online]. Available: <https://publications.jrc.ec.europa.eu/repository/handle/JRC122431>
- [2] European Climate, Infrastructure and Environment Executive Agency (CINEA). "Development of standardisation methods for eco-design and energy labelling of photovoltaic products (Ecoston PV)." (n.d.). Accessed: Jan. 29, 2026. [Online]. Available: <https://ecodesign-pv-testing.eu/the-study/>
- [3] E. Dunlop, A. Gracia Amillo, E. Salis, T. Sample, and N. Taylor, "Transitional methods for PV modules, inverters and systems in an Ecodesign Framework," *1831-9424*, 2019, doi: 10.2760/496002. [Online]. Available: <https://publications.jrc.ec.europa.eu/repository/handle/JRC114099>
- [4] M. G. Deceglie *et al.*, *RdTools*. National Laboratory of the Rockies (NLR). [Online]. Available: <https://github.com/NatLabRockies/rdtools>
- [5] M. Kempe, S. Ovaitt, M. Springer, Jordan, Ford, Tobin, and J. Karas, "The "PVLib" of Degradation: PVDeg," [Online]. Available: <https://github.com/NREL/pvdegradationtools>
- [6] P. Gebhardt, *maple_tcm* (2026). Fraunhofer Institute for Solar Energy Systems ISE. [Online]. Available: https://gitlab.cc-asp.fraunhofer.de/maple/maple_tcm
- [7] European Parliament and of the Council, *Regulation (EU) 2017/1369 setting a framework for energy labelling and repealing Directive 2010/30/EU* (2017), (n.d.). Accessed: Aug. 17, 2026. [Online]. Available: <http://data.europa.eu/eli/reg/2017/1369/oj>
- [8] D. Polverini, A. G. Amillo, N. Taylor, T. Sample, E. Salis, and E. D. Dunlop, "Building Criteria for Energy Labeling of Photovoltaic Modules and Small Systems," *Solar RRL*, vol. 6, no. 5, 2022, Art. no. 2100518, doi: 10.1002/solr.202100518. [Online]. Available: <https://onlinelibrary.wiley.com/doi/10.1002/solr.202100518>
- [9] S. Ravindrababu, I. Hädrich, U. W. Paetzold, and P. Gebhardt, "Development of a modular approach for photovoltaic module lifetime and reliability estimation," *Energy Reports*, vol. 15, p. 109323, 2026, doi: 10.1016/j.egy.2026.109323. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352484726002921>
- [10] *Photovoltaic Geographical Information System (PVGIS)*. European Commission. Accessed: Aug. 1, 2026. [Online]. Available: <https://photovoltaic-geographic-information-system.ec.europa.eu/en>
- [11] P. Zippenfenig, *Open-Meteo Weather API* (2023). Accessed: Aug. 1, 2026. [Online]. Available: <https://open-meteo.com/>
- [12] J. Duan *et al.*, "Lifetime Prediction of TOPCon Modules Based on Accelerated Damp Heat Life Tests," *IEEE Journal of Photovoltaics*, vol. 16, no. 2, pp. 232–241, 2026, doi: 10.1109/JPHOTOV.2025.3645277.
- [13] A. Sinha, S. Pore, A. Balasubramanian, and G. Tamizhmani, "Acceleration Factor Modeling for Degradation Rate Prediction of Photovoltaic Encapsulant Discoloration," in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, Waikoloa Village, HI, 2018, pp. 1342–1346, doi: 10.1109/PVSC.2018.8547944.

- [14] P. Hacke *et al.*, "Accelerated Testing and Modeling of Potential-Induced Degradation as a Function of Temperature and Relative Humidity," *IEEE Journal of Photovoltaics*, vol. 5, no. 6, pp. 1549–1553, 2015, doi: 10.1109/JPHOTOV.2015.2466463.
- [15] I. L. Repins *et al.*, "Long-term impact of light- and elevated temperature-induced degradation on photovoltaic arrays," *MRS Bulletin*, pp. 1–13, 2022, doi: 10.1557/s43577-022-00438-8. [Online]. Available: <https://link.springer.com/article/10.1557/s43577-022-00438-8#article-info>
- [16] M. Köntges *et al.*, "Degradation and Failure Modes in New Photovoltaic Cell and Module Technologies," IEA International Energy Agency, Rep. Report IEA-PVPS T13-30:2025, 2025, doi: 10.69766/ATBD2730. [Online]. Available: <https://iea-pvps.org/key-topics/degradation-failure-modes-new-cell-module-technologies/>
- [17] *IEC TS 62915:2018 - PV Modules - Type approval, design and safety qualification - Retesting*, International Electrotechnical Commission (IEC).