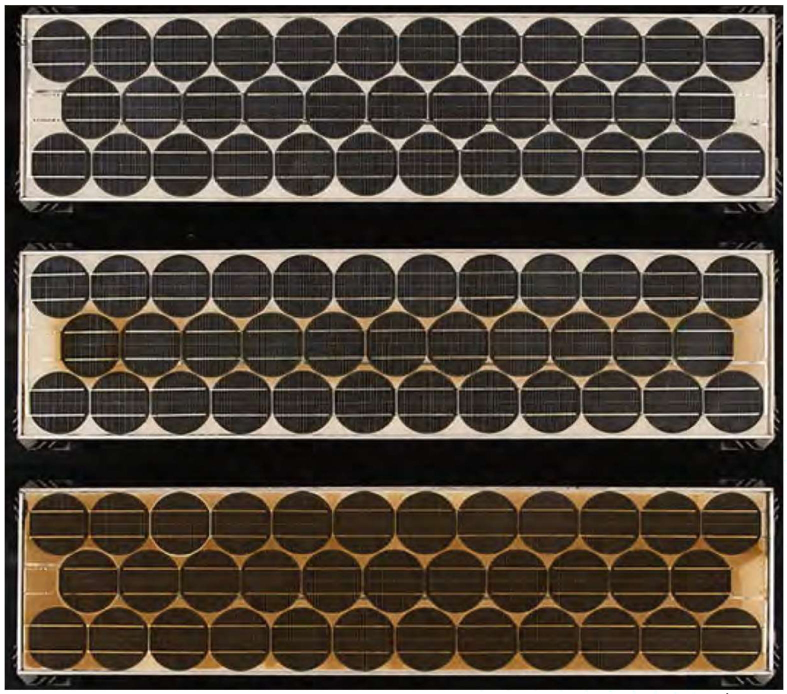
DNV's method for the assessment of PV module useful life



Example of modules fielded for 35 years*

The *useful life* of a PV module cannot be directly measured or predicted like efficiency, temperature coefficient, or energy yield. However, financial models rely on modules with long, durable useful lives to determine crucial elements such as returns on investment, levelized cost of energy, and the general investment thesis. Early module failures lead to lost investments and confidence, impacting future PV industry investments and the viability of the energy transition. DNV has created a methodology to classify the useful life of modules by evaluating their design (bill of materials and accelerated testing) as well as manufacturing quality (factory audits, production monitoring, and pre-shipment inspections).

Issue	Date	Prepared by	Contributors	Reviewed by	Approved by
A	20 December 2024	Henry Hieslmair	Parth Bhatt April Jeffries	Pranav Patel Cesar Hidalgo	MinWah Leung

* Annigoni, Eleonora, et al. "35 years of photovoltaics: Analysis of the TISO‐10‐kW solar plant, lessons learnt in safety and performance—Part 2." Progress in Photovoltaics: Research and Applications 27.9 (2019): 760-778.

Table of Contents

List of Abbreviations

Abbreviation	Meaning	Abbreviation	Meaning
AQL	acceptable quality level	ML	mechanical load test
BDS	backsheet durability sequence	MSS	mechanical load stress sequence
BOM	bill of materials	O&M	operations and maintenance
DH	damp heat test	PERC	passivated emitter and rear contact
DML	dynamic mechanical load test	PID	potential-induced degradation
EL	electroluminescence	Pmax	maximum power
EPC	engineering, procurement, and construction	POE	polyolefin
EROI	energy returned on energy invested	PV	photovoltaic
EVA	ethylene vinyl acetate	QA	quality assurance
HALT	highly accelerated lifetime testing	QCP	quality control plan
HF	humidity freeze test	QMS	quality management system
IEC	International Electrotechnical Commission	ROI	return on investment
IQC	incoming quality control	SML	static mechanical load test
IR	Infra-red	TC	thermal cycle test
Isc	short-circuit current	TOPCon	tunneling oxide passivated contact
LCOE	levelized cost of electricity	UVID	ultra-violet induced degradation
LeTID	light & elevated temperature-induced degradation	Voc	open-circuit voltage
LID	light-induced degradation	W	watt(s)
MES	manufacturing execution system	Wp	Peak watts

1 INTRODUCTION

The financial model for a PV project simulates revenues and expenses over the entire course of a project's expected life. It is the financial model that is the basis for financing and calculating the expected return on investment. The assumed project life in the financial models has been trending upwards. In the mid-2010s, the useful life assumptions were 20 to 25 years. More recently, financial models commonly assume 35 years and 16% of assumptions at 40 years, as shown in Figure 1-1.

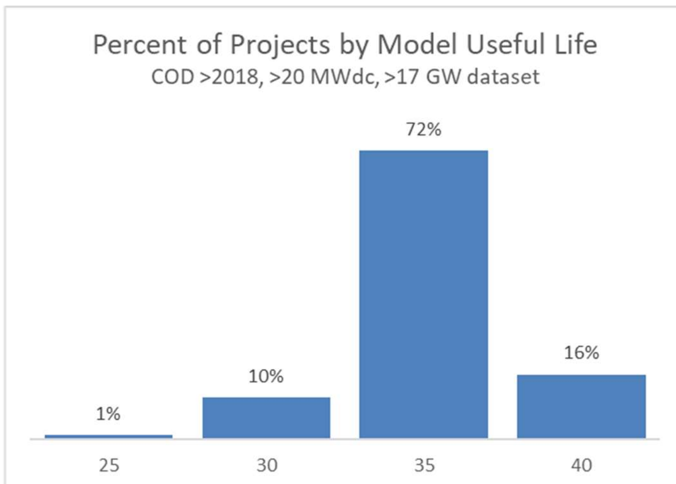


Figure 1-1 Histogram of useful life in DNV reviewed utility scale solar projects in the U.S.

The consequence of short-lived modules can be dire for a project and such consequences are not reflected in financial models that determined the investment thesis for the project. When PV modules fail at higher rates than the financial model anticipates, stakeholders will lose money regardless of the warranty situation. If a significant number of stakeholders in the photovoltaic (PV) industry incur financial losses, investment activity will decelerate, and the cost of capital will rise.

Unfortunately, there is no straightforward test to verify that PV modules will endure throughout a project's lifespan. Procurement teams are typically provided with information on price, warranty, and less tangible factors such as reputation, experience, tier, bankability, and scorecards. The lack of a direct method to assess module durability weakens the market, as manufacturers are unable to sufficiently command higher prices for high durability materials and manufacturing processes that offer greater longevity.

Although modules now have 25- or 30-year warranties, the warranty durations are commercially driven and not based on a technical assessment. The reality is that manufacturing PV modules at large scales that can last in the environment for multiple decades is challenging and may be compromised by short-term price pressures that encourage circumvention of manufacturing quality constraints. Furthermore, project owners and financial models cannot depend on the module manufacturer's warranty to fully mitigate financial costs of early module failures, as will be discussed subsequently.

In the following sections, we review financial models and how early module failures undermine the investment thesis, and in this context then explain how DNV assesses module useful life.

2 FINANCIAL MODELS AND MODULE REPLACEMENT

A solar project is developed and financed based on a financial model predicting revenues and expenses, like O&M (operations and maintenance) costs, over the project's assumed useful life. The financial models provide guidance on the expected return on investment (ROI), levelized cost of electricity (LCOE), and the investment thesis. For expenses, O&M modeling typically does not consider needing to replace any portion of the PV modules before the end of the project beyond the spare modules on hand; spare quantities typically range from 0.05% to 0.5% of the total number of modules in the project.

2.1 Premature module failure is not included in the financial model

O&M budgets usually include some allocation for inverter refurbishment at around 10 to 15 years, which is considered "routine corrective maintenance." However, replacing early failing PV modules is considered "non-routine corrective maintenance". The portion of the O&M budget that is allocated to modules typically covers module cleaning (routine), inspection (routine), and a few module replacements from spares for the occasional module failure from thrown rock or other causes (routine corrective). A general overview of O&M activities is shown in Table 2-1; listed scope is not fulsome, but rather examples of types of scopes by category to illustrate what typically is or is not considered in financial modeling. [1]

Financial models often base their projected future O&M costs on present O&M contract prices. However, today's O&M contracts are often for periods less than eight years, and since the U.S. (and global) PV fleet is relatively young, very low rates of module failure are expected in this time frame. Thus, by extrapolating present O&M costs, the financial models may be significantly underestimating the long-term module replacement costs. To better develop financial models with more accurate longer-term (20 to 40 year) module replacement cost estimates, the useful life of modules and associated re-engineering costs of replacements beyond spare quantities must be better understood and reflected in O&M budgets.

Table 2-1 High-level overview of example O&M activities by category

Category	Example activities
Routine or Preventative Maintenance	Overall system inspection - annual or semi-annual
	Electrical equipment checks and tests
	Thermal inspections, on ground and/or aerial
	Vegetation management
	Module cleaning
	Tracker visual inspection
	Incident detection
	Performance monitoring
	Asset management
Routine corrective	Planned inverter maintenance
	Tracker controller batteries
	Small scale module replacement from spares
Non-routine corrective [Not included]	Module replacement before end of system life Lack of compatible replacements
	Connector issues
	Wire management issues
	Large scale tracker replacement– trackers, damper or bearing
	Module replacement related re-engineering costs

Financial models may assume some replacement of modules from spares. Such “like-for-like” module replacement incurs only the labor costs to switch out the modules. Typical projects have 0.5% or less of spare module quantities. For instance, a failure of 7% of modules would a) deplete the spares population as well as overwhelm the on-site O&M technician’s capacity to repair, b) be noticeable in the reduction of energy production and loss of revenue compared to the financial model, and c) require the replacement of the failed modules with newer modules, which may not be compatible with the existing project modules or system design.

For context, the preventative and routine corrective O&M prices for distributed-generation (DG) and utility-scale global O&M costs are shown in Figure 2-1 from Wood Mackenzie. [2] There is no allocation for non-routine corrective maintenance issues such as the cost of module replacement beyond spares.

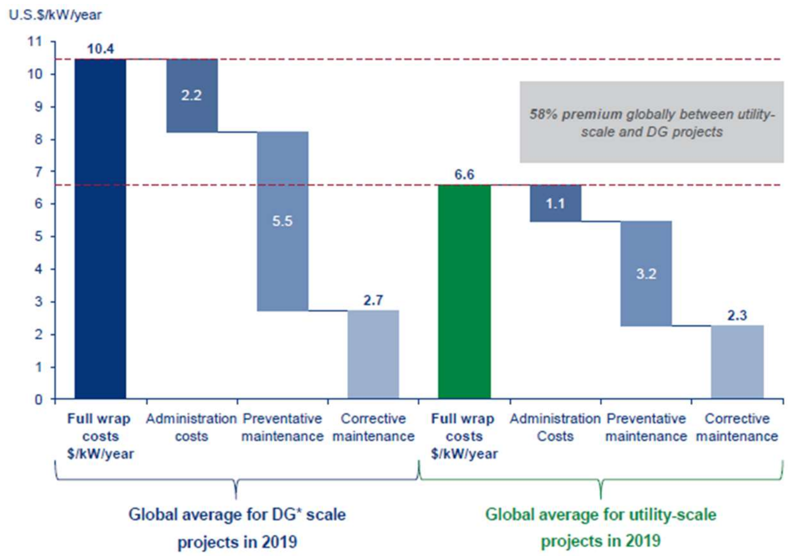


Figure 2-1 Global O&M prices and breakdown for DG and utility-scale projects in 2019

2.2 Warranties are insufficient to mitigate module failure risks

Standard PV module warranties have two components: the product warranty and the performance warranty.

Product Warranty: The standard product warranty for PV modules covers defects in materials and workmanship, such as shorted diodes, delamination, and defective junction boxes, while excluding aesthetic defects. Although product defects are generally easier to document and claim, DNV has observed considerable blame-shifting among various parties. This includes attributing issues (e.g. broken glass, moisture ingress, or ground loop faults) to such things as poor installation practices by the EPC, poor racking design, or poor O&M practices. Obtaining module warranty remedies may require 6 months to more than 2 years to resolve. This will require owner's time and resources to investigate, perform root cause analysis, and potentially engage independent engineers and legal counsel. All the while, revenues from energy production may be reduced.

Performance Warranty: The typical performance warranty guarantees that the module will maintain the described level of performance over the warranty period. The performance warranty period is usually 25 years for modules with a polymer backsheet, and 30 years for modules with dual-glass construction. Performance warranties typically guarantee first-year performance and a linear decline over the remaining period specified annual rate. A 3% measurement uncertainty is commonly applied to module testing measurements and is in addition to the warranted performance. For example, if the first-year warranty is 98%, the modules would need to perform under 95% of nameplate before warranty coverage may apply. Particularly with performance issues, owners are faced with a lengthy process of identifying the source of system underperformance which may last a year or more. Even after this, there may be a dispute with the manufacturer as to whether the modules, balance of system components, or EPC construction practices are the main culprit of underperformance. All the while, revenues from energy production may be reduced.

Obtaining warranty remedies can be a long and arduous process requiring arbitration, 3rd party inspection, laboratory testing, site visits, and significant operational data. If successful, the manufacturer has the option to choose which of the remedies in the warranty it will honor. Typical remedy options include:

- **Replacement:** The manufacturer may choose to replace the defective modules with new ones that have similar electrical characteristics and physical mounting capabilities. However, due to the rapid pace of PV innovation, DNV expects that no suitable (commercially-available) replacement modules will be available after three to five years from the original module's production date. This will incur additional costs as explained in Section 2.6 and will represent a significant departure from the financial model.
- **Repair:** Unlike large inverters, PV modules are not intended to be serviceable in the field. Some repairs to the connectors and junction box may be possible (although discouraged). Backsheet repairs, however, are very problematic. The project's value will typically decrease if it contains 'repaired' modules and the repairs may not be certified to required industry safety standards such as UL or IEC 61730.
- **Salvage:** The manufacturer may elect to refund the salvage value of the defective modules based on the market price of the modules and remaining fraction of the warranty period or based on other parameters. DNV expects the owners to realize a significant financial loss with such a remedy.
- **Additional modules:** Supplying additional modules can, depending on the system, make up for the energy shortfall caused by the underperforming modules. However, most PV facilities do not have extra space or racking to install additional modules, nor funds to expand the PV system for extra modules. Permitting additional capacity may also be problematic at most PV sites.
- **Financial compensation:** Some manufacturers may elect to directly compensate the module owners financially for the energy or power shortfall. However, the actual amount of the compensation is often calculated through a complex formula taking into account the current market price of modules and a determined linear depreciation.

Additionally, the owner is typically responsible for customs fees, labor for replacement modules, and module disposal. Manufacturers may in some cases pay for basic transportation costs, but not for additional tariffs.

Serial defect warranties also have issues. First, definitions of serial failures may be vague and testing requirements for burden of proof may be at the discretion of the module manufacturer. Second, serial defect warranties often specify that a certain number of module failures must be due to a single failure mechanism to meet the warranty threshold. This means that if the total number of failed modules meets the threshold, but the failures are due to multiple different mechanisms, each below the threshold, the warranty claim may be denied.

In general, module warranties will not make the project whole and will represent a major departure from the financial model even with an honored warranty claim.

2.3 How has durability of modules changed with technology?

Over the past 25 years, the industry has seen huge price reductions, scaling of manufacturing, intense competition, and stunning innovations. A graphical history of the expansion of the global PV industry and the technological evolution is shown in Figure 2-2. Some innovations help with durability. For example, multi-busbars show improved durability but were developed to help lower silver consumption. Dual-glass modules are more hermetic, something that is known to improve long-term durability. However, to save costs, the glass was thinned and modules made larger, with negative impacts on mechanical strength. Thus, while certain advancements have contributed to improved module durability, ongoing cost pressures can hinder the adoption of higher-quality materials and the enforcement of rigorous manufacturing standards.

As a result, purchasers and stakeholders have tried to ensure that quality and durability do not suffer from such intense commercial pressures. More accelerated tests have been standardized, and the practice of testing has become widespread and expected in the U.S., even for project-specific module bill of materials (BOMs). For the U.S. market, DNV has seen increasing focus on third-party pre-production factory audits, production monitoring, and pre-shipment inspections.

When issues occur in the field – cracking of backsheets, light-induced degradation (LID), light and elevated-temperature-induced degradation (LeTID), and potential-induced degradation (PID) – the industry has responded with defined durability tests for these conditions. There may yet be some presently unknown degradation/failure mechanisms as module technologies evolve. However, the present suite of testing is quite comprehensive for the field conditions that can be expected.

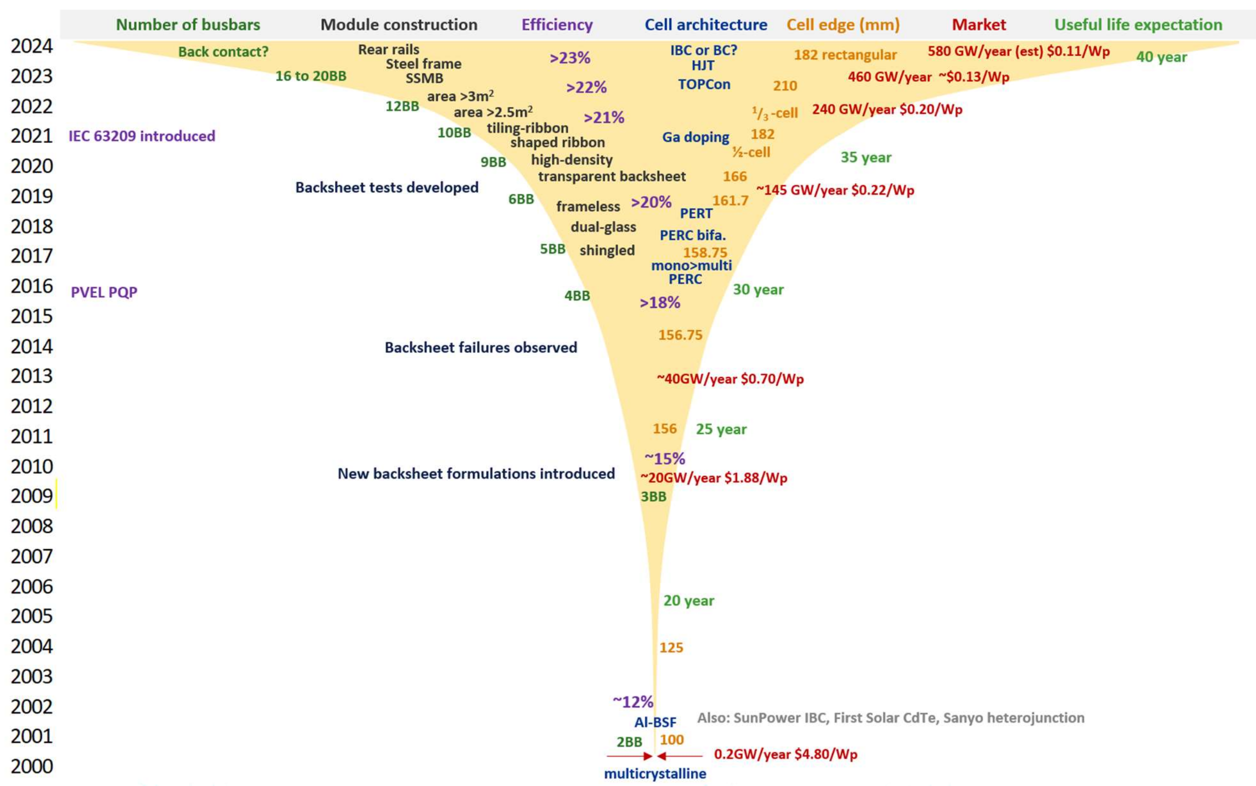


Figure 2-2 Evolution of module technology, market size (width) and testing methods over the last 24 years

Most module manufacturers have generally been able to *outgrow* the negative impacts of warranty claims. Such outgrowing warranty claims may not be a viable strategy in the future. For example, consider a manufacturer where 20% of modules made 15 years ago are now failing under warranty. In the meantime, the manufacturer's annual production capacity has grown by 20x and can produce modules at a substantially lower $/Wp. Thus, replacing the failed modules now represents only 1% of its present production capacity. While inconvenient and impactful to project margins, such a volume of modules is not a major threat to the viability of the manufacturer. Looking ahead, continued growth at this scale is not certain, and manufacturers may not be able to rely on expansion to offset the consequences of warranty-related issues.

2.4 The problem with like-for-like module replacement assumptions

Even in situations when modeling non-routine module replacement O&M costs (beyond module spare quantities), O&M models will often assume like-for-like replacement of modules – only parts and labor. This assumes similar modules can be purchased on the market and simply swapped into the project as needed. This is unrealistic as even a 6-year-old project would not be able to obtain replacement modules today comprising 158.75 mm wide PERC cells with the dimensions and electrical properties of that vintage module. Not only are today's module widths incompatible with those of 6 years ago (e.g., 1004 mm vs today's 1134 mm or 1303 mm) but the currents are also vastly different; ~10 A I_{sc} vs ~14 A to ~18 A I_{sc}. The ongoing evolution of module size and specifications will likely continue into the future. This evolution makes like-for-like replacement unrealistic in financial models.

Table 2-2 Evolution of module specifications driven by wafer size and cell technology

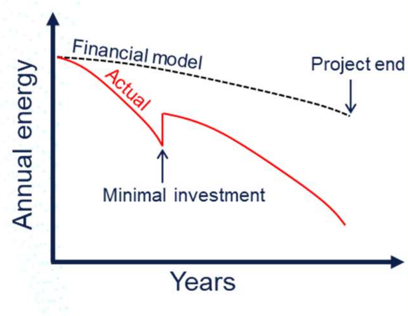
Cell width (mm)		156	156.75	158.75	161.7	163.75	166	182	210
Approx vintage		<2018	2017-2019	2018-2021	2020-2021	2020-2021	2020-2022	2022-pres.	2022-pres.
Technology		AL-BSF	AL-BSF, PERC	PERC	PERC	PERC	PERC	PERC, TOPcon	PERC, TOPcon, HJT
Module width (mm) typical									
	6 columns	990	992	1004	1030	1034	1044	1134	1303
Module length (mm) typical									
Number of cells	132								2384
	144	1956	1975	2040	2045	2070	2096	2280	
	156							2430	
Area (m2)									
Number of cells	132								3.11
	144	1.94	1.96	2.05	2.11	2.14	2.19	2.59	
	156							2.76	
Weight (kg) approx.									
Number of cells	132								37.8
	144	22	23	24	25	26	27	32.8	
	156							33	
Isc (A) approx.									
	6 columns	9.2	9.7	10.3	10.8	11	11.5	13.8, 14.8	18.4, 18.7, 17.8
Voc (V) approx.									
Number of cells	132								45.8, 48.7, 49.8
	144	47	48	48.5	49	49.5	49.5	49.8, 52.8	
	156							53.6	

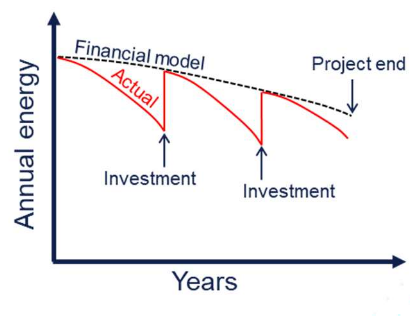
2.5 Strategies to handle premature module replacements

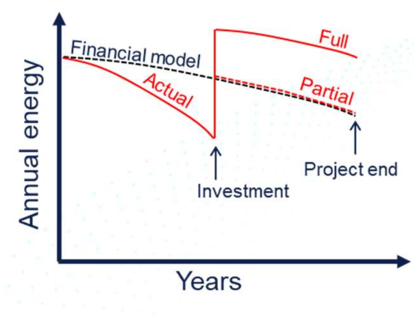
As mentioned earlier, the useful life of a module is not straightforward to assess during procurement; there are no direct tests or measurements that will predict the useful life of any module a priori. If the project needs more replacement modules during operation than available spare module quantities, it is simplistic to assume that new modules can simply be purchased on the open market at such time in the future. This "like-for-like" replacement model is not financially burdensome as the average price of modules, $/Wp, is expected to decline over time. However, as described in Section 2.4, "like-for-like" is not realistic as PV module design and performance will continue to evolve. Long term financial models should also consider the cost of re-engineering or repowering the site. Below we define refurbishing, re-engineering, and repowering as the three general strategies to deal with an underperforming project.

Table 2-3 Various strategies for replacing obsolete modules with contemporary modules

Refurbish*	Re-engineer	Repower*
▪ Minimal investing to fix limited issues. ▪ Refurbishing maintains system safety. ▪ The system will still be lagging the performance assumed in the financial model. ▪ Replacement of some parts that don't require extensive re-engineering. ▪ Allow retirement of some strings and distribute functional modules across remaining strings. ▪ Not likely to require permiting.	▪ Investing in repairs and replacements of multiple components to attain the performance assumed in the financial model. ▪ New equipment on the market is likely not compatible with existing equipment. ▪ Bespoke engineering, partial equiment removal and replacement of failed modules and may include inverters, cabling, combiner box, mounting hardware, and other BOS. ▪ May require multiple investments as equipment fails. ▪ May require new permitting.	▪ Generally removing all equipment from the entire site or part of a site - including modules, inverters, and cables. Piles may also be upgraded. ▪ Parts from a partial repowering can be used as spares. ▪ Installation of all new equipment with full design and system compliance to any new codes. ▪ New system benefits with improved performance and revenue, potentially above initial model. ▪ May require new permitting.







*Nomenclature from Curtis, Taylor, et al. "Best practices at the end of photovoltaic system performance period." NREL,2021.

The key point is that to maintain the financial model's projected energy production and revenue when modules fail, investments must be made to restore or even exceed the original energy output. We anticipate that innovation will continue, and future modules and equipment will differ significantly from current models. Based on recent trends, future modules are likely to be larger, more efficient, and feature automated installation, higher voltage ratings (such as 2000V [3]), and higher current capacities. Therefore, replacing 10% or more failed modules in 20 years with then available equipment will require custom engineering to address specific constraints, such as the existing cable current capacities, inverter specifications, and tracker load capabilities.

The labor and the re-engineering costs to do such replacements is presently very expensive and cannot be amortized across a large project. It may be the case that re-engineering costs themselves will drop in the future as the industry becomes more adept at re-engineering or repowering. Certainly, there will be some cost declines; however, solar project construction and equipment vary widely today, and detailed digital as-built records tend to be uncommon. Thus, streamlined re-engineering does not seem obvious at this point. Additionally, manufacturers may go out of business or update their products in a way that is not compatible with legacy systems.

2.6 Cost of replacing original modules with future modules

The extent and costs of trying to replace failed original modules with future module technologies is highly bespoke and difficult to estimate in a general manner, which is likely part of the reason why it has not been commonly included in O&M models. No financial model assumes, for example, replacing 25% of the project modules as well as new cabling and inverters at year 25.

When trying to utilize today's modules to replace failed modules from just 6 years ago, the electrical incompatibility (e.g., higher I_{sc} and I_{mp} currents) are immediately noticeable as shown in Table 2-2. Higher currents inevitably require replacement of wiring and digging up trenched cables or the added cost of string optimizers. Furthermore, digging up the cables often cannot be performed with heavy machinery lest other buried cables are damaged.

Based on initial construction cost information from Wood Mackenzie [4] for a 10 MWp system (e.g. 10% module failure of a 100 MWp system), we have compiled some considerations and a most optimistic cost scenario estimate, based on the following:

- Utility sites likely have central inverters, and we assume new strings with new modules will have either optimizers or separate string inverters for compatibility with new modules.
- Some structural retrofitting costs are incurred for larger modules with thinner frames.
- Electrical BOS costs such as grounding, some cabling, fuses and combiner boxes need to be updated.
- Labor required will include removal of old modules, and installation of new modules.
- Some EPC costs are incurred including design and procurement.
- For U.S. markets, with the tariffs on imported modules, higher module costs are expected compared to European markets.

The assumptions are summarized in Table 2-4.

Table 2-4 Optimistic module re-engineering cost estimate (USD/Wp)

Source	Greenfield, utility 10 MWp single-axis, central inverter Wood Mackenzie	DNV estimate of re-engineering (add string optimizer to match inverter) DNV optimistic estimate
Module	$0.31	assume warranty replacement
Inverter	$0.04	-
Electrical balance of system (EBOS)	$0.11	$0.05
Structural balance of system (SBOS)	$0.15	$0.07
Labor	$0.17	$0.09
Design & engineering	$0.02	$0.02
Permitting & inspection	$0.01	$0.01
Logistics & misc.	$0.08	$0.03
Civil	$0.11	-
EPC overhead & margin	$0.18	$0.07
Turnkey EPC pricing	$1.18	-
Developer costs	$0.23	-
All-In construction cost ($/W)	**$1.41**	**$0.35**

Module prices in the future are expected to drop, but for the U.S. market, prices are expected to remain higher than available elsewhere due to tariffs. Furthermore, for purchase orders of a smaller number of modules, the prices will likely remain elevated. Assuming a manufacturer will provide replacement modules of future design, the estimate for re-engineering costs can reach over $0.35/Wp (USD). If new modules need to be purchased because they are not supplied by a manufacturer's warranty, the total costs can reach over $0.65/Wp (USD) in the U.S. where module prices are expected to remain high. There is considerable uncertainty and variability in this estimate as re-engineering is highly bespoke work.

3 ASSESSING MODULE USEFUL LIFE

3.1 What is module useful life?

The term module useful life is frequently used and sometimes confused with project life, design life, service life, or module life. Conceptually, most products follow a “bathtub” curve as shown in Figure 3-1 (adapted from [5]). A bathtub curve features an initial high failure rate of early life failures (burn-in period). For PV modules, early failures may be due to poor installation practices, manufacturing quality issues, or transportation damage. The burn-in period is followed by the useful life period which has a low failure rate (“random failures”). The underlying concept is that during the useful life phase, the environmental stresses on the module create damage that accumulates. The damage accumulation may or may not yet cause an observable reduction in module power. However, the damaged components are less capable of functioning and withstanding further stresses past a threshold. For example, the adhesion strength of various polymers and sealants degrades with heat, moisture, and ultra-violet light. Polymer degradation occurs, often unobserved, until a threshold is reached and delamination or moisture ingress occurs, resulting in steep drops in power due to open circuits, corrosion, or similar issues. Other damage accruals can cause observable and slow declines in module power output, such as EVA yellowing (due to UV exposure) or cell cracking and crack multiplication.

Over time, enough damage may be accumulated in the population of modules that the failure rate increases as individual components fail (such as backsheets) or synergies between damaged components accelerate the failures (such as loss of polymer adhesion that accelerates moisture ingress and corrosion). This is conceptually the transition from useful life period to the wear-out period. For modules, failure typically means:

- Significant reduction in power, e.g. below financial model assumptions or below warranted levels.
- Safety issues, such as a compromised backsheet or other loss of electrical insulation.

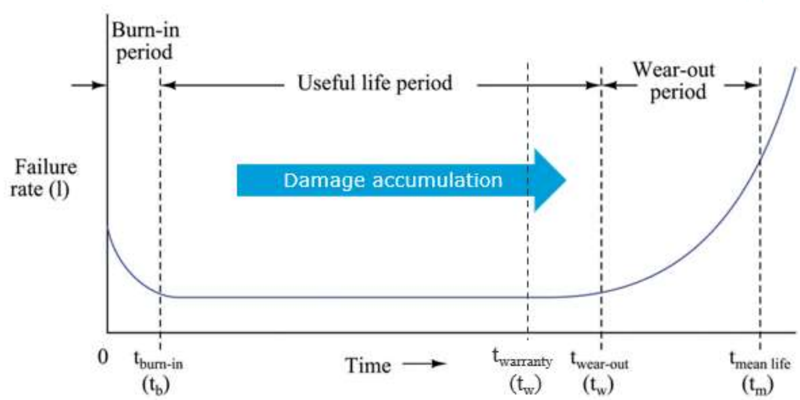


Figure 3-1 A conceptual bathtub curve applied to a PV module

The end of the module useful life is the beginning of the wear-out period where the *failure rate* begins to increase. There is no correct way to predict the onset of the wear out period. Often Weibull curves are utilized for modeling failure rates. While Weibull distributions are commonly used to model failure rates statistically, they rely on assumptions and historical data that may not fully capture the complex and evolving degradation mechanisms in newer PV modules.

From a financial modeling perspective, what matters is when modules need to be replaced to maintain the prescribed energy output and expected revenues. While the definition of ‘useful life’ is arbitrary, DNV adopts the end of the useful life as determined by when 10% of modules (cumulative) have been replaced to maintain system energy yield levels. Once this 10% threshold is met, the rate of failures in the future is assumed to accelerate significantly. The module replacements may be due to a variety of causes including outright failure (significant drop in power output), modest power output reduction of small number of modules that disproportionally impacts the entire string due to mismatch, leakage currents that may cause inverter tripping, development of hot-spots or damaged junction boxes, or any general safety issues.

The rapid pace of module innovations means that there is no historical data on which to base useful life durations for new modules. Thus, the only method to assess the durability of modern modules is based on accelerated testing.

3.2 Accelerated testing and its limitations

Over the last 40 years, the PV industry has observed a wide variety of field failures and failure mechanisms. As a reaction, accelerated tests have been devised and tuned to address the observed failures. These accelerated tests are based on the qualification tests defined in the IEC 61215 but are extended or repeated. These tests are loosely referred to by various names such as HALT (highly accelerated lifetime tests), extended-duration tests, Thresher tests, PQP tests (after the Kiwa PVEL Product Qualification Program), 3x IEC 61215, IEC 63209, or IEC 63209+. Presently, the most relevant suite of tests has been defined in the IEC 63209 specifications, which probe known degradation and failure modes with extended testing and sequential testing. A partial table of failure modes and tests that probe the failure modes is shown in Figure 3-2.

	Light induced Degradation	Light and Elevated Temperature Induced Degradation	Thermal Cycling	Damp Heat	Backsheet Durability Sequence	Mechanical Stress Sequence	Hail Stress Sequence	Potential-Induced Degradation (PID)
Corrosion of cell metallization				✓		✓	✓	
Junction box failure (solder joints, arcing, etc.)			✓			✓	✓	
Glass fracture						✓	✓	
Bypass diode failure (short or open)			✓	✓		✓	✓	
Cracked cells			✓			✓	✓	
Solder joint degradation			✓			✓	✓	
Delamination				✓	✓			
Junction box detach				✓				
Connector embrittlement (moisture ingress)			✓	✓	✓			
Frame tape or frame adhesive failure						✓		
Frame fatigue						✓		
Optical degradation of encapsulant and backsheet					✓			
Light-Induced Degradation (LID)	✓							
Light and Elevated Temperature Induced Degradation (LETID)		✓						
Outgassing of in-laminate materials (Chemical incompatibilities)			✓	✓	✓	✓	✓	
Backsheet embrittlement leading to cracks			✓	✓		✓	✓	
Busbar sharp edges, solder peaks, cutting through backsheet			✓					
Electrochemical corrosion of busbars or cell metallization								✓
Ion migration / Polarization / Potential-Induced Degradation (PID)								✓
Discoloration of frame, junction box, or polymeric materials				✓	✓	✓	✓	
Backsheet stack layer delamination				✓		✓	✓	
Hail damage							✓	

Figure 3-2 Failure modes and tests that probe them (from Kiwa PVEL)

While highly accelerated testing in a laboratory can provide an indication of durability, unfortunately, they cannot predict field useful life. There are many reasons for this, as discussed below.

Testing time constrains and acceleration factors: The longer the useful life, the greater the acceleration factor needed to make laboratory testing practical. Trying to assess a 35-year field exposure in a laboratory test with only a 2 month duration requires an acceleration factor of over 200x. Such high acceleration factors means that stresses applied are not representative of the field conditions and may invoke unrealistic failure modes.

Complexity of conditions: Field exposures consist of varied and often multiple simultaneous stressors. Some at NREL are attempting combined accelerated stress testing (CAST) [6] to improve accelerated testing predictive capabilities. However, such methods presently are limited to coupons (small samples rather than a full actual size modules). The mechanical stress sequence (MSS), for example, is intended to combine stressors to more adequately reflect the conditions in the field.

System complexity: A PV module is a complex system with interdependent components. In complex systems, the failure or degradation of one component can affect others. Synergies between failure modes (see list in Figure 3-2) make it difficult to predict overall reliability.

Material degradation: Materials may degrade in unexpected ways over time, particularly when exposed to high acceleration factors for UV radiation or damp heat. In other words, high acceleration factors may result in failure modes not observed in the field. Alternatively, small, incremental damage over time may not be evident in short-term tests but could lead to failure over the long term.

Cost, time, and resources: Accelerated tests require resources, equipment, facilities, and personnel, which means costs. Some testing can have high costs. Yet, the tests cannot quantitatively predict the useful life and the incremental value of a more durable module. This makes the value proposition of the tests difficult to quantify. Furthermore, companies often face trade-offs between time-to-market and thorough reliability testing.

Sampling: Accelerated tests are conducted on an exceedingly small sample of the manufacturing population. Thus, the results of the accelerated testing cannot be generalized across a large population of modules unless the manufacturing quality across large numbers of modules remains constant. This depends on a manufacturer's experience and quality systems.

3.3 DNV's approach to assessing useful life

Since there exists no official method to assess or predict useful life, no encompassing accelerated test, and little relevant historical field data (and this will continue to be true as module technologies continue to evolve), DNV adopts the best practices of testing and manufacturing quality as guidance for useful life models. Hence, DNV assigns a useful life duration after a thorough evaluation of module design (BOM and accelerated testing) and manufacturing quality (factory audits, production monitoring, and pre-shipment inspections).

DNV has designated 4 useful life classes. The classes were chosen to represent module useful lives spanning as short as 20 years or less for poorly manufactured modules to as long as 45 years for well-designed and well-manufactured modules (the aspirational Department of Energy target) as shown in Table 3-1. Here, we define a useful life as the year a cumulative 10% of the modules are replaced. The modules are classified to reflect differences in product quality, with Class A representing higher quality modules and Class D representing lower quality modules. The span of these four classes is meant to capture the wide possibilities of module durability and quality.

To categorize a particular set of modules into a class, DNV reviews the module BOM, accelerated reliability test reports (e.g. IEC 63209), as well as recent factory quality audit reports, in-line production monitoring, and pre-shipment inspections. The BOM and extended-duration test results provide insight into the durability of the module design while the factory audit, production monitoring, and pre-shipment inspections speak to the manufacturing quality – the repeatability of the design across the hundreds of thousands of modules produced for a particular model. Thus, the module classification is project-specific and not generalized for a specific manufacturer or model.

For Class A, DNV concurs with CFV's extensions of the IEC 63209 tests for accelerated testing, herein referred to as "IEC 63209+". Further details of accelerated tests including IEC 63209 and the modified "IEC 63209+" are included in

Section 3.4. For modules with higher levels of degradation on the accelerated testing results or modules with less information available (such as testing, BOM, or manufacturing quality information), DNV assigns a lower classification. These classifications are used by DNV in our O&M cost modeling.

Table 3-1 Classification of module quality by accelerated testing, BOM review and factory audits and inspections

	Target useful life (years)	Class A 45	Class B 32	Class C 25	Class D 20
	Certification requirements	ISO 9001	ISO 9001	ISO 9001	
Design and materials durability	Testing requirements	IEC “63209+” IEC 61215 IEC 61730	IEC 63209 IEC 61215 IEC 61730	IEC 63209 IEC 61215 IEC 61730	IEC 61215 IEC 61730
	▪ Thermal cycle test degradation	<2% TC1000	<2% TC600	<5% TC600	pass
	▪ Damp heat test degradation	<2% DH2000	<2% DH2000	<5% DH2000	pass
	▪ Mechanical stress sequence degradation	<2%	<2%	<5%	-
	▪ Backsheet UV Sequence (if backsheet)	No fail	No fail	No fail	-
	▪ UV ID degradation	<2% 360 kWh/m^2	<2% 120 kWh/m^2	<5% 120 kWh/m^2	-
	▪ PID 192 hr (-1500V & +1500V)	<2%	<2%	<5%	<5%
	▪ LeTID (75°C, Isc-Impp, 3x162 hours)	<2%	<2%	<5%	-
	BOM(s) details and specifications	Detailed BOM for all modules	Detailed BOM for all modules	High level BOM(s)	-
Manuf. quality[*]	Factory audit result[†]	leading	leading or in-line	leading or in-line	-
	Production monitoring	✓	✓	✓	-
	Pre-shipment inspection	✓	✓	✓	-

3.4 Descriptions of the IEC 63209 and IEC 63209+ test sequences

Below is an edited version of the Kiwa PVEL PQP testing graphic to show the main testing elements of the IEC 63209. This follows the IEC 63209 with the addition of the LeTID test (IEC TS 63342) and the UV ID sensitivity test (IEC 61215).

[*] Checkmark indicates these reports exist for the project modules and have been reviewed by a 3rd party. As best practice, the reports should cover 100% of the lots/batches produced for the project.

[†] Factory quality systems are leading or in-line compared to typical module factories in the industry.

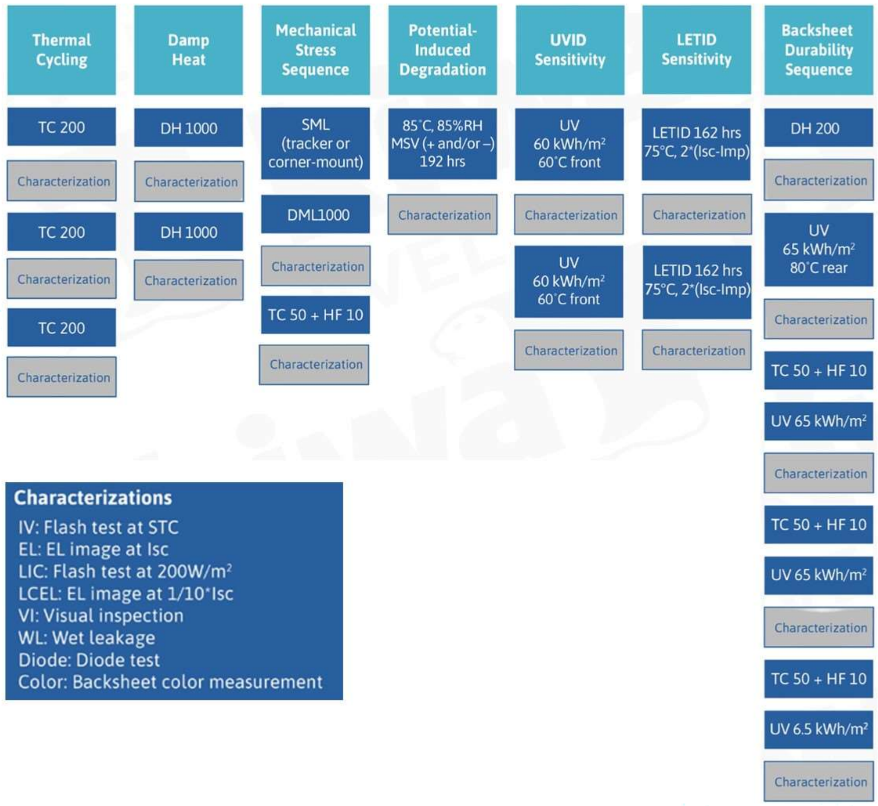


Figure 3-3 IEC 63209 test sequences (adapted from Kiwa PVEL PQP)

For Class B, many modules pass the tests with less than 2% P_{mp} degradation - most often, glass/glass modules as shown in Figure 3-4.

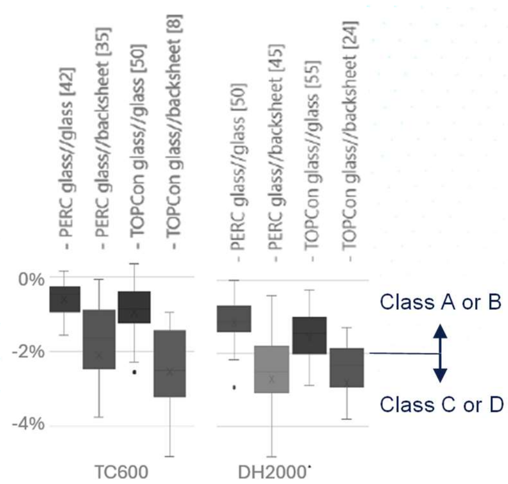


Figure 3-4 Test result summary for TC600 and DH2000 testing from Kiwa PVEL showing that many glass/glass modules pass the tests with less than 2% degradation (number of modules in brackets)

An augmented test schedule dubbed “IEC 63209+” extends some of the testing to better probe for 40+ years of module useful life. While the previous UV ID test was 120 kW/m^2, the IEC 63209+ schedule goes to 360 kW/m^2. Similarly, the TC600 is extended to TC1000.

3.5 Factory audit

While the BOM and extended-duration testing provide an assessment of the durability of the module design and materials, in order to maintain such durability across thousands of modules, the manufacturing quality of the module must be assessed. This is accomplished through factory audits, in-line production monitoring and pre-shipment inspections.

Factory audits assess the ability of the manufacturer to repeatably produce high-quality modules at specific factories and manufacturing lines. Factory audits assess many categories; however, the categories most relevant to DNV to assess the manufacturing quality are shown in Table 3-2.

Table 3-2 High-level third-party factory audit topics

Incoming materials management: ·Incoming materials QC ·Non-conformity management ·Record keeping ·Expiration control ·FIFO control ·Warehouse temp, humidity, & cleanliness	**Non-conformance handling:** ·Non-conforming definitions and identification ·Rework and rework tracking ·Non-conforming module isolation ·MES updating ·Module disposition
Production area cleanliness and safety: ·General cleanliness and organization ·Waste management ·Observation of safety practices	**Off-line testing review:** ·Incoming material testing ·Production line testing (e.g. gel content tests) ·In-house testing capabilities ·On-going reliability testing
Production process: ·SOP at every station ·Training of personnel ·EL criteria and imaging ·Visual inspections ·Equipment set points including temperature ·MES integration ·Process controls	**Quality management** ·MES ·Change management ·Continuous improvement ·Supplier qualification processes
Equipment management: ·Equipment maintenance ·Maintenance record keeping ·Calibration and records	**Employee management:** ·Employee trainings ·Factory safety ·Turn-over rate

A typical factory audit uses the terms “critical,” “major,” or “minor” to describe risks associated with a finding. A critical finding is likely to result in unsafe conditions and/or severe underperformance and reliability issues in the short- to mid-term. A major finding is very likely to result in underperformance or reliability issues in the long term. A minor finding is somewhat likely to result in underperformance or reliability issues in the long term. The results of the Factory Audit, specifically within the categories that pertain to the useful life of the modules (detailed above), aid in the classification of the modules into distinct classes. The classification is further elaborated in the table that follows.

Table 3-3 Factory audit results necessary for each module class

Critical Issues = 0 Major Issues ≤ 1 with all having corrective actions in place Minor Issues ≤ 5 with all having corrective actions in place	Leading
Critical Issues = 0 Major Issues ≤ 3 with all having corrective actions in place Minor Issues ≤ 5 with all having corrective actions in place	In-line
Critical Issues ≤ 1 with all having corrective actions in place Major Issues ≤ 6 with all having corrective actions in place Minor Issues ≤ 10 with all having corrective actions in place	Lagging
No factory audit	Class D

3.6 Production monitoring

While the factory audit provides an assessment of the ability of the manufacturer to repeatably produce high quality modules at a specific factory, third-party production monitoring helps the buyer supervise and verify that the project-specific products are being manufactured according to their project specifications consistently and accurately, adhering to the quality standards. Additionally, third-party production monitoring also ensures that the BOM and quality processes at various stages of manufacturing are followed to ensure high-quality products. If the manufacturer is entitled to deliver modules from, for example, five different BOMs, then each BOM should be properly observed in the production monitoring to confirm product conformity to each specified BOM. Typically, third-party production monitoring consists of an auditor being present in the factory, overseeing 20% to 35% of the total module production for the project.

Production monitoring assesses many categories; however, the categories most relevant for useful life are noted in the following table.

Table 3-4 High-level summary of 3rd party production monitoring activities

BOM verification
IQC process verification tests of glass, cell IV and EL
Silicone adhesion test
Flux acid and solid content value test
Flash tester calibration verification and maintenance
EL inspection criteria is considered acceptable as reviewed by DNV or independent expert
Climatic conditions verification (temp, humidity) in production line and storage
Pre-production inspection materials used for production not expired
Process monitoring including:
Soldering quality check
Wet leakage insulation (sampling plan for wet leakage)
Lay-up visual inspection
Calibration of laminator temperature
Gel content (80-95%)
Peel off test (encapsulant - front or back layer) >70 N/cm
ESD controls at manual soldering and JB application
JB potting curing test
Other equipment calibration verification and maintenance
Ongoing Quality Control (OQC) including:
Sealant inspection (ensure enough sealant is present around the frame)
Flash inspection pass
Visual inspection pass
EL inspection pass
Hi-pot and ground continuity test pass
Dimension check – pass

3.7 Pre-shipment inspections

As a last check on the manufacturing quality control, a pre-shipment inspection may be performed. Prior to shipping the modules from the factory to the project site, modules may undergo additional testing or re-testing. Modules are grouped into "lots" or "batches" which can have many definitions such as 1 or 2 weeks' worth of production, 5 to 20 MWp, or 10,000 to 40,000 modules. The definition of a batch should also consider the type of modules and BOMs. For instance, if the manufacturer is entitled to deliver modules from 5 different BOMs, then each BOM should be properly covered in the sampling for quality control. The pre-shipment inspection contract needs to specify what the lot size is and the sampling schedule as specified in ISO 2859-1.

Inspections and tests as shown in Table 3-5 are performed to provide an accept or reject decision on the batch of modules based on the agreed upon inspection levels (which define sampling rates) and acceptable quality limits (AQL) defined in ISO-2859 "Sampling procedures for inspection by attributes". General inspection levels (I-II-III) are typically indicated for non-destructive inspections like visual inspections, flash tests or electroluminescence (EL). For defects observed in visual and/or EL inspections, three levels of defect severity are typically defined in the inspection criterion: Critical, Major, and Minor.

- Critical: Likely to result in hazardous conditions and possibly damage to other equipment
- Major: Likely to result in underperformance or premature failure, AQL from 1 to 2.5

DNV

- Minor: May not result in performance issues but considered to be an indication of poor workmanship, AQL from 2.5 to 6.5

Assigned to each defect severity is an AQL. Typically, for Critical defects, the AQL is set to 0 which denotes zero tolerance of such defects. Definitions of the defect classifications must be agreed upon by the manufacturer and buyer. DNV recommends EL criteria based on cells with >9 busbars where cracks become less deleterious.

During a pre-shipment inspection (PSI), the modules produced for the project are kept isolated at the manufacturer's warehouse and samples of modules are randomly selected from the batch by a third-party inspector for additional testing and inspection. Often, the tests and inspections are performed at the manufacturer's site with the manufacturer's equipment, e.g., flash testing and EL, with a 3rd party inspector overseeing the calibration and measurements. While the purchaser could reject the entire batch for exceedance of an AQL, typically an investigation is conducted to understand the root cause and to isolate and replace any affected modules.

Flash testing can have multiple criteria. One criterion (considered critical with AQL set 0) could be that the *average* reflash power cannot be less than the nominal power. A second criterion could be that the total number of modules re-flashing below x% of the initial flash should be limited to a number determined by the AQL (e.g., AQL 1.0).

Table 3-5 Pre-shipment inspections and example testing requirements for module classes

Visual Inspection (e.g. General 1, AQL 0 CR; 1.5 MA; 4.0 MI)	Class A, B, and C
EL (e.g. General 1, AQL 0 CR; 1.5 MA; 4.0 MI)	Class A, B, and C
Flash test (e.g. General 1, AQL 0 average reflash < nominal power)	Class A, B, and C
Wet insulation test (e.g. Special Level S3, AQL 0)	Optional
Hi-pot test (e.g. Special Level S3, AQL 0)	Optional

4 USING THE CLASSIFICATIONS TO MODEL O&M EXPENSES

The cumulative failures for each class are modeled using Weibull curves shown in Figure 4-1. As shown, the end of the useful life (and the start of the 'wear out period') is assumed to be at 10% cumulative replacements. These replacement curves can then be used to calculate O&M costs for modules using both the expected cost of replacement modules and estimates of re-engineering costs discussed in Section 2.6.

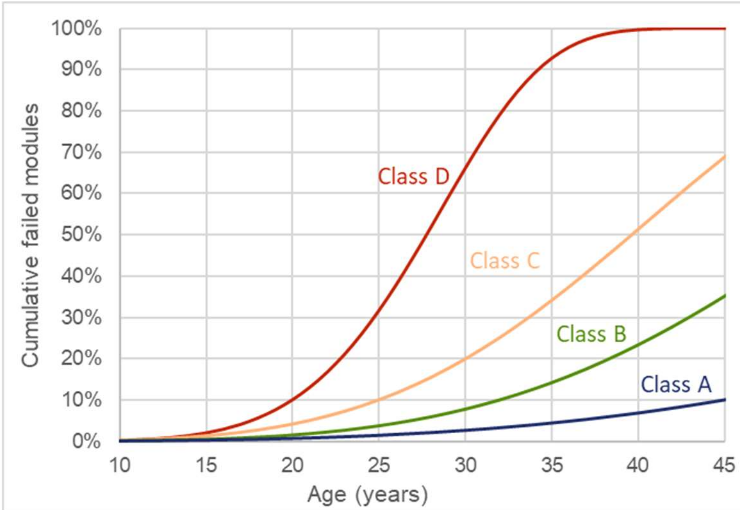


Figure 4-1 Examples of various replacement rates

The four classes of modules demonstrate how varying quality of design, materials, and manufacturing could impact the O&M costs over long periods of time. Using various assumptions for inputs, plots of non-routine module replacement costs (excluding other O&M costs from Figure 2-1) can be calculated as shown in Figure 4-2. For modules under a 30-year warranty (assuming the manufacturer provides replacement modules), re-engineering costs for the U.S. are as described in Section 2.6 at >$0.35/Wp. Without warranty coverage (after 30 years or manufacturer insolvency), the re-engineering costs are increased by an additional $0.30/Wp for modules in the U.S., or $0.12/Wp in countries without import tariffs.

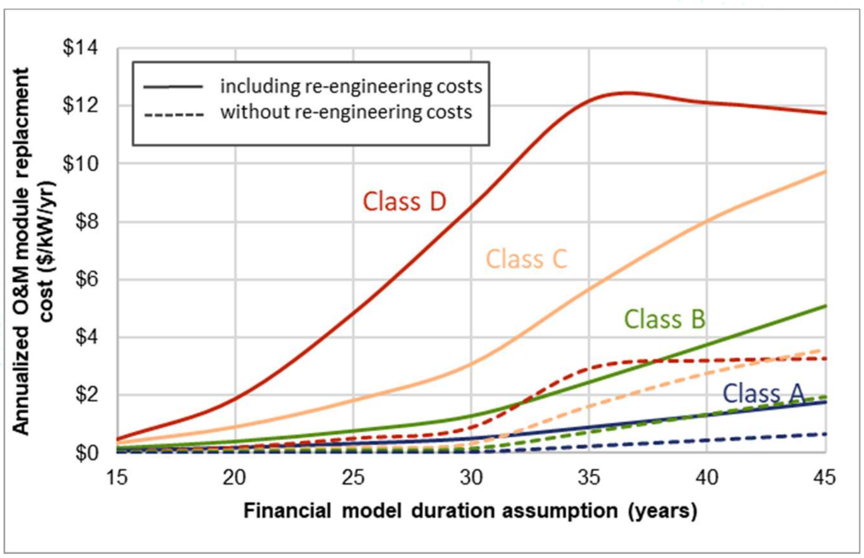


Figure 4-2 Comparison of annualized (non-routine corrective) module replacement costs ($/kWdc/year) with and without re-engineering costs assumed

The costs shown are annualized, meaning that the annual O&M costs to cover non-routine module failures increase as the assumed project useful life in the financial model increases. This model shows that assuming like-for-like module replacement (dashed curves without re-engineering costs) in the later years significantly underestimates the actual costs when including a re-engineering strategy. Based on Figure 4-2, one can see that for an assumed 30-year project life, Class C and Class D module replacement costs with re-engineering quickly exceed the magnitude of the typical O&M costs.

5 CONCLUSION

The long-term financial viability of solar PV projects hinges on realistic assumptions about module useful life. Current financial models often underestimate the costs associated with premature module failures, relying on unrealistic like-for-like replacement assumptions. As module technologies evolve rapidly, future replacements will likely require costly re-engineering due to incompatibilities in size, electrical characteristics, and system design. To complicate matters further, there exists no simple accelerated tests to precisely determine the module useful life. DNV addresses this challenge with a methodology of classifying module useful life based on design, durability tests, and manufacturing quality. DNV believes that these classifications enable a more realistic modeling of O&M expenses, helping stakeholders better anticipate long-term risks and costs. Ultimately, integrating realistic module durability assessments into financial models is essential to sustaining investor confidence and ensuring the success of the energy transition.

6 REFERENCES

[1] Based on the Wood Mackenzie 2021 Solar PV O&M Market report.
[2] D. Liu, LG da Fonseca; "2019 Global PV Operations & Maintenance Report", Q2 2020 Wood Mackenzie woodmac.com
[3] see https://pv-magazine-usa.com/2024/09/04/trinasolar-us-displays-2000-v-module-trackers-energy-storage-and-more/ and https://www.pv-tech.org/breaking-the-2000v-pv-system-threshold/
[4] Wood Mackenzie's Interactive US Solar PV System Cost Model - H2 2024 version
[5] Control Automation, https://control.com/textbook/process-safety-and-instrumentation/practical-measures-of-reliability/.
[6] https://www.nrel.gov/docs/fy19osti/73984.pdf