Photovoltaic-Reliability R&D Toward a Solar-Powered World

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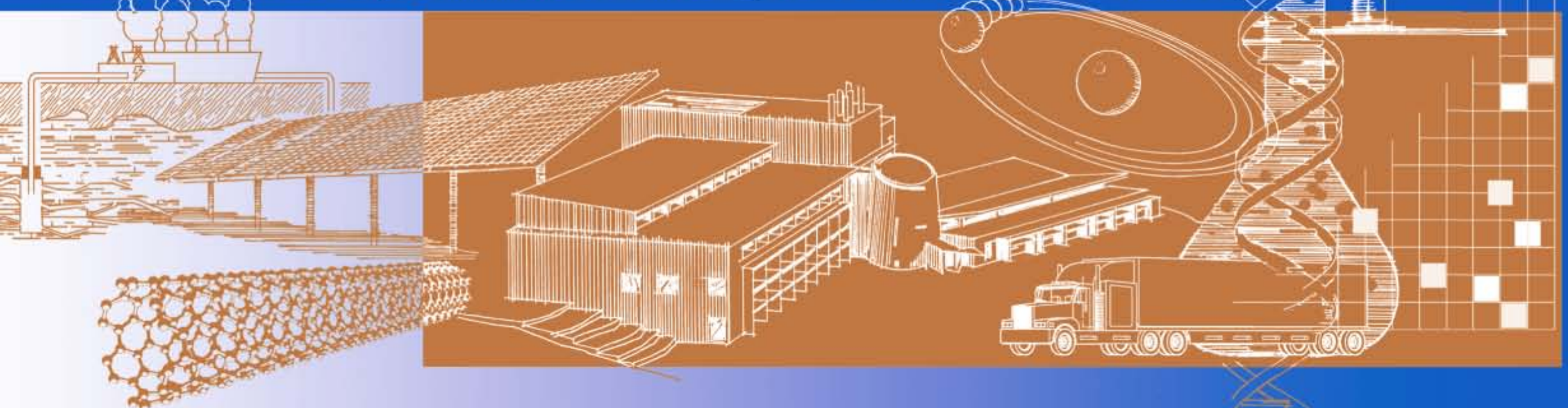

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Photovoltaic-Reliability R&D toward a Solar-Powered World

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ABSTRACT

The continued exponential growth of photovoltaic technologies paves a path to a solar-powered world, but requires continued progress toward low-cost, high-reliability, and high-performance PV systems. High reliability is an essential element in achieving low-cost solar electricity by reducing operation and maintenance (O&M) costs and by extending system lifetime and availability, but these attributes are difficult to verify at the time of installation. Utilities, financiers, homeowners, and planners are demanding this information in order to evaluate their financial risk as a prerequisite to large investments. Reliability research and development (R&D) is needed to build market confidence by improving product reliability and by improving predictions of system availability, O&M cost, and system lifetime. Universities, industry, National Labs, and other research entities can be most effective by working together and in complementary ways. The Department of Energy supports a variety of research projects to improve PV-system reliability. These projects and current reliability issues for each PV technology are surveyed.

Keywords: PV, reliability, failure analysis, accelerated testing, field-testing, lifetime prediction

1. INTRODUCTION

1.1 Growth of PV industry

The world PV industry grew exponentially from shipments of ~ 300 MW in 2000 to ~ 7 GW in 2008, as shown in Fig. 1. If this rate of growth can be continued, by 2016, the PV-installation rate will equal the average world new-electricity-capacity installation rate between 1996 and 2006, and, by 2018, the PV-installation rate would replace, annually, 5% of the current electricity generating capacity [1]. A solar-powered world will require even higher installation rates, but the possibility of reaching these significant milestones in < 10 years supports the vision of a solar-powered world.

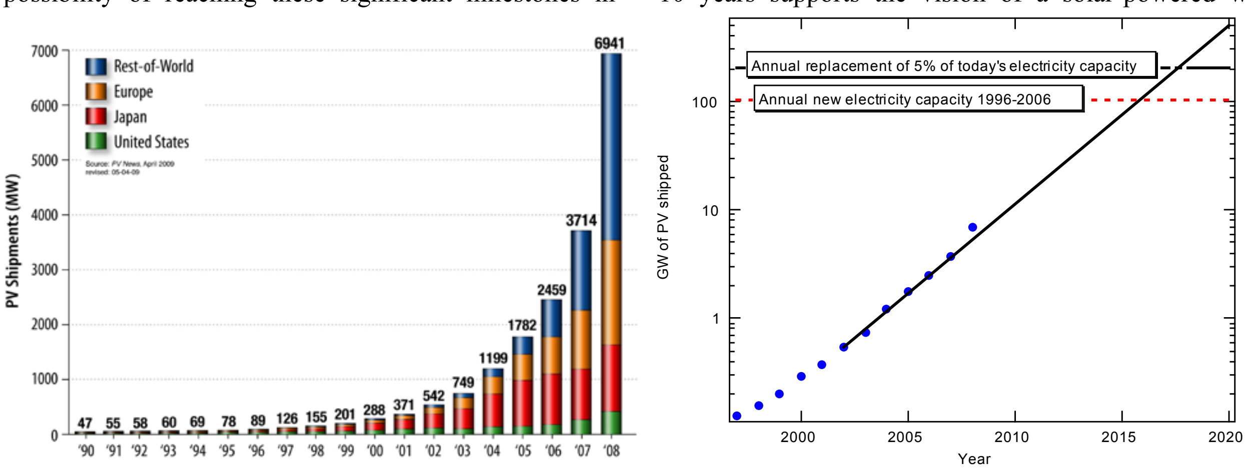

Fig. 1. PV-industry growth curve showing exponential growth in recent years and how that growth might extrapolate into the future.

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Maintaining this exponential growth will require two key elements: achieving 1) acceptable costs and 2) low enough risk to facilitate adequate investment. Reliability plays a key role in both of these.

1.2 Importance of reliability

Improved system reliability will be essential toward maintaining the current exponential growth curve as well as to community acceptance of solar as a mainstream power source. The exponential growth shown in Fig. 1 could result in huge financial losses if systems fail to deliver as promised. Ultimately, a solar-powered world will define reliability in the context of "the lights go on when the switch is flipped." This will require energy storage for when the sun isn't shining – a topic that is outside of the scope of this paper. For this paper, we define reliability as "*a PV system working as expected when the sun is shining with low O&M costs and long life.*" Some of the ways in which reliability affects the cost and performance of PV are shown in Table 1.

The Solar Advisor Model [2] calculates the cost of solar electricity including factors such as the cost of money, incentive programs, etc. It's also useful to consider the fundamental costs to society for deploying solar and how these are affected by reliability. Table 2 summarizes a simple analysis.

Table 1. Importance of reliability to reducing the cost of solar electricity.

Reliability factor	Effect on cost of solar electricity	Comments
System lifetime	Allows initial costs to be distributed over more kWh of production	Utility applications may benefit from ultra-long lifetimes, whereas rooftop products may optimally be designed to have lifetimes similar to roof lifetimes.
System availability	When system is not functioning because of failure or maintenance, fewer kWh are generated	System availability can significantly increase cost if the lack of system availability goes undetected or if replacement parts are unavailable, delaying repair.
Degradation in performance	A 1% degradation per year over a 20 year lifetime will decrease the kWh generated by ~10%	Modules have shown < 1% degradation per year, but new products can show much higher degradation rates.
O&M costs	All systems require maintenance, which translate directly into added cost of electricity	The O&M costs for the same product vary depending on installation quality and the distance the repairman travels.
Predictability	Confident predictions of system performance, availability, and lifetime translate directly into lower interest and insurance rates	The interest and insurance rates are highly dependent on the application and financing scheme.

Table 2. Simplified cost analysis as a function of key assumptions.

Cost ($/W)	Generation rate (kWh/kW/yr)	Degradation rate (%/yr)	Average O&M cost ($/kW/yr)	Lifetime (yr)	Generation in lifetime (kWh/kW)	Cost in lifetime ($/kW)	Electricity cost (cents/kWh)
5	**1000**	0	50	20	20,000	6000	30
5	2000	0	50	20	40,000	6000	15
5	2000	**1**	50	20	36,000	6000	17
5	2000	0	**500**	20	40,000	15,000	38
5	2000	0	50	**50**	100,000	7500	7.5

2. QUALIFICATION-TEST DEVELOPMENT

2.1 History of Jet Propulsion Laboratory (JPL) Block Buys

In the late 1970s, JPL conducted a series of Block Buys of PV modules [3]. For each Buy, they required that the module design pass a set of tests. The modules were deployed and the resulting failures analyzed to revise the set of tests. A summary of the requirements is shown in Table 3 along with a subset of the requirements of today's international qualification test for silicon modules, IEC 61215 [4]. The IEC 61215 also includes a number of other tests, including application of damp heat for 1000 hrs. Qualification tests for thin-film (IEC 61646) and concentrator (IEC 62108) modules are similar. The use of these qualification tests to identify design flaws has been very helpful toward improving field performance. Whipple reported [5] that modules tested to JPL Block V had failure rates of < 0.1% compared with 45% for pre-Block-V testing. A Block VI Buy was planned, but not implemented [6].

Table 3. Comparison of some of the primary features of JPL Block testing and today's qualification test, IEC 61215.

Test	Block I	Block II	Block III	Block IV	Block V	IEC 61215
Year	1975	1976	1977	1978	1981	2009
Thermal Cycle (°C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90	200 cycles -40 to +85 w current flow
Humidity or humidity/freeze (RH is relative humidity)	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C	10 cycles 85 C, 85%RH to -40 C; 1000 hr 85 C, 85%RH
Hot spots	-	-	-	-	3 cells, 100 hrs	5 hr, worst case
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa	3 cyc. 2400 Pa
Hail	-	-	-	9 impacts 3/4" - 45 mph	10 impacts 1" - 52 mph	11 impacts 25 mm - 23 m/s
High pot	-	< 15 μA 1500 V	< 50 μA 1500 V	< 50 μA 1500 V	< 50 μA 2*Vs+1000	1 min at 2*Vs+1000, then measure @ 500 V: R X A > 40 MΩ⊕m^2

2.2 History of additional qualification test development

In parallel with JPL's work, the Joint Research Center of the European Commission, Ispra, Italy also developed qualification tests. Their early testing (CEC 201) [6] included hail, UV, wind, temperature cycling, "smog," humidity cycling, and thermal degradation including shocks from cold-water spray. The CEC 201 test later evolved into CEC 501 and 502 [6]. Clemson University subjected PV modules to the 85°C/85% relative humidity (damp-heat) test commonly used by the semiconductor industry [7]. The damp-heat test has been retained in today's qualification tests and is often one of the most difficult tests to pass [8]. A review of the development of the qualification standards tests was published in 2008 [6].

3. DESIGN FOR RELIABILITY AT ALL DEVELOPMENT STAGES

3.1 Product development cycle

Consideration of reliability issues at every stage of development can save time and cost in the long term. Before a prototype is ever made, reliability should be systematically evaluated and anticipated issues addressed. Numerous tools are commonly used both in the design and design-review stages including Advanced Product Quality Planning, Design Failure Modes Effects and Analysis, Fault Tree Analysis, Design for Manufacturability, and Design Review Based on Failure Mode (originally developed by Toyota). Fig. 2 shows a simple depiction of the sort of cycle that is used to identify and remove design flaws at the prototyping stage. Design flaws can shorten product/system lifetime and reduce performance in the field, and, in some cases, can kill a development cycle before product realization even takes place. An outgrowth of this cycle is the development of a qualification test, as described in section 2, above, and, subsequently, tests/controls for use during manufacturing. The qualification test standard represents the cumulative knowledge of the community. However, such tests may not uncover failures for which tests have yet to be devised. The process in Fig. 2

or a related process must be reapplied every time a part of the design is changed. Thus, as long as the industry is attempting to reduce cost and improve performance, the product must be reevaluated for potential failures.

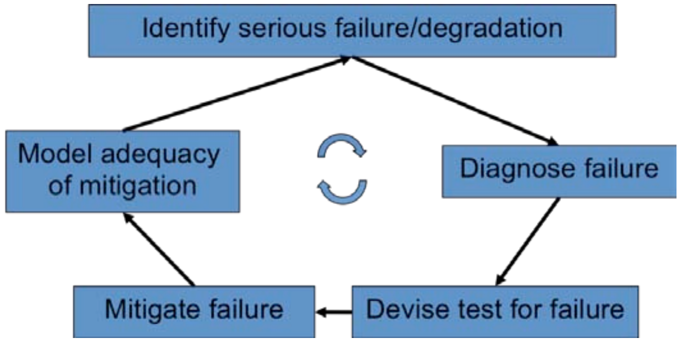

Fig. 2. Cycle for identifying and mitigating design flaws during product development.

3.2 Quality assurance (QA) during manufacturing

Careful control of manufacturing processes (a QA program) is an essential element of being able to deliver a consistently reliable product. After a product design is frozen and the product is put into production, the reliability of the product may falter if raw materials vary in purity, process conditions drift outside of acceptable ranges, new employees execute processes in a new way, etc. One simple strategy for QA is to periodically repeat the qualification test procedure on some fraction of the manufactured product. However, IEC 61215 can take weeks or months to complete, potentially allowing millions of dollars of flawed product to be shipped before a problem is identified. A preferred approach is to qualify each new raw material that comes into the process, identify acceptable ranges for each process control parameter, and use rapid tests to ensure that all aspects of the manufacturing are under control. Many companies use an ISO 9001 process for ensuring control of the manufacturing process, but the ISO 9001 standard provides only the framework for tracking whether prescribed controls are in place; it does not attempt to define what controls are needed. Research is needed to identify the best (effective and low-cost) QA tests and controls to use. The results of these tests (e.g. silicon purity and adhesion strength) may be used as relevant information in a model that predicts long-term reliability.

3.3 Confident predictions

In section 1.2 we presented the importance of annual energy production, system degradation, O&M costs, and system lifetime on lowering the cost of solar electricity. Potential PV-system investments are evaluated using these and related metrics. Confident predictions are needed for both current and next-generation products. Ideally, industry can develop a new product/component and immediately predict the long-term performance of the modified system in the customer's application/environment. Past history has shown that even small changes in product design can cause startling changes in reliability, sometimes in ways that were unexpected. Module and inverter qualification test sequences have been very successful in identifying design flaws that are likely to lead to early field failures; but these pass/fail tests provide the basis for only qualitative, not quantitative, predictions. Careful control of manufacturing processes is an essential element of being able to deliver a consistently reliable product. In addition, confident predictions require statistically significant data from fielded systems with variable conditions as well as laboratory-generated accelerated-life-test data.

Reliability predictions can be made by 1) identifying a failure mechanism, 2) identifying the stresses that cause that failure, 3) determining the functional relationship (linear, quadratic, exponential, etc.) between the application of stress and the rate of failure, 4) applying accelerated stress and measuring the failure rates to quantify this functional relationship, 5) quantifying the stress expected in the field, and 6) putting all of this information together and applying probabilistic methods to predict the expected performance. Each of these steps is, ideally, repeated for each failure mechanism. Each measurement and model has an uncertainty. The challenge is to complete these steps with a prediction that has a high degree of confidence.

Fortunately, there are some PV products, primarily c-Si modules, which have been in the field for more than 20 years, allowing limited assessment of long-term performance from real-world experience, including identification of failure mechanisms, estimation of performance-degradation rates, and putting bounds on system lifetime. Based on such observations [9, 10], we may predict that "mature" Si modules will exhibit degradation rates between 0% and 1% per year and will last 15-30 years. "Mature" thin-film modules typically exhibit degradation rates between 0% and 3% per year and last 10-20 years. By "mature" modules, we mean modules that have passed the qualification test sequence, have been tested in the field for at least 2-5 years, and have been manufactured long enough to have a strong QA program. Although these predictions do not come with 100% confidence for all "mature" modules, these predictions serve as a benchmark against which to compare new predictions for modules.

There is less information available on Balance of System (BOS) components; inverters, disconnects, combiners, etc. Test standards for inverters have elevated the quality of the products entering the marketplace; historic field data reflect inferior service life compared with today's improved inverters. Projected lifetimes based on warranties, have increased as well. Studies are being conducted to better define inverter performance degradation and develop acceleration factors. Still, the available information generated from system evaluations indicates that BOS components are significant contributors to reduced reliability/availability of fielded PV systems and are likely to be more important than the PV modules in determining system lifetime/performance [11].

Some failure mechanisms affect products in reproducible, quantifiable, and, therefore, predictable ways. For example, the life of a transistor may be quantified as a function of operating temperature, using measurements from thousands of samples to elucidate the variability and factors leading to that variability. In contrast, field failures of PV components are often traced to widely varied environment conditions, improper installation or local unexpected conditions (such as a critter that chews on wires). Thus, a prediction of the degradation or failure rate for one specific failure mechanism as a function of a specific stress becomes irrelevant if the life of a component is limited by a different failure mechanism or stress.

Recognizing the challenges helps to direct efforts. It is the reliability of the PV *system*, rather than the individual PV component, that is typically most important to the customer. A systems-level approach to reliability predictions requires 1) understanding of how each component affects system performance, 2) identification of interactions between components that increase the probability that reliability is impacted, 3) identification of the system components that dominate the system reliability, 4) quantification of the reliability functions for these most important components, and 5) use of these reliability functions to predict availability, reliability, O&M, and degradation rates of new systems. Literature studies have consistently shown that, at the system level, inverters dominate maintenance costs. For example, a study at Tucson Electric Power showed that 69% of unscheduled maintenance costs for PV-system operation were attributed to inverters [11], as shown in Fig. 3. This distribution depends on the age of the system [12].

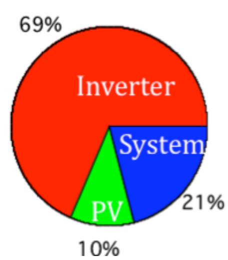

Fig. 3. Unscheduled maintenance costs for PV system operation [11].

Sandia National Labs has been documenting best-practice reliability methodologies [13] and developing a systems-level reliability model called PVRAM (Photovoltaic Reliability and Availability Model). PVRAM is a comprehensive approach to estimating the reliability and availability of photovoltaic systems. A fully functioning stochastic model will incorporate aggregated field data from multiple systems in multiple environments and with multiple technologies. This data includes field failures, failure times, and repair times; a consistent time stamp is extremely important. Data is used to generate summaries of failures, failure distributions, and failure rates; and ultimately predict annual energy production, reliability, and availability. Fidelity is added to the model by generating information on specific failure modes and degradation rates through lab-based accelerated testing and controlled exposure tests, which aid in quickly defining the reliability functions used in the modeling.

4. SPECIFIC R&D TOPICS

The PV community has impressive experience with reliability testing, but substantial R&D is still needed. It is useful to distinguish the need for reliability testing from the need for R&D on reliability testing. The most common failures for PV modules were identified and largely addressed in the late 1970s and in the 1980s, as described above. These common failures are seen in new, poorly designed products today, but test methods for these failures are fairly well defined. In contrast, there are some types of failures for which appropriate test methods still need to be defined. For all of the areas described below, there is a need to 1) compile/understand failure modes, 2) develop diagnostics that assist in system failure mitigation, and 3) develop accelerated life tests and subsequent test standards. In general, much research is needed to understand how to improve the confidence in prediction of long-term performance. Confidence in long-term predictions can only be achieved through correlation of field data with the measurements that are done during application of the QA program and/or from accelerated tests of companion products.

4.1 Balance of system

Despite improvement in the performance of many system components, these still tend to dominate PV-system maintenance costs [11]. Sandia National Labs is supporting an effort to develop an inverter qualification test. Reduction in cost and improvement in performance may be realized through new mounting systems (especially for building integration) and optimized system design to reduce losses from shading, etc. Key R&D topics currently include development of microinverters, improving arc-fault protection circuits, and extending the lifetime of the inverters by avoiding failures with electrolytic capacitors, fans, and other components. Table 4 summarizes some of the issues.

Table 4. Summary of reliability issues for system components.

Issue	Description	Tests	References	R&D need
Inverter malfunction	Inverter may disconnect or stop functioning; electrolytic capacitors are especially problematic; the need to use a fan can limit lifetime.	UL 1741; qualification test for inverters is being developed. Related standards include: IPC-9592; EN 60730-1; GB/T 19064.		Mitigation, including all-solid-state (no capacitors) design; qualification test; early-failure test.
Arcing or other failure of system connections	Imperfect electrical contact at connectors can cause arcing leading to fires.			Arc-fault detection & mitigation; qualification test.
Improper installation	Installation does not follow National Electric Code; modules are improperly mounted; many other possibilities	Training of installer	[14, 15]	

4.2 Common issues for all types of PV modules (including packaging)

Table 5 summarizes some of the most important reliability issues that are common to all types of PV modules. As the industry is looking for ways to reduce cost and improve the performance of PV modules, every element of the module is scrutinized. For many years cerium was added to solar glass to increase the absorption in the UV, thereby reducing the exposure of the encapsulant, e.g. ethylene vinyl acetate (EVA), to UV. Recently, some companies have begun using glass without cerium along with EVA that has been formulated to tolerate high UV doses. This change may be beneficial unless the EVA formulation is uncontrolled. Kempe, at NREL, has shown that modules without cerium lose adhesion 8X sooner, highlighting the importance of careful control of the EVA formulation for the UV-transmissive glass [16].

Replacement of EVA with other encapsulant materials could result in new failure modes. For example, some encapsulant materials soften at high temperatures, allowing module components to creep, potentially causing safety issues. A recent study by Kurtz, et al, documented the temperatures that are observed in the field and extrapolated these to the hottest places on earth to quantify expected thermal aging and the temperatures that might lead to a creep condition [32]. These and related results will be used as a basis for a standard method for testing the modules and materials.

Table 5. Reliability issues to consider for most PV modules.

Issue	Description	Tests	References	R&D need
Loss of electrical connections (to cells, in junction box, or leads coming out of module)	Thermal cycling or other mechanical movement causes increase in series resistance through broken solder bonds or other failure.	Thermal cycling (with forward-bias current to increase heating of weak points); robustness of terminations test; outdoor exposure.	[17, 18]	
Delamination with subsequent moisture ingress	There can be many reasons for decreased adhesion and associated delamination; the subsequent moisture ingress can cause corrosion, safety issues, loss of mechanical integrity.	Damp heat exposes sensitivity to moisture ingress; humidity-freeze testing can accelerate delamination when adhesion is poor; UV exposure may cause decrease in adhesion; the wet leakage current test detects failure; outdoor exposure.	[19-28]	EVA has been studied extensively, but new encapsulants are not as well understood.
Improper installation	Can lead to mechanical damage of glass or frame, corrosion of frame and/or ground, and many other things.	Training of installer.	[14, 15]	
Glass fracture	Fracture of the glass can lead to serious safety issues; may be a result of weak glass, improper handling of modules, hail, vandalism, etc.	Hail impact; mechanical load.	[29, 30]	Understanding of ramifications of using thinner glass or glass replacements; design of frame.
Hot spots that are not adequately controlled by bypass diodes (hot spots can also be caused by loss of electrical connection, see above) or bypass diode failure	Inconsistency in manufacturing or nonuniform illumination (e.g. shading) can cause variation in photocurrent that leads to hot spots. If bypass diode protection is inadequate, the associated heating can cause numerous types of failures.	Hot-spot endurance.	[3]	Identification of tests for new encapsulant materials that may soften or degrade at the high temperatures associated with shading or product nonuniformity.
Junction-box failure	Junction boxes can fail in many ways including mechanically because of poor mounting or because of thermal degradation since the junction box often operates above the module temperature.	Robustness of terminations; temperature cycling; damp heat; mechanical load.	[31]	The mechanical and thermal properties of many new materials are not well understood; test criteria need to be developed.

4.3 Silicon modules

Some silicon modules have performed very well in the field, with less than 1 % degradation/yr for more than 20 years [9, 10]. However, the demonstration that long life is possible is no guarantee that every module will perform well. Some of the key reliability issues for silicon modules are summarized in Table 6. Silicon module manufacturers are refining their product designs and processes to reduce cost and improve performance. R&D is needed to identify what effects these changes will have on performance in the field and whether these will be associated with reliability issues. One issue that is specific to silicon modules is the effect of reduced silicon wafer thickness on cracking of wafers.

A key desire of silicon-module manufacturers is to be able to do accelerated testing that will give quantitative assessments of service lifetimes or of expected reliability compared with other designs. The test-to-failure protocol described by Carl Osterwald [33], and following on previous work [34, 35], has been applied to a set of silicon modules, and preliminary results show the importance of voltage in driving corrosion and other degradation mechanisms [36].

Table 6. Key reliability issues for silicon modules. See also Table 5 for issues that are common to all module types.

Issue	Description	Tests	References	R&D need
Effects of use of new materials	As companies attempt to reduce the cost and improve the performance of Si modules, replacements for every component are being considered.	All	[32]	The ramifications of replacing each component need to be carefully scrutinized and test procedures modified appropriately.
Use of lower grade silicon	A common trend during the silicon shortage was to use silicon of lower or unknown purity. The lower purity can lead to increased light-induced degradation or other problems.	Outdoor exposure; thermal cycling; etc.		How to classify cells, understand localized hot spots, and appropriately use bypass diodes for minimization of hot-spot degradation.
Cracked cells	Thinner wafers can lead to cracked cells, loss of electrical connection to parts of the cells, and hot spots.	Performance (I-V curve); IR or EL imaging	[37-40]	Understanding of how wafer thickness is related to cracking, how the cracking relates to performance, and how to mitigate the effects of cracking.

4.4 Thin-film modules

The challenge of designing reliable thin-film products is reflected in the 70% failure rate for the damp-heat test reported recently [8]. Some of the key issues that are specific to thin-film modules are summarized in Table 7. The newer thin-

Table 7. Key reliability issues for thin-film modules. See also Table 5 for issues that are common to all module types.

Issue	Description	Tests	References	R&D need
Increase in series resistance after exposure to moisture	Moisture ingress is known to increase the series resistance of ZnO and some other materials commonly used in thin-film modules; this is a special issue for flexible products.	Damp heat	[27, 51] [41]	Development of thin-film products that are not sensitive to moisture or development of a barrier that keeps moisture out of sensitive layers.
Instability of thin-film layers caused by delamination and/or diffusion	Thin-film products usually require many layers; if any of these has poor adhesion, delamination may occur, often breaking the electrical connection between active layers. Also, Cu and other elements are known to diffuse, causing changes in how the cells perform.	Damp heat; temperature cycling	[18, 23, 52-57]	Develop understanding of the diffusion/delamination mechanisms, what affects them, and how to test for instabilities.
Nonuniformities in manufacturing, including scribe-line issues	Nonuniformities can lead to "weak diodes" that may then run hotter than the rest of the module, providing a weak point for degradation. Similarly, many other manufacturing nonuniformities (especially at scribe lines) can lead to reliability problems.	Damp heat; temperature cycling	[23, 58]	Much work is needed to understand what parameters must be carefully controlled during manufacturing and what nonuniformities can be tolerated.

film materials do not benefit from the large literature heritage that the semiconductor industry has provided silicon-PV manufacturers. The mechanisms for failure (including sensitivity to moisture, diffusion within the layers, problems at scribe lines, and the effects of non-uniform layer coating) are not thoroughly understood; so many years of research will be required to fully elucidate these. Kempe, at NREL, subjected copper indium gallium selenide (CIGS) minimodules to humid conditions and found an increase in series resistance that appeared to be associated with a reaction between the ZnO and water [41]. This sensitivity may be compounded by the sensitivity of other layers [42]. There are two strategies for addressing the sensitivity of thin-film modules to moisture: harden the cell or harden the packaging. Some transparent conductors are less sensitive than ZnO to moisture. Notably, indium tin oxide, fluorinated tin oxide, and amorphous indium zinc oxide are candidates [43, 44], but they must be grown in such a way that they enable good cell performance while still retaining their stable properties [45-47].

The study of the reliability of thin-film modules is complicated by metastabilities [48]. It has long been known that light causes amorphous silicon cells to degrade, with almost full recovery after annealing in the dark. However, metastabilities are also observed for CdTe and CIGS modules. In a recent study of CIGS modules, we observed a metastabilty of up to 30% in one module's efficiency. Such metastabilities may be related to copper or other elemental diffusion, or may be related to the filling and emptying of trap states. It will be useful to define procedures for "stabilizing" the modules so as to separate reversible from irreversible changes [49, 50].

4.5 Concentrating PV (CPV) modules

The modularity of CPV designs increases the number of possible reliability issues, but also provides more flexibility in solving these. Table 8 summarizes some of the key issues that are specific to CPV. A lack of control of the temperature of the concentrator cell can lead to catastrophic failure. Methods for testing this bond have been established, but prototype development could proceed more quickly if faster tests could be applied, and some of the companies are questioning the current temperature cycling test because the flow of large currents in forward bias can cause cell failure. Bosco, et al, recently presented a thermal-cycling study that more than doubled the rate of cycling and showed a method for imaging voids with an infra-red camera [59]. Acceleration of the effects of high solar flux are particularly challenging because CPV optics are usually designed to deliver the highest concentration that is easily practical. However, results presented at this conference by Miller, et al, show that lens materials may absorb enough UV to avoid significant UV transmission to the cell [60].

Table 8. Key reliability issues for CPV modules. See also Table 5 for issues that are common to all module types.

Issue	Description	Tests	References	R&D need
Failure of thermal control for cell	In contrast to the case for flat plate, loss of thermal contact between a CPV cell and its heat sink can cause catastrophic failure.	Thermal cycling (with current to increase heating of weak points)	[59, 61]	Faster test to identify low-cost, reliability thermal management schemes.
Effect of concentrated light (especially UV)	Some CPV systems experience hundreds of suns of UV exposure; even without UV light, the concentrated light can cause failures.	UV exposure	[60, 62]	Identify when UV is important; identify the causes of other failures, including a quantitative understanding of the effect of heat and how to accelerate testing.
Degradation of optics	Abrasion and other environmental exposure can cause loss of optical throughput.	Hardness; UV exposure	[62]	Different types of optical materials are sensitive to different types of stresses. The R&D must start with identifying which failure mechanisms are most important for the different designs.

5. COMPLEMENTARY ROLES

The many R&D needs highlighted in the tables above represent a critical barrier to achieving a solar-powered world. Companies need to develop products quickly (within investors' window) and the probability of success is dramatically increased if national laboratories and universities work alongside to explore a fundamental understanding of the science behind the failures and their solutions. Universities specialize in educating students; national labs can tackle problems that are long term or too difficult to be practical for universities. Fundamentally, industry exists to provide a return on investment, whereas universities and national labs strive to increase our knowledge and communicate that knowledge to the community. All three thrive through innovation. Companies have the best chance of success when working closely with universities and national labs to solve problems. Unfortunately, today's venture capitalists often treat start-up PV companies similarly to the dot-com companies: they demand a novel idea and expect the product to be brought to market in secret within a short period of time. Success will be more likely if investors encourage sharing of information about reliability issues and agree to a time line that allows opportunity for adequate product development and reliability testing.

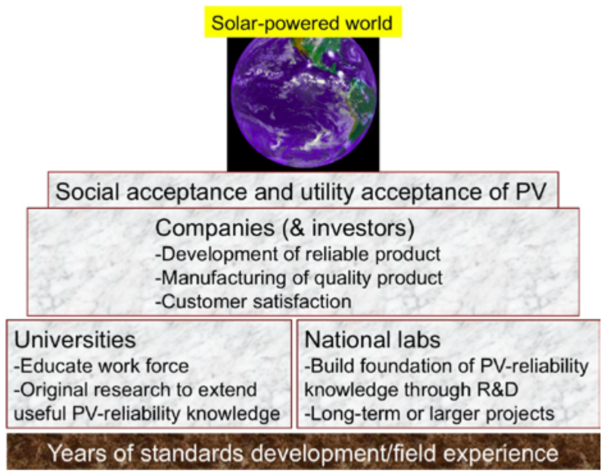

Fig. 4. Schematic showing how the universities and national labs can work together to build a foundation upon which the companies can build a solar-powered world. Opportunities for innovation arise at every development stage.

6. SUMMARY

The phenomenal exponential growth of the PV industry positions the industry for reaching significant production volumes in less than ten years, but the creation of a solar-powered world requires that these systems operate reliably. Reliable products have been demonstrated in the field, but new products have unknown reliability. The failure mechanisms for PV systems are diverse and complicated. Reliability R&D is needed to identify and understand new failure modes, to develop new and better test methodologies, and to develop reliability models that allow confident predictions of system availability, performance, and lifetime. Industry's efforts to develop reliable products are effectively supported by efforts at the universities and national labs to understand the fundamentals of PV-system reliability.

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14. ABSTRACT *(Maximum 200 Words)*
The continued exponential growth of photovoltaic technologies paves a path to a solar-powered world, but requires continued progress toward low-cost, high-reliability, and high-performance PV systems. High reliability is an essential element in achieving low-cost solar electricity by reducing operation and maintenance (O&M) costs and by extending system lifetime and availability, but these attributes are difficult to verify at the time of installation. Utilities, financiers, homeowners, and planners are demanding this information in order to evaluate their financial risk as a prerequisite to large investments. Reliability research and development (R&D) is needed to build market con¬fidence by improving product reliability and by improving predictions of system availability, O&M cost, and system lifetime. Universities, industry, National Labs, and other research entities can be most effective by working together and in complementary ways. The Department of Energy supports a variety of research projects to improve PV-system reli¬ability. These projects and current reliability issues for each PV technology are surveyed.

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