DOE Solar Energy Technologies Program TPP Final Report

Budget Period I

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Cost-Sharing Partners:	Xantrex Technology, Inc.

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Project Objective

General Electric's (GE) DOE Solar Energy Technologies TPP program encompassesd development in critical areas of the photovoltaic value chain that affected the LCOE for systems in the U.S. This was a complete view across the value chain, from materials to rooftops, to identify opportunities for cost reductions in order to realize the Department of Energy's cost targets for 2010 and 2015. GE identified a number of strategic partners with proven leadership in their respective technology areas to accelerate along the path to commercialization. GE targeted both residential and commercial rooftop scale systems.

To achieve these goals, General Electric and its partners investigated three photovoltaic pathways that included bifacial high-efficiency silicon cells and modules, low-cost multicrystalline silicon cells and modules and flexible thin film modules. In addition to these technologies, the balance of system for residential and commercial installations were also investigated. Innovative system installation strategies were pursed as an additional avenue for cost reduction.

Technical Approach

GE focused on three distinct technical pathways for the module, as well as a technical pathway that addresses the inverter/balance of system, and installation. These pathways include bifacial high-efficiency silicon module, low-cost multi-crystalline silicon module and flexible thin film module. Each pathway was self-contained, spanned the value chain to include materials, solar device, and system, as well as included critical technologies and partners. A stage-gated process was used to down-select to the most favorable approach or partnership.

Bifacial High-Efficiency Silicon Module

GE worked to develop a 20%+ efficient solar cell based on a graded amorphous silicon on crystalline silicon hybrid technology us a scalable fabrication process. The bifacial nature of this solar cell presented an opportunity for the fabrication of a highly effective 2-5x concentrator module that could reduce silicon area while maintaining the form factor of a standard one-sun design. In all high-efficiency cells, including the GE graded hybrid, the wafer represents the dominant cost. GE has partnered with Solaicx to provide a high lifetime silicon wafer that can be produced at lower cost using a CZ ingot pulling process that supports the growth of multiple ingots from a single crucible. GE was also developing a low–cost, high-quality Si feedstock based on a carbothermic reduction process.

Low-Cost Multicrystalline Silicon Module

GE worked to develop a solar cell based on a molded silicon wafer fabricated in a continuous casting process that eliminates the waste associated with conventional sawing, resulting in a wafer that is 2x less expensive to produce. The quality of molded silicon wafers will be improved so as to approach that of conventional polycrystalline cast wafers. GE also worked to develop a low-cost silicon feedstock based on a carbothermic reduction process that would be easier to scale than other processes currently in use. This process takes advantage of GE Global Research’s knowledge of high quality quartz manufacturing.

Flexible Thin Film Module

GE worked with vendors, who are developing technology for copper indium gallium diselenide (CIGS) on flexible substrates, as a source of flexible solar cells. This technology has great potential for low cost and the creation of unique building integrated products. A weakness of CIGS (and all other thin films using a thin conductive oxide) is sensitivity to moisture, limiting life well below that of a silicon module. GE has developed a set of packaging technologies for flexible organic light emitting diodes (OLEDs) that will be directly applied to the CIGS material. A novel multilayer SiN/organic film that can be directly deposited onto the solar cell or a polycarbonate sheet forms the basis for a moisture-tight package that provides four orders-of-magnitude better protection than the Teflon-based materials currently being used. In addition to moisture protection, thin film packages require UV protection as well. GE will leverage its extensive experience in the area of UV protection of polymer films to realize a fully encapsulated thin film product.

Balance of System (BOS)

GE and Xantrex Technology, Inc. will lower inverter cost and improve performance through the development of innovative new circuit designs, the implementation of high performance components, and by taking advantage of higher volume component pricing made possible by market growth. A large element of the cost is embedded in the system engineering and integration functions and in the installation. GE will be working with top PV installers to identify internally driven cost elements related to time and materials and external factors such as local codes and regulations that influence costs non-uniformly, and to develop a streamlined process flow. Additionally, in a partnership with GAF, GE is looking to market and develop new solar systems and roofing systems for residential and commercial customers.

Budget Period 1 Progress

Task 1: Validate Market and System Requirements

Goal

Task 1 is focused on understanding the market drivers for each application and determining the key system requirements. Through these activities, opportunities for cost-out will be observed and can be implemented in GE's system designs. The goal for this task can be broken up into four individual objectives. First, a more effective channel into the U.S. residential and commercial markets will be established. Specifically this channel should increase the exposure of solar to a broader cross section of consumers while providing an installation pathway that will reduce the overall installed cost and address concerns associated with system reliability. Second, a process for segmenting and comparing the cost of different PV cell, module, balance of system, and installation technologies and processes on a "level playing field" will be developed. This process will manifest itself as a framework for cost modeling of PV system up through the installed cost. This framework will leverage a database of common assumptions to help the GE team compare the different technologies.

Third, transfer functions that link the key technology parameters (Critical Success Factors or CSFs) for each technology area to the installed system cost will be constructed for each technology. Each of the technical program areas is tracking those critical success factors that best represent technical progress. Because the installed system cost is the most important input into the LCOE determination, the transfer functions can be used to identify those factors having the largest impact on LCOE. Finally, the Solar Advisor Model will be used to calculate the current project LCOE as a function of the installed system cost and compare this result with the DOE Solar Energy Technologies TPP Program guidelines for 2010 and 2015 to determine the level of success for each technical program area.

Progress Summary

1.1 Market Requirements

GE has formed an alliance with GAF to market and develop new solar systems and roofing systems for residential and commercial customers. GAF is North America's largest manufacturer of residential and commercial roofing, with a network of more than 12,000 contractors, distributors and roofing installers nationwide. The total U.S. roofing market is valued at ~$12B. Asphalt shingles account for the largest segment of the roofing market (~$8B) and for the majority of GAF's share of the steep-slope residential market. Elastomeric or membrane roofing only accounts for $1.3B, but is the fastest growing segment of the commercial low-slope market. GAF has a 30% share of the U.S. commercial market and has made a significant investment in thermoplastic olefin (TPO) producing 100 squares of TPO material at their recently opened factory in Gainesville, TX[1]. GAF has a 40% share of the asphalt shingle residential market. Based on the 2006 Fredonia roofing report this market share corresponds to 2.7M homes per year. Given a 3.5 kW per home average system, the full annual residential entitlement is ~9.5GW.

GE and GAF are working to establish joint marketing activities in the three GAF sales regions most favorable to solar sales: Northeast (includes New Jersey), Southwest (includes Arizona), and West. These territories account for 56% of GAF U.S. sales. A series of focus group sessions have been held with GAF commercial and residential contractors as well as solar integrators, and specifiers in these regions. The purpose of these sessions was to introduce the contractors to the alliance, present information on the solar industry and elicit feedback on how these roofing contractors would expect to roll solar roofing into the present business. The information from these sessions has been used to drive a nationwide training program and define requirements for roofing-friendly solar installation products (Task 5.3).

Several key marketing takeaways: 6 out of 10 homes are "solar ready" meaning they have the right orientation, roof access and shading, 65% of roofing customers would consider a solar roof, and every $1,000 of energy savings adds $20,000 to home valuation[2]. On this basis the annual entitlement for GE-GAF residential solar installations in the U.S is greater than 2GW.

1.2 LCOE Transfer Functions (Installed Cost Model)

GE has developed a comprehensive integrated decision support system to evaluate the impact of new photovoltaic technology choices on consumer cost and business

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[1] Note for reference: 100 squares of a flexible solar integrated roofing material, e.g. CIGS-based operating at 10% efficiency would produce over 4GW of power.

[2] These sessions were held before the new ITC rulings that remove the residential cap and further discussions and analysis of IRR and cash flows indicate that over 75% of roofing customers would consider a solar roof based on economics.

economics under a variety of scenarios. This system provides a structured framework for expert users to enter process details associated with different technical pathways and to compare the manufacturing costs of different process options. This system will also support competitive analysis. The transfer functions produced will establish the relationship between key technical parameters for each technical pathway (including the critical success factors) and installed cost.

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1.3 Update SAM LCOE

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Task 2: Bifacial High-Efficiency Silicon

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Task 3: Develop Low-Cost Multicrystalline Silicon

Goal

This task addresses the development of a multicrystalline silicon PV product from silicon feedstock to completed module. Two paths were taken for silicon feedstock, 1) a novel, low-cost, carbothermic approach based on high purity quartz, and 2) utilizing the small powder (sub-micron to 20 mm) material from a fluidized bed reactor. Wafers are produced using a continuous single wafer casting process. Once the wafer is formed, novel solar cell processes and module assemblies have been investigated to lower cost and optimize module performance.

Progress Summary

3.1 Develop Carbothermic Solar-Grade Polysilicon Process

As discussed in detail in the original GE proposal, the primary programmatic goal was to reduce the system-level LCOE through:

- Improvements in module-level efficiency
- Improvements in inverter efficiency and reliability
- Reduction of PV system manufacturing cost
- Vertical integration of value chain through strategic partnerships

Subtask 3.1 specifically targeted the reduction of the silicon cost in multi-crystalline silicon (mc-Si) photovoltaics. Based on 2010 DOE Solar Energy Technologies TPP Program targets of ~$2.78/W module price, silicon would constitute nearly 22% of module cost if all else remained the same. The currently practiced silicon production technology is a relatively mature process compared to the rest of the value chain. Consequently, the prevailing belief is that most of the opportunity for cost-out has been exercised. Based on projected estimates of manufacturing cost, it is reasonable to assume that the cost of silicon via chlorination/distillation will put considerable pressure on upstream manufacturing cost-out in order to meet DOE Solar Energy Technologies TPP Program 2010 and 2015 targets. A low-cost solar-grade silicon manufacturing technique has an opportunity to make significant impact to the system LCOE.

The tactical goal of subtask 3.1 was to design, construct, and commission a pilot-scale carbothermic reduction reactor and compare/contrast this new material to conventional polysilicon with respect to purity and cost. This was divided into two stages. Stage 1 focus consisted of process development, and Stage 2 focus consisted of process optimization. As GE's involvement with DOE Solar Energy Technologies TPP Program was terminated after tollgate 1 of the program, the development discussed here will be limited to Stage 1 development. A pilot-scale carbothermic reduction reactor has been installed. Though development did not progress far enough to operate the furnace as envisaged, the furnace is designed to operate continuously; an insulated fused-quartz capture crucible is located below the furnace to collect silicon generated in the reactor.

Process Thermodynamics:

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Process Kinetics:

Work began on an empirical model for the GE carbothermic reduction process by separating the process into the constituent reactions discussed in the previous section. The purpose of these experiments was to determine the reaction kinetics associated with reactions [1] and [3], which when taken together represent the following global reaction:

$$SiO_2 + 3C \rightarrow SiC + 2CO \qquad [6]$$

This reaction constitutes the first part of the overall carbothermic reduction process discussed earlier. This reaction can be modeled empirically using the general reaction equation:

$$\text{Rate} = k[SiO_2]^a[C]^b$$

The constant k is the rate constant, $[SiO_2]$ is the silica concentration, [C] is the carbon concentration, and a, b are exponents describing the reaction order for each reactant. As the reaction leads to the formation of CO, measuring the evolution of CO as a function of time and temperature yields results sufficient for the calculation of the necessary rate information. Provided the aforementioned rate equation is constant (i.e. a, b constant) over the temperature range in question, the rate constant (k) follows an Arrhenius equation of the form:

$$k = k_0 \exp(-\frac{E}{RT})$$

Thus, it is possible to determine the activation energy of the reaction provided the variation of the rate constant with temperature is known.

The experimental set-up for performing these measurements is shown in Figure 3.1.4. A mass flow meter (MFM) connected in series with the exhaust was used to measure CO evolution. Prior to entering the MFM, the gas was cooled by flowing through a water-cooled heat exchanger. The datalogger collected time-resolved data for CO evolution rate. Typical collection time was 3 hours. The resultant data is shown in Figure 3.1.5.

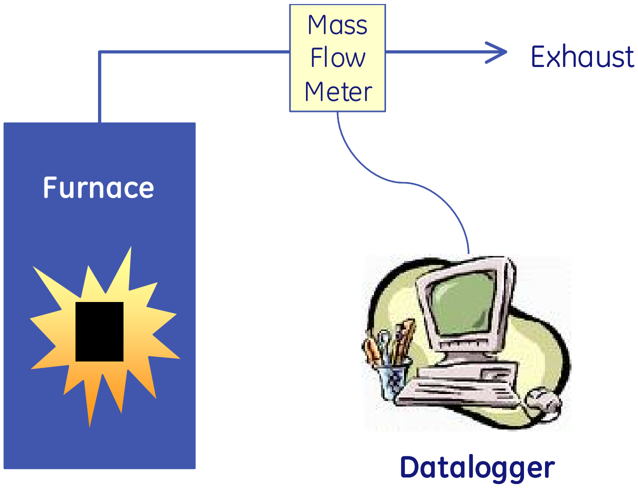

Figure 3.1.4: Experimental apparatus for measuring CO evolution in SiO_2 + C specimens.

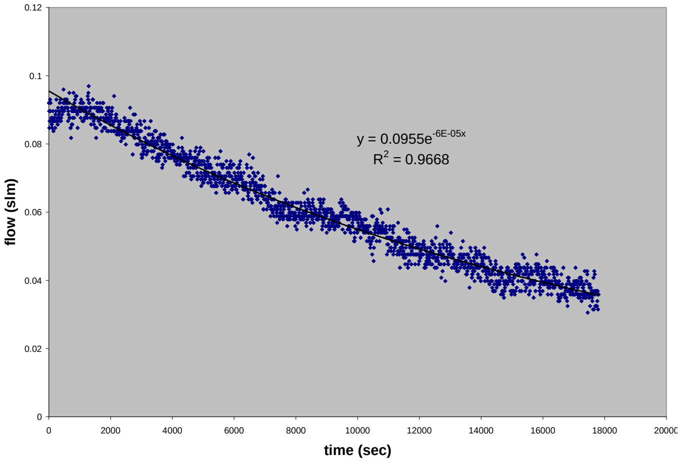

Figure 3.1.5: Raw data from mass-flow meter.

The data requires manipulation to produce the form required to extract *k*. First, d[CO]/dt is determined from the initial flow data. Similarly d[C]/dt and d[SiO_2]/dt is extracted from the data using the stoichiometric relations:

$$-d[SiO_2]/dt = 1/2 \cdot d[CO]/dt$$

$$-d[C]/dt = 3/2 \cdot d[CO]/dt$$

$$d[SiC]/dt = 1/2 \cdot d[CO]/dt$$

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Process Results:

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Table 3.1.1: Trace impurity analysis for representative silicon samples.

Sample	Testing Method	Detection Limits (ppmw)	Boron (ppmw)	Phosphorous (ppmw)	Total Transition Metals (ppmw)
GE Solar run 14	ICP-MS	0.05	0.72	0.30	1.69
GEGR 091108	ICP-MS	0.05	0.42	0.60	11.04
GEGR 092508	SIMS	0.0002	0.13	0.11	---
GEGR 061708	SIMS	0.0002	0.27	0.13	---

3.2 Evaluate Fluidized Bed Reactor Process

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3.3 Improve Molded Wafering Process

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3.4 Optimize Cell Process

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3.5 Create Innovative Module Products

The GE team is developing a model of the solar contacts and module interconnects to evaluate and optimize interconnect strategies. This model will mainly rely on a Spice-based analysis to compare and contrast different approaches for cell-to-cell interconnection. Development work has focused on the Metal Wrap Through (MWT) design. Although development was initially slowed due to the delay in Molded Wafer production issues and the availability wafers, the GE team is now working with ECN to obtain some MWT cells and modules for evaluation.

Task 4: Develop Low-Cost Flexible Thin Film Modules

Goal

The goals for the period of performance were to validate that the DOE Solar Energy Technologies TPP Program LCOE 2010 goals can be met, to identify cell-to-cell and power-off-module interconnect strategies for flexible modules, and to model resistance losses for these strategies. Additional milestones were defining, procuring, and validating the performance of test cells from vendors, identifying barrier requirements for CIGS devices via moisture degradation models, demonstrating barrier films that could pass damp heat testing, and defining and testing of UV stabilization schemes for plastic packaging. All goals and milestones were met.

Progress Summary

Performance data for cells from three vendors (17-25cm^2) is summarized in Table 4.1. Companies A and B supplied ~100 experimental cells each. Global Solar supplied ~1800 Gen-1 production cells used in their portable battery charger products. To date they have supplied over 1800 cells. Both company A & B cells are made via a two-step process and have lower band-gap (confirmed by QE measurements) and thus lower V_{oc} than Global solar cells, which are co-evaporated, but they also exhibit lower fill factors. Global Solar cells showed improvement over the course of this work.

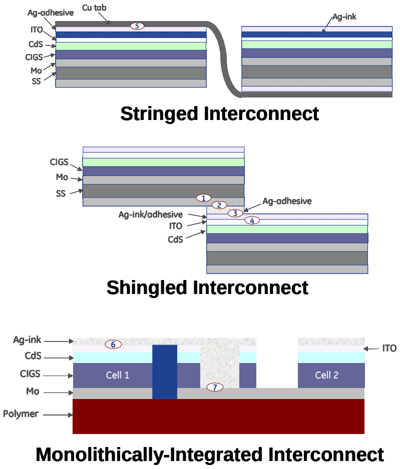
Table 4.1 Validation of CIGS cells from vendors.

	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	Fill Factor (%)
GSE 2009	11.59	576	31.8	63.3
GSE 2008	10.16	547	32.1	58.0
Company B	9.12	508	32.9	54.6
Company A	6.52	433	29.9	50.3

Three interconnect strategies were considered; namely tabbed/stringed cells, shingled cells, and monolithically integrated cells, shown in Figure 4.1. The combination of the various bulk and contact resistances impact the overall power loss in the modules. Moreover, the arrangement of the cells (combinations of series vs. parallel) will further affect the contribution of the interconnects. Two experimental test structures were used to accurately extract the contact and sheet resistance of the different materials used in the 3 interconnect strategies. Structures based on both the transmission line measurement (TLM) method and the Kelvin resistance method (KRM) were used. KRM structures will be encapsulated to study the degradation of interconnects under accelerated life testing conditions.

A tool was developed to predict the electrical performance for the three different interconnect strategies under consideration. A hierarchical model was created in PSpice. The model incorporates a full cell with series (including on-cell resistance) and shunt resistances. The cells are further connected in series to form a string. The string hierarchy incorporates the cell-to-cell interconnect resistance. A number of strings are connected in parallel to form a module. The module hierarchy includes power-off interconnects. The information from the contact resistance measurement studies served as the input to the electrical model, and was validated with cell measurements.

A screening study was performed where the cell width and module power were held constant and the cell length and interconnect contact width varied. As the cell length is reduced, a higher number of cells is required to output the same power which increases interconnect losses and a loss of module productive area due to spacing between cell strings, but at the same time the on-cell resistance decreases. Thus cells that are too short are poor due to interconnect losses and dead areas of interconnects and cell spacings, while cells that are too long are poor due to on-cell resistance losses. This is shown in Figure 4.2, where there is an optimum cell length for each interconnect strategy. There is also an optimum interconnect width as a result of resistance losses at narrow connections and dead area at wide connections. These initial results indicate that shingled gives the highest efficiency, followed by gridded monolithic, and then stringed. Gridded monolithic is superior when one considers the cost of the cell areas covered by shingling.



Stringed Interconnect

Shingled Interconnect

Monolithically-Integrated Interconnect

Figure 4.1 Interconnect strategies .

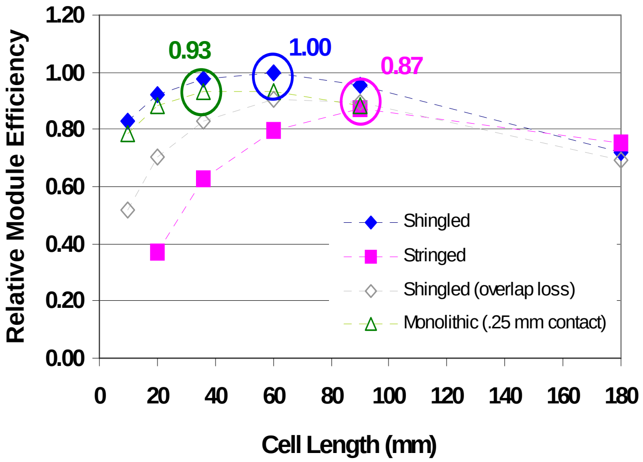


Figure 4.2 Electrical performance of interconnect strategies .

This tool was used to evaluate the electrical losses due to spacing, shading, cell-to-cell interconnect resistance, and on-cell resistance, for each of the three strategies. The cell-to-cell losses are a function of the interfacial resistances and contact geometries described above. The on-cell losses are a function of the sheet and contact resistances of the ITO and Ag-ink and their geometries as they vary with cell size. Figure 4.3 shows a plot of the normalized efficiency in the five cases for the three interconnect strategies. The power loss is the lowest for the module with shingled interconnects, followed by monolithic and stringed strategies. On-cell interconnects have the largest impact on the shingled case. For the monolithic interconnected module, the largest contribution to the power loss is due to the shading that is worsened by the 'dead' interconnection areas. As expected, the strung cells have significant power loss due to cell-to-cell spacing and on-cell resistance. In all the three strategies, the cell-to-cell interconnect resistance was never the biggest contributor toward power-loss. The monolithic strategy had the largest power-loss due to cell-to-cell interconnect resistance among the three considered. This is primarily due to narrow contact geometries in monolithic modules. Figure 4.4 summarizes the contributors to power losses in each strategy. The three interconnect strategies were also compared for high output voltage modules (400V). The effective power-loss in monolithic integrated modules would be similar to that of shingled modules. The distinct electrical advantage of shingled modules seemed to decrease in high voltage application. The power-loss in stringed modules was significantly higher due to shading and on-cell losses.

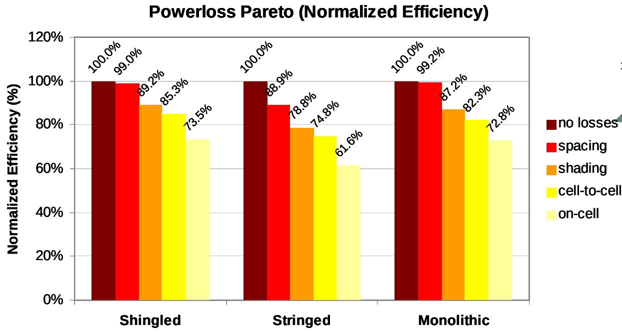


Figure 4.3. Model output of power-loss in medium/low voltage modules.

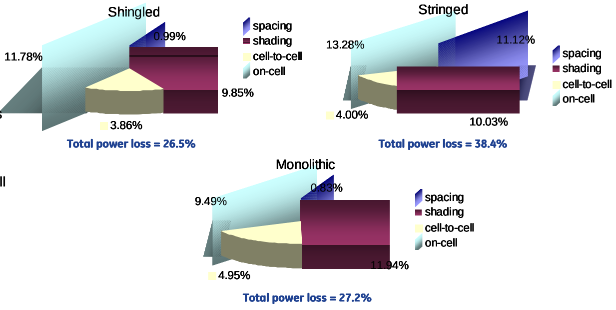
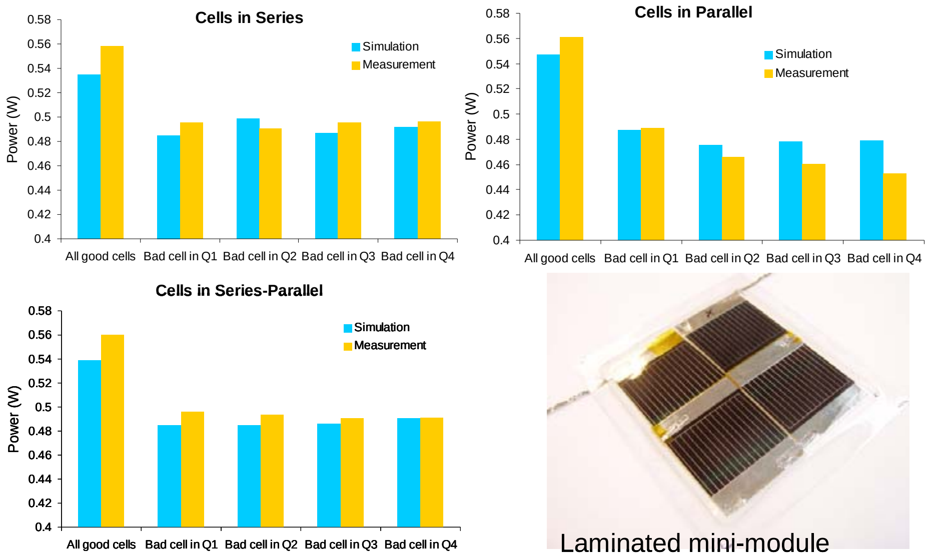


Figure 4.4. Contribution of different factors to power-loss in medium/low voltage modules.

The model was validated through a series of experiments. The on-cell resistance was validated using the method of multiple light intensity measurements to estimate on-cell series resistance for cell of various area ratios thus drastically changing the grid geometry. For all cases the predicted values of P_{max} were within 4% of the measured ones. The cell-to-cell resistances were validated by adding known series resistances between cells in a 4-cell module. The predicted values of P_{max} were within 6% of the measured ones. Finally, the impact of mismatch in cell performance in a module was compared between simulations and experiments by baselining a mini-module performance with closely matched (10%) cells, then substituting a low-efficiency (6%) cell in each of the 4 positions, for the three configurations of a) All cells in series, b) All cells in parallel, and c) Two strings of series connected cells in parallel. Figure 4.5 shows that the predicted and measured values were within 3%.



Laminated mini-module

Figure 4.5. Comparison of simulated and experimental power loss due to cell mismatch in series and parallel connected modules.

CIGS cells are known to be sensitive to moisture, thus some type of barrier layer is needed for flexible modules where glass is replaced by permeable plastic. There are three objectives, namely 1) pass IEC 6-1647 “Damp Heat” 85^{o}C/85%RH for 1000 hrs with less than 10% degradation, and 2) predict the real-world lifetime of a module, and 3) develop a cost-effective package to provide ~20 year life.

The moisture-induced degradation rate of CIGS solar cells at 22-85^{o}C and 0-100% RH was measured, and results fit to a kinetic rate expression, shown in Figure 4.7. This expression is coupled to a model of moisture diffusion into a package and typical meteorological input data to create a cumulative damage model to predict lifetime of packaged cells (Figure 4.8). For a 10^{-4} g/m^{2}/day barrier and EVA encapsulant the diffusion half-time is about 20 years, but the calculation shows that in Miami there is rapid enough degradation to make the module fail long before equilibrium is approached. While Kempe [Kempe, M.D., “Modeling of rates of moisture ingress into photovoltaic modules,” *Solar Energy Materials & Solar Cells* **90** pp. 2720–2738, 2006.] reasoned correctly that the lifetime should scale with diffusion half-time, our CIGS degradation kinetic data combined with this model allows us to compute the actual scale factor for any measured cell degradation kinetics.

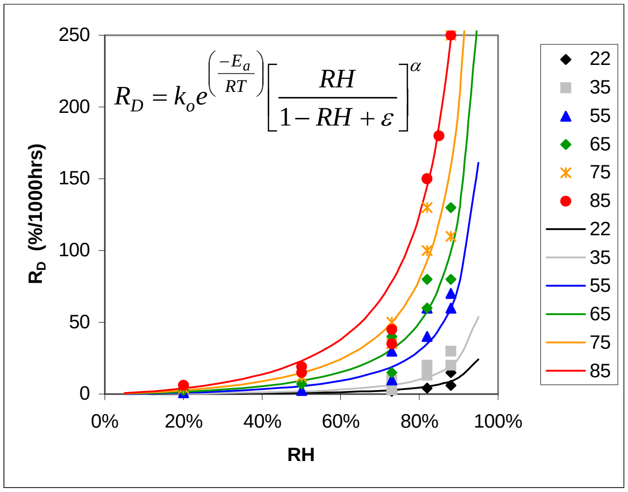


Figure 4.7 Degradation rate vs temperature and humidity.

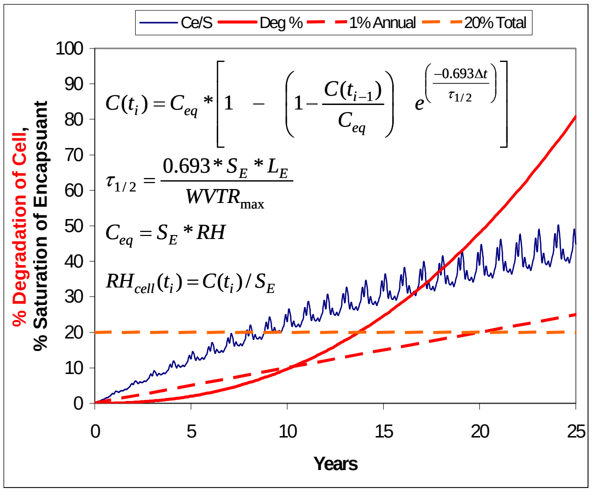


Figure 4.8 Diffusion and degradation of a module with 1x10^{-4} g/m^2/day barrier in Miami.

The model was run for packages with a range of WVTR and for exposure conditions of Miami, Phoenix, and Golden CO; and for the cases where both sides are cooled by convection and radiation vs having one side insulated (simulating BIPV). Figure 4.9 plots the module life, defined as the number of years to reach 20% degradation of P_{max}. Results for the kinetic parameters measured for these GSE cells indicate that a barrier of <10^{-4} g/m2/day or better will be required to assure 20 year lifetime in Miami. Other less stable cells will require 10-100X better moisture barrier, while more stable cells will require ~10^{-3} g/m^2/day. It was found that the conductive adhesive on these cells was moisture sensitive and caused catastrophic R_S rise at low temperature and high humidity, indicating that these low life predictions are in part due to degradation of the conductive adhesive, so that using a more stable one will result in a different set of kinetic constants and thus a longer predicted life. Figure 4.9 also shows that modeling the back as insulated dramatically increases the module temperature during the day, but also significantly reduces the moisture content the air at the module surface. These two effects tend to cancel out for the CIGS degradation kinetics measured here.

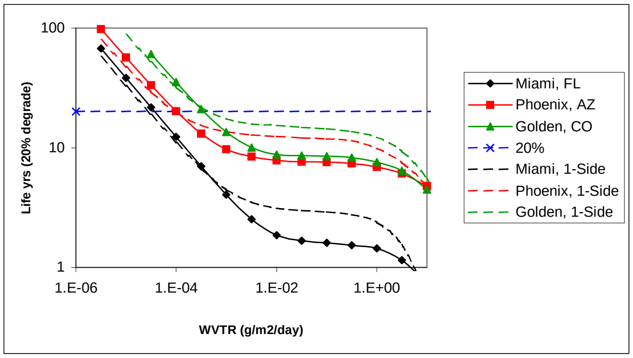


Figure 4.9. Module life as a function of moisture barrier water vapor transmission rate and geographic location, for 2-side cooled (with symbols) and 1-side insulated (dashed) modules.

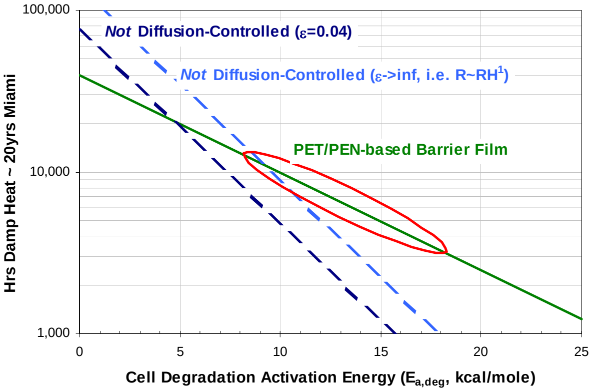


Figure 4.10. Hours of 85C/85%RH required to simulate 20 years Miami exposure, as a function of cell degradation activation energy.

Analytic solution of the degradation is possible assuming constant temperature and humidity. For an initially dry module, the time-dependent degree of encapsulant saturation (shown in Figure 4.8) can be substituted into the degradation rate (shown in Figure 4.7) and integrated to give the cumulative degradation vs time as

$$\frac{D(\tau)}{R_{Do}t_c} = \tau + (\beta+1)\ln\left(\frac{\beta+e^{-\tau}}{\beta+1}\right) \qquad \beta = \frac{1+\varepsilon-RH_o}{RH_o}; \quad \tau = t/t_c; \quad t_c = \frac{L_E S_{E,o}}{WVTR_{\max,o}}$$

where R_{D0} is the degradation rate at a reference temperature and humidity, both conveniently chosen as ambient averages. The above degradation expression is valid for outdoor exposure for all times as long as t_c>>1yr and the correct average temperature is chosen as a reference. This equation closely matches the full numerical solution for Miami for a package that is diffusion-controlled. Only as the diffusion time gets less than one year does the approximation of constant average environmental humidity and temperature cause any inaccuracies.

One can define a service life L as the time for a certain cumulative degradation D_L to be reached, which can be approximated by manipulation of the above equation to solve for the life L as

$$L = \left(\frac{2D_L(\beta+1)}{\beta}\right)^{\frac{1}{2}}\left(\frac{t_c}{R_{Do}}\right)^{\frac{1}{2}} = \left(\frac{2DL(\beta+1)}{\beta}\right)^{\frac{1}{2}}\left(\frac{L_E S_E}{R_{D0}WVTR_{\max}}\right)^{\frac{1}{2}}$$

The first term is a constant that depends only the exposure location and the CIGS degradation fit (ε). The life thus depends on the square root of the diffusion time and degradation rate – i.e. doubling the life requires reducing by a factor of 4 either the WVTR or degradation rate. Cells with double the degradation rate will either have 1/1.4=0.7X the life or will require a package with half the WVTR.

The model now allows us to compute acceleration factors for stress testing such as "damp heat." Since there are two processes occurring simultaneously and each is accelerated differently, there is no simple "acceleration factor" between damp heat and Miami for all cells and packages. General expressions for acceleration are

$$A_{diffusion} = \exp\left(\frac{E_{a,\deg}+E_{a,perm}-E_{a,S}}{2R}\left(\frac{1}{T_u}-\frac{1}{T_a}\right)\right)\left(\frac{RH_a}{RH_u}\right)^{\frac{1}{2}}; \quad A_{linear} = \exp\left(\frac{E_{a,\deg}}{R}\left(\frac{1}{T_u}-\frac{1}{T_a}\right)\right)\left(\frac{RH_a(1-RH_u+\varepsilon)}{RH_u(1-RH_a+\varepsilon)}\right)$$

for the diffusion-controlled and not-diffusion-controlled ("linear") cases, respectively. The factor of 2 in the denominator of the exponential term of the diffusion-controlled equation is a result of the square root dependence of this diffusion-controlled process.

Figure 4.10 shows the acceleration of "damp heat" vs Miami for a typical plastic package. Since the cell activation energy measured here is only 8 kcal/mole, it would take 12,000 hours of damp heat to simulate 20 years in Miami. Other cells and adhesives might give higher activation energies and therefore require fewer hours in damp heat testing. A cell degradation activation energy of about 22 kcal/mole (~1eV) would be required for 1,000 hours to be an adequate test for a diffusion-controlled package. This clearly shows the danger of arbitrarily assuming a value of activation energy in interpreting accelerated test results. If the process were not diffusion-controlled (blue dashed line in Figure 4.10) then much greater acceleration is possible at the higher activation energies.

This section of the report contains proprietary information that has been omitted.

We identified two fundamentally different stabilization schemes for transparent but not inherently stable polymer films (i.e. polycarbonate, PET, PEN; not ETFE). The first approach uses coatings with high-performance UV stabilizers, where such thin coatings are relatively low-absorbance and degradation is governed by initial absorbance and stability of UV screener molecule. For these systems we must follow absorbance vs. time and temperature at accelerated conditions, and look for a constant rate of absorbance loss per year to aid in extrapolating to the dose required for failure. We investigated three highly stable UV absorbers: DBR (4,6-dibenzoylresourcinol), SDBR (silated dibenzoylresourcinol), and LA-46 (a commercial triazine from Adeka-Palmarole). A multi-temperature experiment was carried out by solvent casting PMMA films containing DBR or LA-46 and laminating those films onto UV-transparent PMMA plaques. SDBR is formulated into a silicone hardcoat and applied to glass microscope slides. The samples are attached to polycarbonate backings of various colors to achieve temperatures ranging from 50 to 75°C when mounted in the offset position in our xenon arc Weather-ometer (approximately 14X acceleration). Extracting the slope from these curves after any initial changes gives the rate constant k in our kinetic model, which uses an Arrhenius temperature dependence. Our results are that a DBR/LA-46 coating with initial absorbance of 5-6 will give 25+ year performance with some safety margin. SDBR in a silicone coating is similar.

The second UV-stabilization scheme uses thermoplastic cap layers made of either resorcinol polyarylate (LEXAN® SLX) or co-extruded highly stabilized polymer layers on base film. Such thick layers are very high absorbance and degradation is governed by physical erosion of the surface in microns/yr. Lifetime is determined by first experimentally determining this erosion rate, and then extrapolating to exposure time when the protective layer thickness approaches zero. We measured erosion rates for polycarbonate containing 6-10% of the conventional UV absorbers Tinuvin 360, Tinuvin 1577, LA-46, Uvinul 3030, and DBR. A reasonable target for a 30 year life would be about 0.8 micron/MJ erosion (requiring a 100 micron cap layer). Data indicates that Tinuvin 1577 and LA-46 at about 8% concentration, as well as resorcinol polyarylate (ITR) seem viable for 30 year life.

Task 5: Develop BOS Components and System Integration Strategies for Lower Cost

Progress Summary

5.1 Residential Inverter

This section of the report contains proprietary information that has been omitted.

5.2 Commercial Inverter

This section of the report contains proprietary information that has been omitted.

5.3 Low Cost Installation

This section of the report contains proprietary information that has been omitted.

5.4 Energy Yield Enhancements

This section of the report contains proprietary information that has been omitted.