Module information for arpa-e ADEPT workshop, Washington, D.C. 2-8-2011

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Common solar module construction

Glass
Low iron AR/Non-AR
(environmental protection, mechanical strength)

Encapsulant
EVA = Ethyl Vinyl Acetate
(adhesive for cell, glass and backsheet)

Backsheet
TPE = Tedlar / Polypropylene / EVA (dielectric insolation, environmental protection)

Frame
(mechanical)

Stringed cells

Wires/Connectors

Junction Box (electrical terminals, bypass diodes)
Very rough typical costs for standard modules

- Rough costs to simply give a sense for typical module conversion costs
  - Note: there is a big range, plus and minus, from these values
  - Includes labor, materials, labor, depreciation, overhead, yield

<table>
<thead>
<tr>
<th>Step cost</th>
<th>$ for 1.65 m² module</th>
<th>$/W for 14.5% effic. module (240W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell interconnect + circuit formation</td>
<td>$10</td>
<td>$0.04</td>
</tr>
<tr>
<td>Glass/encapsulant/backsheet/frame/packaging/test</td>
<td>$60</td>
<td>$0.25</td>
</tr>
<tr>
<td>Wires+connectors</td>
<td>$5</td>
<td>$0.02</td>
</tr>
<tr>
<td>Junction box</td>
<td>$8</td>
<td>$0.03</td>
</tr>
<tr>
<td>Diodes</td>
<td>$1</td>
<td>$0.004</td>
</tr>
<tr>
<td></td>
<td>$84</td>
<td>$0.35</td>
</tr>
</tbody>
</table>

- Total module costs continue to fall
  - Trina in-house costs of $1.08/W in Q3’2010 (average 14%?, 180W?)
  - First Solar costs of $0.77/W in Q3’2010 (average 11.3%, 81W)
Other connection approaches

- SunPower all-back contact

- Day4 energy wire mesh
Some thin film examples

- Monolithic on glass
  - First Solar CdTe
  - Applied Materials a-Si
  - Solar Frontier CIGS
- Singulation then tile connect
  - NanoSolar
- Singulation then string like cSi cells
  - Global Solar
- Monolithic on foil then connect
  - Unisolar
  - Fuji
  - Ascent

Photos from Nanosolar.com

From K Moriwaki, et. al, 25th EUPVSEC, Sept 2010, Valencia, Spain
“Monolithic module assembly” with cSi

- Years of effort and progress, but not yet in large scale production

Applied Materials

DEVELOPMENT AND QUALIFICATION OF MONOLITHICALLY ASSEMBLED MODULES FOR BACK CONTACT PV CELLS

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ECN

Module, which shows the placement of the different components, is given in Figure 2.

Figure 2: Illustrative image of the MWT module, showing the placement of the different components.

Module manufacturing is performed in our automated pilot line, a photo of the pilot line is shown in Figure 3.

Figure 4: ECN-MWT efficiency throughout the years.
“Module” can include mounting approach

- SunPower T5 system
  - Integrated, non-penetrating roof mount
  - Fast installation
  - High density, low weight (2.4 lb/ft²; 7 Wp/ lb)

- Solyndra and others have their own unique approaches
Bypass diodes

- By-pass diode in common modules:
  - Bypass diode will be in forward bias (and thus bypass the string) if string pair would otherwise be in reverse bias
  - For some modules, the diodes are needed to protect against hot spots (from localized shunting of high reverse-bias voltage) which could cause module damage
  - Diodes can be a major failure point if best practices are not followed
    - Poor quality diodes in hot conditions
    - Insufficient lightning protection
Many cell types have integrated bypass diode characteristics

- IV curve of a SunPower cell:
  - Uniform non-damaging reverse breakdown at ~-5.5V

United States Patent

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Power electronics as fix for module problems?

- At $2/W system, 2% energy boost worth ~$0.04/W
- Larger problems must be fixed very cheaply to compete against other technologies which do not have the problem
  - For example, results of SunPower tests of two manufacturers modules using a high accelerated life test of damp heat with bias

Electroluminescence images show damaged cells around the perimeter, where leakage current to the frame is highest.

Manufacturer #1
- Power loss
  - Sample 1: -12%
  - Sample 2: -23%

Manufacturer #2
- Power loss
  - Sample 1: -3.2%
  - Sample 2: -4.4%
Cracked cell problems?

Dynamic Load HALT:

- 1,000 alternating cycles of +/-2400 Pa (standard wind load), then 4 temp. cycles -40 to 60°C
Dynamic load HALT

Initial

After 1000 load cycles

After 4 temp cycles

223.9W

-2.1%

-3.4%
Dynamic load HALT - SunPower 145µm-thick cells

Initial: 305 W

After 1000 load cycles: +0.5%

After 4 temp cycles: -0.7%

SunPower all-back-contact cells: cell cracked, but very little power difference
What are “state-of-the-art” modules?

SunPower back-contact-cell modules: long-term testing example

Thermal cycling: 22X cert. std.
Humidity freeze: 26X cert. std.
Damp heat: 7.3X cert. std.
Residential inverter approaches

String Inverter – Traditional
- Serial DC connectivity – same current thru array circuit, with increasing voltage
- MPPT function across multiple strings/modules impacting total energy harvest
- String Inverter CEC efficiency ~ 85%
- High DC voltage, safety concern

Micro-Inverter
- Parallel AC connectivity – same voltage thru array circuit, with increasing current
- MPPT per module to maximize power output
- Efficiency; most MI’s worse than transformer string inverters. Enphase exception at 95% CEC, TL string inverters with 1% advantage.
- Reduces voltage level, arc fault concerns

DC-DC Series
- Serial DC connectivity – same voltage thru array circuit, with increasing current
- MPPT function per module to maximize aggregated power, active only when needed
- Efficiency; MPPT box at 99.5% + string/central inverter at typical level, up to 97% CEC
- High DC voltage, longer DC runs increase chance of arc fault, but capable manual shut off

Inverters and junction boxes are high on pareto of field failure rates
AC modules and MPP trackers

- AC and MPP manufacturers and some 3rd party studies have shown data with significant energy gains for some applications.

- Some 3rd party studies show small gains for most applications, even with shade.

**LIGHT AND SHADOW – WHEN IS MPP-TRACKING AT THE MODULE LEVEL WORTHWHILE?**

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25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain
Literature

- Samples for this presentation taken solely from 25th PVSEC to illustrate availability of information

25th European Photovoltaic Solar Energy Conference and Exhibition /
5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain

The peer reviewed version of this paper is published in the journal Progress in Photovoltaics http://wileyonlinelibrary.com/journal/pip

MODULE INTEGRATED ELECTRONICS - AN OVERVIEW

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ABSTRACT: PV module integrated electronics is becoming more and more important. There are a lot of different tasks and applications for module integrated electronics, such as: operational displays, data monitoring, theft protection, safety shut down, reduction of mismatch losses [1], DC/DC conversion and DC/AC conversion. This paper gives an overview of the products that are available today.
Comment

- When considering the goals and approaches for power electronics, use the right benchmark:
  - Costs are dropping very rapidly
    - Grid-parity-driven growth in 2013-5 will accelerate cost reductions (costs without subsidies lower than avoided costs in more and more locations around the world)
    - Major companies with large research budgets involved
  - Both low cost and high performance are required
  - Look for ways to provide additional value to the grid
  - System costs can be higher when the *value* of the system is higher (e.g., on a residential roof)
Closing comment: PVDock

- SunPower, SolarBridge, and Tigo formed PVDock SIG (Special Interest Group) to encourage the development of a standard mechanical and communications interface that would enable a module supplier to swap out a variety of power electronics (ACPV, DC/DC, Diodes, Fire shut off switch, …).

- SunPower recommends a broader participation, and funding, for the PVDock SIG

Note: PV-Dock™ is a registered trademark of SolarBridge

Thank You

www.sunpowercorp.com
Deploying high-reliability PV Modules: Overall Process

**Design for Reliability**
- Reliability Requirements
- Design Concepts

**FMEA**
- Field Experience
- HALT
- Theoretical understanding

**Qualification Testing**
- Testing-to-failure
- Long-term testing
- Field testing

**Cert. testing**

**Supplier Quality Control**
- PSC Audit
- STARS score
- Inc. Mat’l Audit

**Out-of-box Audit**
- Cont. Mfg. Testing
  - ORT
  - HASA

**Statistical Process Control**

**Closed-loop learning**

**Customer**
SunPower simulation tool

- PVSim provides accurate prediction of energy production:
  - Standard deviation of error in actual vs. predicted for 17 large systems across broad range of locations and mounting approaches = 1.3%.
  - Actual energy delivery is 1.2% higher than predicted.

![PVSim System-Level Accuracy for Annual Simulations](image)

- Powerguard = flat fixed mount
- T0 = horizontal 1-axis tracked
- T10 = 10° fixed tilt
- T20 = 20° tilt 1-axis tracked

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SunPower Products

Panels
- 225 W
- 318 W

Trackers

Monitoring

Roof top and roof integrated solutions

Power Plants

> 22% efficiency all-back contact cell
Solar cell equivalent circuit

I-V curve

Solar cell in dark (is a diode)

Solar cell in light

Cell equivalent circuit

Rs
Rsh
Cells in a module

- All cells are in series
- If cell cannot pass current of other cells, it goes into reverse bias (and takes away 6V from module voltage and up to ~30W from module power)

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**Diagram:**

- 0 A
- 5.3 A
- 0 0.57V
- 0 0.57V
- 0 0.57V
- 0 0.57V
- -6V
- 0

- normal cell
- normal cell
- normal cell
- normal cell
- bad cell (piece broken off or partially shaded)
Designed for Roof Compatibility & Longevity

Molded frame, mounting system and deflectors

Engineered polymer exceeds stringent 30-yr design-life requirement.

- GE engineered material 20% glass-filled polyphenylene & polystyrene blend.
- Excellent dimensional stability and high impact resistance
- Very low creep behavior, even at elevated temperatures
- Hydrolytic stability: lowest water absorption of all engineering thermoplastics
- Decades of real life field exposure: electrical enclosures, automotive parts, sprinkler heads, water pumps, roof tiles, solar water heaters, PV modules
**Performance**

*Huge driver for cost of PV-generated energy*

\[ \text{LCOE} = \text{NPV} \left[ \frac{\text{Total System Installed Costs} + \text{O&M Costs}}{\text{Energy produced}} \right] \]

- **Energy / rated W**
  - Environmental conditions
  - Mounting (tracking, tilt, …)
  - System design
  - Module type

- **System availability** (uptime)

- **System Quality and Reliability**
  - System Lifetime
  - Degradation rates
  - Failure rates

*Confidence* in the energy production and O&M estimates very strongly affects selling price and financing rates.

LCOE ≡ Levelized Cost of Energy

NPV ≡ Net Present Value

Total system costs includes cash flow impact of financing

O&M ≡ Operation and Maintenance
Cost of PV-generated energy

- Levelized-cost of energy (LCOE) is one analytical tool. A simplified version:

\[
LCOE \approx \frac{\text{Total Costs}}{\text{Energy produced}} \approx \frac{\text{Total System Installed Costs} + \text{NPV (O&M Costs)}}{\text{Sunlight Collection} \times \text{Conversion Efficiency}}
\]

*Note: Some calculations use the Net Present Value (NPV) of the energy produced

\[
\text{Energy produced} = \text{Rated power} \times \text{Capacity Factor}
\]

- LCOE calculation using cash flows:

\[
LCOE = \frac{\sum_{n=1}^{N} \left( \frac{\text{Initial Investment}}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate}) \right) + \sum_{n=1}^{N} \left( \frac{\text{Annual Costs}}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate}) \right) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^n} + \sum_{n=1}^{N} \left( \frac{\text{Initial kWh/kWp}}{(1+\text{Discount Rate})^n} \times (1 - \text{System Degradation Rate})^n \right)}{1}
\]

Financing terms have a very large impact on LCOE. Influences on them include:
- Availability of capital, assumption for inflation, perception of risk