Optimizing Busbar Design in Full and Halved Cell Modules and Impact on the Cell-to-Module Yield

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• Methodology to predict annual yield losses and gains caused by solar module design and materials under field exposure

• Aim:
  – Enable rapid virtual prototyping of new concepts and designs
  – Enable optimization of key design elements (e.g. backsheet, ribbon, glass) by separating individual loss/gain mechanisms
  – Enable optimizing modules for different climates under realistic conditions (angular & spectral irradiance, environmental factors)
Separating 12 yield loss and gain mechanisms using timestep approach

At each timestep:
- Calculating optical cell-to-module losses and gains
- Iteratively calculating cell temperature
- Calculating electric losses

Model validation

CTM (STC)

- Validation under STC conditions
- Comparison of model against measurement-based reference data [1]
- Overall in good agreement!

<table>
<thead>
<tr>
<th>Loss/Gain Mechanism from Cell to Module</th>
<th>Modelled values</th>
<th>Reference [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STC nameplate</td>
<td>285.0</td>
<td>285.0</td>
</tr>
<tr>
<td>Spectral mismatch to AM1.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Angular</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Reflection front glass</td>
<td>-11.4</td>
<td>-11.4</td>
</tr>
<tr>
<td>Absorption glass</td>
<td>-3.8</td>
<td>-3.3</td>
</tr>
<tr>
<td>Absorption embedding</td>
<td>-3.1</td>
<td>-3.5</td>
</tr>
<tr>
<td>Coupling gain (CG) finger</td>
<td>5.2</td>
<td>5.3</td>
</tr>
<tr>
<td>CG ribbons</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>CG backsheet</td>
<td>3.0</td>
<td>4.4</td>
</tr>
<tr>
<td>CG cell surface</td>
<td>5.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Low level irradiance (LLI)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ohmic interconnection</td>
<td>-9.4</td>
<td>-9.0</td>
</tr>
<tr>
<td><strong>Final module power</strong></td>
<td><strong>270.8</strong></td>
<td><strong>271.2</strong></td>
</tr>
</tbody>
</table>

Three interdependent models

CTMY

POA
Temperature
Power

NREL, Golden, CO

CTMY model validation

POA

Temperature

Power

<table>
<thead>
<tr>
<th></th>
<th>Irradiance</th>
<th>Temperature</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[W/m²]</td>
<td>[%]</td>
<td>[K]</td>
</tr>
<tr>
<td>Our model at location Denver (NREL)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MBE</td>
<td>0.55</td>
<td>0.01</td>
<td>-0.03</td>
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<tr>
<td>WMBE</td>
<td>2.27</td>
<td>0.4</td>
<td>-0.47</td>
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<tr>
<td>RMSE</td>
<td>22.6</td>
<td>4.2</td>
<td>2.8</td>
</tr>
</tbody>
</table>
CTMY model validation

The modelling uncertainty is similar or better compared to published values.

Note that we model **three interdependent** parameters, compared to only one of the parameters at a time for the reference values.
Goal: Determine impact of busbar in full and halved cell modules on CTM-Yield

Step 1: Optimise the cell design in combination with the cell interconnection design for an optimum performance
   - inside a module
   - under STC

Step 2: Calculation of annual yield for best performing designs
What is optimized?

- number of fingers
- number of interconnectors
- width of the connectors
- type of interconnectors
- Example of optimization for a full-cell, planar ribbons
- Cell optimization in air (including ribbon) may underestimate coupling gains, e.g. from light-redirecting films (LRF)
Optimizing front metallization

- Optimum number of fingers within module embedding slightly higher, due to
  - Reduced electrical losses (lower current)
  - Increased optical gain
• LRF structures allow to increase the ribbon width due to the reduced optical width after embedding
• The optimized width is 1300 μm compared to 800 μm for planar ribbons
Annual yield

- Theoretical yield reduced for cells in air with wider LRF ribbons due to increase shading losses

![Bar chart showing annual yield comparison between 72-cell mono-PERC and 144-cell halved cell mono-PERC modules with different configurations (5BB planar, 7BB planar, 8BB LRF, 35 wires, 5BB planar, 6BB LRF, 20 wires). The chart indicates a decrease in annual yield for cells in air with wider LRF ribbons.]
Annual yield – optical gain and ohmic loss

72-cell mono-PERC
full-cell module

144-cell halved cell mono-PERC
half-cell module

- Coupling gain interconnector (%)
- Ohmic loss (%)

5BB planar, 7BB planar, 8BB LRF, 35 wires, 5BB planar, 6BB LRF, 20 wires

STC, full year
• After embedding the cells with LRF ribbons perform best due to coupling gain and low ohmic losses
Both, reduction in electrical losses and increase in optical gain contribute to an increase in the annual yield.

### Bar Chart

- **72-cell mono-PERC**
  - full-cell module: 1.4%
  - half-cell module: 5.4%
- **144-cell halved cell mono-PERC**
  - full-cell module: 1.8%
  - half-cell module: 5.9%
  - 20 wires: 4.5%
Cell-to-Module-Yield Methodology

- Validated using module outdoor measurements at NREL

- Applied to busbar / metallization designs optimized for full and halved-cells after module embedding
  - Light-redirecting-films enable using much wider ribbons (optimized width of 1300 μm compared to 800 μm for planar)
  - 1.8% yield gain for full-cell 8BB with LRF compared to 5BB planar ribbon reference
  - Halved-cells further increase CTMY energy yield by 3-4%

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Thank you for your attention

We are open for collaboration!

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More information and free download of SunCalculator and high-time resolution TMY datasets for Australia at www.marcoernst.net

Acknowledgements

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