OUTDOOR CHARACTERIZATION OF BIFACIAL MODULES AT HANWHA Q CELLS

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Hanwha Q CELLS GmbH
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Hanwha Q CELLS Co., Ltd. (NASDAQ: HQCL) is the largest cell manufacturer and one of the largest solar module manufacturers in the world.

**WHO WE ARE**

**OVERVIEW**

**HEADQUARTERS**

South Korea (Global Executive HQ) and Germany (Technology & Innovation HQ)

**TECHNOLOGY LEADERSHIP**

R&D Centers in 4 countries (Germany, South Korea, Malaysia and China)

**MANUFACTURING FACILITIES**

Manufacturing Plants in 3 countries (South Korea, Malaysia and China)

**40+ SALES NETWORK**

Spanning Europe, North America, Asia, South America, Africa and the Middle East

**CELL AND MODULE PRODUCTION CAPACITY OF**

8+ GW

As of Q1, 2018

**OUR PRODUCT RANGE**

- Modules
- Kits & Bundles
- Power Plants
OUTLINE

1. MOTIVATION
2. REAR SHADING & MISMATCH
3. LONG TIME ENERGY YIELD
4. SUMMARY & RESULTS
1. MOTIVATION
- Influences on bifacial energy yield gain -

External influences which effect the energy output of bifacial systems

- Mounting system & Ground coverage ratio
- Albedo: Reflectivity of ground
- Rear shading
- Distance to ground
- Orientation & tilt angle
- Location & weather

BIFACIAL ENERGY YIELD
Approach here:

As a starting point, put bifacial modules in a “monofacial” system design

Two questions:

- Shading in monofacial systems leads to serious mismatch. Is rear shading & mismatch a serious problem, too?

- Which bifacial energy yield gain can be expected?
OUTLINE

1. MOTIVATION
2. REAR SHADING & MISMATCH
3. LONG TIME ENERGY YIELD
4. SUMMARY & RESULTS
Variations in rear side contribution are small compared to total current
Mismatch losses arise at operation at non-optimal current/voltage.

Mismatch losses come on top of the optical shading losses.
2. REAR SHADING & MISMATCH
- Instrument module -

Features of 72 cells instrument module

**Rear side:**
Spatially resolved irradiation measurement

**Front side:**
3 cells to measure front side irradiation

**Data visualisation:**
Rear irradiation w/ respect to front side irradiation

Special instrument module for spatially resolved irradiation measurements
2. REAR SHADING & MISMATCH
- Rear irradiation along a string -

**Approach**

- Existing PV-System
- Move Instrument module along the string and measure rear irradiation
# 2. REAR SHADING & MISMATCH

- Rear illumination along a string -

<table>
<thead>
<tr>
<th>Module table end</th>
<th>Vertical bars</th>
<th>Rear side irradiance by distance to table end</th>
</tr>
</thead>
<tbody>
<tr>
<td>11% 12% 11% 10% 9%</td>
<td>9% 10% 10% 10% 10%</td>
<td>9% 10% 10% 10% 10%</td>
</tr>
<tr>
<td>7% 8% 8% 8% 7% 6%</td>
<td>6% 8% 8% 8% 8% 8%</td>
<td>8% 8% 8% 8% 8% 8%</td>
</tr>
<tr>
<td>9% 10% 10% 10% 10%</td>
<td>8% 9% 9% 9% 9% 9%</td>
<td>7% 8% 8% 8% 8% 8%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>7% 8% 8% 8% 8% 8%</td>
<td>6% 8% 8% 8% 8% 8%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>6% 8% 8% 8% 8% 8%</td>
<td>5% 6% 6% 6% 6% 6%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>5% 6% 6% 6% 6% 6%</td>
<td>4% 6% 6% 6% 6% 6%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>4% 6% 6% 6% 6% 6%</td>
<td>3% 5% 5% 5% 5% 5%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>3% 5% 5% 5% 5% 5%</td>
<td>2% 4% 4% 4% 4% 4%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>2% 4% 4% 4% 4% 4%</td>
<td>1% 3% 3% 3% 3% 3%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>1% 3% 3% 3% 3% 3%</td>
<td>0% 2% 2% 2% 2% 2%</td>
</tr>
<tr>
<td>10% 11% 10% 10% 10%</td>
<td>0% 2% 2% 2% 2% 2%</td>
<td>-1% 0% 0% 0% 0% 0%</td>
</tr>
</tbody>
</table>

- Rear side irradiation decreases with increasing distance from frame end
- Average rear shading factor: 8%
Partially rear shaded Bifa string: MM in particular module < 4% depending on ratio unshaded/shaded
2. REAR SHADING & MISMATCH
- Worst case simulation-

Mismatch for different unshaded/shaded Bifa-String configurations

<table>
<thead>
<tr>
<th>Fraction of unshaded Bifa modules in partially shaded string</th>
<th>Mismatch loss [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.0</td>
</tr>
<tr>
<td>86%</td>
<td>-0.2</td>
</tr>
<tr>
<td>71%</td>
<td>-1.4</td>
</tr>
<tr>
<td>57%</td>
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</tr>
<tr>
<td>43%</td>
<td></td>
</tr>
<tr>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

Total mismatch losses in bifacial string around 0.2 % (only mounting structure shading)
Worst case mismatch losses in string are 1.4% (for moderate rear irradiation*)

* around or below 10% of front contribution
1. MOTIVATION
2. REAR SHADING & MISMATCH
3. LONG TIME ENERGY YIELD
4. SUMMARY & RESULTS
3. LONG TIME ENERGY YIELD
- Long term track record -

Long term measurements in realistic mounting scenario

Field configuration
- Modules placed within module row
- Other rows in front and back
- Row distance: 5.9 m / GCR = 34%
- Orientation: South, 30°
- Height over ground: 1.2 m
- Grass ground
- Bifaciality: 60%

Compare Measurements to PVSYST-Simulation
- Version 6.6.7
- Albedo: 25%
- Rear shading factor: 8%
- Bifaciality: 60%
- Rear mismatch loss: 2.2%
  0.2% total MM equals 0.2% / 9%
  = 2.2% rear MM
3. LONG TIME ENERGY YIELD
- Long term track record -

**Comparsion of measured to simulated bifacial energy yield gain**

- Total measured gain: 9%
- Total simulated gain: 8%
- Generally good fit, weather conditions led to variant Albedo
1. MOTIVATION
2. REAR SHADING & MISMATCH
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4. SUMMARY & RESULTS
- Summary -

RESULTS

- Significant bifacial energy yield gains can be achieved even under non-optimized conditions (here: 9% p.a.)

- Mismatch due to rear shading is only a minor problem (<1.4% MM loss) for moderate* rear side irradiation

- Simulation in the right order of magnitude but in tendency conservative due to Albedo variances (Snow / yellowed grass)

* around or below 10% of front irradiation
2. REAR SHADING & MISMATCH
- Shading bar in varying distance -

Experiment: Varying distance of shading bar to rear side

- shading bar: 6 cm x 10 cm
- short side facing module rear

![Graph showing losses by distance](image)

**Losses by distance**

**Distance of obstacle to rear side [cm]**

- Loss of rear side irradiance compared to homogeneous illumination (9%)
- Total irradiance loss (front+rear)
- Mismatch loss
- Total Power loss
2. REAR SHADING & MISMATCH
- Shading bar in varying distance -

Mismatch behaves nearly linear under moderate(*) rear irradiation and shading

(*) around 10% of front irradiation
2. REAR SHADING & MISMATCH

- Introduction -

- Inverter MPPT controls string current to global MPP
- Each module in string is operated at this current

IV-Curve of string and single module

- Module 7 IV-Curve
- Module 1 IV-Curve
- String IV-Curve
- String MPP
- Operating Point
- Impp
- Pmodule string
2. REAR SHADING & MISMATCH

- Introduction -

Mismatch loss due to operation of module with beyond-MPP current