High efficiency spectrum splitting prototype submodule using commercial CPV cells

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Motivation 1: Record Spectrolab cell

- Excess Ge subcell response
- Divert selected wavelength band to Si cell
  - Lateral spectrum splitting $\rightarrow$ Eff $\uparrow$, heat load $\downarrow$

King et al, EUPVSEC-24 (2009)

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Spectrum splitting: Concept

Solar spectrum

Bandpass filter

Si (1.1 eV)

GaInP (1.88 eV)

Monolithic TJ cell stack

GaInAs (1.41 eV)

Ge (0.67 eV)

Colours are indicative only

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Spectrum splitting: LIV

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Motivation 2: CPV power tower

- World first demonstration of a heliostat CPV plant in 2008 (140 kWp)

- Replace conventional receiver with spectrum splitting receiver

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
CSPV power tower: RayGen

- Combines CPV with CST + storage

- First site deployment 0.2 MW (Newbridge)
  - 64 heliostats, 200 kW receiver, 1 inverter

- A$60M investment + distribution agreement with China Intense Solar
  - 0.2 MW pilot, 1.0 MW demonstration, 10 MW commercial scale by Aug 2016
Spectrum splitting prototype: Cells

- Target highest performance, using commercial (1 cm²) TJ and Si CPV cells
- 4-terminal electrical connection

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Optical design

- Zemax 3D ray tracing
  - Maximise optical Eff (96.8% for full capture), acceptable non-uniformity

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Heatsink + optional SOE (secondary optical element)

Si cell on heatsink

Optional SOE

TJ cell (at Voc)

SOE quarters

SOE installed

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Concentrating mirror

- 8-inch diameter parabolic mirror (f = 1000 mm, aperture area)
- ‘Enhanced silver’ coating by Optical Coating Associates Pty Ltd
  - Ag + 2-layer dielectric (Al₂O₃/Ta₂O₅)
Bandpass filter

- Adjust filter cut-on & cut-off to match TJ subcell currents (+ margin)
  - Input = AM1.5D spectrum, optics (mirror R, filter T & R), cell EQEs, simple LIV model
- Custom filter by Omega Optical
  - AOI 23°, HCA 6°
  - Design iterations, refine specs
  - Dielectric stack: 158 layers of Nb$_2$O$_5$ and SiO$_2$ (total 20 um)
  - Front surface ‘mirror’ on UV-grade silica (non absorbing)
Bandpass filter: Close-up

- Adjust filter cut-on & cut-off to match TJ subcell currents (+ margin)
  - Input = AM1.5D spectrum, optics (mirror R, filter T & R), cell EQEs, simple LIV model
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Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Bandpass filter: Tunability

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Weighted EQEs: TJ cell alone

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Weighted EQEs: With spectrum splitting

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
Outdoor testing at UNSW

UNSW 22 Oct 2014

Si cell
Filter
TJ cell
Receiver
Mirror

Prototype
Tracker
Chiller
Pyrheliometer
LIV curve tracer

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014
UNSW: Highest efficiency

<table>
<thead>
<tr>
<th>Cell</th>
<th>Split: TJ</th>
<th>Split: Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timestamp</td>
<td>22/10/2014 17:02</td>
<td>22/10/2014 17:03</td>
</tr>
<tr>
<td>DNI (W/m²)</td>
<td>795</td>
<td>798</td>
</tr>
<tr>
<td>P_in (W)</td>
<td>22.8</td>
<td>22.9</td>
</tr>
<tr>
<td>T_ambient (°C)</td>
<td>21.8</td>
<td>21.9</td>
</tr>
<tr>
<td>T_heatsink (°C)</td>
<td>22.0</td>
<td>NA</td>
</tr>
<tr>
<td>T_CCA (°C)</td>
<td>23.5</td>
<td>21.7</td>
</tr>
<tr>
<td>V_oc (V)</td>
<td>3.04</td>
<td>0.78</td>
</tr>
<tr>
<td>I_sc (A)</td>
<td>3.14</td>
<td>1.59</td>
</tr>
<tr>
<td>V_mpp (V)</td>
<td>2.71</td>
<td>0.67</td>
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<tr>
<td>I_mpp (A)</td>
<td>2.99</td>
<td>1.50</td>
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<tr>
<td>FF (%)</td>
<td>85.0</td>
<td>81.1</td>
</tr>
<tr>
<td>P_mpp (W)</td>
<td>8.1</td>
<td>1.0</td>
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<tr>
<td>Efficiency (%)</td>
<td>35.7</td>
<td>4.4</td>
</tr>
</tbody>
</table>

TJ cell W1-7, Si cell 333, filter AOI 21°, air mass 2.3
Independent confirmation

Keevers et al, WCPEC-6, Kyoto, 23-27 Nov 2014

\[35.7 + 4.7 = 40.4\%\]
Conclusion

- Spectrum splitting prototype submodule, using a custom bandpass filter and commercial CPV cells, has achieved an independently confirmed efficiency of 40.4%.
- Proof-of-concept that this approach improves efficiency.
- Possible application to CPV power towers.

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