The Capital Intensity of Photovoltaics Manufacturing
Barrier to Scale and Opportunity for Innovation*

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Global PV Manufacturing Capacity

Note that annual production is always less than rated capacity.

What Comes Next?
Predictions are Hard, so Keep it Simple

The future of PV manufacturing is determined by:

• How much is invested
  – Capital Investment Rate: $CapIR$

• How much it costs
  – Capital Demand Rate: $CapDR$
Capital Investment Rate

Capital Investment Rate \( (\text{CapIR}) \)

Baseline \( \text{CapIR} = $0.075/W \)

Slope = $0.075/W

Slope = $0.57/W
• **Capital expense (Capex) of PV-specific manufacturing plants**
  – Normalized to production capacity expressed in rated module watts per year

• **The normalized Capex for each sector in the value chain is lower in Asia**
  – But more sectors need to be included: backsheet, EVA, frame, paste, etc.
  – More PV-specific sectors in Asia means similar Capex in Asia as in USA
Capex-Related Cost Components

Margin required for WC such that the IRR = WACC

Margin required for Capex such that the IRR = WACC

$0.15/W
Capital Demand Rate

<table>
<thead>
<tr>
<th>PV-Critical Manufacturing</th>
<th>Capex ($yr/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon Production</td>
<td>0.33</td>
</tr>
<tr>
<td>Ingot Casting/Wafer Slicing</td>
<td>0.25</td>
</tr>
<tr>
<td>Cell Fabrication</td>
<td>0.30</td>
</tr>
<tr>
<td>Module Assembly</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1.01</strong></td>
</tr>
</tbody>
</table>

- **Capital expense (Capex) normalized to nominal manufacturing capacity**
  - Within estimation and location error, assume a globally nominal 1 $yr/W

- **Capital Demand Rate (CapDR)**
  - Capex normalized to nominal manufacturing capacity (1 $yr/W)
  - Divided by the average life of the manufacturing assets (10 yr)
  - Increased to account for the weighted average cost of capital (WACC@10%/yr)
  - Baseline *CapDR* = $0.15/W
Baseline Scenario*

• **CapIR stays near its current level**
  – Price competition limits profits available to increase investment
  – Companies with declining investment will lose market share

• **CapDR stays near its current level**
  – The size of the PV industry has already achieved most of the benefits of scale
  – Improvements require real innovation on a massive scale, which is slow

• **What will happen if CapIR and CapDR stay near their current levels?**
  – **CapIR < CapDR** is not sustainable in the long term!
  – Not enough investment to replace manufacturing assets as they are retired
  – PV Manufacturing will peak in the next few years and then decline!

Impact on Future PV Generation Capacity

- Assumptions:
  - 20-yr average life for fielded systems
  - ~10% of global demand for electricity

- Note similarity of these two curves

Increasing CapIR by another $0.10/W is similar to decreasing CapDR by half.
Opportunities for Capex Innovation

- Innovative Process Innovations
- Disruptive Process Innovations
- Platform Innovations
- Financial Approaches
Incremental Process Innovation

- **Increase tool throughput**
  - Grow faster (tolerance for defects, tolerance for nonuniformity)
  - Process faster (temperature optimization, reduce thermal mass, heat locally)
  - Assemble faster (fewer pieces, fewer movements, shorter distances)

- **Increase tool lifetime**
  - Avoid obsolescence (replaceable components, standardized interfaces)
  - Avoid wear-out (less corrosive processes, proper materials selection)
  - Avoid catastrophic failure (early-warning indicators, fault intervention)

- **Reduce facility cost**
  - Defect tolerance (airborne particulates, water impurities, gaseous impurities)
  - Timing tolerance (in process, between processes, maintenance schedules)

- **But don’t increase tool cost, or adversely impact module quality!**
Other Forms of Capex Innovation

• **Disruptive process innovation**
  – Process simplification (eliminate steps, combine steps, multi-purpose layers)
  – Non-PV examples: Float glass, razor blades
  – PV examples: UMG, kerfless wafers, epi cells, module-scale processing

• **Platform innovation**
  – Thin-film materials (earth-abundant, defect-tolerant, stable)
  – Solution-based deposition (uniform, consistent, low-hazard)
  – Optical concentration (low-concentration, high-concentration)

• **Financial approaches**
  – Leasing of capacity (tools, facilities)
  – Contract manufacturing (outsourcing, insourcing)
  – Downstream integration (installation, financing)
Summary

- **Existing PV manufacturing capacity is sufficient to supply 5% of the world’s electricity, but only if capacity can be replaced as it is retired**
  - Maintaining the economic status quo is not enough
  - Profits are too low and capex is too high!
  - The industry must quickly transition to a state of $CapIR > CapDR$

- **Capex reduction leverages both sides of this inequality**
  - Reduces the cost of manufacturing modules – increase $CapIR$
  - Reduces the cost of manufacturing capacity – decrease $CapDR$

- **There are numerous opportunities for Capex innovation**
  - Incremental process innovation
  - Disruptive process innovation
  - Platform innovation
  - Financial approaches