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1 Introduction to NREL and Solar and Storage Technoeconomic Analysis
2 Global PV Manufacturing Capacities Across the Supply Chain
3 Bottom-Up PV Manufacturing Cost Modelling Methodology
4 Results for Polysilicon, Ingot and Wafer, Solar Cell and Module Assembly
5 Monte Carlo Uncertainty Analysis of PV Manufacturing Costs
6 Future Analysis Including the United States Inflation Reduction Act
7 Conclusions
NREL’s Solar + Storage Technoeconomic Analysis Portfolio

### Bottom-Up Component Cost Models

<table>
<thead>
<tr>
<th>Modules</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Silicon</td>
<td>Batteries</td>
</tr>
<tr>
<td>Thin-Film</td>
<td>Solar Fuels</td>
</tr>
</tbody>
</table>

### System Capital Cost Models ($)

<table>
<thead>
<tr>
<th></th>
<th>PV Systems</th>
<th>PV Plus Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modules</strong></td>
<td>Crystalline Silicon</td>
<td>Batteries</td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td>Batteries</td>
<td>Solar Fuels</td>
</tr>
</tbody>
</table>

### Solar and Storage Project Pro Forma Analysis

- **Levelized Cost of Electricity (LCOE) Metric**
- **Internal Rate of Return (IRR) Metric**

- Any applicable incentives
- FIT or PPA Revenues
- Residual Value (±)
- Years
- Any preventative and routine O&M, including asset management
- Any corrective O&M including battery and inverter replacements and unplanned weather-related events

Upfront Capital Cost for System Installation

Solar and Storage System Components Scoped for More Detailed Analyses in the Future

- Inverters
- Storage (Beginning with Batteries)
- Structural Balance of System
- Electrical Balance of System
- Labor Costs and Workforce Needs for Installations and Manufacturing

☑ Module

Introduction to NREL and Solar and Storage Technoeconomic Analysis

Global PV Manufacturing Capacities Across the Supply Chain

Bottom-Up PV Manufacturing Cost Modelling Methodology

Results for Polysilicon, Ingot and Wafer, Solar Cell and Module Assembly

Monte Carlo Uncertainty Analysis of PV Manufacturing Costs

Future Analysis Including the United States Inflation Reduction Act

Conclusions
2022 Commissioned Capacity
Facility Locations and Manufacturing Capacities

Maps generated by Billy Roberts (NREL) using data from the BNEF PV Equipment Manufacturers Database, August 2022.
2022 Commissioned Capacity
Facility Locations and Manufacturing Capacities

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Overview of the Crystalline Silicon (c-Si) PV Module Supply Chain

Source of figure: NREL.

TOTAL COST OF OWNERSHIP (TCO) INPUTS

Inputs For Calculations of Direct Costs
- Tool throughput including downtime
- Equipment price and training
- Facilitation and building
- Materials and consumables
- Utilities (Electricity and Water)
- Waste disposal (Wastewater and exhaust air)
- Labor: Direct operators and supervisors
- Maintenance
- Account of yield loss

Location Specific Costs Considerations
- Local wage rates: Direct operators and supervisors
- Local utility rates: Electricity and water
- Leased or purchased building
- Local considerations for CapEx and materials

GAAP AND IFRS ACCOUNTING STANDARDS

Variable (cash) costs within the cost of goods sold (COGS)
- Input materials
- Direct labor
- Utilities
- Maintenance of equipment and facilities

Fixed (non-cash) costs
- Equipment
- Building and facilitation
- Installation and training

COGS to Delivered MSP
- Research and Development (R&D)
- Sales, General, Administration (S,G, & A)
- Profit across the supply chain
- Taxes, tariffs and import/export duties (Input per destination)
- Sea- and land-based shipping, port entry fees, warehouse, and insurance (Input per destination)

Delivered Minimum Sustainable Price (MSP)

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf
Going From Direct Cost of Goods Sold (COGS) to Delivered MSP

1. Direct Cost of Goods Sold
   - Materials
   - Labor and Utilities
   - Maintenance
   - Equipment and Facilities

2. Overhead and Profit
   - Research and Development (R&D)
   - Sales, General and administration (S, G, &A)
   - Gross and Operating Profit
   - Other Revenues and Losses (Not Included)

Factory Gate Minimum Sustainable Price (MSP)

3. Taxes and Trade Duties
   - Sales, value-added or other taxes
   - Customs or other import duties
   - Anti-dumping and countervailing duties (AD/CVD)
   - Input per source and destination

4. Shipping and Delivery
   - Sea shipping: Modules per container and shipping container costs
   - Land shipping: Miles from port to destination and cost per mile/kilometer
   - Insurance, entry bond, shipping fees
   - Warehouse
   - Input per source and destination

Delivered Minimum Sustainable Price (MSP)
Introduction to NREL and Solar and Storage Technoeconomic Analysis

Global PV Manufacturing Capacities Across the Supply Chain

Bottom-Up PV Manufacturing Cost Modelling Methodology

Results for Polysilicon, Ingot and Wafer, Solar Cell and Module Assembly

Monte Carlo Uncertainty Analysis of PV Manufacturing Costs

Future Analysis Including the United States Inflation Reduction Act

Conclusions
Total of Results from NREL’s Bottom-Up Cost Models

Total of Factory Gate MSPs for Global Solar PV Supply Chains
Sum of Mean Results For Polysilicon, Wafer, Cell and Module Assembly Cost Models for Each Country

- Overhead and Profit
- Tariffs or BCD for Equipment and Materials
- Depreciation of CapEx (Equipment and Facilities)
- Maintenance
- Utilities
- Labor
- Materials

2022 U.S. Dollars per Wdc

United States | China | Malaysia | Thailand | Vietnam | India | South Korea | Japan | Germany

- $0.152
- $0.148
- $0.152
- $0.152
- $0.152
- $0.152
- $0.152
- $0.152
- $0.152

Overall:
- $0.33
- $0.27
- $0.27
- $0.27
- $0.28
- $0.33
- $0.36
- $0.38

Individual Costs:
- Overhead and Profit
- Tariffs or BCD for Equipment and Materials
- Depreciation of CapEx (Equipment and Facilities)
- Maintenance
- Utilities
- Labor
- Materials
Differences in the Cost of Goods Sold (COGS) for Nationally-Integrated PV Supply Chains

NREL Manufacturing Cost Model Results Including Polysilicon, Monocrystalline Ingot and Wafer, and PERC Cell and Module
Differences in the Cost of Goods Sold (COGS) for Nationally-Integrated PV Supply Chains

NREL Manufacturing Cost Model Results Including Polysilicon, Monocrystalline Ingot and Wafer, and PERC Cell and Module
Monte Carlo Analysis of Multiple Input Variables for the U.S.

Normal Distributions of Multiple Input Variables for PERC (1,000 Samples)

One standard deviation equals +/- 1% change in *relative cell and module efficiency*

One standard deviation equals +/- 15% change in *CapEx*

One standard deviation equals +/- 20% change in *labor intensity*

One standard deviation equals +/- 5% change in *factory downtime and throughput*

One standard deviation equals +/- 10% change in *factory production volume*
Monte Carlo Analysis Results for Nationally-Integrated PV Manufacturing Supply Chains

Aggregated Factory Gate Minimum Sustainable Price (MSP) Calculations for Polysilicon to Monocrystalline PERC Modules

Samples Created Using Normal Input Distributions for Efficiency, CapEx, Labor Intensity, Downtime, and Throughput
Presentation Outline

1. Introduction to NREL and Solar and Storage Technoeconomic Analysis
2. Global PV Manufacturing Capacities Across the Supply Chain
3. Bottom-Up PV Manufacturing Cost Modelling Methodology
4. Results for Polysilicon, Ingot and Wafer, Solar Cell and Module Assembly
5. Monte Carlo Uncertainty Analysis of PV Manufacturing Costs
6. Future Analysis Including the United States Inflation Reduction Act (IRA)
7. Conclusions
Incentives for PV Installations Within the United States Following Passage of the Inflation Reduction Act (IRA)

<table>
<thead>
<tr>
<th>ITC in the United States</th>
<th>2022—2032</th>
<th>2033</th>
<th>2034</th>
<th>2035</th>
<th>2036</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>30%</td>
<td>26%</td>
<td>22%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Commercial</td>
<td>30%</td>
<td>30%</td>
<td>4.5—22.5%</td>
<td>3—15%</td>
<td>0%</td>
</tr>
<tr>
<td>Utility</td>
<td>30%</td>
<td>30%</td>
<td>4.5—22.5%</td>
<td>3—15%</td>
<td>0%</td>
</tr>
<tr>
<td>Domestic Content</td>
<td>+10%</td>
<td>+10%</td>
<td>+10%</td>
<td>+10%</td>
<td>+10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PTC Alternative in the United States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base PTC</td>
</tr>
<tr>
<td>0.5—3.2 ¢/kWh</td>
</tr>
<tr>
<td>0.6—3.2 ¢/kWh</td>
</tr>
<tr>
<td>0.5—2.4 ¢/kWh</td>
</tr>
<tr>
<td>0.3—1.6 ¢/kWh</td>
</tr>
<tr>
<td>0.0 ¢/kWh</td>
</tr>
<tr>
<td>Domestic Content</td>
</tr>
<tr>
<td>+0.1—0.3 ¢/kWh</td>
</tr>
<tr>
<td>+0.1—0.3 ¢/kWh</td>
</tr>
<tr>
<td>+0.0—0.3 ¢/kWh</td>
</tr>
<tr>
<td>+0.0—0.2 ¢/kWh</td>
</tr>
<tr>
<td>0.0 ¢/kWh</td>
</tr>
</tbody>
</table>

Incentives for PV Manufacturing Within the United States Following Passage of the Inflation Reduction Act (IRA)

<table>
<thead>
<tr>
<th>Manufacturing PTC in the United States</th>
<th>2022—2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
<th>2033</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>$3/kg</td>
<td>$2.3/kg</td>
<td>$1.5/kg</td>
<td>$0.8/kg</td>
<td>$0/kg</td>
</tr>
<tr>
<td>Wafers</td>
<td>$12/m²</td>
<td>$9/m²</td>
<td>$6/m²</td>
<td>$3/m²</td>
<td>$0/m²</td>
</tr>
<tr>
<td>Solar Cells</td>
<td>4¢/W</td>
<td>3¢/W</td>
<td>2¢/W</td>
<td>1¢/W</td>
<td>0¢/W</td>
</tr>
<tr>
<td>Assembly</td>
<td>7¢/W</td>
<td>5.3¢/W</td>
<td>3.5¢/W</td>
<td>1.8¢/W</td>
<td>0¢/W</td>
</tr>
<tr>
<td>Thin Film</td>
<td>18¢/W (projected)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backsheets</td>
<td>$0.4/m²</td>
<td>$0.3/m²</td>
<td>$0.2/m²</td>
<td>$0.1/m²</td>
<td>$0/m²</td>
</tr>
<tr>
<td>Inverters</td>
<td>0.25—11.0¢/W</td>
<td>0.19—8.3¢/W</td>
<td>0.13—3.3¢/W</td>
<td>0.06—2.8¢/W</td>
<td>0¢/W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Title</th>
</tr>
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</tr>
<tr>
<td>4</td>
<td>Results for Polysilicon, Ingot and Wafer, Solar Cell and Module Assembly</td>
</tr>
<tr>
<td>5</td>
<td>Monte Carlo Analysis of PV Manufacturing Costs</td>
</tr>
<tr>
<td>6</td>
<td>Future Analysis Including the U.S. Inflation Reduction Act</td>
</tr>
<tr>
<td>7</td>
<td>Conclusions</td>
</tr>
</tbody>
</table>
Conclusions

• Market price is expected to lower or higher than minimum sustainable price (MSP) during periods of oversupply or undersupply. These are common symptoms for PV. Therefore, MSP is an important metric for long-term technology planning and regional costs comparisons.

• Significant capital investments and skilled engineers are required to establish successful new manufacturing endeavors. Timelines are 6 months to four years, depending upon the step in the supply chain.

• Variations in MSP are to be expected due to uncertainty in input data. Variable labor ($/hr) and electricity rates ($/kWh) are currently believed to be the greatest source of differences in regional PV manufacturing costs. Variations are also expected for delivery of input materials and equipment.

• The recently passed Inflation Reduction Act presents many opportunities for accelerated demand and manufacturing within the United States. Please follow-up to learn more!

Thank You
Presentation Outline

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7 Supplementary Information
Funding Disclaimer

www.nrel.gov

NREL/PR-7A40-84036

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Solar PV Module Technologies Within The NREL Portfolio

**Crystalline Silicon**
- Polysilicon production (Siemens with Trichlorosilane (TCS) and Fluidized Bed Reactor (FBR))
- Ingot and wafering: Czochralski (Cz), directional solidification (DS), and kerfless technologies yielding Cz and DS equivalents
- Cell conversion: Monofacial and bifacial PERC, TOPCon, HJT, and IBC by screen-printing, electroplating, and busbarless
- Module assembly: Standard tabbing and stringing, busbarless, and shingling

**Thin Film**
- CdTe
- CIGS
- III-Vs
- Perovskites

**Multi-junction**
(Two and four terminal)
- All III-Vs and III-Vs on Si
- All Perovskites
- Perovskites on Si

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf
Process Flow for Polysilicon Production

Metallurgical Grade (MG) Silicon
Si
98—99% Purity (98% to 2N)

Source: Alibaba

Production and distillation of trichlorosilane, $\text{SiHCl}_3$

Polysilicon
Si
99.99999—99.999999999% (7—11 N) purity for Solar
11—12 N purity for Semiconductor

Source: Daqo

Harvesting, breaking, washing/etching, and packaging.

Siemens Chemical Vapor Deposition (CVD)

Source: GCL Poly

Summary of Results from NREL’s Bottom-Up Cost Models

Polysilicon Direct Production Costs Across the Globe
Sum of Results From NREL's Polysilicon Cost Model Run for Each Country

<table>
<thead>
<tr>
<th>Country</th>
<th>Import Costs for Equipment and Materials</th>
<th>Depreciation of CapEx (Equipment and Facilities)</th>
<th>Maintenance</th>
<th>Utilities</th>
<th>Labor</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.0</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>China</td>
<td>$8.4</td>
<td>$0.7</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>Malaysia</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>Thailand</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>Vietnam</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>India</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>South Korea</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>Japan</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
<tr>
<td>Germany</td>
<td>$8.8</td>
<td>$0.8</td>
<td>$2.6</td>
<td>$4.6</td>
<td>$2.7</td>
<td>$2.0</td>
</tr>
</tbody>
</table>

2022 U.S. Dollars per kg

- United States: $18.3
- China: $14.3
- Malaysia: $17.1
- Thailand: $17.0
- Vietnam: $17.3
- India: $18.9
- South Korea: $20.3
- Japan: $26.0
- Germany: $28.0
Process Flow for Ingot and Wafer Production

1. Polysilicon feedstock: Siemens chunk. FBR granules are also sometimes added.
2. Load Siemens chunk (and sometimes FBR granules) into crucible.
4. Introduction of the seed crystal.
5. Beginning of crystal growth.
6. Crystal pulling.
7. Extraction of crystal ingot from puller with some pot scrap left in crucible.

Etch (recondition) cropping and squaring scrap

Boule cords.

Boule crown and tail.

8. Cropping (band sawing) of silicon ingot.
9. Bricking or squaring (band sawing).
10. Grinding and polishing of ingot corners.
11. Gluing to glass substrate.

13. Chemical bath to dissolve glue and release wafers from glass.
14. Cleaning, singulation, and inspection of 150-180 μm monocrystalline silicon wafers having a surface area equal to 244 to 440 cm² per wafer. The net silicon utilization (including all kerf and yield losses, and with crown, tail, and chords recycling) is calculated to be around 13 g for 244 cm² wafers to 25 g for 440 cm². For a cell efficiency of 22-25%, this would be 2.4-2.8 g/W(24).

Source of figure: NREL.
Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf
Summary of Results from NREL’s Bottom-Up Cost Models

Ingot and Wafer Direct Production Costs Across the Globe

Sum of Results From NREL's Ingot and Wafer Cost Model for Each Country

- Import Costs for Equipment and Materials
- Depreciation of CapEx (Equipment and Facilities)
- Maintenance
- Utilities
- Labor
- Materials

2022 U.S. Dollars per W_{dc}

- United States
- China
- Malaysia
- Thailand
- Vietnam
- India
- South Korea
- Japan
- Germany

Costs:
- $0.068
- $0.050
- $0.051
- $0.051
- $0.054
- $0.066
- $0.072
- $0.078

Cost Breakdown:
- $0.015
- $0.013
- $0.015
- $0.015
- $0.016
- $0.015
- $0.016
- $0.015

- $0.003
- $0.006
- $0.006
- $0.006
- $0.009
- $0.013
- $0.012
- $0.016

- $0.008
- $0.002
- $0.002
- $0.007
- $0.005
- $0.009
- $0.009
- $0.016

- $0.028
- $0.027
- $0.028
- $0.028
- $0.028
- $0.028
- $0.028
- $0.028
PERC Cell Process Flow

1. Scan wafer.
2. Saw damage removal, surface texturization, and pre-diffusion clean.
3. POCl₃ diffusion.
4. Laser-driven selective emitter formation.
5. Wet chemical PSG etch, rear side planarization, and isolation etch by rear side phosphorous removal.
6. High temperature silicon oxide (SiO₂) formation and PECVD or ALD of aluminum oxide (AlOₓ or Al₂O₃) for rear side silicon-aluminum surface passivation.
7. PECVD of silicon nitride (SiNₓ) on the front and back for frontside anti-reflection, backside reflection, and surface passivation for the solar cell.
8. Laser opening of dielectric layers for ohmic contact between Si and Al BSF.
9. Screen-print Ag and Al pastes for tabbing and BSF formation, respectively. Screen-print Ag pastes for fingers and optional busbars on front. Cofire.
10. Optional hydrogenation step under illumination (or bias) that improves efficiency and passivates and stabilizes defects responsible for LID.
11. J-V measurement, visual inspection, and cell binning.

20 – 24% Cells

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf
Summary of Results from NREL’s Bottom-Up Cost Models

Direct Production Costs for PERC Solar Conversion Across the Globe

Sum of Results From NREL's Solar Cells Cost Model for Each Country

- Import Costs for Equipment and Materials
- Depreciation of CapEx (Equipment and Facilities)
- Maintenance
- Utilities
- Labor
- Materials

2022 U.S. Dollars per W_{dc}

<table>
<thead>
<tr>
<th>Country</th>
<th>Units</th>
<th>Cost Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td>$0.0225</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>$0.043</td>
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<tr>
<td>Malaysia</td>
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<tr>
<td>India</td>
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<td>$0.044</td>
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<tr>
<td>Germany</td>
<td></td>
<td>$0.066</td>
</tr>
</tbody>
</table>
Module Assembly Process Flow

1. Automated glass loading.
2. Laydown of first encapsulant sheet.
3. Automated cell loading, tabbing, stringing, and contactless infrared soldering to front and back silver on cells.
5. Laydown of second encapsulant sheet.
7. Automated module edge trimming. Aluminum frame and silicone sealant.
9. I-V module testing and electroluminescence inspection. Module sorting and palletizing. Move to warehouse to await shipping to customer.

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf
Summary of Results from NREL’s Bottom-Up Cost Models

Direct Production Costs for Module Assembly Across the Globe

Sum of Results From NREL's Module Assembly Cost Model for Each Country

- Import Costs for Equipment and Materials
- Depreciation of CapEx (Equipment and Facilities)
- Maintenance
- Utilities
- Labor
- Materials

2022 U.S. Dollars per Wdc

<table>
<thead>
<tr>
<th>Country</th>
<th>Cost per Wdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>$0.0772</td>
</tr>
<tr>
<td>China</td>
<td>$0.0770</td>
</tr>
<tr>
<td>Malaysia</td>
<td>$0.0772</td>
</tr>
<tr>
<td>Thailand</td>
<td>$0.0772</td>
</tr>
<tr>
<td>Vietnam</td>
<td>$0.0772</td>
</tr>
<tr>
<td>India</td>
<td>$0.0773</td>
</tr>
<tr>
<td>South Korea</td>
<td>$0.0772</td>
</tr>
<tr>
<td>Japan</td>
<td>$0.0772</td>
</tr>
<tr>
<td>Germany</td>
<td>$0.0772</td>
</tr>
</tbody>
</table>
### Equipment and Facilities Costs Drivers for PV Manufacturing

<table>
<thead>
<tr>
<th>Fixed Costs</th>
<th>$/W or $/unit produced</th>
<th>Net Throughput $^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Initial capital expenditure per Watt or per module, cell, wafer, or kg of annual capacity</td>
<td>per finished unit: Metric tonnes per annum (polysilicon) or wafers, cells and modules per year</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>Price for Manufacturing Tool</td>
<td>Rated Throughput kg, wafers, cells, and modules per hour</td>
</tr>
<tr>
<td></td>
<td>Installation and Training Costs (Manufacturing Equipment)</td>
<td>Uptime Net planned and unplanned downtime</td>
</tr>
<tr>
<td></td>
<td>Footprint and Facilitation Costs (Facility)</td>
<td>Account of Yield Loss Scale is an interdependency. Efficiency impacts $/W.</td>
</tr>
</tbody>
</table>
## Capital Investments

- Range of data collected by NREL from interviews of multiple equipment vendors and manufacturers at each stage.
- Balance-of-plant or factory includes building, facilitation and office space.
- CapEx estimates do not include investments for new capacity for supporting materials including glass, encapsulants and back sheets, specialty chemical suppliers, etc.

### Fixed Cost Drivers

<table>
<thead>
<tr>
<th>Polysilicon</th>
<th>Ingot and Wafer</th>
<th>Cell Conversion</th>
<th>Module Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Capital Expenditure</strong>&lt;br&gt;(US$ per Watt of annual capacity)&lt;br&gt;for equipment:</td>
<td><strong>$0.11-0.14/W</strong>&lt;br&gt;($40—50/kg, 2.8 g/W)</td>
<td><strong>$0.08-0.10/W</strong>&lt;br&gt;($0.54/wafer, 6.0 W for M6)</td>
<td><strong>$0.05-0.13/W</strong>&lt;br&gt;(PERC to Advanced technology)</td>
</tr>
<tr>
<td>for balance-of-plant or factory</td>
<td><strong>$0.06—0.08/W</strong></td>
<td><strong>$0.06—0.07/W</strong></td>
<td><strong>$0.03—0.10/W</strong></td>
</tr>
<tr>
<td><strong>1 GW&lt;sub&gt;dc&lt;/sub&gt; Investment</strong>&lt;br&gt;for equipment:</td>
<td><strong>$110—140M</strong></td>
<td><strong>$80—100M</strong></td>
<td><strong>$50—130M</strong></td>
</tr>
<tr>
<td>for balance-of-plant or factory</td>
<td><strong>$65—80 M</strong></td>
<td><strong>$60—70 M</strong></td>
<td><strong>$30—100M</strong></td>
</tr>
<tr>
<td><strong>Time to Build</strong>&lt;br&gt;(Engineering to production)&lt;br&gt;(All-new, not retrofit)</td>
<td>3—4 years</td>
<td>1—3 years</td>
<td>1—3 years</td>
</tr>
</tbody>
</table>

Data source for figure: NREL.
Available online: https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain
## Labor Costs Drivers for PV Manufacturing

<table>
<thead>
<tr>
<th>Labor Costs</th>
<th>Labor Rate</th>
<th>Labor Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>Burdened $/hour</td>
<td>Employees per Gigawatt (GW) or Per unit produced</td>
</tr>
<tr>
<td>Details</td>
<td>$/hour direct wage (Direct Operators)</td>
<td>Staffing plan for each station</td>
</tr>
<tr>
<td></td>
<td>$/hour direct wage (Supervisors)</td>
<td>Throughput, scale, and yield are interdependencies. Efficiency impacts $/W.</td>
</tr>
<tr>
<td></td>
<td>$/hour direct wage (Engineers)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Benefits</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Cafeteria, Health Insurance, Retirement, etc.)</td>
<td></td>
</tr>
</tbody>
</table>
## Utilities Costs Drivers for PV Manufacturing

<table>
<thead>
<tr>
<th>Utilities Costs</th>
<th>Utility Rate</th>
<th>Utilities Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>$/year</td>
<td><strong>per finished unit:</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>kWh/kg (polysilicon)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kWh/wafer, kWh/cell and kWh/module</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m$^3$ per finished unit</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>$/kWh</td>
<td><strong>per station:</strong></td>
</tr>
<tr>
<td></td>
<td>(Electricity Rate)</td>
<td>kW operating power</td>
</tr>
<tr>
<td></td>
<td>$/m^3</td>
<td>m$^3$ per unit or per hour</td>
</tr>
<tr>
<td></td>
<td>(Water Rate)</td>
<td></td>
</tr>
</tbody>
</table>

Throughput, scale and yield are interdependencies. Efficiency impacts $/W.$
Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy22osti/80505.pdf
Timelines and Other Considerations For New PV Manufacturing Capacity

**Initiate Business Plan**
- Financing secured
- Key personnel at the executive level have been identified
- Key partners for technology licensing have been established

**Select Equipment Vendors**
- Conduct technoeconomic assessment to consider cost-performance tradeoffs for each piece of manufacturing equipment
- Collect engineering-dependent price quotes from equipment suppliers

**Design and Permit Manufacturing Facility**
- Work with equipment suppliers to design an appropriate manufacturing facility, which must consider electrical, water and wastewater, and safety codes that vary by region
- Obtain all necessary facility design and construction permits

**Execute Equipment Supplier Agreements**
- Equipment supplier begins to ramp production for the project at an agreed-upon rate. Production, shipment, installation and initial qualification of new manufacturing equipment occurs on a rolling basis.
- Building permits approved and facilitation completed

**Execute Sales**
- Secure customers that will pay the necessary price and at sufficient volume
- Establish the economic justification to scale production

**Nameplate Capacity Achieved**
- Debottlenecking completed
- Full staffing of facility in place
- Sales contracts secured

**Achieve Product Qualification**
- Modules: Work with independent engineers and submit the product for third-party indoor and outdoor reliability testing
- Polysilicon, ingot, wafer, cell: Qualify product for downstream customers
- Meet ESG requirements (if applicable)
Figure Source (NREL): Hope M Wikoff, Samantha B Reese, and Matthew O Reese, "Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics", Joule (2022)
Costs Analysis from the International Energy Administration (IEA)

Costs Analysis from the International Energy Administration (IEA)