Technoeconomic Analysis of the Solar Photovoltaic (PV) Supply Chain and PV Systems Coupled with Storage

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Presentation Overview

Introduction to NREL and Our Solar and Storage TEA Portfolio

1. The International Supply Chain and Major Markets for PV
2. NREL’s Bottom-Up Cost Modeling Methodology and the GAAP and IFRS
3. Most Recent Cost Model Results from NREL and Roadmap for PV Modules
4. Introduction to Solar Plus and ITRPV Projections for PV Systems with Storage
5. NREL Cost Model Results for PV Systems Including Storage
6. Conclusions
7. Supplementary Information
Introduction to NREL

Main Campus in Golden, Colorado

NREL's Washington, D.C. office provides energy analysis and technical program support to the U.S. Department of Energy.

Source of figures: https://www.nrel.gov/about/visiting-nrel.html

Main campus for 16 primary research areas including laboratory-level work in solar, storage, and grid integration technologies.
NREL’s Solar + Storage Technoeconomic Analysis Portfolio

Component Manufacturing Costs ($)

<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 Costs ($)

<table>
<thead>
<tr>
<th>PV Systems</th>
<th>PV Plus Storage</th>
</tr>
</thead>
</table>

Project Pro Forma Analysis

Levelized Cost of Electricity (LCOE)
- Any applicable incentives
- Any preventative and routine O&M, including asset management
- Upfront Capital Cost for System Installation

Internal Rate of Return (IRR)
- FIT or PPA Revenues
- Any corrective O&M including battery and inverter replacements and unplanned weather-related events

Levelized Cost of Solar + Storage (LCOSS)
- Residual Value (+/-)
- Years

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The Global Nature of the Photovoltaic Industry
Facility Locations and Manufacturing Capacities for the Top 500 Companies

Polysilicon Capacity
- China: 45%
- Korea: 11%
- Europe: 16%
- USA: 16%
- ROW: 4%

Wafer Capacity
- China & Taiwan: 91%

Cell Capacity
- China: 79%
- Korea: 15%

Module Capacity
- China & Taiwan: 73%

Input data sources for map and pie chart: IHS and BNEF.
The Global Nature of the Photovoltaic Industry
Facility Locations and Manufacturing Capacities for the Top 500 Companies

Input data sources for map and pie chart: IHS and BNEF.
Global Annual PV Capacity Additions by Country

- From 2010–2019, global PV capacity additions grew from 17 GW to 115 GW.
- European markets led in the beginning of the decade, but PV growth transitioned to Asia.
  - At the end of 2019, 57% of cumulative PV installations were in Asia compared to 22% in Europe and 15% in the Americas.
  - The United States is the country with the second largest cumulative installed PV capacity.
  - There has also been a recent surge of ROW installations, indicating the “globalization” of PV.

Original data source: IEA “PVPS Snapshot 2020” and “Trends in Photovoltaic Applications 2019”
• In 2010, PV represented approximately 4% of new U.S. electric generation capacity.

• Since 2016, PV has represented approximately 30% of new electric generation capacity, with an estimated 34% in 2019.
  – Combined with wind, two-thirds of all new capacity in 2019 came from renewable sources.
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ITRPV Results for Increased Utilization of Storage

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### Cell and Module Technologies

#### Crystalline Silicon
- Polysilicon production
- Ingot and wafering: Czochralski (Cz), directional solidification (DS), kerfless technologies yielding Cz and DS equivalents
- Cell conversion: Monofacial and bifacial PERC, PERT, SHJ, 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

### Step-by-Step Cost of Ownership (COO) Inputs

#### Desired COO Format
- Production and throughput (Uptime and scheduled and unscheduled downtime)
- Equipment prices and relevant depreciation schedules
- Floor space
- Materials and consumables
- Utilities (Electricity, compressed air, cooling water)
- Waste disposal (Wastewater, non-aqueous solvents, and exhaust air)
- Labor: Person-hours per task and by labor class (Operators, Supervisors, Engineering, and Maintenance)
- Cost of yield loss

#### Location Specific Costs
- Local wage rates by task
- Local electricity rates
- Leasing versus purchasing the building business models

### GAAP and IFRS Standards

#### Variable (cash) costs within the cost of goods sold (COGS)
- Input materials
- Direct labor: Skilled and unskilled wages and benefits
- Electricity
- Maintenance of equipment and facilities

#### Fixed (non-cash) costs
- Equipment
- Building and facilitation

#### Research and Development (R&D) and Sales, General, and Administration (S, G, &A)
- Organization management
- Human resources
- Accounting staff
- Technology sales, marketing, and promotion to customers
- Future technology research and development

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**Bottom-Up Cost Model Results**
Drivers of Price Reductions

- Improved cell efficiencies and reduced cell-to-module derate
- Reduced cell metallization costs by way of lower Ag usage
- Lower input material costs
- Increased tool throughput (lower CapEx and OpEx)
- Supply and demand (industry is frequently in overcapacity)

Original data source for figure: BNEF Solar Spot Price Index (May 27, 2020)
2020 Cost Model Results Using the 2020 ITRPV

July 15, 2020

**Cost Model Results for the Monocrystalline Silicon Supply Chain**

All-New Greenfield Production Facilities in Urban China. Pricing Does Not Include Shipping or Import Tariffs.

- Polysilicon price reductions: From $21/kg to $7.5/kg. Transition from slurry-based to diamond wire wafering. Reduce kerf loss from 150 μm to 70 μm. Efficiency advancements by moving from Al BSF to PERC. Metallization improvements including silver utilization: From 200 mg/cell to 90 mg/cell. Move to larger wafers as well as half-cut and multi busbar cells. Process engineering and economies of scale.

2020 ITRPV Roadmap Results: 170 μm to 150 μm wafer thickness and 70 μm to 50 μm kerf loss. Move to M10 format by 2025. Increase ingot mass from 400 kg to 600 kg. Reduce Ag to 50 mg/cell. 50% increase in cell conversion and module assembly tool throughput.

- 0.5%/year module-area efficiency improvements. $/m² balance-of-module materials held constant.

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**2020 U.S. $ per W_{dc}**

- **2015** (16% Module Efficiency)
  - $0.107
  - $0.102
  - $0.083

- **Q1 2020** (20.5% for PERC)
  - $0.023
  - $0.017
  - $0.085
  - $0.020
  - $0.010
  - $0.036
  - $0.021

- **Processing Advancements**
  - $0.029
  - $0.017
  - $0.085
  - $0.020
  - $0.010
  - $0.036
  - $0.021

- **Efficiency Gains** (23% by 2025)
  - $0.019
  - $0.011
  - $0.085
  - $0.014
  - $0.001
  - $0.031
  - $0.017

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**15% GM Price Target**

5% to 25% for Error Bars

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DRAFT Update. Do Not Cite or Reference. Reviewer Comments Appreciated Before Publication.
Introduction to Solar Plus

Most Recent Projections From the ITRPV

World Market Share of PV systems which are combined with storage

NREL System Cost Benchmark

**Goal:** identify cost reduction opportunities, such as the impact of using higher module conversion efficiencies, helping policymakers make future research and development (R&D) decisions etc.,

- NREL has been modeling U.S. photovoltaic (PV) system costs since 2009.
- U.S. solar & storage benchmarks for residential, commercial, and utility-scale systems.
- Bottom-up methodology, accounting for all system and project-development costs.
- Model typical installation techniques and business operations from an installed-cost perspective.
- Costs represent the price at which components are purchased by the developer/installer, not accounting for preexisting supply agreements or other contracts.
- Profit the installer/developer receives, as a separate cost category.
Key Cost Components

<table>
<thead>
<tr>
<th>System Cost Components</th>
<th>What it is based of?</th>
<th>$/unit required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module/ Battery</td>
<td>System Size</td>
<td>$/watt</td>
</tr>
<tr>
<td>PV/Battery Inverter</td>
<td>System Size</td>
<td>$/watt</td>
</tr>
<tr>
<td>Structural BOS</td>
<td>Site Preparation, Racking, Mounting Panels, Trenching, Tracking Components, Containers, Inverter &amp; Transformer Housing</td>
<td>Qty &amp; Material-Cost/unit</td>
</tr>
<tr>
<td>Electrical BOS</td>
<td>Site Staging, Conduit &amp; Wiring, DC Cabling, Combiner Boxes, Switchgear &amp; Transformers, EMS, Monitoring &amp; Control System.</td>
<td>Qty &amp; Material-Cost/unit</td>
</tr>
<tr>
<td>Installation Labor &amp; Equipment</td>
<td>Equipment &amp; Labor Cost Associated with SBOS &amp; EBOS</td>
<td>Qty &amp; Equipment-Cost/unit, Labor Hours/ Activity &amp; Labor Wages/Occupation</td>
</tr>
<tr>
<td>Permitting &amp; Interconnection</td>
<td>BLM Cost, Building &amp; Electrical, Interconnection</td>
<td>US Avg.</td>
</tr>
<tr>
<td>Sales Tax</td>
<td>By state</td>
<td>%</td>
</tr>
<tr>
<td>Overhead</td>
<td>EPC &amp; Developer Overhead by system size</td>
<td>%</td>
</tr>
<tr>
<td>Profit Margin</td>
<td>By system size</td>
<td>%</td>
</tr>
</tbody>
</table>
Q1-2020
Utility PV Model Preliminary Results

Drivers of Cost Reduction
- Lower module price
- Higher module efficiency
- Lower structural BOS costs due to reduced material cost
- Removal of land acquisition cost
Q1-2020 PV Cost Benchmark Preliminary Results

- ~5% reduction between 2019 and 2020 total system cost benchmark.
- Across all sectors, the major drivers of price reduction is material & equipment costs and labor costs due to increased module efficiency.
- Q1-2020 total system cost estimates with Mono-PERC modules are in ballpark of industry average.
- Cost difference with industry average is mainly due to the way soft cost components are accounted.

<table>
<thead>
<tr>
<th>Soft Costs (P!i, OH&amp;P, SG&amp;A etc..)</th>
<th>Install Labor &amp; Equipment</th>
<th>Electrical BOS</th>
<th>Structural BOS</th>
<th>Inverter</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>$0.26</td>
<td>$0.22</td>
<td>$0.08</td>
<td>$0.22</td>
<td>$0.37</td>
</tr>
<tr>
<td>Commercial</td>
<td>$0.77</td>
<td>$0.13</td>
<td>$0.12</td>
<td>$0.09</td>
<td>$0.37</td>
</tr>
<tr>
<td>Commercial</td>
<td>$0.56</td>
<td>$0.17</td>
<td>$0.11</td>
<td>$0.06</td>
<td>$0.37</td>
</tr>
<tr>
<td>Utility Fixed-Til</td>
<td>$1.45</td>
<td>$1.05</td>
<td>$0.31</td>
<td>$0.17</td>
<td>$0.34</td>
</tr>
<tr>
<td>Utility One-Axi</td>
<td>$1.60</td>
<td>$1.05</td>
<td>$0.31</td>
<td>$0.17</td>
<td>$0.34</td>
</tr>
</tbody>
</table>

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Q1-2020 Utility Scale Storage Preliminary Results

AC Coupled vs. DC Coupled Assumptions

- Exclude switchgear and transformer related components & construction costs for DC Coupled Systems
- Reduced foundation and site preparation for DC Coupled Systems
- Higher labor due to additional charge-controller/smaller battery packs and associated wiring labor etc., for DC Coupled Systems
- At different sites, wiring and electrical costs increases, PII costs doubles.
- AC coupled systems are preferred in retrofits. Also, installation cost of new-builds are cheaper than retrofits.

- 60MW, 30 MWh – 240MWh Nameplate capacity
- Developer Overhead 2.5%, EPC OH&P – 5%

- Battery cost: $194/kWh - $242/kWh
- Bidirectional inverter: 0.06 $/W
Q1-2020 Storage Cost Benchmark Preliminary Results

- Q1-2020 4-hour estimates are in ballpark of industry estimates.

Improvements

- Accounting for Depth of Discharge, Roundtrip Efficiency, throughput or No. of cycles over lifetime.
- Using usable kWh rather than rated or nameplate or theoretical kWh.
- Changing BOP & soft costs as a function of duration.
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Conclusions

• R&D and the supply chain for solar PV module production is a global enterprise.
• The costs to produce PV modules has declined over time, but price pressures constrained 2010—2019 industry median gross margins to the 5—25% range. Industry median operating margins were in negative territory from Q3 2016 to Q2 2019.
• NREL cost model results for the full mono- PERC supply chain are roughly $0.02/W silicon cost, $0.04/W for ingot and wafer production, $0.03/W for cell conversion, $0.10/W for module assembly, and $0.03/W for R & D plus S, G, & A. We also calculate around $0.25/W ASP would have provided around 15% operating margin in H1 2020.
• Additional solar cell technologies including PERT, SHJ or HJT, and IBC are now calculated to be within $0.05/W of the costs for standard Al BSF and PERC.
• Long-term growth scenarios for the solar PV industry may be less dependent upon further cost reductions in module and utility-scale systems than integration with storage technologies, advanced on-grid and off-grid engineering technologies, and other power generation systems.
• Please follow-up with any questions!
Thank You
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<table>
<thead>
<tr>
<th>Category</th>
<th>Modeled Value</th>
<th>Description</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>System size</td>
<td>5-100 MW</td>
<td>A large utility-scale system capacity</td>
<td>Model assumption</td>
</tr>
<tr>
<td>Module efficiency</td>
<td>20.14%</td>
<td>Average module efficiency</td>
<td>Based on YOY increment using LBNL’s Tracking the sun (2018)</td>
</tr>
<tr>
<td>Module price</td>
<td>$0.36/Wdc</td>
<td>Ex-factory gate (first buyer) price, Tier 1 modules</td>
<td>GTM 2019</td>
</tr>
</tbody>
</table>
| Inverter price                 | $0.04/Wdc (fixed-tilt & 1-axis Tracker) | Ex-factory gate (first buyer) price, Tier 1 inverters  
DC-to-AC ratio = 1.36 for fixed-tilt and 1.30 for one-axis tracker | GTM 2019                                                                                          |
| Structural components (racking) | Varies by location and system size | Fixed-tilt racking or one-axis tracking system                                                 | ASCE (2006), Model assumptions, NREL (2018), RSMeans (2019)                                       |
| Electrical components          | Varies by location and system size | Our model has been upgraded to 1,500 Vdc system, including conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, etc. | Model assumptions, NREL (2018), RSMeans (2019)                                                       |
| EPC overhead (% of equipment costs) | 8.67%–13% for equipment and material (except for transmission line costs); | Costs associated with EPC SG&A, warehousing, shipping, and logistics | NREL (2018)                                                                                       |
| Sales tax                      | Varies by location     | National benchmark applies an average (by state) weighted by 2017 installed capacities         | RSMeans (2019), GTM and SEIA (2018)                                                               |
| Direct installation labor      | Electrician: $19.74–$38.96 per hour;  
Construction Laborer: $12.88–$25.57 per hour;  
Varies by location | Modeled labor rate assumes both non-union and union labor and depends on state; national benchmark uses weighted average of state rates | BLS (2019), NREL (2018)                                                                            |
| Burden rates (% of direct labor) | Total nationwide average: 31.8% | Workers compensation (state-weighted average), federal and state unemployment insurance, FICA, builders' risk, public liability | RSMeans (2019)                                                                                     |
| PII                            | $0.01–$0.04/Wdc        | For construction permits fee, interconnection, testing, and commissioning                       | NREL (2018)                                                                                       |
| Transmission line (gen-tie line) | $0.00–$0.02/Wdc        | System size < 10 MW, use 0 miles for gen-tie line  
System size > 200 MW, use 5 miles for gen-tie line  
| Developer overhead             | 2%–12%                 | Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions | Model assumptions, NREL (2018)                                                                    |
| Contingency                    | 3%                     | Estimated as markup on EPC cost                                                                | NREL (2018)                                                                                       |
| Profit                         | 5%–8%                  | Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, developer overhead, etc. | NREL (2018)                                                                                       |
Analysis Disclaimer

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