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NATIONAL RENEWABLE ENERGY LABORATORY

The Global Solar Photovoltaic Supply Chain and Bottom-UP Cost Model Results

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World Conference on Photovoltaic Energy Conversion (WCPEC)
Milan, Italy

September 26, 2022

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Presentation Outline

NREL's Solar + Storage Technoeconomic Analysis Portfolio

Bottom-Up Component Cost Models

Modules

Crystalline Silicon

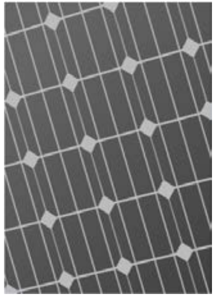

Illustration by Al Hicks, NREL

Thin-Film

Photo from iStock, 1033236964

Storage

Batteries

Photo by Dennis Schroeder, NREL 56318

Solar Fuels

Photo from iStock, 932140864

System Capital Cost Models ($)

PV Systems

Photo by Dennis Schroeder, NREL 60073

PV Plus Storage

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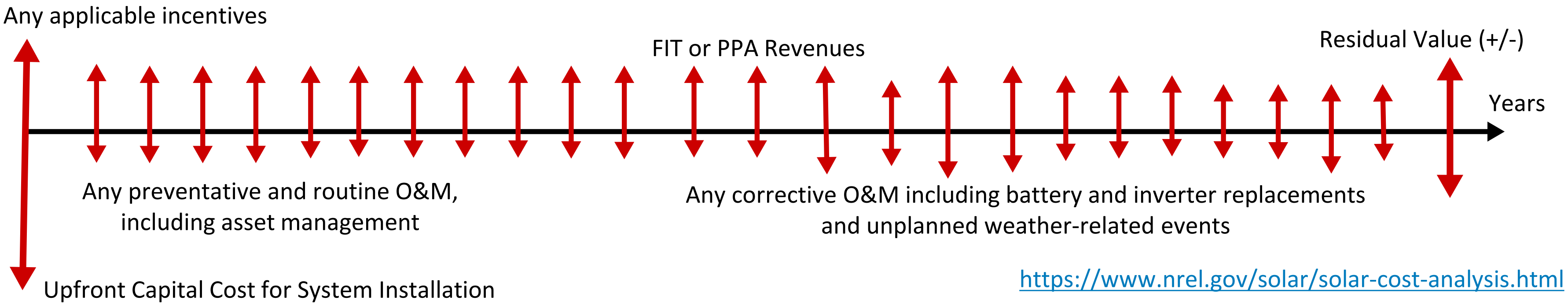
Solar and Storage Project *Pro Forma* Analysis

Levelized Cost of Electricity (LCOE) Metric

Internal Rate of Return (IRR) Metric



https://www.nrel.gov/solar/solar-cost-analysis.html

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

https://www.nrel.gov/solar/solar-cost-analysis.html

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

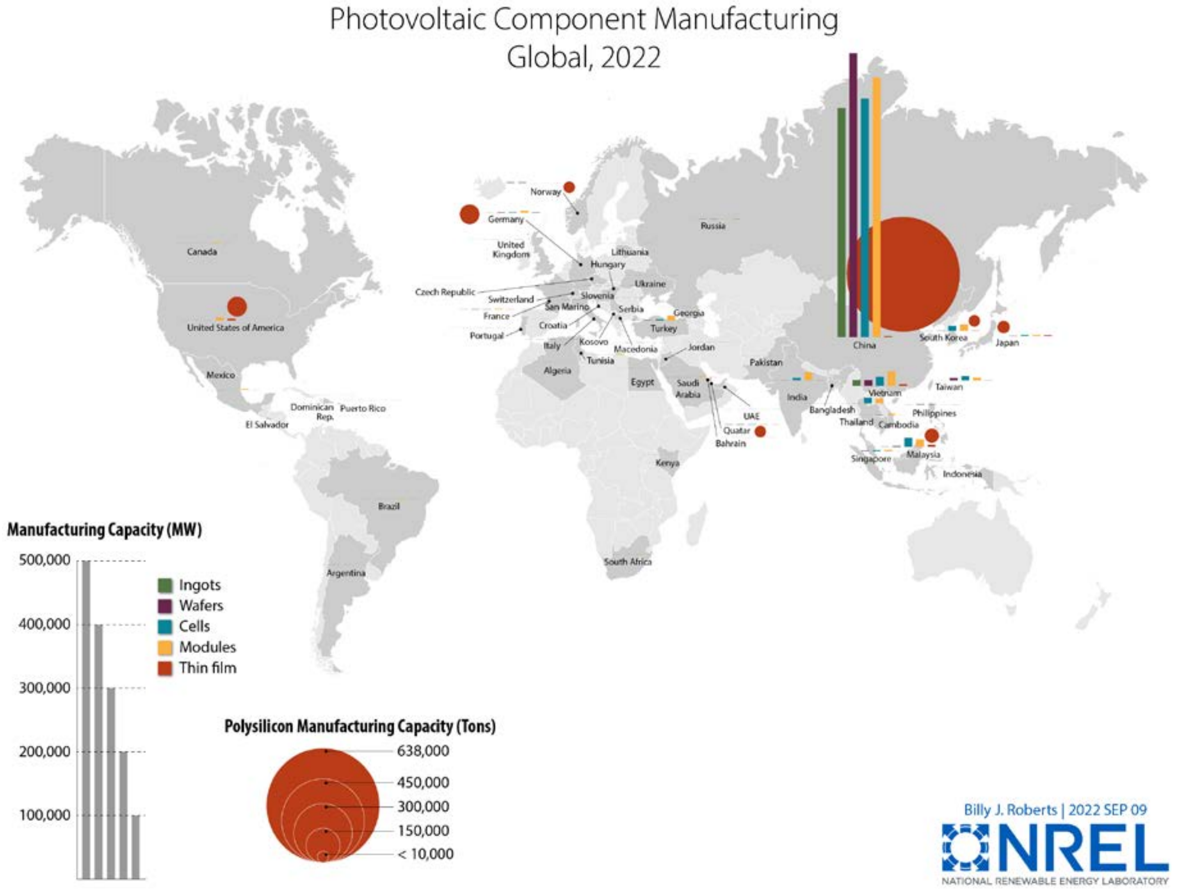
5 Monte Carlo Uncertainty Analysis of PV Manufacturing Costs

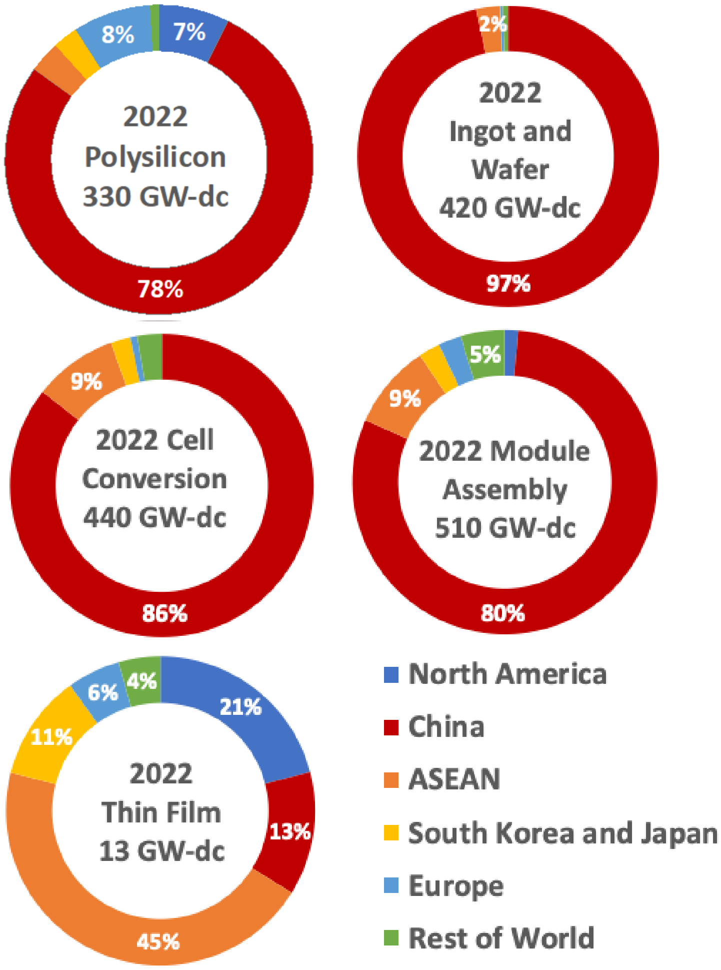
6 Future Analysis Including the United States Inflation Reduction Act

7 Conclusions

2022 Commissioned Capacity

Facility Locations and Manufacturing Capacities

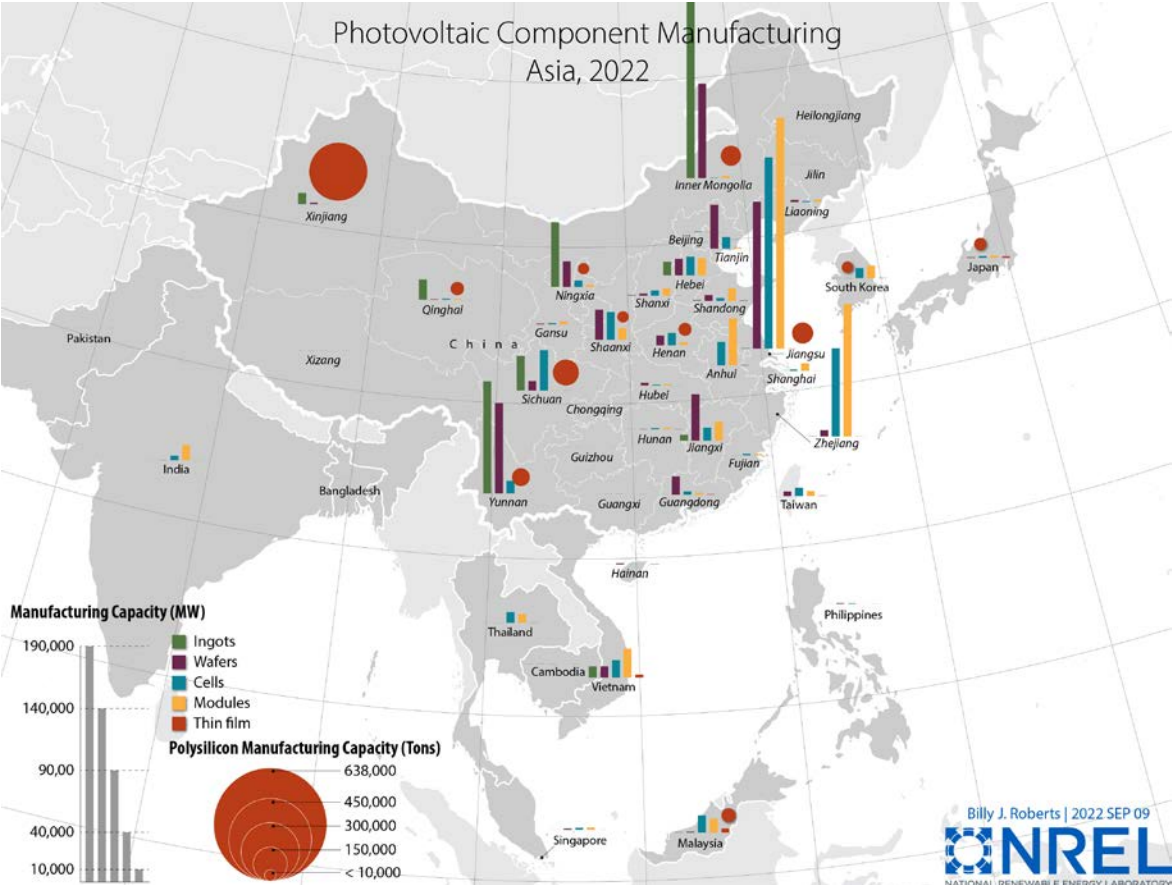


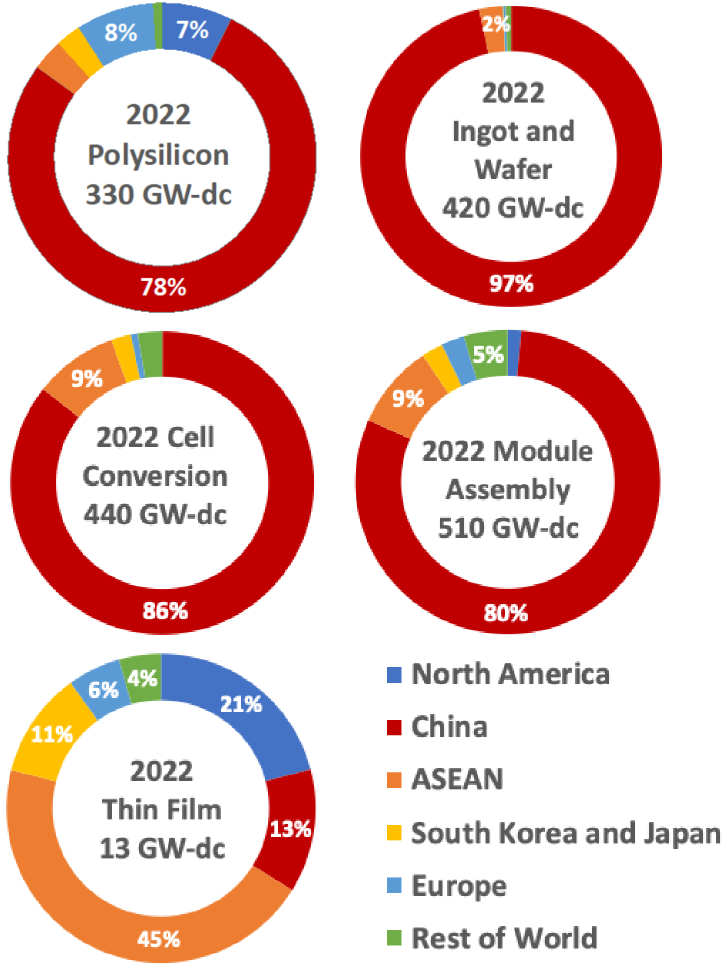


Maps generated by Billy Roberts (NREL) using data from the BNEF PV Equipment Manufacturers Database, August 2022.

2022 Commissioned Capacity

Facility Locations and Manufacturing Capacities





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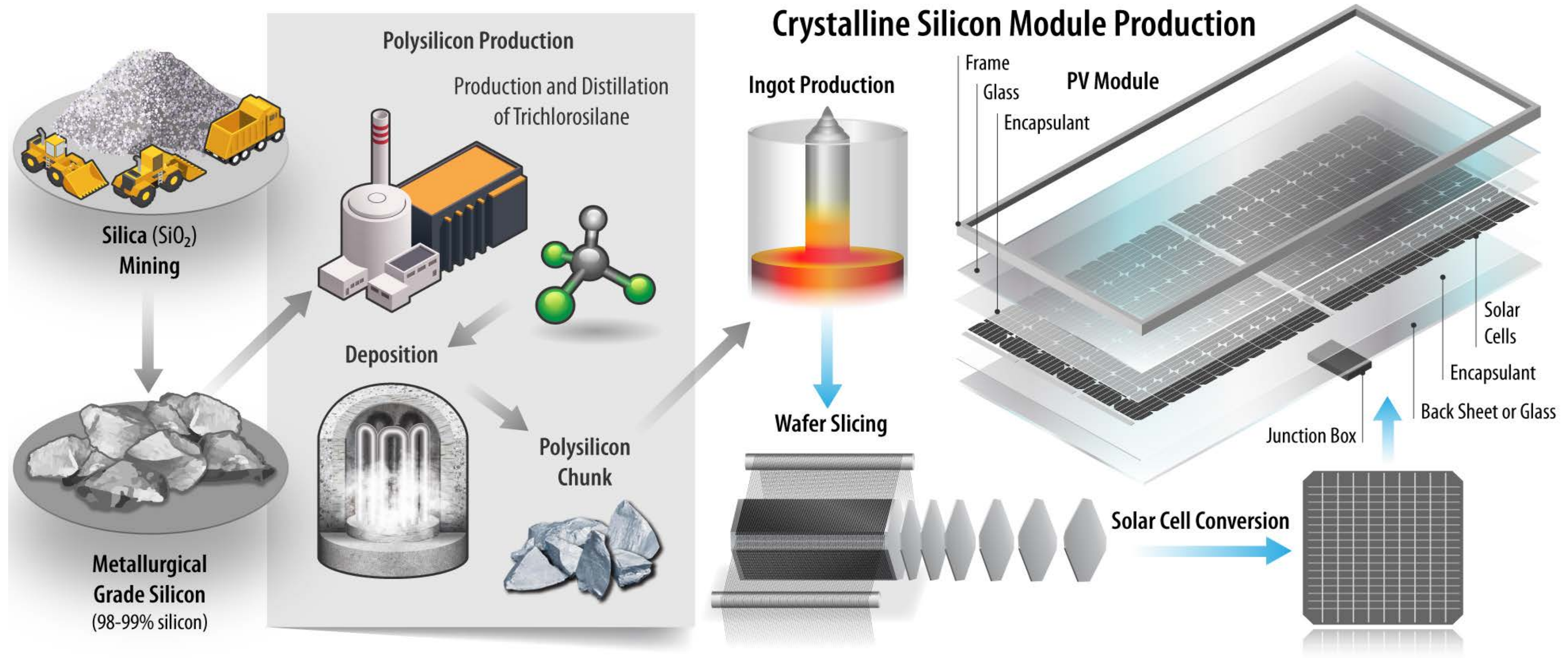
Presentation Outline

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



Source of figure: NREL.

https://www.nrel.gov/solar/solar-cost-analysis.html

NREL Cost Model Structure for Manufacturing and Delivery

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)

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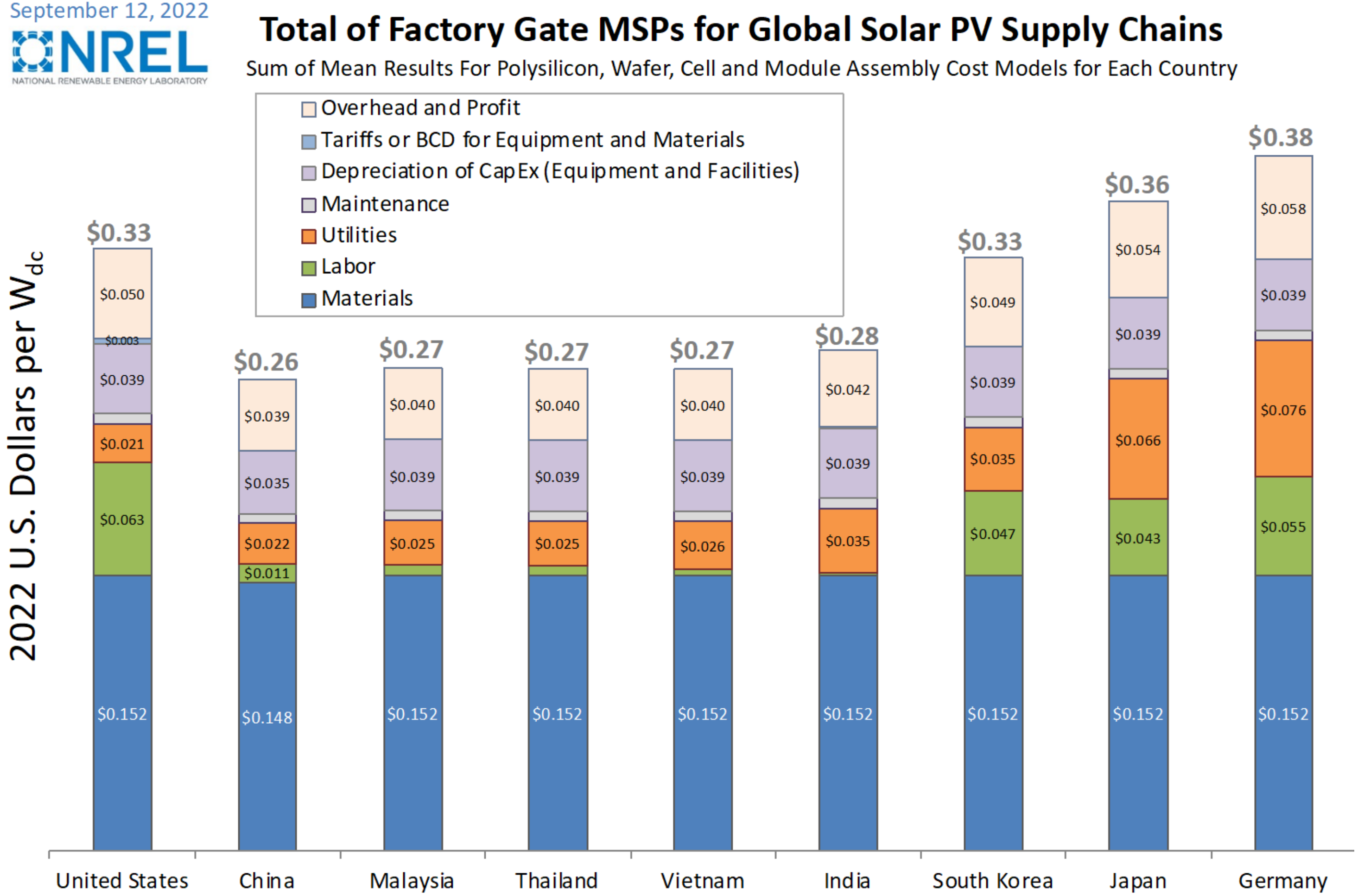
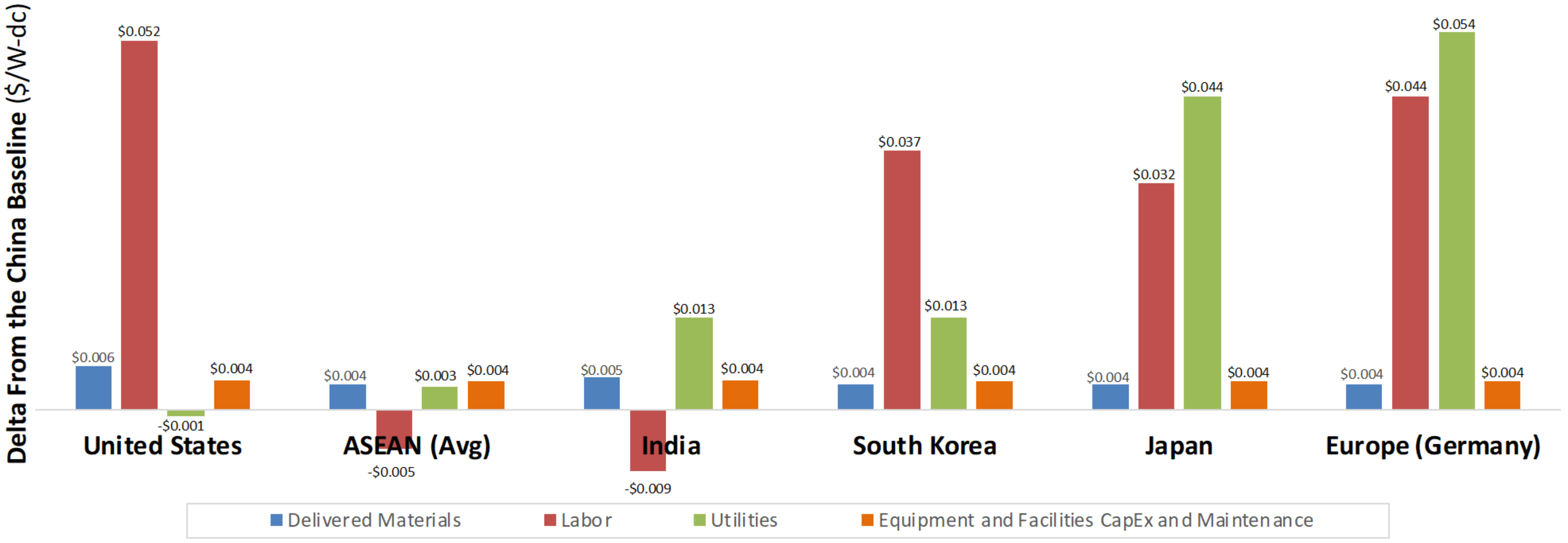
Total of Results from NREL's Bottom-Up Cost Models

September 12, 2022



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



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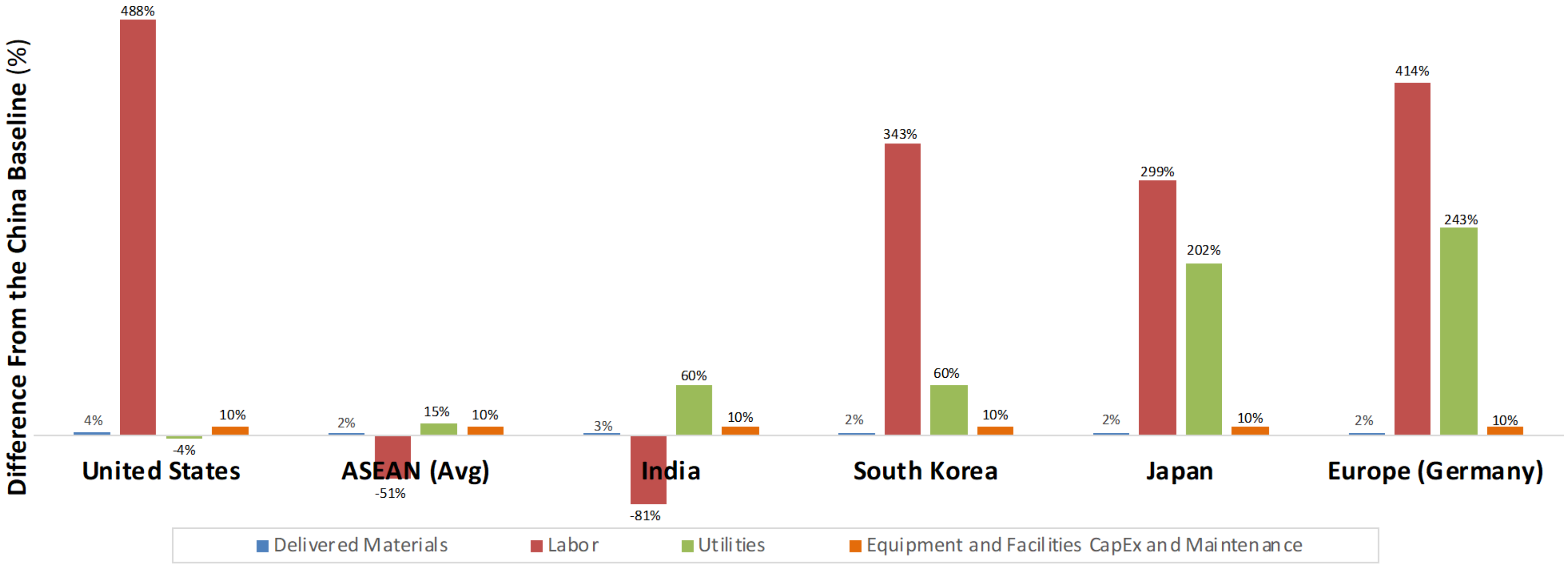

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Monte Carlo Analysis of Multiple Input Variables for the U.S.

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

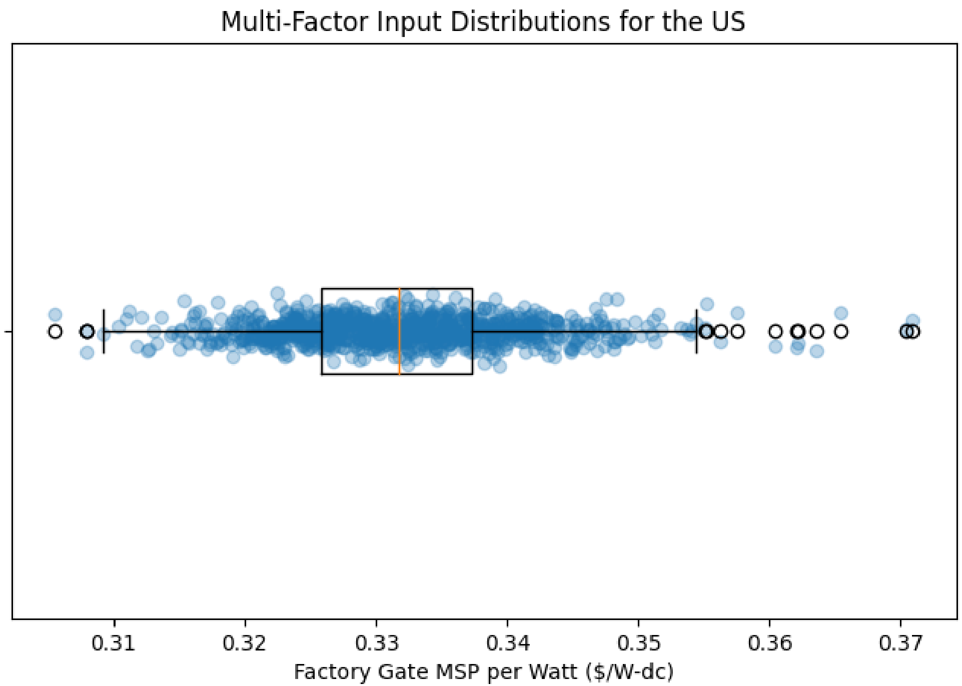
One standard deviation equals +/- 1% change in *relative cell and module efficiency*

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

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

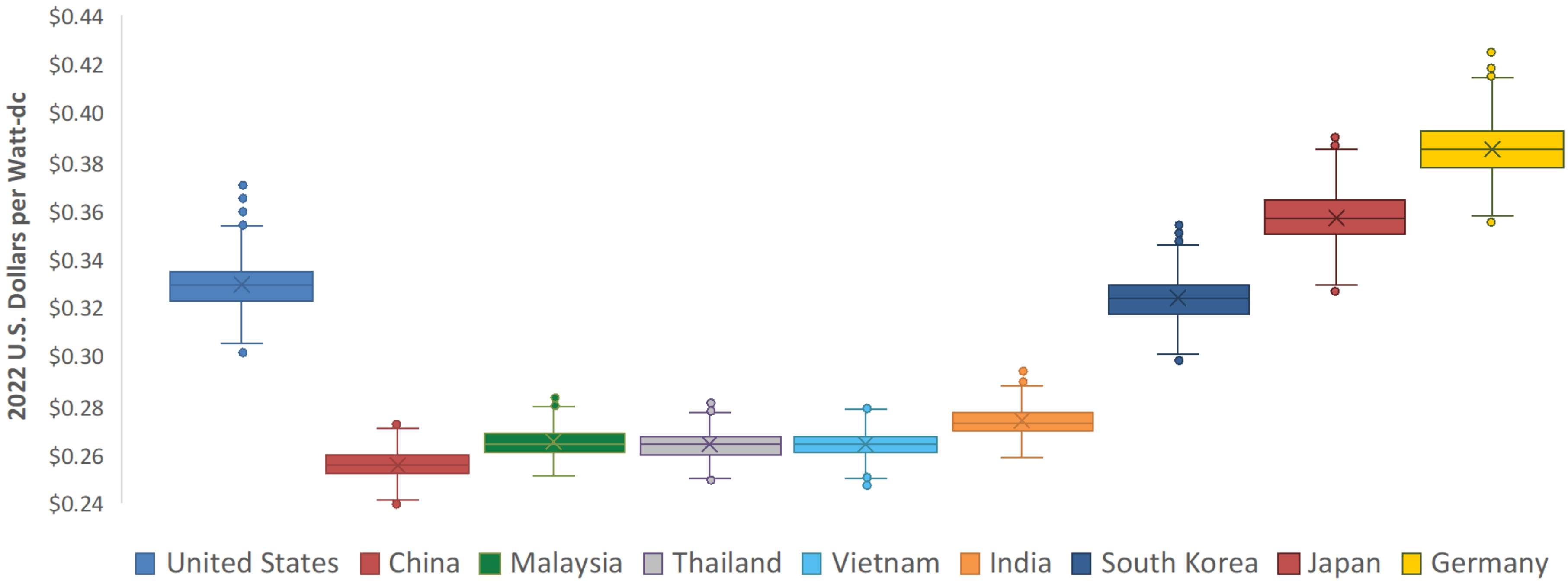
One standard deviation equals +/- 5% change in *factory downtime and throughput*

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



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

ITC in the United States	**2022—2032**	**2033**	**2034**	**2035**	**2036**
Residential	**30%**	26%	22%	0%	0%
Commercial	**30%**	30%	4.5—22.5%	3—15%	0%
Utility	**30%**	30%	4.5—22.5%	3—15%	0%
Domestic Content	**+10%**	+10%	+10%	+10%	+10%

PTC Alternative in the United States					
Base PTC	**0.5—3.2 ¢/kWh**	0.6—3.2 ¢/kWh	0.5—2.4 ¢/kWh	0.3—1.6 ¢/kWh	0.0 ¢/kWh
Domestic Content	**+0.1—0.3 ¢/kWh**	+0.1—0.3 ¢/kWh	+0.0—0.3 ¢/kWh	+0.0—0.2 ¢/kWh	0.0 ¢/kWh

Sources: (1) United States House of Representatives Resolution 5376: https://www.congress.gov/bill/117th-congress/house-bill/5376/text
(2) IRA Solar Energy and Energy Storage Provisions", SEIA, 2022: https://www.seia.org/research-resources/inflation-reduction-act-solar-energy-and-energy-storage-provisions-summary

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

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

Sources: (1) United States House of Representatives Resolution 5376: https://www.congress.gov/bill/117th-congress/house-bill/5376/text
(2) IRA Solar Energy and Energy Storage Provisions", SEIA, 2022: https://www.seia.org/research-resources/inflation-reduction-act-solar-energy-and-energy-storage-provisions-summary

Presentation Outline

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!

https://www.nrel.gov/solar/solar-cost-analysis.html

Thank You

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Transforming ENERGY

Presentation Outline

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7 **Supplementary Information**

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NREL/PR-7A40-84036

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NREL Transforming ENERGY

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)

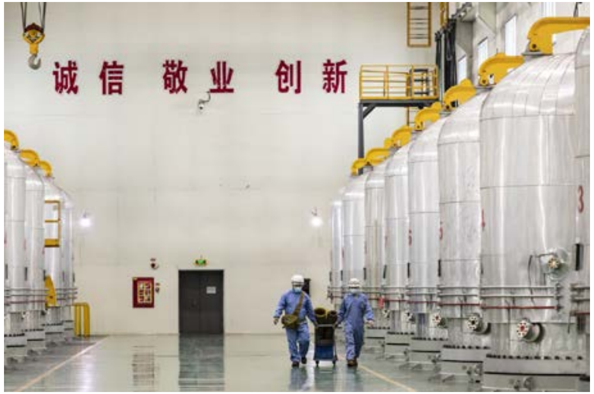
Source: Alibaba

Hydrochloric Acid
HCl

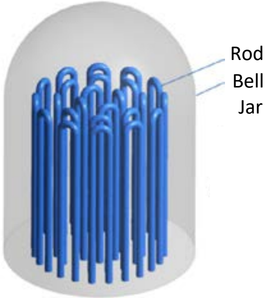
Production and distillation of trichlorosilane, $\mathbf{SiHCl_3}$

Source: Daqo

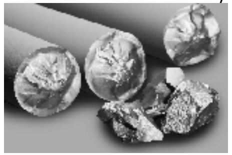
Siemens Chemical Vapor Deposition (CVD)



Source: Daqo



Source: GCL Poly



Harvesting, breaking, washing/etching, and packaging.

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

Source: Hemlock Semiconductor

Source of figure: NREL. https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain

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

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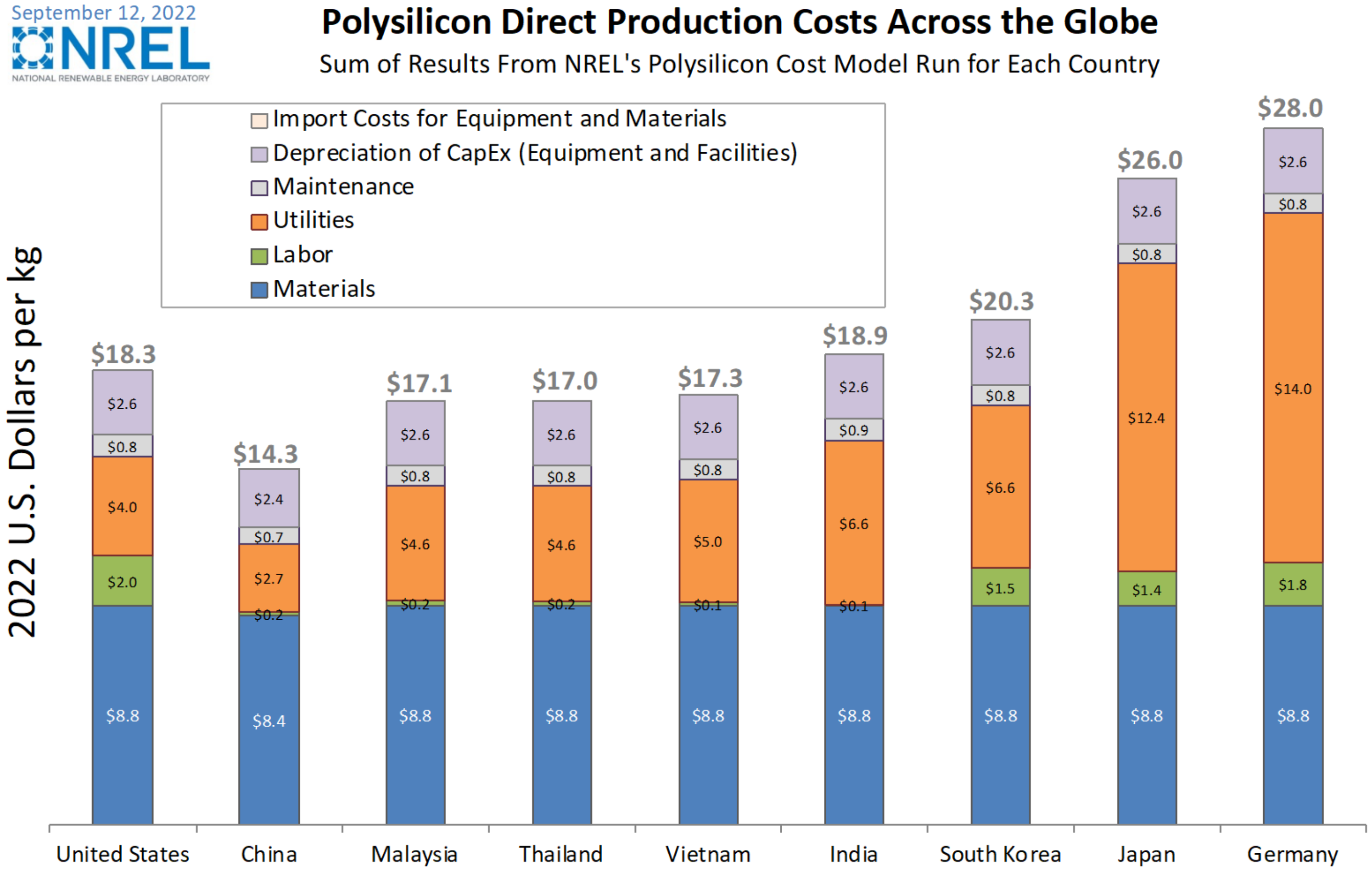
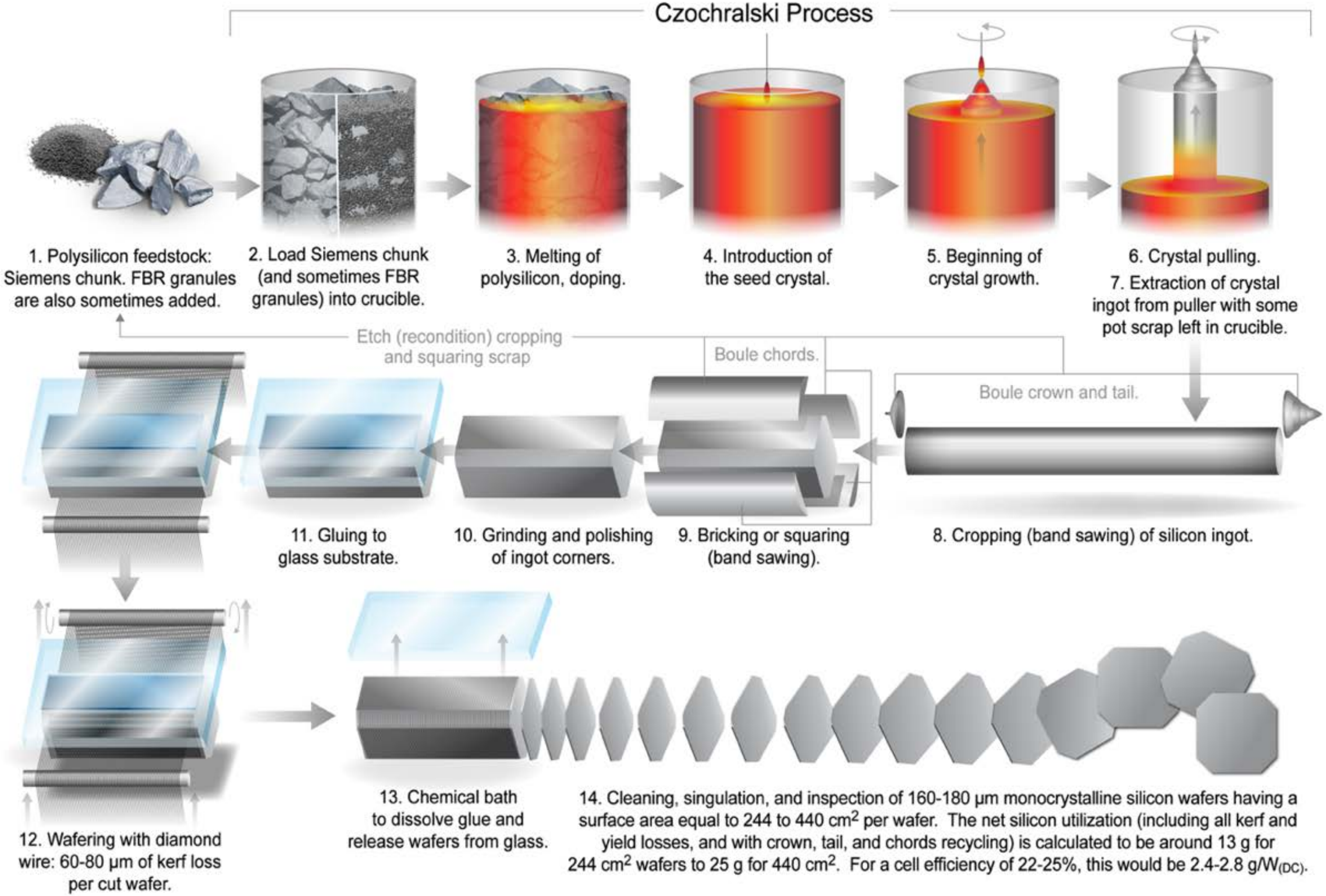


Process Flow for Ingot and Wafer Production



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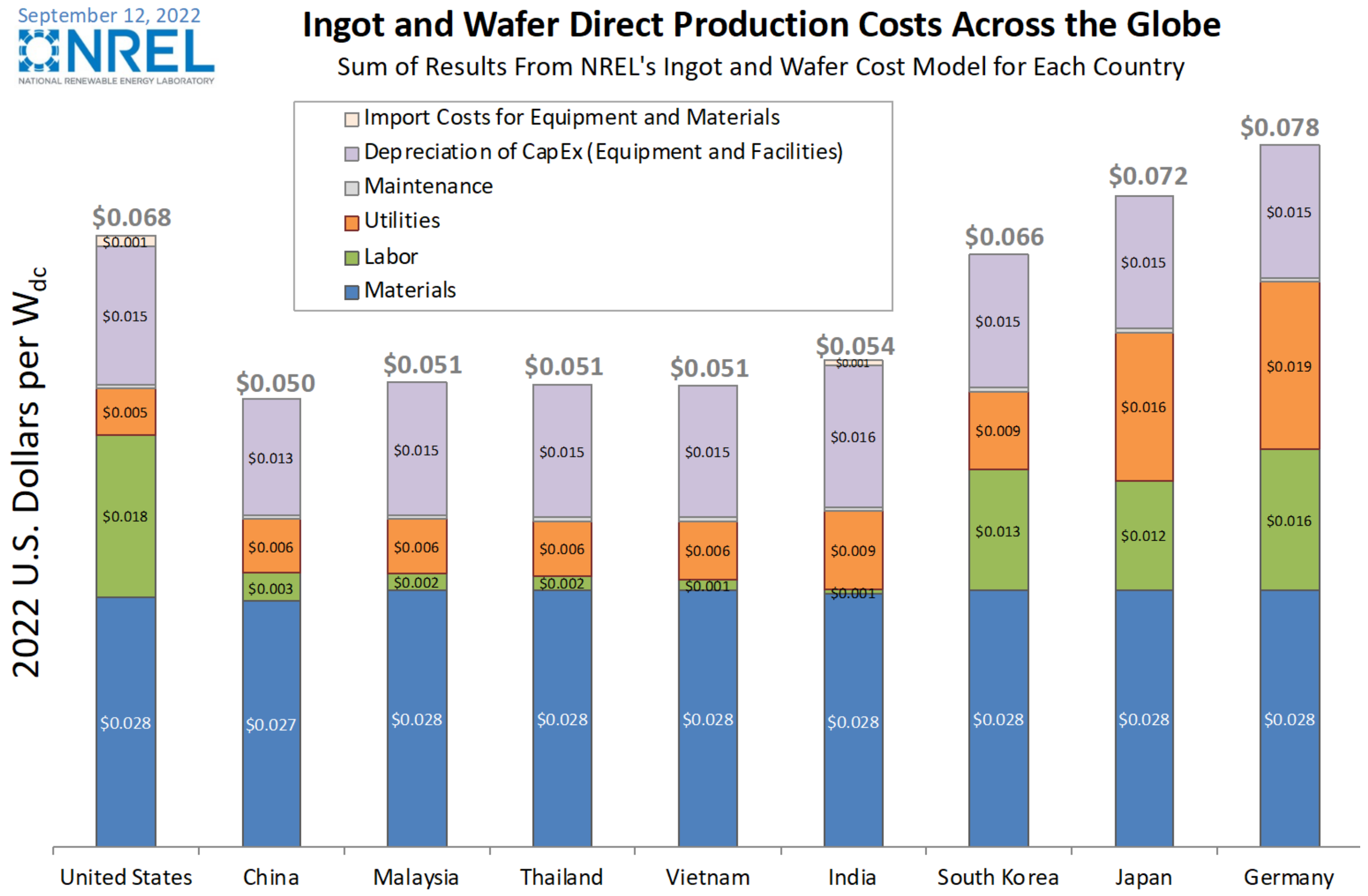
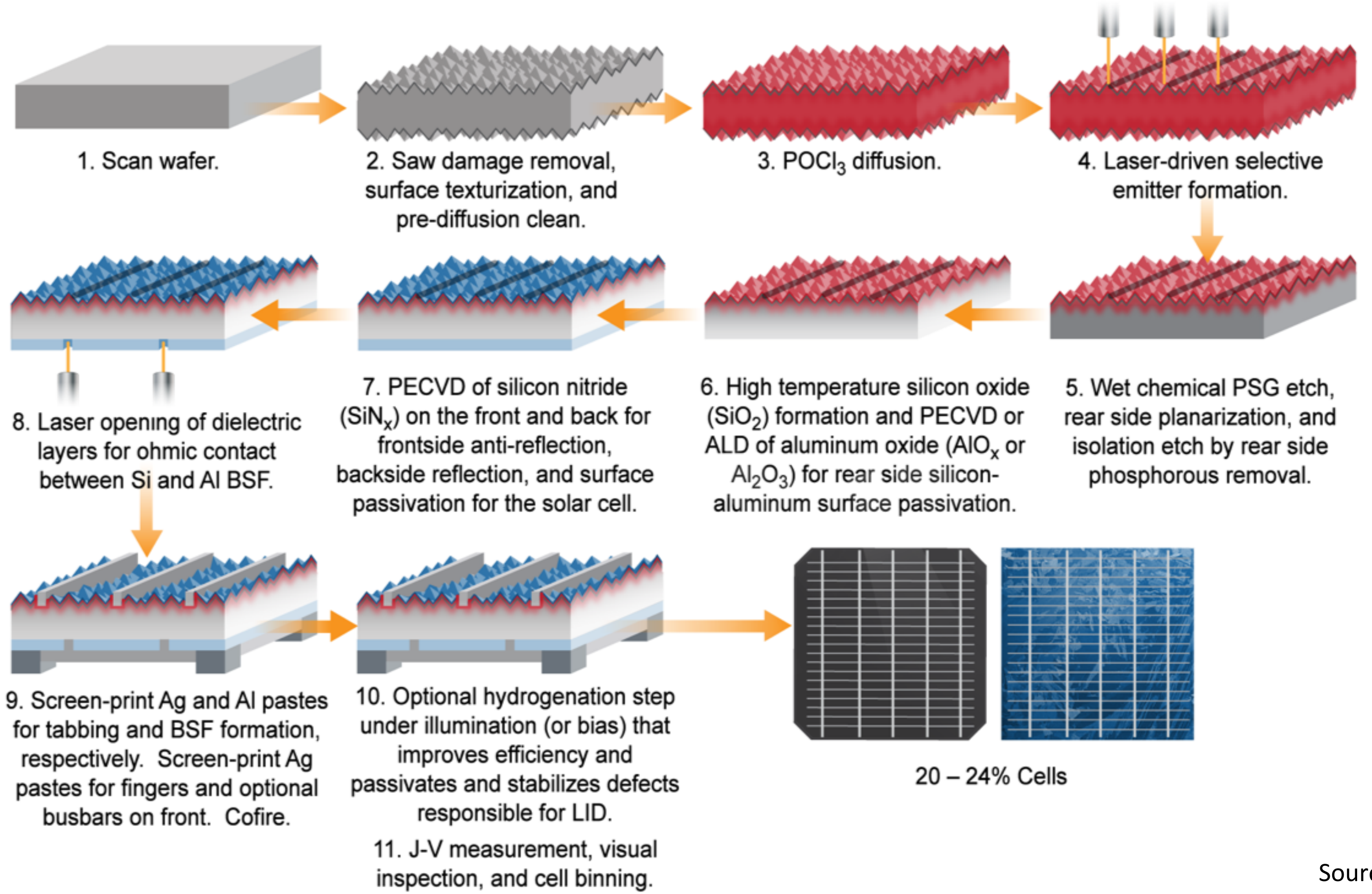


PERC Cell Process Flow



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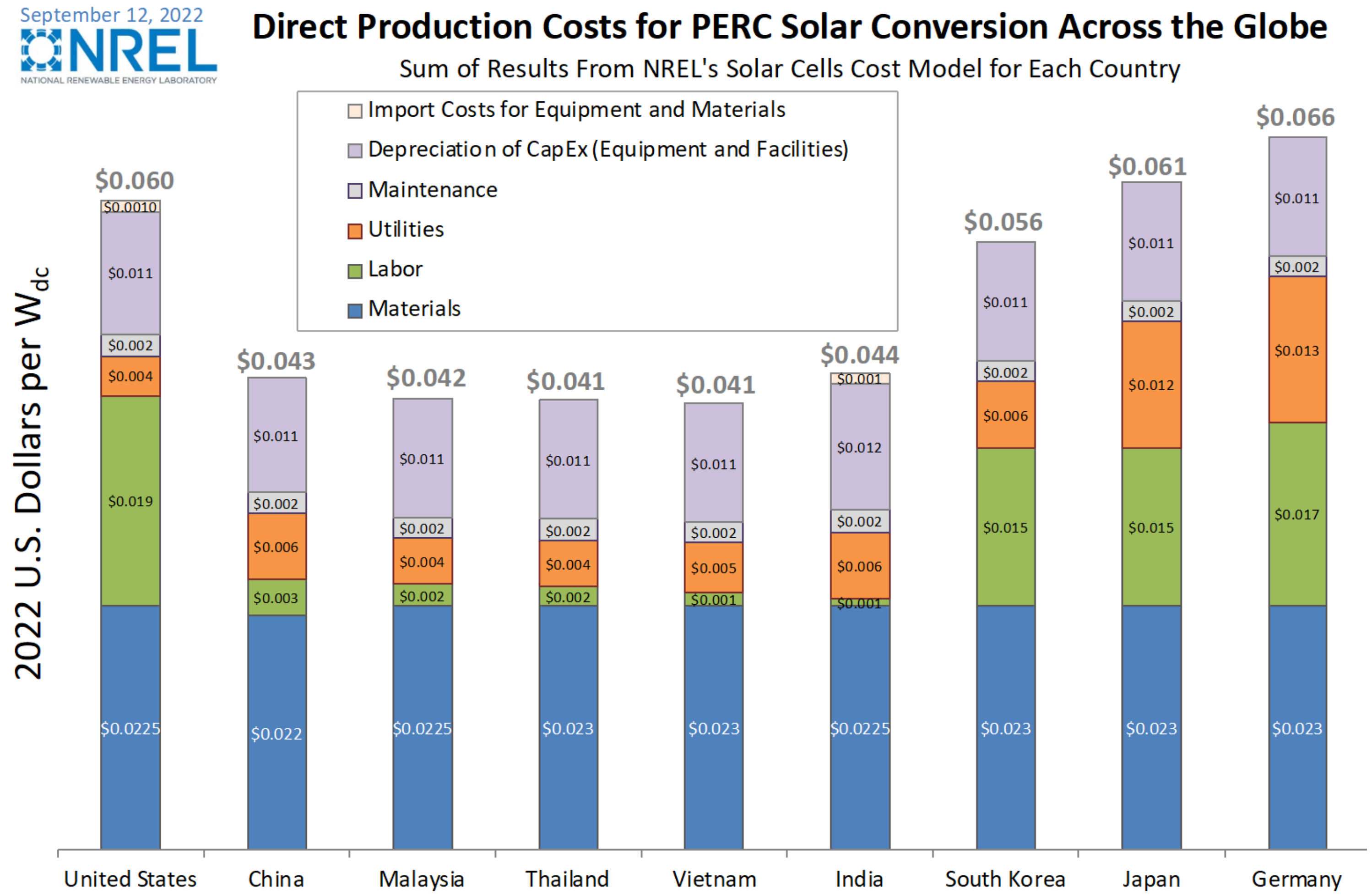
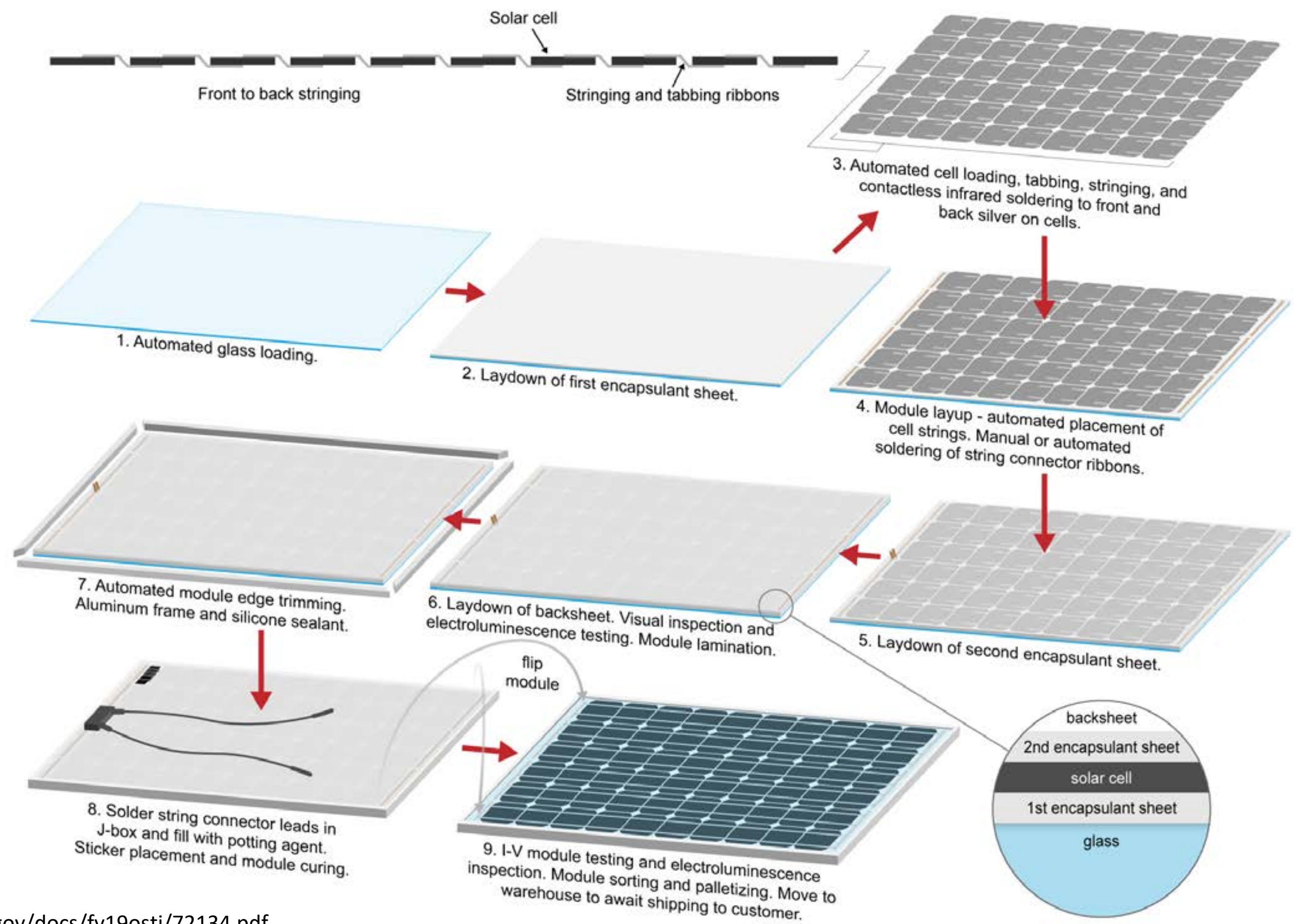


Module Assembly Process Flow



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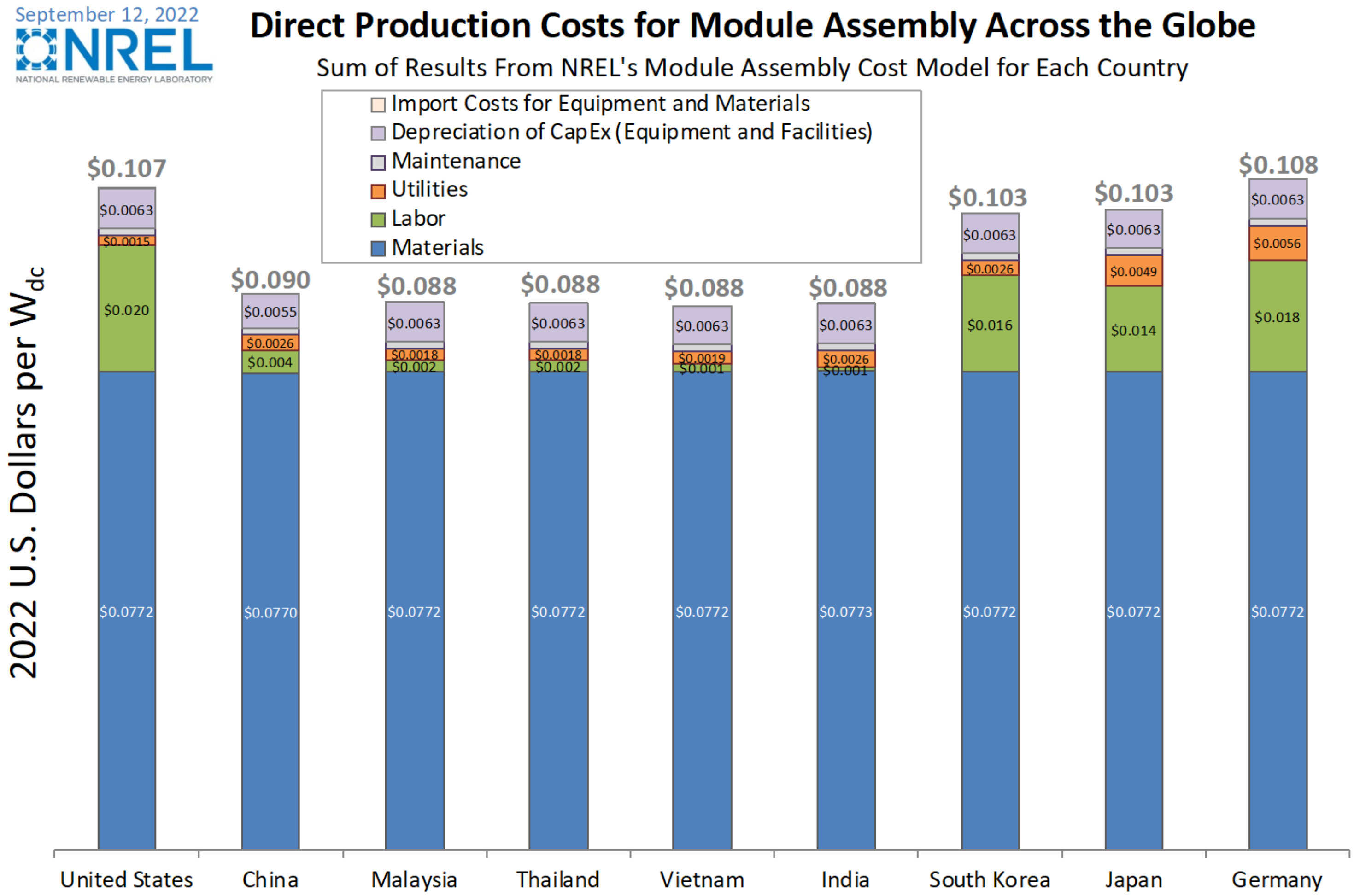


Equipment and Facilities Costs Drivers for PV Manufacturing

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

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	c-Si Supply Chain			
	Polysilicon	Ingot and Wafer	Cell Conversion	Module Assembly
Initial Capital Expenditure ($USD per Watt of annual capacity)	$0.11-0.14/W ($40—50/kg, 2.8 g/W)	$0.08-0.10/W ($0.54/wafer, 6.0 W for M6)	$0.05-0.13/W (PERC to Advanced technology)	$0.05-0.08/W (Standard to Busbarless)
for equipment:	$0.06—0.08/W	$0.06—0.07/W	$0.03—0.10/W	$0.03—0.05/W
for balance-of-plant or factory	$0.04—0.06/W	$0.02—0.03/W	$0.02—0.03/W	$0.02—0.03/W
1 GW_{dc} Investment	$110—140M	$80—100M	$50—130M	$50—80M
for equipment:	$65—80 M	$60—70 M	$30—100M	$30—50M
for balance-of-plant or factory	$45—60 M	$20—30 M	$20—30M	$20—30M
Time to Build (Engineering to production)	3—4 years (All-new, not retrofit)	1—3 years	1—3 years	1—3 years

Data source for figure: NREL.
Available online: https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain

Labor Costs Drivers for PV Manufacturing

Labor Costs $\propto$	**Labor Rate**	**Labor Intensity**
Summary	Burdened \$/hour	Employees per Gigawatt (GW) or Per unit produced
Details	\$/hour direct wage (Direct Operators) \$/hour direct wage (Supervisors) \$/hour direct wage (Engineers) Benefits (Cafeteria, Health Insurance, Retirement, etc.)	Staffing plan for each station

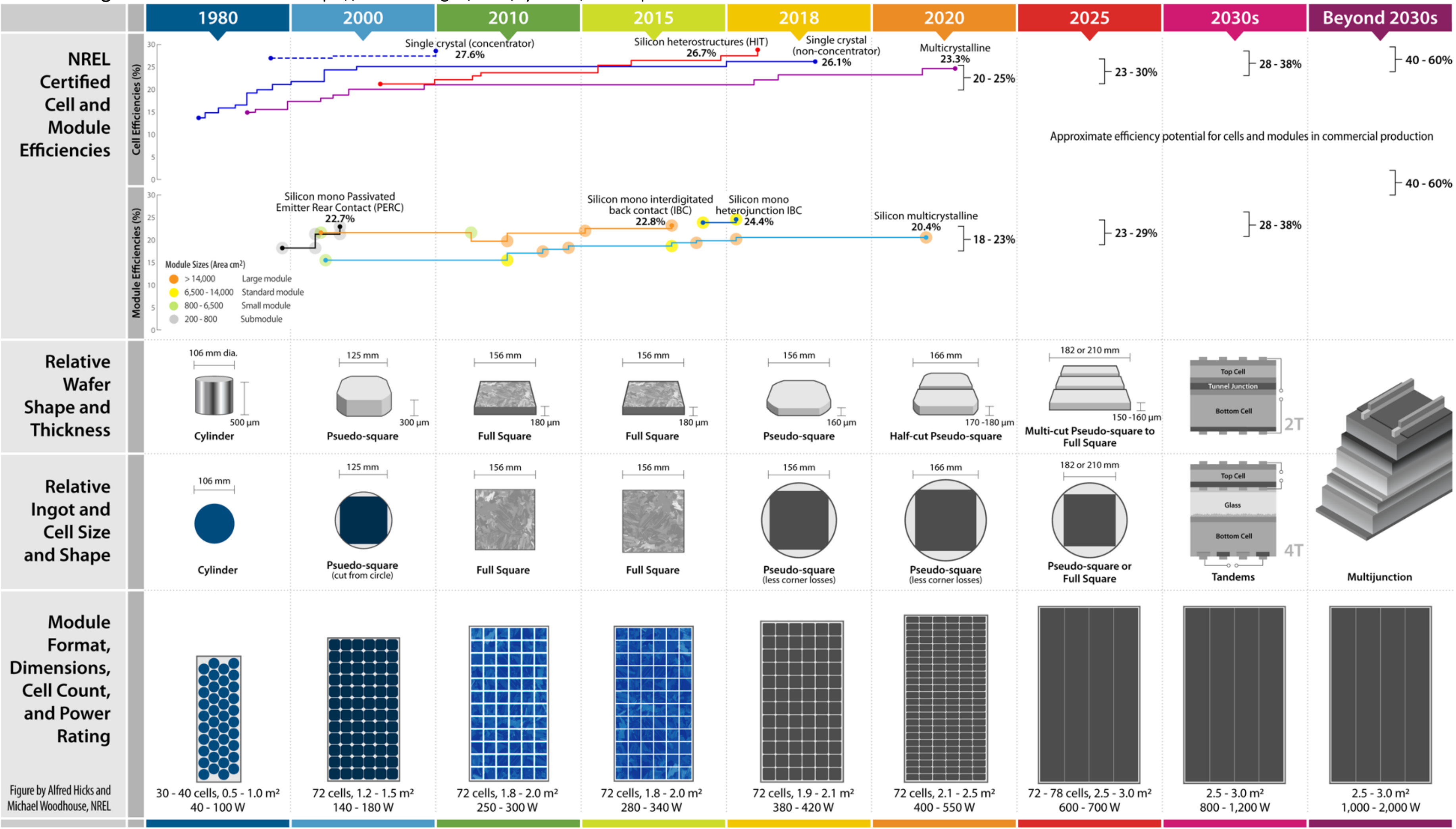
Throughput, scale, and yield are interdependencies.
Efficiency impacts \$/W.

Utilities Costs Drivers for PV Manufacturing

Utilities Costs $\propto$	Utility Rate	Utilities Intensity
Summary	\$/year	per finished unit: kWh/kg (polysilicon) kWh/wafer, kWh/cell and kWh/module m^3 per finished unit
Details	\$/kWh (Electricity Rate) \$/m^3 (Water Rate)	per station: kW operating power m^3 per unit or per hour

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

Time = 6—24 months (Inexperienced)

0 to 12 months

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

0 to 12 months

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

Time = 0 (Experienced)
Time = 0—18 months (Inexperienced)

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

Time = 0—18 months

Execute Sales

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

Time = 0—18 months

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)

Time = 12 to 18 months (Experienced)
Time = 24—60 months (Inexperienced)

Nameplate Capacity Achieved

- Debottlenecking completed
- Full staffing of facility in place
- Sales contracts secured

Thin Film Manufacturing Capacities (Not Including New Announcements)

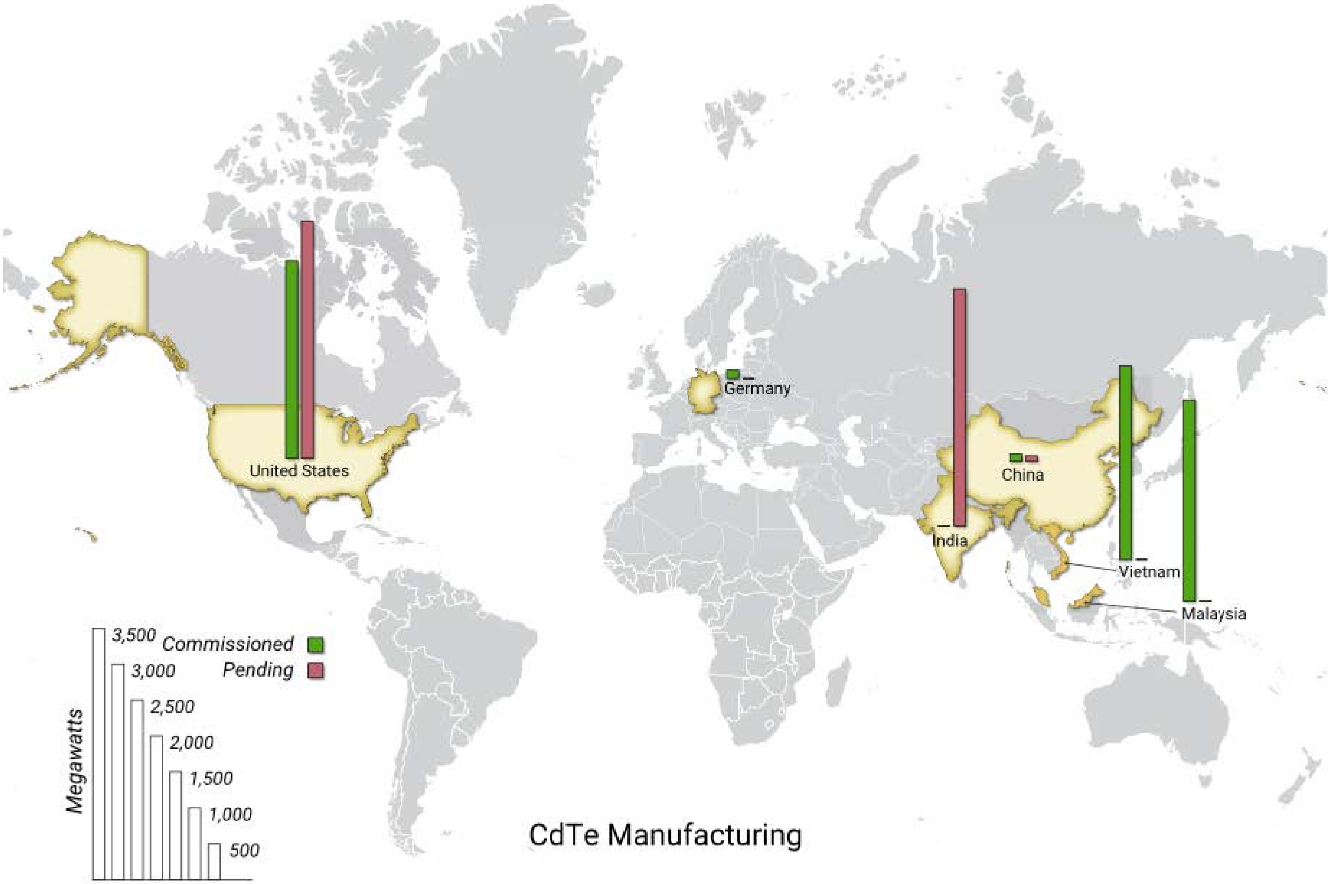
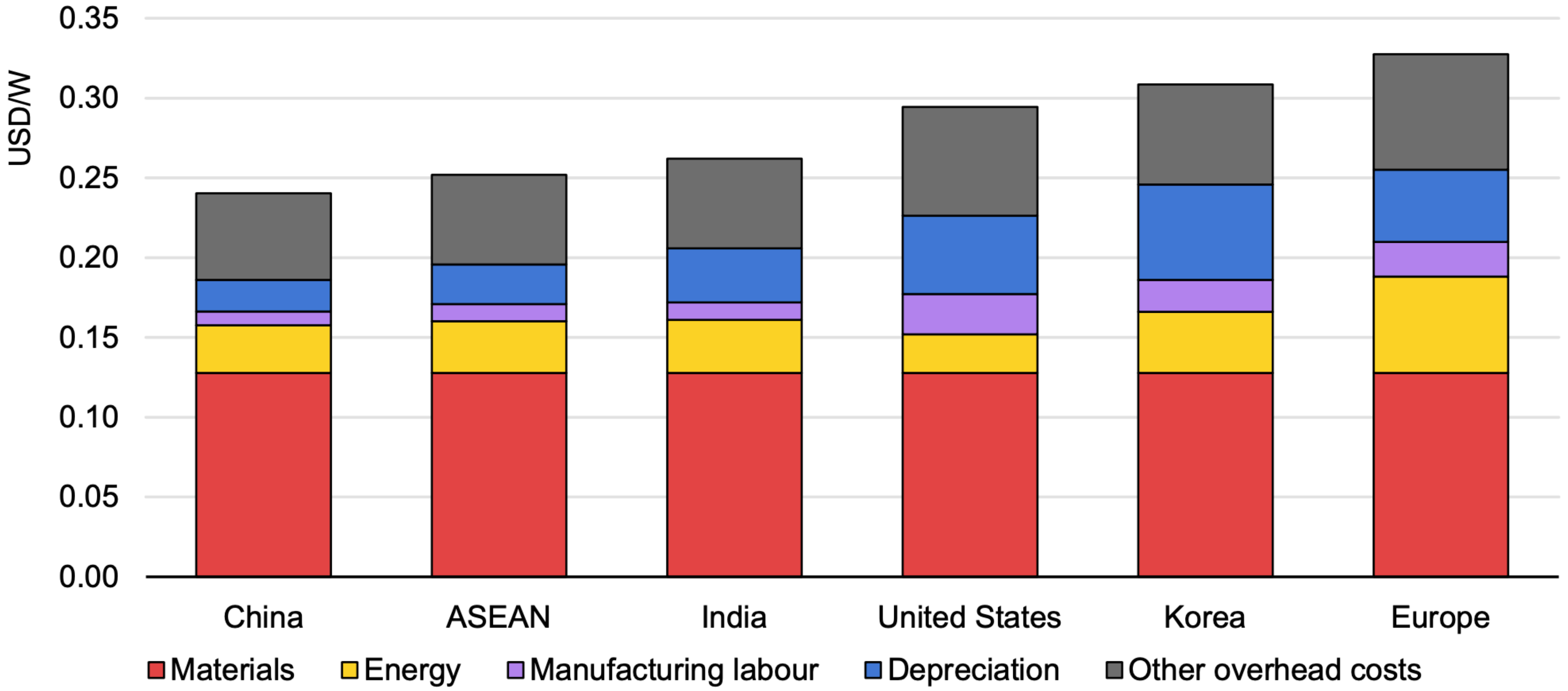


Figure Source (NREL): Hope M Wikoff, Samantha B Reese, and Matthew O Reese, ”Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics”, Joule (2022)

Costs Analysis from the International Energy Administration (IEA)



Source: IEA "Special Report on Solar PV Global Supply Chains", 2022. https://www.iea.org/reports/solar-pv-global-supply-chains

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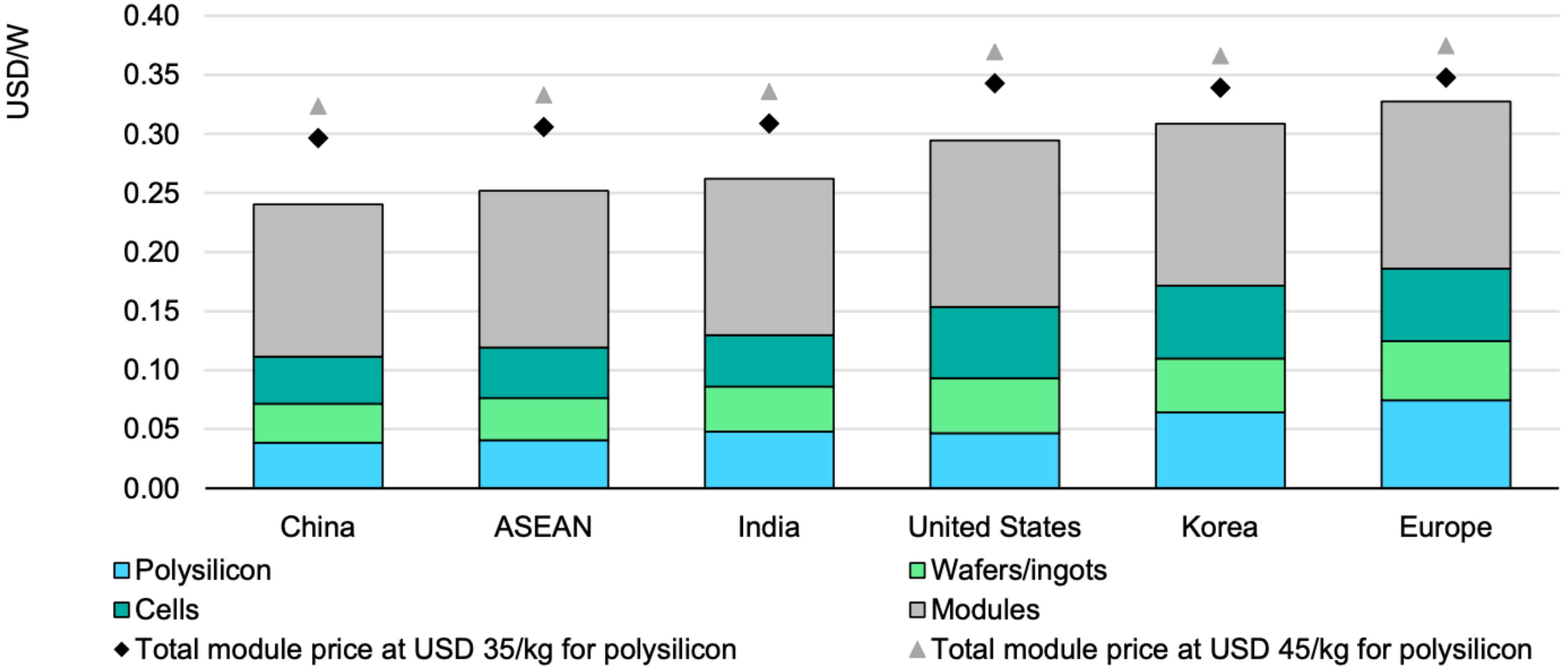

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