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Reflections on 15 Years of PV Module and System Price Declines and Where Things Go From Here

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Silicon Workshop
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Presentation Overview

NREL's Solar + Storage Technoeconomic Analysis Portfolio

Detailed Component Manufacturing Cost Models

Solar PV Components

Modules

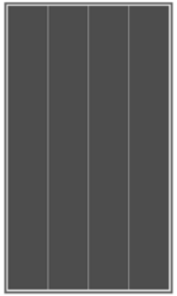


Illustration by Al Hicks, NREL

Inverters

Photo from https://www.energy.gov

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

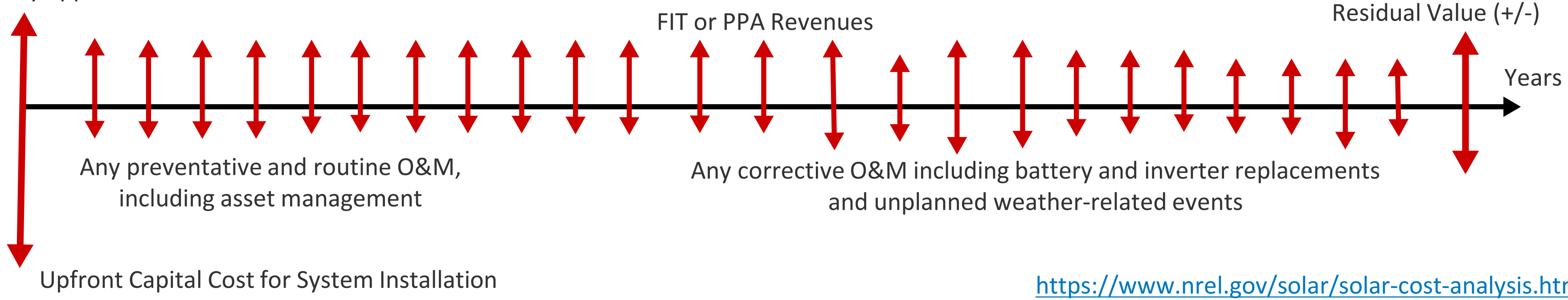
PV Plus Storage

Photo from iStock, 1128871378

Solar and Storage Project *Pro Forma* Analysis

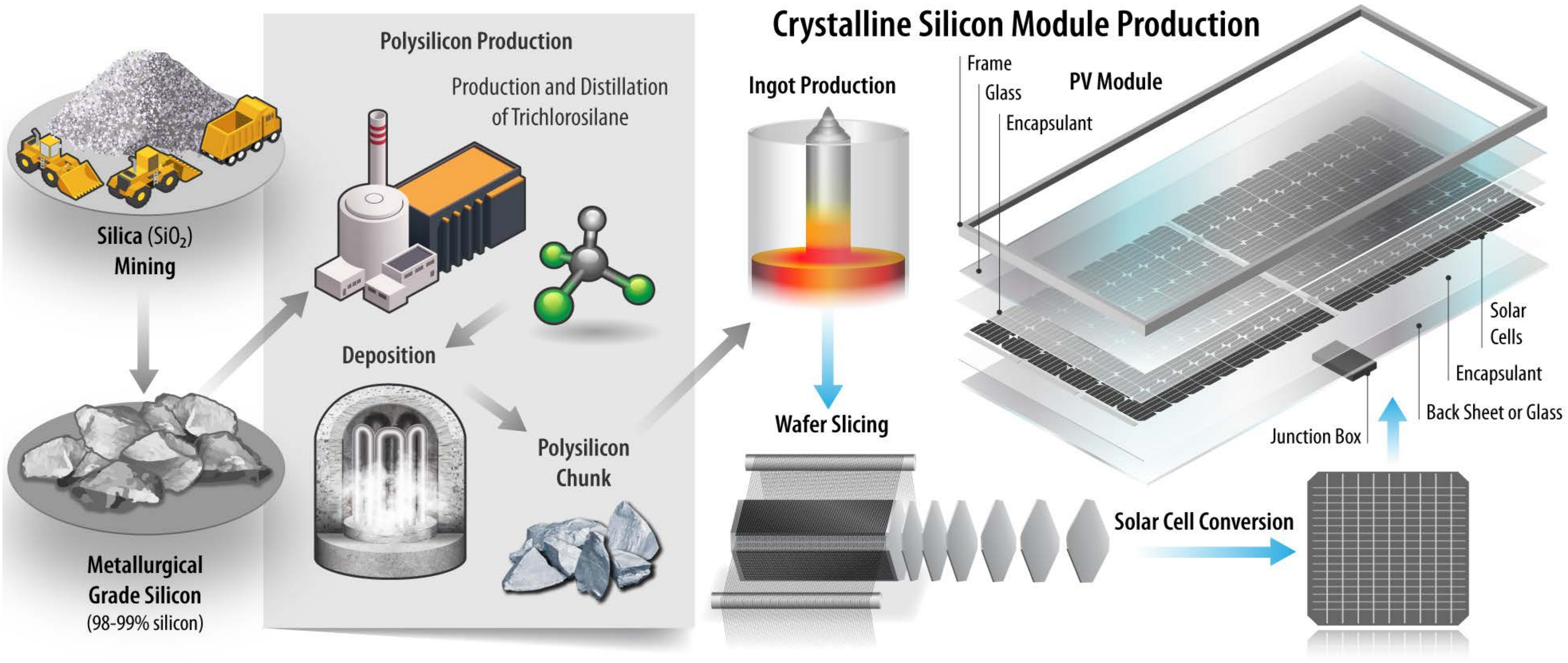
Levelized Cost of Electricity (LCOE) Metric

Internal Rate of Return (IRR) Metric



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

Scope of Crystalline Silicon (c-Si) PV Module Cost Models



Source of figure: NREL.

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

Reflections on 15 Years of PV Module and System Price Declines

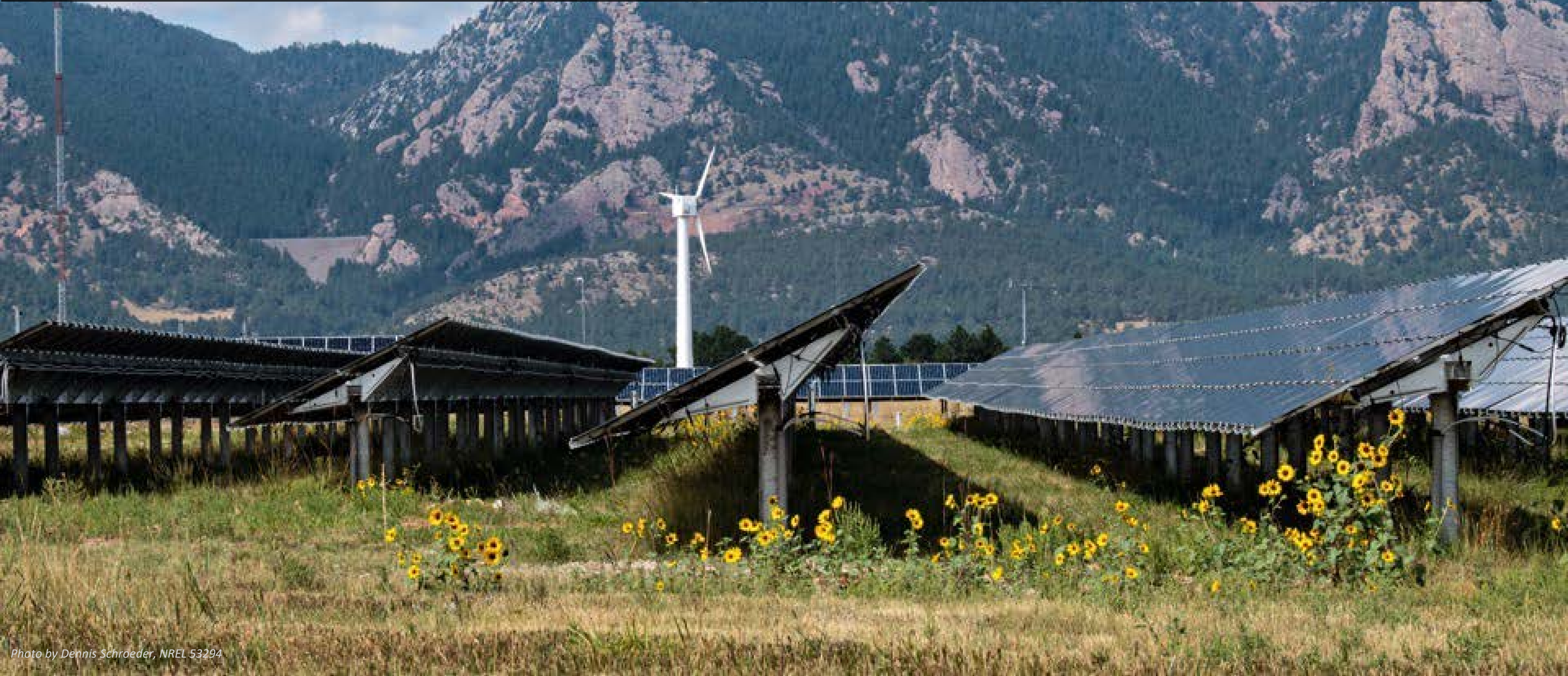


Photo by Dennis Schroeder, NREL 53294

Manufacturing and Delivery Cost Model Structure

COST OF OWNERSHIP (COO) 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)

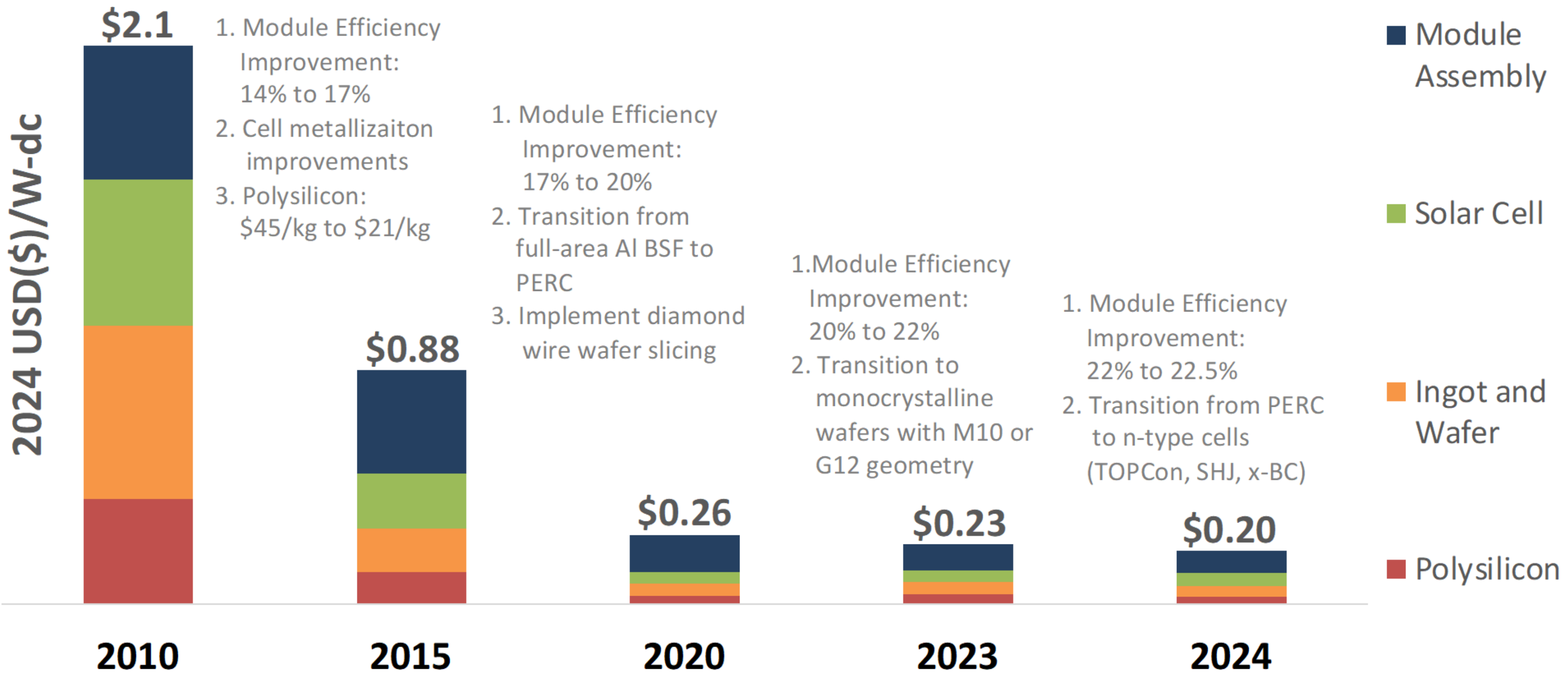
Delivered Minimum Sustainable Price (MSP)

Source of figure: NREL. Please see: https:// www.nrel.gov/docs/fy19osti/72134.pdf

Historical Cost Model Results for Solar PV Module Manufacturing

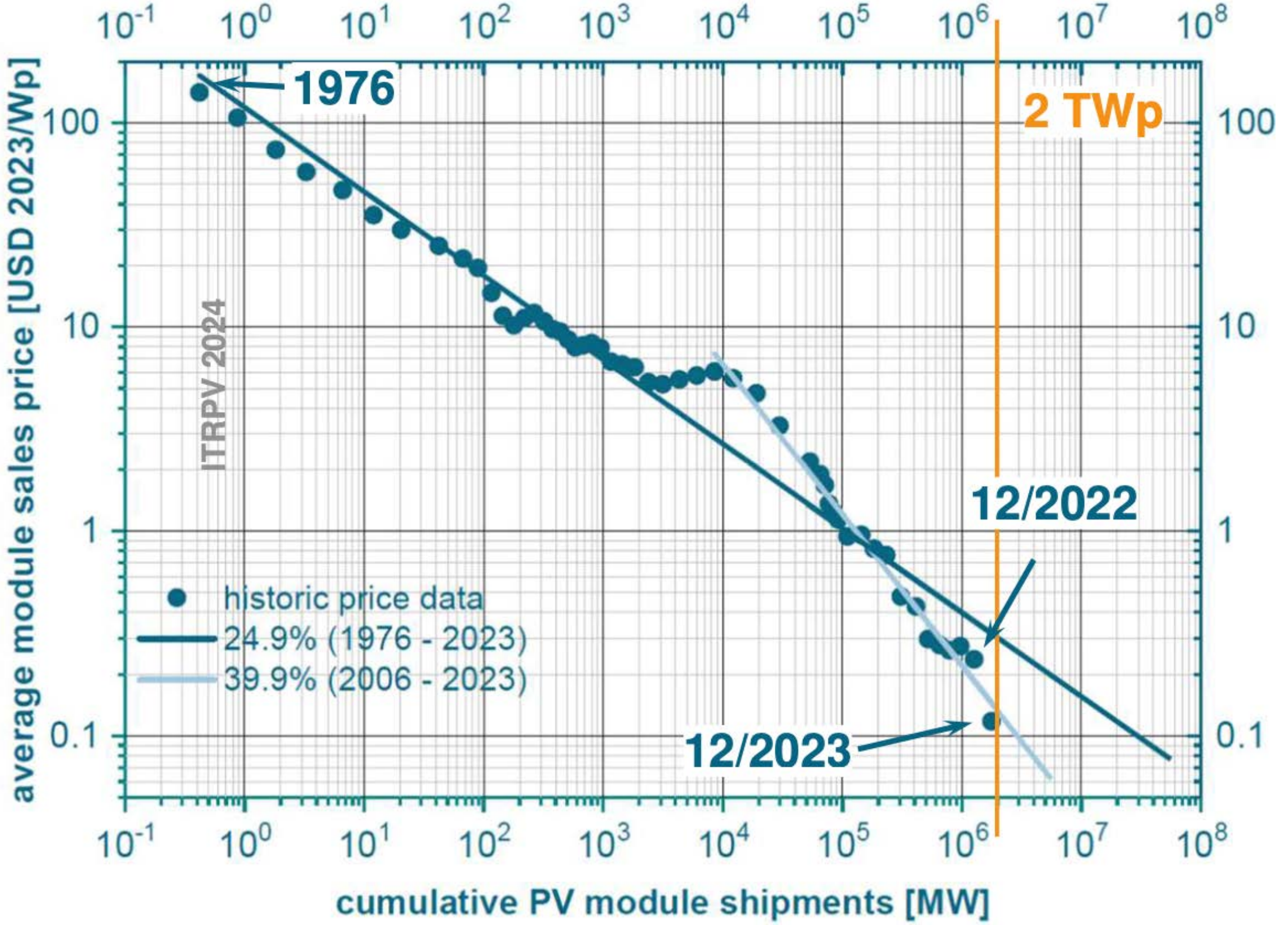
Factory Gate MSP For Each Subcomponent. Results Reflect Production in Asia.

July 26, 2024



See References on Slide 38: SunShot Vision Study (2010), On the Path to SunShot (2015), Solar Futures Study (2020), 2023 Benchmark, DRAFT 2024 Updates in Progress

Solar PV Module Price Learning Curve



Global Module Pricing Trends:

2010: $2.0—2.5/W-dc

2022: $0.20—0.25/W-dc

2023—2024: $0.10—0.15/W-dc

Manufacturing Capacity:

> 1 TW-dc for polysilicon through module assembly in 2024

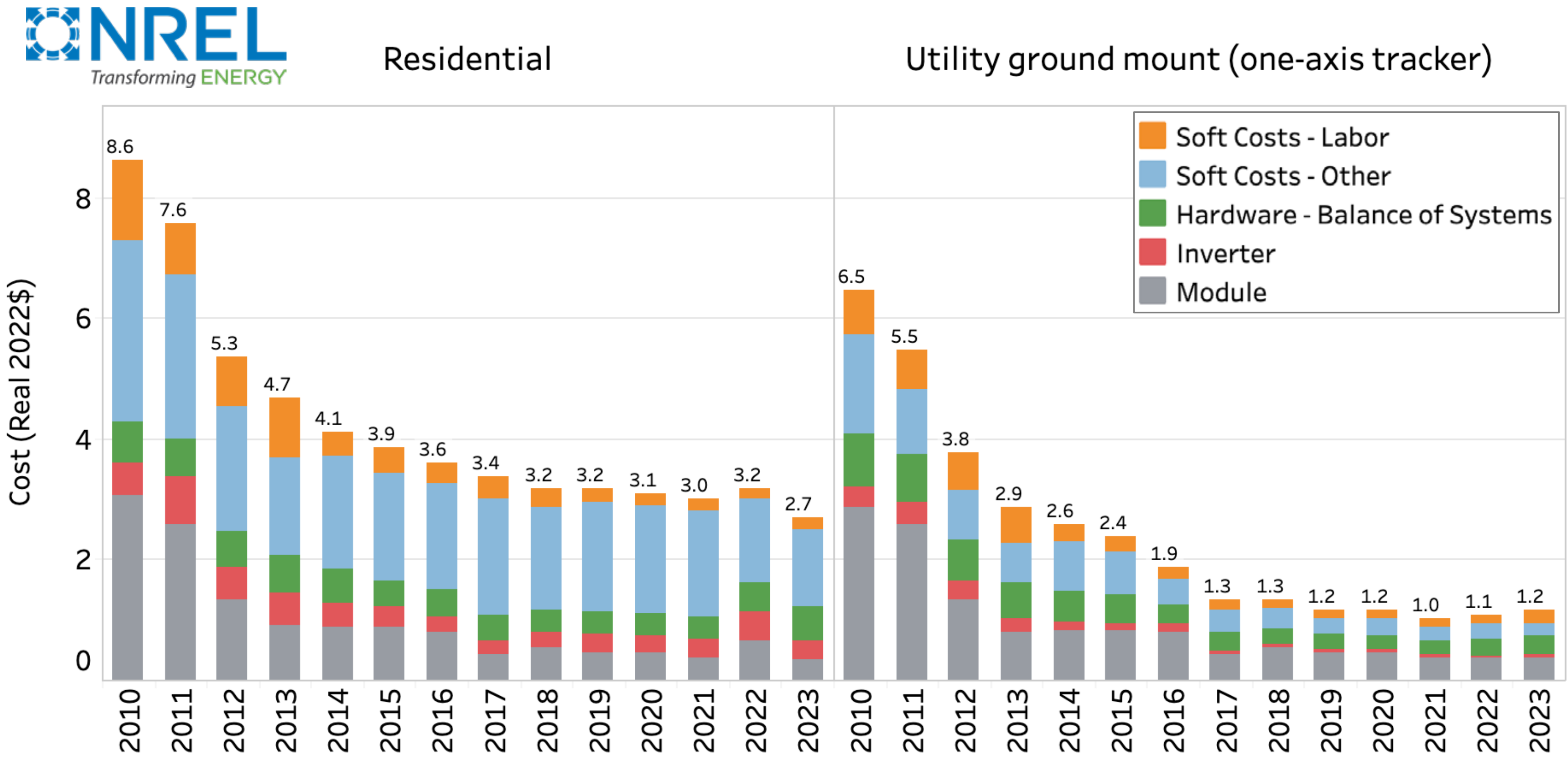
Installations (IEA):

402 GW in 2024

(https://www.iea.org/energy-system/renewables/solar-pv)

Source: International Technology Roadmap for Photovoltaic (ITRPV), 15th Edition, 2024. Available online: https://www.vdma.org/international-technology-roadmap-photovoltaic

Annual Tracking of System Capital Costs ($/W-dc)



Please see the interactive dataset and archive of NREL Benchmark Reports here: https://www.nrel.gov/solar/market-research-analysis/

Where Things Go From Here Part I: The Module

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Source of Photo: The NREL Flatirons Campus, where Solar, Wind and BESS components are tested and integrated into new energy systems

Crystalline Silicon (c-Si) Module Evolution

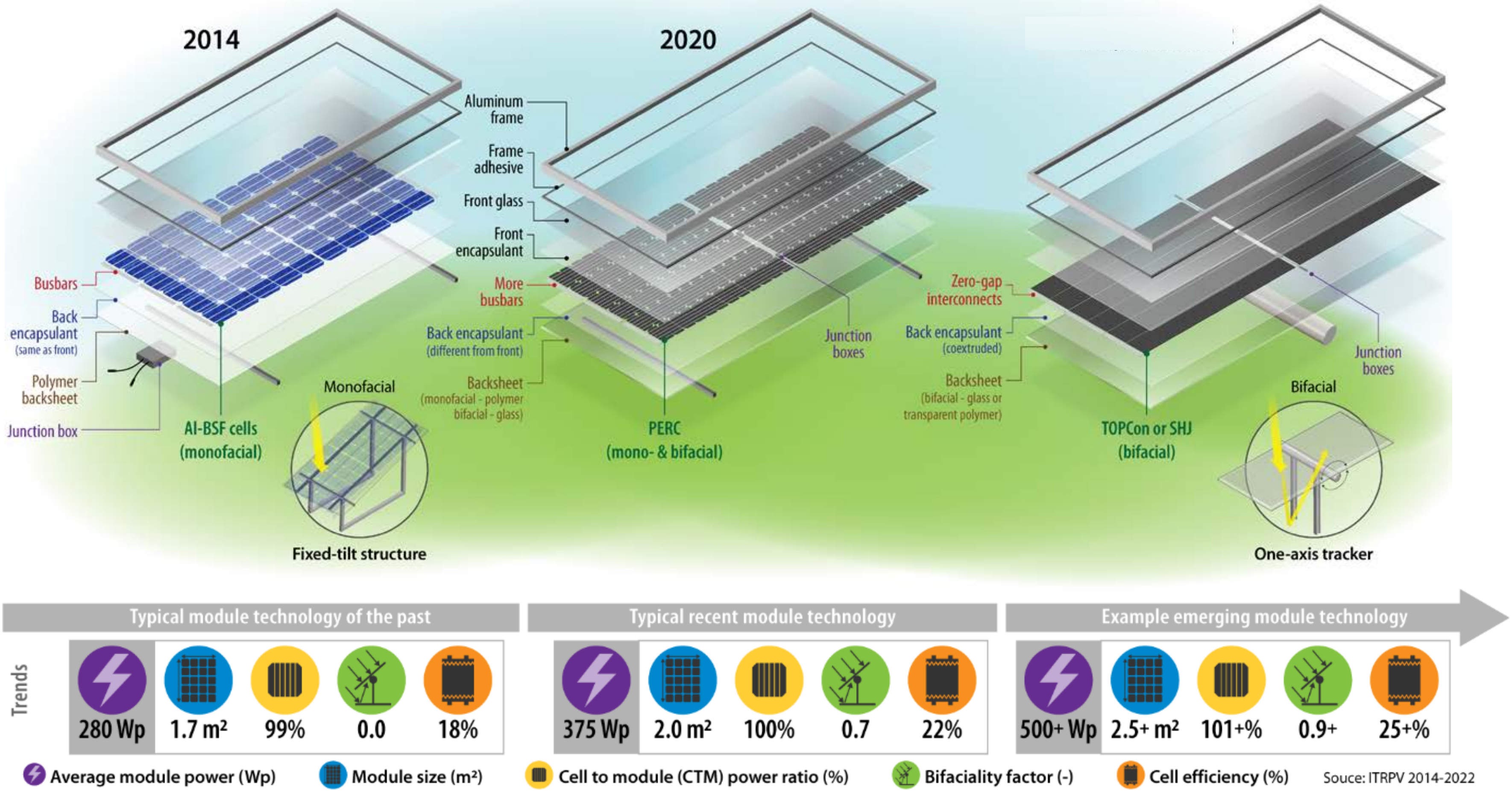


Figure source (NREL): https://ieeexplore.ieee.org/document/10347402

Looking Back and Where Things Might Go From Here

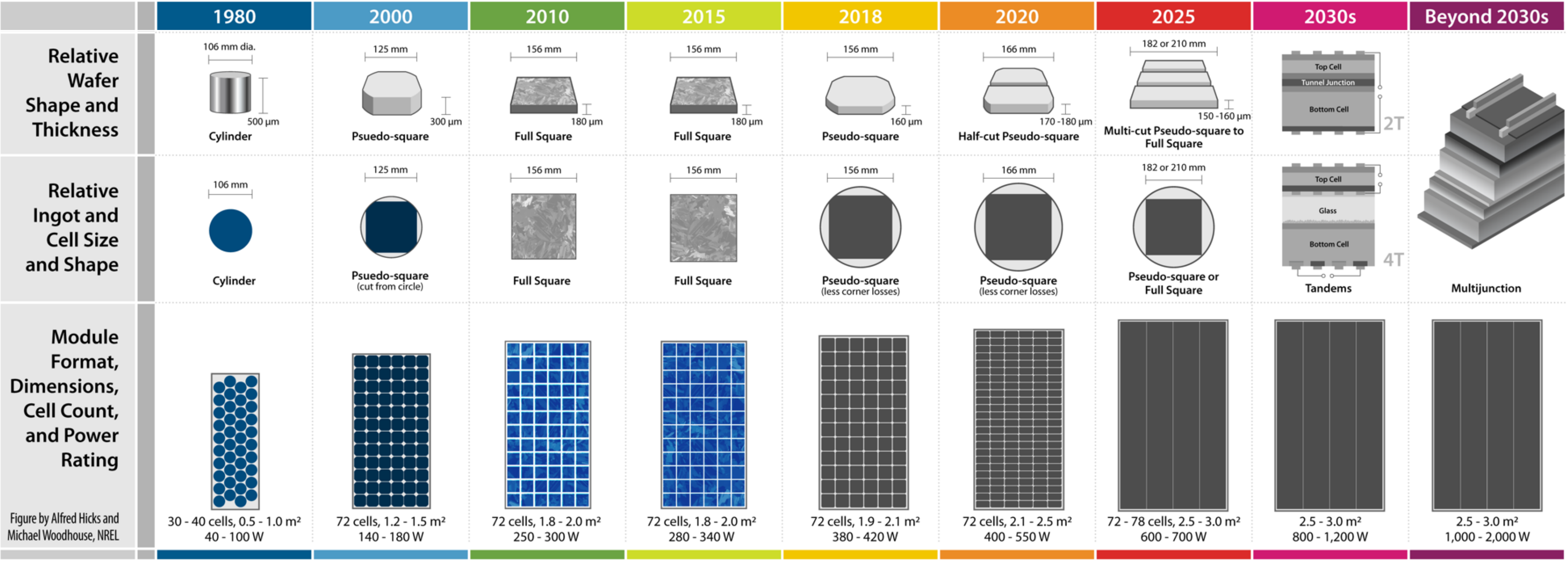
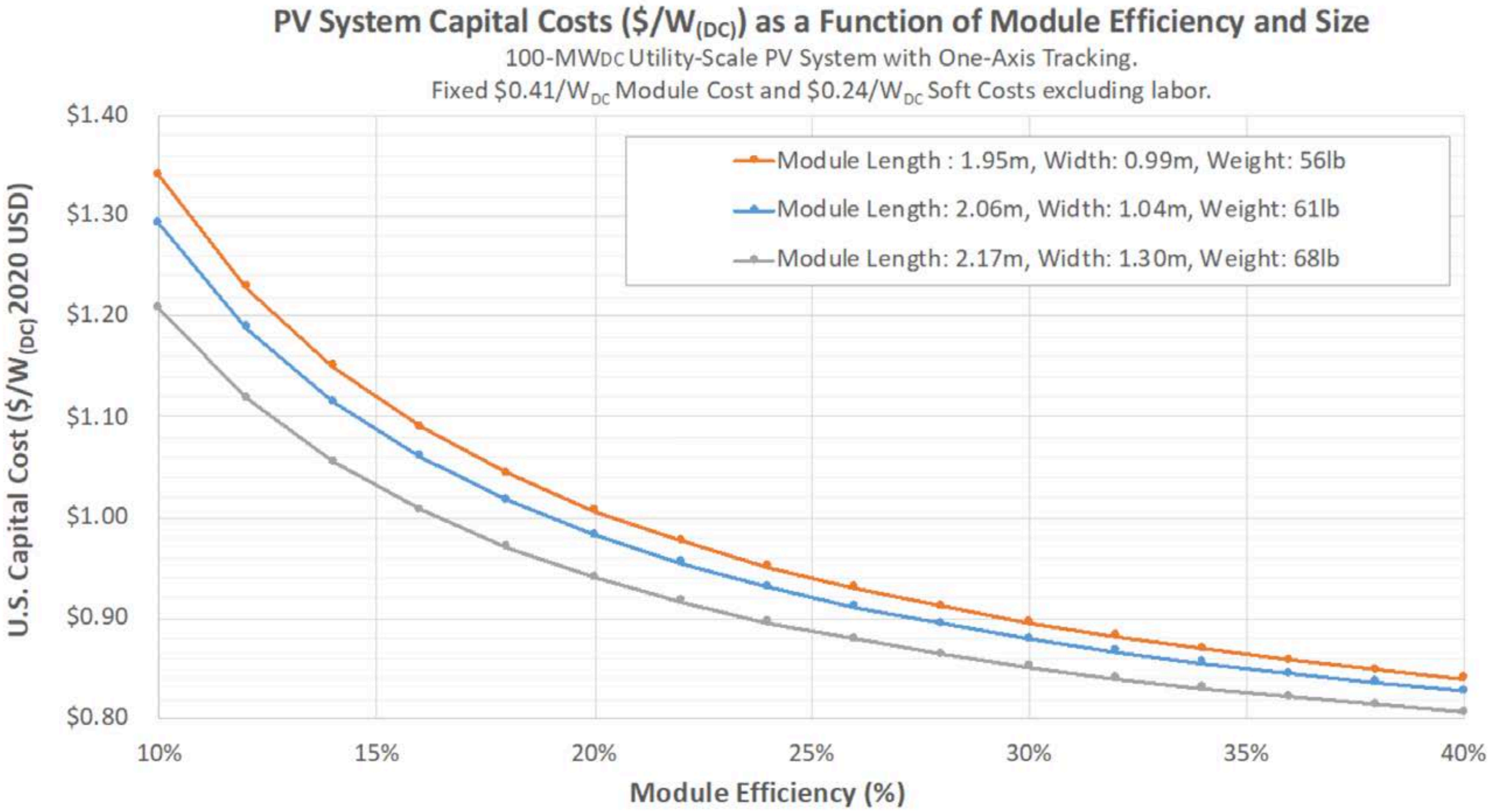


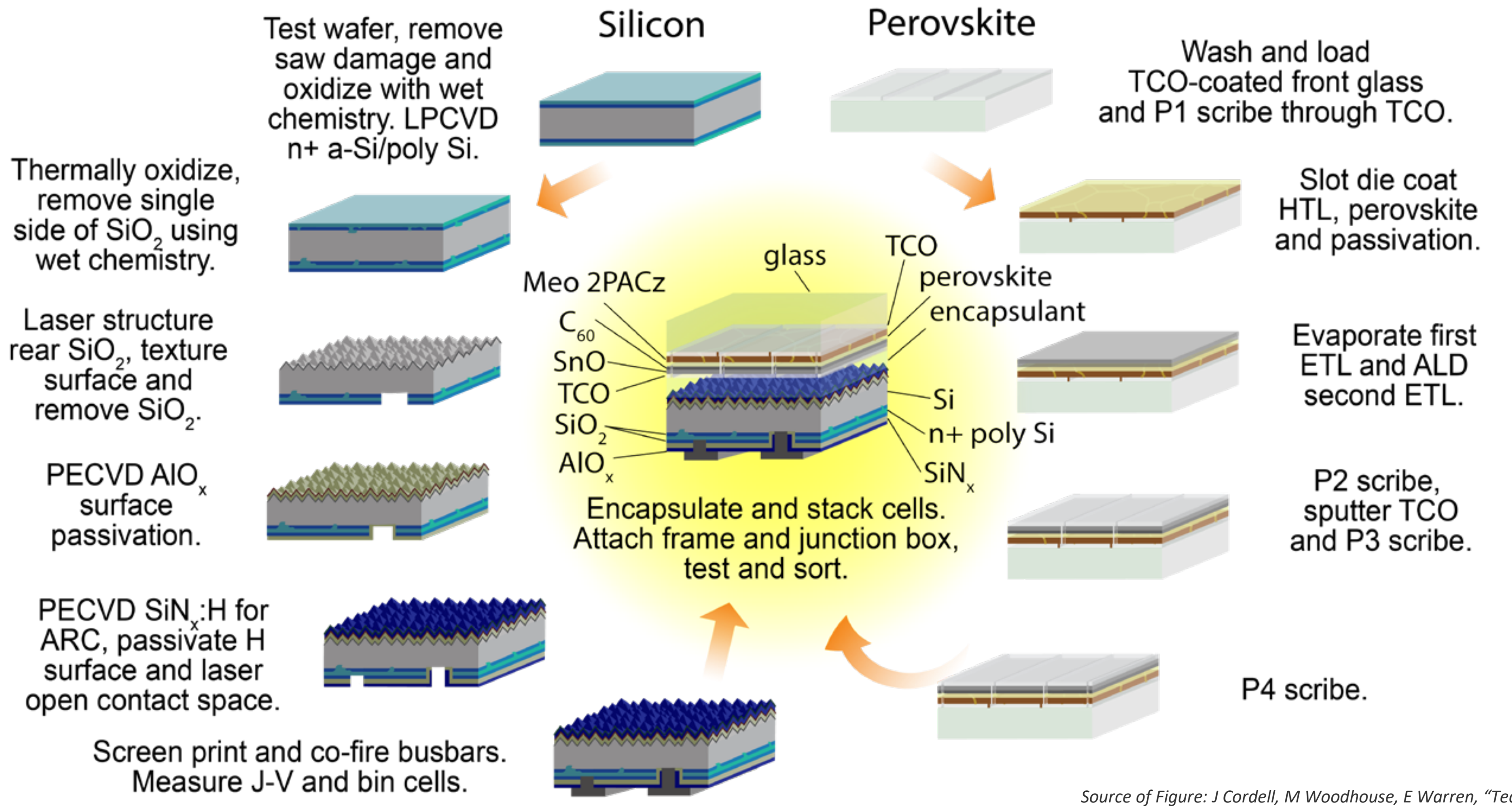
Figure source (NREL): https://www.energy.gov/eere/solar/solar-futures-study

Efficiency Benefits Total System Costs and LCOE



Source of figure: https://www.energy.gov/eere/solar/solar-futures-study

Four-Terminal Perovskites on Silicon



Source of Figure: J Cordell, M Woodhouse, E Warren, "Technoeconomic Analysis of Perovskite/Silicon Modules, Submitted to Joule

LCOE Breakeven in the U.S. Considering Reliability

9—12¢/W	6—9¢/W	3—6¢/W	0—3¢/W	0—Negative 3¢/W	Negative 3—6¢/W	Negative 6—9¢/W

ITC	Degradation Rate				
	0.25%/year	0.50%/year	0.75%/year	1.0%/year	1.5%/year
-Two Std Dev					
-One Std Dev					
Mean Solar Resource	9-12 ¢/W	6-9 ¢/W	3-6 ¢/W	0-3 ¢/W	Negative -6 to -9 ¢/W
+One Std Dev					
+Two Std Dev					-3 to -6 ¢/W

PTC	Degradation Rate				
	0.25%/year	0.50%/year	0.75%/year	1.0%/year	1.5%/year
-Two Std Dev					Negative -3 to -6 ¢/W
-One Std Dev					
Mean Solar Resource	6-9 ¢/W		3-6 ¢/W	0-3 ¢/W	
+One Std Dev					0 to Negative -3 ¢/W
+Two Std Dev					

Results from the NREL System Advisor Model (https://sam.nrel.gov/), reV Model, and Online LCOE Calculator (https://www.nrel.gov/pv/lcoe-calculator/)

Where Things Go From Here Part II: U.S. PV Systems

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Source of Photo: The NREL Flatirons Campus, where Solar, Wind and BESS components are tested and integrated into new energy systems

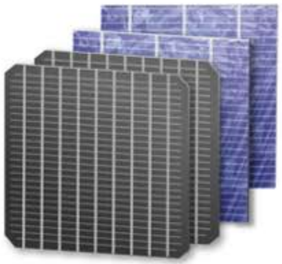
Inflation Reduction Act (IRA) 45X Credits for Solar Manufacturing

Polysilicon

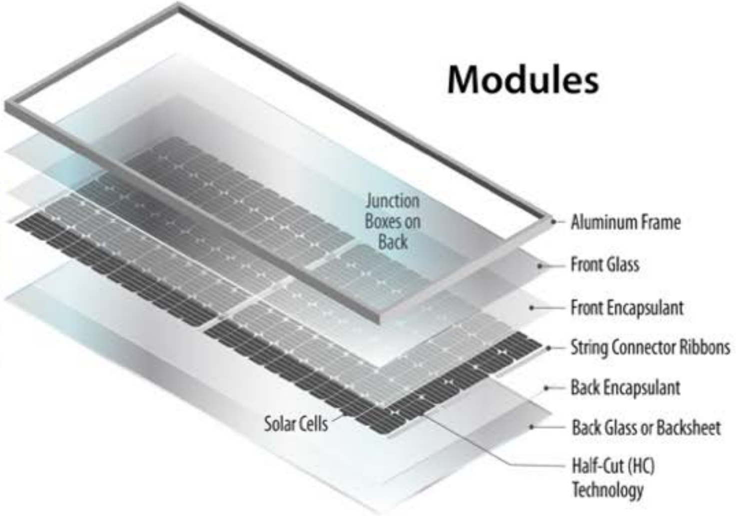
Ingots

Wafers

Solar Cells



Modules



2022—2029 $3/kg	**2022—2029 $12/m²**	**2022—2029 4¢/W**	**2022—2029 7¢/W** (+$0.4/m² for backsheet)
2030 $2.3/kg	2030 $9/m²	2030 3¢/W	2030: 5.3¢/W
2033 $0/kg	2033 $0/m²	2033 $0/W	2033: $0/W

PTC credits (45X) are shown in the tables.
ITC credits (48C) are another option for covering up to 30% of eligible investments.

The Additive Possibilities Within the IRA for PV Systems

30% ITC or 2.8¢/kWh PTC → 40% ITC or 3.1¢/kWh PTC → ≥50% ITC or 3.4¢/kWh PTC

Up to 30% ITC or 2.8¢/kWh PTC	***Up to 40% ITC or 3.1¢/kWh PTC***	***Up to and beyond 50% ITC or 3.4¢/kWh***
1. Under 1 MW-ac in size or meets prevailing wage and apprenticeship requirements 2. Only 6% ITC or 0.6¢/kWh PTC if prevailing wage and apprenticeship is not met 3. Direct pay options for tax exempt entities (e.g., schools) 4. Credits can be transferred between eligible taxpayers	All requirements are met for 30% ITC or 2.8¢/kWh PTC AND Domestic Content Bonus OR Siting in an Energy Community OR Low- and Moderate-Income (LMI) census tract or on Indian land	All requirements are met for 40% ITC or 3.1¢/kWh PTC AND Domestic Content Bonus AND Siting in an Energy Community AND/OR LMI Community

Factors That Bring Additional Value for the U.S. Market

Efficiency. Higher solar cell efficiency lowers balance-of-module and balance-of-system capital costs.

Energy Yield. More kWh equals more PPA revenues (utility) and electricity savings (C&I and Residential).

Reliability. Improved durability improves *lifetime* energy yield. Unreliable modules and systems erode project IRR and should be avoided.

Products that Qualify for 45X Production Credits. These credits help to offset higher manufacturing costs for domestic production.

Products that Contribute Toward the System Domestic Content Bonus. Having a Domestic Module supplier (or combination Domestic/Imported) helps to reach the minimum 40% threshold. Having a Domestic Solar Cell really helps the numerator.

Where Things Go From Here Part III: Solar + Storage

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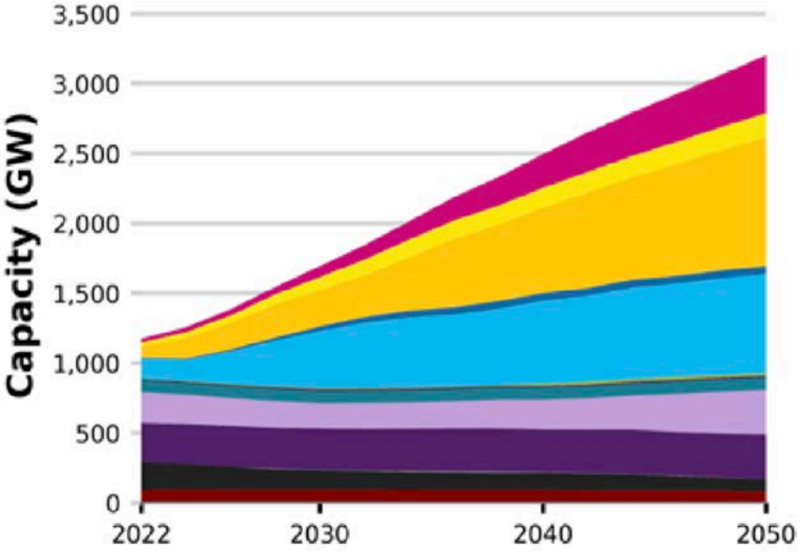
Source of Photo: The NREL Flatirons Campus, where Solar, Wind and BESS components are tested and integrated into new energy systems

Annual Capacity Additions: Standard Scenarios

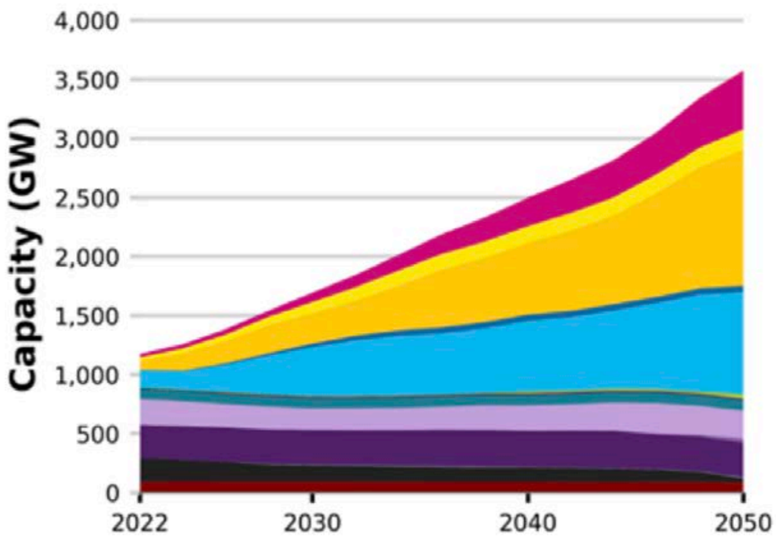
Mid-Case
Current Policies



2024 to 2050

Solar PV: 188 GW-ac to 1,090 GW-ac per year (**6X**)
Wind: 152 GW-ac to 710 GW-ac per year (**5X**)
4- and 8-Hour Storage:
12 GW-ac to 368 GW-ac per year (**30X**)

Mid-Case
95% CO_2 Reduction by 2050



2024 to 2050

Solar PV: 188 GW-ac to 1,323 GW-ac per year (**6X**)
Wind: 152 GW-ac to 910 GW-ac per year (**5X**)
4- and 8-Hour Storage:
12 GW-ac to 447 GW-ac per year (**40X**)

Figure source: P Gagnon, A Pham, W Cole, et. al., “2023 Standard Scenarios Report”. https://www.nrel.gov/docs/fy24osti/87724.pdf

Conclusions

Conclusions

Manufacturing. 2024 PV module MSP is calculated to be approximately 10% of the 2010 benchmark.

Systems. 2023 Utility PV system MSP is calculated to be approximately 20% of the 2010 benchmark, and 2023 Residential PV system MSP is calculated to be approximately 30% of the 2010 benchmark.

Module Technology Advancements. (1) There is still quite a bit of room for single-junction c-Si efficiencies to improve: Approximately 10% absolute efficiency remains available between theoretical maximum and commercial production averages. (2) Beyond module price, energy yield and reliability impacts LCOE. (3) Tandem technologies may provide the leapfrog for true technology differentiation.

Market Growth. Storage deployments needs to catch up with PV deployments for the wholescale energy transition to occur.

References

- SunShot Vision Study: https://www.energy.gov/eere/solar/sunshot-vision-study
- On the Path to SunShot: https://www.energy.gov/eere/solar/path-sunshot
- Solar Futures Study: https://www.energy.gov/eere/solar/solar-futures-study
- 2023 Benchmark Report: https://www.nrel.gov/docs/fy23osti/87303.pdf

Acknowledgements and Support

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Thank You

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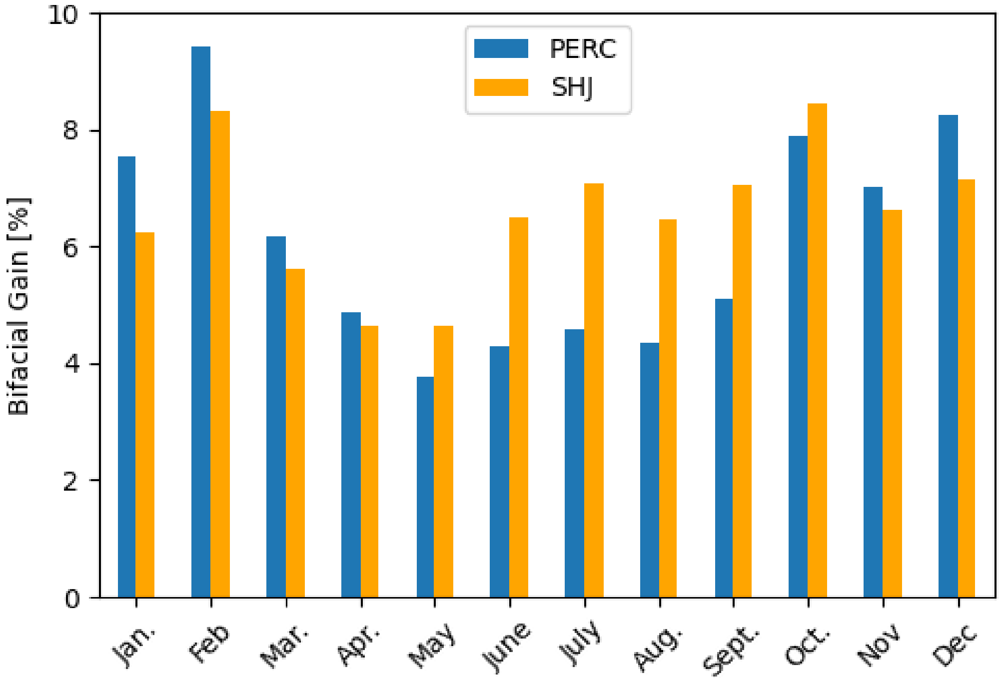
Energy Yield Measurements From The Field

Source of figures: NREL (Silvana Ovaitt and Chris Deline)

$$Bifacial\ Gain\ (\%) = \frac{Energy\ bifacial}{Energy\ monofacial} - 1$$

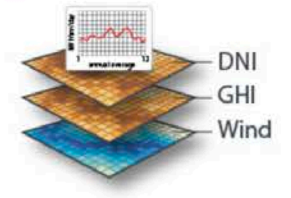
Full Year Results from the NREL Bifacial Test Bed:
PERC bifacial gain: 6.1%, SHJ bifacial gain: 7.6%

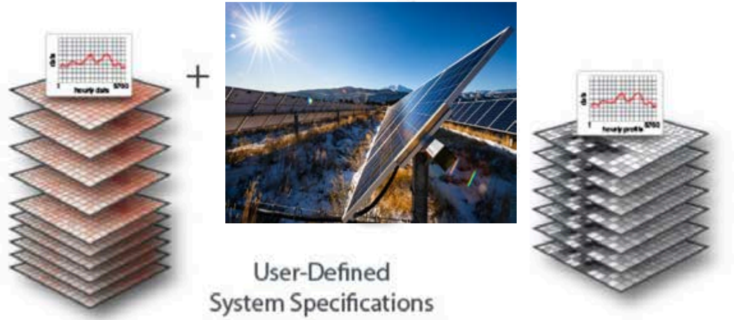


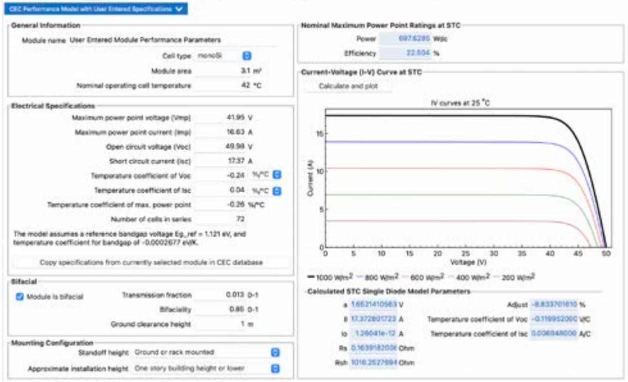
	PERC Passivated Emitter and Rear Cell	**CdTe** Cadmium Telluride	**TOPCon** Tunnel Oxide Passivated Contacts	**SHJ** Silicon Heterojunction	**IBC** Interdigitated Back Contact
Bifaciality	0.65—0.80	----	0.85—0.90	0.80—0.95	0.40—0.70
Temperature Coefficient	0.35—0.40 %/^{o}C	0.25—0.35%/^{o}C	0.30—0.35 %/^{o}C	0.25—0.30 %/^{o}C	0.25—0.30 %/^{o}C

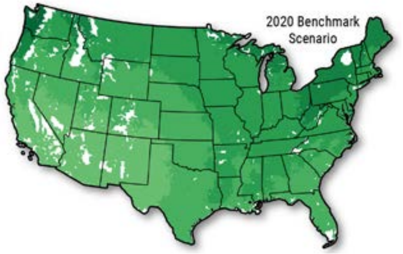
Performance Modeling: Overview of NREL's SAM and reV Capabilities

Resource Data Set → System Generation Modeling → Energy Yield and LCOE









System Advisor Model (SAM)

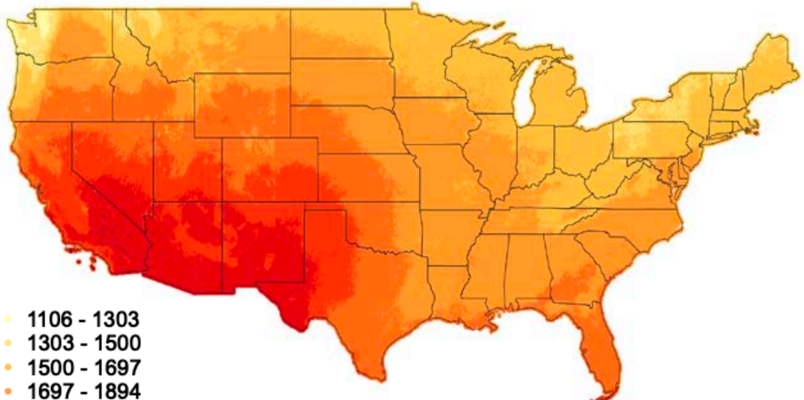
System Advisor Model

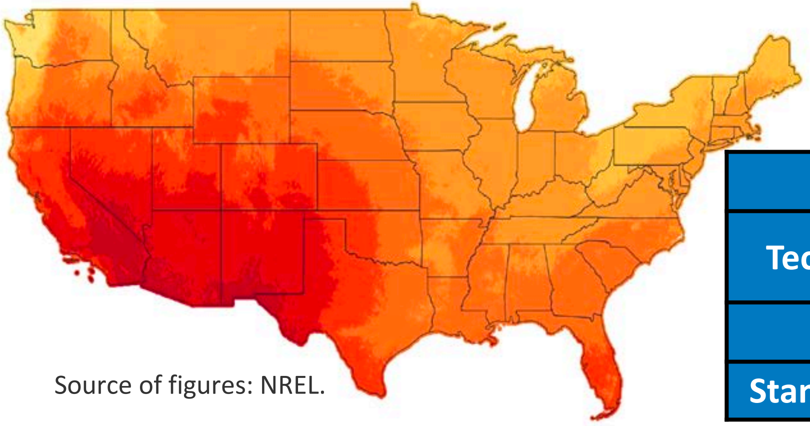
Renewable Energy Potential (reV)

reV

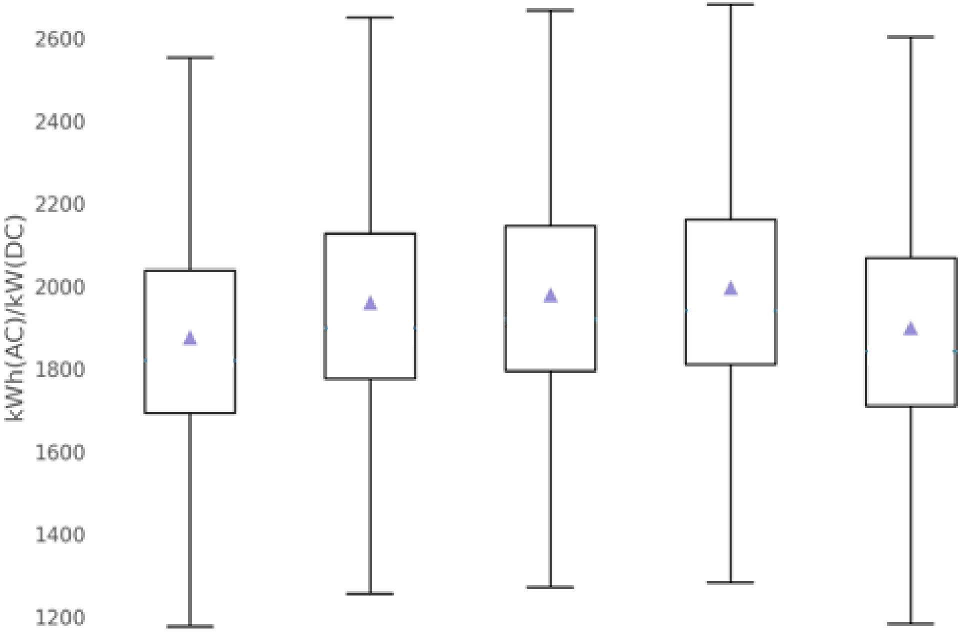
Source of LCOE Figures (Right): "R&D Priorities to Advance Solar Photovoltaic Lifecycle Costs and Performance", DOE Solar Futures Study
For access to the SAM and reV tools, please see https://sam.nrel.gov/ and https://www.nrel.gov/gis/renewable-energy-potential.html

Results from SAM and reV





Source of figures: NREL.

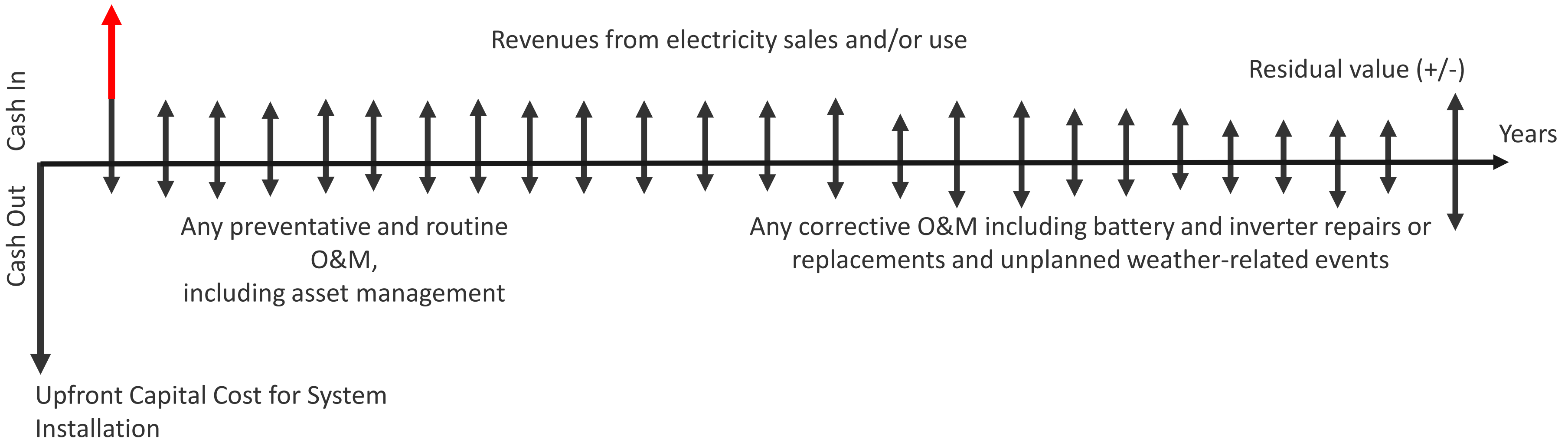


Energy Yield Statistics for the United States (kWh-ac/kW-dc)					
Technology	Monofacial A	Bifacial PERC	Bifacial TOPCon	Bifacial SHJ	Monofacial B
Mean	1,874	1,959	1,978	1,995	1,898
Standard Dev	248	250	250	249	257

How the U.S. IRA Applies to Solar Systems

Option 1: Investment Tax Credit (ITC) For Installed Systems

- Monetized as a percentage of original system capital cost after the first full year of operation
- 30% construction ITC until 2033, then stepping down to 22.5% in 2034, 15% in 2035, and 0% in 2036
    - Credit could be extended if greenhouse gas emissions targets are not met.
- There are bonus credits for using domestic content, siting in an energy community, or targeting low-income communities.



How the U.S. IRA Applies to Solar Systems

→ Option 2: Production Tax Credits (PTC) for Installed Systems

- Projects must choose either the ITC or the PTC
- 2.75 cents/kWh from 2023 to 2033, 2.0 cents/kWh in 2034, 1.3 cents/kWh in 2035, ending in 0.0 cents/kWh in 2036. These 2023 reference currency points will be adjusted annually for inflation.
- There are bonus credits for using domestic content or siting in an energy community.