NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Solar and Storage Techno-Economic Analysis Tutorial for the IEEE Photovoltaic Specialist Conference (PVSC)

Michael Woodhouse, Brittany Smith, Vignesh Ramasamy and David Feldman

Sunday, June 5, 2022

Introduction of Presenters

Michael Woodhouse

Energy Technologies, Economics and Policy Analyst

Introduction and Component Manufacturing Cost Models

David Feldman

Solar Financial Analyst

Levelized Cost of Energy Supply Chain Analysis

Brittany Smith

Solar Techno-Economic Analyst

Levelized Cost of Energy Supply Chain Analysis

Vignesh Ramasamy

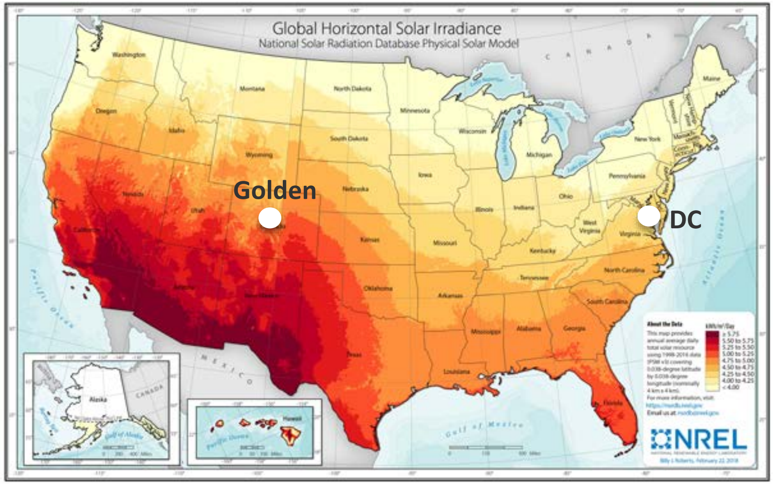
Researcher– Solar and Storage TEA

System Capital Cost Modeling

Tutorial Overview

1. **Introduction to NREL Solar and Storage Technoeconomic Analysis Team**
2. Component Manufacturing Cost Modeling
3. System Capital Cost Modeling
4. Levelized Cost of Electricity (LCOE)
5. Supply Chain Analysis
6. Resources for Follow-Up

Introduction to NREL
Main Campus in Golden, Colorado



Main campus for 16 primary research areas including laboratory-level work in solar, storage, and grid integration technologies.

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

NREL's Solar + Storage Technoeconomic Analysis (TEA) Portfolio

Component Manufacturing Cost Models

Modules		Storage	
Crystalline Silicon	Thin-Film	Batteries	Solar Fuels

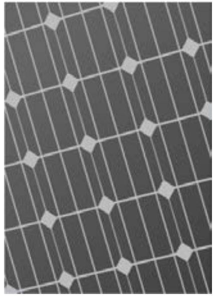


Illustration by Al Hicks, NREL

Photo from iStock, 1033236964

Photo by Dennis Schroeder, NREL 56318

Photo from iStock, 932140864

System Capital Cost Models ($)

PV Systems	PV Plus Storage

Photo by Dennis Schroeder, NREL 60073

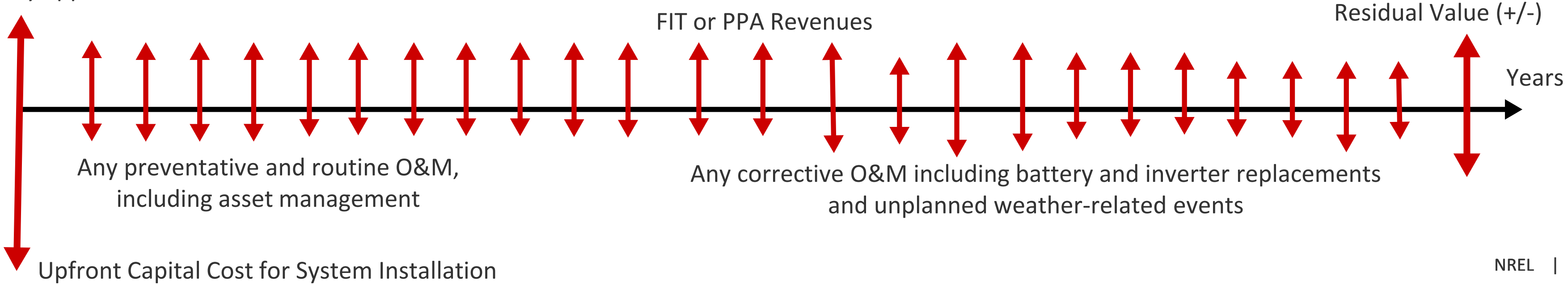
Photo from iStock, 1128871378

Solar and Storage Project *Pro Forma* Analysis

Levelized Cost of Electricity (LCOE)

Internal Rate of Return (IRR)

Any applicable incentives



Solar and Storage Technology Topics Covered in This Tutorial

Component Manufacturing Cost Modeling

- Review bottom-up cost model templates across the PV supply chain: Thin film and c-Si module assembly, cell conversion, ingot and wafer production, and polysilicon production
- Methodology for calculating direct production costs and overhead (R&D and S,G, &A)
- Provide a framework for assessing potential technology improvements

System Capital Costs

- Framework to collect system cost model inputs and calculate aggregated results
- Sectors covered: Distributed (Residential and Commercial) and Utility Scale (Fixed Tilt and Tracking)
- Consider changes to utility and distributed generation system design over time and adapt models to novel configurations (BIPV, FPV, PV + Ag, Solar +)

Levelized Cost of Energy (LCOE)

- Demonstrate online PV LCOE calculator supported by DuraMAT
- Use SAM Detailed PV models and reV to input technology- and application-specific input parameters that affect energy yield across varying climates
- Link component manufacturing costs models, system capital costs models, O&M models, and financing parameters to benchmark LCOE over time

Presentation Overview

Solar Technologies and Manufacturing Cost Model Structure

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, 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

STEP-BY-STEP COST OF OWNERSHIP (COO) INPUTS

COO Format

- Tool production and throughput (Uptime and scheduled and unscheduled downtime)
- Depreciation of Equipment
- Depreciation of Facilities
- Materials and consumables
- Utilities (Electricity, water)
- Waste disposal (Wastewater and exhaust air)
- Labor: Direct operators and supervisors
- Maintenance
- Account of yield loss

Location Specific Indices

- Local wage rates for direct operators and supervisors
- Local utility rates
- Leasing versus purchasing the building business models
- Local considerations for CapEx and materials expenses relative to the baseline

GAAP AND IFRS 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

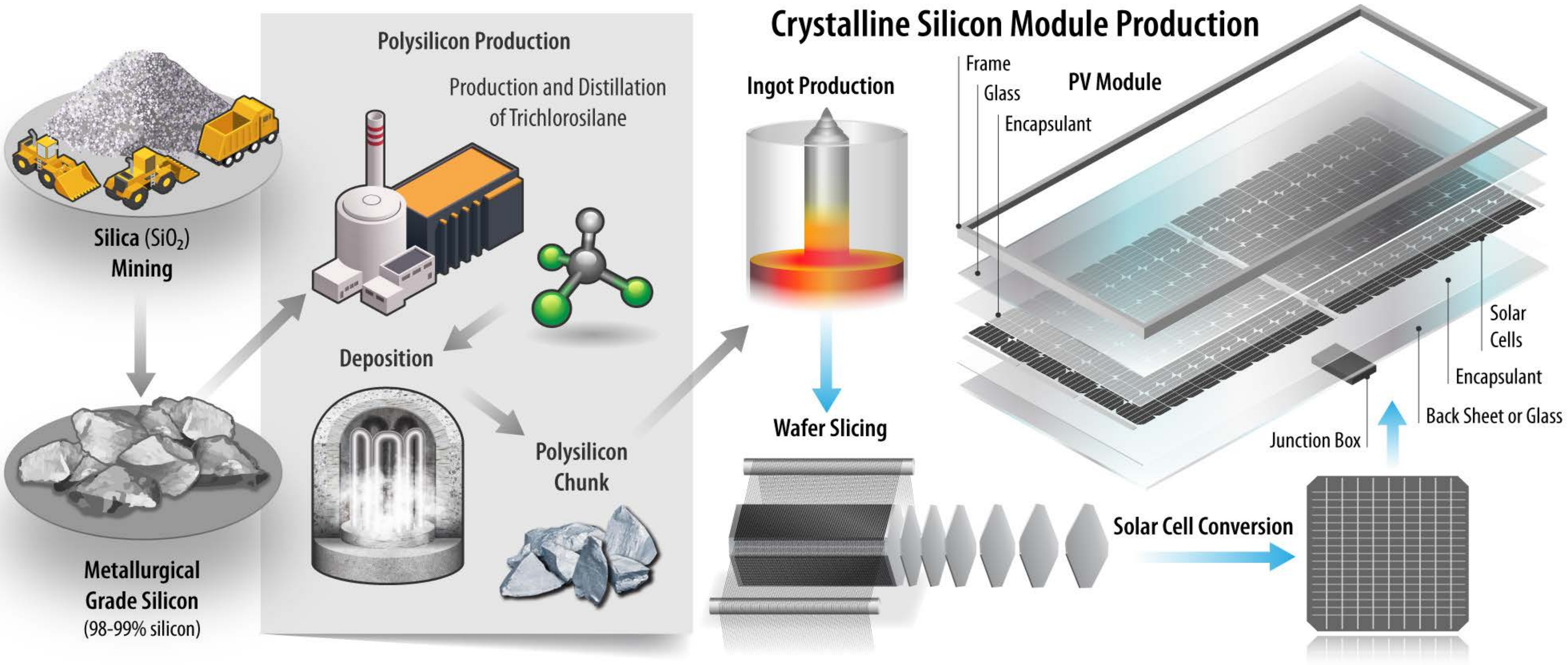
- Equipment
- Building and facilitation
- Installation and training

COGS to Delivered MSP

- Overhead: Research and Development (R&D) and Sales, General, and Administration (S, G, & A)
- Profit for manufacturers across the supply chain
- Sales taxes, other taxes, tariffs and export duties (Input per destination)
- Sea- and land-based shipping, port entry fees, warehouse, and insurance (Input per destination)

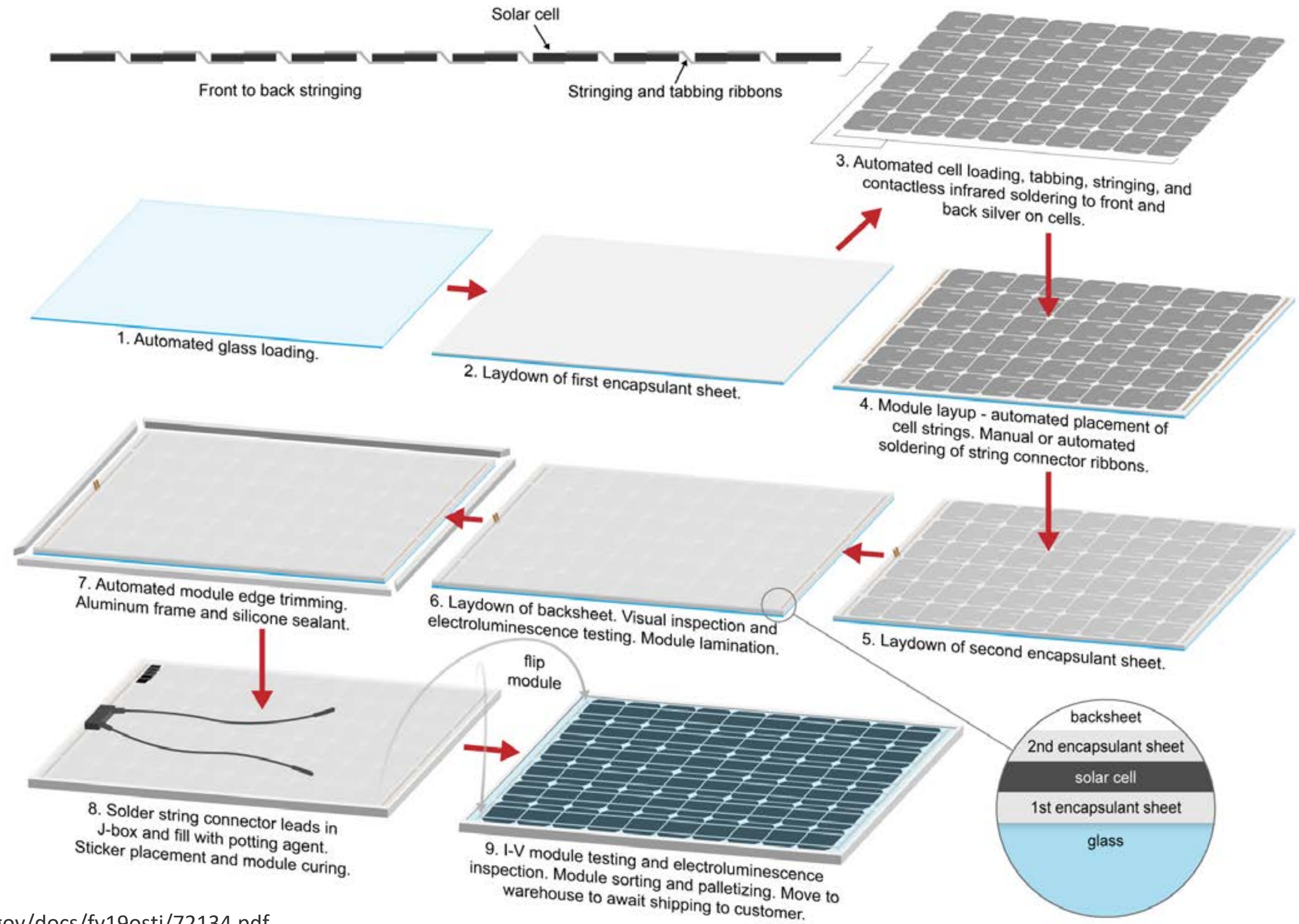
Delivered Minimum Sustainable Price (MSP)

Overview of the Solar PV Module Supply Chain



Source of figure: NREL.

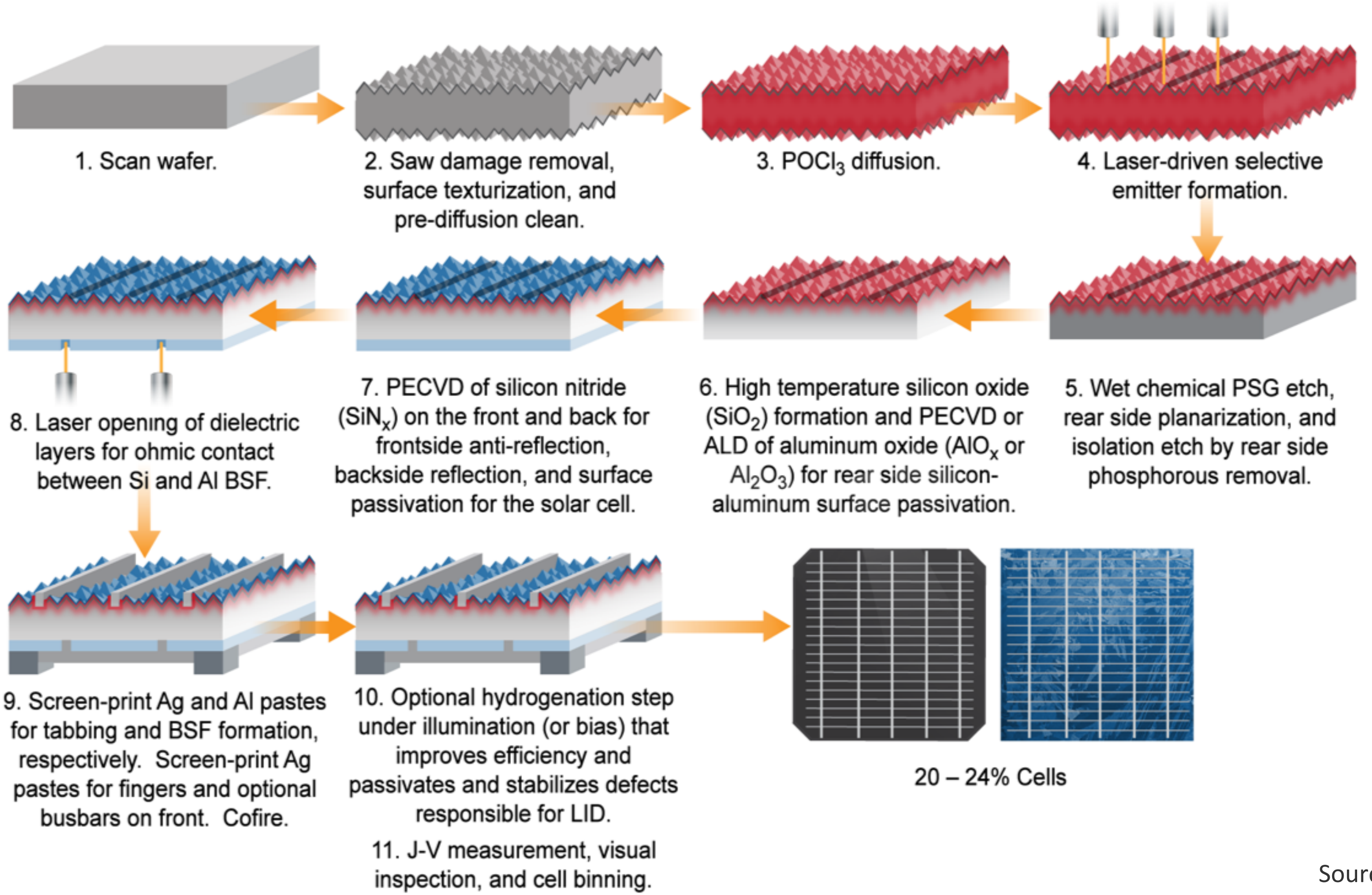
Module Assembly Process Flow



Source of figure: NREL.

Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf

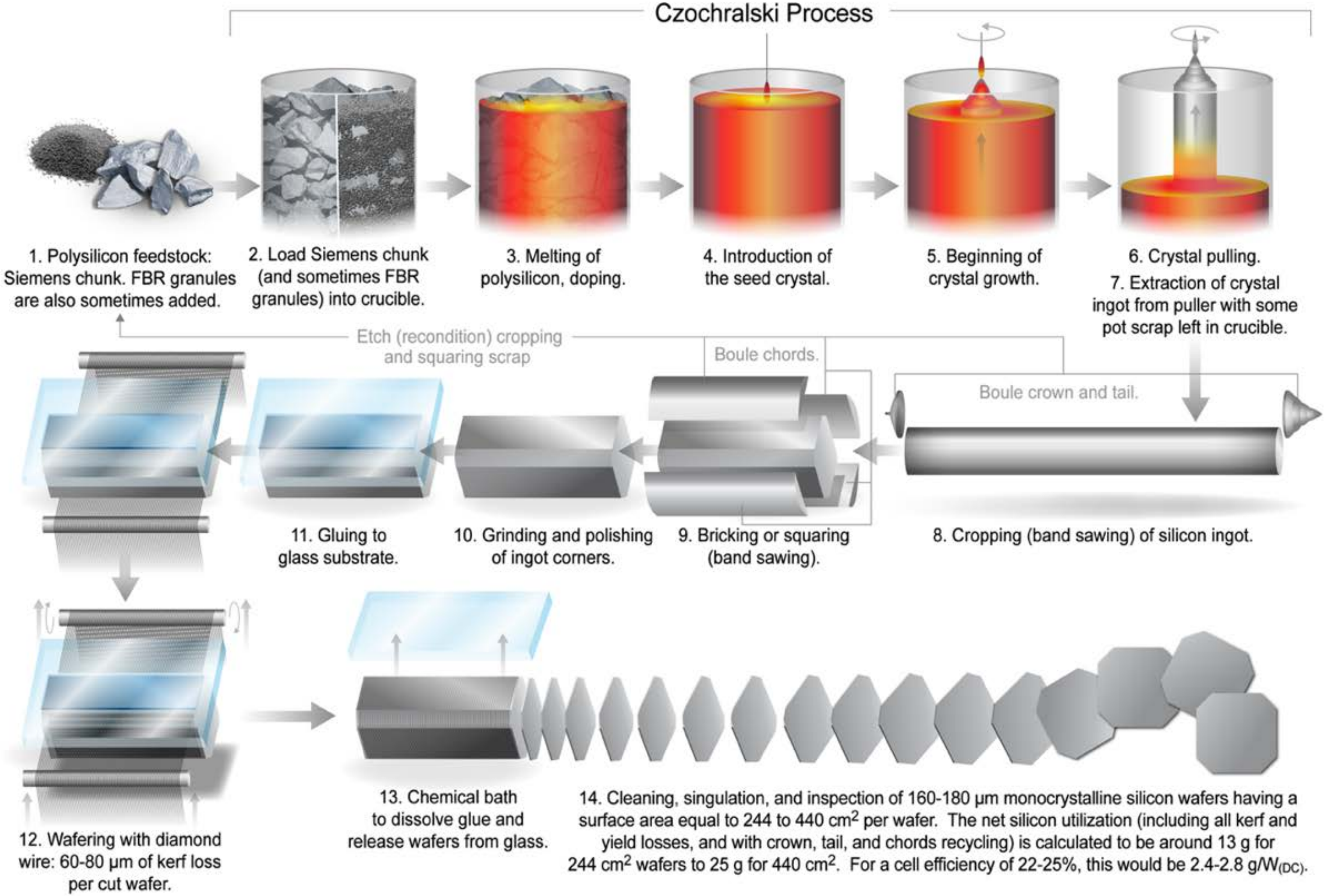
PERC Cell Process Flow



Source of figure: NREL.

Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf

Process Flow for Ingot and Wafer Production



Source of figure: NREL.

Please see: https://www.nrel.gov/docs/fy19osti/72134.pdf

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)	Staffing plan for each station
	$/hour direct wage (Supervisors)	
	$/hour direct wage (Engineers)	
	Benefits (Cafeteria, Health Insurance, Retirement, etc.)	Throughput, scale, and yield are interdependencies. Efficiency impacts $/W.

Labor Costs Drivers

Labor Cost Drivers	c-Si Supply Chain				CdTe Module Production
	Polysilicon	Ingot and Wafer	Cell Conversion	Module Assembly	
Labor Intensity (Direct full-time employees (FTE) per MW_{dc} of production)	0.035—0.070 (40—85 MT per year per FTE for Siemens to FBR. @ 2.8 g/W)	0.40—0.80 (Labor intensity in U.S or Europe to China)	0.15—0.45 (Advanced technology to PERC)	0.50—0.70 (Advanced technology to PERC)	0.40—0.60
Direct Manufacturing Jobs at 1 GW_{dc} Scale	35—70	400—800	150—450	500—700	400—600
Assumed Hourly Labor Rates for Cost Models ($2020 USD)	$4.1—5.0 per hour for direct operators in China $6.2—7.5 per hour for first-line supervisors in China Housing, cafeteria, and insurance expenses included. $14.3—22.0 per hour for direct operators in electronics assembly in the United States $23.3—38.8 per hour for first-line supervisors in the United States Additional 35% benefits expense assumed for workers in the United States				

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

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.

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)

Monte Carlo Analysis of Multiple Input Variables for a Country

Normal Distributions of Multiple Input Variables (500 Samples)

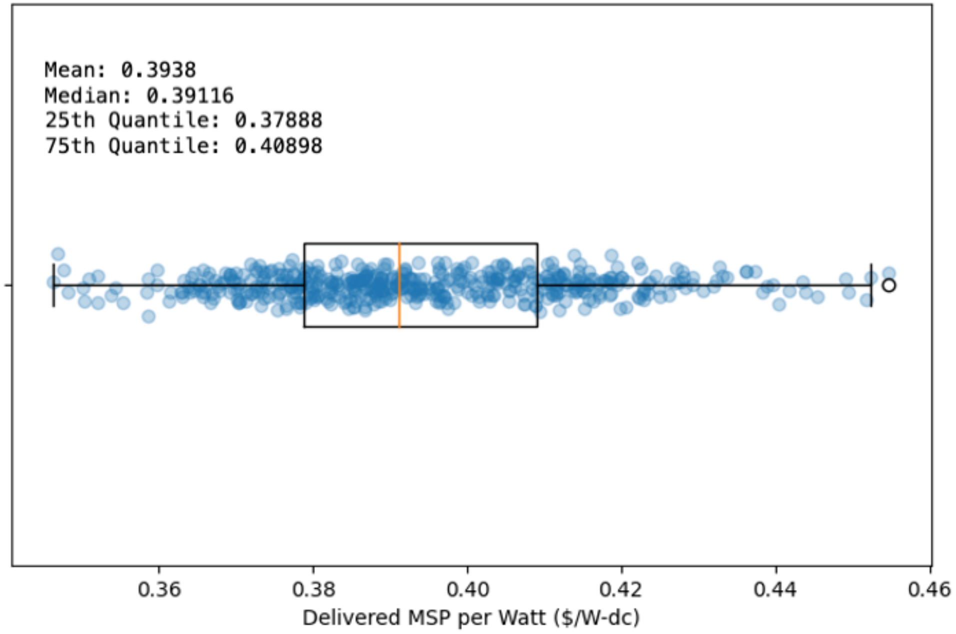
One standard deviation equals +/- 5% change in *cell efficiency (relative)*

One standard deviation equals +/- 10% change in *CapEx*

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

One standard deviation equals +/- 5% change in *factory uptime*

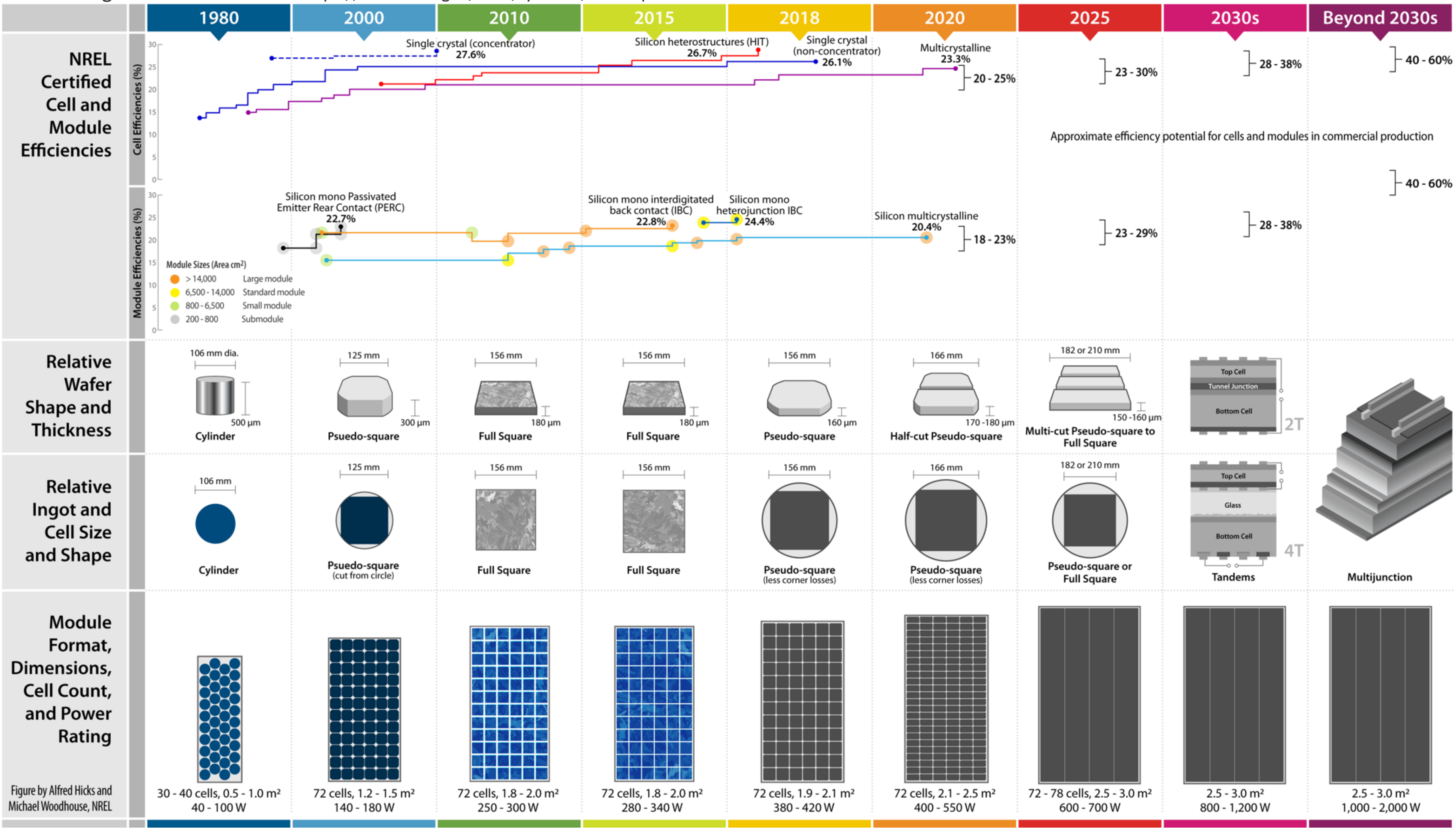
One standard deviation equals +/- 25% change in *factory production volume*



All input distributions and resultant $/W calculations are also saved as CSV files

Delivered MSP included around $0.045/W shipping and delivery costs that were above the factory gate price

Source of figure: NREL. Please see: https://www.nrel.gov/docs/fy22osti/80505.pdf



Presentation Overview

1 Introduction

2 Component Manufacturing Cost Modeling

3 **System Capital Costs**

4 Levelized Cost of Electricity (LCOE)

5 Supply Chain Analysis

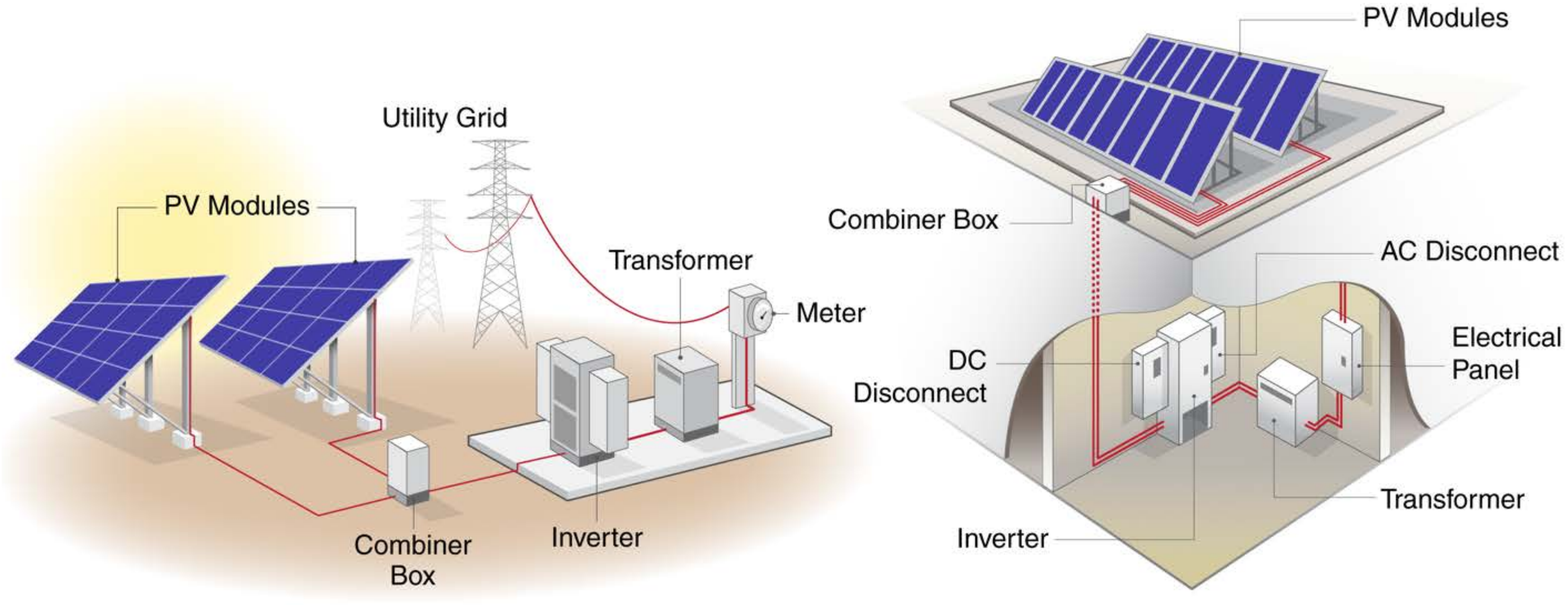
6 Resources for Follow-Up

System Cost Benchmark

Goal: Identify cost reduction opportunities, such as the impact of using PV modules with higher efficiency, 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 typical 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.

System-Level PV Components



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

Key Cost Components

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

High Level Framework

Inputs I
- Location
- Project Year
- Project Size
- Module Efficiency
- Tracker?
- MVDC?
- Overhead/Profit %

Inputs II
- Wind mph
- Snow psi
- Labor Wage by skill
- Sales Tax
- Material & Equipment Cost Factor

Inputs III
- Inflation
- Construction Cost Index
- Steel Price Index
- Cum. Installation by state in MWs

Modules/Inverter
Based on Efficiency, Watt/Panel, System Vdc, calculate string & inverter qty.

Loading Analysis
Estimate, qty of support structures based on wind & snow load in a region.

Labor Estimation
Calculate Avg. Electrical & Construction labor/hour by activity including labor overhead

Category	Activity	Qty	Material $/unit	Equipment $/unit or $/hr	Labor Hours/ Unit	No. of Labors	Labor $/hr	Material $	Equipment $	Labor $
Structural BOS	Horizontal Support Structure	n1	a1	b1	c1	l1	m1	=n1*a1	=n1*b1	=n1*c1*l1*m1
	Module Mounting	n2	a2	b2	c2	l2	m2	=n2*a2	=b2*c2	=n2*c2*l2*m2
	Trenching	n3	a3	b3	c3	l3	m3	=n3*a3	=n3*b3*c3	=n3*c3*l3*m3
Electrical BOS	Conduits & Wiring	..	..	..	..	..	..	..	..	..
Soft Cost	EPC Overhead %							Material $ * OH %	Equipment $ * OH %	

Steps - PV System Cost Estimation

Key Cost Categories	Data Source	Sub-Cost-Components	Values	Units
Module	Woodmac	N	0.34	$/w
Inverter	Woodmac	N	0.05	$/w
Site Preparation	RS Means Construction Cost Book	Y		
Site Staging	RS Means Construction Cost Book	Y		
Structural BOS	RS Means Construction Cost Book	Y		
Electrical BOS	RS Means Construction Cost Book	Y		
Install Labor & Equipment	BLS, RS Means Construction Cost Book	Y		
EPC/Contractor Overhead	Interviews	N	8%	%
Sale Tax (if any)	RS Means Construction Cost Book	N	6%	%
Permitting Fee (if any)	Literature	N	$ 250,000	$
Interconnection Fee	Literature	Y		
Transmission Line (if any)	Literature	Y		
Contingency	Interviews	N	3%	%
Developer Overhead	Interviews	N	2%	%
EPC/Developer Net Profit	Interviews	N	5%	%

Steps - PV System Cost Estimation

Project Inputs		
System Capacity	100	MW_{DC}
ILR	1.3	#
Inverter Capacity	77	MW_{AC}
PV Module Inputs		
PV Panel Power Rating	390	W
PV Panel Width	77	inches
PV Panel Height	39	inches
PV Panel Weight	60.8	lb

Steps - PV System Cost Estimation

Site Staging	Unit	Qty	Material Cost	Equipment Cost
Preconstruction Surveys	Acre	= 4.56 Acre*100 MW	= 23*Qty	
Access Roads and Parking	S.Y	= 1%*4.56 Acre*100 MW*4840	= 3.39*Qty	
Security Fencing	L.F			
Temporary Office	#			
Storage Box	#			
O & M Building	S.F			
Site Preparation				
Site Preparation (Geotechnical Investigation)	Day			
Site Preparation (Clearing and Grubbing)	Acre			= 1675*Qty
Site Preparation (Soil Stripping and stockpiling)	C.Y.			
Site Preparation (Grading)	S.Y.			
Site Preparation (Compaction)	E.C.Y			
Strucural BOS				
Foundation for /inverter/transformer/ PVSC	S.F.			
Trenches	L.F.			
Foundation for Vertical Support	V.L.F.			
Horizontal Support Structures	L.F.	=no.of PV modules*width of pv panel in ft	= 43*Qty	= 29*Qty
Welding or Bolting	Hr			
Modules Mounting	Ea	=no.of PV modules	= 10.53*Qty	
T- Connection	Ea			
Electrical BOS				
Conduit, Wiring	L.F.			
Grounding, DC Cable	C.L.F			
Junction/Combiner Boxes	Ea			
Inverter House	Ea			
On-site Transmission	Ea			
PV Combining Switchgear (PVCS)	Ea			
On-site transformer & Substation	Ea			
230kV Transmission Line				
Tower: Foundation Installation	Hr			
Tower: Structure Costs	Each			
Tower: Top Assembly	Hr			
Conductor and Cable	C.L.F			
Misc. Assembly Units	%			
Interconnection				
Interconnection fee	$/w			
Equipment Upgrade Cost	MW	= 100 MW	= 161,270*Qty	

Steps - PV System Cost Estimation

Site Staging	Unit	Labor Hrs Per Laborer Per Unit	No. of laborers per unit
Preconstruction Surveys	Acre	7.273	1 CL
Access Roads and Parking	S.Y	0.067	3CL
Security Fencing	L.F	0.12	.
Temporary Office	#	32	.
Storage Box	#	8.89	.
O & M Building	S.F	0.06	.
Site Preparation			
Site Preparation (Geotechnical Investigation)	Day	24	1 EO
Site Preparation (Clearing and Grubbing)	Acre	48	1 EO, 2 CL
Site Preparation (Soil Stripping and stockpiling)	C.Y.	0.008	.
Site Preparation (Grading)	S.Y.	0.008	.
Site Preparation (Compaction)	E.C.Y	0.04	.
Strucural BOS			
Foundation for /inverter/transformer/ PVSC	S.F.	0.137	2 CL
Trenches	L.F.	0.02	2 CL
Foundation for Vertical Support	V.L.F.	0.084	4 CL
Horizontal Support Structures	L.F.	0.966	2 CL, 2 EO
Welding or Bolting	Hr	1	3 CL
Modules Mounting	Ea	0.25	2 CL
T- Connection	Ea	1	2 CL
Electrical BOS			
Conduit, Wiring	L.F.	0.1	2 EL
Grounding, DC Cable	C.L.F	0.8	2 EL
Junction/Combiner Boxes	Ea	8	3 EL
Inverter House	Ea	8	2 EL, 1 CL
On-site Transmission	Ea	8	3 EL, 1 EO, 1CL
PV Combining Switchgear (PVCS)	Ea	16	.
On-site transformer & Substation	Ea	80	.
230kV Transmission Line			
Tower: Foundation Installation	Hr	.	
Tower: Structure Costs	Each	.	
Tower: Top Assembly	Hr	.	
Conductor and Cable	C.L.F	.	
Misc. Assembly Units	%	.	
Interconnection			
Interconnection fee	$/w	.	
Equipment Upgrade Cost	MW	.	

Occupation	$/hour (nonunion US. Avg)
Electrician (EL)	$28.87
Construction Laborer (CL)	$17.38
Equipment Operator (EO)	$23.25

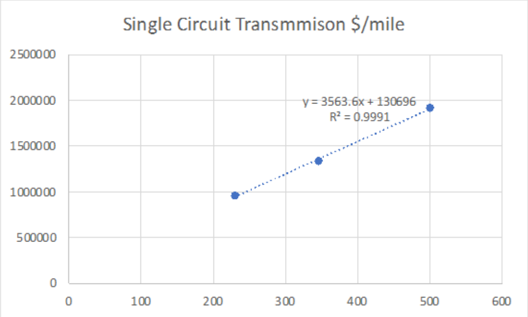
Total Labor Cost of each activity = Qty* Labor Hours per unit* No. of Laborers per unit* Hourly Labor Wage by specialty

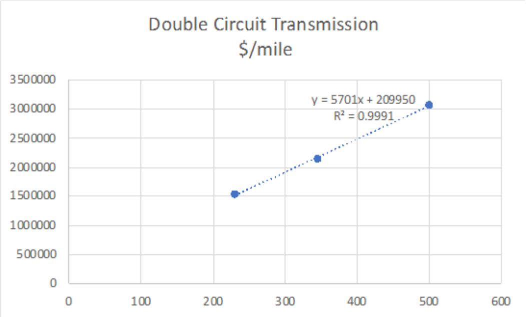
Steps - PV System Cost Estimation

Transmission kV	Single Circuit $/mile (2017 USD)	Double Circuit $/mile (2017 USD)
230	$959,700	$153,6400
345	$1,343,800	$2,150,300
500	$1,919,450	$3,071,750

Source: https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf

Transmission Terrain Multiplier	
Dessert	1.05
Flat	1
Farmland	1
Forested	2.25
Rolling Hill	1.4
Mountain	1.75
Wetland	1.2
Suburban	1.27
Urban	1.59





Transmission Cost, $ = Single or Double Circuit $/mile * transmission miles * transmission terrain multiplier * USD adjustment

Steps - PV System Cost Estimation

Key Cost Categories	Data Source	Sub-Cost-Components	Values	Units	Total $
Module	Woodmac	N	0.34	$/w	$ 34,000,000
Inverter	Woodmac	N	0.05	$/w	$ 5,000,000
Site Preparation	RS Means Construction Cost Book	Y			$ 1,012,429
Site Staging	RS Means Construction Cost Book	Y			$ 4,822,601
Structural BOS	RS Means Construction Cost Book	Y			$ 14,207,809
Electrical BOS	RS Means Construction Cost Book	Y			$ 8,690,768
Install Labor & Equipment	BLS, RS Means Construction Cost Book	Y			$ 11,157,365
EPC/Contractor Overhead	Interviews	N	8%	%	$ 854,892
Sale Tax (if any)	RS Means Construction Cost Book	N	6%	%	$ 4,875,936
Permitting Fee (if any)	Literature	N	$ 250,000	$	$ 250,000
Interconnection Fee	Literature	Y			$ 3,166,512
Transmission Line (if any)	Literature	Y			$ 1,701,924
Contingency	Interviews	N	3%	%	$ 3,029,086
Developer Overhead	Interviews	N	2%	%	$ 2,456,780
EPC/Developer Net Profit	Interviews	N	5%	%	$ 5,053,980
					$ 100,280,082

Q1-2022 Preliminary Modeling Inputs/Assumptions

	Residential	Commercial	Utility	Source
Module Type	Mono-C-Si	Mono-C-Si	Mono-C-Si	CA NEM
Module Power (W)	360	360	405	CA NEM
Module Area (m2)	1.76	1.76	2.01	CA NEM
Module Efficiency %	20.19%	20.19%	20.19%	CA NEM
Module MSP $/Wdc	0.33	0.33	0.33	PV Module Manufacturing Cost Model
Installer Market Share	Not Updated	NA	NA	Woodmac
Inverter Market Share	Not Updated	Not Updated	NA	Woodmac
Inverter $/Wac	Not Updated	Not Updated	Not Updated	Woodmac, BNEF

Q1-2022 Preliminary Modeling Inputs/Assumptions

	Residential	Commercial	Utility	Source
SBOS – Material & Equipment $/unit	Updated	Updated	Updated	Commercial & Utility - RS Means, Residential - Renvu, Ecodirect, RSMeans
Labor Wage - Hrs, $/Hr	Partially Updated	Partially Updated	Partially Updated	RSMeans, BLS
Cost Indices – Location, Material & Equipment, Steel, CPI	Updated	Updated	Updated	Fred, RSMeans
Soft Costs – Sales Tax, PII, Overhead, Profit	Partially Updated	Partially Updated	Partially Updated	RSMeans, Interviews

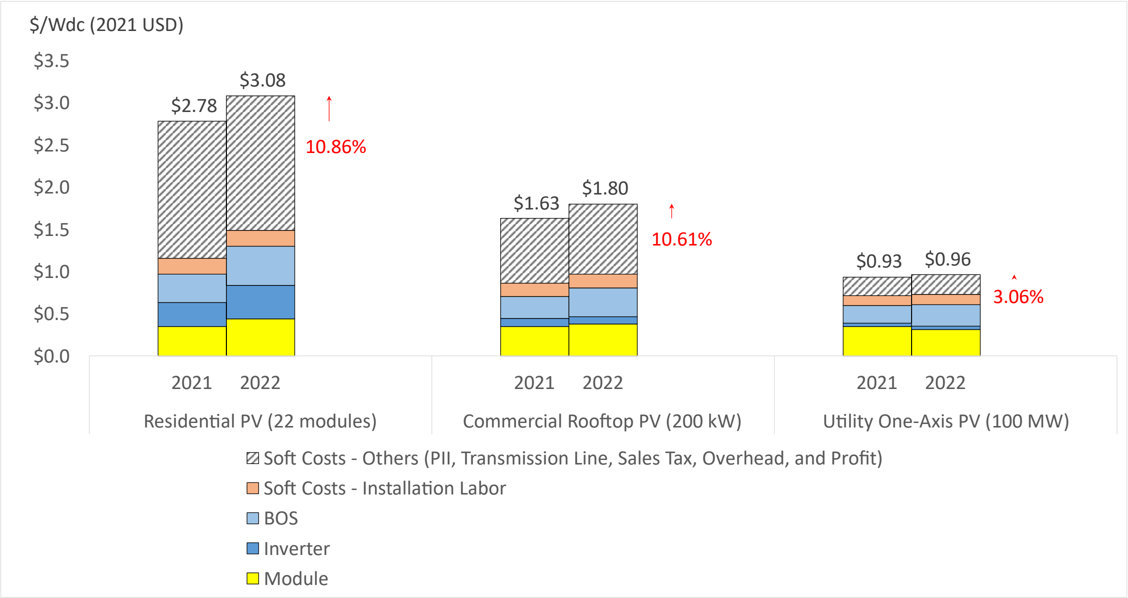
Q1-2022 Utility PV Model Inputs & Assumptions

Category	Modeled Value	Description	Sources
System size	100 MW; range: 5 MW–100 MW	A large utility-scale system capacity	Model assumption
Module efficiency	20.1% (405W, 2.01m2)	Average monocrystalline module efficiency (System Size > 5MW)	CA NEM Q1-2022 (Jan, Feb)
Module price	$0.33/W_{DC}$	Module MSP (Duty/Tariff Free)	NREL's PV Module Manufacturing Cost Model
Inverter price	\$0.05/W_{AC} (fixed-tilt) \$0.05/W_{AC} (one-axis tracker)	Ex-factory gate (first buyer) price, Tier 1 inverters DC-to-AC ratio = 1.31 for fixed-tilt and 1.28 for one-axis tracker	Wood Mackenzie and SEIA 2021; Bolinger et al. 2020
Structural components (racking)	\$0.13-\$0.22/W_{DC} for a 100-MW system	Fixed-tilt racking or one-axis tracking system	MEPS 2019; model assumptions; NREL 2021
Electrical components	\$0.08–\$0.16/W_{DC} Varies by system size	1,500-V_{DC} system that includes conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, and other electrical connections	Model assumptions; NREL 2021; RSMeans 2021
EPC overhead (percentage of equipment costs)	8.67%–13% for equipment and material (except for transmission line costs); 23%–69% for labor costs; varies by system size and labor activity	Costs associated with EPC SG&A, warehousing, shipping, and logistics	NREL 2021
Sales tax	National average: 5.1%	Sales tax on equipment costs	RSMeans 2021
Direct installation labor	Electrician: \$28.9/hour Construction Laborer: \$18.2/hour Equipment Operator: \$23.3/hour	Modeled labor rate assumes national average nonunionized labor	BLS 2022; NREL 2021
Burden rates (percentage of direct labor)	Total nationwide average: 31.7%	Workers' compensation, federal and state unemployment insurance, Federal Insurance Contributions Act, builders' risk, public liability	RSMeans 2021
PII	\$0.02–\$0.04/W_{DC} Varies by system size	For construction permits fee, interconnection, testing, and commissioning	NREL 2021
Transmission line (gen-tie line)	\$0.00–\$0.01/W_{DC} Varies by system size	System size < 10 MW uses 0 miles for gen-tie line, thus no transmission cost System size > 200 MW uses five miles for gen-tie line System size = 10–200 MW uses linear interpolation	Model assumptions; NREL 2021
Developer overhead	2%–12% Varies by system size (100 MW uses 2%; 5 MW uses 12%)	Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions	Model assumptions; NREL 2021
Contingency	3%	Estimated as markup on EPC cost	NREL 2021
Profit	5%–8% Varies by system size (100 MW uses 5%; 5 MW uses 8%)	Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, and developer overhead	NREL 2021

DRAFT results in support of NREL's 2022 Solar and Storage System Costs Benchmark.

2021 vs 2022 PV System Cost Results

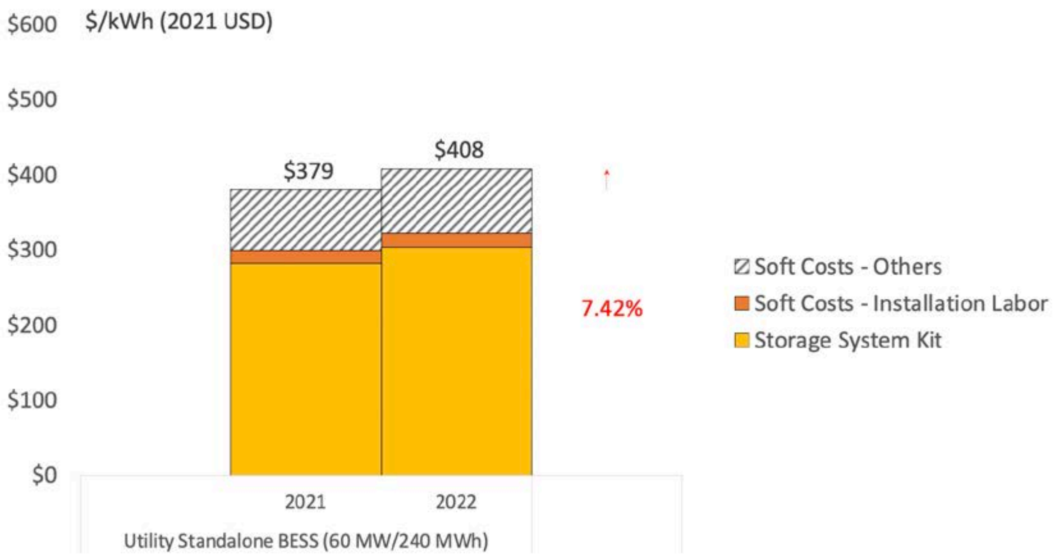
- BOS materials cost is the key cost driver
- Drivers of cost increment – Balance of System Material/Equipment Rental cost, Hourly Labor Wage.
- Residential PV Cost – Weighted average of all inverter types. Includes both small and large installers.



DRAFT results in support of NREL's 2022 Solar and Storage System Costs Benchmark.

2021 vs 2022 Utility BESS System Cost Results

- Increased battery pack cost and electrical material/equipment cost are key cost drivers.
- Storage System Kit includes – Li-Ion battery cabinets (battery packs, racking, HVAC, TMS), Inverter, BOS.

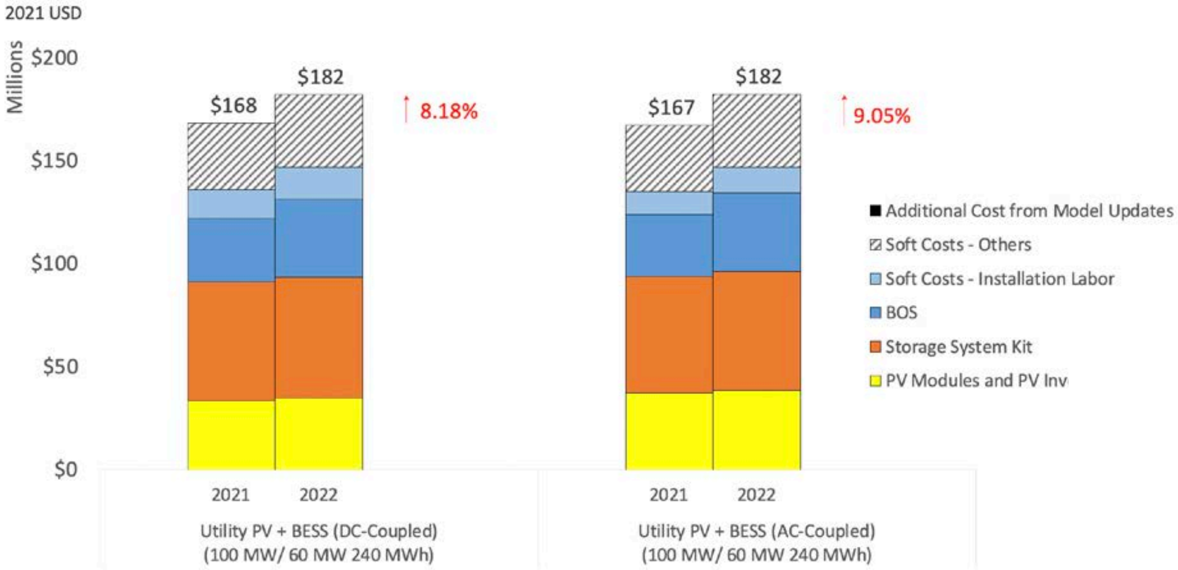


DRAFT results in support of NREL's 2022 Solar and Storage System Costs Benchmark.

2021 vs 2022 Utility PV + BESS System Cost Results

AC Coupled vs. DC Coupled Assumptions

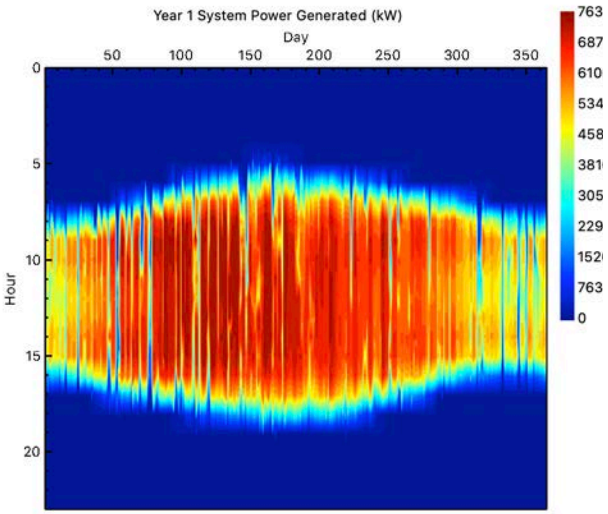
- AC-coupled systems have independent PV and battery systems with separate inverters, this hybrid configuration enables redundancy.
- Number of inverters – DC Coupled - 1 (bidirectional inverter for battery + DC-DC converters), AC Coupled - 2 (bidirectional inverter for battery plus grid-tied inverter for PV).
- Assumes higher skilled labor work for DC coupled systems.



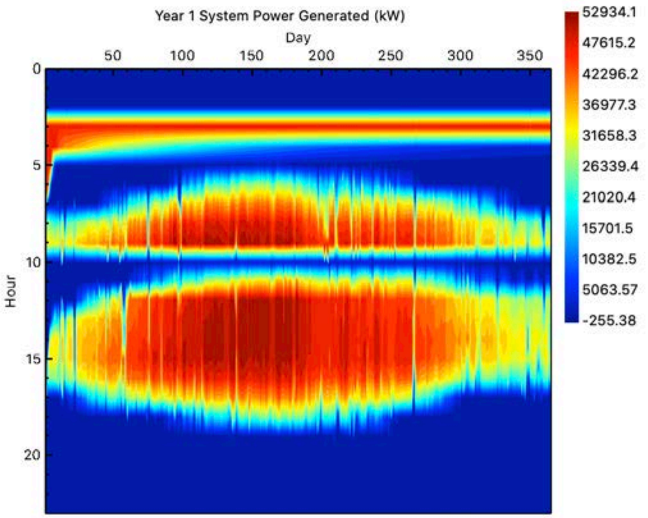
DRAFT results in support of NREL's 2022 Solar and Storage System Costs Benchmark.

LCOE of Utility PV & PV + BESS System

Assumptions	*PV*	*PV + BESS*
System Size	100 MWdc	100 MWdc + 60 MWdc/240 MWh
Installed Cost	$0.96	$1.83
Annual Degradation	0.7%	0.7%
Preinverter Derate	86%	86%
Inverter Efficiency	96%	96%
O&M $/kW-Yr	$16	$28
ILR	1.3	1.3
Analysis Period	30 Years	30 Years
Debt Fraction	71.8%	71.8%
Debt Interest	5%	5%
Debt Term	18 Years	18 Years
Initial Energy Yield (kWh/kWDC)	1,694	1,397
Real LCOE $/kWh	**4.3**	**7.8**

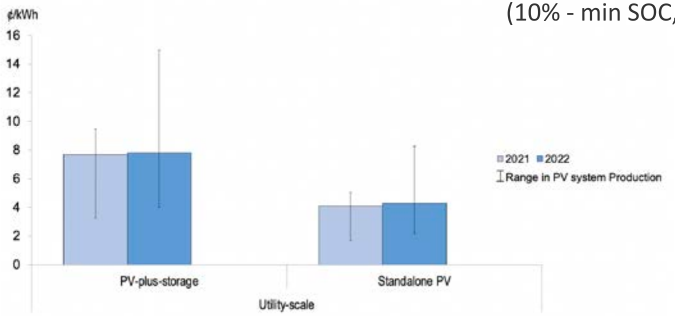


PV Only Dispatch



PV + BESS Dispatch

(10% - min SOC, 90% max SOC)

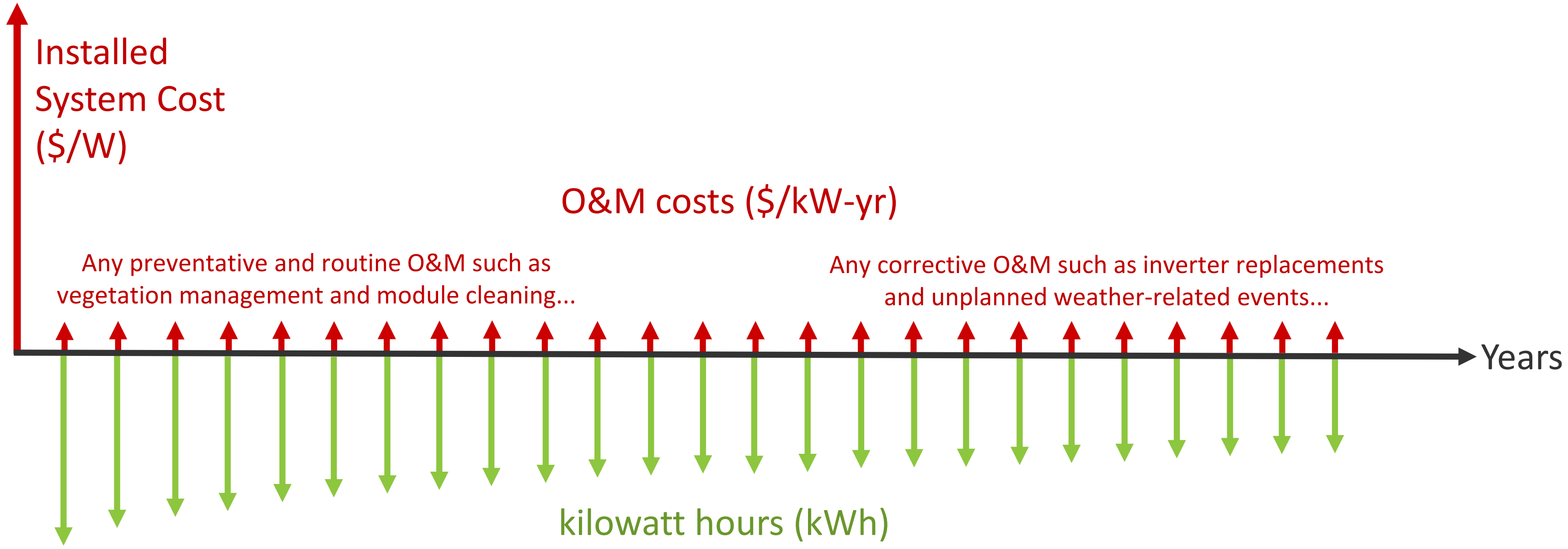


DRAFT results in support of NREL's 2022 Solar and Storage System Costs Benchmark.

Presentation Overview

Introduction

$$\text{LCOE (\$/kWh)} = \frac{\text{Total Costs over Service Life (\$)}}{\text{Total Energy Produced over Service Life (kWh)}}$$



Drivers of PV System LCOE

Price

- Manufacturer's ability to fulfil the order at the lowest possible price
- Shipping, tariffs (if applicable), insurance, sales or value added taxes, etc., also factor in

Efficiency and BOS Considerations

- Lower module count to reach nameplate rated capacity equals lower balance of system (BOS) capital costs.
- Higher power rating—by higher efficiency and/or larger physical dimensions—equals lower module count
- However, tradeoffs exist once a module reaches a certain size and weight: Tracker requirements, wind design, column spacing, containerizing and handling

Reliability, Durability, Bankability

- Standardized testing and outdoor field history as a basis for estimating performance.
- Module warranty and warranty profile (Year 1 and subsequent years)
- Assumed useful lifetime of the module, module replacement rates, and associated operations and maintenance (O&M) expenses

Energy Yield

- Temperature coefficient and spectral response
- Bifaciality
- Ability to mitigate DC losses including soiling; cell, module and string mismatch, etc.

Tools for Calculating LCOE

NREL's System Advisor Model (SAM)

sam.nrel.gov

- Many features, including:
  - More sophisticated financials
  - Many options for modifying specifics of module & system technologies, and designs
  - Ability to pair with storage
- Can be used in detailed site planning or analysis
- Used by NREL team to benchmark LCOE numbers
- Some researchers find SAM has a learning curve; can be difficult to accurately/quickly understand potential impacts of different R&D directions; may introduce confounding variables

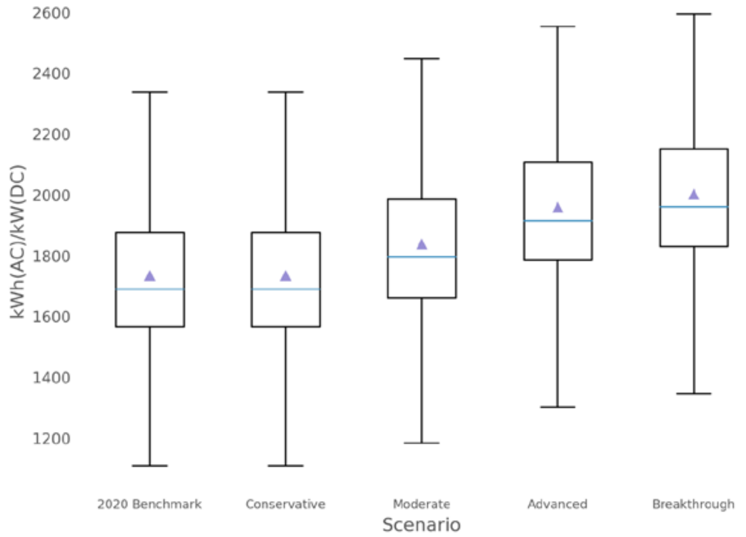
NREL's reV model (Renewable Energy Potential Model) pairs with SAM to create maps on the following slides...

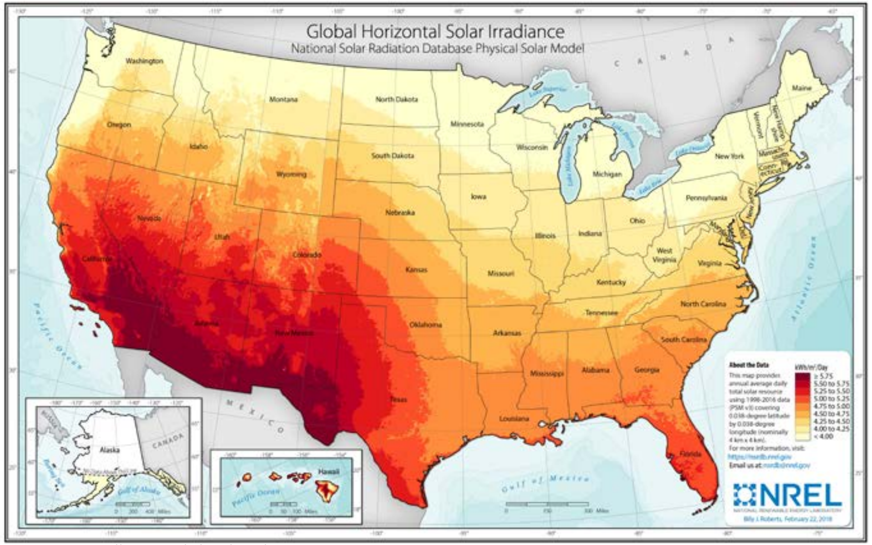
NREL's Online PV LCOE Calculator

pvlcoe.nrel.gov

- Simplified online tool targeted at PV researchers who want to quickly explore potential impacts of different high-level R&D directions
- PV-specific, has more detailed breakdown of cost components within a PV module
- Not as accurate or fully featured as SAM, so not a great option for detailed project planning

Energy Yield Statistics from NREL's SAM and reV Tools

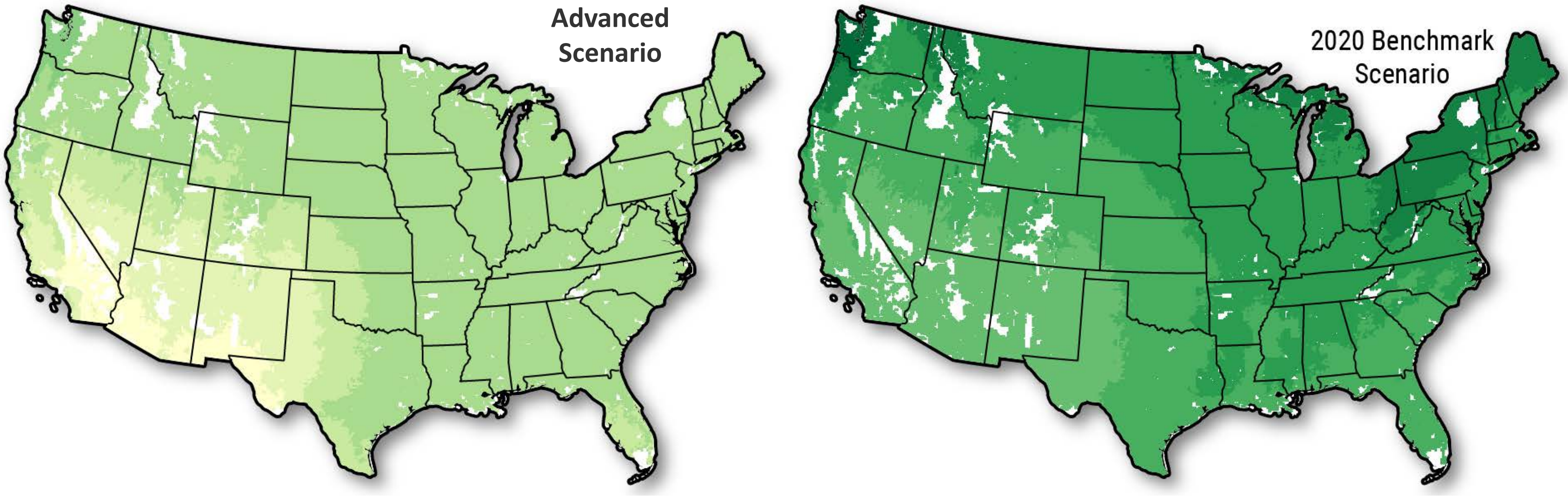




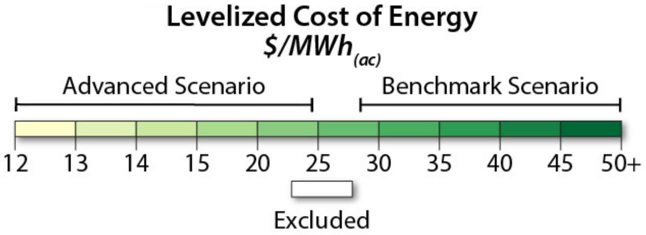
Source of Figure: https://www.nrel.gov/gis/assets/images/solar-annual-ghi-2018-usa-scale-01.jpg

	2021 Benchmark	Moderate	Advanced	Breakthrough
Bifaciality	Monofacial	Monofacial	0.85	0.95
Total DC and AC Losses	14%	9%	7%	4%
Relative Mean for Annual (First Year) Energy Yield	100%	106%	110% (Before optimizing ILR & GCR)	114% (Before optimizing ILR & GCR)

Utility-Scale LCOE Progress Milestones for the United States



	2020 Benchmark	Advanced Scenario
Capital Cost	$1.0/W	$0.5/W
O&M (Including land and overhead)	$17.5/kW-yr	$8/kW-yr
Degradation Rate	0.7%	0.2%



Source of figure: NREL/DOE Solar Futures Study. Available online.

DuraMAT
Durable Module Materials Consortium

Instant, Online, Simplified PV LCOE Calculator Tool

Brittany L. Smith
National Renewable Energy Laboratory

Updated under DuraMAT award, August 2021

Simplified PV-LCOE Calculator

- PV technology-specific
- Editable preset fields targeted towards research applications
- Instant comparison of proposed changes to a baseline system

Calculator access:

- pvlcoe.nrel.gov
- nrel.github.io/PVLCOE/
- github.com/NREL/PVLCOE

Previous Calculator Tutorials:

– nrel.gov/docs/fy22osti/80842.pdf

Calculator co-architects:

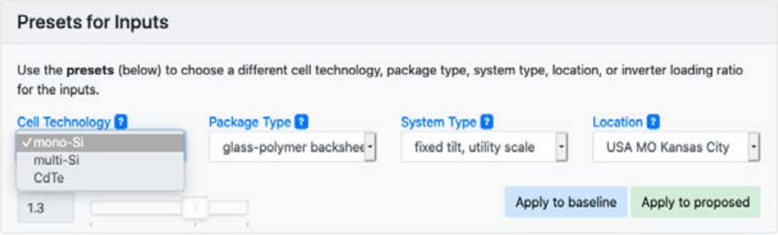
Tim Silverman

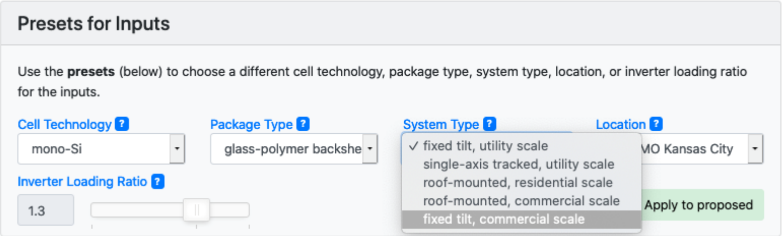
Mike Deceglie

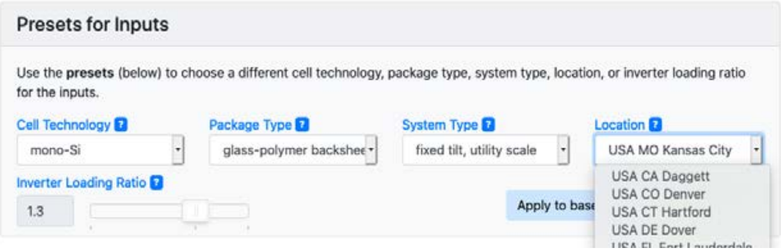
Sophie Andrews

Kelsey Horowitz

Preset Menus

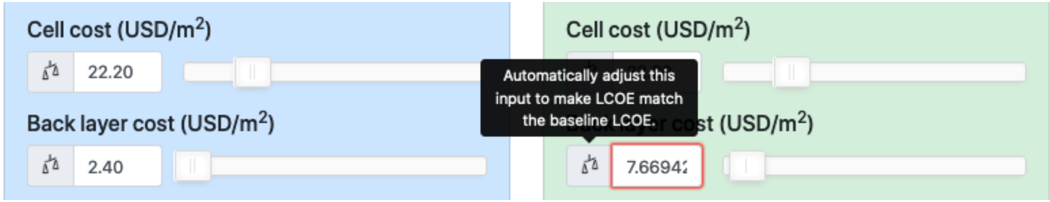


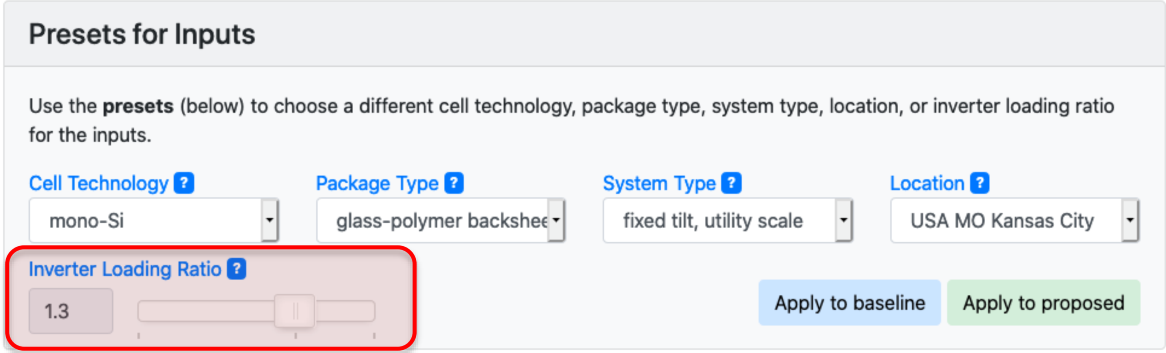




Updated Calculator Features

- Breakeven buttons
- Inverter Loading Ratio

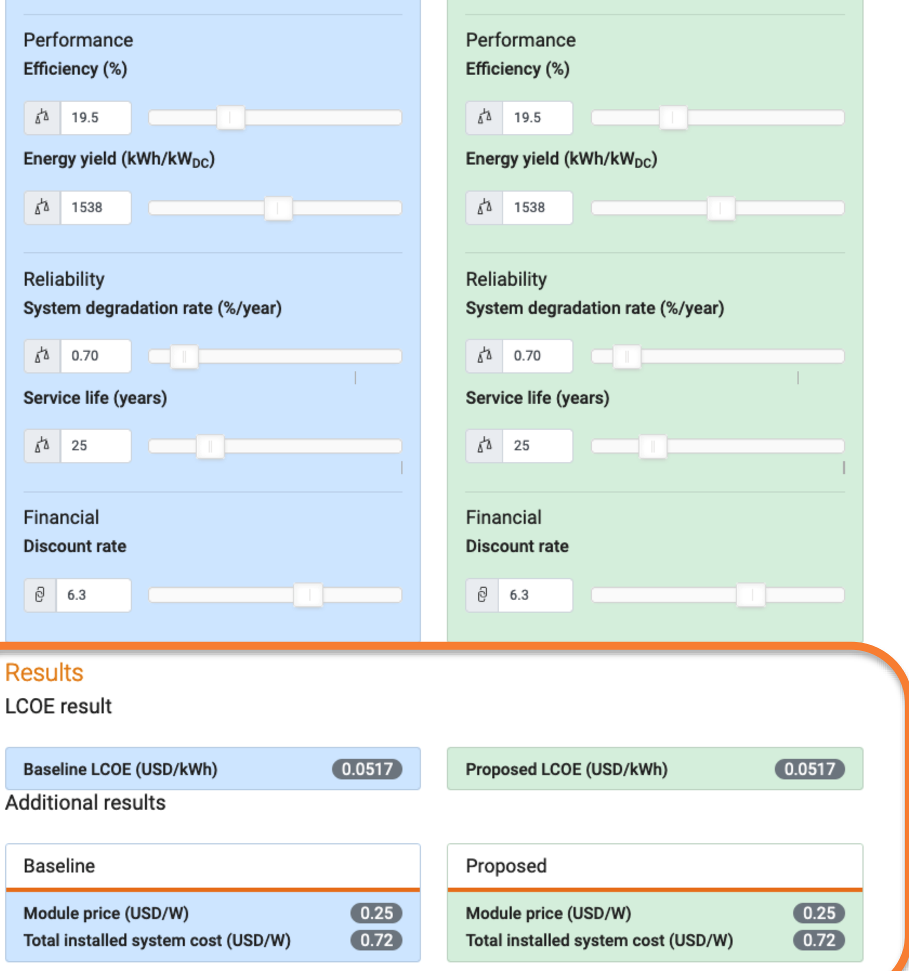




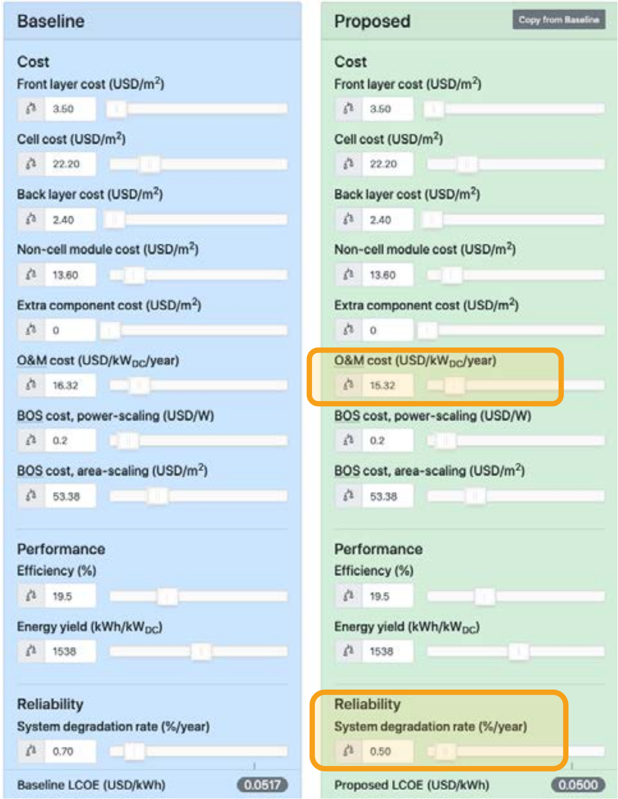
Inverter Loading Ratio affects both BOS costs and energy yield

Results

- LCOE
- Module Price
- System Cost



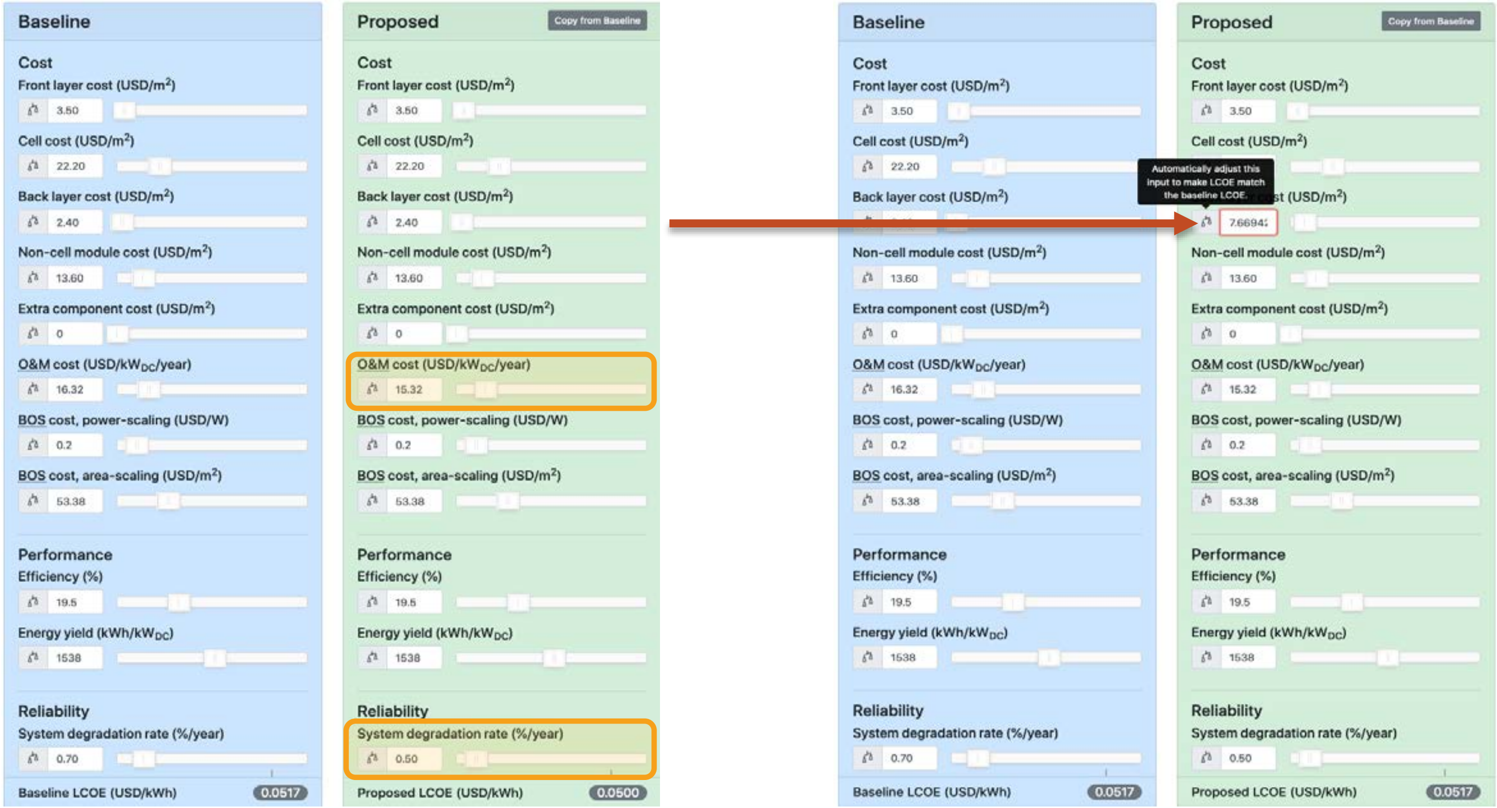
Example use: a hypothetical miracle backsheet



Let's say you had a miracle backsheet that somehow created a lower system degradation rate & reduced maintenance costs.

How much could this backsheet cost and still be cost-competitive with the incumbent technology?

Breakeven Cost for Hypothetical Backsheet



Energy Yield Values called directly from SAM

Previously, the calculator relied on a table of energy yield values that was built manually from SAM using the Detailed PV Model:

https://sam.nrel.gov/

Now, PySAM package is used by calculator to call SAM directly. Relies on:

- PVWatts model: https://pvwatts.nrel.gov/
- NSRDB weather data: https://nsrdb.nrel.gov/

Degradation Rate Relationship

Exponential Relationship:

$$e_n = e_{yield}(1-r)^{(n-1)}$$

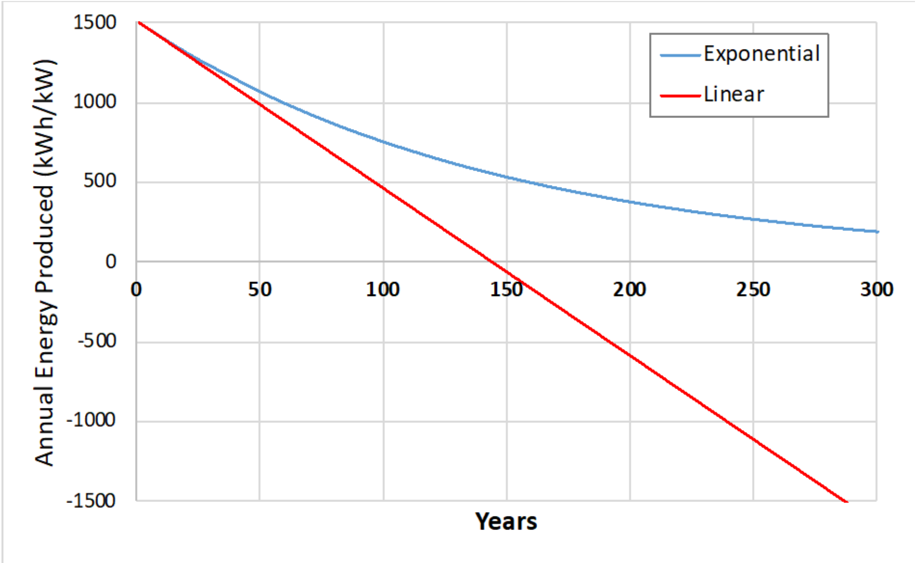
Linear Relationship:

$$e_n = e_{yield}[1-r(n-1)]$$

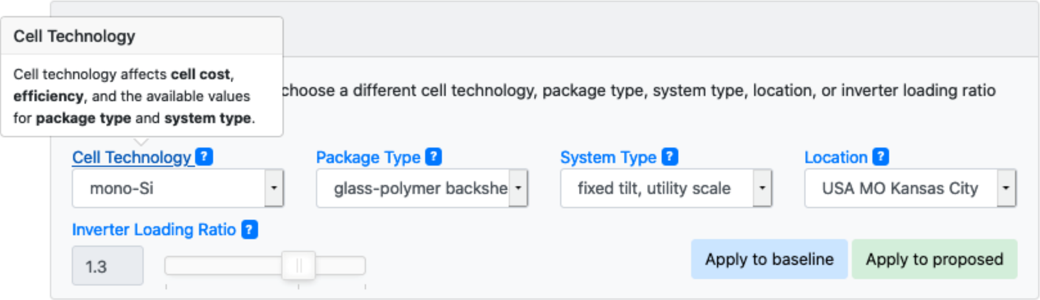
r is the degradation rate
n is the year of operation
e is the energy produced

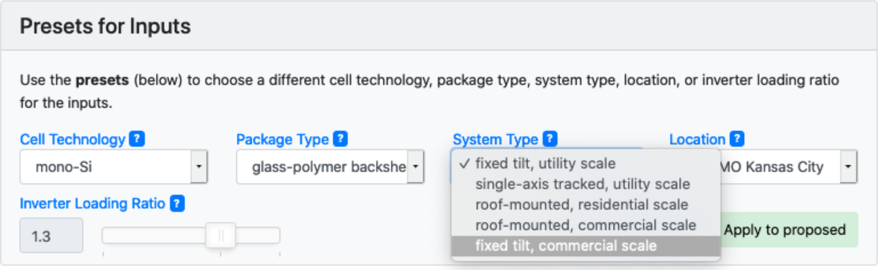
For a system with:

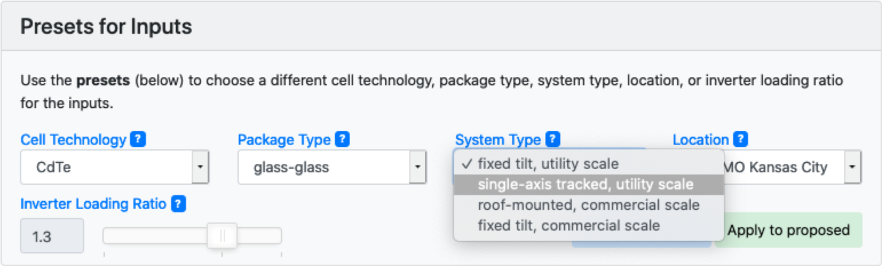
- 0.7% degradation rate
- 1500 kWh/kW first year energy yield



Preset Constraints

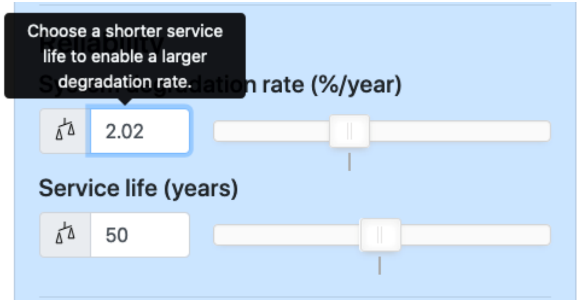






Limits on Numerical Ranges

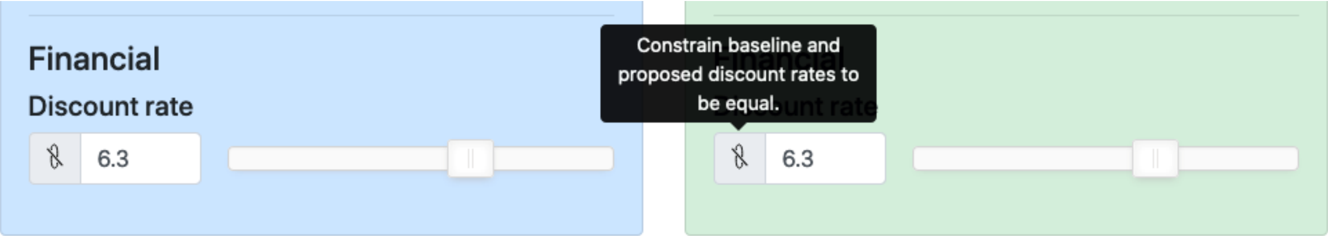
Restricted service life range & added dead zone to slider to keep energy non-negative and prevent continuous costs on a PV system that does not generate energy.



Physically-motivated limits on:

- efficiency (0-100%)
- energy yield > 0
- degradation rate > 0%

Discount Rate Comparison



- Sync / unsync discount rates (instead of breakeven button)

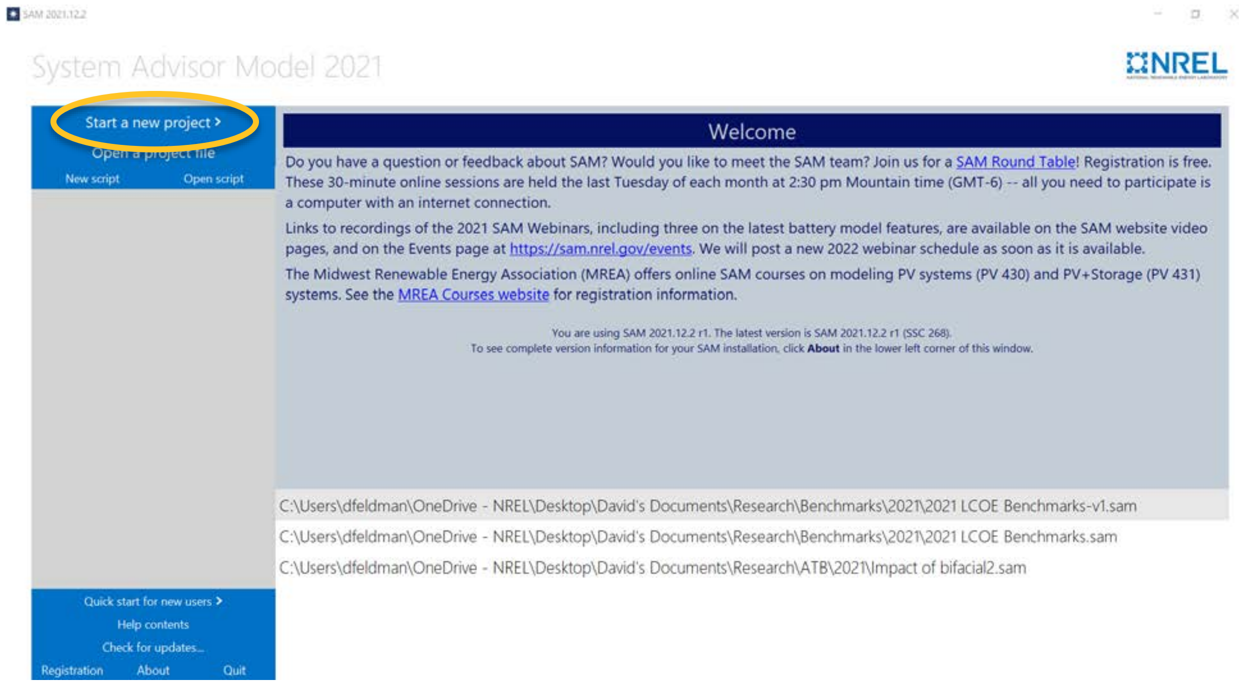
Equations versus Cash Flow Modeling

Simplified LCOE relies on an equation with a capital recovery factor:

sLCOE = {(overnight capital cost * capital recovery factor + fixed O&M cost)/(8760 * capacity factor)} + (fuel cost * heat rate) + variable O&M cost

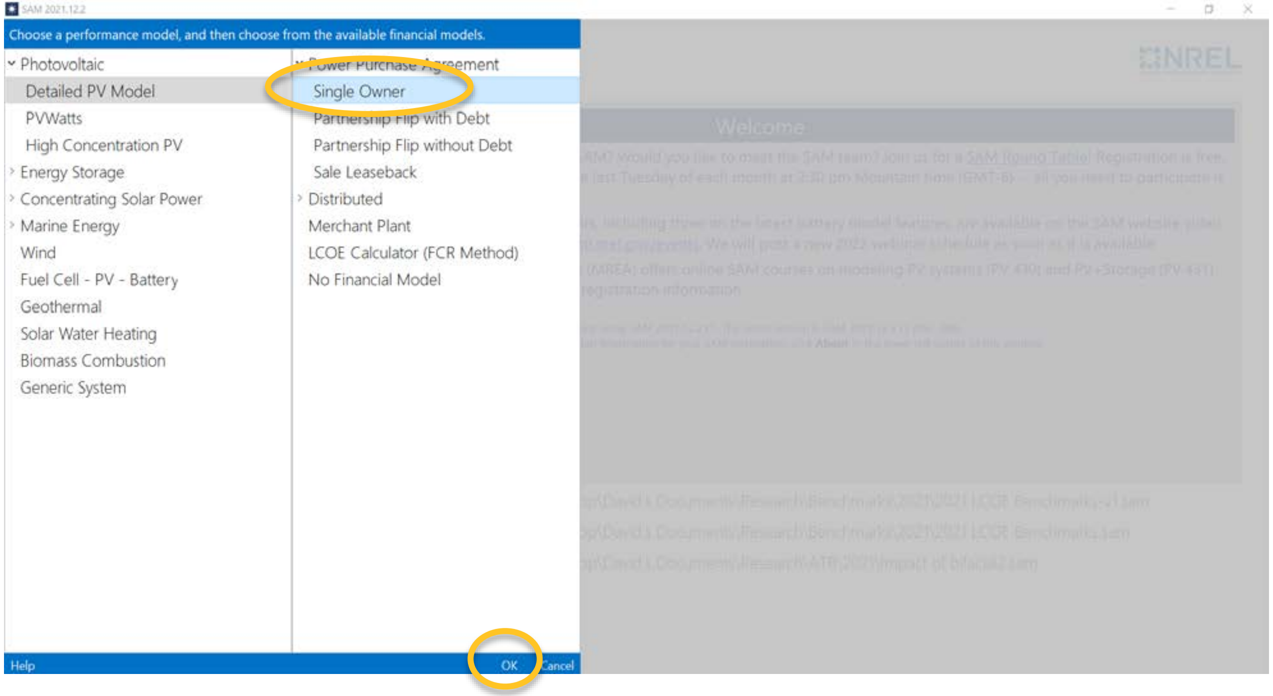
Equations are efficient for running multiple scenarios over time and looking at the cost impact of a specific input. However, discounted cash flow (DCF) modeling provides a more accurate cost projection and allows for incorporating significant model variations.

System Advisor Model DCF Modeling



Start a new project

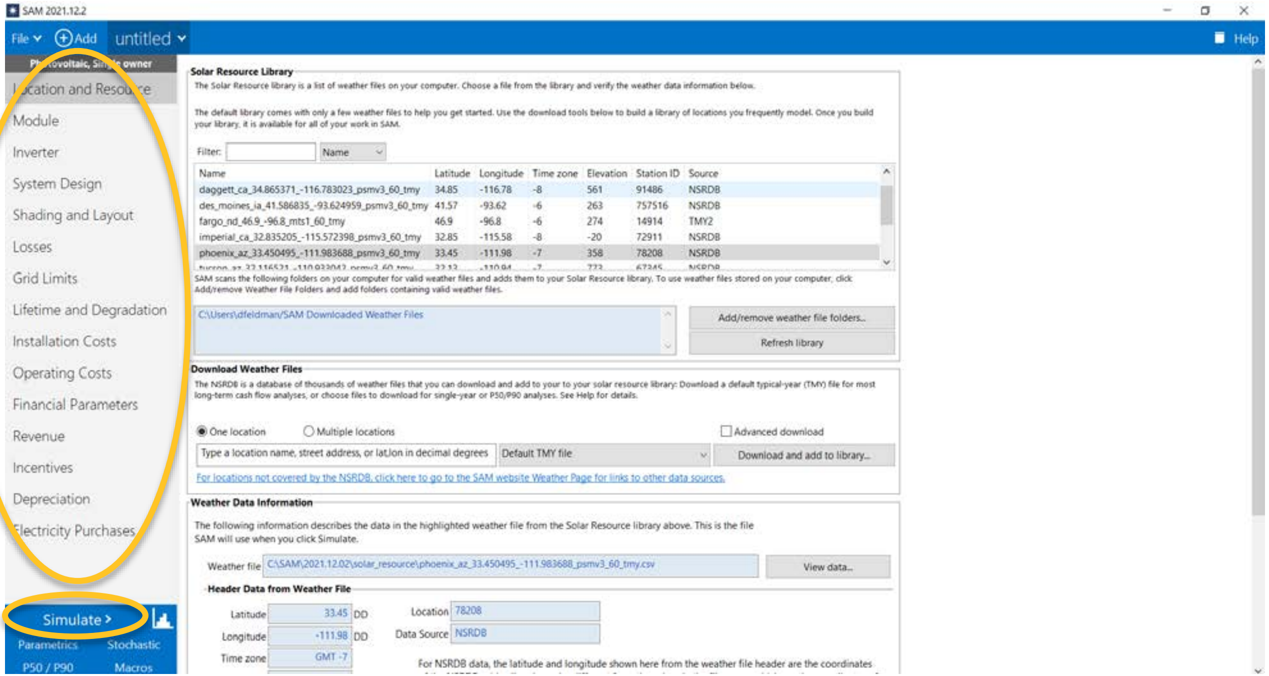
System Advisor Model DCF Modeling



Choose your technology and financial model

https://sam.nrel.gov/

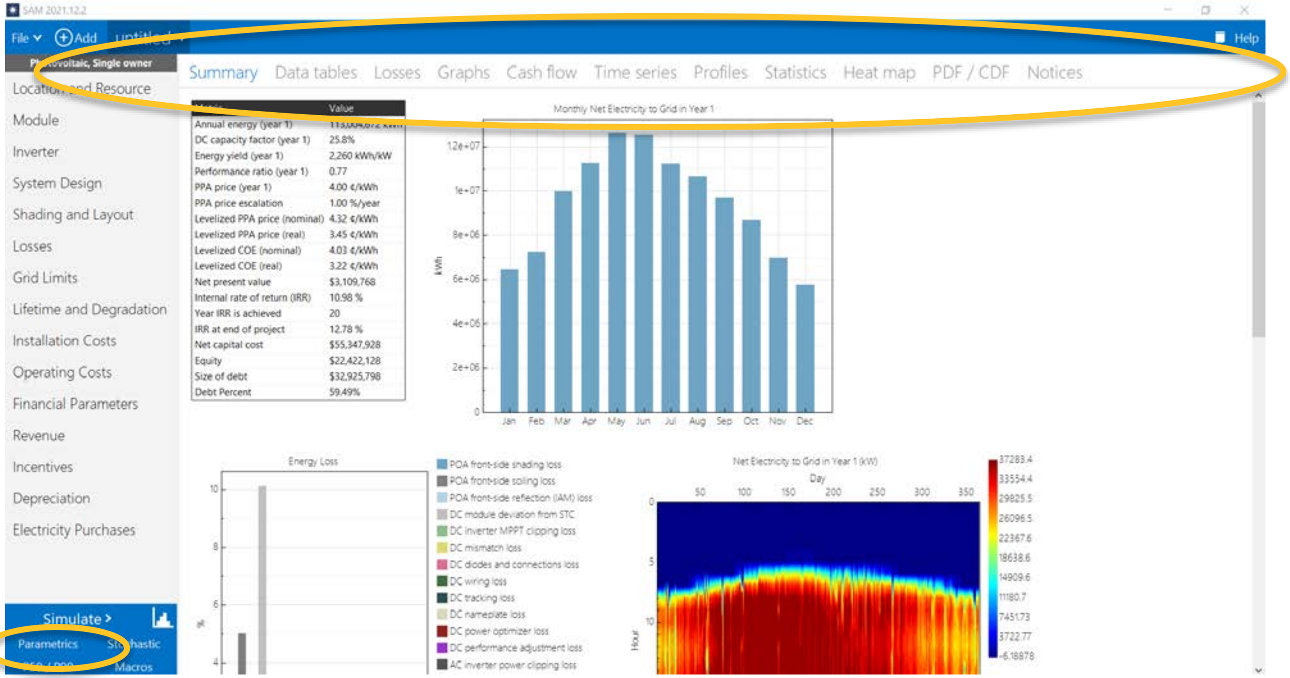
System Advisor Model DCF Modeling



Input project specifics, including: system design, installation, operation, and financing costs, and how the electricity is sold.

Press "simulate" and the model will calculate a discounted cash flow and output variables.

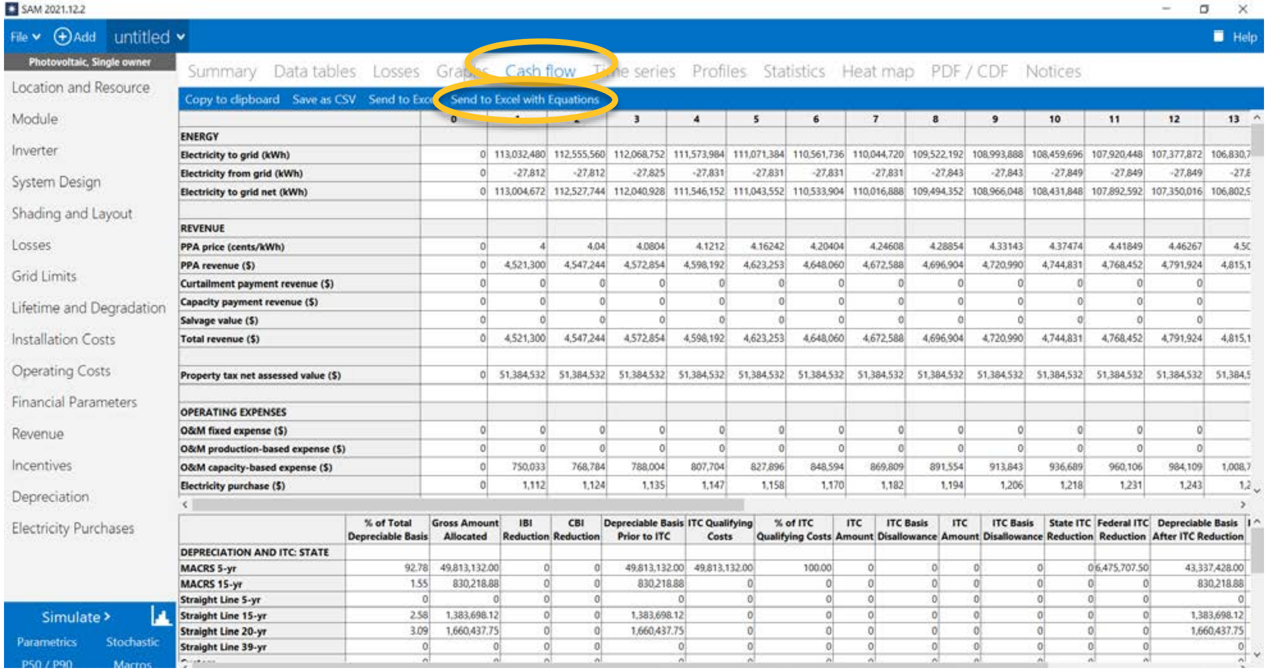
System Advisor Model DCF Modeling



View the output tabs of the model, including LCOE.

You can also run sensitivity analyses of input variables using the “parametrics” function.

System Advisor Model DCF Modeling



To view the DCF model with equations in Excel, go to the “Cash flow” tab and click “Send to Excel with Equations”.

Basic DCF Inputs and Equations

Year	Y0	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15	Terminal Year
Electricity Production		14,500	14,399	14,298	14,198	14,098	14,000	13,902	13,804	13,708	13,612	13,516	13,422	13,328	13,235	13,142	
Investment	(6,330)																
Buyout																	3,000
PPA Revenue		$866	$882	$897	$913	$930	$946	$963	$980	$998	$1,015	$1,033	$1,052	$1,071	$1,090	$1,109	
Operating Expenses (O&M, Insurance, Management)		($190)	($195)	($200)	($205)	($210)	($215)	($220)	($226)	($231)	($237)	($243)	($249)	($256)	($262)	($268)	
Interest		($347)	($329)	($311)	($293)	($273)	($253)	($232)	($210)	($187)	($164)	($139)	($113)	($87)	($59)	($30)	
Operating Cash flow		$329	$357	$386	$416	$447	$478	$511	$544	$579	$615	$651	$689	$729	$769	$811	$3,000
Depreciation		($2,220)	($3,552)	($2,131)	($1,277)	($1,277)	($644)										
Earnings Before Taxes		($1,891)	($3,195)	($1,745)	($861)	($830)	($166)	$511	$544	$579	$615	$651	$689	$729	$769	$811	$3,000
Taxes		$510	$862	$471	$232	$224	$45	($138)	($147)	($156)	($166)	($176)	($186)	($197)	($208)	($219)	($810)
ITC	$3,900																
Principal		($433)	($450)	($468)	($487)	($507)	($527)	($548)	($570)	($593)	($616)	($641)	($667)	($693)	($721)	($750)	$0
Net Cash flow	($2,430)	$407	$769	$389	$161	$164	($4)	($175)	($172)	($170)	($168)	($165)	($163)	($161)	($160)	($158)	$5,190
Present Value of net cash flows	($2,250)	($1,901)	($1,291)	($1,005)	($895)	($792)	($794)	($889)	($975)	($1,054)	($1,126)	($1,191)	($1,252)	($1,306)	($1,357)	($1,403)	$0
IRR	#NUM!	-83%	-35%	-19%	-14%	-10%	-10%	-18%	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	8%
NPV	$0																

- Each row represents a calculated variable in eventually determining a project’s net cash flow. Adjustments can be made to alter (for example): when the cash is received; time periods; additional revenue; additional costs; cash flows from different investors; and important metrics necessary for a project.

An accompanying Excel will calculate this basic model and a more complicated financial structure (partnership-flip).

Presentation Overview

Supply Chain Data Resources

U.S. Imports, Exports, Trade Classifications, Tariffs

- U.S. International Trade Commission (USITC) DataWeb: https://dataweb.usitc.gov/
- Search Harmonized Tariff Schedules (HTS), then
- Search U.S. Energy Information Administration (EIA)

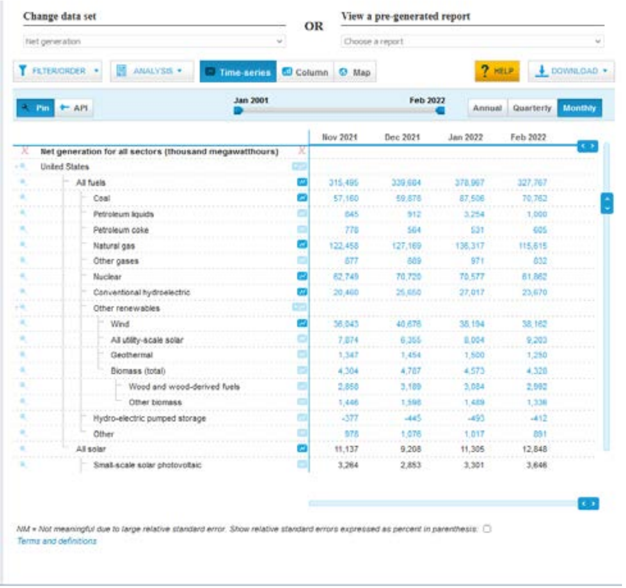
Global Imports/Exports

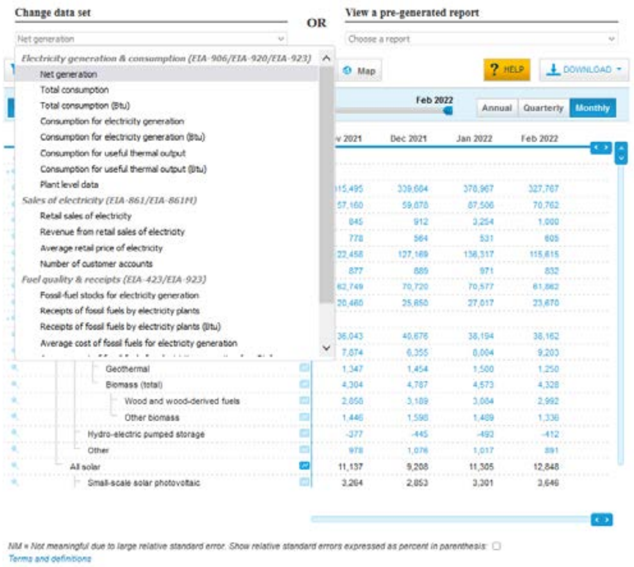
- UN Comtrade: International Trade Statistics Database: https://comtrade.un.org/

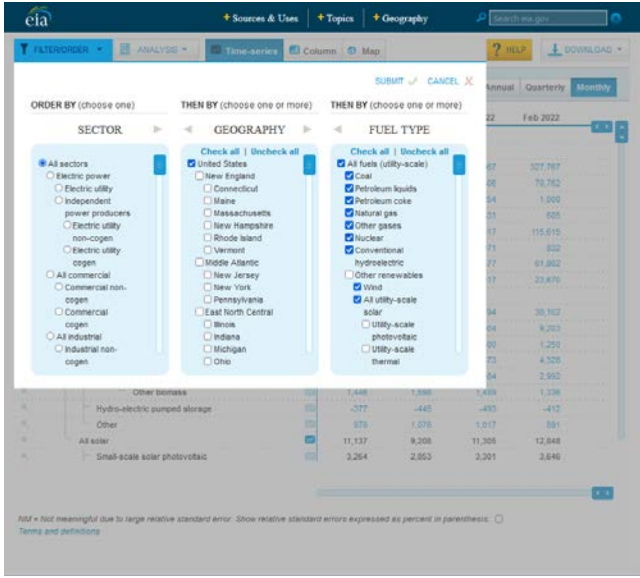
EIA Data Resources (non-exhaustive)

Source (frequency)	Information	location
Electric Power Monthly and Annual	Electricity generation and capacity by technology, by utility, sector, and state. Sales, Revenue, and Average Price of Electricity.	https://www.eia.gov/electricity/monthly/
Form 923 (monthly & annual)	Collects detailed electric power data on electricity generation, fuel consumption, fossil fuel stocks, and receipts at the power plant and prime mover level.	https://www.eia.gov/electricity/data/eia923/
Form 860 (monthly & annual)	Generator-specific information for electricity generation projects greater than 1 MW (in-service, planned, and decommissioned). Annually, there is more project specific data, such as technology type, AC/DC capacity, and more.	https://www.eia.gov/electricity/data/eia860/
Form 861 (monthly & annual)	Customer focused. Sales, revenue, and customers by utility and state. Small-scale PV capacity and generation. Customer, capacity, and energy sold back to utility of net-metered systems (including PV, storage, distributed wind).	https://www.eia.gov/electricity/data/eia861m/
Form 63B (monthly & annual)	U.S. Photovoltaic Module Shipments.	https://www.eia.gov/renewable/monthly/solar_photo/
Annual Energy Outlook / International Energy Outlook	Annual cost and deployment regional, national, and international forecasts.	https://www.eia.gov/outlooks/aeo/ https://www.eia.gov/outlooks/ieo/
Wholesale Electricity and Natural Gas Market Data (bi-weekly)	Historical market price and volume data on a selection of markets.	https://www.eia.gov/electricity/wholesale/

EIA Data Resources (data browser)

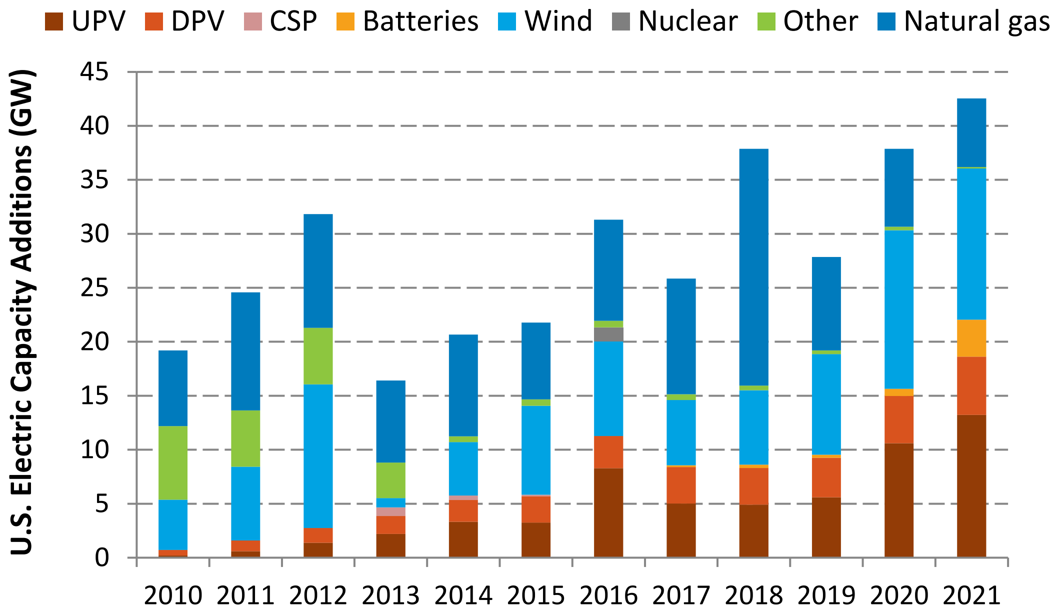






https://www.eia.gov/electricity/data/browser/

New U.S. Capacity Additions, 2010–2021



Example of EIA data

- In 2021, PV represented approximately 44% of new U.S. electric generation capacity (31% UPV, 13% DPV), compared to 4% in 2010.
  - Wind represented 33% of added capacity.
  - Since 2017, PV has represented approximately 35% of new electric generation capacity.
- Over 35 GWac of new installed capacity was either from renewable energy or battery technologies in 2021, surpassing last year's record and nearly matching the total U.S. capacity additions in 2020 and 2018.
- Combined with wind, 77% of all new capacity in 2021 came from renewable sources.
- Battery installations jumped by a factor of 5 from 2020 to 2021; it now represents 8% of capacity additions.

Note: "Other" includes coal, geothermal, landfill gas, biomass and petroleum. DPV = Distributed PV; UPV = Utility-scale PV
Sources: EIA, "Electric Power Monthly" Tables 6.1, 6.2B, 1.1, 1.1A; Forms 860M & 861M. April 2022.

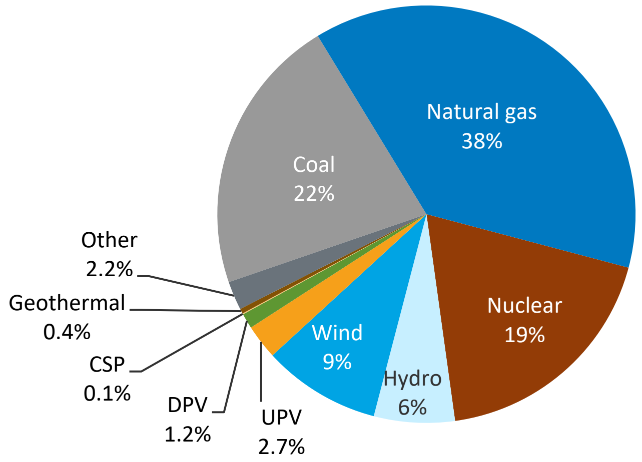
2021 U.S. Generation and Capacity

- Renewables are becoming an increasingly large part of the U.S. electric generation mix, representing 27% of capacity and 21% of generation in 2021.
  - Adding nuclear, non-carbon sources represented 35% of capacity and 40% of generation.

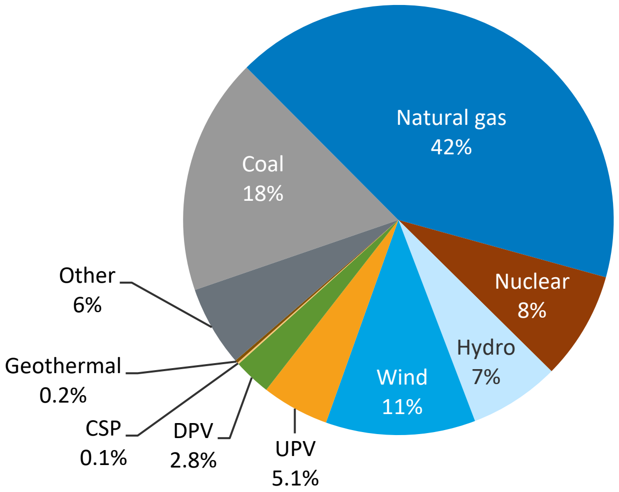
Example of EIA data

- percentag … generation mix.
  - In 2021, solar represented 8.0% of net summer capacity and 3.9% of annual generation.
- Capacity is not proportional to generation, as certain technologies (e.g., natural gas) have lower capacity factors than others (e.g., nuclear).

2021 U.S. Generation (Total 4,165 TWh)



2021 U.S. Generation Capacity (Total 1.2 TW)

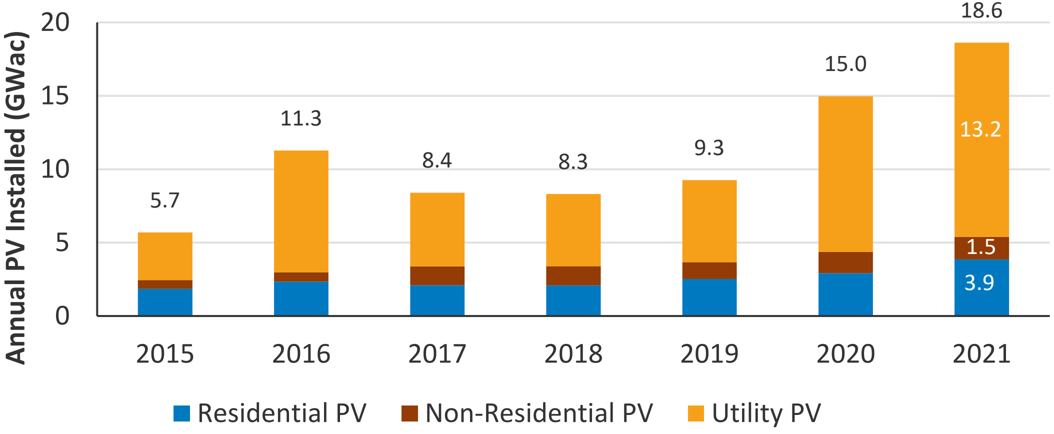


Sources: EIA, "Electric Power Monthly" Tables 6.1, 6.1A, February 2022, "Electricity Data Browser," April 5, 2022.

U.S. Installation Breakdown Annual: EIA (GWac)

- Despite the impact of the pandemic on the overall economy, the United States installed 18.6 GWac of PV in 2021, its largest total ever—up 24% y/y.
  - Residential (3.9 GWac), C&I (1.5 GWac), and utility-scale PV (13.2 GWac) were up 32%, 5%, and 25%, respectively, in 2021.

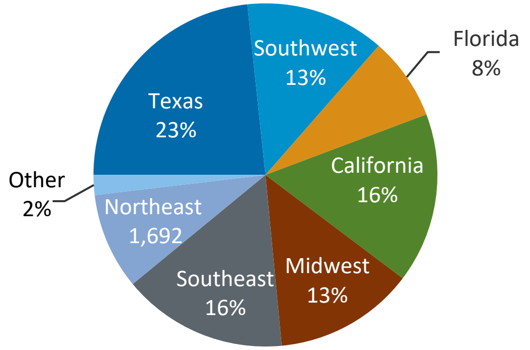
U.S. PV Installations by Market Segment



Example of EIA data

- Approxim… …pacity installed in 2021 was in Texas, Florida, and California.
- Despite a concentration of PV installations in the top three markets, diversification of growth continues across the United States.
  - 19 states had more than 1 GWac of cumulative PV installations at the end of 2021 (New Mexico and Illinois both achieved this distinction for the first time in 2021), and 25 states installed more than 100 MWac in 2021.

2021 U.S. PV Installations by Region (18.6 GWac)



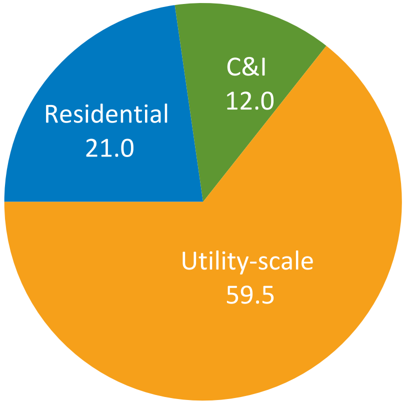
Note: EIA reports values in Wac which is standard for utilities. The solar industry has traditionally reported in Wdc. See the next slide for values reported in Wdc.
Sources: EIA, "Electric Power Monthly," forms EIA-023, EIA-826, and EIA-861 (April 2022, February 2021, February 2019).

U.S. Installation Breakdown Annual: EIA (GWac)

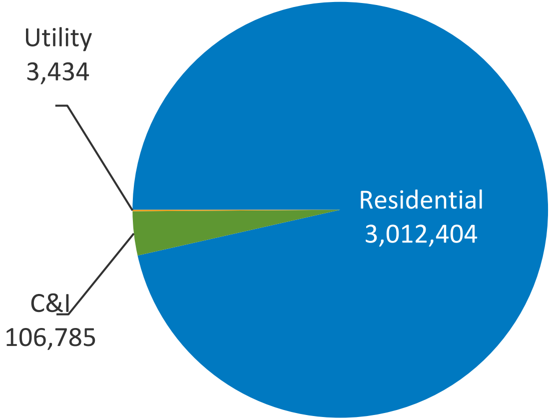
Example of EIA data

- At the end of 2021, there were 92.5 GWac of cumulative PV installations.
- EIA reports that at the end of 2021, 64% of U.S. installed PV capacity was from utility-scale PV systems.
- Despite representing only 23% of installed U.S. PV capacity at the end of 2021, 96% of PV systems—over 3 million systems—were residential applications.

Cumulative U.S. PV Installations as of December 2021 (92.5 GWac)

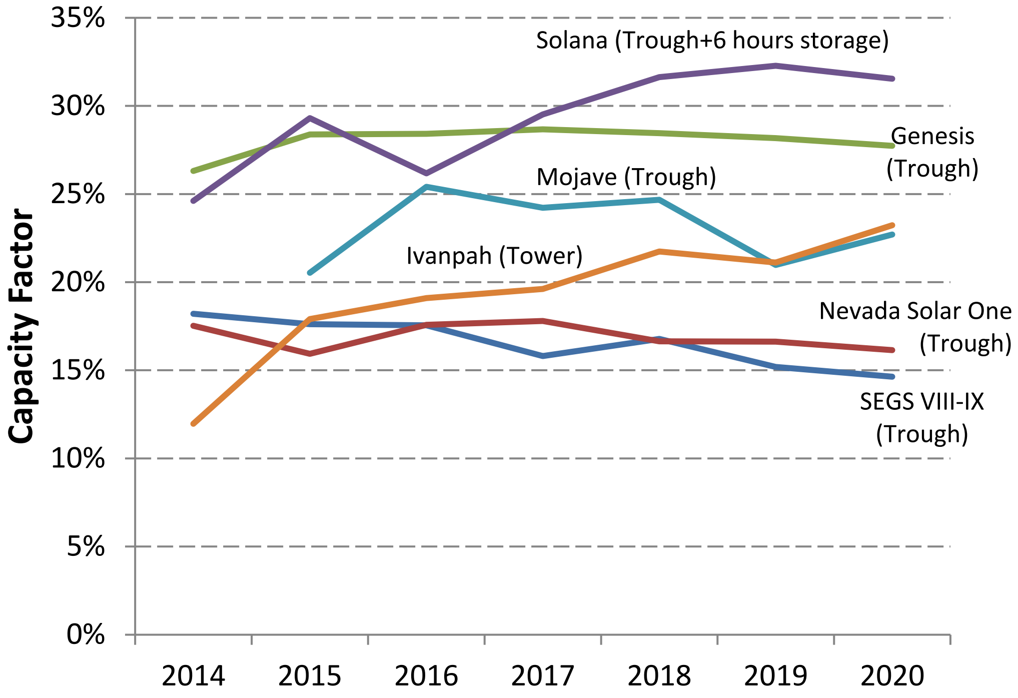


Cumulative U.S. PV Installations as of December 2021 (number)



Note: EIA reports values in Wac which is standard for utilities. The solar industry has traditionally reported in Wdc. See the next slide for values reported in Wdc.
Sources: EIA, "Electric Power Monthly," forms EIA-023, EIA-826, EIA-860, and EIA-861 (April 2022, February 2021, February 2019).

U.S. CSP Project Generation Performance, 2010–2020



Source: EIA, Form 923.

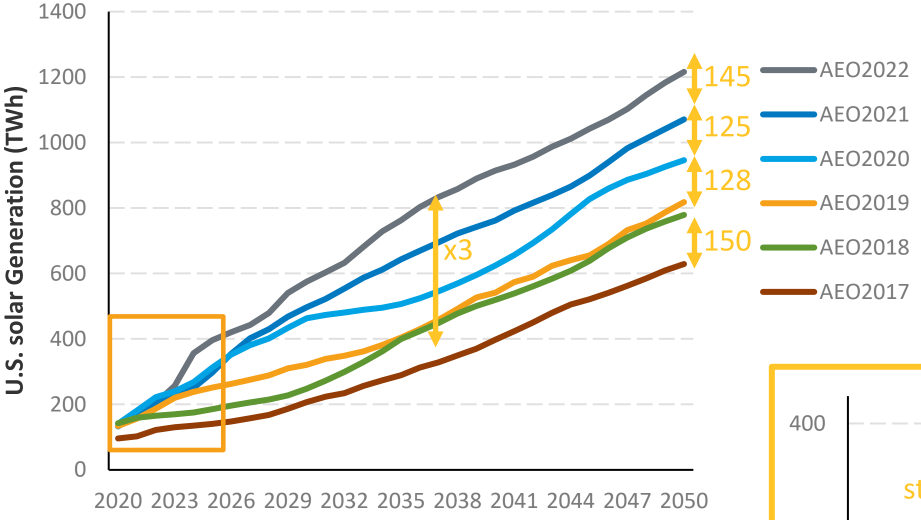
Example of EIA data

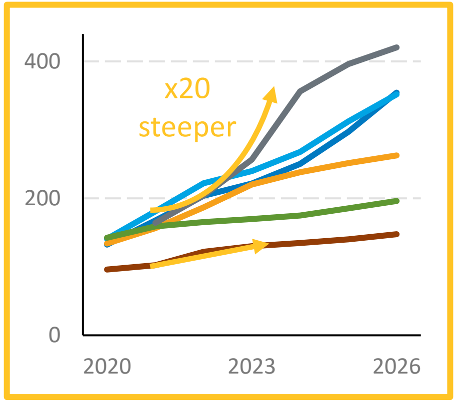
- Thou… …he operation of th… …between 2013 and 201…, four of them now generally perform better than when they began operation.
  - Annual weather variation also caused some of the differences in annual production.
- Plants with newer technology, such as towers and storage, took longer to ramp up than trough plants, which have decades of operating experience.
  - The lone U.S. tower plant with storage, Tonopah, which began operating in 2015, had consistent operating problems, and was shut down for all of 2020 after its PPA was canceled.
- Absolute capacity factor is not necessarily the best metric for performance, as plants can be designed and operated differently.
  - The capacity factors of the SEGS plants have decreased over time as the PPAs of these plants have expired and they have shifted to merchant production.

EIA Projections Over Time

Example of EIA data

- Between EIA's Annual Energy Outlook (AEO) 2017 and EIA's AEO2022, PV projections have increased significantly.
  - AEO2022 projects 145 TWh more deployment by 2050 than AEO2021, continuing a trend a of the past few years (except for AEO2018/2019 which gave similar 2050 predictions).
  - Between 2024 and 2034, projections of solar generation nearly tripled between AEO2017 and AEO2022.





  - AEO2022 projects a markedly steeper ramp (over 20x faster than that predicted in AEO2017) in solar generation from 2023 to 2024.

Sources: EIA, 2022 Annual Energy Outlook, reference case.

Presentation Overview

NREL Resources for Follow-Up

NREL Solar-TEA team website

- nrel.gov/solar/market-research-analysis/solar-cost-analysis.html

All NREL tools

- nrel.gov/research/data-tools.html

LCOE tools

- pvlcoe.nrel.gov
- sam.nrel.gov
- nrel.gov/gis/renewable-energy-potential.html
- nrel.gov/analysis/tech-lcoe.html

Other Resources

U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021 (2020 USD)

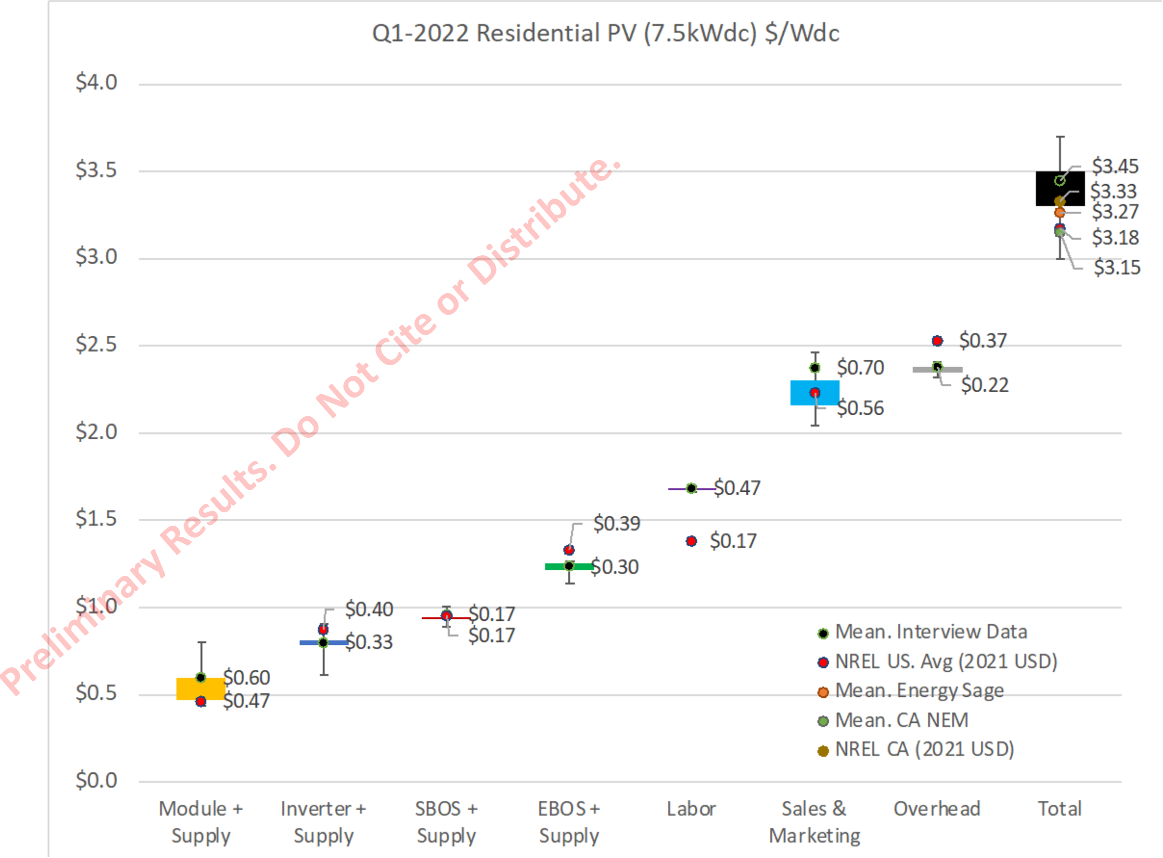
– https://www.nrel.gov/docs/fy22osti/80694.pdf

Appendix

Q1-2022 (2021 USD) Residential PV System Cost Results

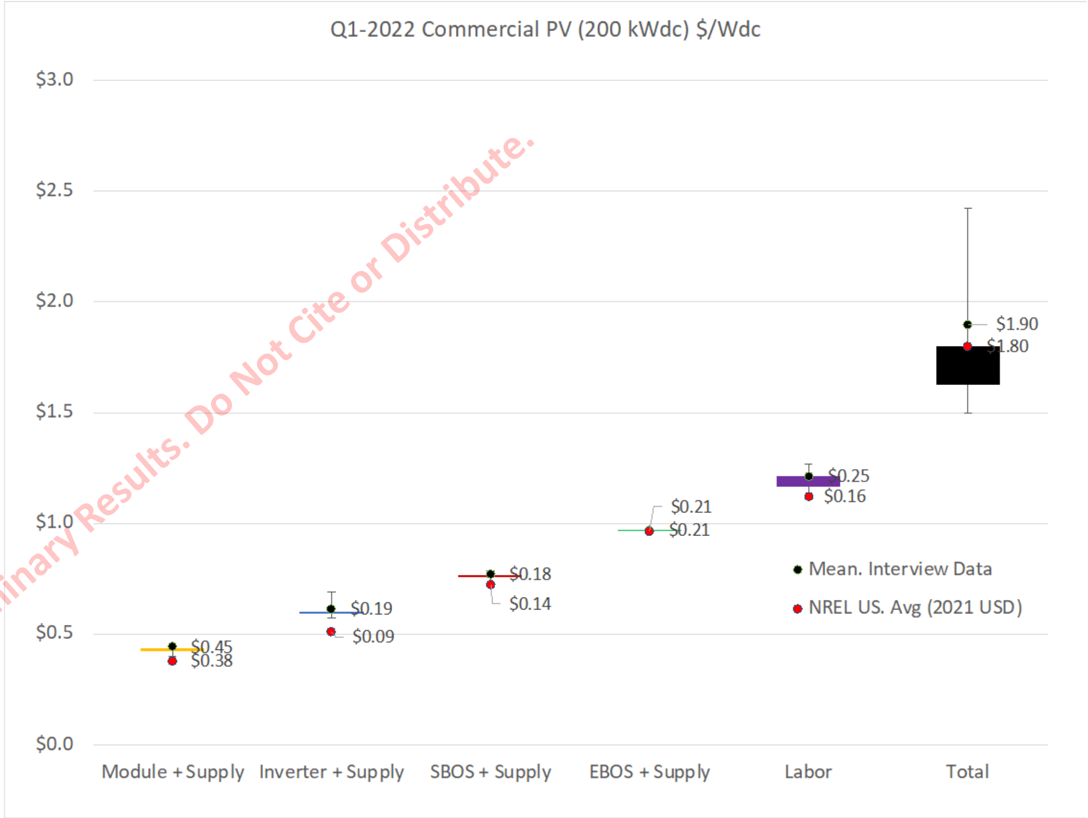
- Standard flush-mounted, pitched-roof racking system.
- Module – Imported outside USA
- Inverter Type - Micro Inverter
- Installer Type – Small Installers
- Module Supply Chain – 41% (Inventory, Shipping/Handling, Procurement)
- Inverter Supply Chain – 20%
- BOS Supply Chain – 15%
- Profit – 17%

$/Wdc (Q1-2022)	Mean	Median
Industry data	$ 3.45	$ 3.50
Energy Sage	$ 3.27	$ 2.80
CA NEM	$ 3.15	$ 3.52



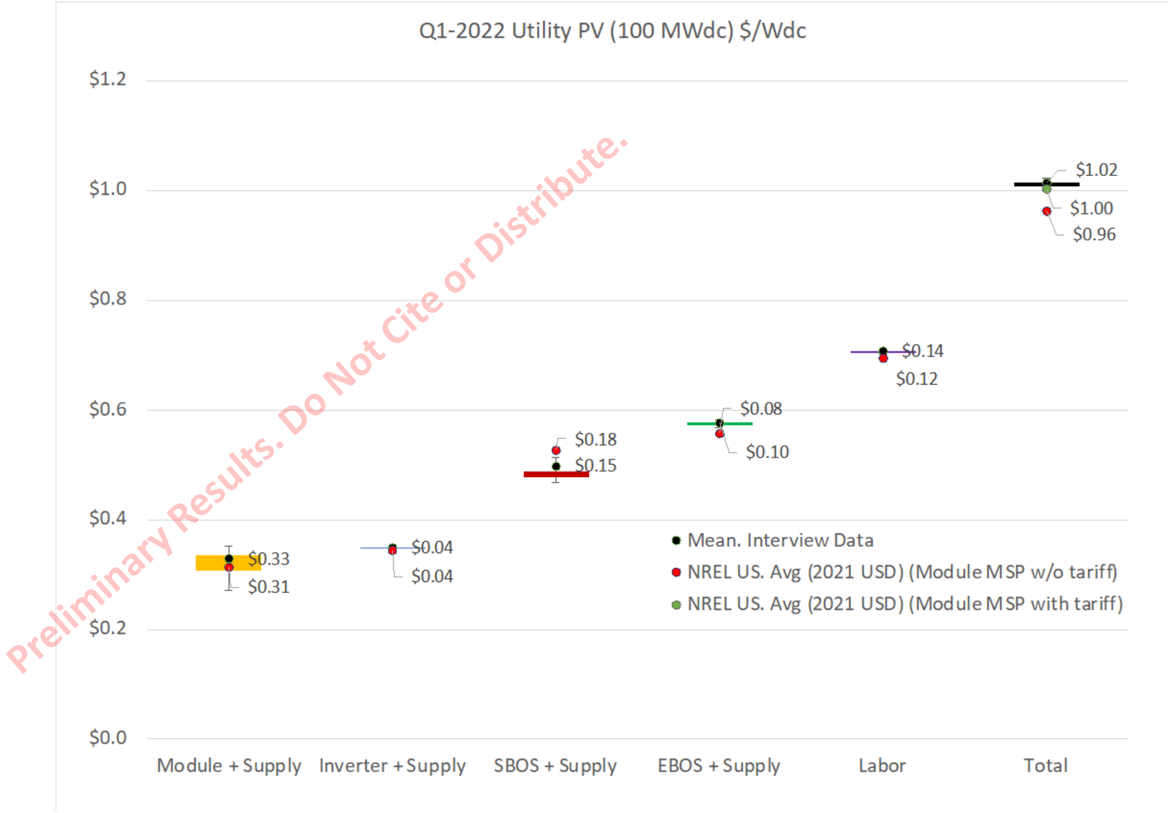
Q1-2022 (2021 USD) Commercial PV System Cost Results

- 200-kW, 1,000-volt DC (VDC), commercial-scale flat-roof system
- Ballasted Racking
- 21% module supply premium to module cost.
- EPC Overhead – 13% (Assumes overhead expenses on materials and equipment rental)
- Developer Overhead – 30% (Assumes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions)
- Profit – 7%



Q1-2022 (2021 USD) Utility PV System Cost Results

- 100-MWDC, 1,500-VDC utility-scale PV one-axis tracking system.
- EPC Overhead – 8.7% (Assumes overhead expenses on materials and equipment rental)
- Developer Overhead – 2% (Assumes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions)
- Profit – 5%



Utility and Commercial Ground Mount PV BOS Cost Components

Preconstruction Surveys	Staging
Access Roads and Parking	
Security Fencing	
Temporary Office	
Storage Box	
O & M Building	
Site Preparation (Geotechnical Investigation)	Site Preparation
Site Preparation (Clearing and Grubbing)	
Site Preparation (Soil Stripping and stockpiling)	
Site Preparation (Grading)	
Site Preparation (Compaction)	
Foundation for /inverter/transformer/ PVSC	Structural Work
Trenches	
Foundation for Vertical Support	
Horizontal Support Structures	
Welding or Bolting	
Modules Mounting	
T- Connection	
U-Joint & Driveline	Tracker
Slave Gearbox	
Motor & Controller Equipment	
Conduit, Wiring	DC Work
Grounding, DC Cable	
Junction/Combiner Boxes	
Inverter House	AC Work
On-site Transmission	
PV Combining Switchgear (PVCS)	
On-site transformer & Substation	
Site Preparation (Clearing and Grubbing)	230 kV Transmission line (4 miles): Tower
Tower: Foundation Installation	
Tower: Structure Costs	
Tower: Top Assembly	
Conductor and Cable	
Misc. Assembly Units	
Site Preparation (Clearing and Grubbing)	35 kV Distribution line (1 miles): Wood Pole
Wood Pole: Foundation Installation	
Wood Pole: Structure Costs	
Wood Pole: Top Assembly	
Conductor and Cable	
Misc. Assembly Units	

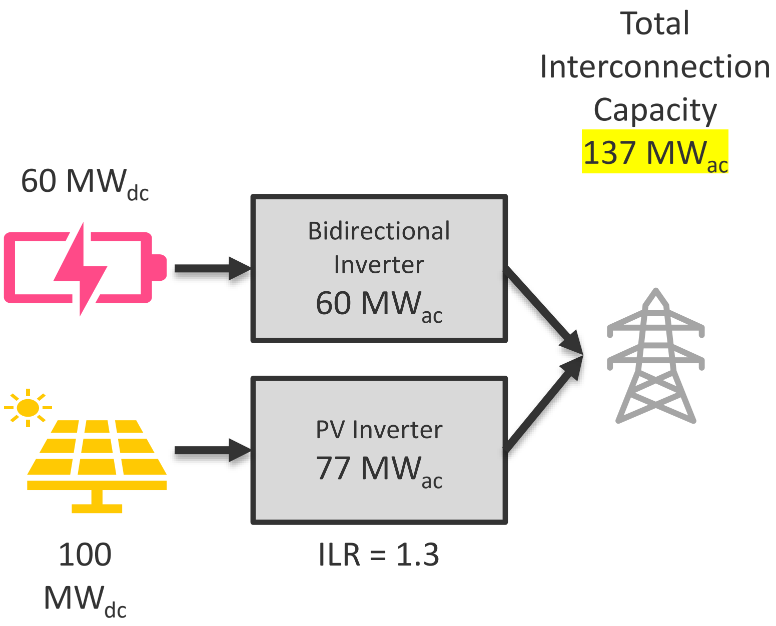
Utility and Commercial BESS BOS Cost Components

Battery Cabinet – Battery Pack, Container (including BMS), Thermal Management, Fire Suppression

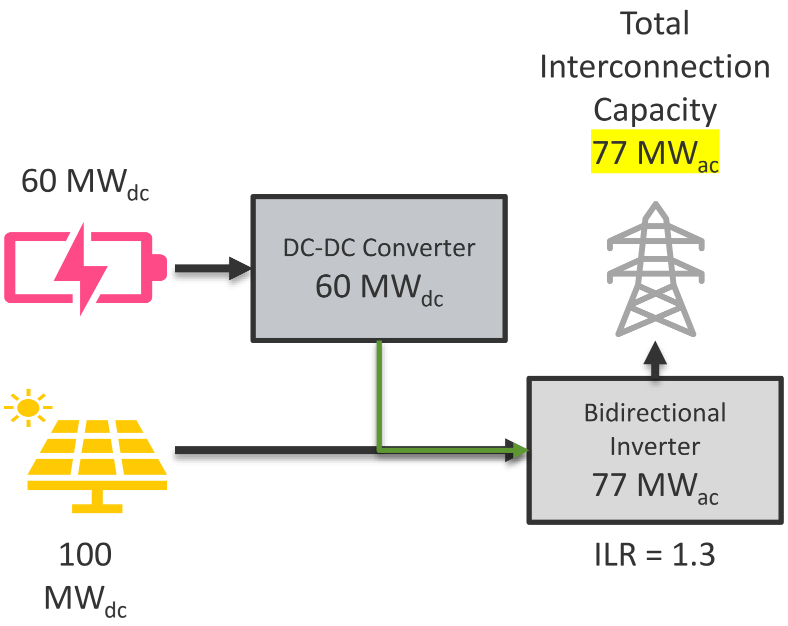
Foundation for battery/inverter/transformer	SBOS
Add battery modules into battery racks	
Bidirectional Inverter House	
Conduit, Wiring	EBOS
DC Cable	
Bidirectional Inverter House	
Energy Management System	
Switchgear	
1,000 kVA transformer	
Monitors, controls, and communication	

Q1 2021 Utility AC- and DC-Coupled Battery Energy Storage System (BESS) Configurations

AC-coupled system



DC-coupled system



**Commercial PV plus battery systems follow a similar schematic*


Thank You
NREL
Transforming ENERGY

Legal Disclaimers and Funding Statements

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding for this work was provided by U.S. Department of Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.