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NATIONAL RENEWABLE ENERGY LABORATORY | 1977 – 2017





Solar System Modeling at NREL

Solar Power International 2018

Nick DiOrio

September 24, 2018

NREL/PR-6A20-72547

NREL at a Glance

1,700 Employees, plus more than **400** early-career researchers and visiting scientists

World-class facilities, renowned technology experts

nearly 750 **Partnerships** with industry, academia, and government

Campus operates as a living laboratory

$872M annually **National economic impact**

’s Science Drives
ation

Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

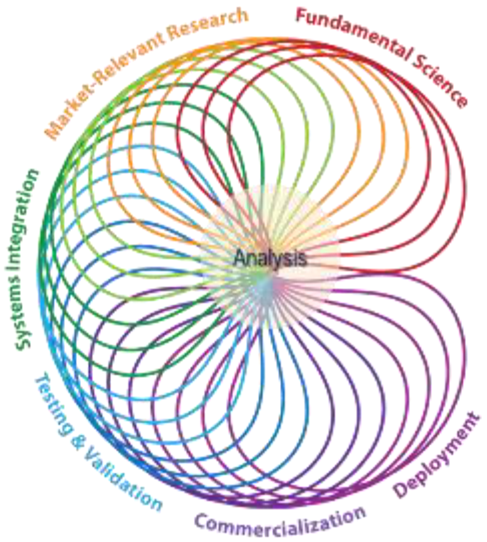
Government Energy Management

Energy Systems Integration

High-Performance Computing

Data and Visualizations

Partnerships are key

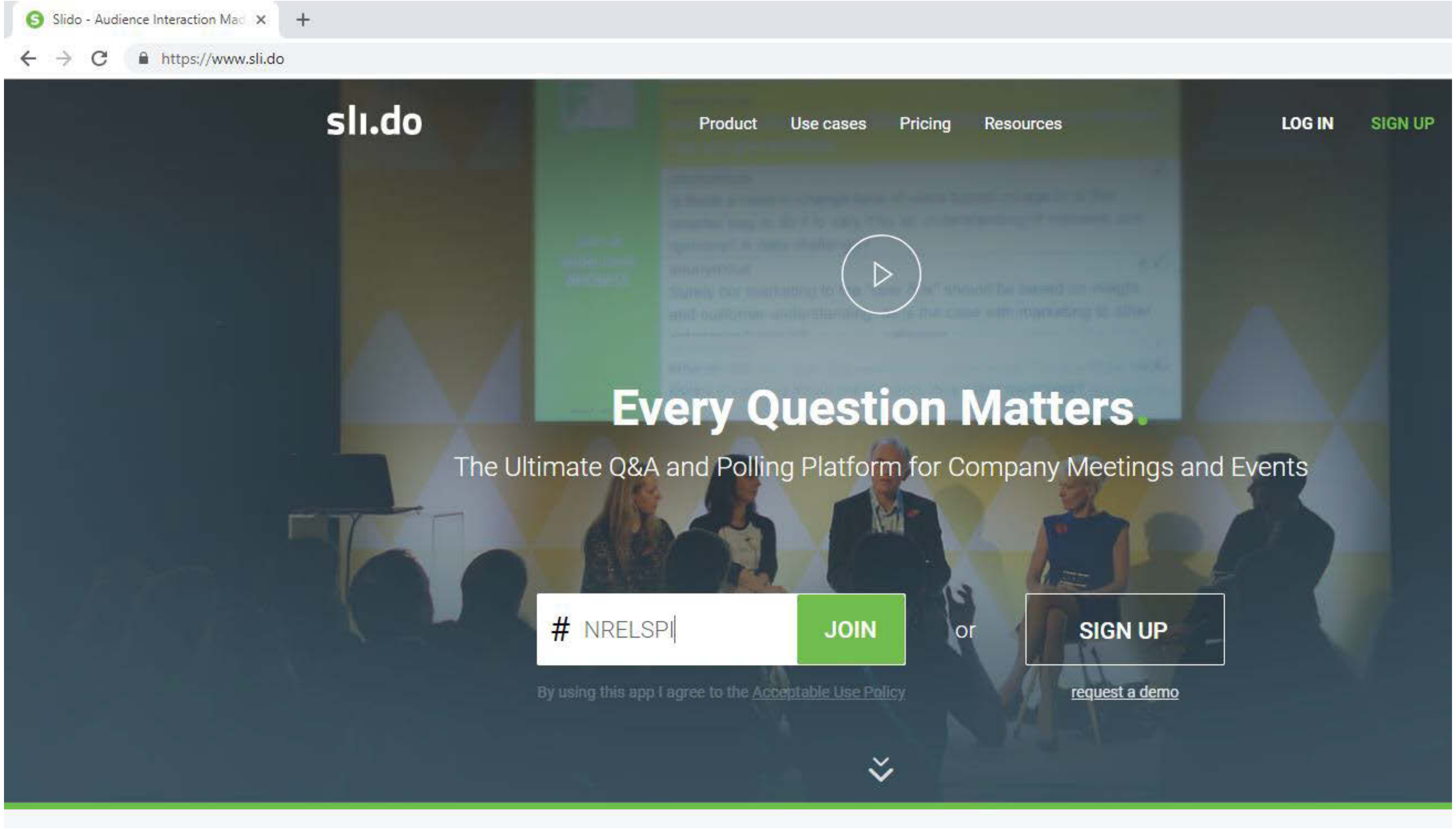


Leveraging Knowledge and Knowhow to Address Energy Challenges

Workshop agenda

8:00	Workshop introduction	Nick DiOrio (NREL)
8:10	Introduction to NREL tools and data	Nate Blair (NREL)
8:25	PVWatts – Overview and demo	Janine Freeman (NREL)
8:45	National Solar Radiation Database (NSRDB)	Aron Habte (NREL)
9:15	REopt Lite Introduction	Nick DiOrio (NREL)
9:25	RdTools	Nick DiOrio (NREL)
9:55	**Break**	
10:10	SAM bifacial and battery modeling	Nick DiOrio (NREL)
11:10	Additional NREL tools	Nate Blair (NREL)
11:40	American-Made Challenge Solar Price	Debbie Brodt-Giles (NREL)
11:45	Questions and break out	

Questions



www.sli.do #NRELSPI

Overview of NREL Solar Data and Tools

Nate Blair

Group Manager

Range of Solar Tools

Community Solar Scenario Tool

Scenario Jedi

Policy Application

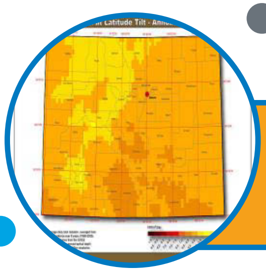
PV Watts

System Advisor Model

Analysis

NSRDB

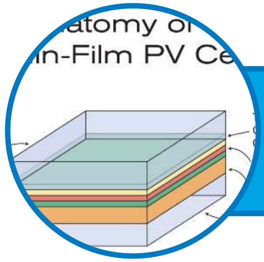
RE Atlas



Maps/Data

RDTools

Cell Models



Engineering Tools

Types of Questions

- Data – cost comparisons between technologies
- Data – How good is the resource?
- Analysis – How much will PV produce here?
- Analysis – what's the impact of energy efficiency option for my house?
- Policy – How many jobs will this project create?

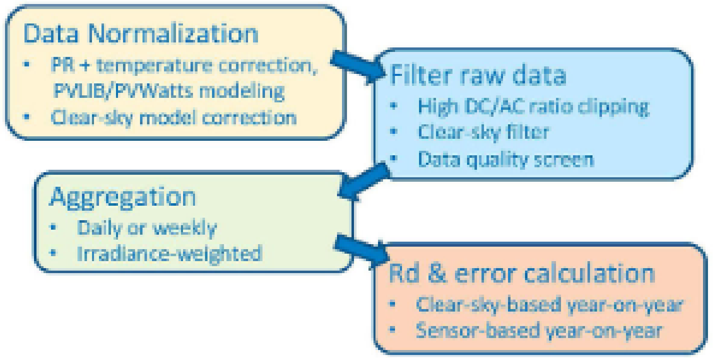
Engineering Model Example

Accurate Degradation Rate Calculation with RdTools

Tool enables accurate time-series photovoltaic data and new insights into technology performance.

RdTools is a set of Python scripts and software for analysis of photovoltaic time-series data. The open-source tools were developed in collaboration with industry to bring together best practices and years of degradation research from NREL. Although the toolkit can be used for many useful PV analysis purposes, the primary use is to evaluate degradation rates over time.

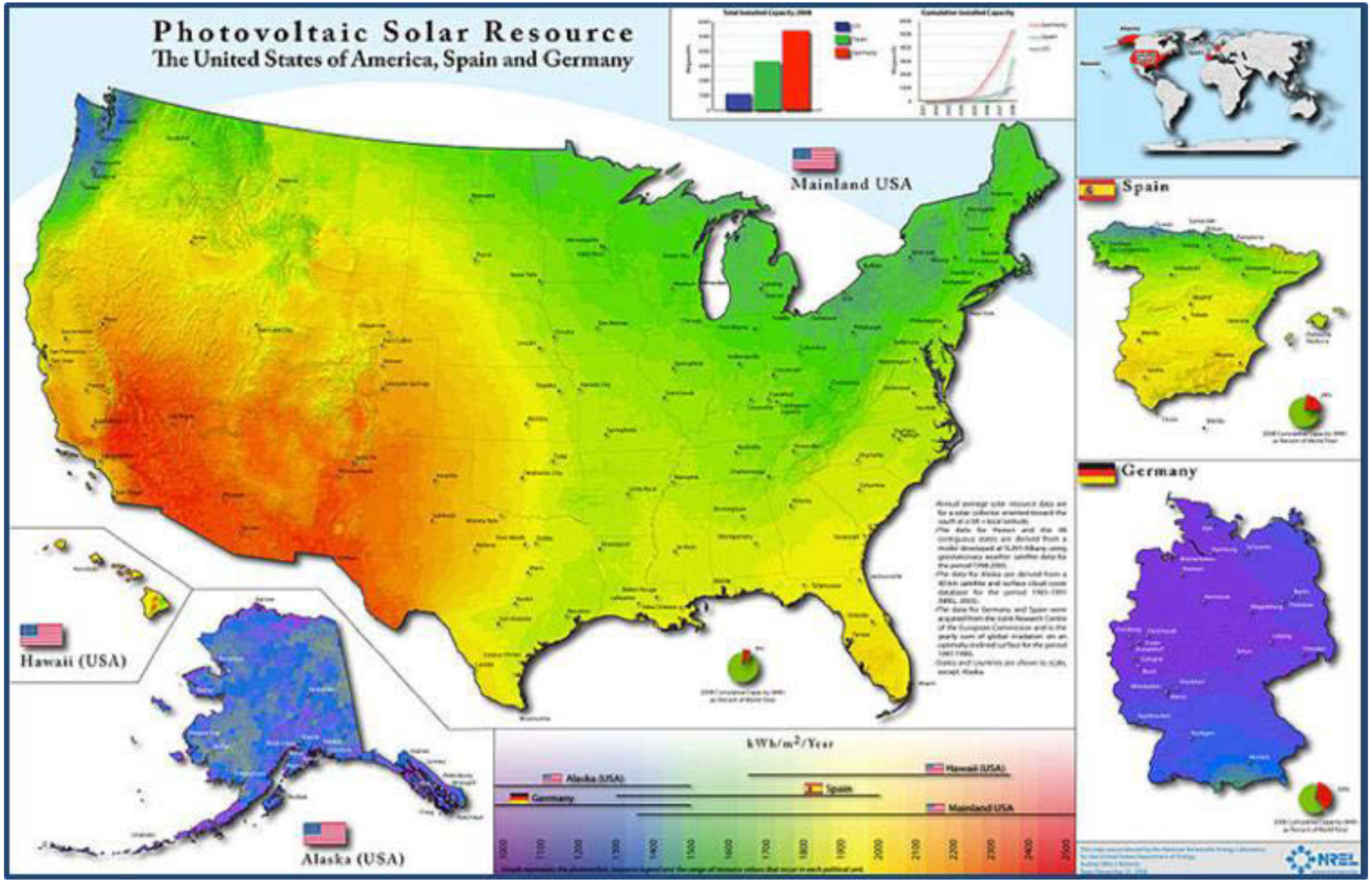
The software can be accessed from the GitHub repo with installation instructions and usage examples provided.



RdTools workflow involves four major steps: Data Normalization, Data Filtering, Aggregation and Degradation rate calculation.

https://www.nrel.gov/pv/rdtools.html

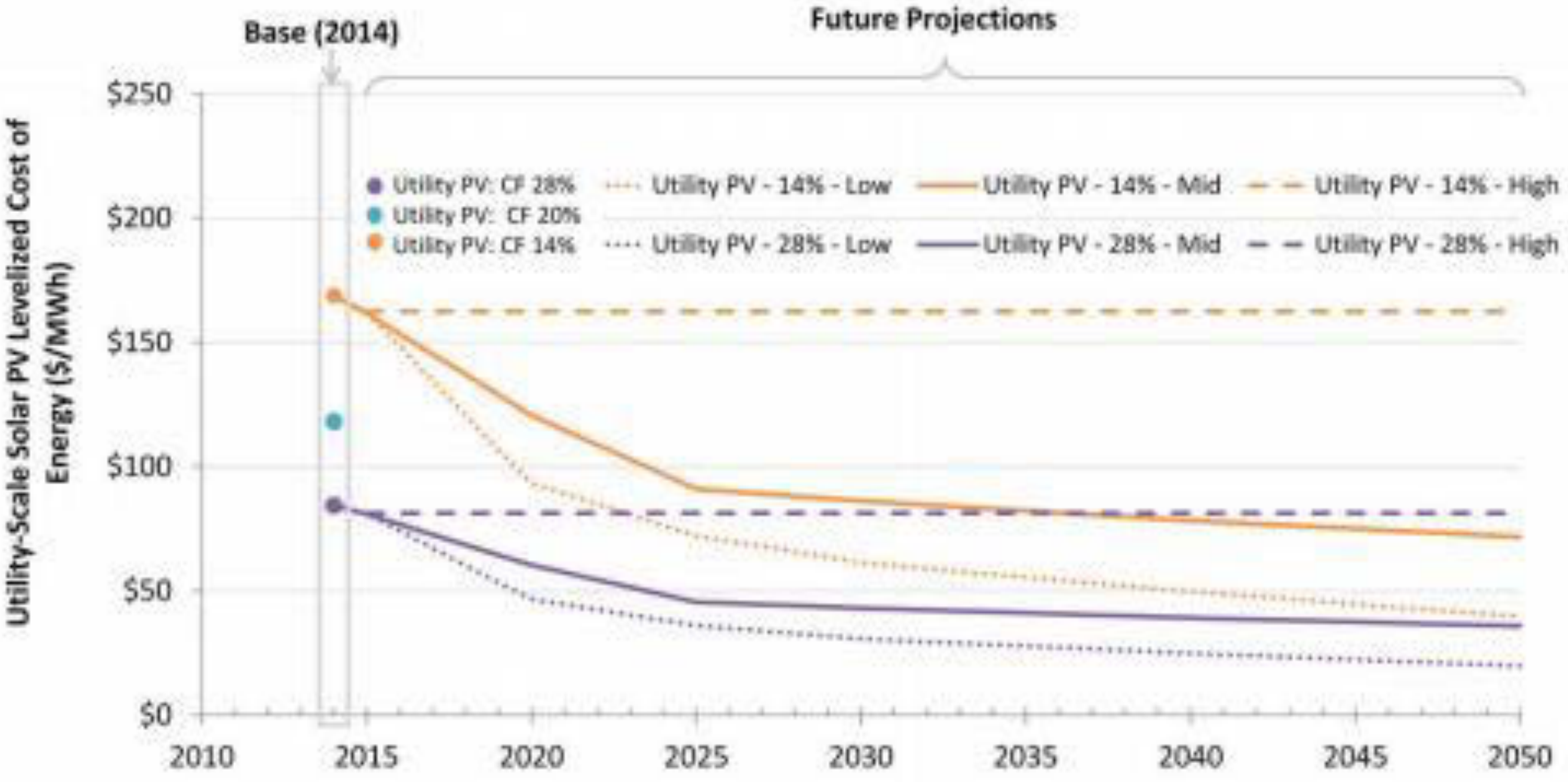
GIS Mapping: Advanced Cartography



http://www.nrel.gov/gis/

Annual Technology Baseline (Solar PV example)

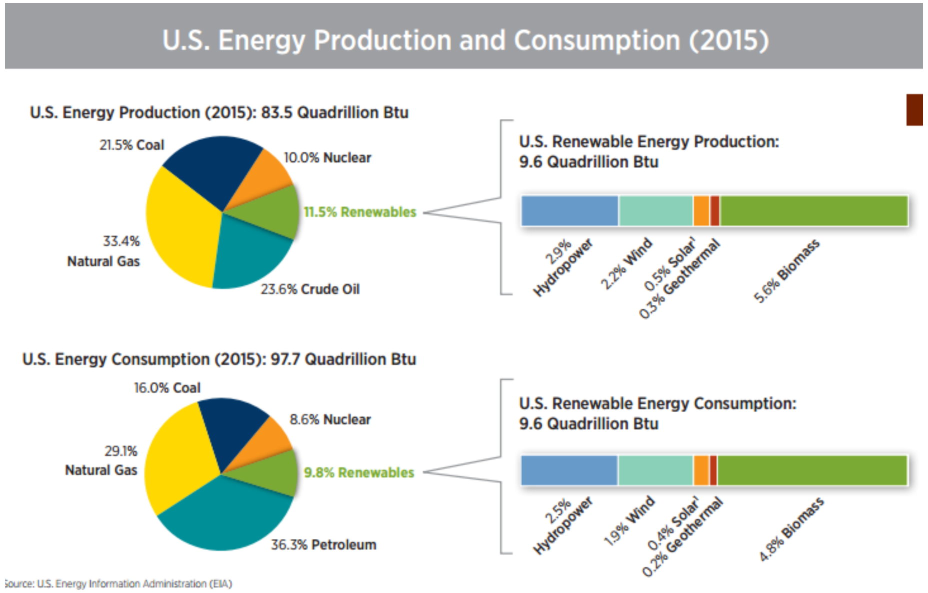
http://www.nrel.gov/analysis/data_tech_baseline.html



- In general, the degree of adoption of a range of technology innovations distinguishes between the low, mid and high cost cases.
- The range of LCOE in 2050 associated with variation in solar resource across the U.S. is reduced from $81-163/MWh for High Cost to $20-40/MWh for Low Cost reduction scenarios.

Renewable Energy Data Book

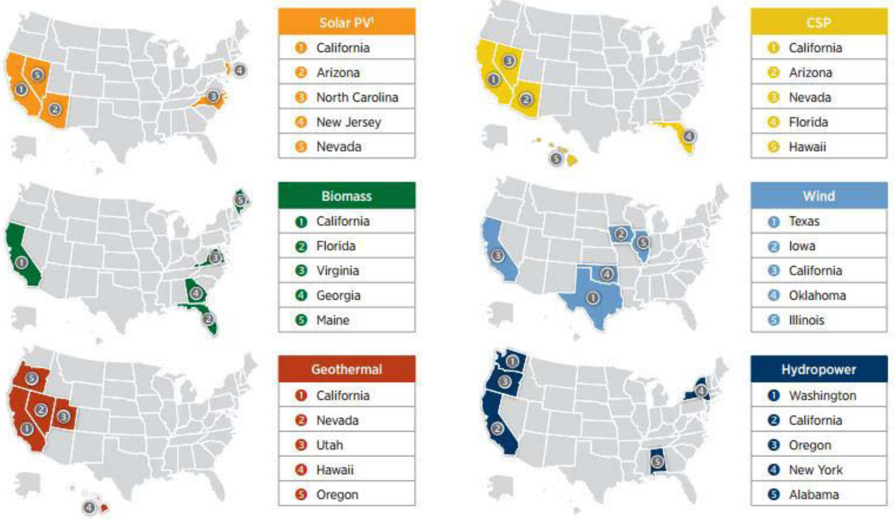
http://www.nrel.gov/docs/fy17osti/66591.pdf



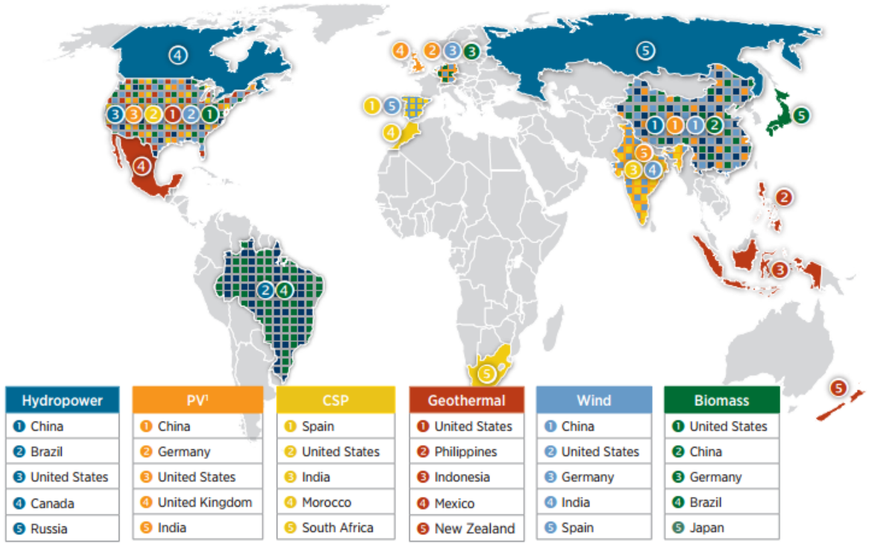
U.S. RE Capacity as % of Total Generating Capacity

	Hydropower	Solar PV[1]	CSP	Wind	Geothermal	Biomass	Total Renewables
2005	7.4%	0.0%	0.0%	0.9%	0.3%	1.1%	9.7%
2006	7.3%	0.0%	0.0%	1.1%	0.3%	1.1%	9.9%
2007	7.3%	0.0%	0.0%	1.6%	0.3%	1.1%	10.3%
2008	7.2%	0.1%	0.0%	2.3%	0.3%	1.2%	11.1%
2009	7.1%	0.1%	0.0%	3.2%	0.3%	1.2%	11.9%
2010	7.0%	0.1%	0.0%	3.6%	0.3%	1.2%	12.2%
2011	6.9%	0.3%	0.0%	4.1%	0.3%	1.2%	12.8%
2012	6.8%	0.5%	0.0%	5.2%	0.3%	1.2%	14.1%
2013	6.8%	0.8%	0.1%	5.3%	0.3%	1.3%	14.6%
2014	6.8%	1.2%	0.1%	5.7%	0.3%	1.3%	15.5%
2015	6.8%	1.7%	0.2%	6.4%	0.3%	1.4%	16.7%

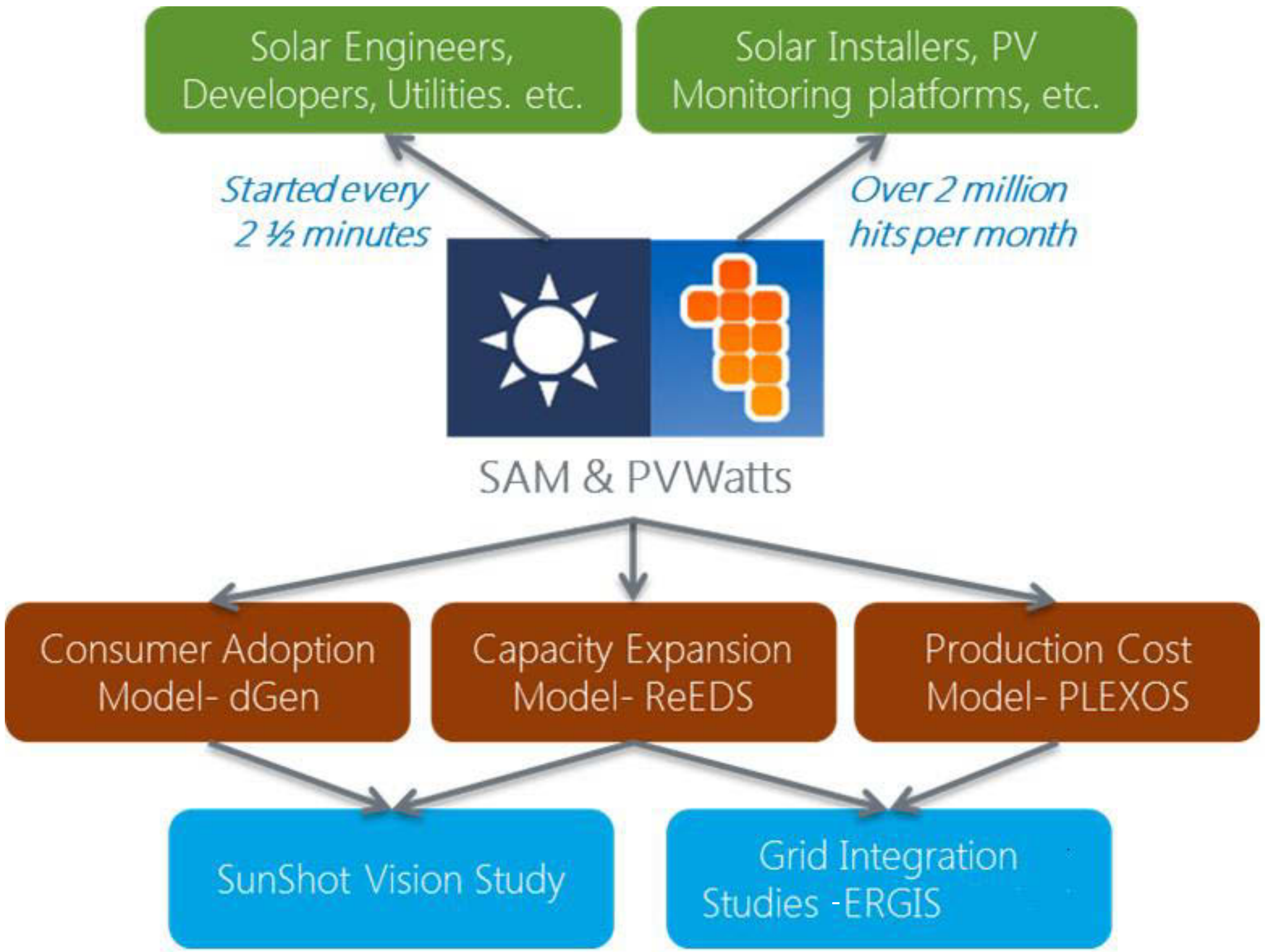
Top States for RE Installed Capacity (2015)



Top Countries for Installed Renewable Generation (2015)



Foundational PV + Battery + Financial Modeling



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JEDI PV – Jobs and Economic Development

- **NOTE: JEDI models exist for wind, biofuels, Solar CSP, Coal, Hydropower, Geothermal, Marine Hydrokinetic, Petroleum, Transmission as well as PV**
- **PURPOSE:** Estimate the economic impacts of constructing and operating photovoltaic power generation at the local and state levels.
- **TYPE:** Spreadsheet-based impact model (PV has a web version as well)
- **TAKEAWAY:** Economic impacts for one, or, a portfolio of projects
- **CONTACT:** JEDISupport@nrel.gov

Local Economic Impacts - Summary Results

During construction and installation period	Jobs	Earnings ($000 (2010))
Project Development and Onsite Labor Impacts [?]		
Construction and Installation Labor	4.2	$275.11
Construction and Installation Related Services [?]	6.7	$313.85
Subtotal	11.0	$588.97

http://www.nrel.gov/analysis/jedi/download.html

NATIONAL RENEWABLE ENERGY LABORATORY

1977 – 2017

PVWatts

Solar Power International 2018

Janine Freeman

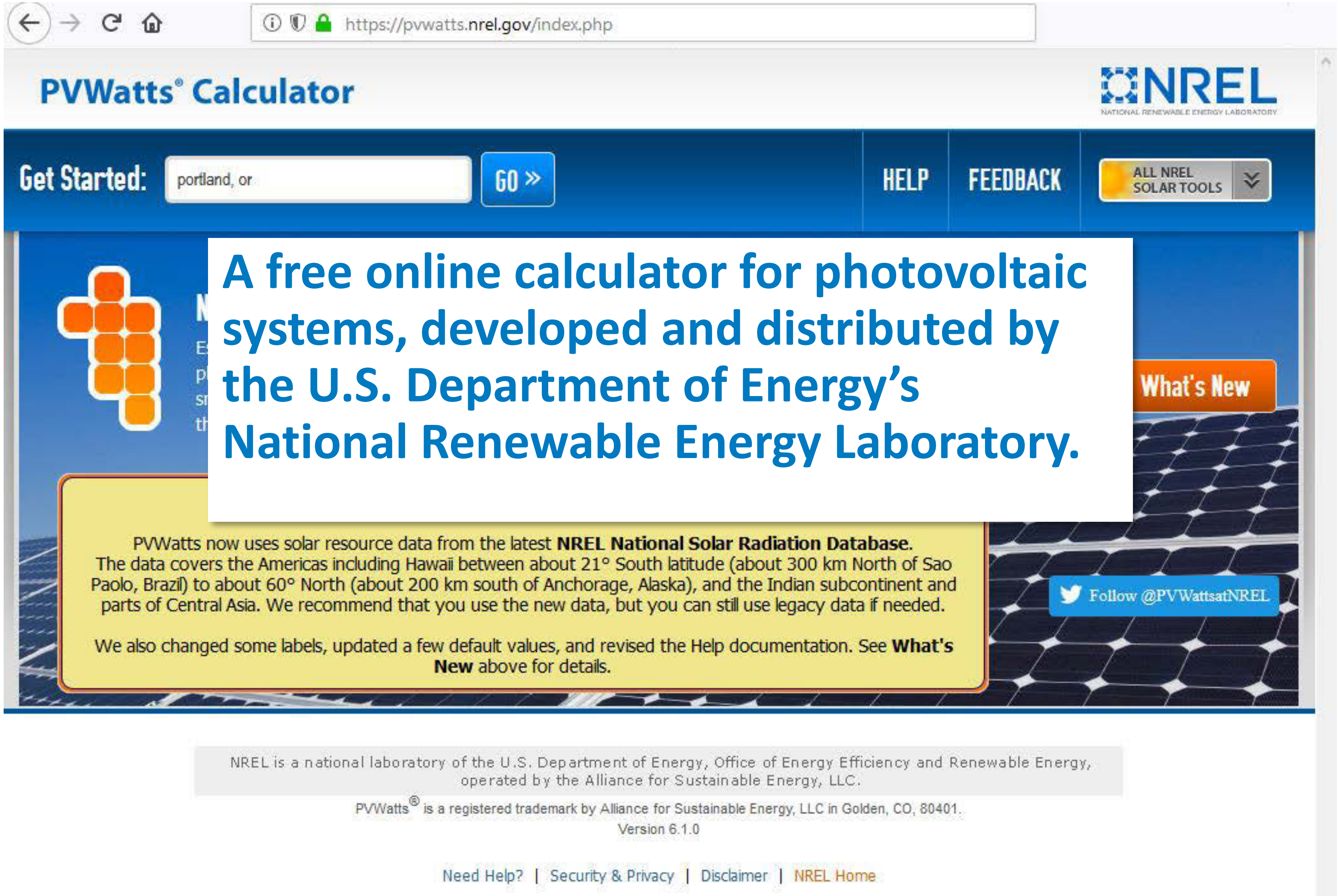
September 24, 2018

Outline

- What is PVWatts?
- How can I access PVWatts?
- Live demonstration
- Questions

What is PVWatts?

What is PVWatts?

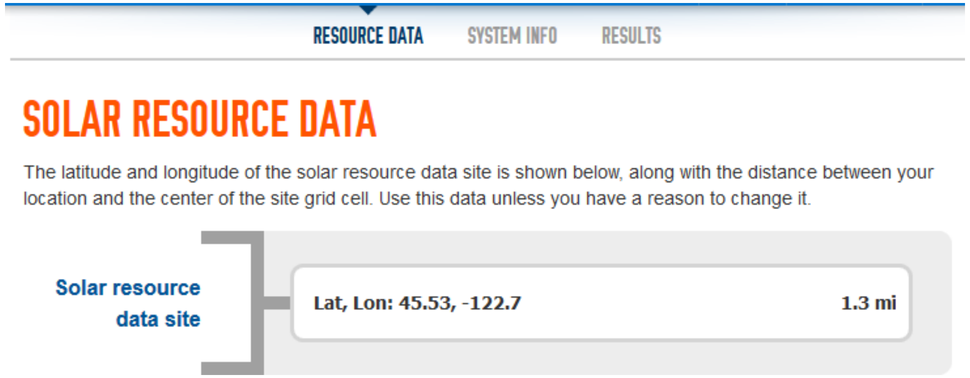


A free online calculator for photovoltaic systems, developed and distributed by the U.S. Department of Energy's National Renewable Energy Laboratory.

Simply put…

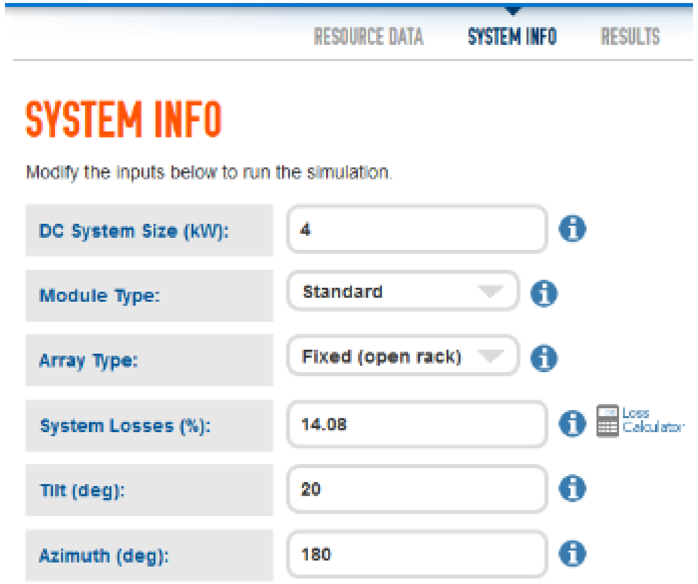
What is PVWatts?

PVWatts requires a few simple inputs to describe the location…



What is PVWatts?

and the system…



What is PVWatts?

to estimate the monthly and annual electrical output of a photovoltaic system.

RESOURCE DATA SYSTEM INFO **RESULTS**

RESULTS

Print Results

4,503 kWh/Year*

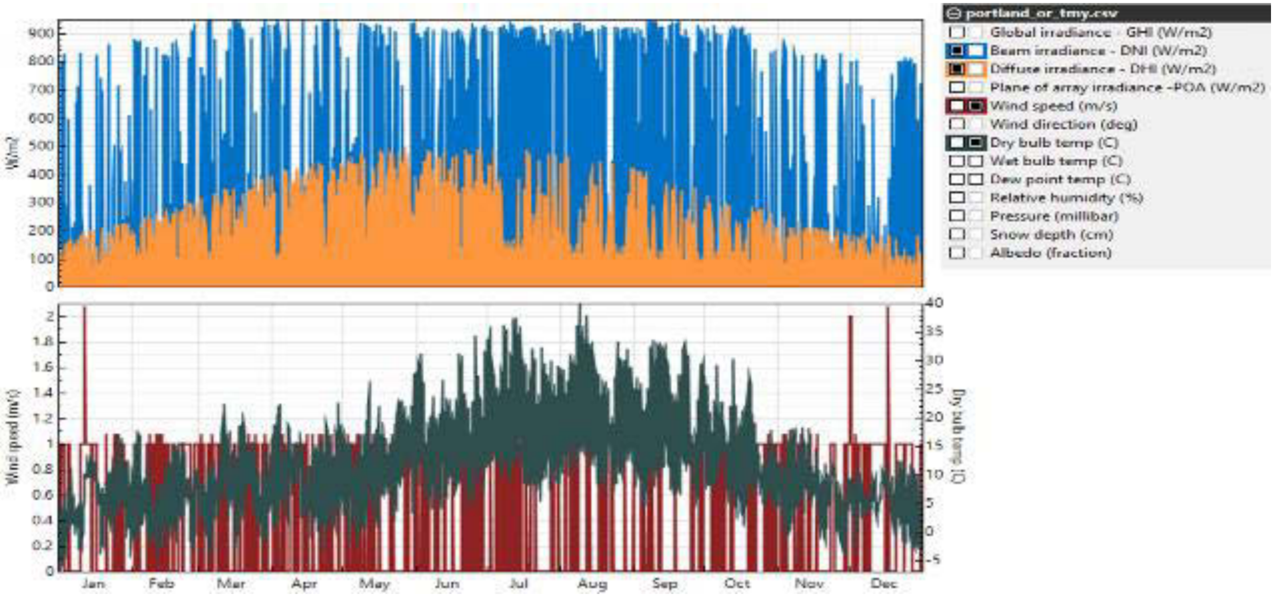
System output may range from 4,220 to 4,743 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	1.48	151	16
February	2.86	260	28
March	3.35	334	36
April	4.85	446	48
May	5.48	519	56
June	5.90	526	56
July	7.04	614	66
August	6.42	570	61
September	5.21	454	49
October	3.18	305	33
November	1.88	179	19
December	1.41	145	15
Annual	4.09	4,503	$ 483

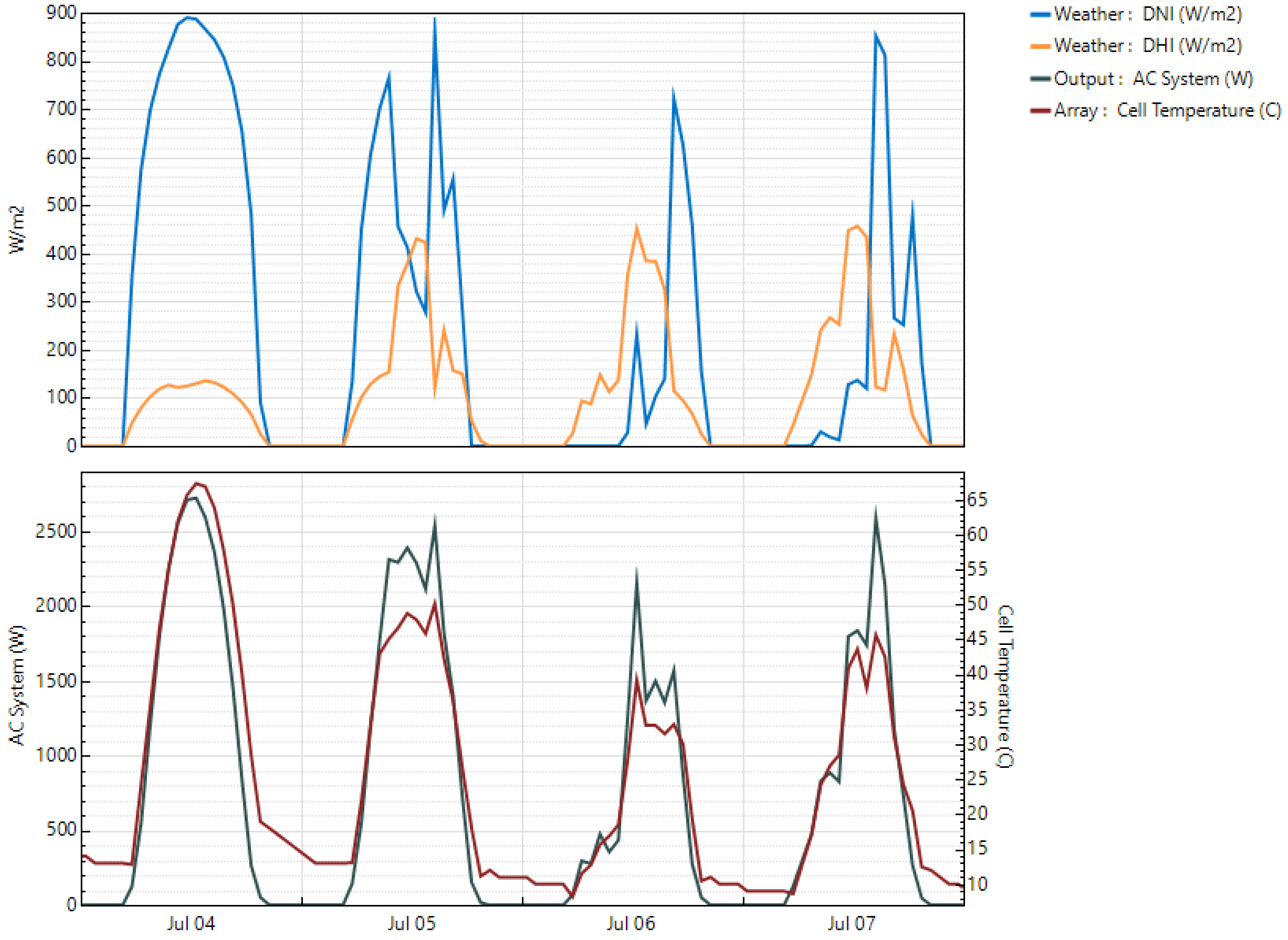
A little more detail…

What is PVWatts?

- Production estimates are based on an hour-by-hour simulation for one full year.
- Estimates account for solar irradiance, cell temperature, module cover optical characteristics.
- Other effect
  System Loss

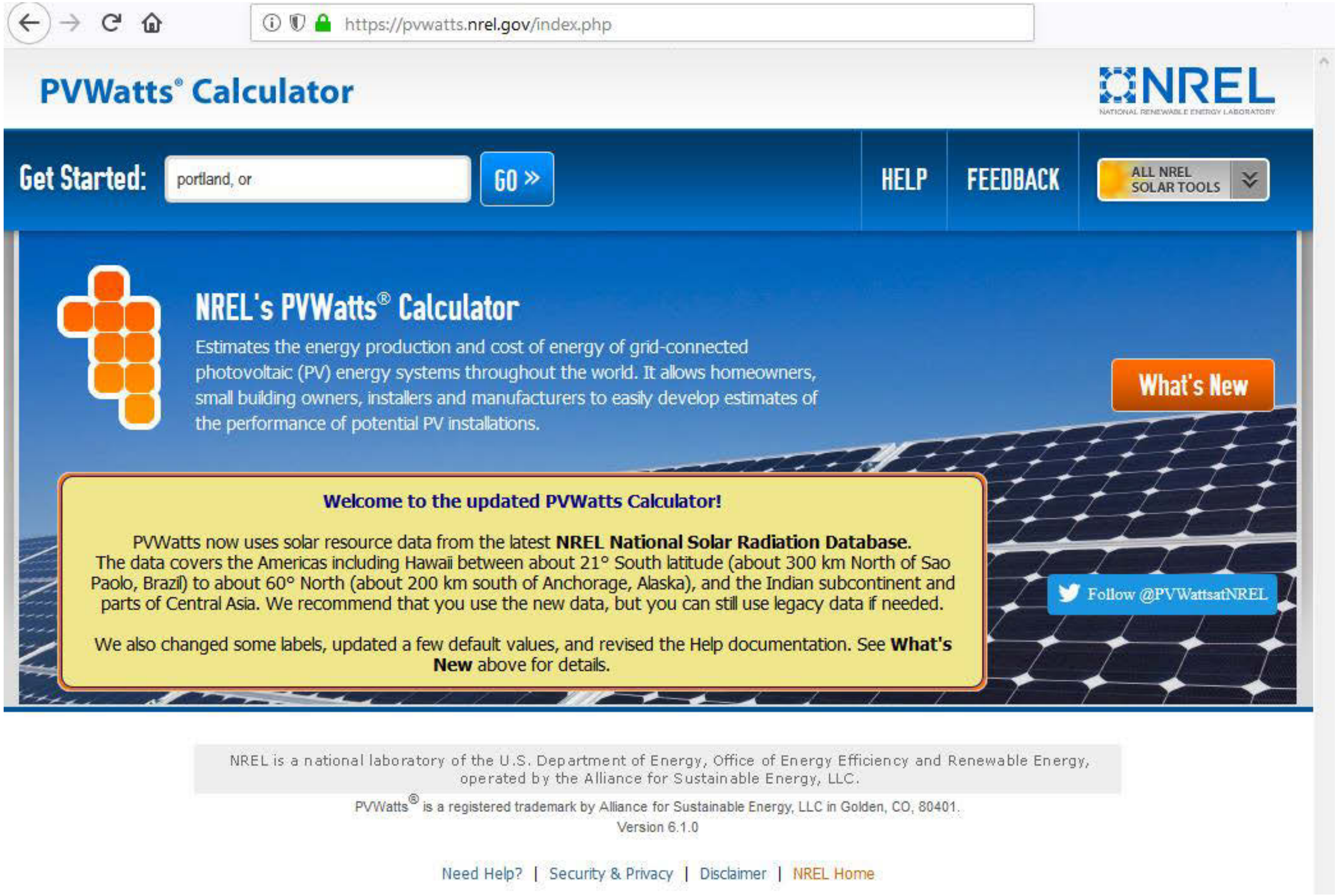


Hourly outputs include array DC output, system AC outputs, and cell temperature.

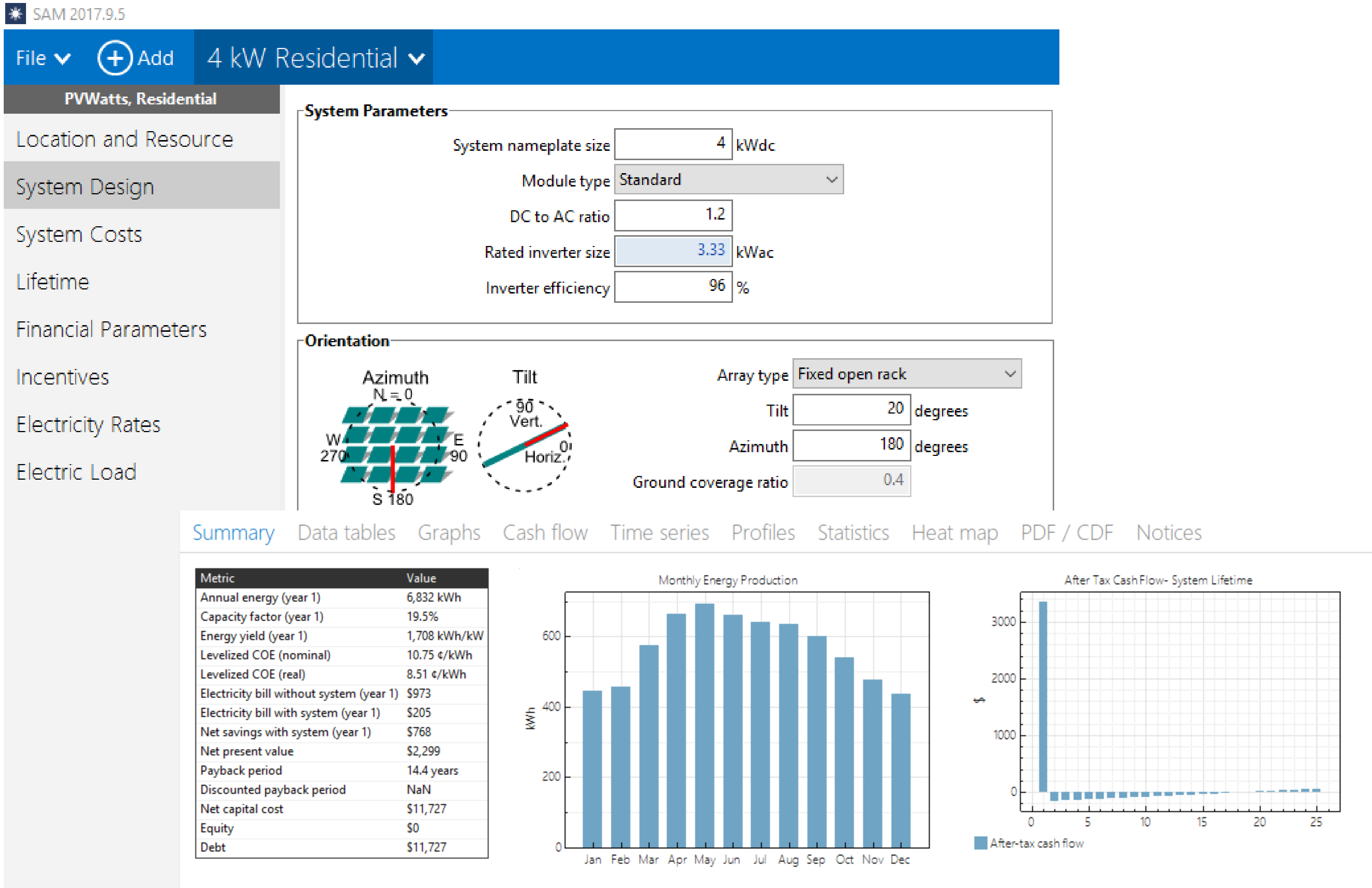


How to Access PVWatts?

https://pvwatts.nrel.gov



System Advisor Model for cost and financial analysis: https://sam.nrel.gov



Metric	Value
Annual energy (year 1)	6,832 kWh
Capacity factor (year 1)	19.5%
Energy yield (year 1)	1,708 kWh/kW
Levelized COE (nominal)	10.75 ¢/kWh
Levelized COE (real)	8.51 ¢/kWh
Electricity bill without system (year 1)	$973
Electricity bill with system (year 1)	$205
Net savings with system (year 1)	$768
Net present value	$2,299
Payback period	14.4 years
Discounted payback period	NaN
Net capital cost	$11,727
Equity	$0
Debt	$11,727

API for web service on developer.nrel.gov

https://developer.nrel.gov/docs/solar/pvwatts/v6/

Developer Network — NREL National Renewable Energy Laboratory

HOME | DOCUMENTATION | COMMUNITY

Documentation » Solar » PVWatts » PVWatts V6

PVWatts V6 (GET /api/pvwatts/v6)

PVWatts Version 6 is an update that uses different weather data by default than Version 5. Version 6 uses the NREL Physical Solar Model (PSM) TMY from the NREL National Solar Radiation Database (NSRDB) by default, however you can select to use NREL NSRDB 1991-2005 TMY3 data, international data, or a 10km gridded dataset covering all of India. PVWatts Version 6 also updates the default DC to AC ratio to 1.2 instead of 1.1, but you can still specify the DC to AC ratio that you wish to use in your simulation.

The algorithms used to calculate energy output have not cha
Dobos, A. P. PVWatts Version 5 Manual. NREL/TP-6A20-62641

Examples

JSON Output Format

GET /api/pvwatts/v6.json?api_key=DEMO_KEY&lat=40&lon=-105&system_capacity=4&azimuth=180&tilt=40&array_type=1&module_type=1&losses=10


```
{
    "inputs": {
        "system_capacity": "4",
        "lat": "40",
        "lon": "-105",
        "azimuth": "180",
        "tilt": "40",
        "array_type": "1",
        "module_type": "1",
        "losses": "10"
    },
    "errors": [],
    "warnings": [],
    "version": "1.4.0",
    "ssc_info": {
        "version": 45,
        "build": "Linux 64 bit GNU/C++ Jul  7 2015 14:24:09"
    },
    "station_info": {
        "lat": 40.0099983215332,
        "lon": -105.0199966430664,
        "elev": 1581.0399658203125,
        "tz": -7,
        "location": "None",
        "city": "",
        "state": "Colorado",
        "solar_resource_file": "W10502N4001.csv",
        "distance": 2029
    },
    "outputs": {
        "ac_monthly": [
            474.4326171875,
            484.3903503417969,
            595.7704467773438,
            592.0599365234375,
            591.2662353515625,
            589.3538208007812,
            583.2352905273438,
            586.4593505859375,
            584.0131713867188,
            561.7291445312S,
            486.1260375976562S,
            445.6881713867187S
        ],
        "poa_monthly": [
            141.4809417724609A,
            145.5711975097656Z,
```

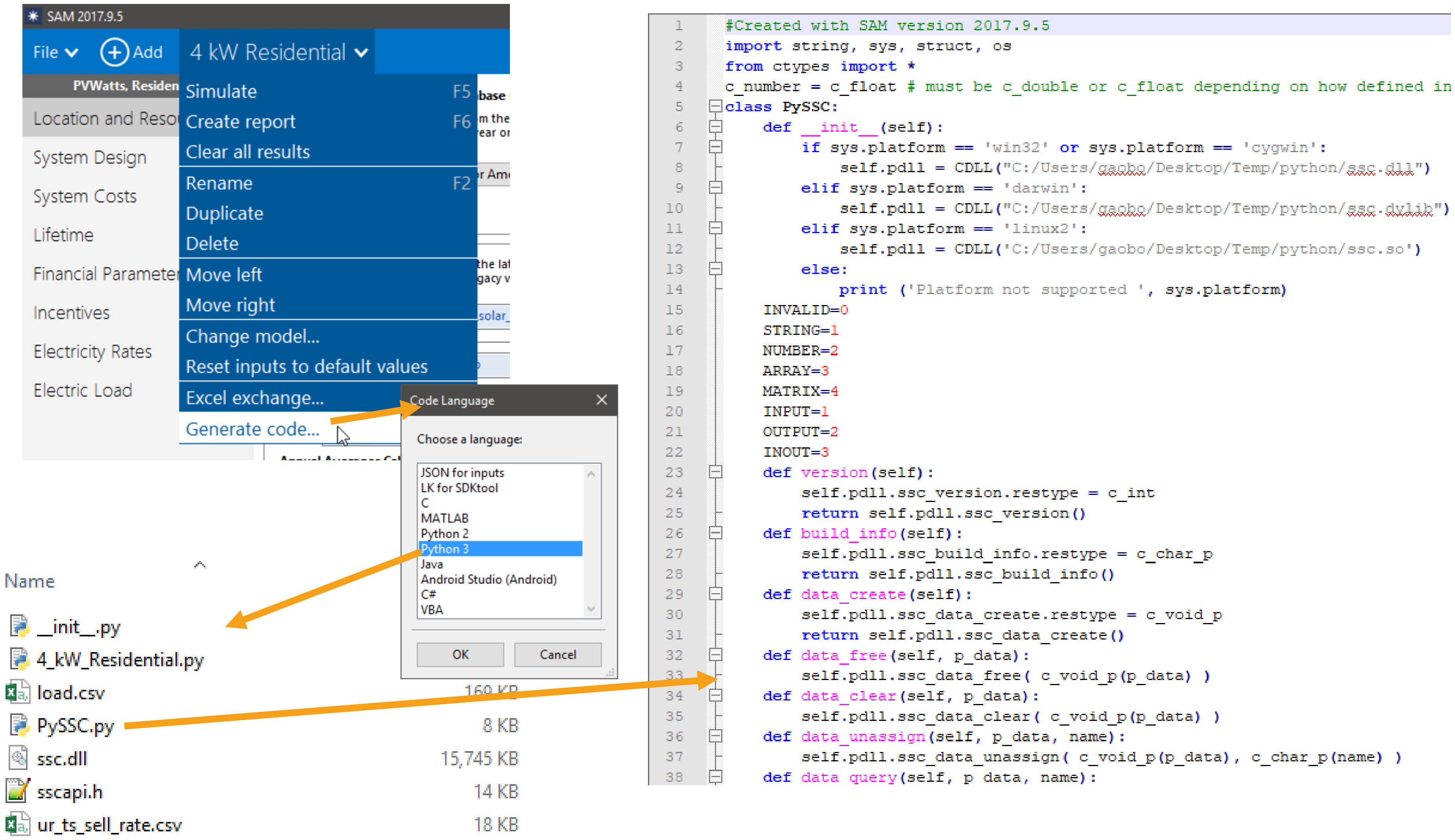

Request URL

```
GET /api/pvwatts/v6.format?parameters
```

Request Parameters

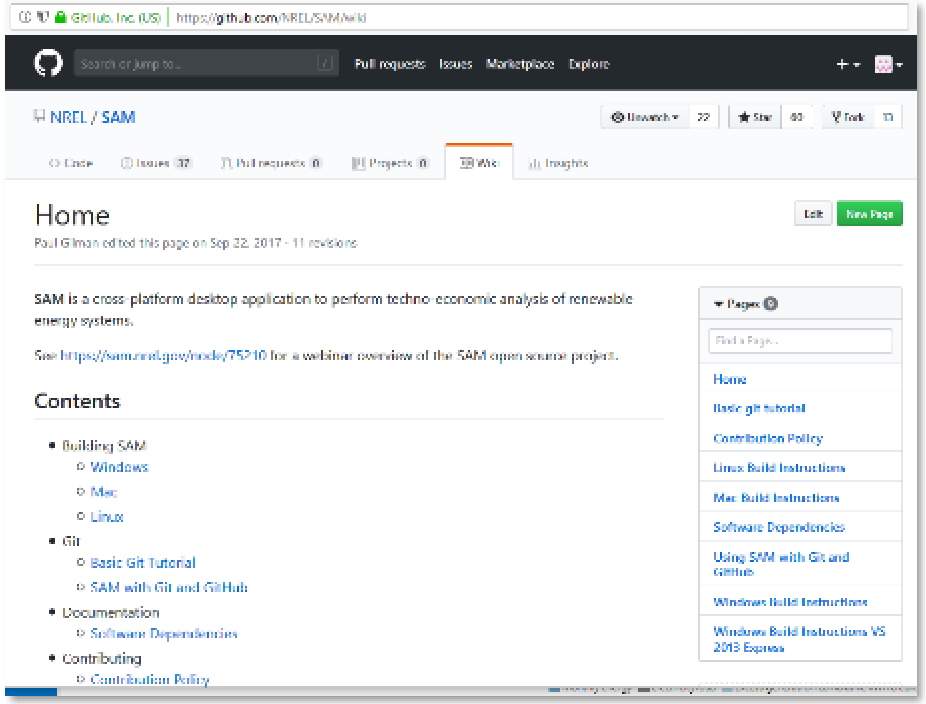
Parameter	Required	Value	
format	Yes	**Type:** string **Default:** None **Options:** *json, xml*	
api_key	Yes	Type: string	Your developer API key. See API keys for more information

API for SAM Simulation Core (SSC) in SAM Software Development Kit: https://sam.nrel.gov



C++ source code on github.com/nrel/sam

```
// cell temperature
pvt = (*tccalc)( poa, wspd_corr, tdry );

// dc power output (Watts)
dc = dc_nameplate*(1.0+gamma*(pvt-25.0))*tpoa/1000.0;

// dc losses
dc = dc*(1-loss_percent/100);

// inverter efficiency
double etanom = inv_eff_percent/100.0;
double etaref = 0.9637;
double A =  -0.0162;
double B = -0.0059;
double C =  0.9858;
double pdc0 = ac_nameplate/etanom;
double plr = dc / pdc0;
ac = 0;

if ( plr > 0 )
{ // normal operation
        double eta = (A*plr + B/plr + C)*etanom/etaref;
        ac = dc*eta;
}

if ( ac > ac_nameplate ) // clipping
        ac = ac_nameplate;

// make sure no negative AC values (no parasitic nighttime losses calculated)
if ( ac < 0 ) ac = 0;
```



https://github.com/NREL/ssc/blob/develop/ssc/cmod_pvwattsv5.cpp

References

https://pvwatts.nrel.gov

2018 PVWatts webinar for Green Home Institute:
https://www.youtube.com/watch?time_continue=2&v=4JQ1PZbFPwY

Dobos, A. (2014). PVWatts Version 5 Manual. NREL Report No. TP-6A20-62641. (PDF 714 KB)

Dobos, A.; (2013). PVWatts Version 1 Technical Reference. 11 pp.; NREL Report No. TP-6A20-60272. (PDF 487 KB)

Marion, B. et al. (2005). Performance Parameters for Grid-Connected PV Systems. NREL Report No. CP-520-37358. (PDF 816 KB)

MacAlpine, S., Deline, Chris. (2015). Modeling Microinverters and DC Power Optimizers in PVWatts. NREL Report No. TP-5J00-6346. (PDF 360 KB)

Live Demonstration

Thank you!

www.nrel.gov

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

40
1977 – 2017





THE NATIONAL SOLAR RADIATION DATABASE (1998-2016)

Presenter: Aron Habte,

Dr. Manajit Sengupta, Aron Habte, Dr. Yu Xie, Anthony Lopez, Dr. Galen Maclaurin, NREL

Dr. Michael J. Foster, CIMMS, University of Wisconsin

Dr. Andrew Heidinger , NOAA/NESDIS, Madison, Wisconsin

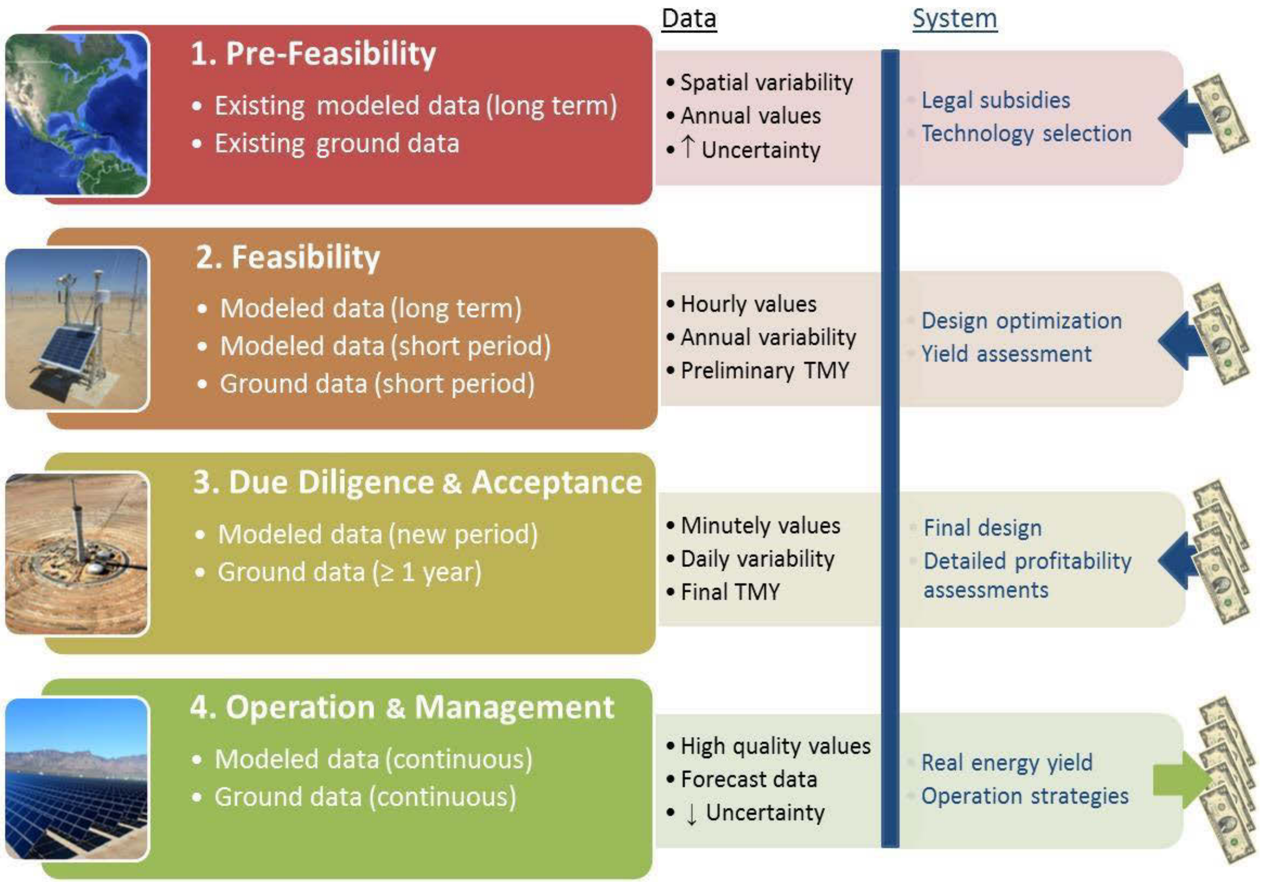
Dr. Christian Gueymard, Solar Consulting Services

Solar Power International Educational Workshop, September 24-27, 2018

Application of Solar Resource Information

Support the U.S. Department of Energy (DOE) SunShot goal of reducing solar deployment and financing costs through improving accuracy in solar resource modeling.

Funded by the SI subprogram of DOE EERE Solar Energy Technology Program

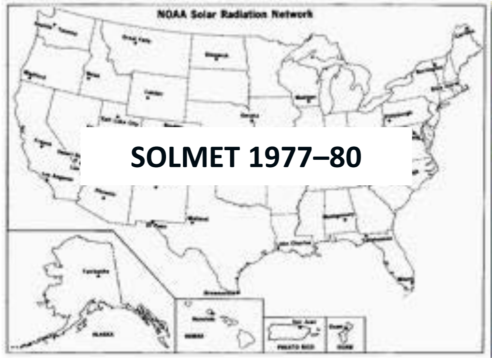


Source: https://www.nrel.gov/docs/fy18osti/68886.pdf

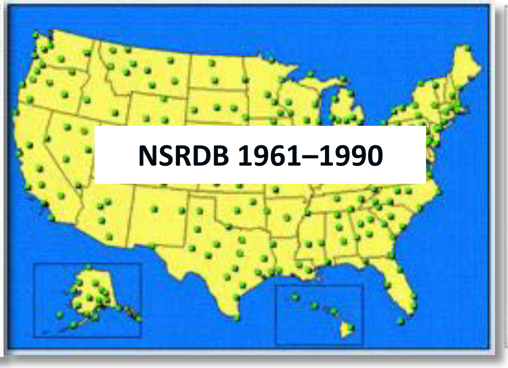
Outline

- Evolution of NSRDB
- The Physical Solar Model (PSM)
- What's new in NSRDB Version 3
- Validation of the NSRDB
- Spectral data
- Typical Meteorological Year (TMY)
- Accessing NSRDB and available parameters
- Future Work

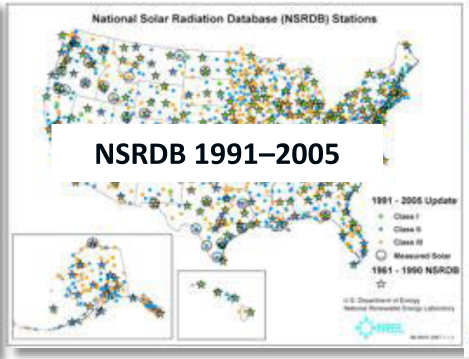
Evolution of the National Solar Radiation Database (NSRDB)



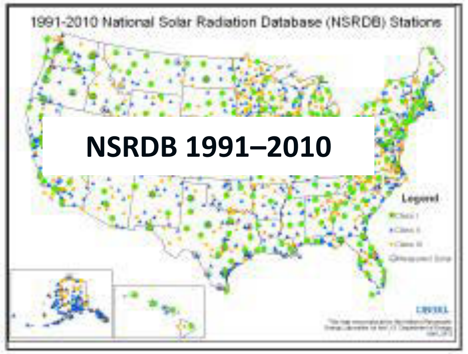
248 weather stations with 26 ***Solar measurement*** stations [ERDA, NOAA, 1979]



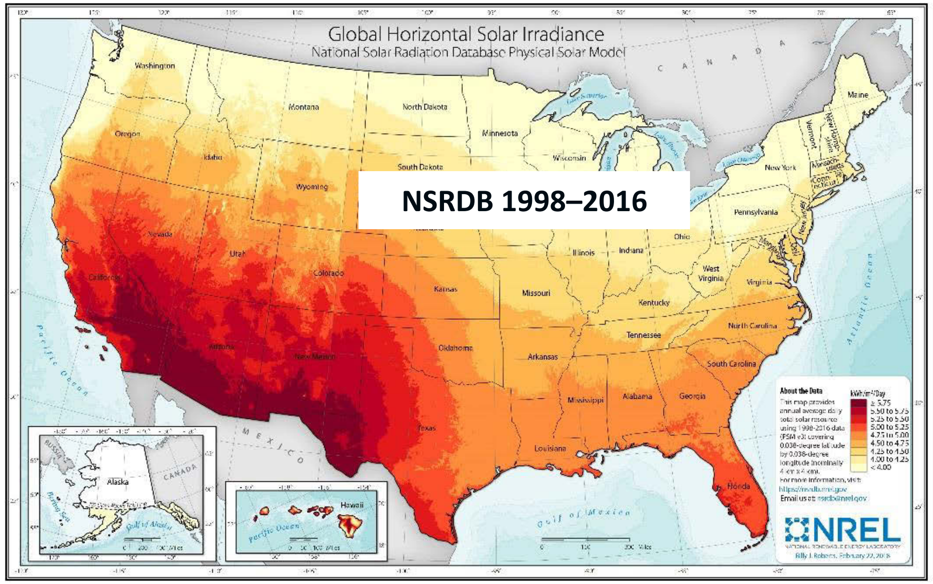
239 ***modeled*** stations with 56 partial measurement stations [DOE, NOAA, 1994]



1,454 ***modeled*** locations [DOE, SUNY-A, NOAA, 2007]



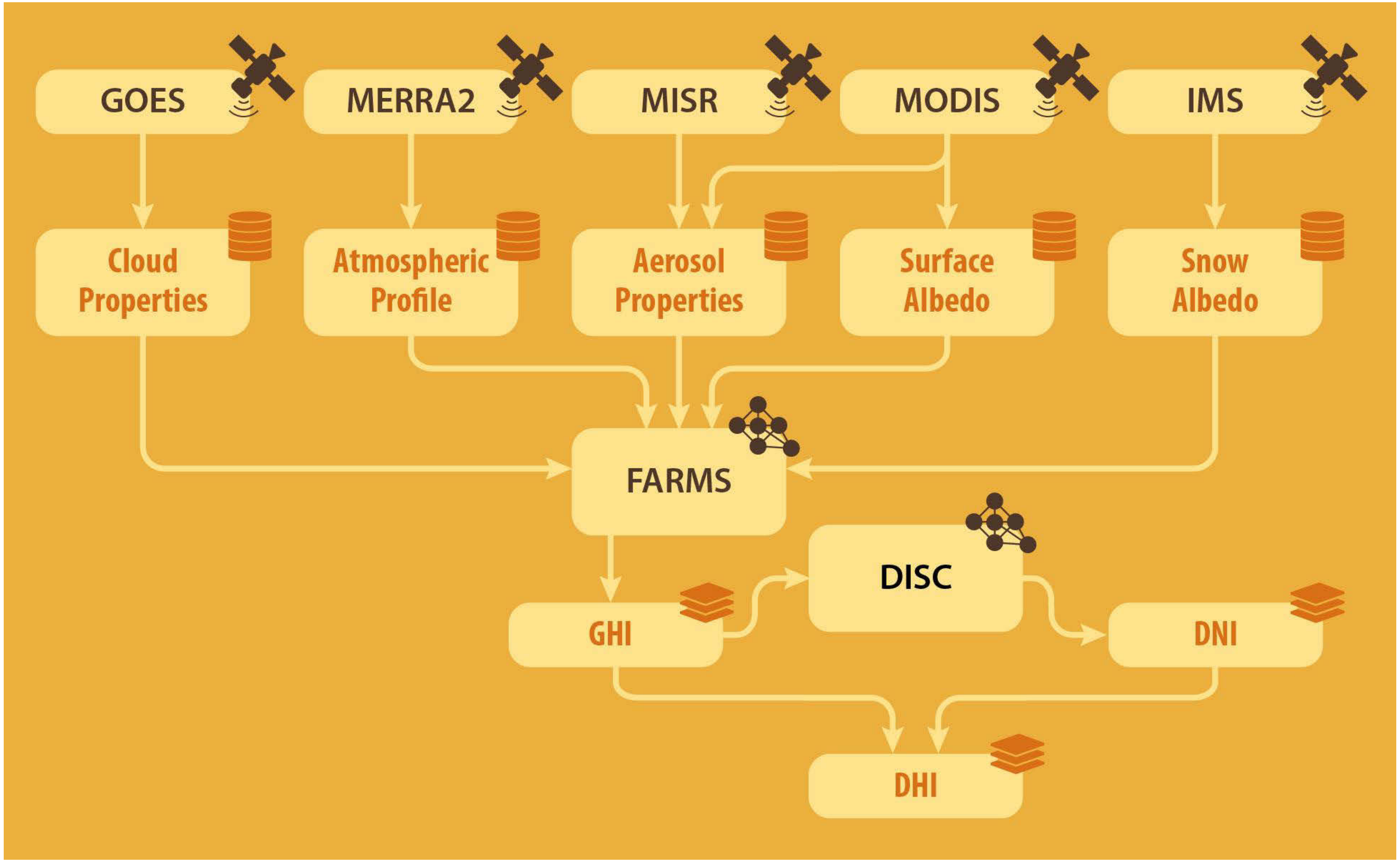
1,454 ***modeled*** locations [DOE, CPR, 2012]



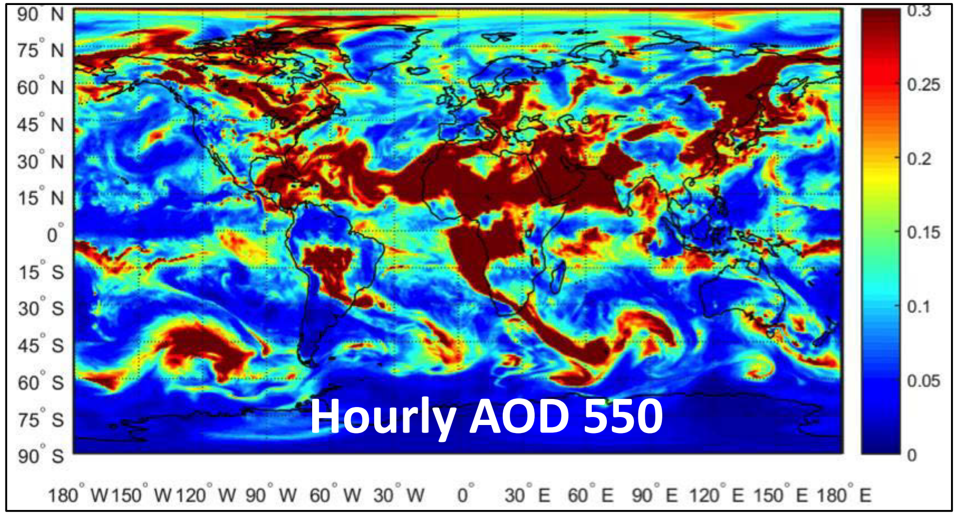
http://nsrdb.nrel.gov

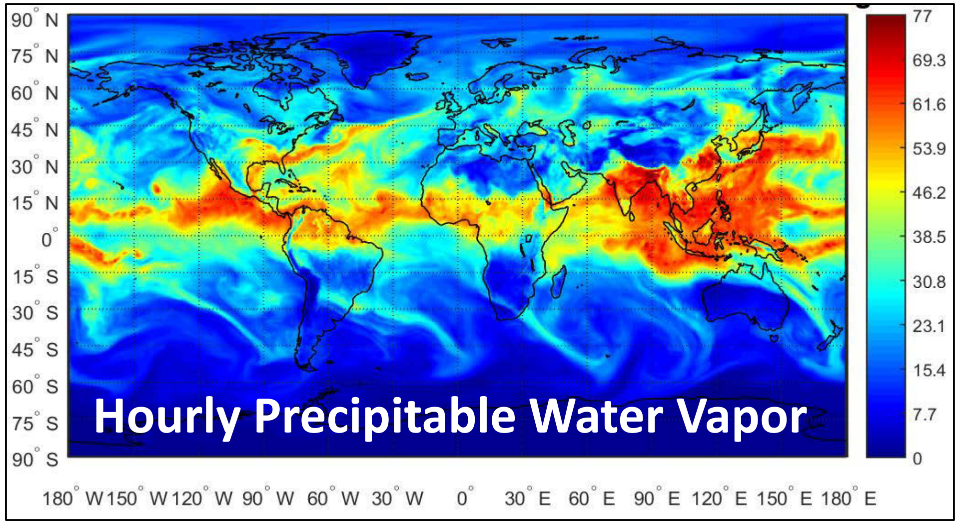
Satellite-based, gridded, 4 km x 4 km, half-hourly [DOE, NOAA, UW, SCS 2016]

Physical Solar Model (PSM) Framework



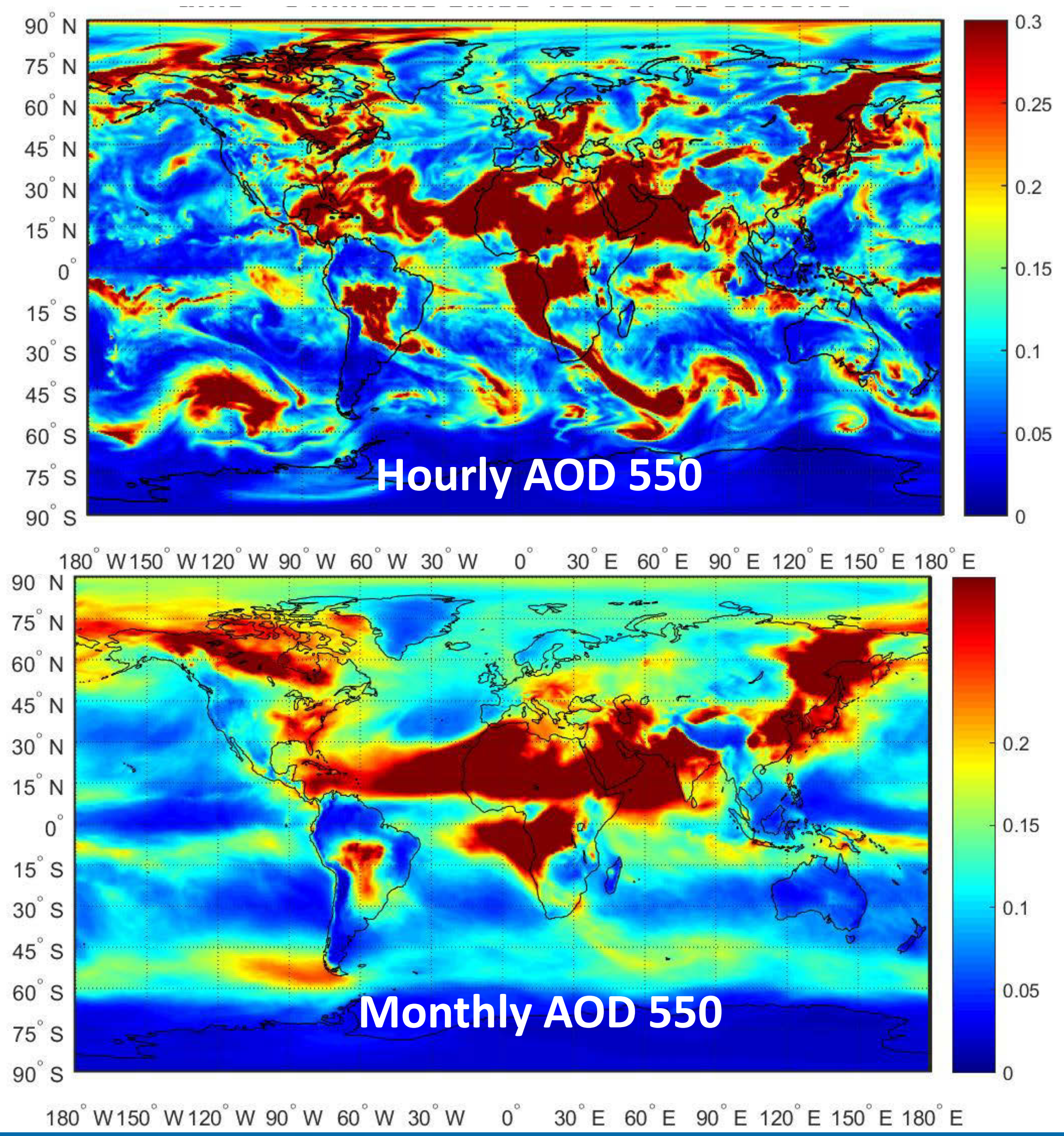
NSRDB (PSM-V3): What's New





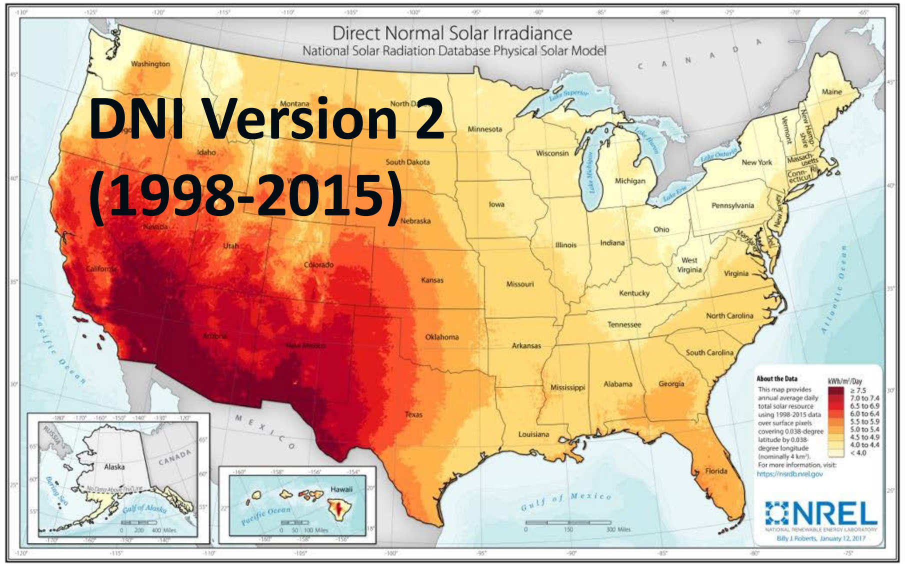
- **Hourly aerosol optical depth (1998-2016) from Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2).**
- **Snow-free Surface Albedo from MODIS (2001-2015) (MCD43GF CMG Gap-Filled Snow-Free Products from University of Massachusetts, Boston).**
- **Snow cover from Integrated Multi-Sensor Snow and Ice Mapping System (IMS) daily snow cover product (National Snow and Ice Data Center).**
- **Ancillary data (pressure, humidity, wind speed etc.) from MERRA2.**

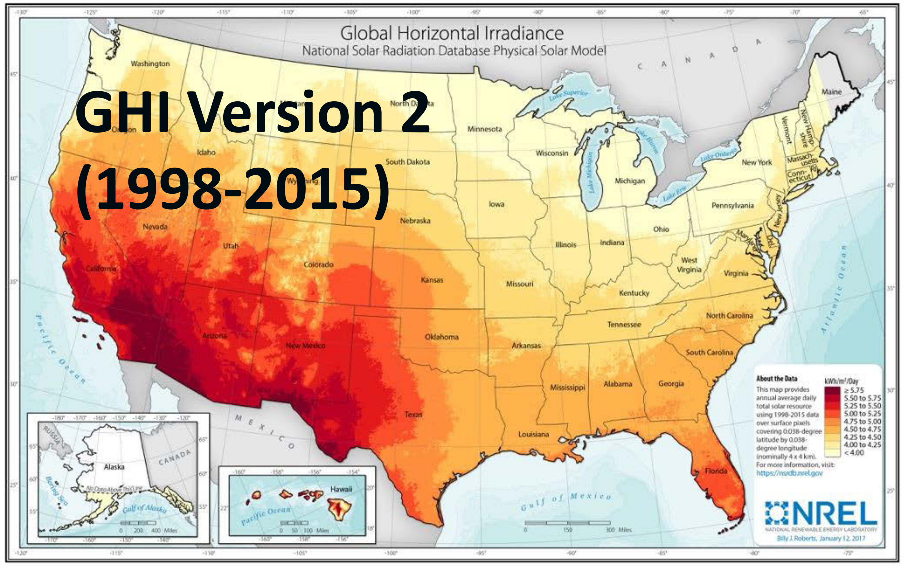
NSRDB (PSM-V3): What’s New

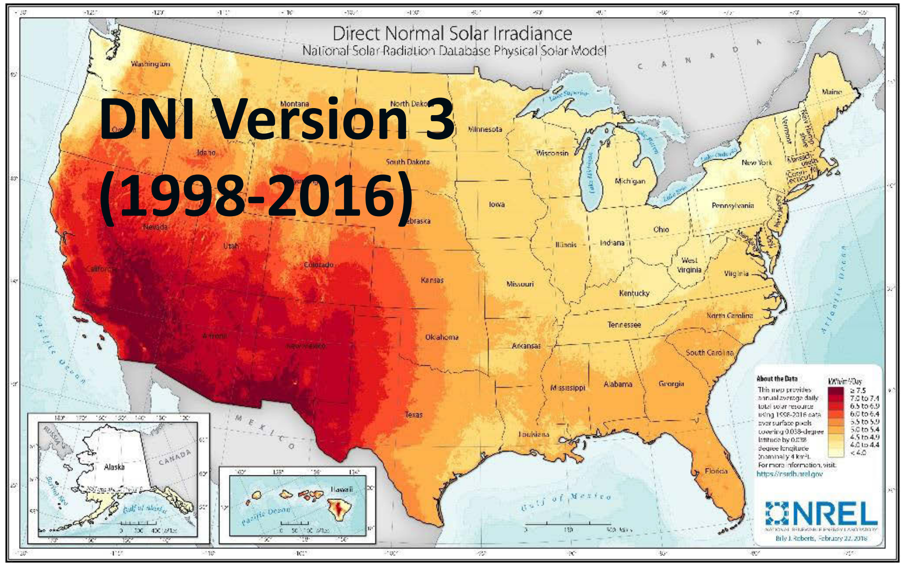


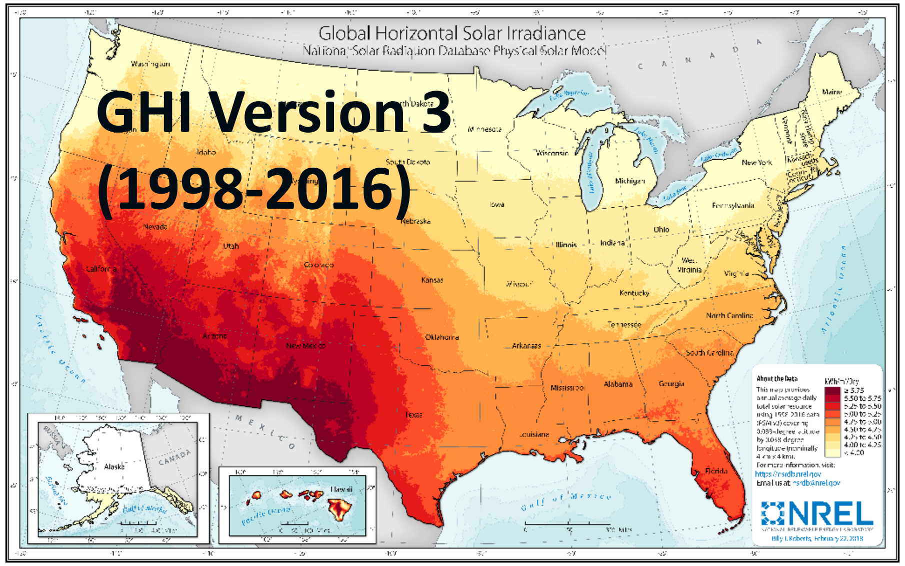
Hourly AOD for one time stamp in July 1998 (Top) versus monthly AOD for July 1998 (Bottom)

NSRDB Version 2 and 3 Comparison



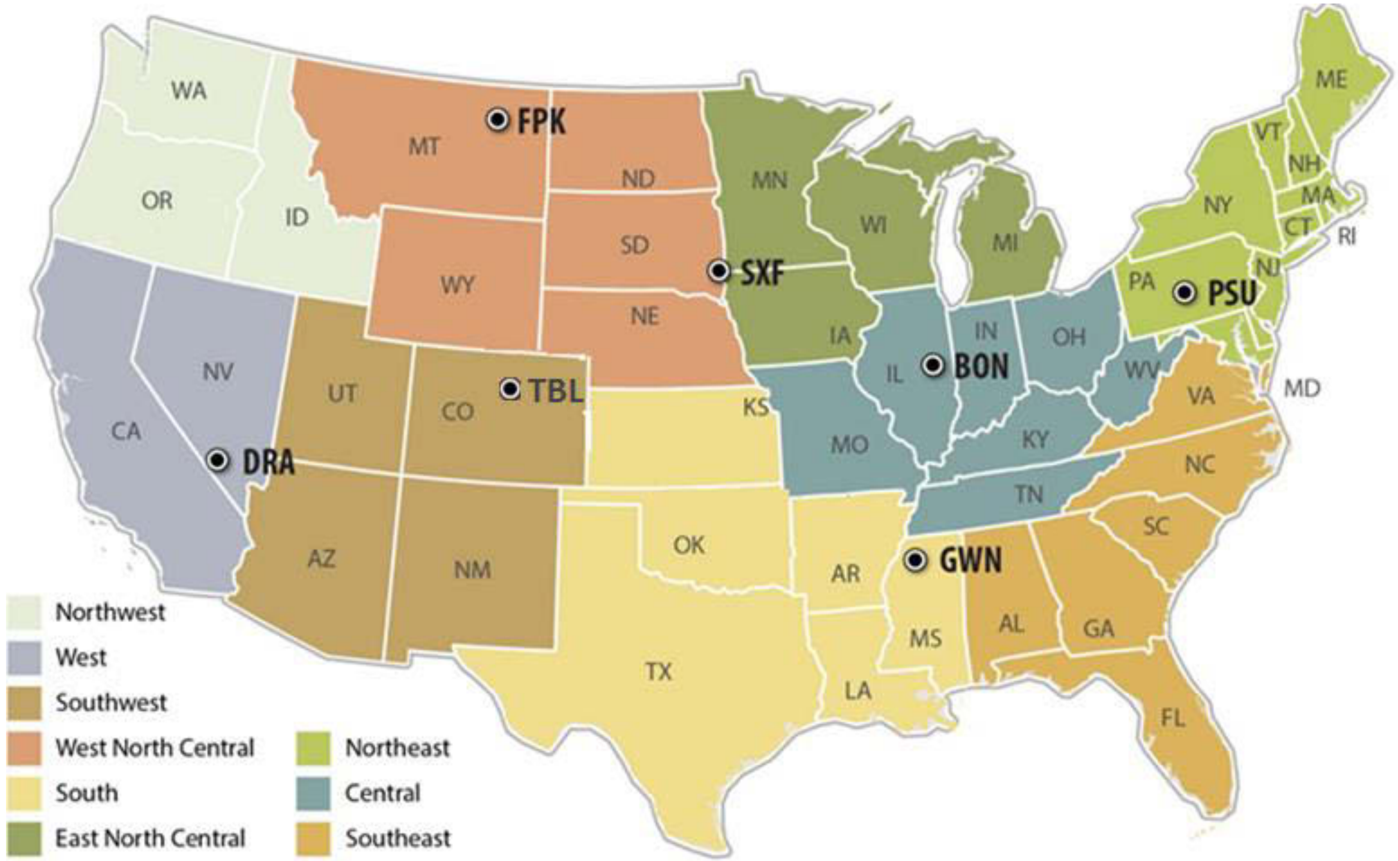






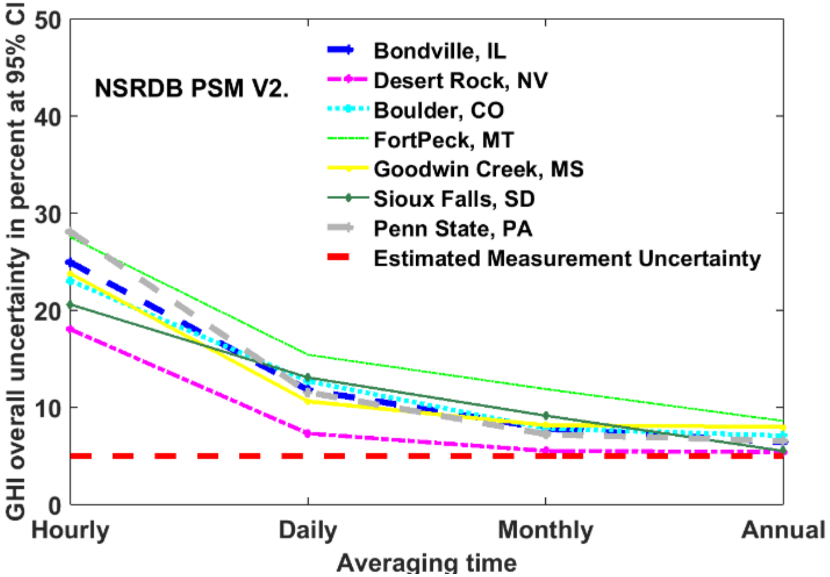
Validation of NSRDB Using Surface-Based Measurements

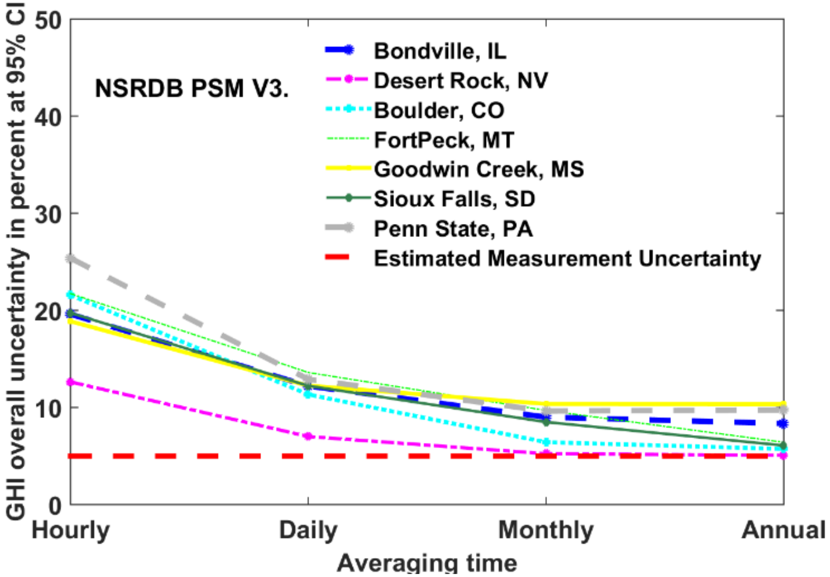
Surface Radiation (SURFRAD) Network



Validation of NSRDB Using Surface-Based Measurements

GHI: Overall estimated uncertainty—NSRDB (1998–2015)

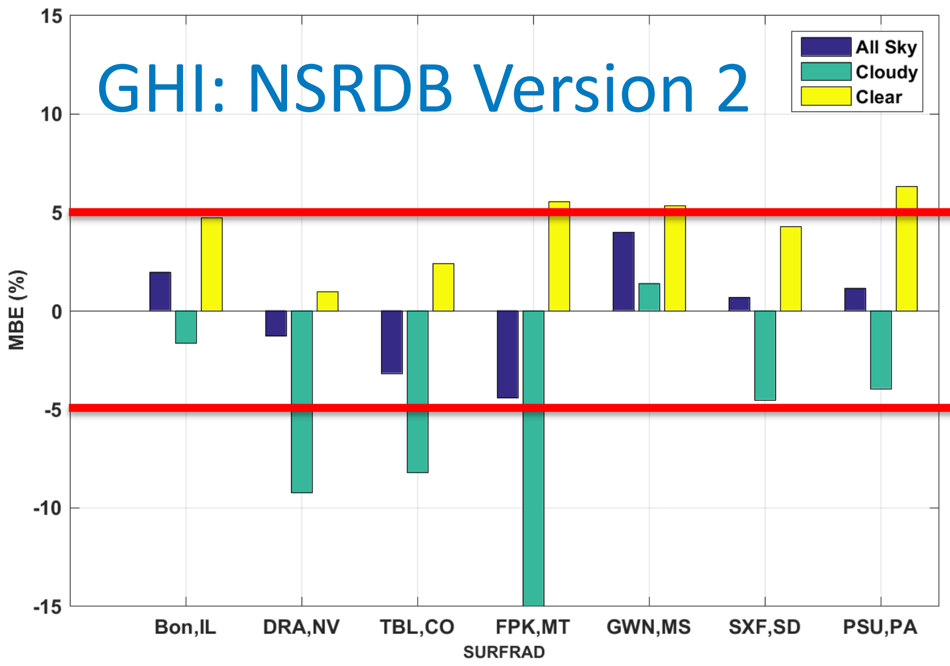


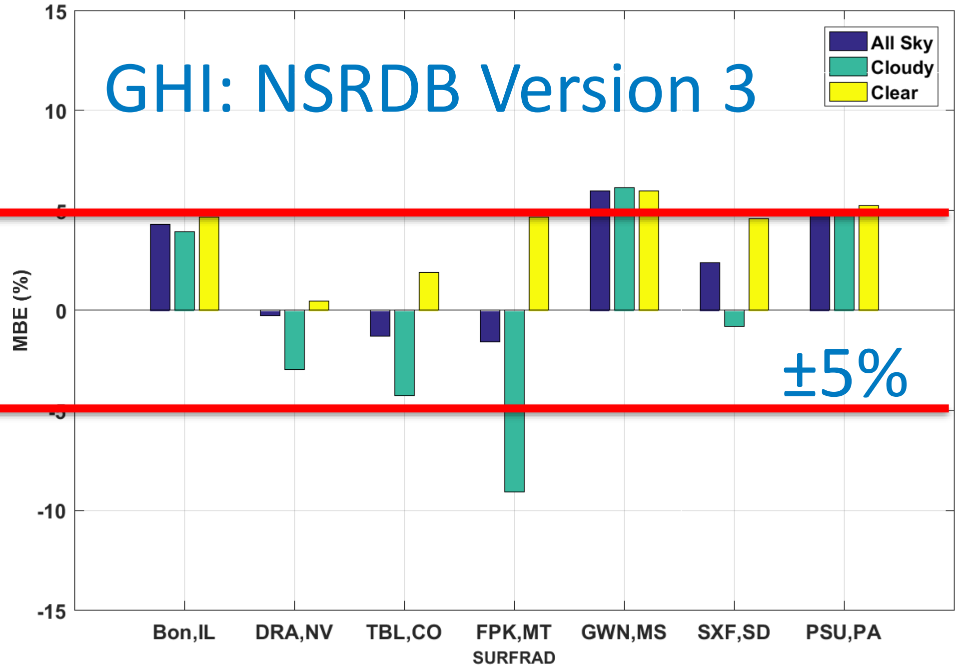


<u>**Uncertainty estimation includes:**</u>

- MBE
- RMSE
- Surface measurement uncertainty.

Validation of NSRDB Using Surface-Based Measurements





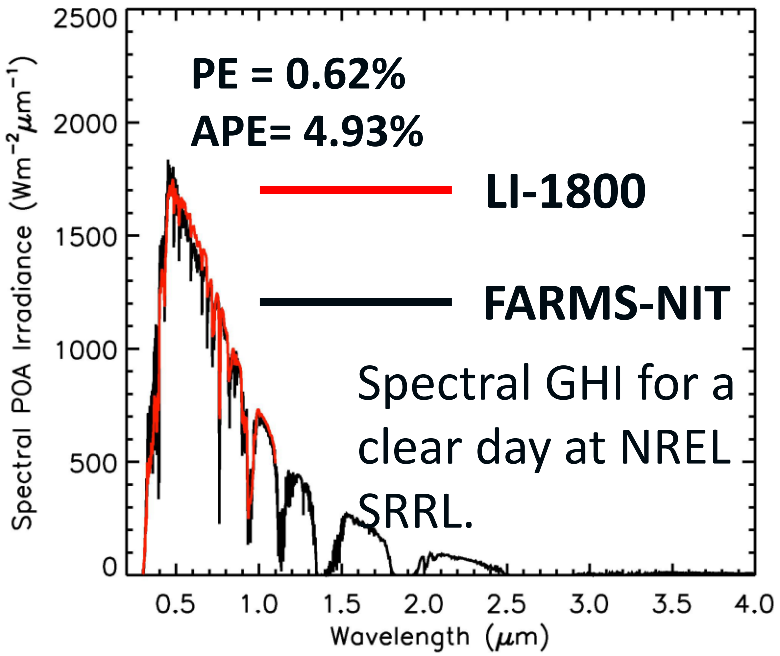
Difference between the two versions:

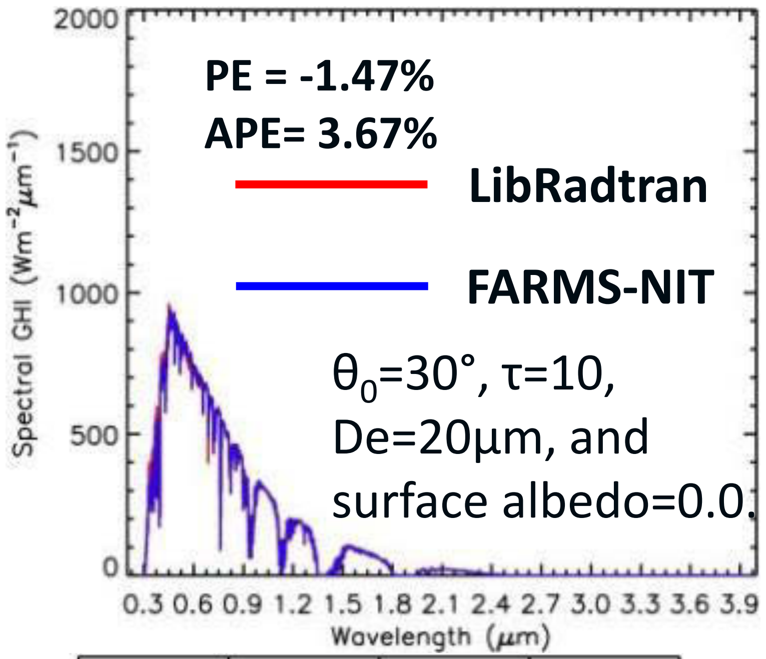
- MERRA-2 AOD vs climatological AOD
- Precipitable water vapor from MERRA2
- Surface Albedo from MODIS and Snow Cover from IMS
- Some of downscaling calculations for ancillary variables

Spectral Data from NSRDB

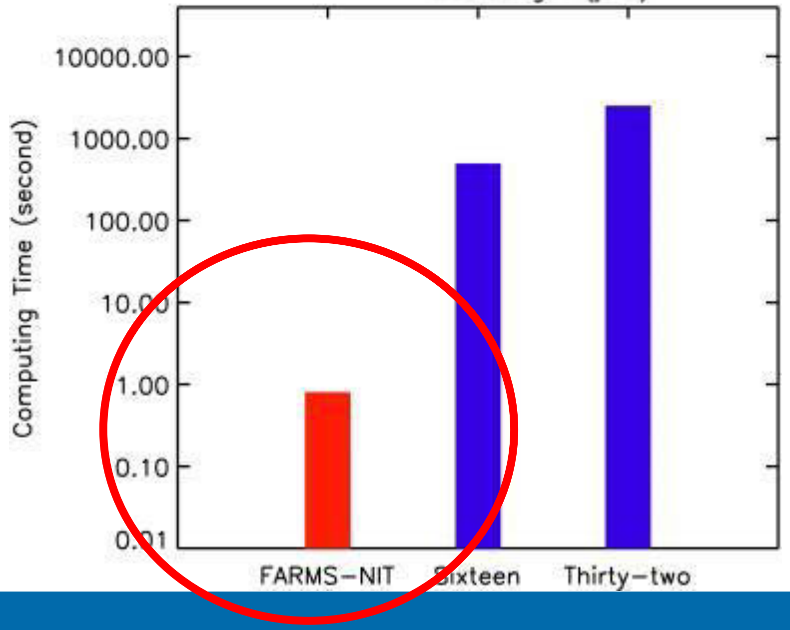
- New capability to provide spectral POA on demand for any fixed-tilt or single-axis tracking orientation.
- POA irradiances are efficiently computed for 2002 wavelength bands (0.28-4.0 mm) from the radiances.
- Spectral radiances are computed by using lookup table of cloud transmittance and solving the radiative transfer equation.
- POA irradiance is computed by integrating radiances over inclined surfaces.

Uncertainty of Spectral Model





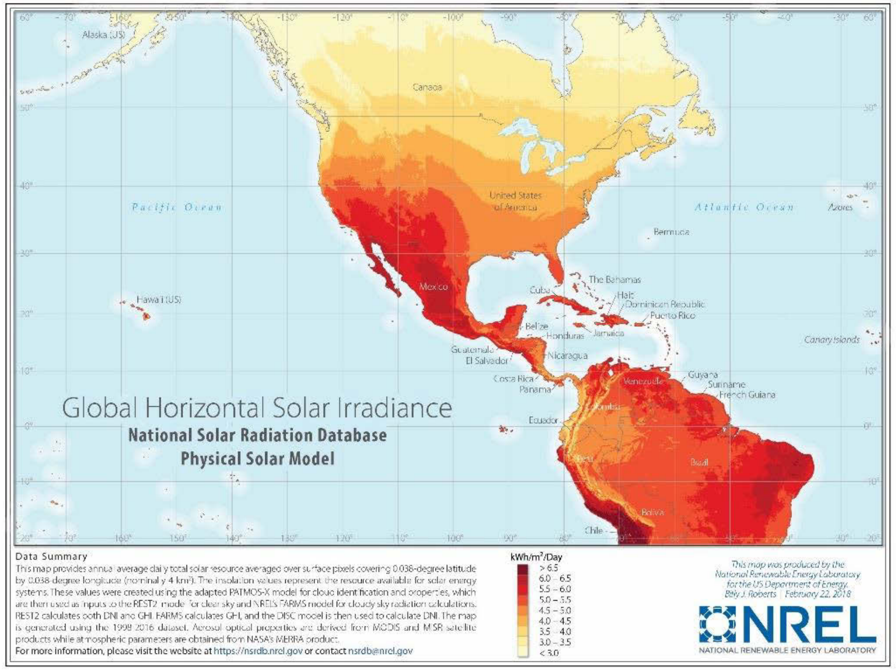
FARMS-NIT: 0.8 second.
LibRadtran (16 stream): 492 seconds.
LibRadtran (32 stream): 2493 seconds.



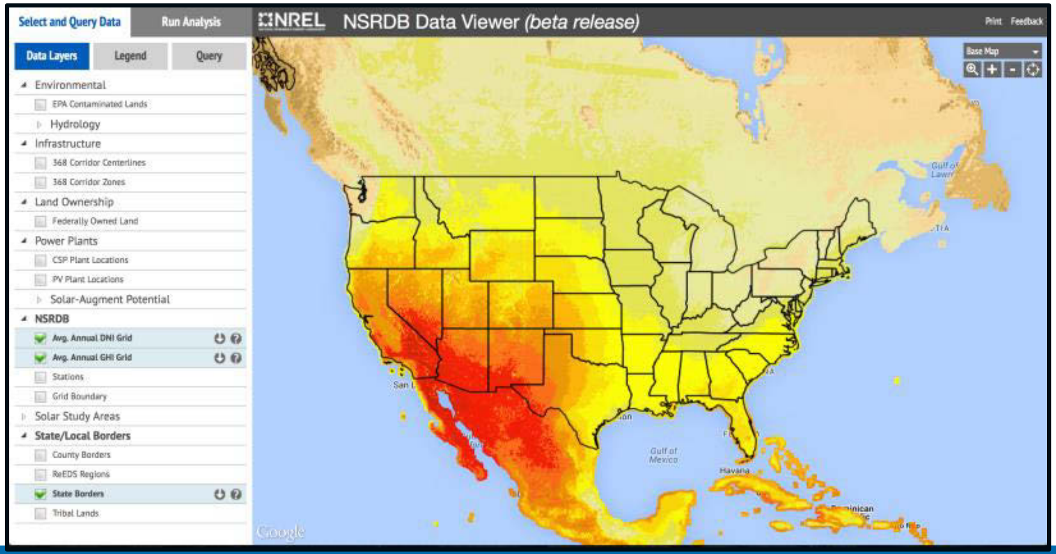
What's Available

<u>**USA and North and South America:**</u>

- Current product (4-km, half-hourly) available from 1998–2016 (Model V3)
- Typical meteorological year (TMY) product is also available.
- Multiple summary products are available with current data sets.
- Spectral data



https://nsrdb.nrel.gov



What’s Available

15 Variables are Delivered Publicly:

Dataset in the NSRDB	
Data used in PSM	**Publicly available datasets**
• MERRA-2 ○ Atmospheric pressure ○ Surface albedo ○ Aerosols ○ Aerosol optical thickness ○ Single scattering albedo ○ Aerosol Angstrom parameter. ○ Total ozone ○ Precipitable water. • GOES (PATMOS-X retrievals) ○ Cloud effective radius ○ Cloud optical depth ○ Cloud type. • Moderate Resolution Imaging Spectroradiometer/National Snow and Ice Data Center ○ Surface albedo.	• Global horizontal irradiance (GHI) • Direct normal irradiance (DNI) • Diffuse horizontal irradiance (DHI) • Clear-sky GHI, DNI, and DHI • Cloud type • Dew point** • Air temperature* • Atmospheric pressure • Relative humidity** • Solar zenith angle • Precipitable water* • Wind direction** • Wind speed.**
* From MERRA-2 ** Recalculated from MERRA-2	

TMY Data Set

- Step 1
  - For each month of the calendar year, 5 candidate months with cumulative distribution functions (CDFs) for the daily indices that are closest to the long-term (30 years for the NSRDB) CDFs are selected.
- Step 2
  - The 5 candidate months are ranked with respect to closeness of the month to the long-term mean and median.
- Step 3
  - The persistence of mean dry bulb temperature and daily global horizontal radiation are evaluated by determining the frequency and run length above and below fixed long-term percentiles.
- Step 4
  - The 12 selected months are concatenated to make a complete year and smooth discontinuities at the month interfaces for 6 hours each side using curve-fitting techniques.

Weighting Parameters for the TMY, TDY, and TGY Data Sets (Modified from Wilcox and Marion 2008)

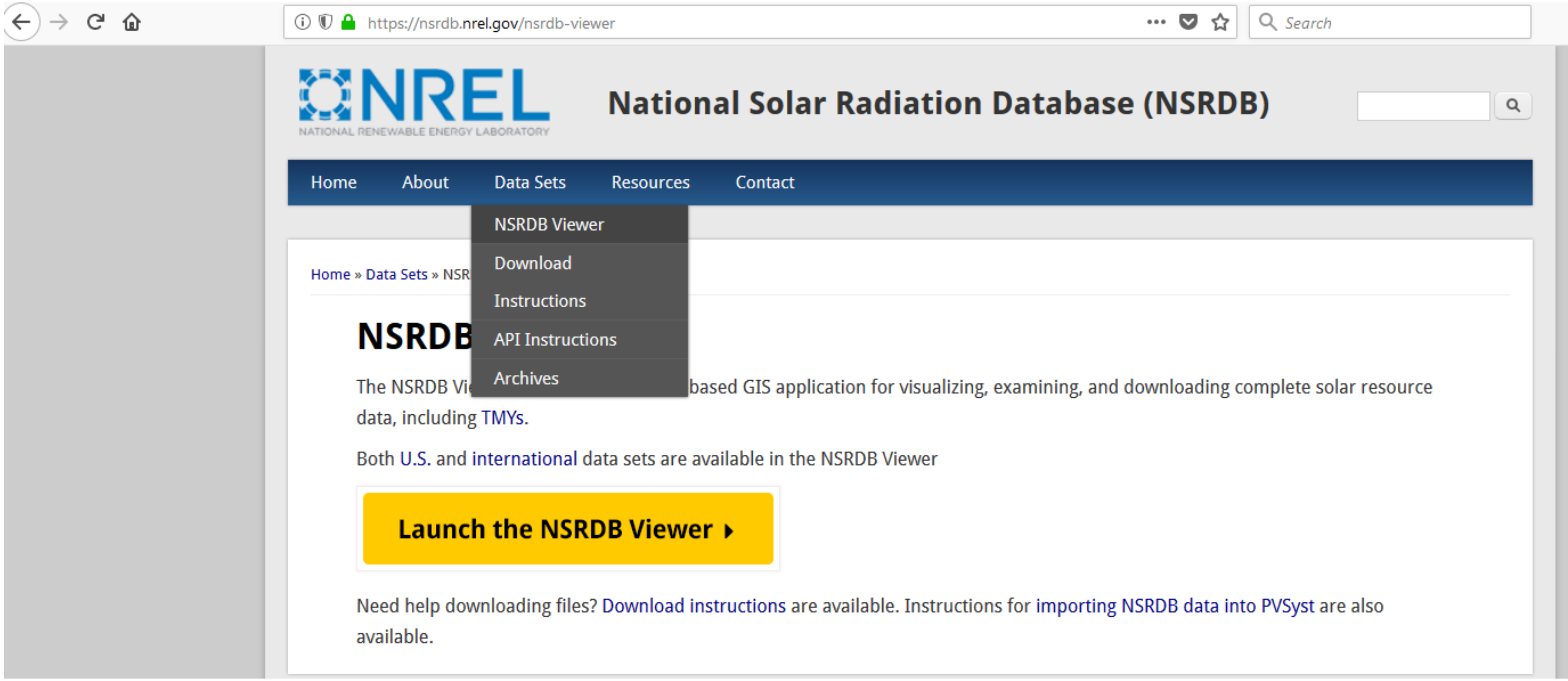
Index	TMY	TDY	TGY
Max Dry Bulb Temp	1/20	0	0
Min Dry Bulb Temp	1/20	0	0
Mean Dry Bulb Temp	2/20	0	0
Max Dew Point Temp	1/20	0	0
Min Dew Point Temp	1/20	0	0
Mean Dew Point Temp	2/20	0	0
Max Wind Velocity	1/20	0	0
Mean Wind Velocity	1/20	0	0
GHI	5/20	0	20/20
DNI	5/20	20/20	0

TMY: Typical meteorological year
TDY: Typical direct normal irradiance year
TGY: Typical global horizontal irradiance year

NSRDB Viewer and Data Access

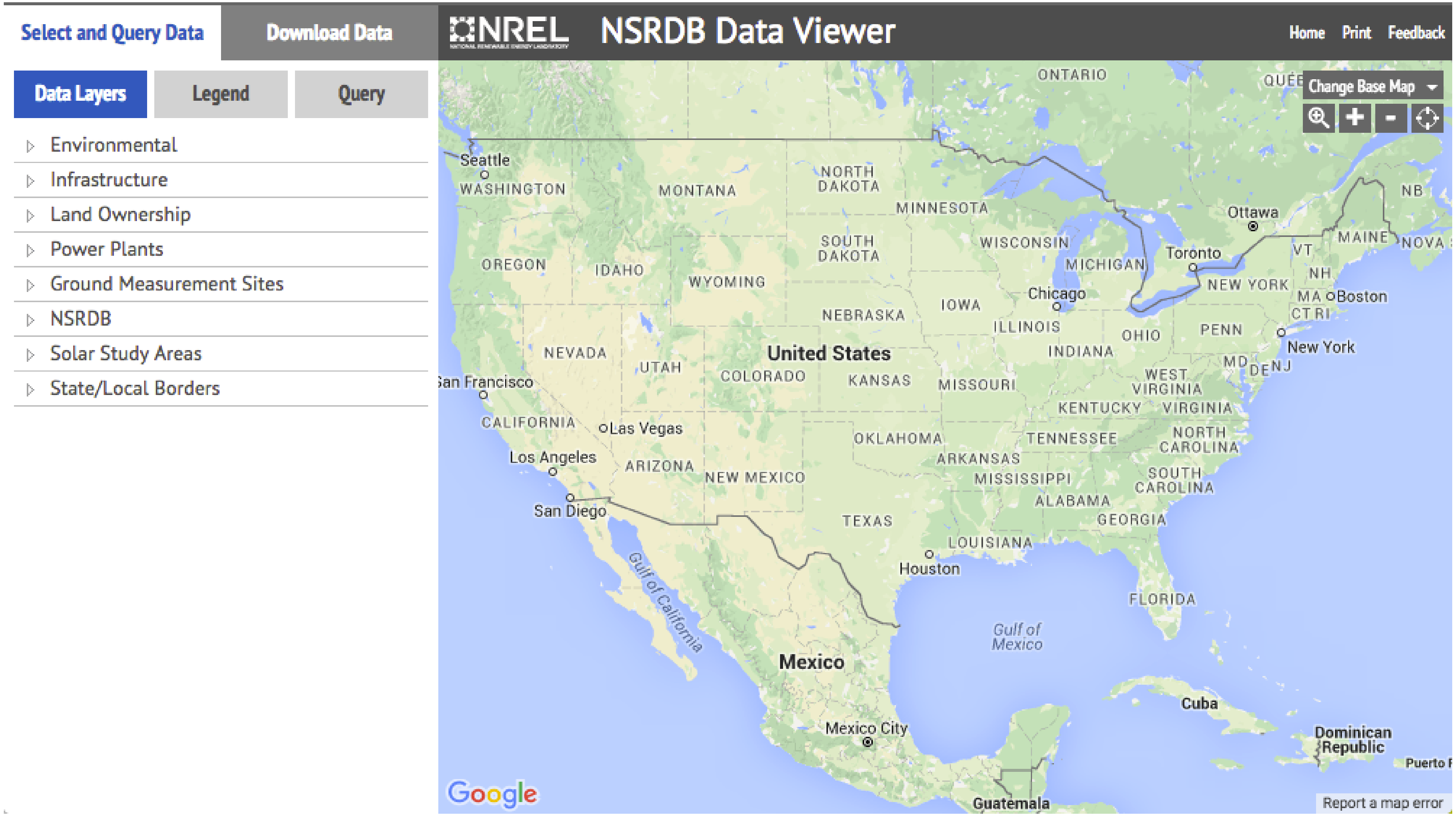
New NSRDB Viewer

https://nsrdb.nrel.gov/nsrdb-viewer

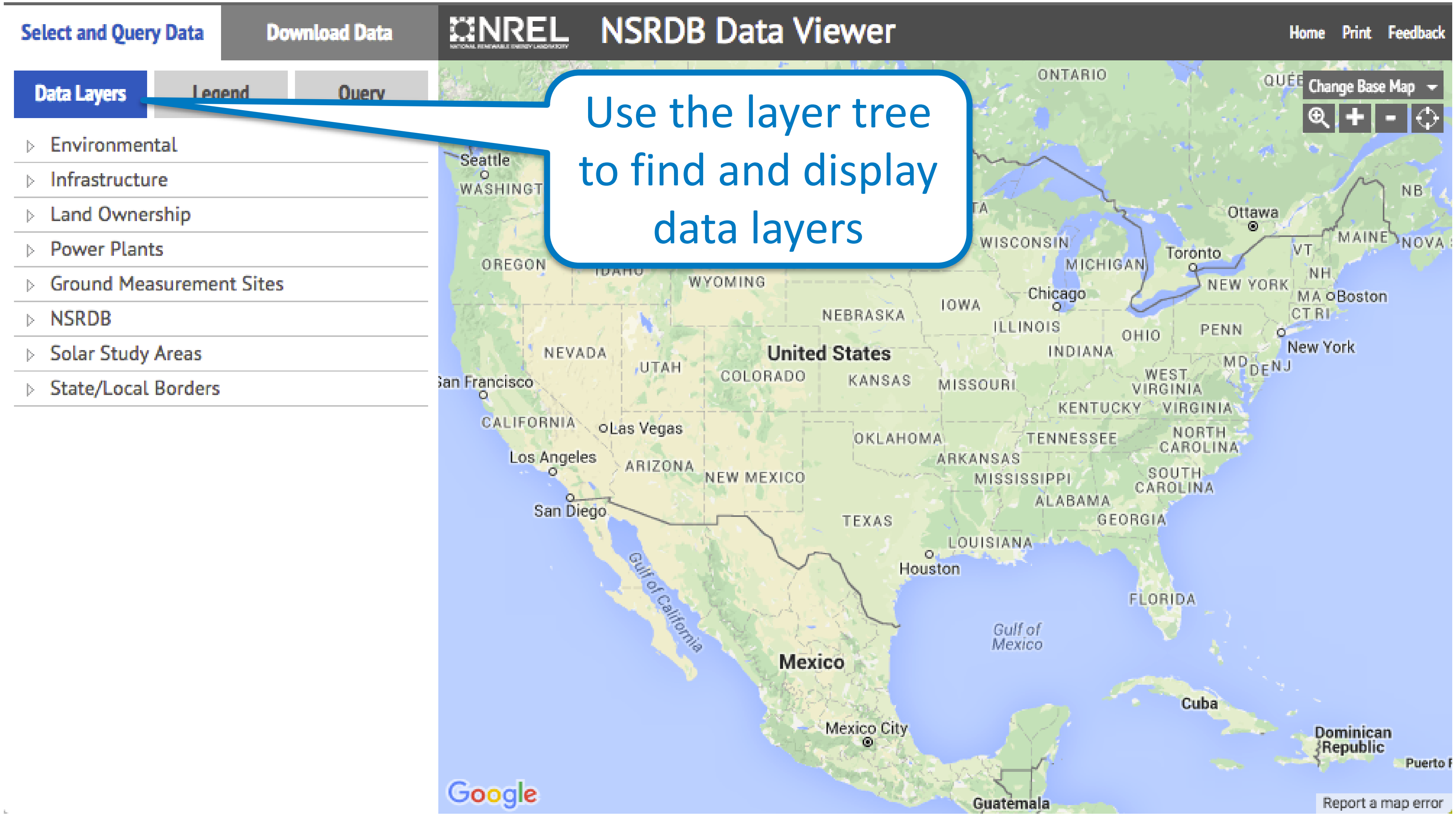


Direct link: https://maps.nrel.gov/nsrdb-viewer

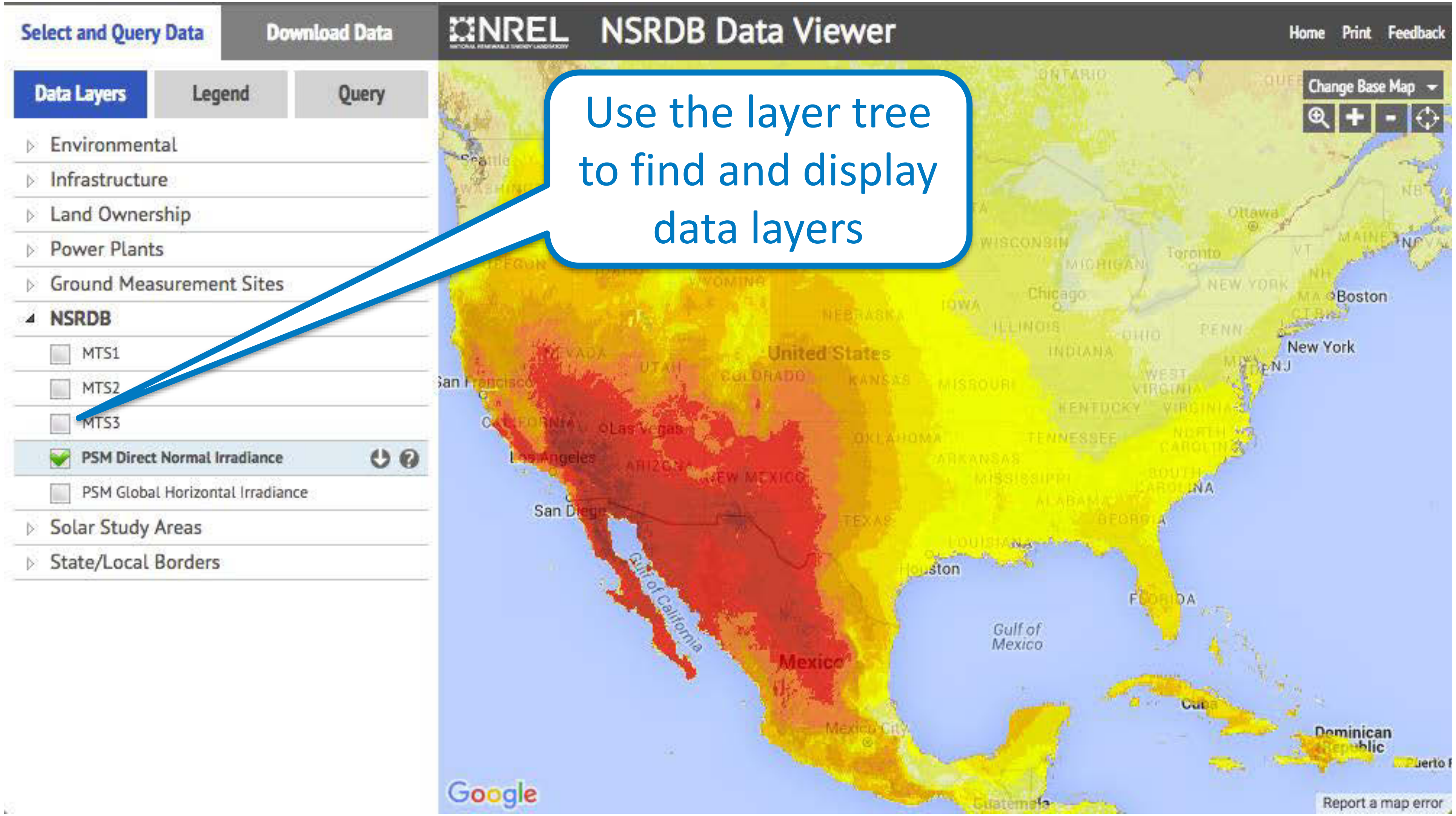
New NSRDB Viewer



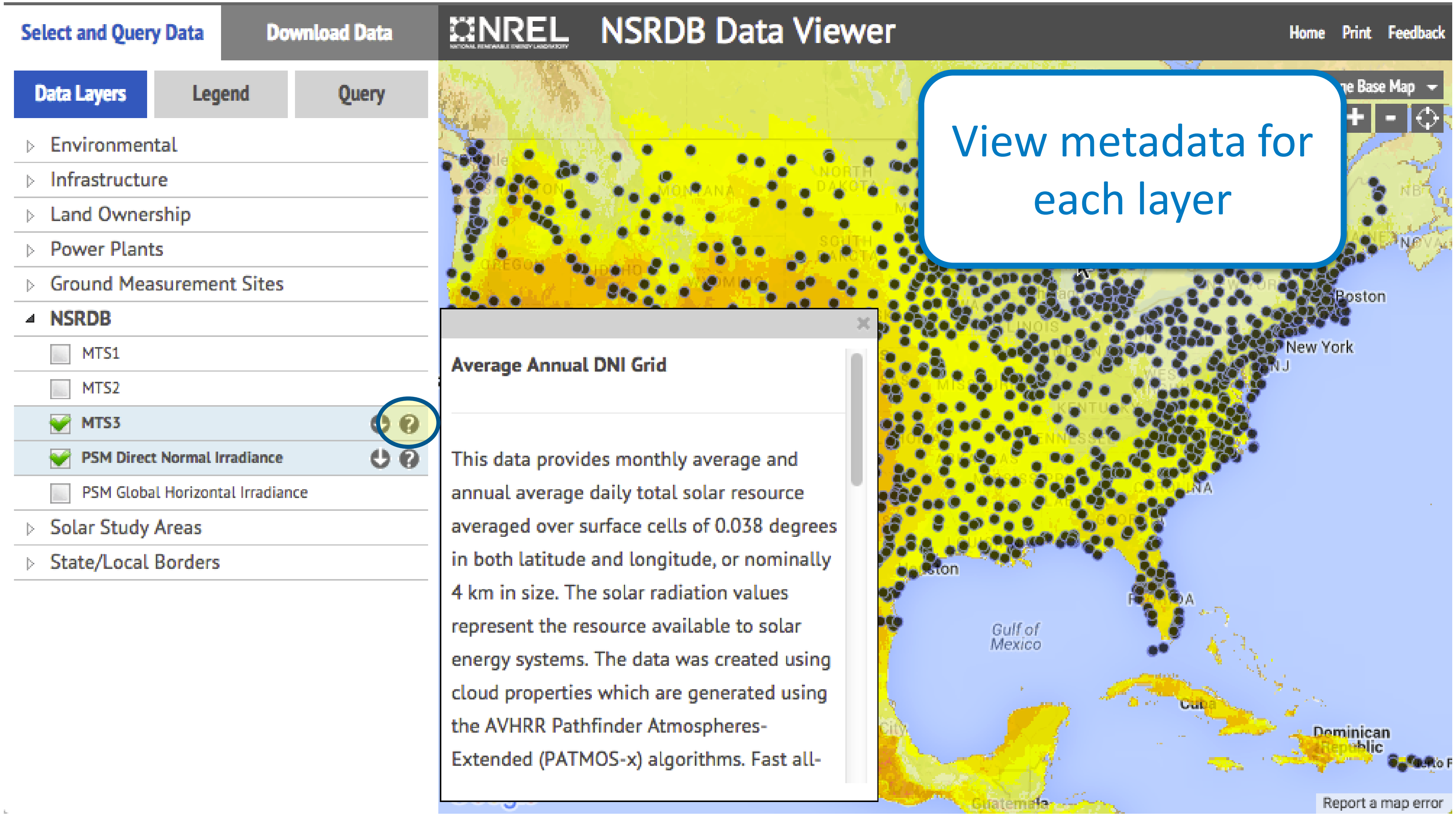
Browse Data Layers



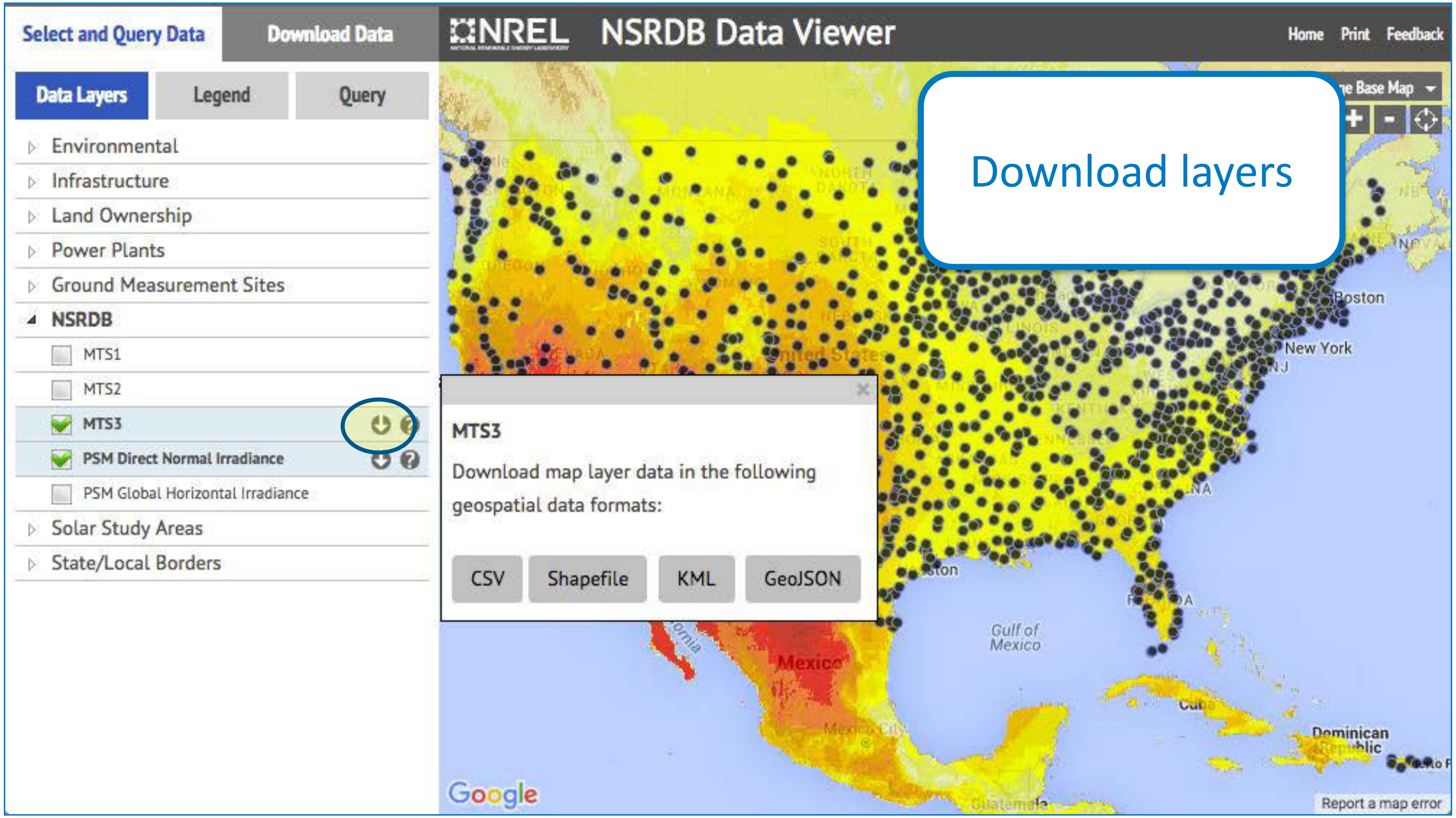
Browse Data Layers



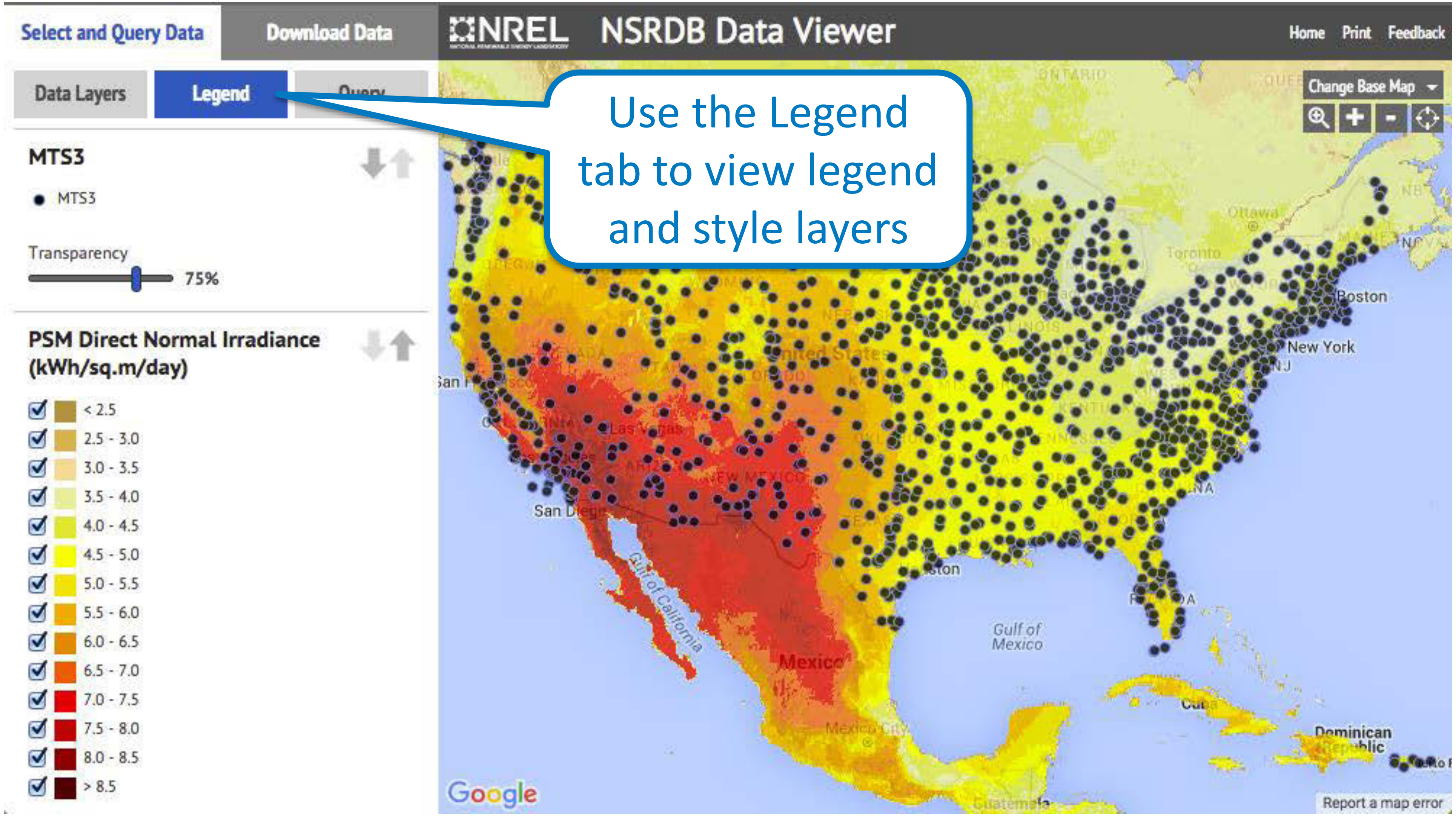
Layer Metadata



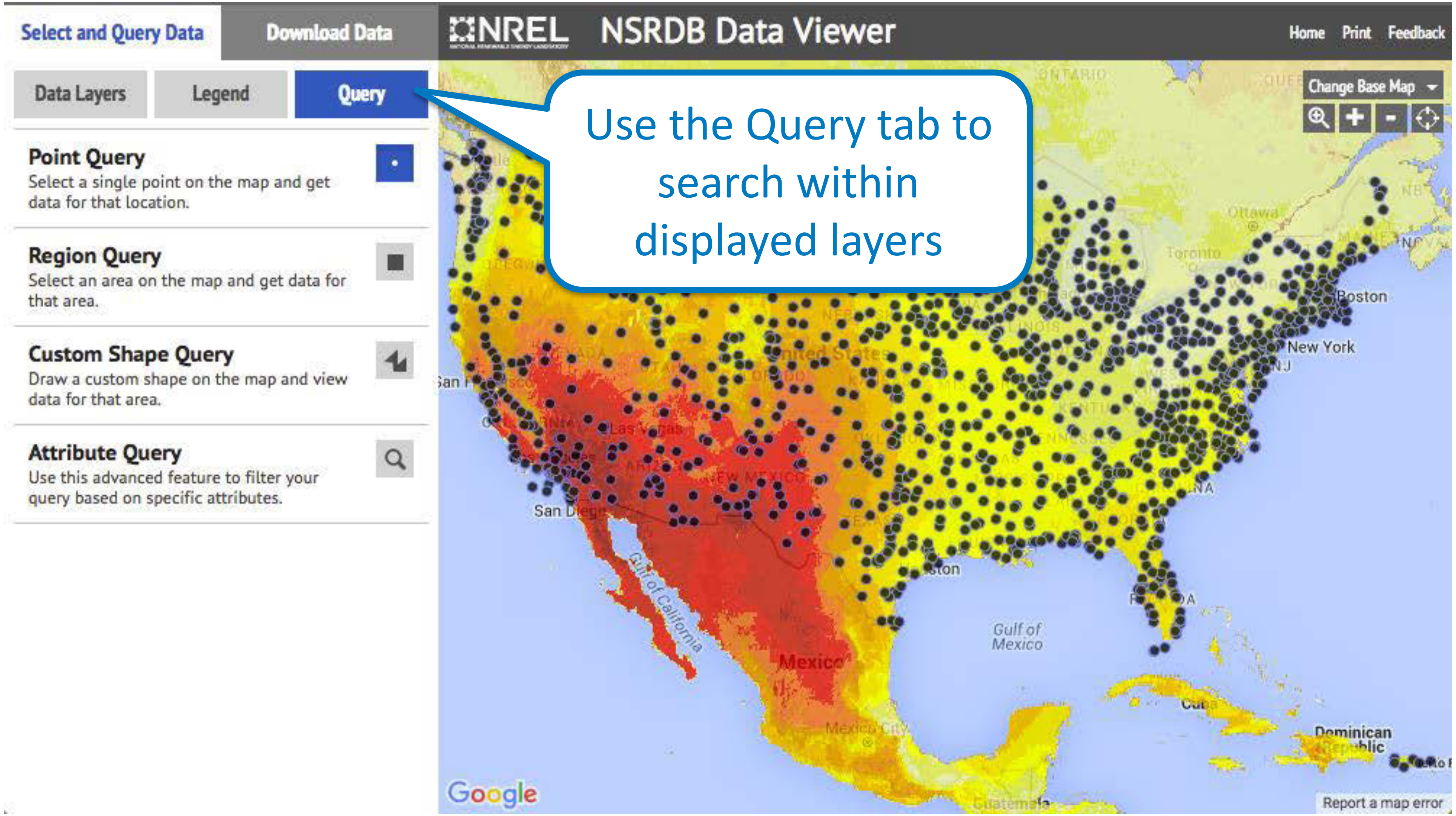
Layer Downloads



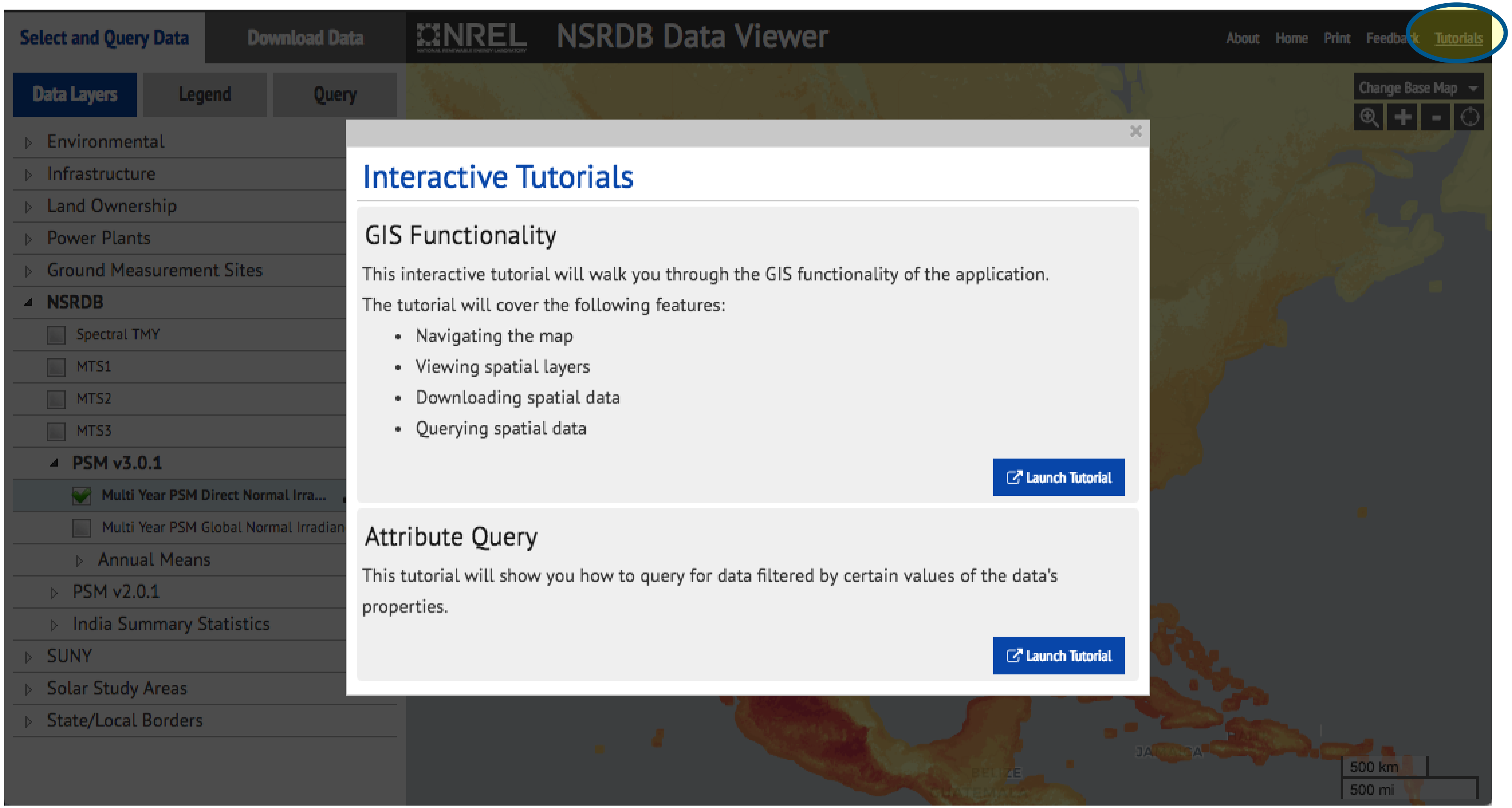
Browse Data Layers



Query Data Layers

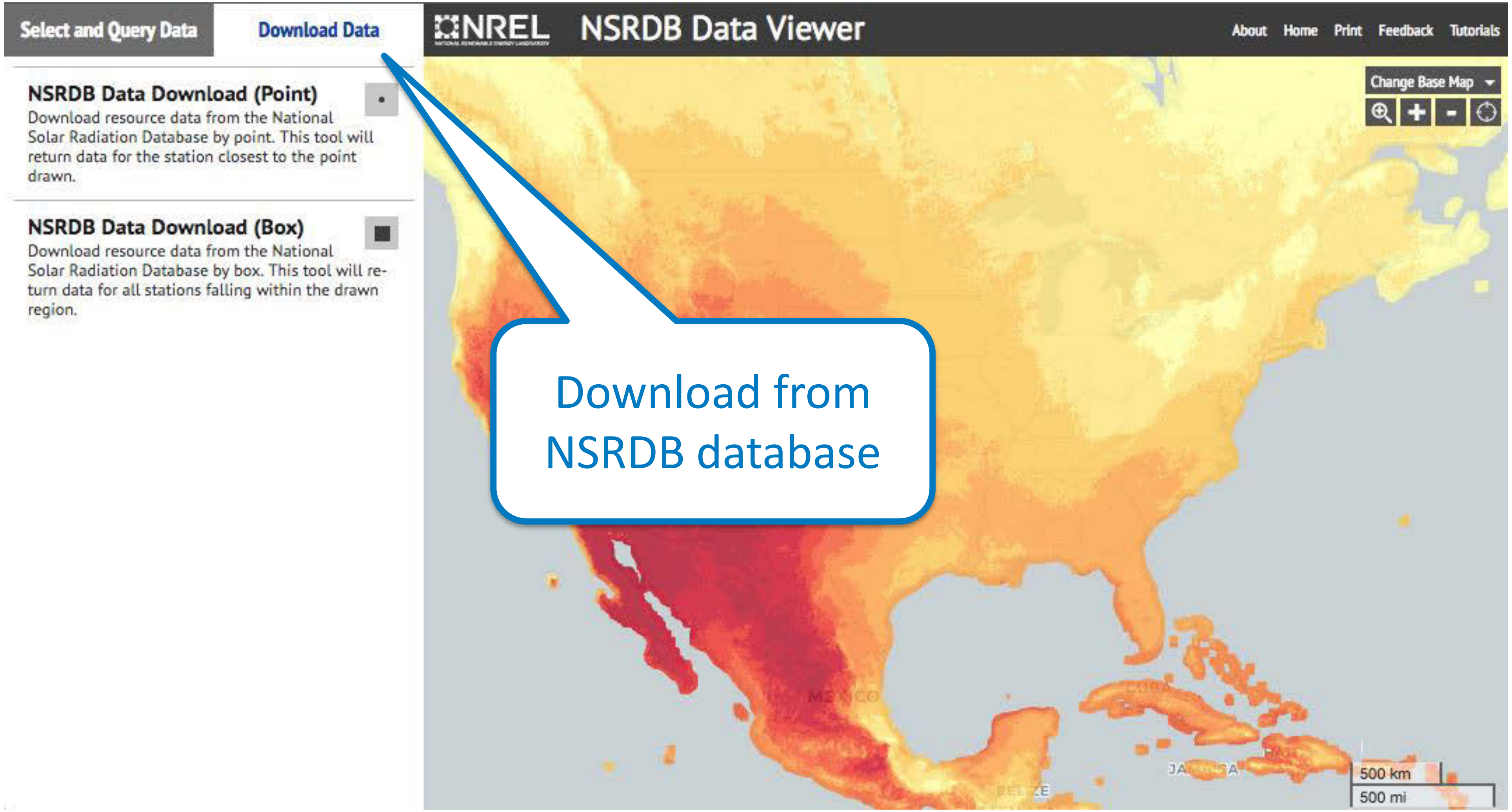


Interactive Tutorials

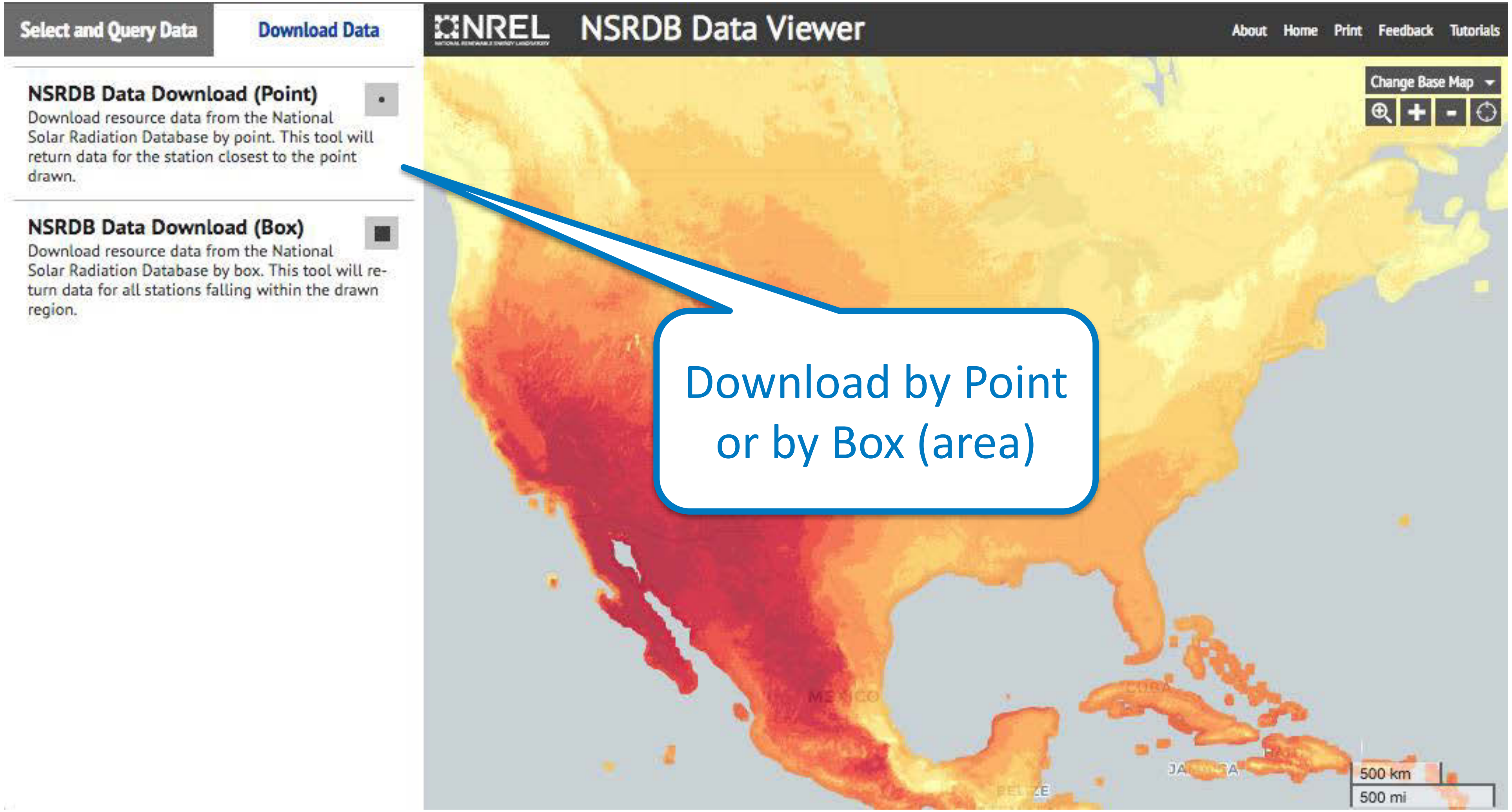


NSRDB Data Downloads

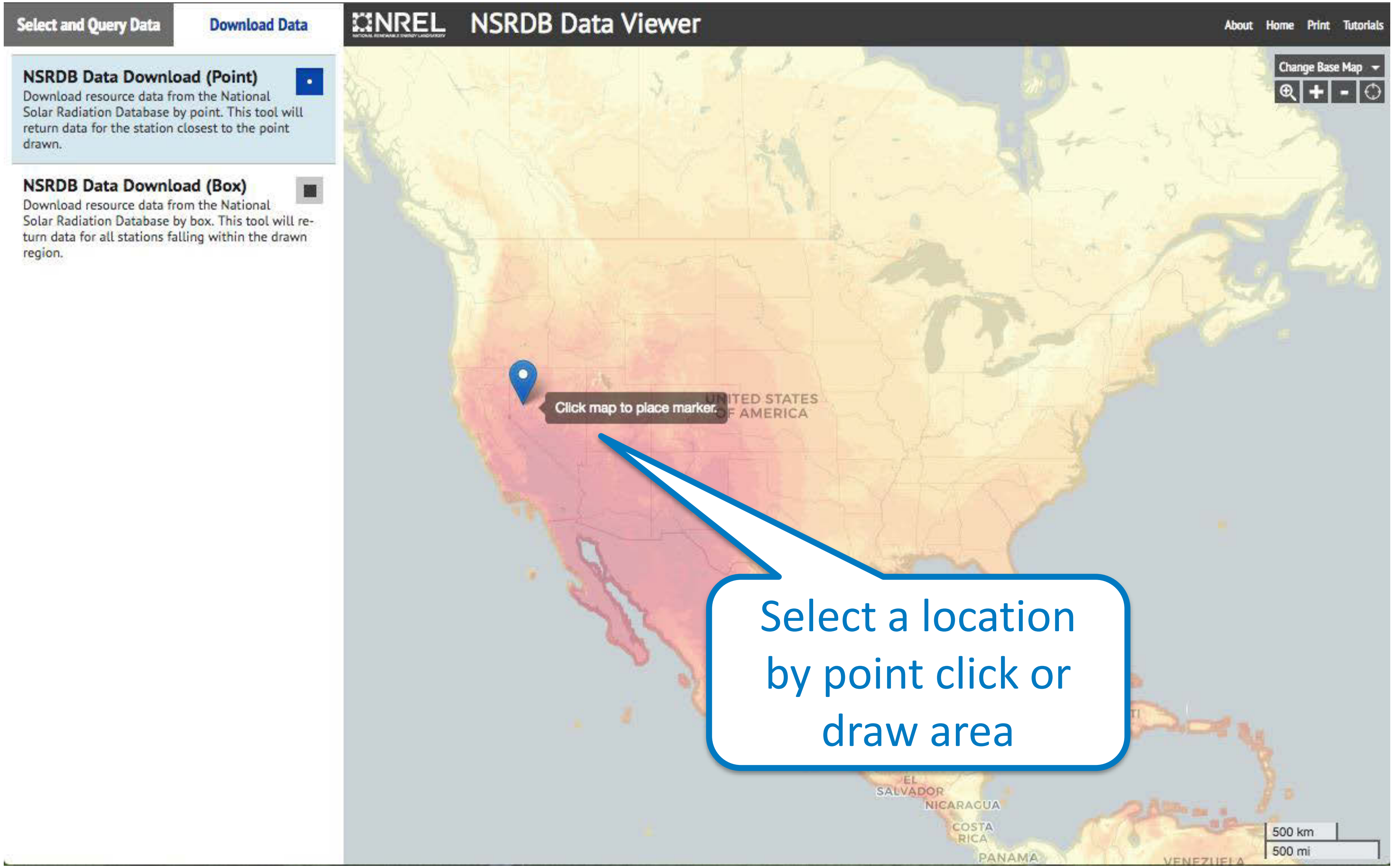
NSRDB Data Download



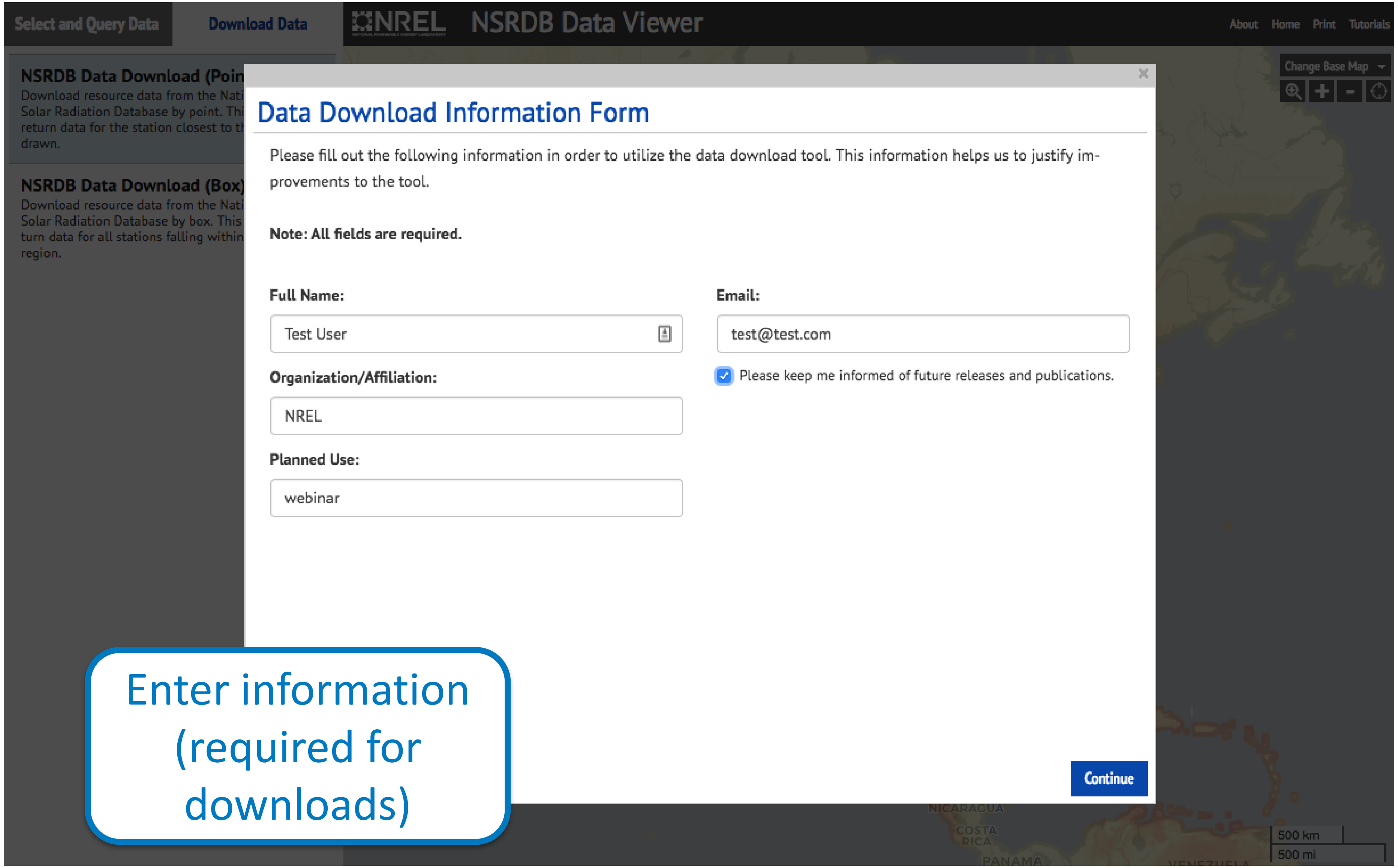
NSRDB Data Download



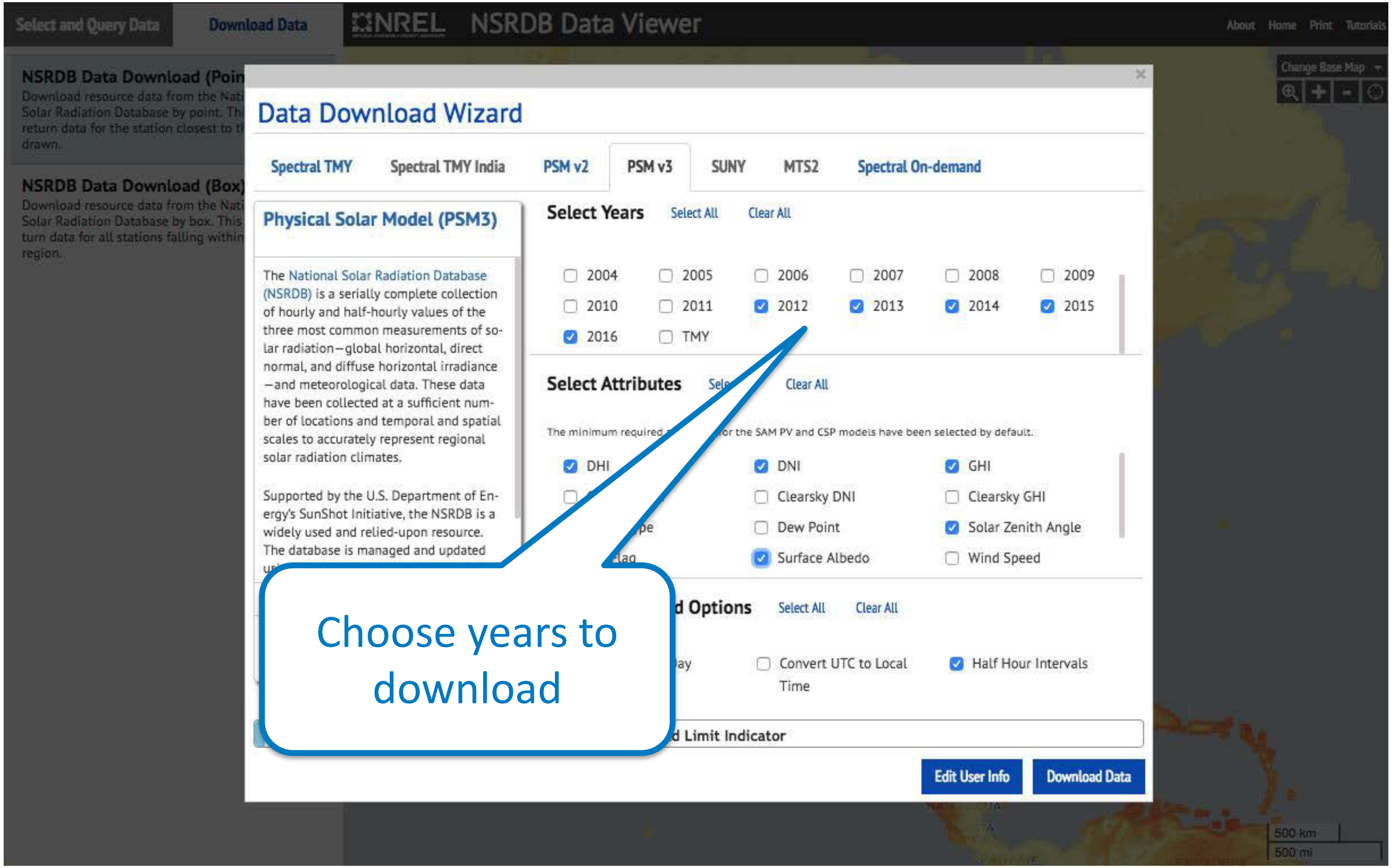
NSRDB Data Download



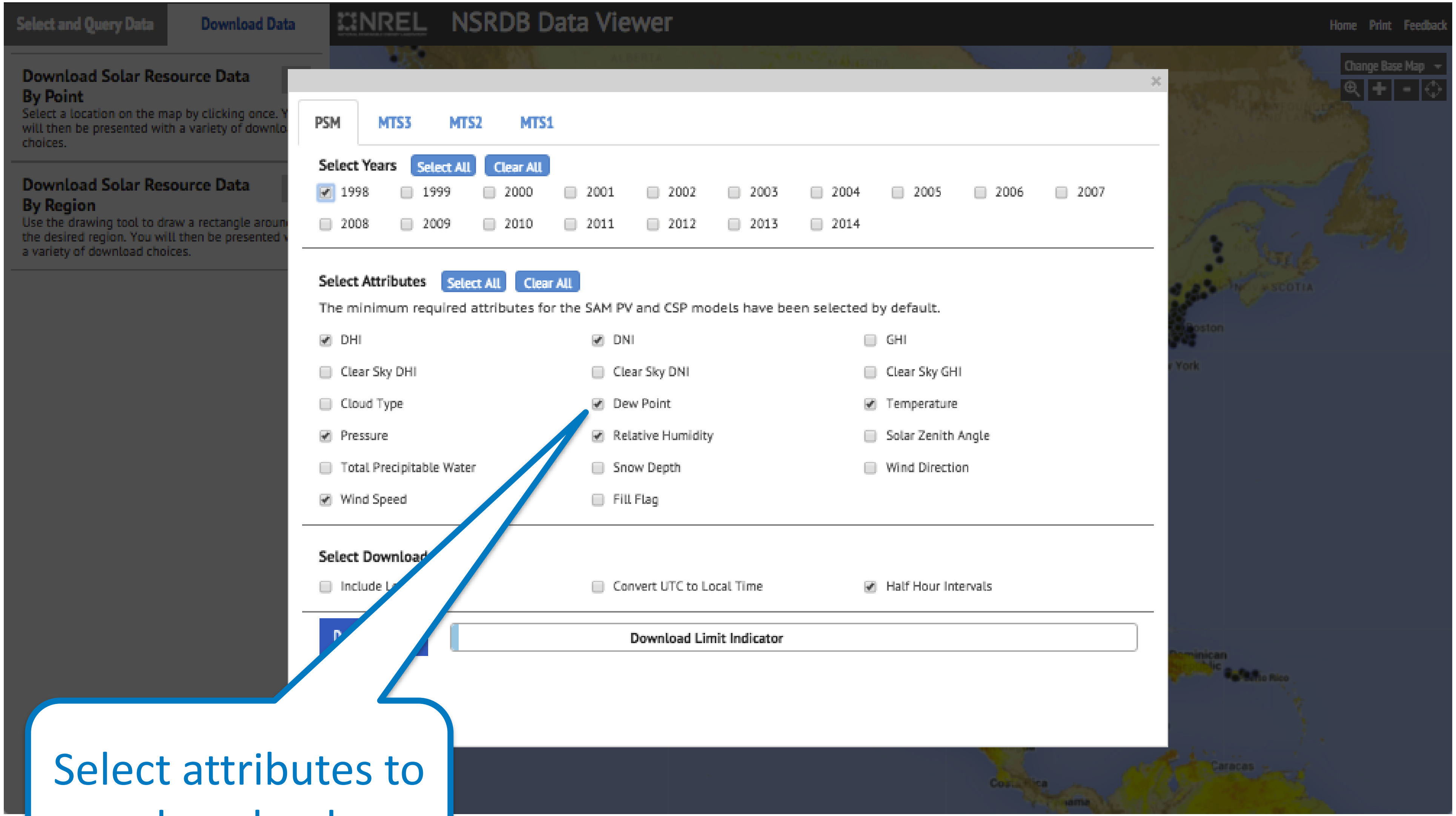
NSRDB Data Download



NSRDB Data Download

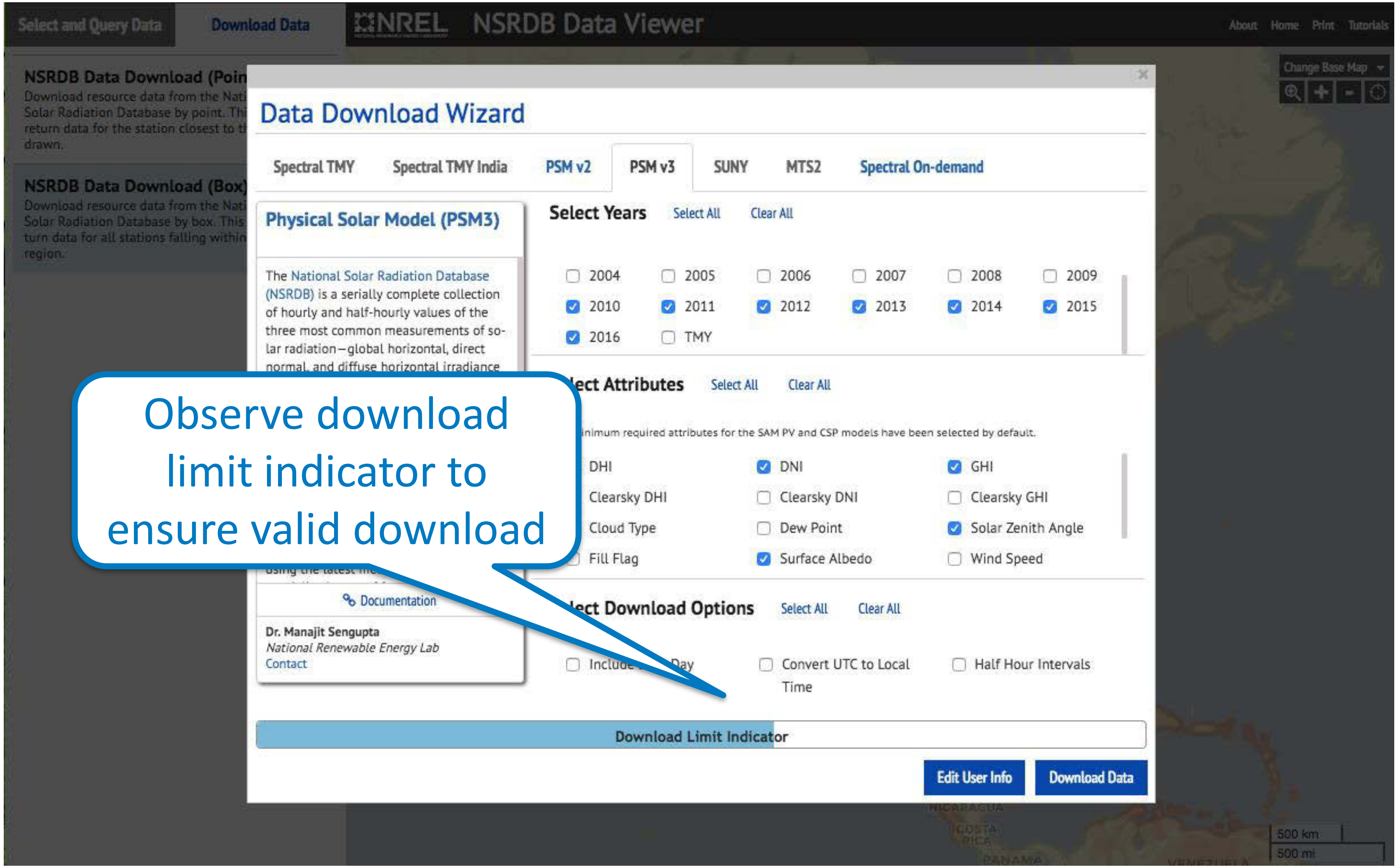


NSRDB Data Download

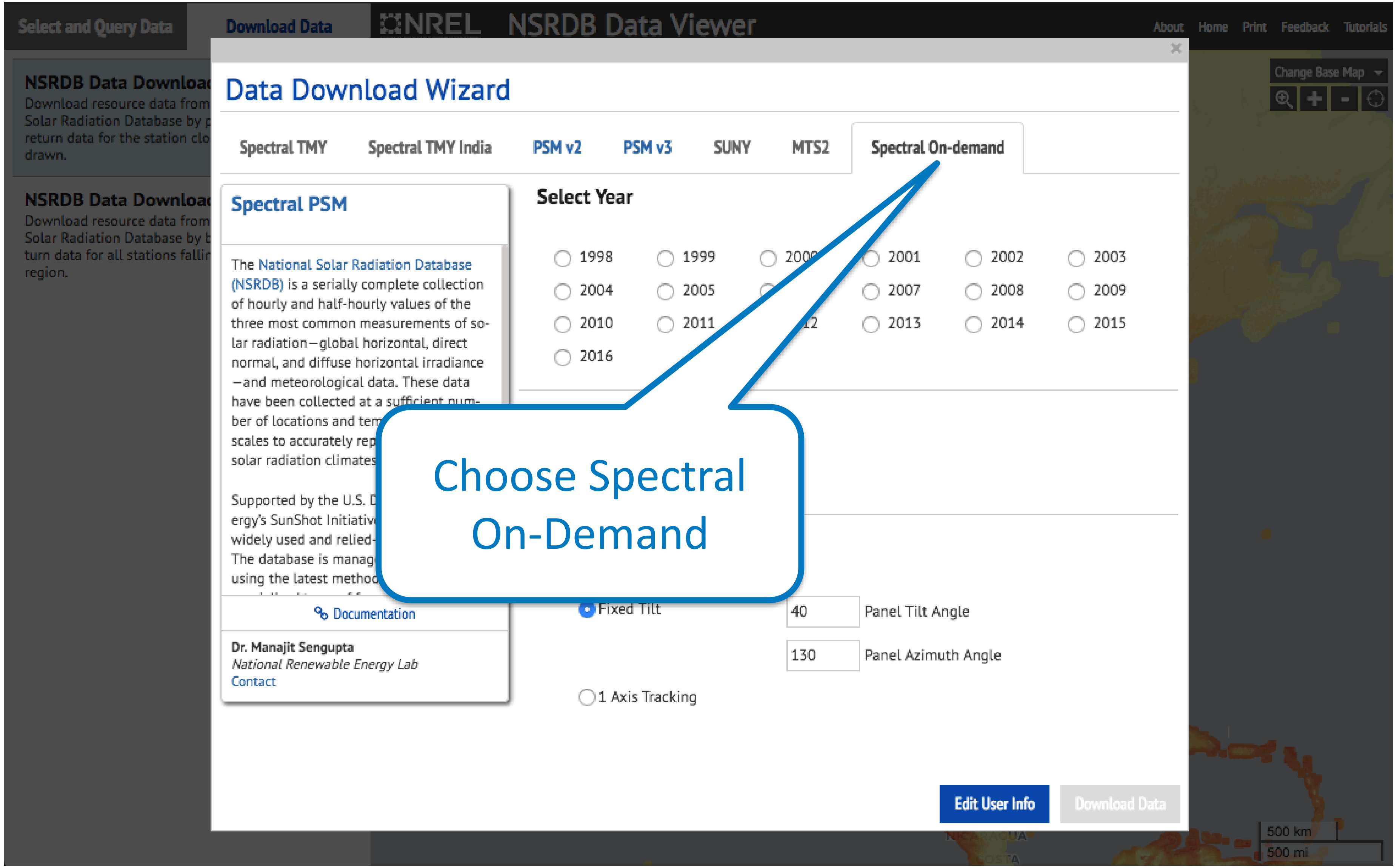


Select attributes to download

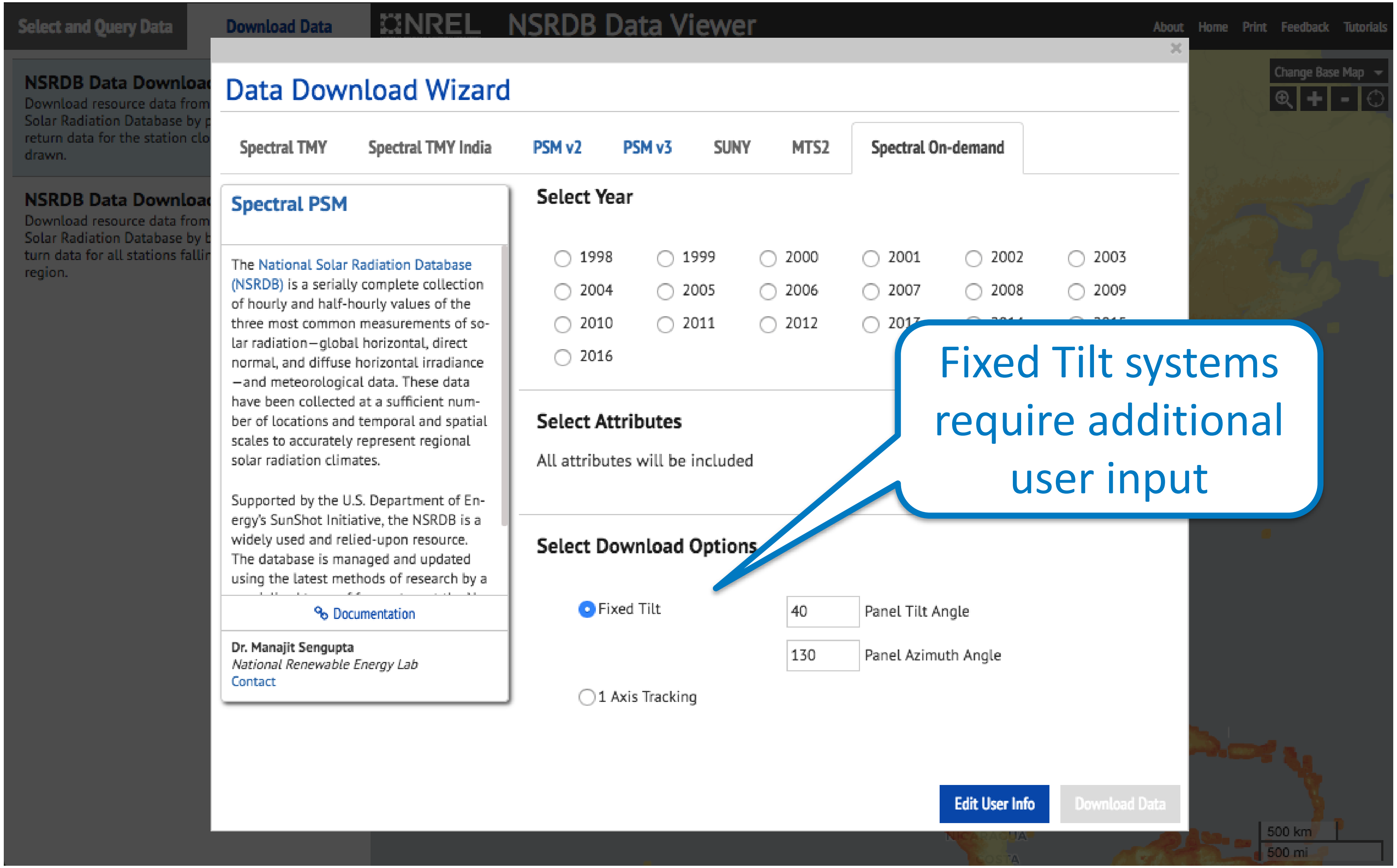
NSRDB Data Download



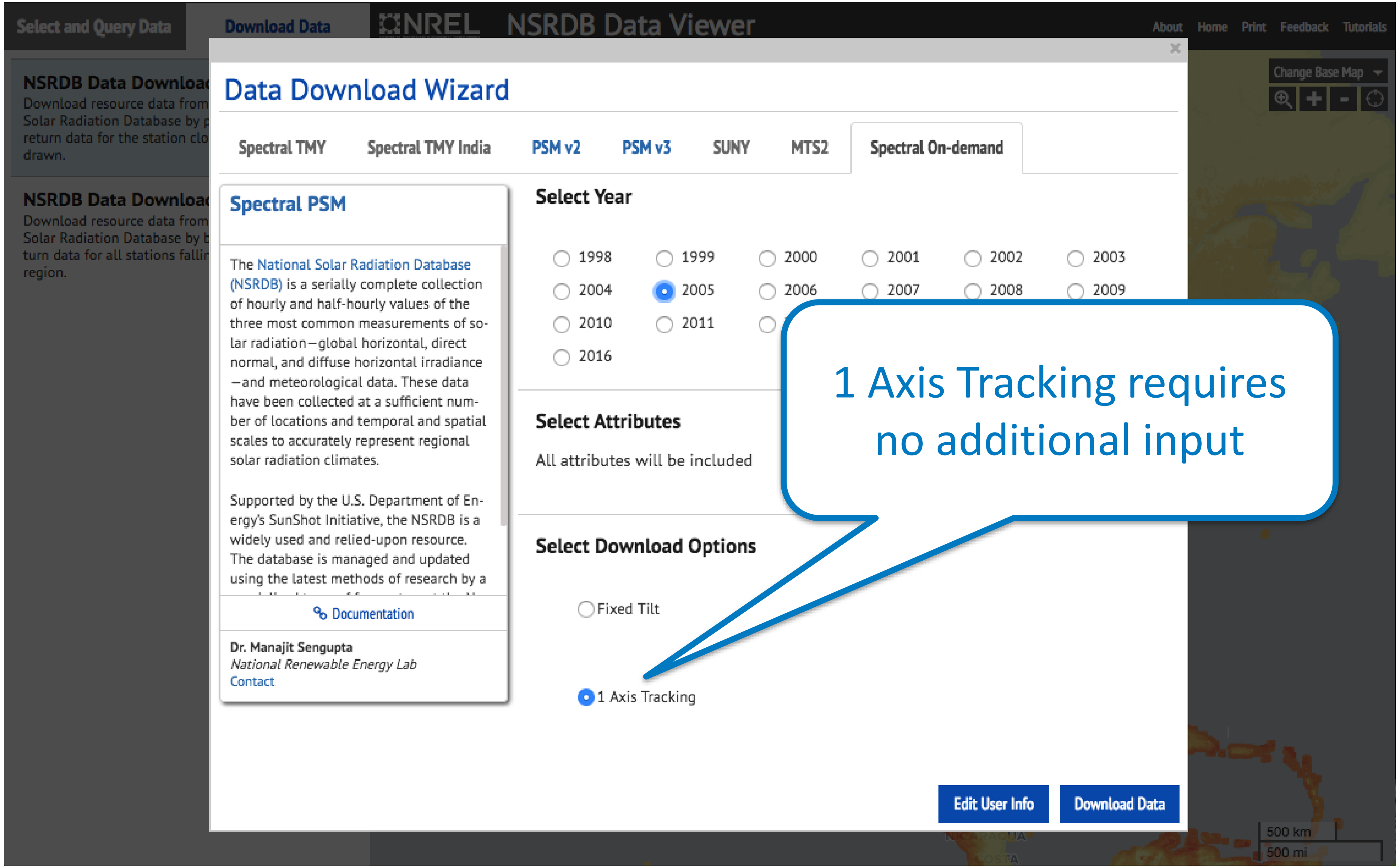
NSRDB Spectral Data Download



NSRDB Spectral Data Download



NSRDB Spectral Data Download



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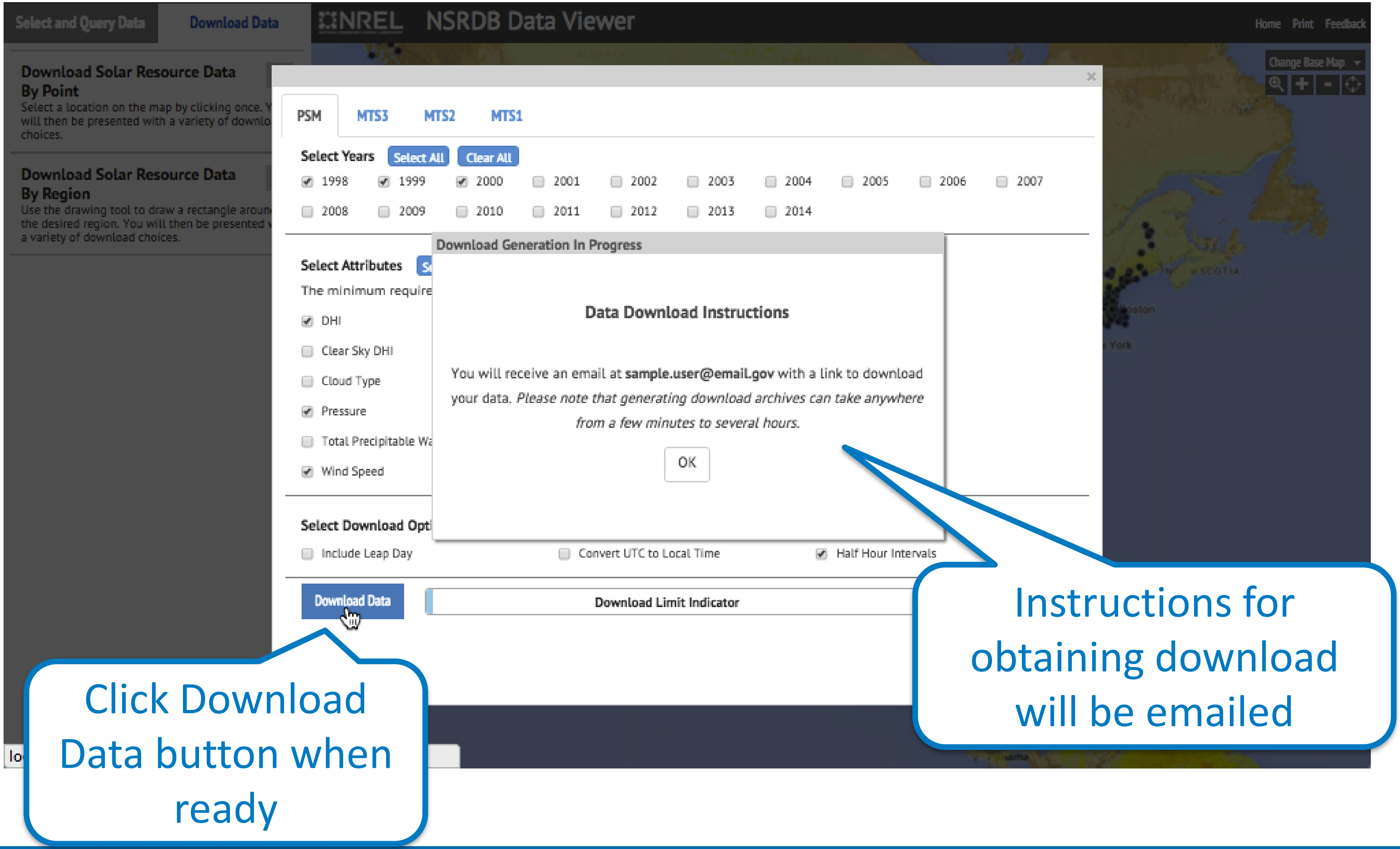

NSRDB Data Download

For downloads less than about 130 GB, a direct link to the zip file will be included in the email

no-reply@nrel.gov
to me

Your data is ready! Please click the l[...]ow to download your file. This link will remain valid for 24 hours.

https://maps-stage.nrel.gov/api/developer_proxy?site_url=solar/nsrdb_file_download&filename=bd73aab1d504c8a7889d6965b8aec79d.zip

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For full instructions on completing your download via Globus Connect, please view the page at: https://nsrdb.nrel.gov/download-instructions

Thank you for using The NSRDB Data Viewer at https://maps.nrel.gov/nsrdb-viewer

Data Format

Standard Time Series Data File Format

also known as **SAM CSV**

Header

Field	Units	Recognized Names
Latitude	degrees	*latitude,lat*
Longitude	degrees	*longitude,lon,long,lng*
Time zone	hours offset from GMT	*tz,timezone,time zone*
Site elevation	meters above sea level	*el,elev,elevation,site elevation*
Year	n/a	*year*
Location ID	n/a	*id,location,location id,station,station id,wban,wban#*
City	n/a	*city*
State	n/a	*state,province,region*
Country	n/a	*country*
Source	n/a	*source,src*
Description	n/a	*description,desc*
URL	n/a	*url*
Units flag	yes or no	*hasunits,units*
Interpolate flag	yes or no	*interpmet*

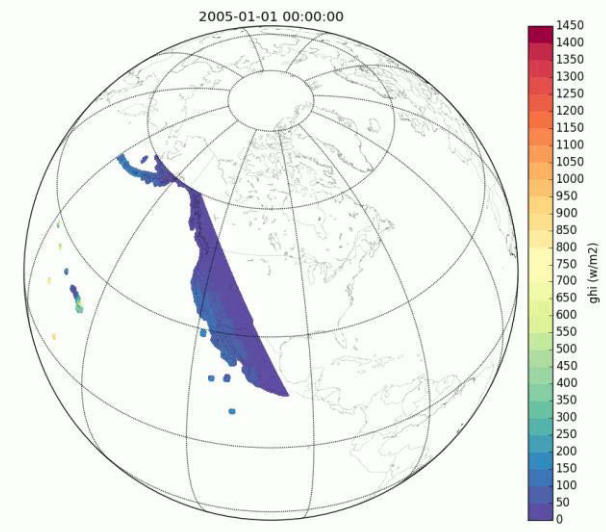
Data Format

Data Columns

Field	Units	Recognized names
Year	1950-2050	*year,yr*
Month	1-12	*month,mo*
Day	1-31	*day*
Hour	0-23	*hour,hr*
Minute	0-59	*min,minute*
Global horizontal irradiance	W/m2	*gh,ghi,global,global horizontal,global horizontal irradiance*
Beam normal irradiance	W/m2	*dn,dni,beam,direct normal,direct normal irradiance*
Diffuse horizontal irradiance	W/m2	*df,dhi,diffuse,diffuse horizontal,diffuse horizontal irradiance*
Ambient dry bulb temperature	C	*tdry,dry bulb,dry bulb temp,temperature,ambient,ambient temp*
Wet bulb temperature	C	*twet,wet bulb,wet bulb temperature*
Dew point temperature	C	*tdew,dew point,dew point temperature*
Wind speed	m/s	*wspd,wind speed*
Wind direction	deg	*wdir,wind direction*
Relative humidity	%	*rh,rhum,relative humidity,humidity*
Atmospheric pressure	millibar	*pres,pressure*
Snow cover	cm	*snow,snow cover,snow depth*
Ground reflectance (albedo)	0..1	*albedo,alb*
Aerosol optical depth	0..1	*aod,aerosol,aerosol optical depth*

Future Work

- Improved identification and use of high albedo surfaces (sand and snow).
- Improved cloud retrievals from GOES-16.
- Aerosol retrieval from GOES-16.
- 5-min. data from GOES-16.



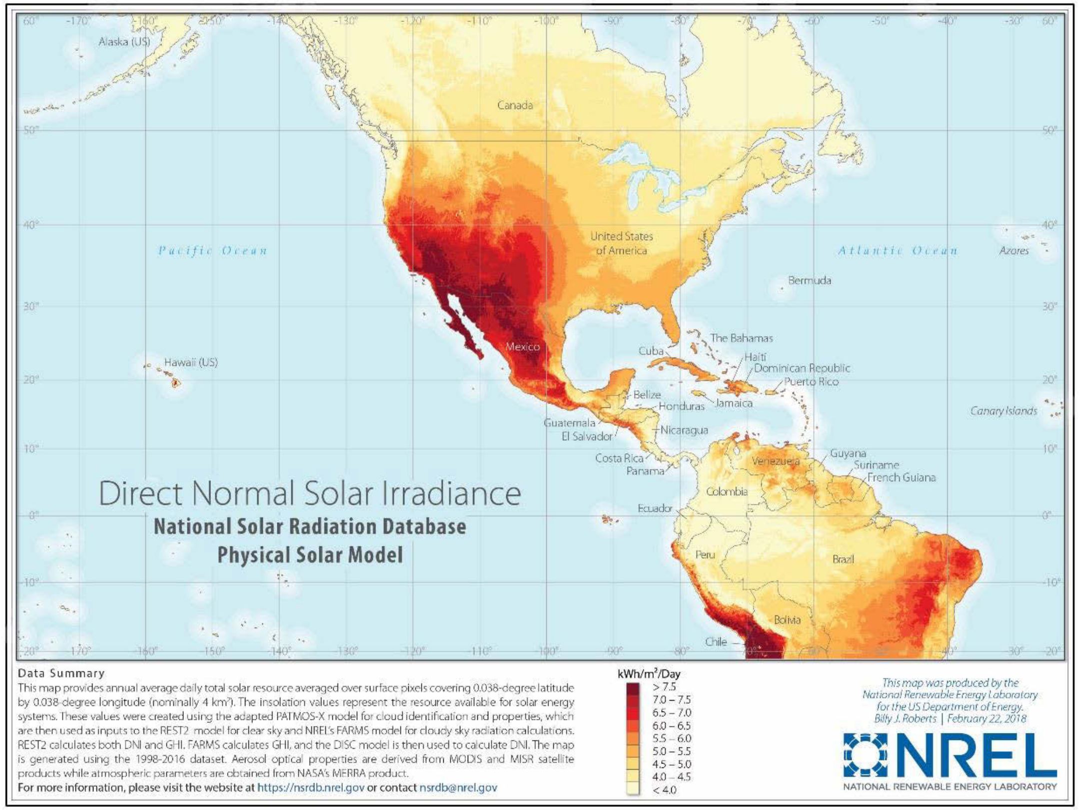
http://nsrdb.nrel.gov

Thank You!

Email questions to: nsrdb@nrel.gov

https://www.sciencedirect.com/journal/renewable-and-sustainable-energy-reviews/vol/89/suppl/C

NSRDB: http://nsrdb.nrel.gov



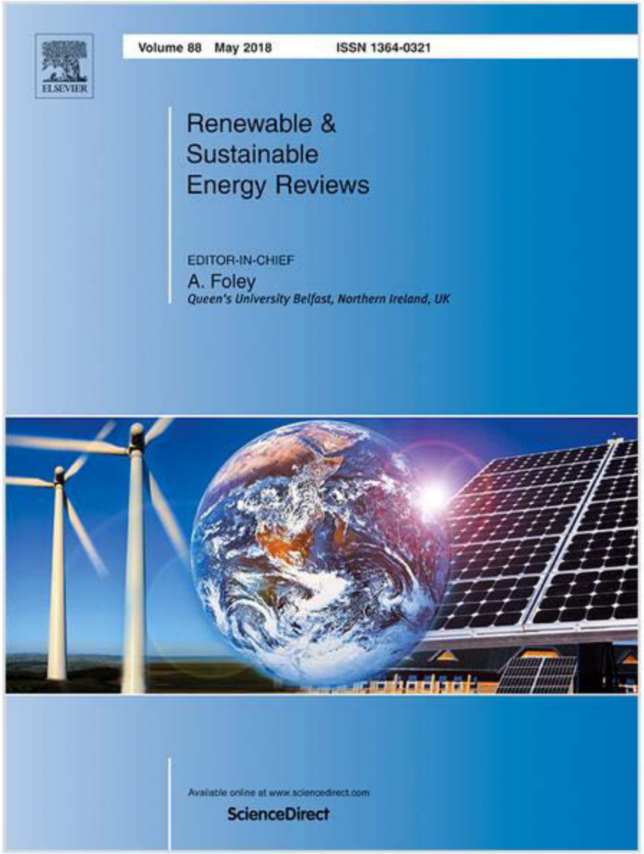
The National Solar Radiation Data Base (NSRDB)

Review article

Pages 51-60

Manajit Sengupta, Yu Xie, Anthony Lopez, Aron Habte, ... James Shelby

Download PDF   Article preview



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REopt Platform and Web Tool Overview for Solar Power International

Emma Elgqvist, NREL

September 24, 2018

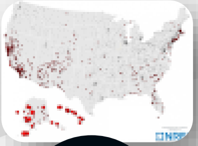
History of REopt™

REopt evolved from an RE screening tool to a platform for energy systems integration and optimization

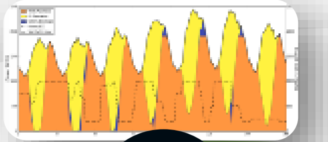
Key capabilities

2007
- Renewable energy integration & optimization

2009
- Portfolio planning
- Net zero analysis



2011
- Mixed integer linear program
- Time series simulation



2013
- Microgrid design
- Energy storage
- Operational energy

2015
- EERE optimization
- Stochastic outage analysis
- Dispatching existing assets

2017
- Web tool
- Macro-economic analysis
- Energy/water nexus

10 sites

100 sites

10,000 sites

100,000+ sites

81

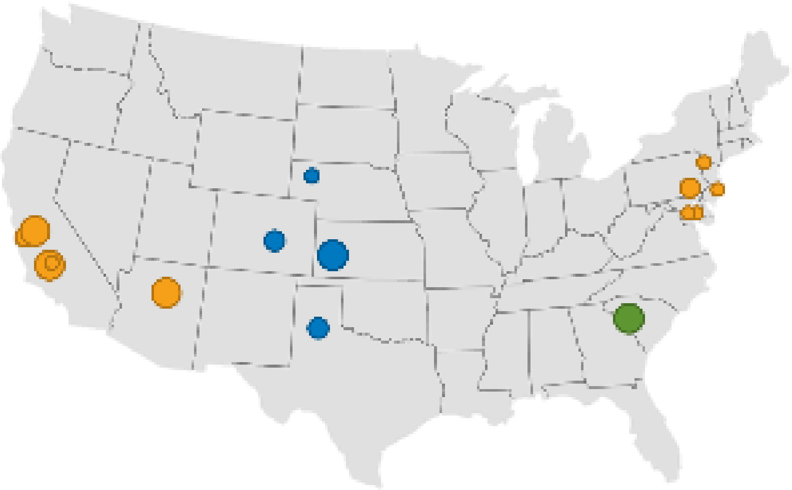
Decision Support through Energy Planning Process

Optimization • Integration • Automation

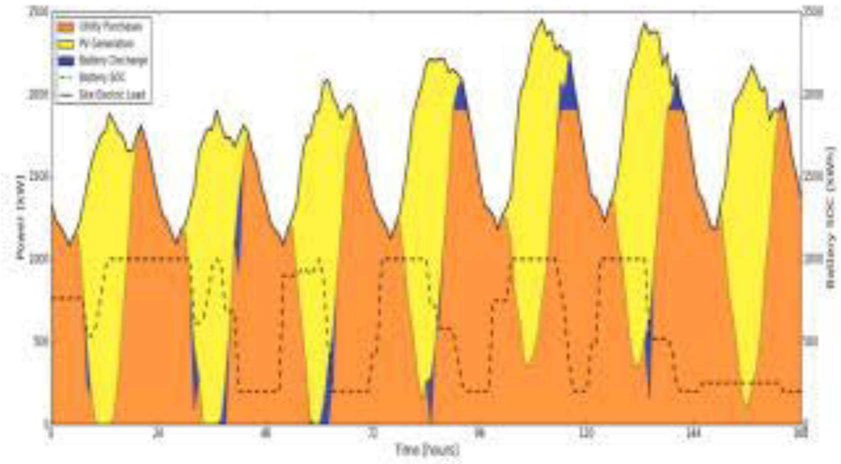
- Portfolio prioritization
- Cost to meet goals

- RE and storage interaction
- Optimal operating strategies

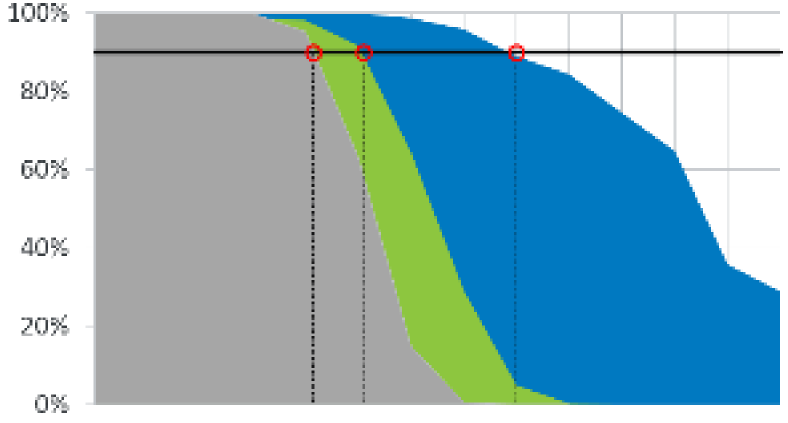
- Microgrid dispatch
- Energy security evaluation



Cost-effective RE at Army bases

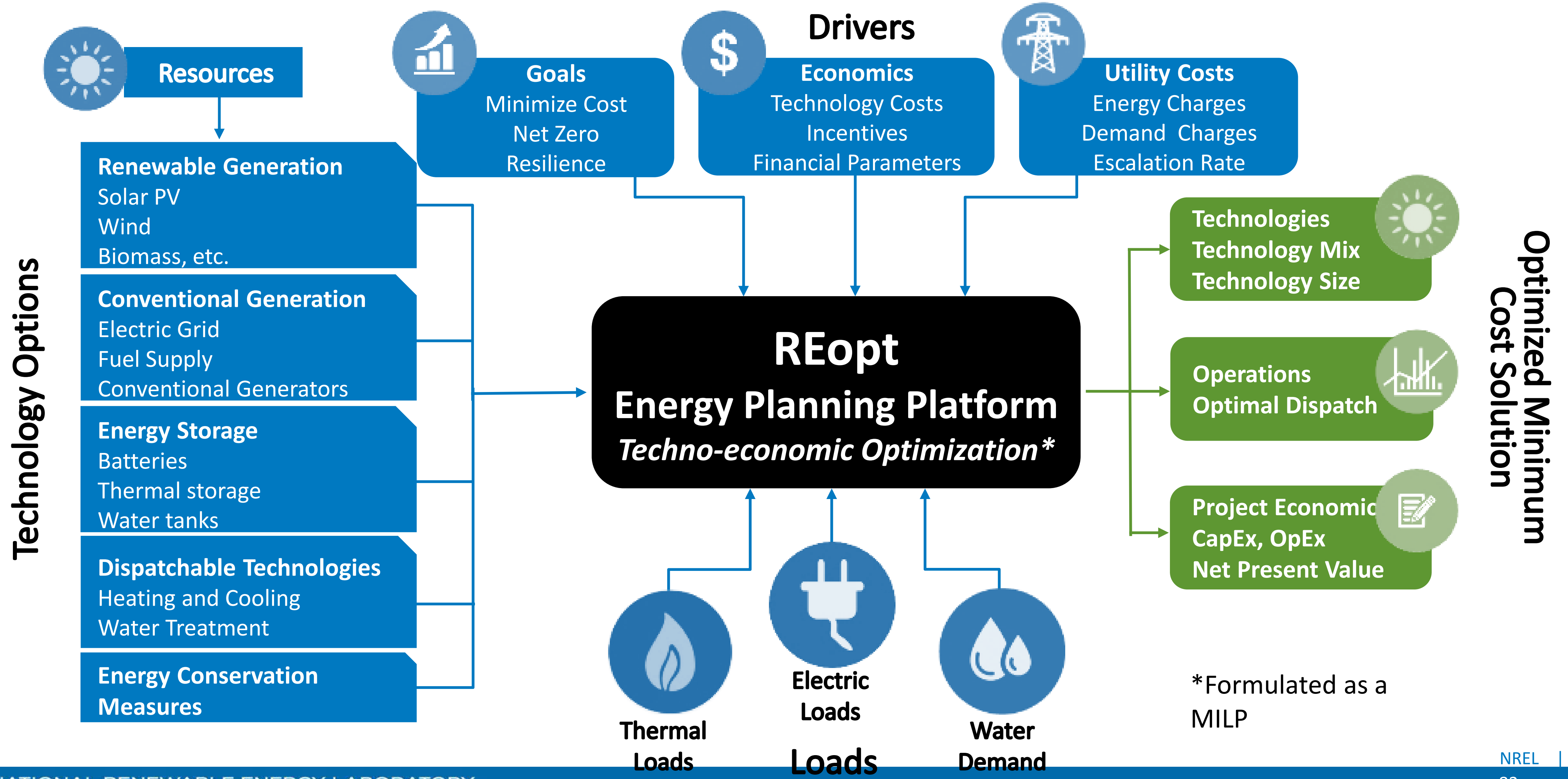


Cost-optimal Operating Strategy



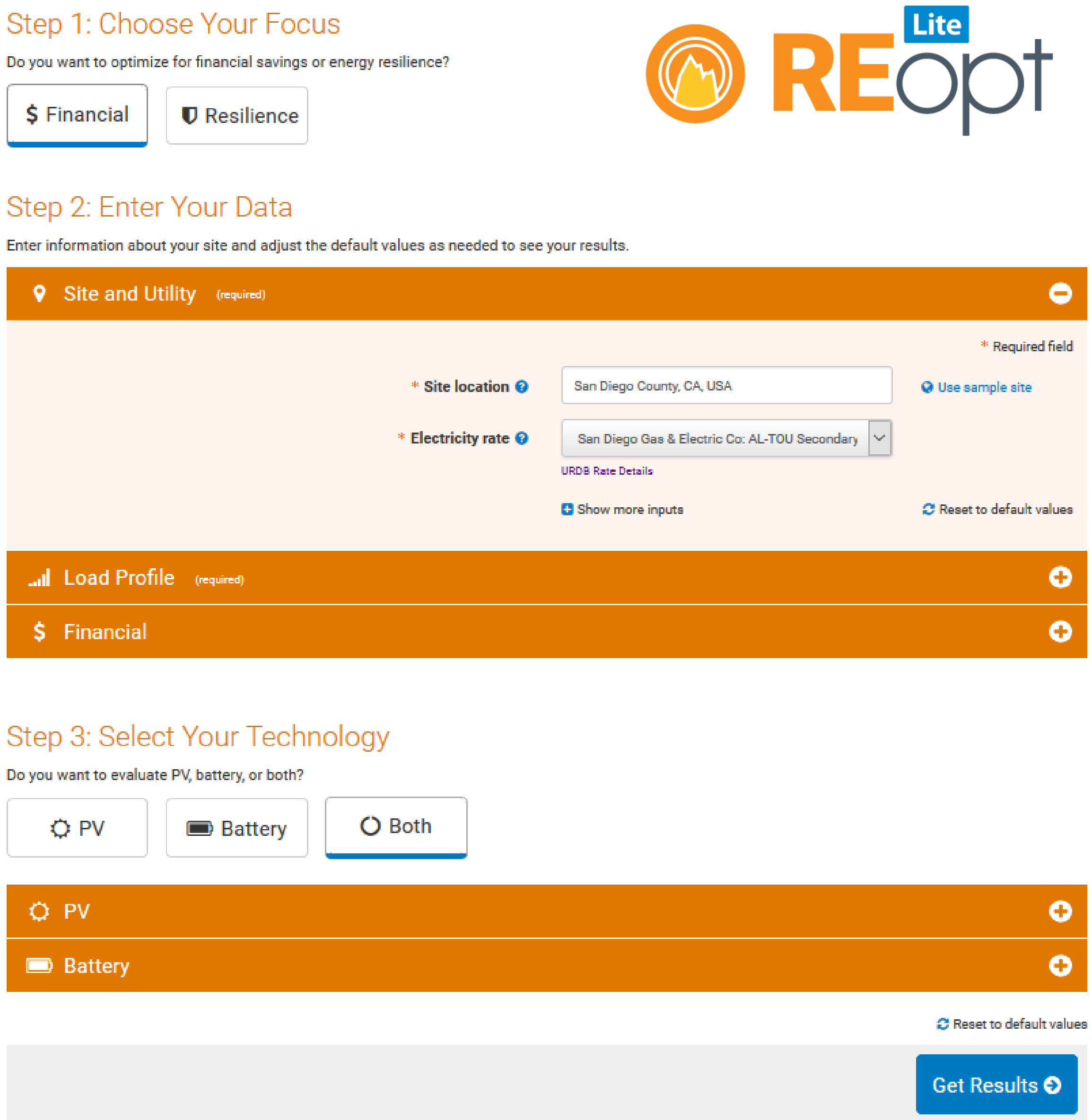
Extending Resiliency with RE

REopt Platform Inputs and Output

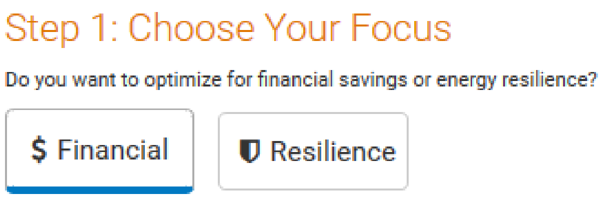


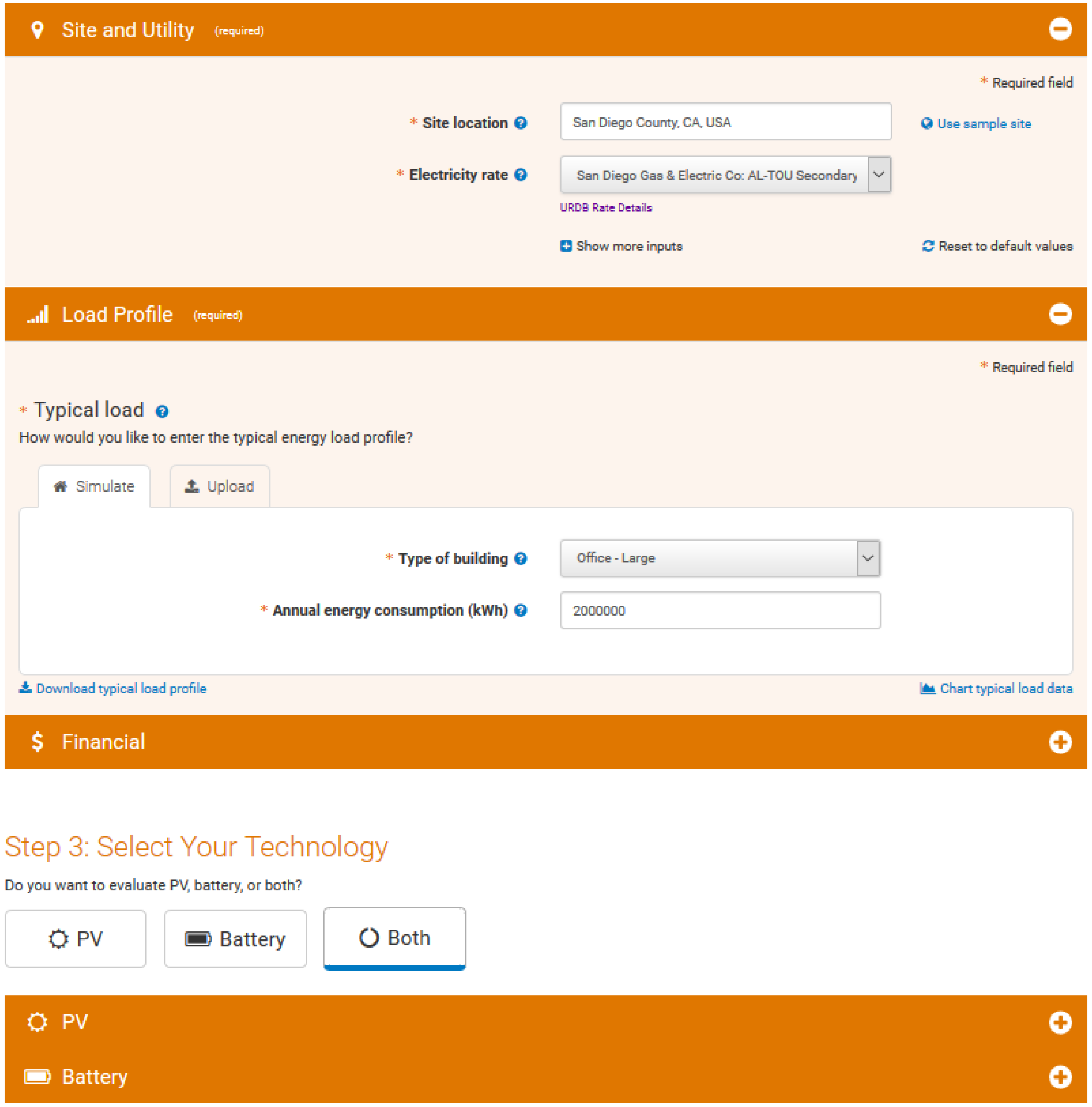
REopt Lite Web Tool

- The REopt Lite Web Tool offers a no-cost subset of NREL's more comprehensive REopt model
- Beta version of web tool launched September 2017; additional features added through 2018 and beyond
- **Financial mode** optimizes PV and battery system sizes and battery dispatch strategy to minimize life cycle cost of energy
- **Resilience mode** sizes PV+storage systems to sustain critical load during grid outages



Required Site Specific Inputs (Financial Mode)



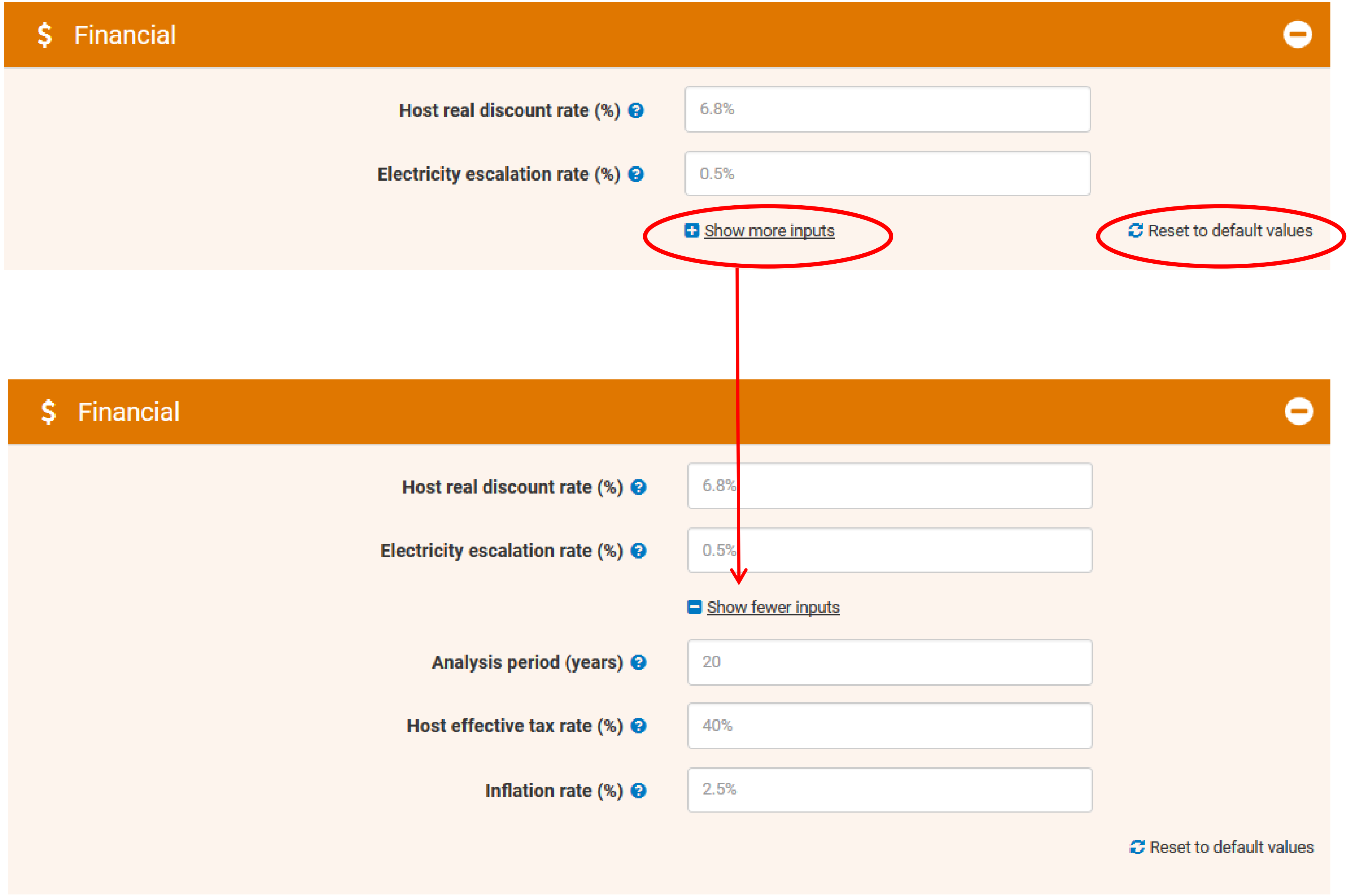


Location and utility rate

Load profile – simulated or actual

Technologies to evaluate

Additional Inputs Can Be Edited, Or Left As Defaults



Summary Results Include System Sizes and Savings

Results for Your Site

These results from REopt Lite summarize the economic viability of PV and battery storage at your site. You can edit your inputs to see how changes to your energy strategies affect the results.

Edit Inputs

REopt Lite

Your recommended solar installation size

781 kW
PV size

Measured in kilowatts (kW) of direct current, this recommended size minimizes the life cycle cost of energy at your site.

Your recommended battery power and capacity

131 kW
battery power

556 kWh
battery capacity

This system size minimizes the life cycle cost of energy at your site. The battery power and capacity are optimized for economic performance.

Your potential life cycle savings (20 years)

This is the net present value of the savings (or costs if negative) realized by the project based on the difference between the life cycle energy cost of doing business as usual compared to the optimal case.

$439,275

Additional Results Output: Economics Summary

	Business As Usual	Optimal Case	Difference
System Size, Energy Production, and System Cost			
PV Size	0 kW	392 kW	392 kW
Annualized PV Energy Production	0 kWh	680,826 kWh	680,826 kWh
Battery Power	0 kW	93 kW	93 kW
Battery Capacity	0 kWh	342 kWh	342 kWh
DG System Cost (Net CAPEX + O&M)	$0	$526,342	$526,342
Energy Supplied From Grid in Year 1	1,000,000 kWh	358,623 kWh	641,377 kWh
Year 1 Utility Cost — Before Tax			
Utility Energy Cost	$118,263	$34,216	$84,047
Utility Demand Cost	$40,008	$18,623	$21,385
Utility Fixed Cost	$3,110	$3,110	$0
Utility Minimum Cost Adder	$0	$0	$0
Life Cycle Utility Cost — After Tax			
Utility Energy Cost	$857,868	$248,200	$609,668
Utility Demand Cost	$290,213	$135,089	$155,124
Utility Fixed Cost	$22,562	$22,562	$0
Utility Minimum Cost Adder	$0	$0	$0
Total System and Life Cycle Utility Cost — After Tax			
Life Cycle Energy Cost	$1,170,644	$932,194	$238,450
Net Present Value	$0	$238,450	$238,450

Download ProForma Spreadsheet

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Additional Results Output: Hourly Dispatch Graph

Thank You!

Emma Elgqvist, NREL

Emma.Elgqvist@nrel.gov

www.nrel.gov

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NATIONAL RENEWABLE ENERGY LABORATORY

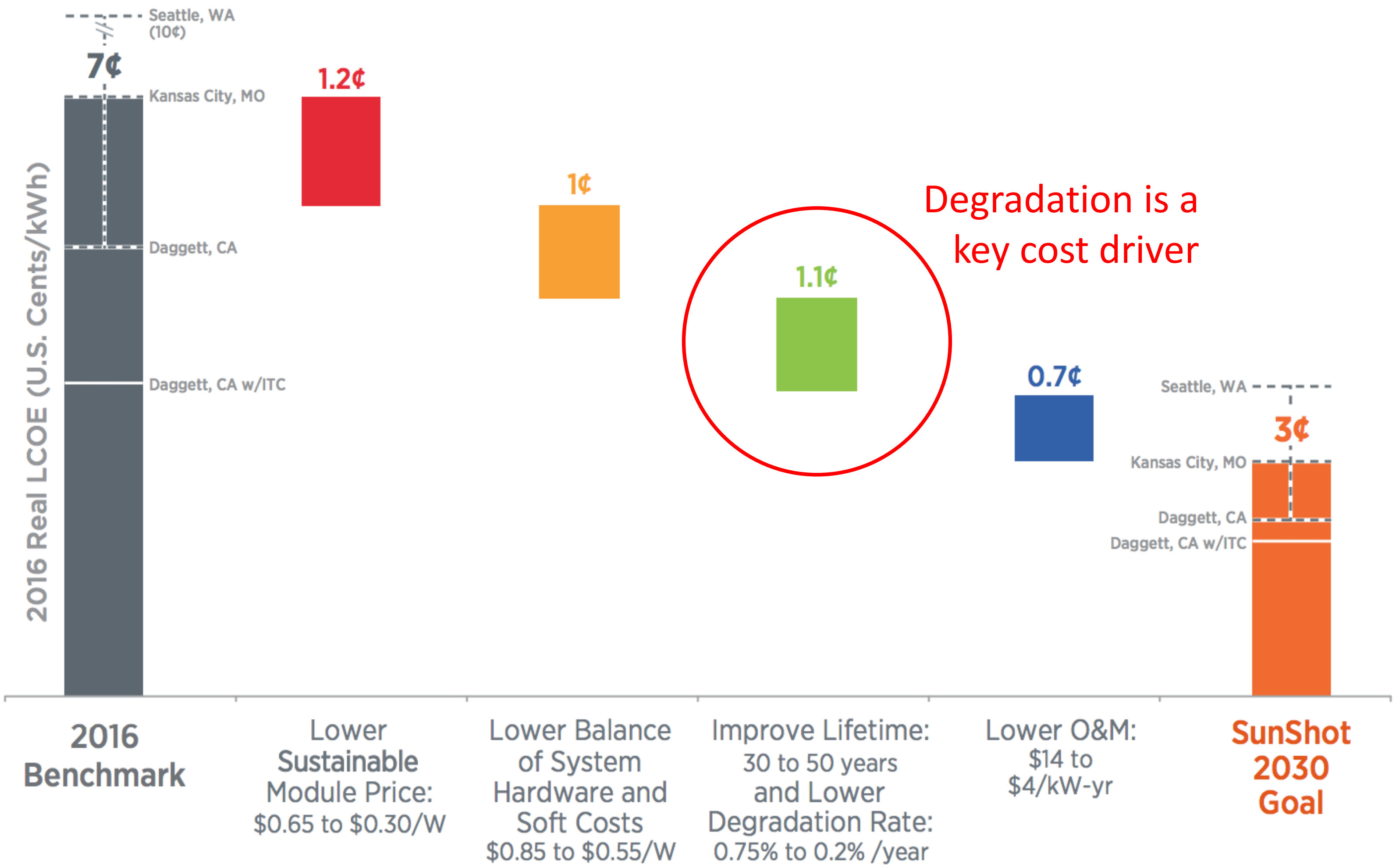
Fleet-scale photovoltaic system degradation analysis applied to hundreds of residential and non-residential PV systems

Michael G. Deceglie[1], Dirk C. Jordan[1], Ambarish Nag[1],
Adam Shinn[2], and Chris Deline[1]

[1]National Renewable Energy Laboratory
[2]kWh Analytics

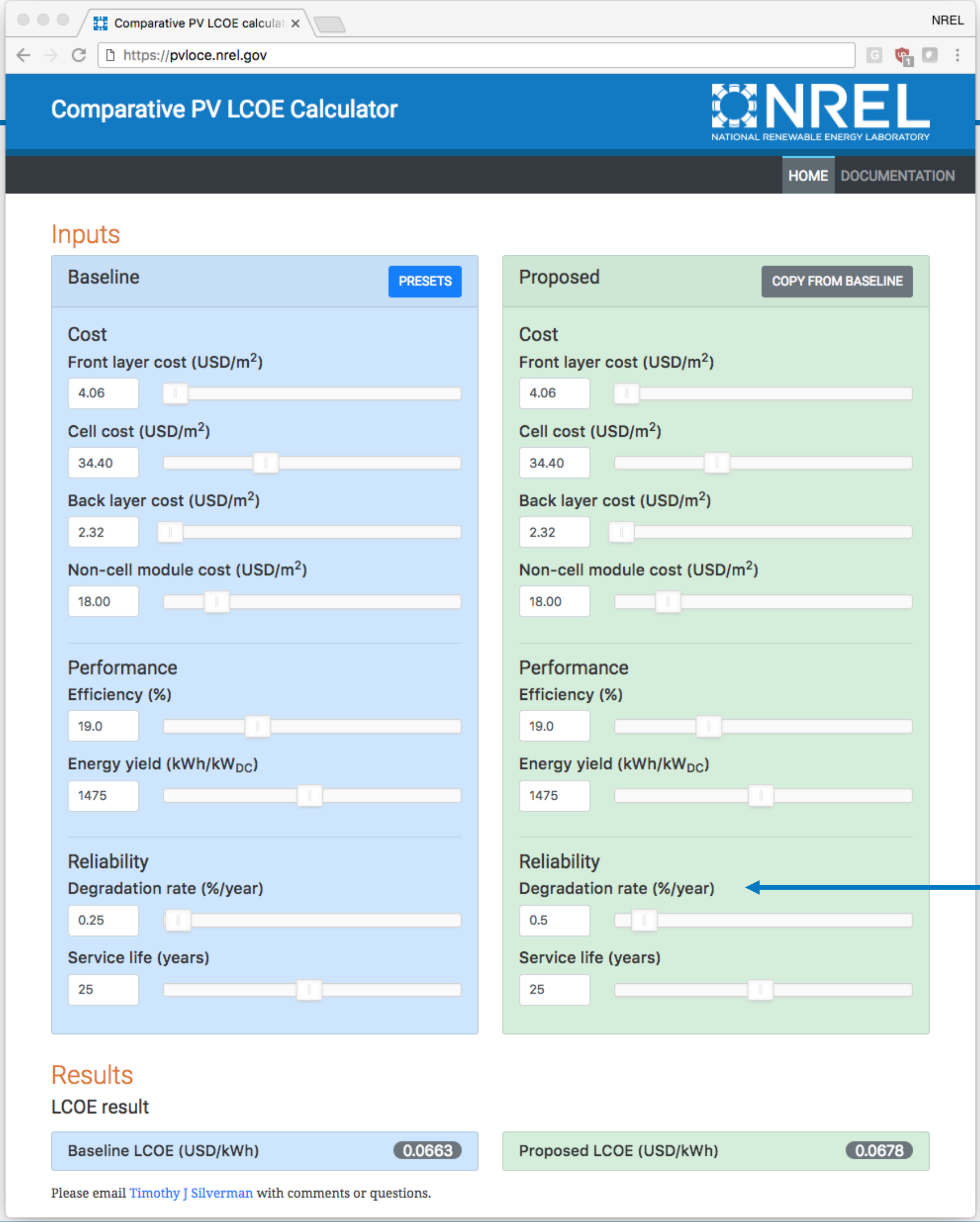
Originally presented at WCPEC 2018

Importance of degradation rate



Degradation is a key cost driver

US Dept. of Energy, SunShot 2030 factsheet



Degradation rate is also important in modeling financials

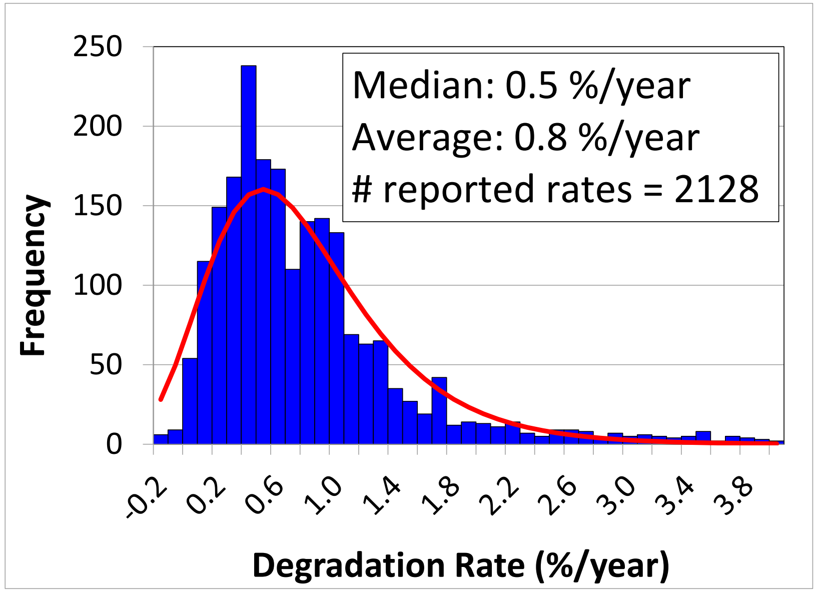
What degradation rate should I use?

pvlcoe.nrel.gov

Reported degradation rates

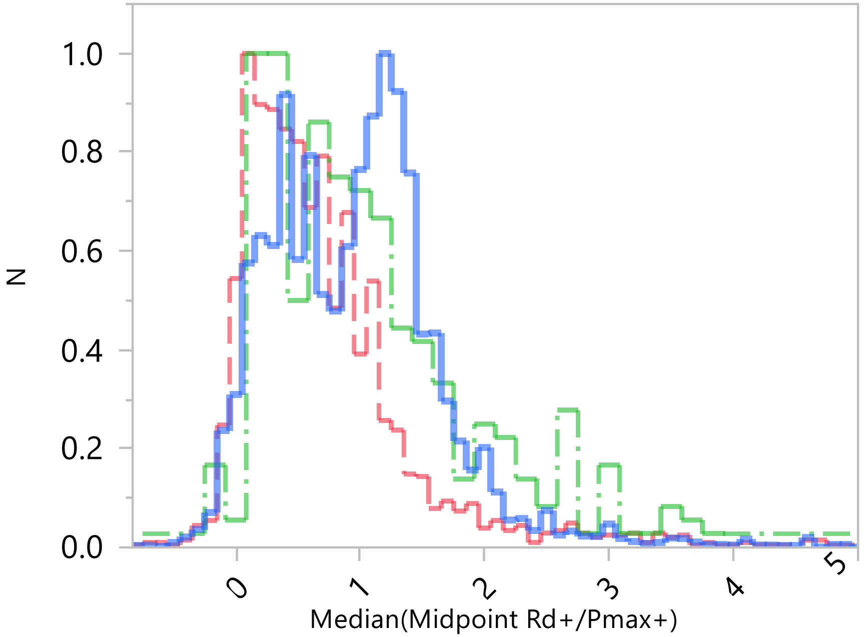
Literature survey

2011



Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

2016

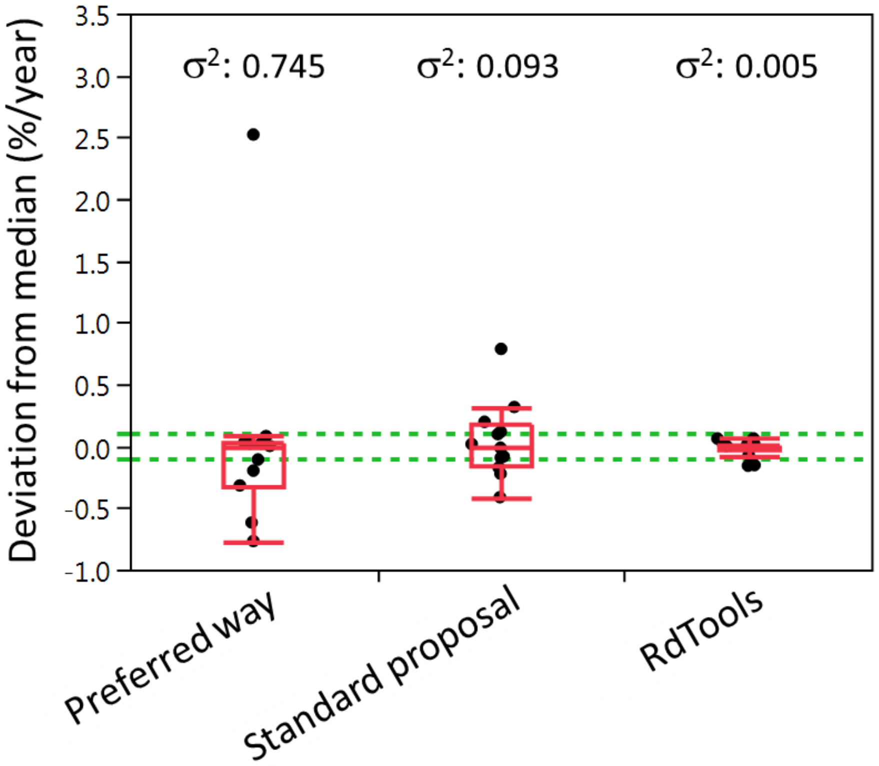


Jordan et al., "Compendium of photovoltaic degradation rates", Progress in PV, 2016

- The literature includes a variety of methods.
- Different methods can lead to bias.
- Large variation because of a lot of different factors such as method, technology, quality, climate, mounting etc. makes it difficult to draw large-scale conclusions.

Improving consistency

Different analysts analyzing the same data sets



With RdTools we can improve accuracy significantly over written procedures or analysts preferred way.

We an open source software library (RdTools) for retrospective analysis of PV system degradation.
more info: https://www.nrel.gov/pv/rdtools.html

Today’s talk

- Our methods and the open-source software we’ve developed to implement them
- Example fleet-scale analysis of 500+ PV systems
  - Differences in shade, technology, system age, and temperature

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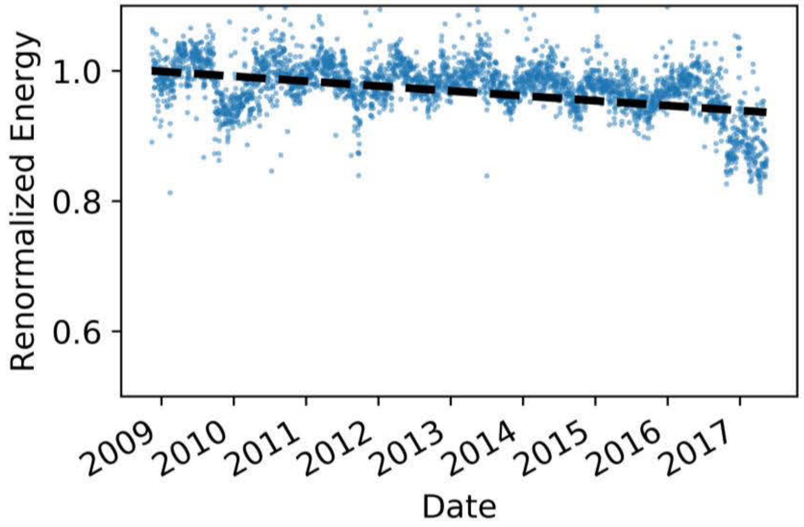
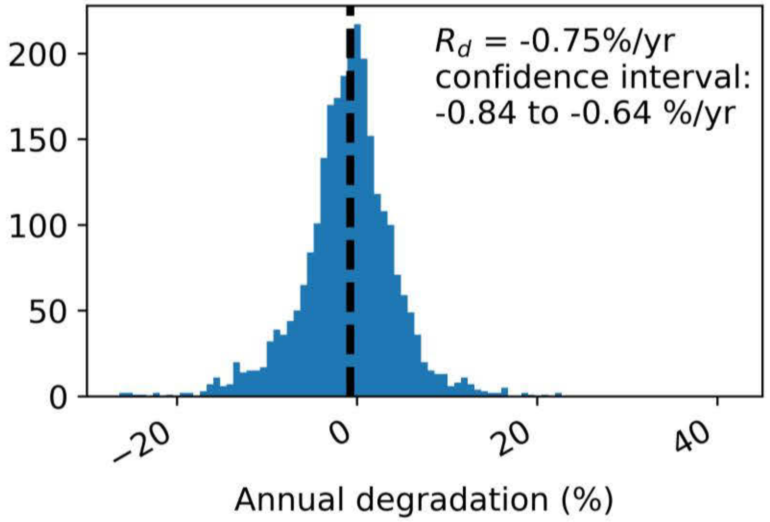
Our approach

Time series performance data → Degradation rate and uncertainty





- Built with RdTools https://www.nrel.gov/pv/rdtools.html
  - Open-source python module for PV data analysis
  - API built around Pandas and PVLIB
- Steps:
  - Normalize
  - Filter
  - Aggregate
  - Analyze Rd

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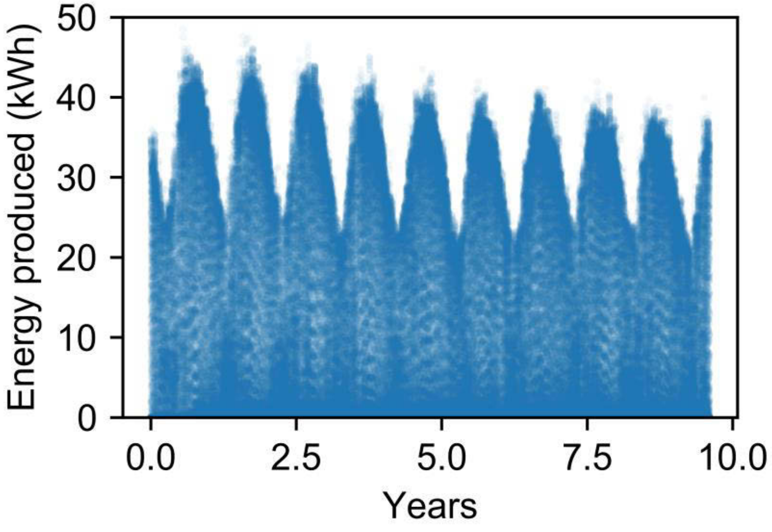
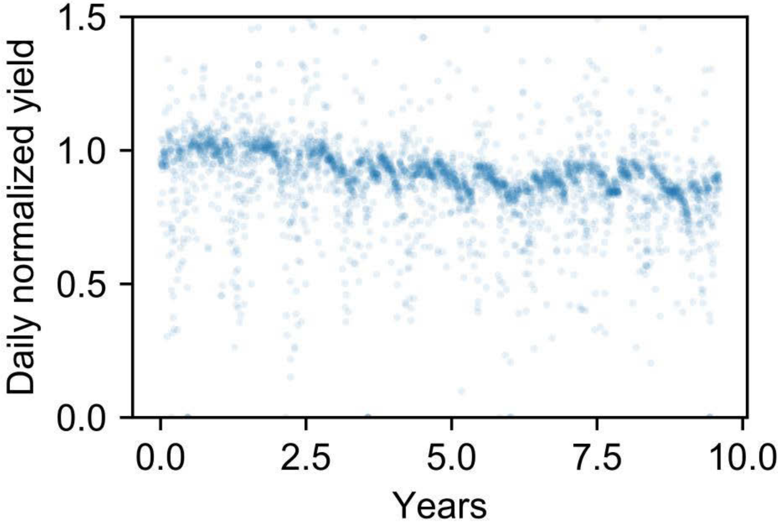
First three steps



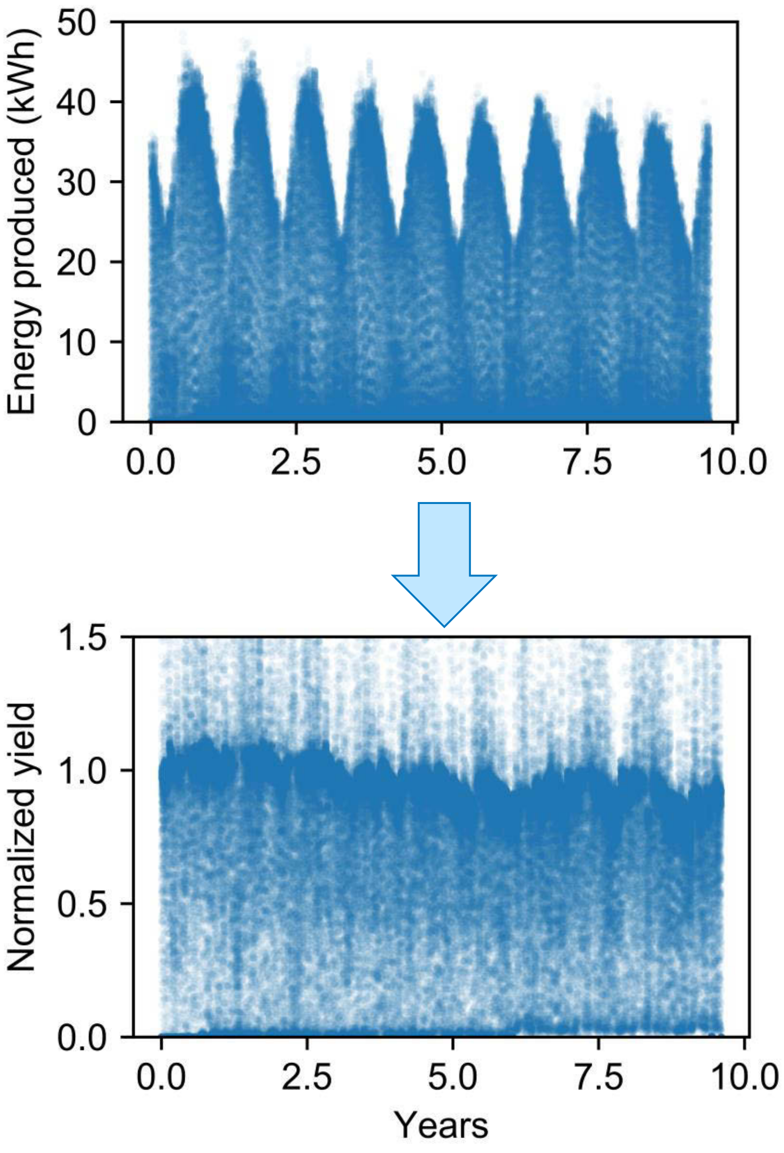
Energy time series

1. Normalize to model
2. Filter
3. Aggregate



Daily normalized energy yield

1. Normalize to a model



- Input: PV energy, Irradiance, cell temperature (modeled or measured)
- Use a simple irradiance and temperature model to calculate normalized high-frequency performance index

$$P = P_0 \frac{G_{POA}}{G_0} (1 + \gamma(T_{cell} - T_0))$$

- Frequency mismatch between weather and energy is automatically handled by RdTools

A. P. Dobos, "PVWatts version 5 manual," NREL, Tech. Rep., 2014

Weather data for model

- The normalization step requires modeled system performance based on weather/irradiance data
- Choices:

Site measured

pros:

- Can be high accuracy

cons:

- May not be available for smaller systems
- Irradiance sensors can drift over time, must be carefully maintained

Satellite based (e.g. NSRDB)

pros:

- Wide availability
- No instrumentation required

cons:

- Lower accuracy than carefully maintained met stations

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pros:

- Wide availability
- No instrumentation required

cons:

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Solution: Clear-sky workflow

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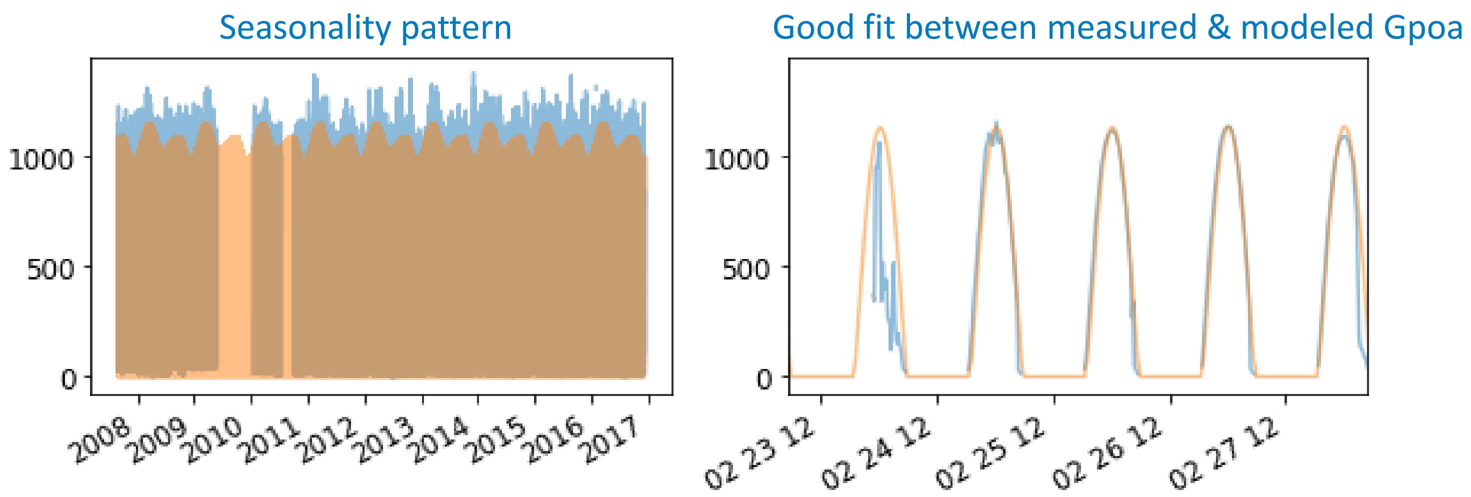
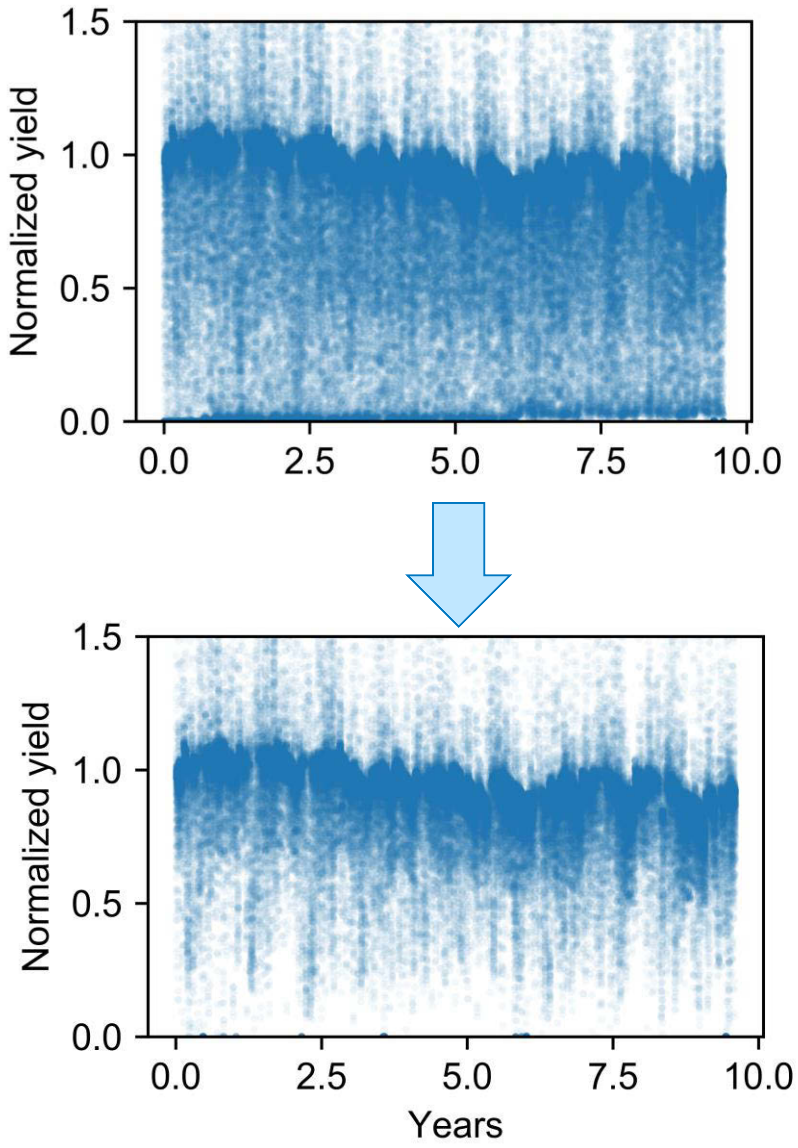
Clear sky workflow



- Alleviates bias due to long term drift in sensors when using site-measured weather data
- Steps
    - Model the irradiance using a relatively simple clear-sky model
    - Compare with measured irradiance to detect clear sky times
    - Use modeled clear-sky irradiance to normalize
    - Filter out non-clear-sky times
    - Example available in the RdTools docs

2. Filter



- Minimal filtering is more conservative
- Remove points:
  - ≤ 0
  - Irradiance < 200
  - Irradiance > 1200
  - T_{cell} < –50°C
  - T_{cell} > 110°C
  - Clearsky method only: Clearness index (measured/modeled Gpoa) < 0.85 and > 1.15
  - Optional: filter out inverter clipping

- Room for innovation:
  - Find outages and outliers without introducing bias

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Note on filtering

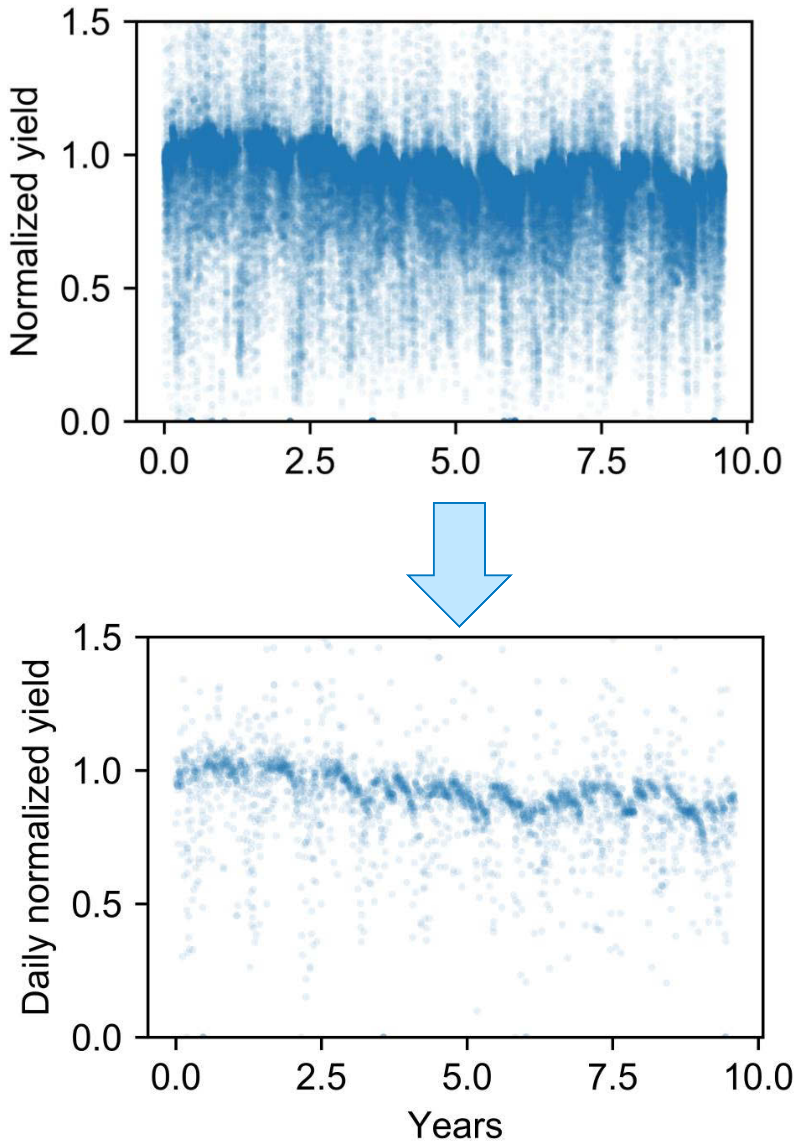
Are you considering **system** or **module** degradation?

vs.

For modules → filter things like tracker downtime and clipping

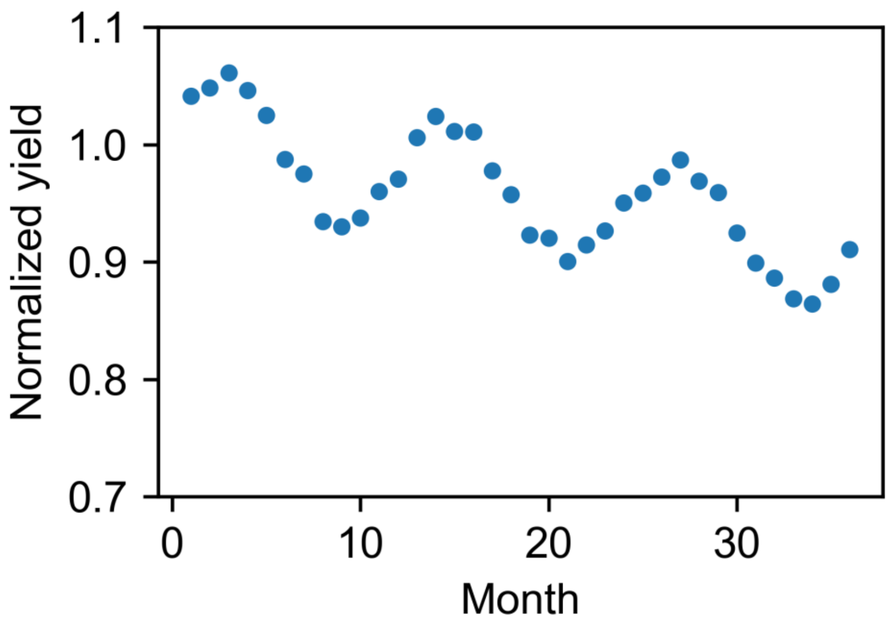
There are subtleties in filtering choices depending on the goals of the analysis

3. Aggregate



Calculate daily irradiance-weighted performance index

4. Rd Analysis: year-on-year



- Year-on-year is robust to seasonality and outliers
- Steps:
  - Compare each day (or week, month, etc.) to its corresponding day a year later
  - Calculate the median of all year-on-year slopes
- Pay attention to the confidence interval

E. Hasselbrink, M. Anderson, Z. Defreitas, et al., “Validation of the PVLife model using 3 million module- years of live site data,” PVSC, p.0007, 2013

…dation methodology comparison—A basis for a standard." PVSC, p.0273, 2016

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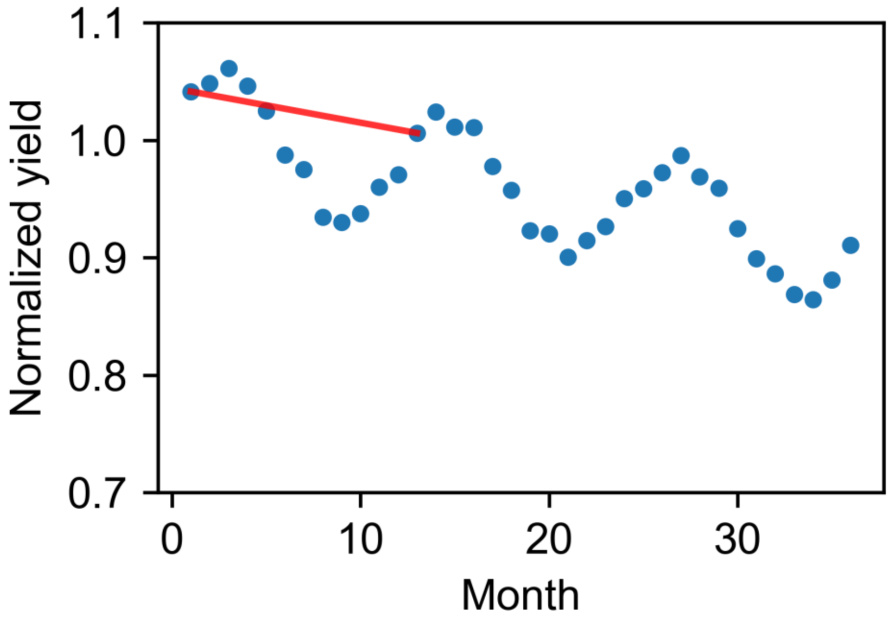

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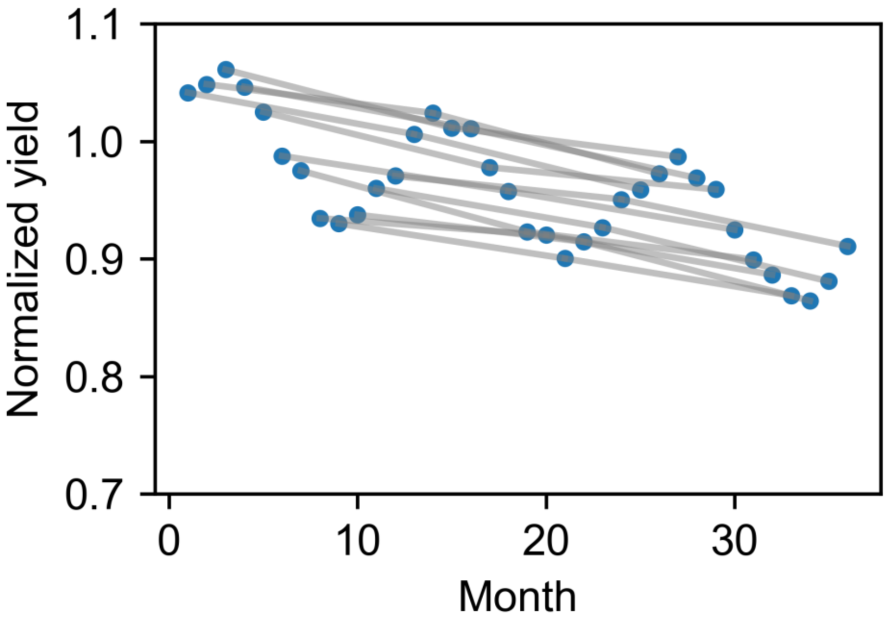

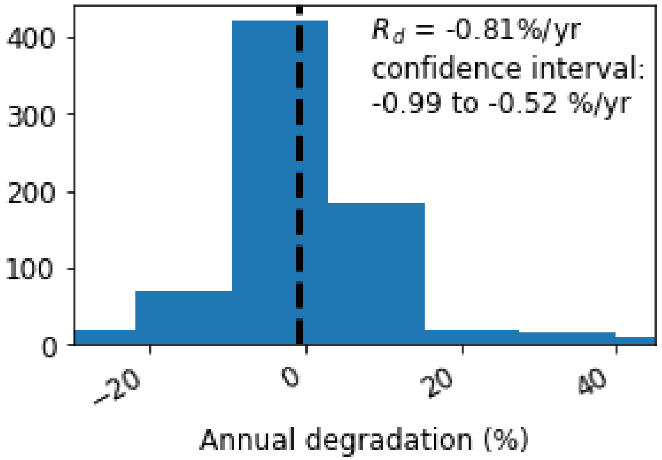

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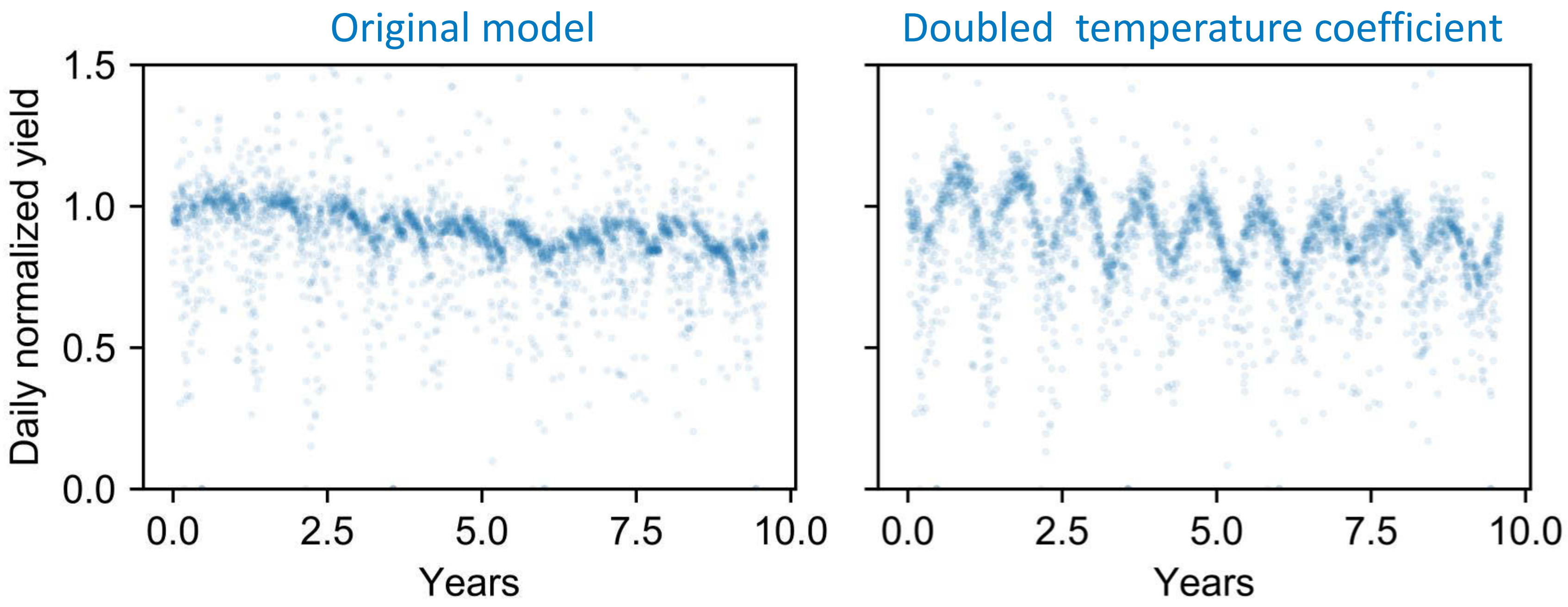
Jordan, Deline, & Kurtz, "PV degradation methodology comparison—A basis for a standard." PVSC, p.0273, 2016

Year-on-year is robust

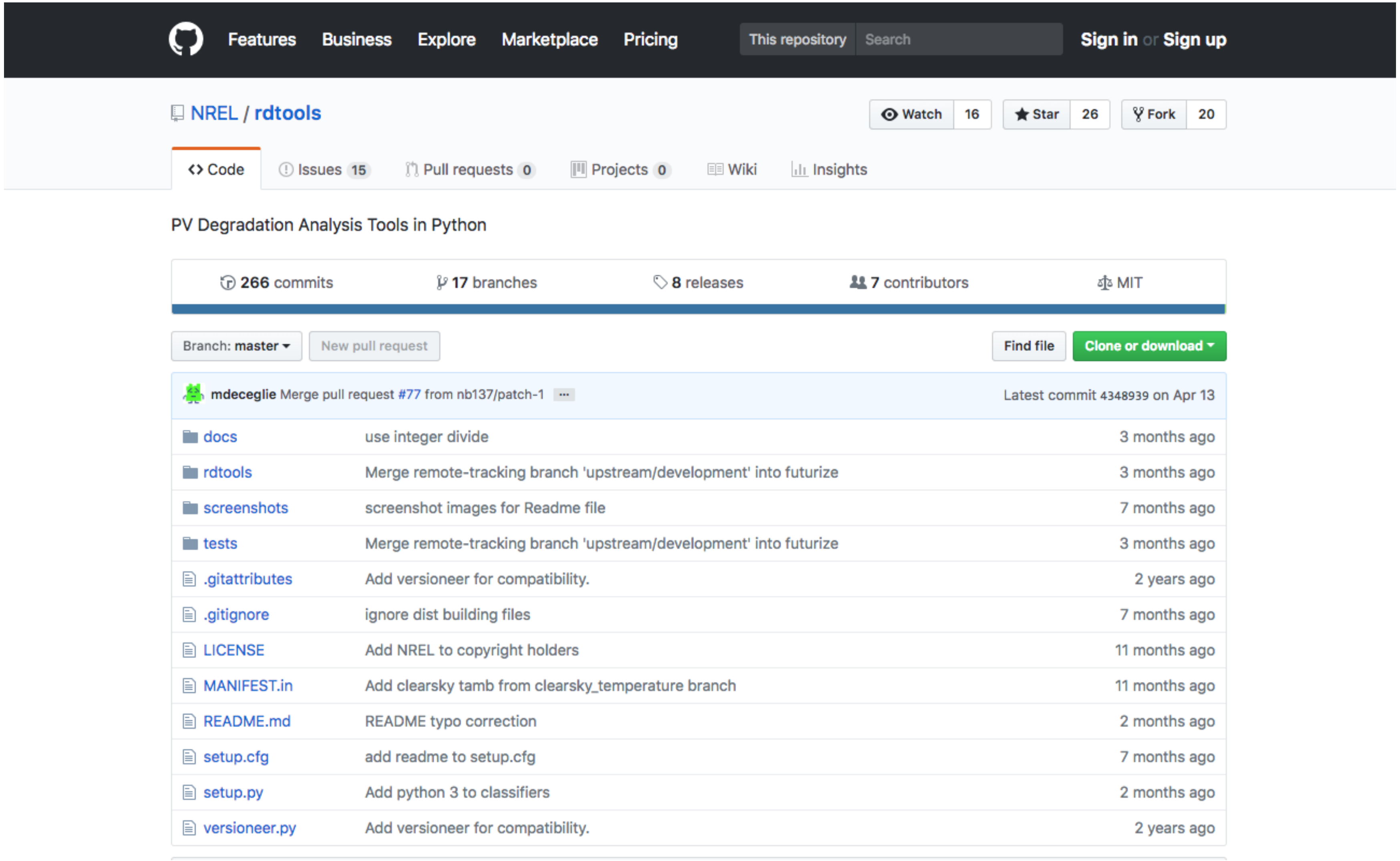


Rd: -2.2 %/year
Conf. Int.: –2.5 to –1.8 %/year

Rd: -1.9 %/year
Conf. Int.: –2.5 to –1.3 %/year

- Example: intentionally induced seasonality
- Results remain consistent
- Confidence interval appropriately expands
- **A very detailed performance model isn't needed**

All this is available in RdTools

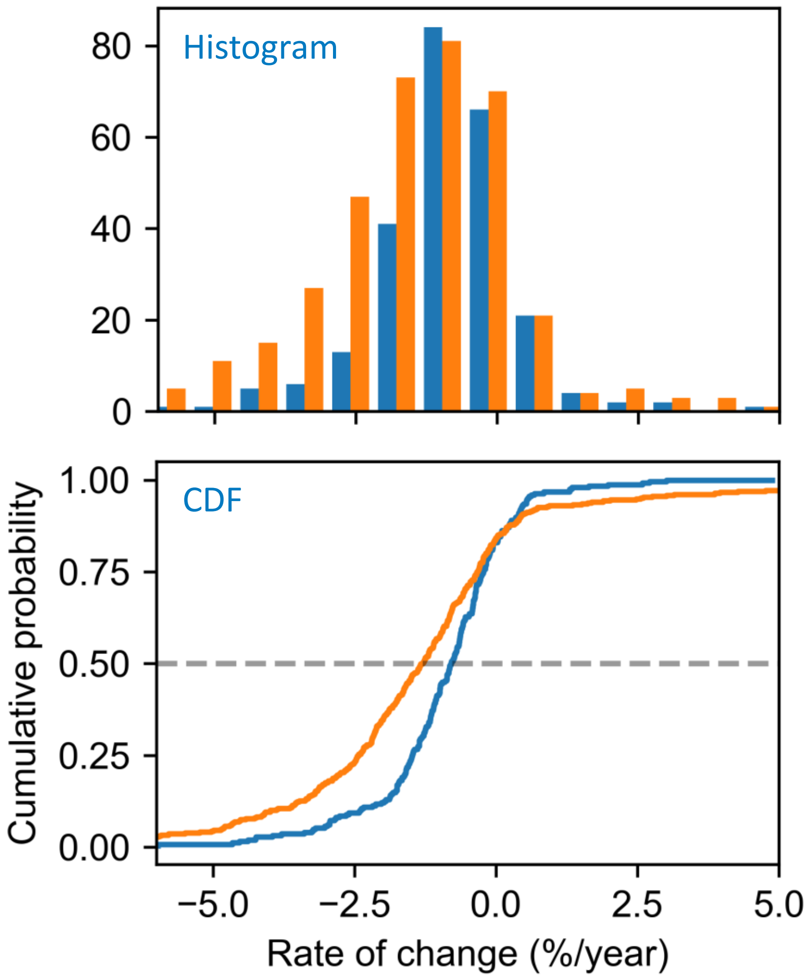


- Read me and examples: https://github.com/NREL/rdtools
- install: pip install rdtools

Fleet-scale analysis

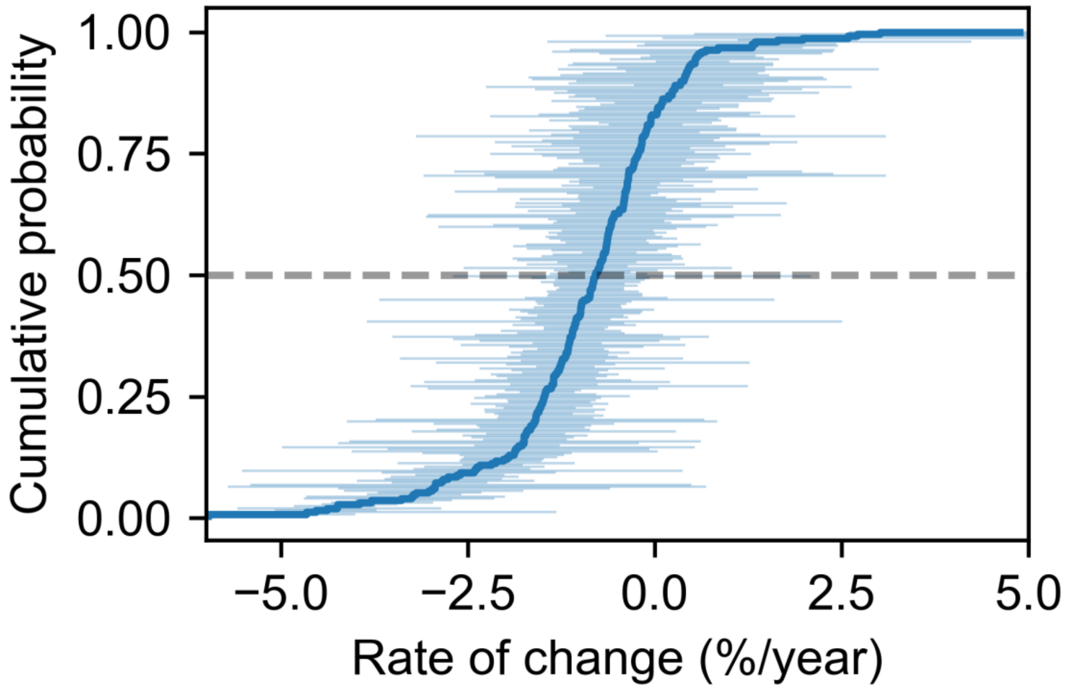
- Analyzed 634 subarrays from 503 PV systems in the United States
- 387 residential systems
- 116 larger, non-residential systems
- >3,400 system-years of time series data
- Used satellite weather data for consistency
- Study system energy-yield degradation

Cumulative distribution functions (CDFs)



- CDFs provide a way to visualize distributions, independent of bin size
- CDFs make it easier to compare two samples

CDFs with individual confidence intervals



We can include each measurement's 95% confidence interval on the plot

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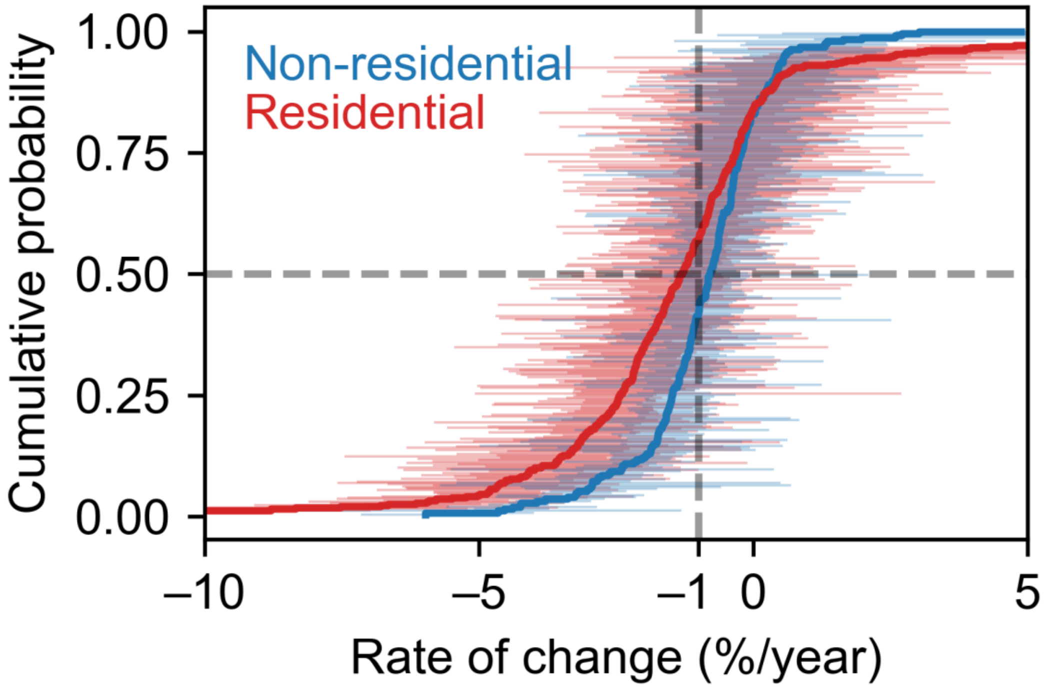
Residential vs. Non-residential



- Recall we are analyzing **system** yield degradation
- Negative rate of change = degradation (-1%/year indicated)

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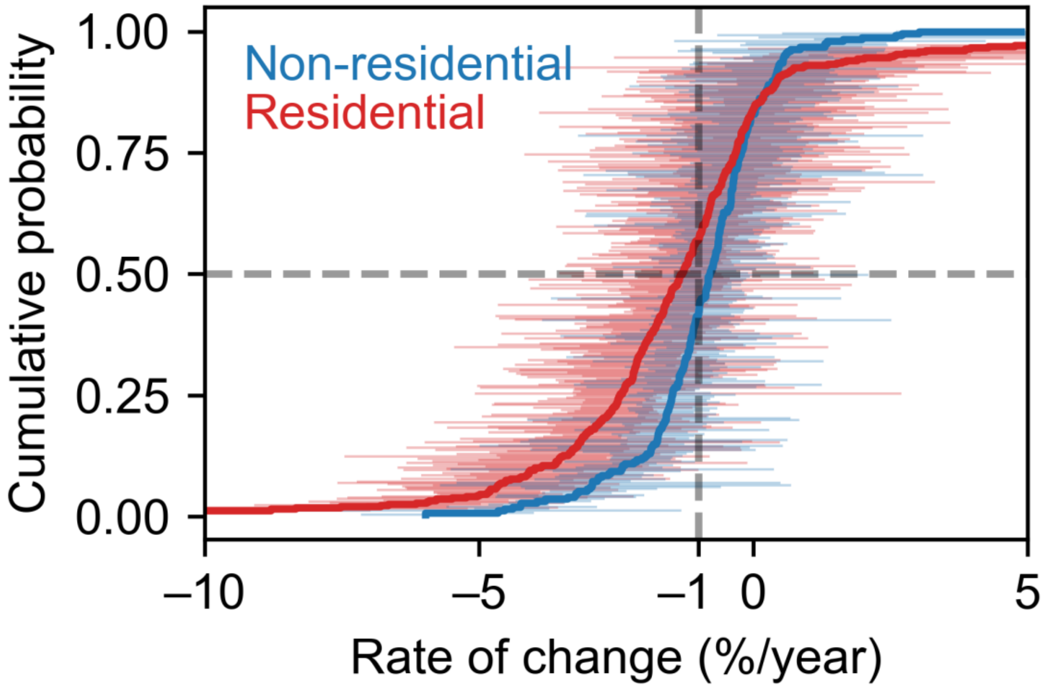
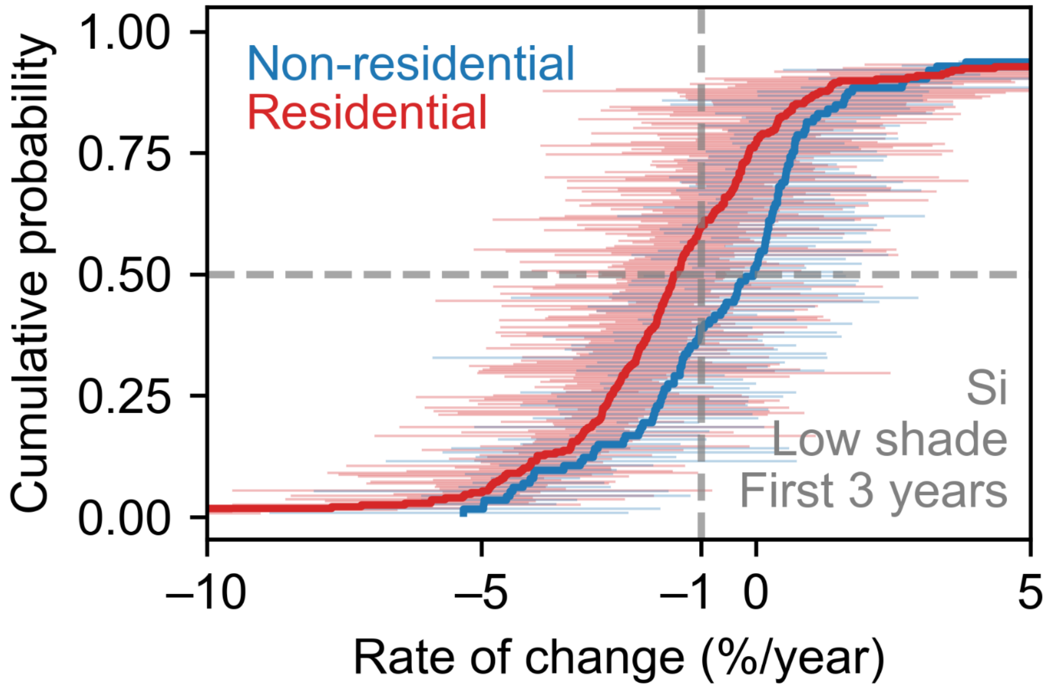
Residential vs. Non-residential



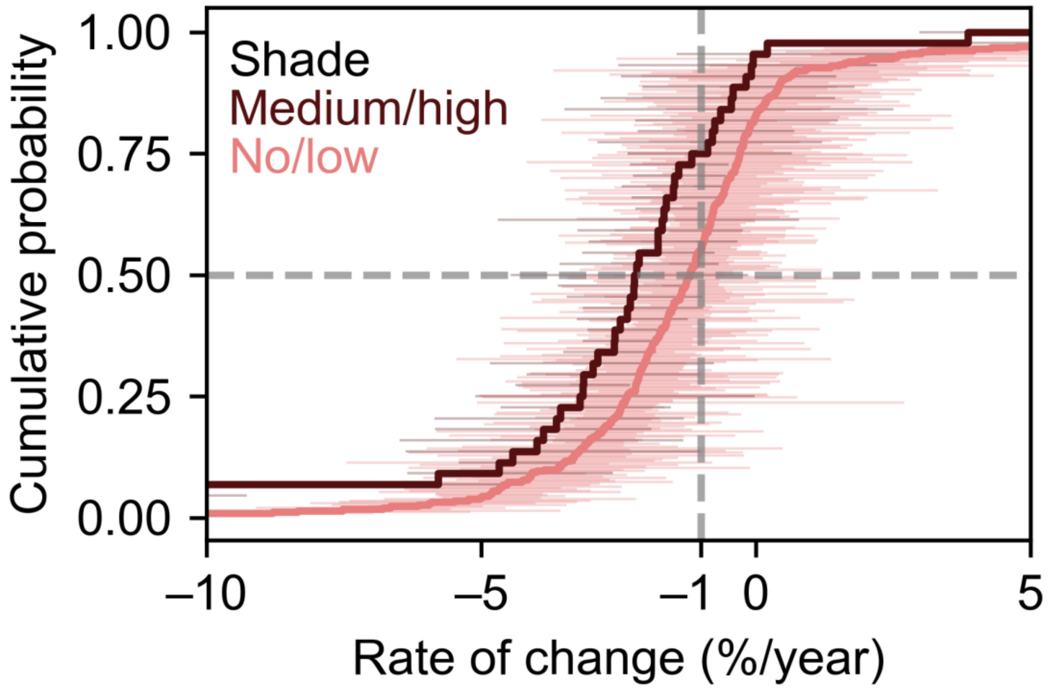
- Residential systems tended to degrade more rapidly
- 29% of residential and 38% of non-residential systems degraded slower than -0.5%/year
- What about differences in age, technology etc.?

Residential vs. non-residential



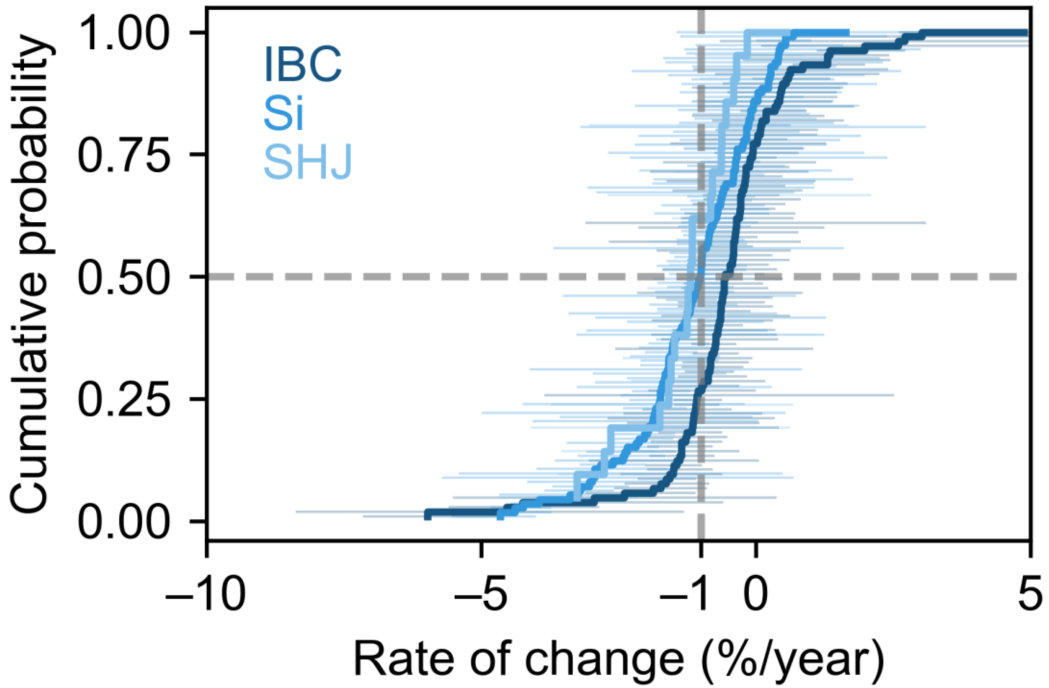
The difference persists with a more direct comparison

Shade in residential systems



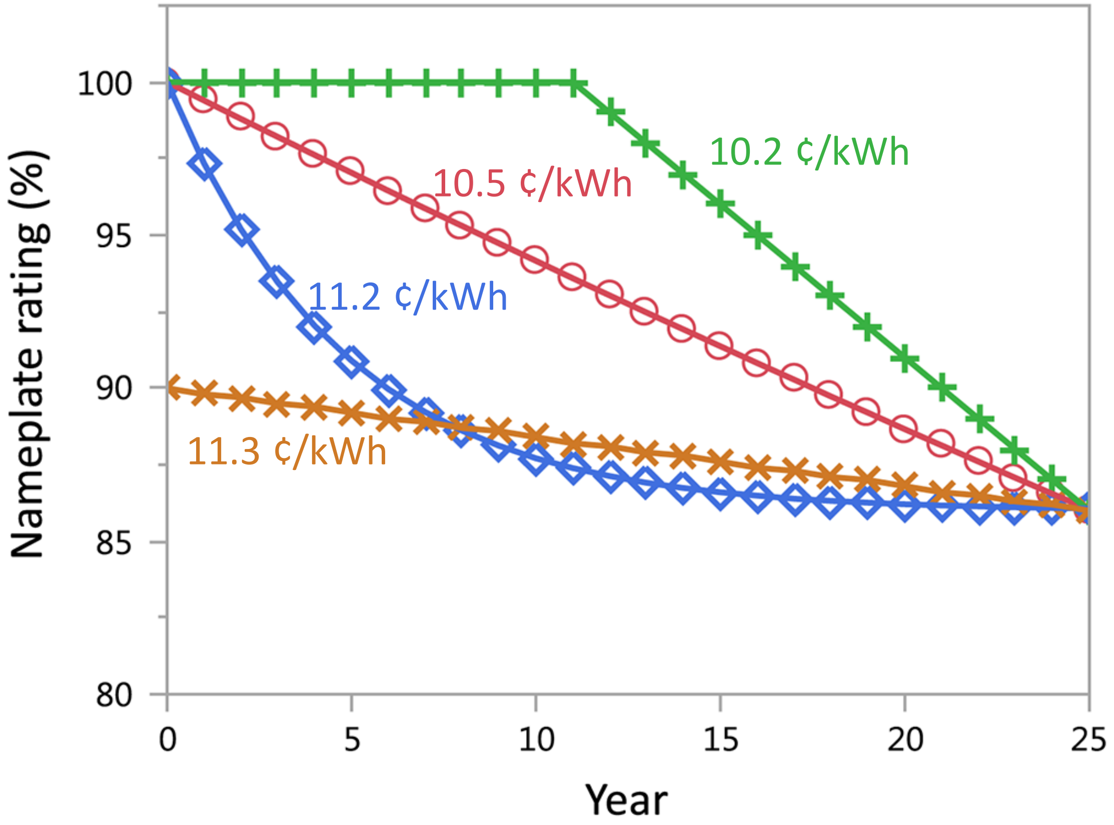
- Systems with higher shade tended to degrade more rapidly
- Possible causes:
  - Foliage growth
  - Hot spots

Cell technology in non-residential systems



- Three cell technologies present in the non-residential dataset
  - Interdigitated back contact (IBC)
  - Conventional Si (Si)
  - Silicon heterojunction (SHJ) e.g. HIT
- IBC-based systems tended to degrade more slowly than other technologies
- Co correlated variables (manufacturer, module construction etc.)

Non-linear degradation



The shape of the degradation profile has financial implications

Jordan et al., "PV degradation curves: Non-linearities and failure modes," *PIP* 25(7), pp. 583–591, 2016

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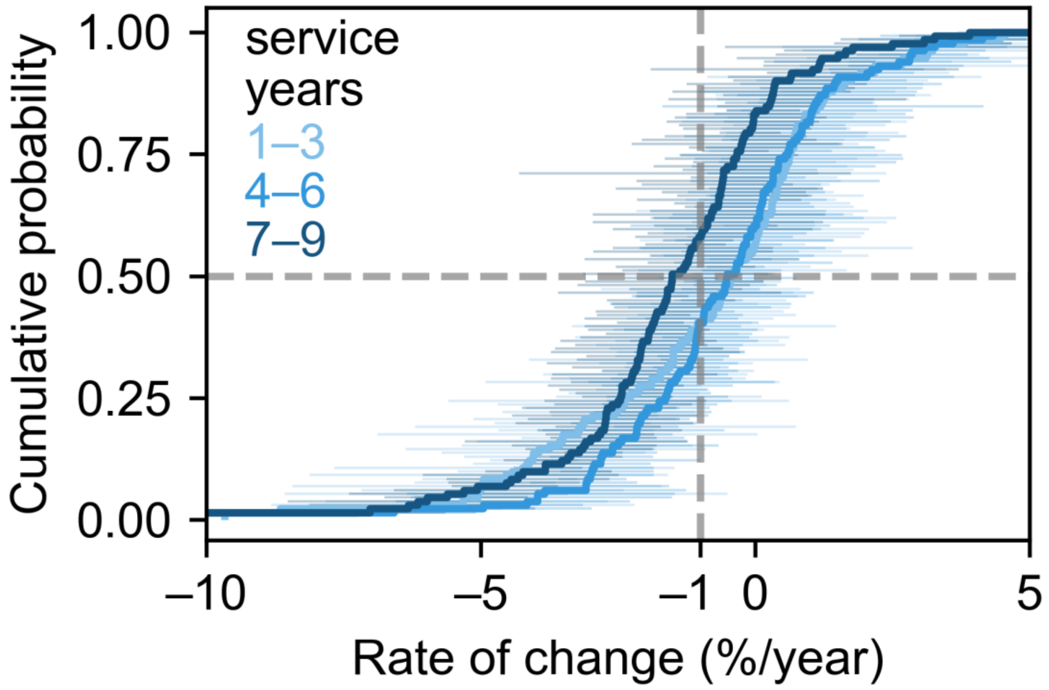
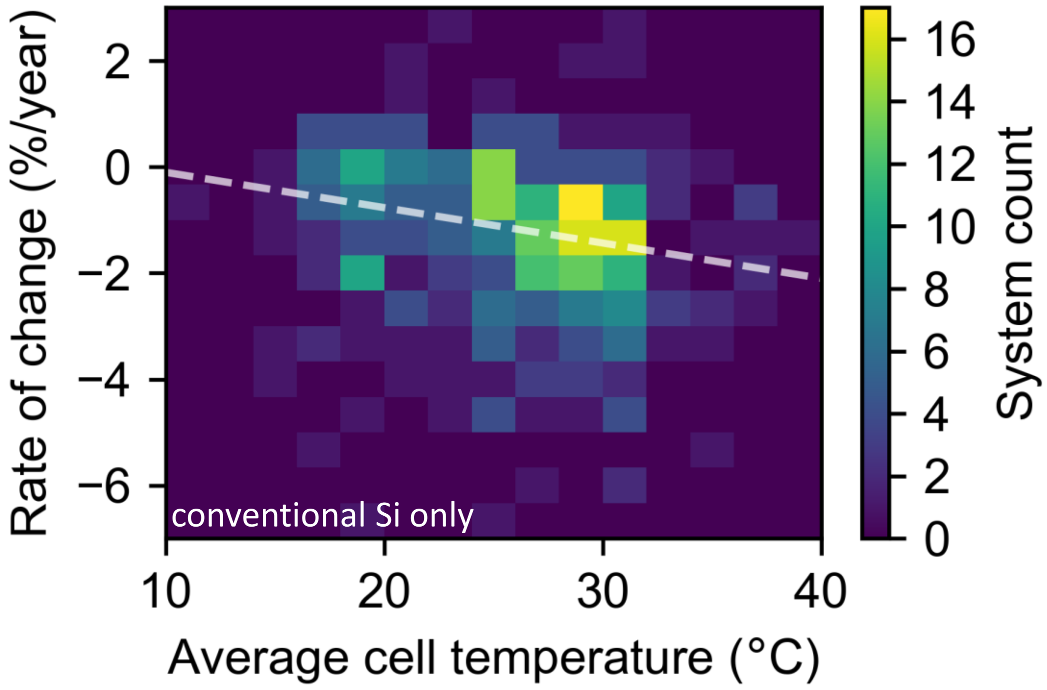
System age in non-residential systems



- The same 142 subarrays at 76 sites are considered over three different stages in system life
- Same systems in each CDF above
- Systems tended to show more rapid degradation later in life
- Should be careful about applying this generally

Temperature



- Systems with higher operating temperatures tended to degrade faster
- Possible explanation: thermally accelerated degradation modes
- Caution: confounding variables, e.g. UV and mounting

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Example study summary

- Fleet-scale analysis elucidates system degradation trends
  - Residential vs. non-residential
  - More rapid degradation later in system life
  - More rapid degradation at higher temperature
  - Differences in module technology
  - More rapid reductions in energy in shaded residential systems

Conclusion

- What you need:
  - Time series energy output (preferably hourly or better)
  - Coincident irradiance and weather data (ground- or satellite-based)
- RdTools is open source and available: github.com/NREL/rdtools
- Be clear about questions at the outset, build the analysis accordingly
- Pay attention to the resulting confidence intervals. Large confidence intervals indicate need for improved model or data
- RdTools is a library, build an application to suit your needs

Funding provided by Solar Energy Technology Office under agreement 30295. NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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System Advisor Model

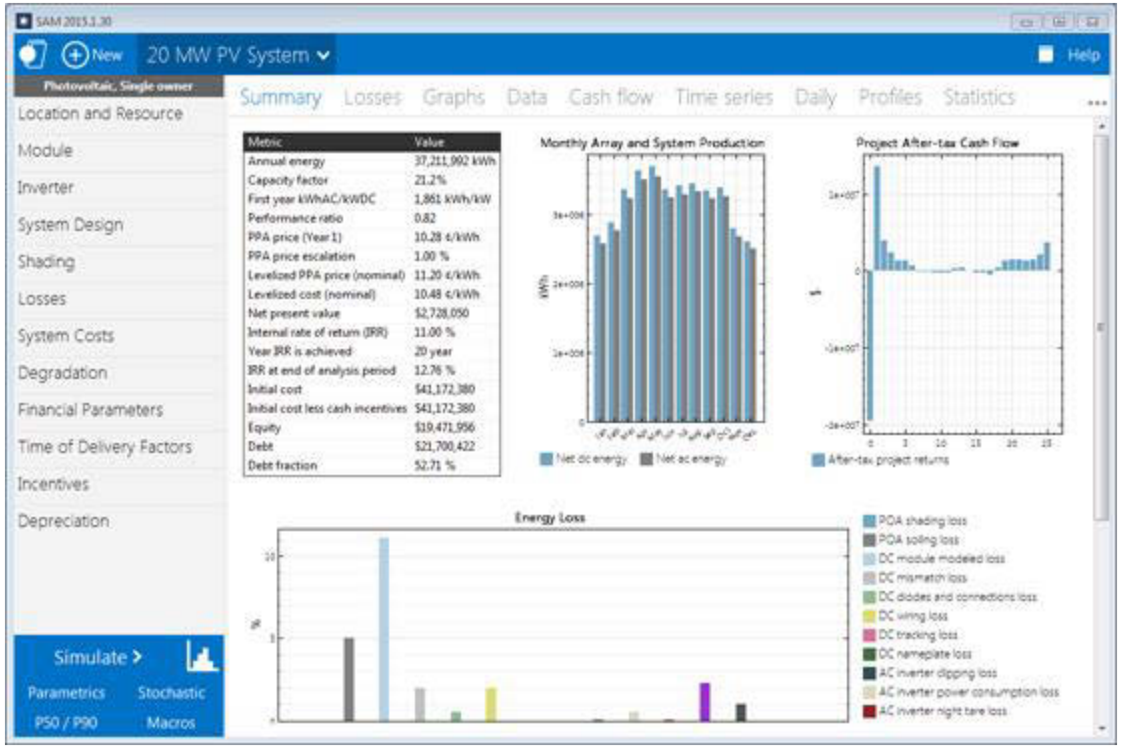
Solar Power International 2018

Nicholas DiOrio

September 24, 2018

System Advisor Model (SAM)

SAM is free software for modeling the performance and economics of renewable energy projects.



http://sam.nrel.gov

github.com/NREL/SAM

- Developed by NREL with funding from DOE
- Windows, OSX, and Linux
- One or two new versions per year
- Software Development Kit (SDK)
- Support

Download Beta version

https://sam.nrel.gov/sites/default/files/content/public_releases/sam-beta-windows-2018-9-10.exe

Technologies

Photovoltaics

- Detailed & PVWatts
- Battery Storage

Wind

Concentrating solar power

Geothermal

Biomass

Solar water heating

Financial Models

Behind-the-meter

- residential
- commercial
- third-party ownership

Power purchase agreements

- single owner
- equity flips
- sale-leaseback

Simple LCOE calculator

History

Developed by

- Department of Energy
- National Renewable Energy Laboratory
- Sandia National Laboratories

Original vision in 2004

- Allow DOE to make R&D choices based on analysis of the entire system including costs
- Model different renewable energy projects in a single platform
- Facilitate technology comparison by handling performance, costs and financing consistently across technologies

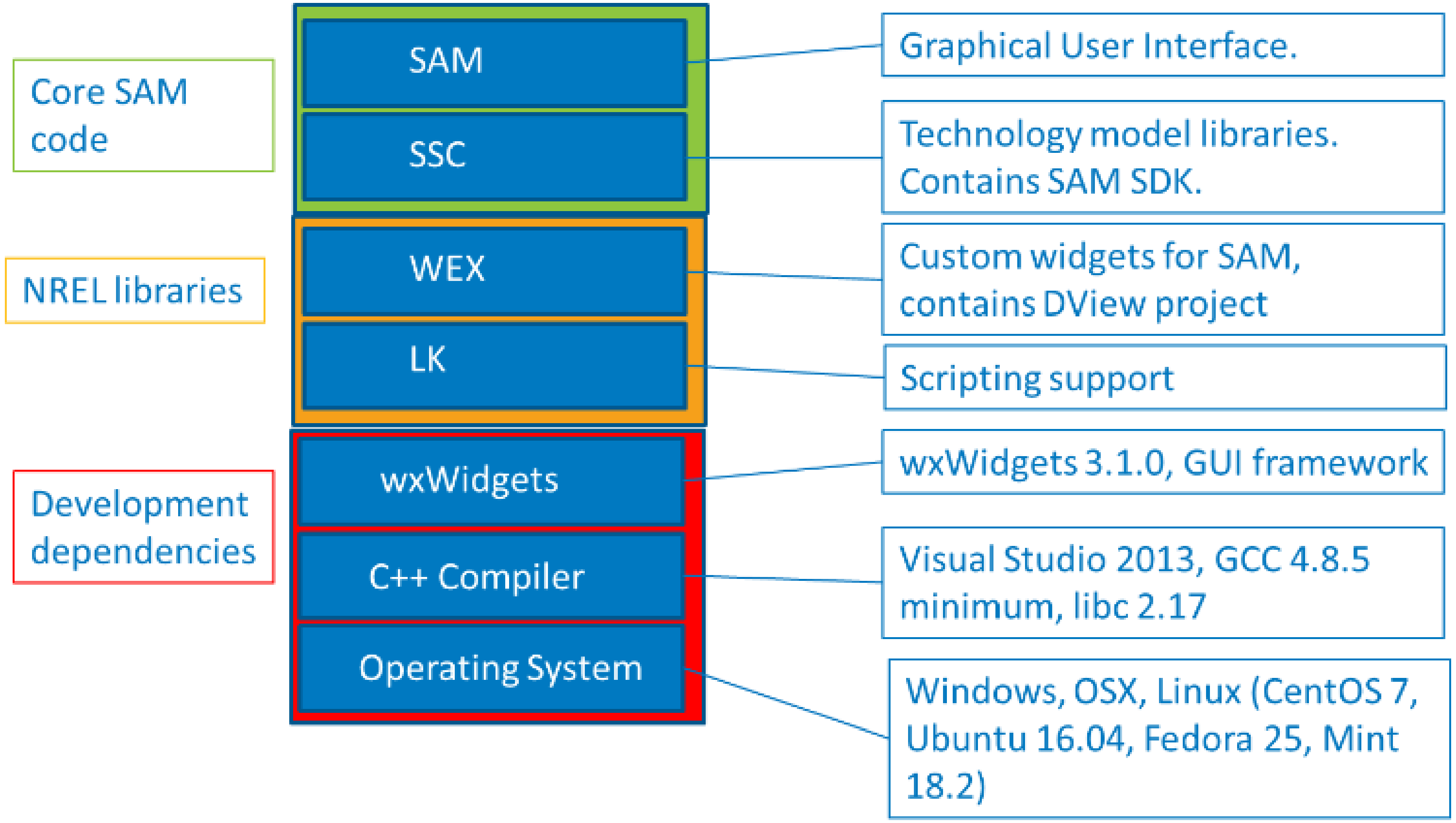
Some Applications

- Feasibility studies, benchmarking for other models, research projects, plant acceptance testing, evaluation of grant proposals

Outline of Topics

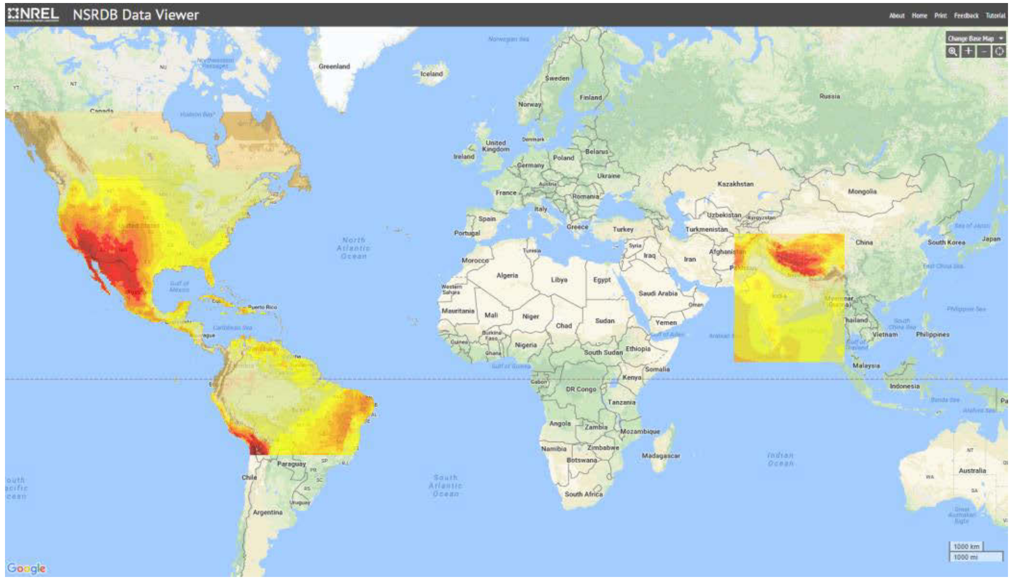
- Open Source Code
- NSRDB Integration
- Photovoltaic Model
- Bifacial modeling
- Solar plus Storage modeling
- Tool comparison

Open Source Code



- Open-sourced all four NREL repositories
- Comprehensive build instructions

Integration with NSRDB data



National Solar Radiation Database

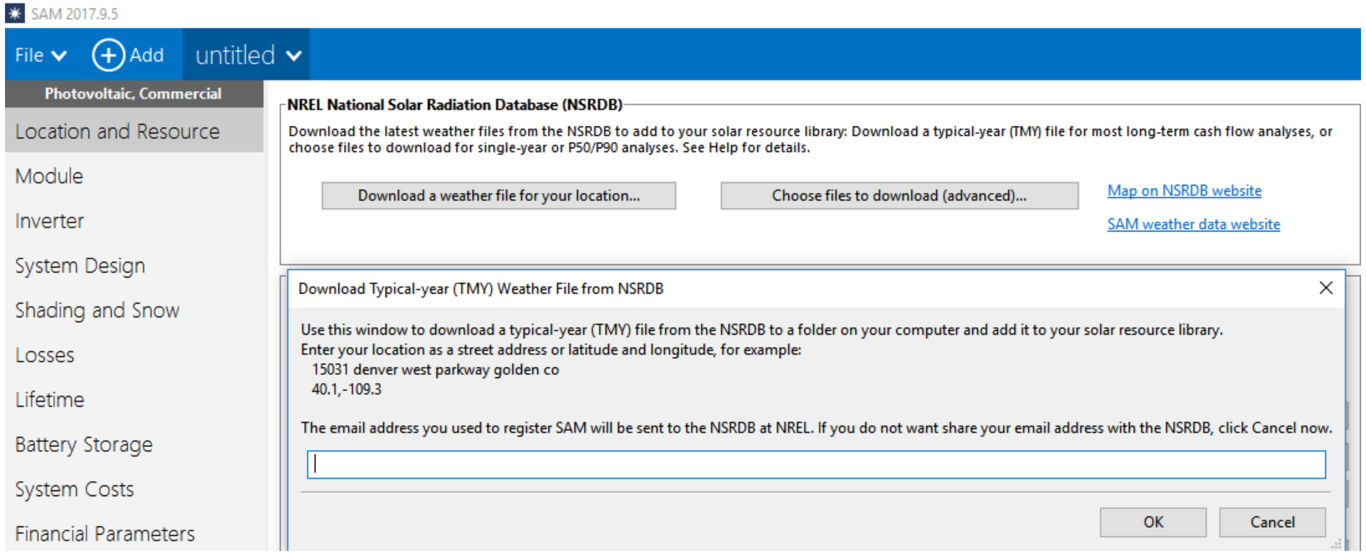
- Collection of hourly and half-hourly solar irradiation and meteorological data
- U.S data – 4x4 km spatial resolution, 30 minute temporal resolution from 1998-2014. Older data available.
- **International data – available in Mexico and Central and South America, South Asia.**

SAM Integration

- Simple interface
- Options for choosing specific data sets

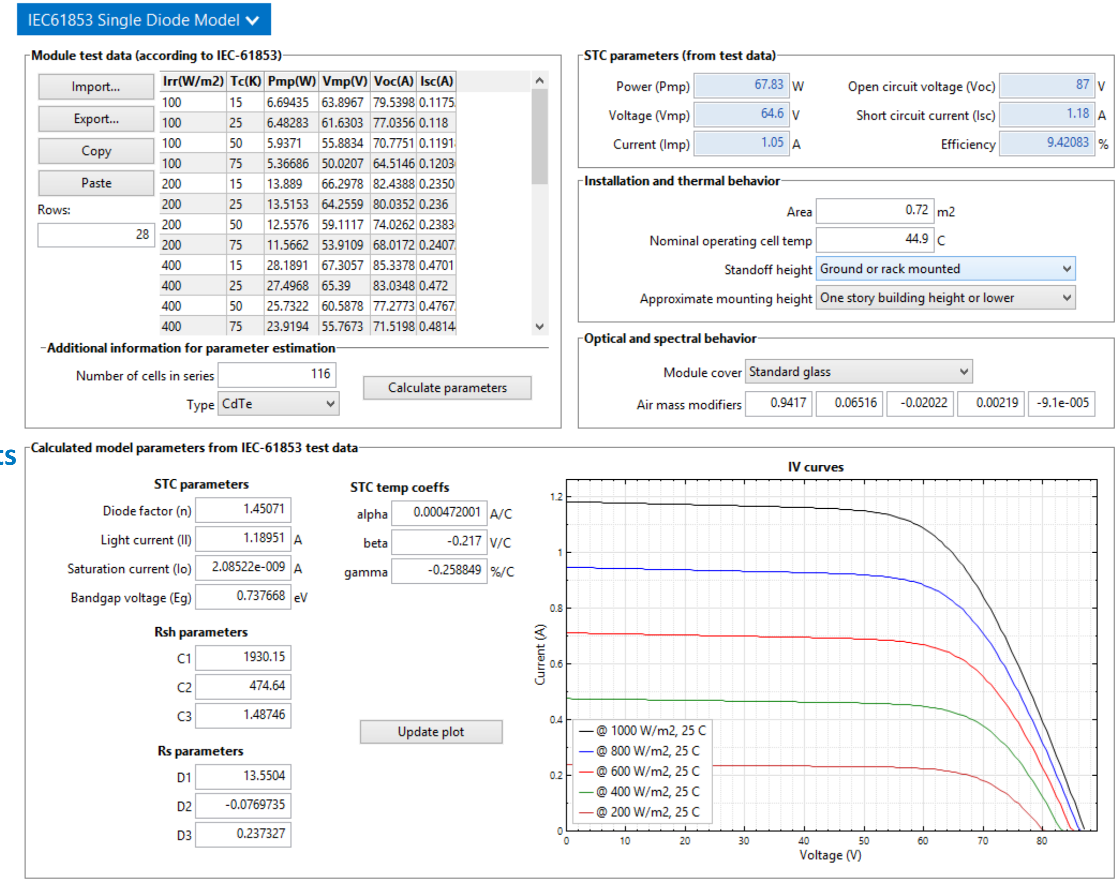
PVWatts Integration

- Upcoming
- Will replace TMY2 as standard dataset



Detailed photovoltaic model

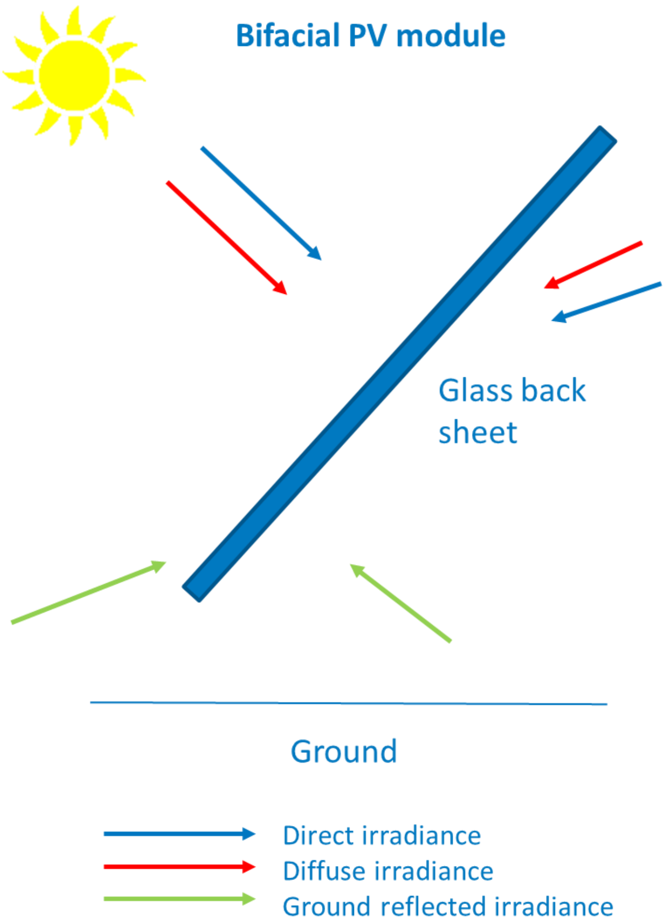
- Irradiance
  - Transposition using Isotropic, HDKR, or Perez
  - Measured plane of array (POA) input
- Shading
  - Irregular obstruction shading from 3D scene
  - Self-shading for regularly spaced rows
  - External input from SunEye, Solar Pathfinder
  - Snow cover loss model
- Module
  - Simple efficiency model
  - Single diode model (CEC database or datasheet)
  - Extended single diode model (for IEC-61853 tests
  - Sandia PV Array Performance Model
- Inverter
  - Sandia/CEC grid-tied inverter model
  - Datasheet part-load efficiency curve
- System
  - Sizing wizard or electrical layout
  - Multiple subarrays
  - Fixed, 1 axis, backtracking, azimuth axis, 2 axis
  - Battery storage
- Degradation
  - Extrapolated single year
  - Lifetime simulation of all years
- Simulation
  - 1 minute to 1 hour time steps



Could be calculated for real site data from RdTools analysis!

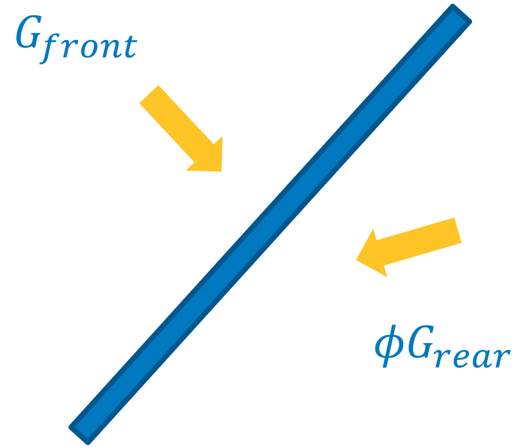
Bifacial Outline

- Overview of bifacial irradiance model
- Bifacial model implementation in SAM
- Example analysis
- Some quantitative results



Model assumptions

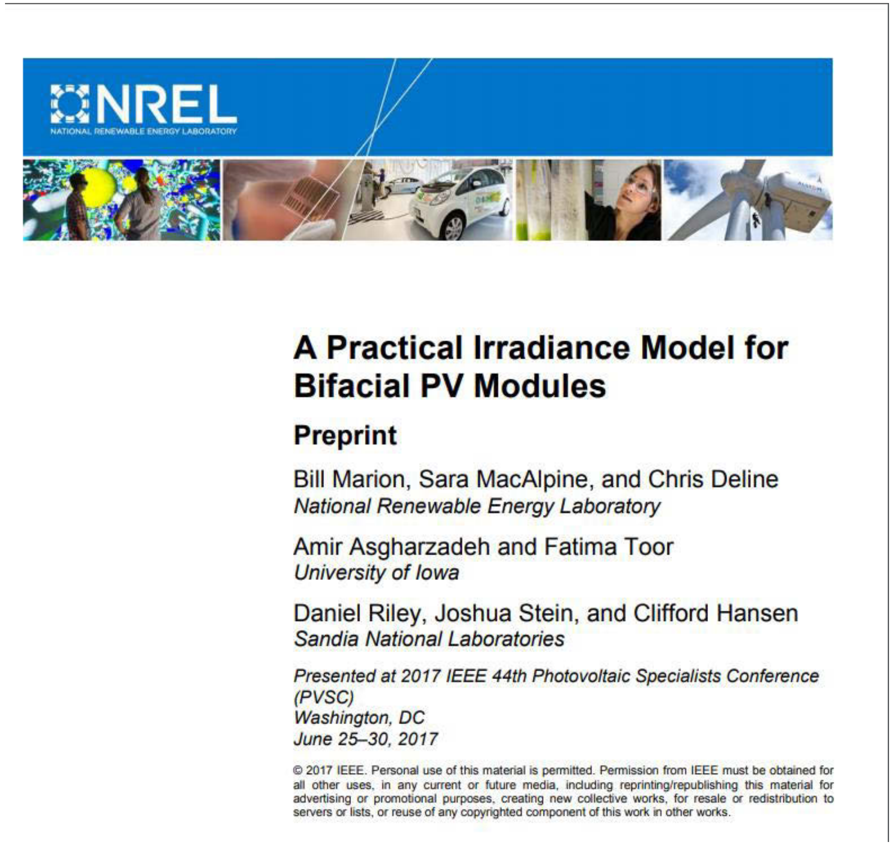
- **Applicable for a row or multiple rows of PV modules, fixed tilt or 1-axis tracked.**
- **Calculation of configuration factors assumes isotropic radiation**
- **Bifacial modules are arranged in rows of infinite length (no irradiance variation along length)**
- **No rear mounting obstructions**
- **The POA rear-side irradiance (weighted by bifaciality) adds to the front-side irradiance.**
- **Combined irradiance is converted to DC power using single-diode model**



$$G = G_{front} + \phi G_{rear}(1 - \eta_{loss})$$

Single diode model

Bifacial irradiance model



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A Practical Irradiance Model for Bifacial PV Modules

Preprint

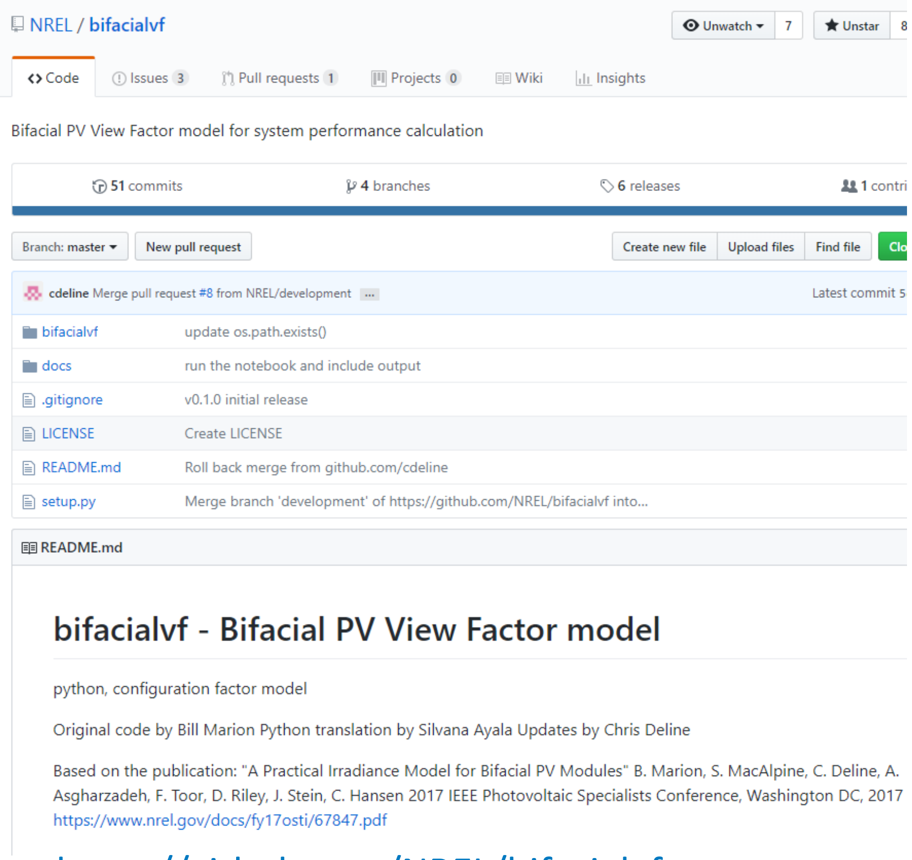
Bill Marion, Sara MacAlpine, and Chris Deline
National Renewable Energy Laboratory

Amir Asgharzadeh and Fatima Toor
University of Iowa

Daniel Riley, Joshua Stein, and Clifford Hansen
Sandia National Laboratories

Presented at 2017 IEEE 44th Photovoltaic Specialists Conference (PVSC)
Washington, DC
June 25–30, 2017

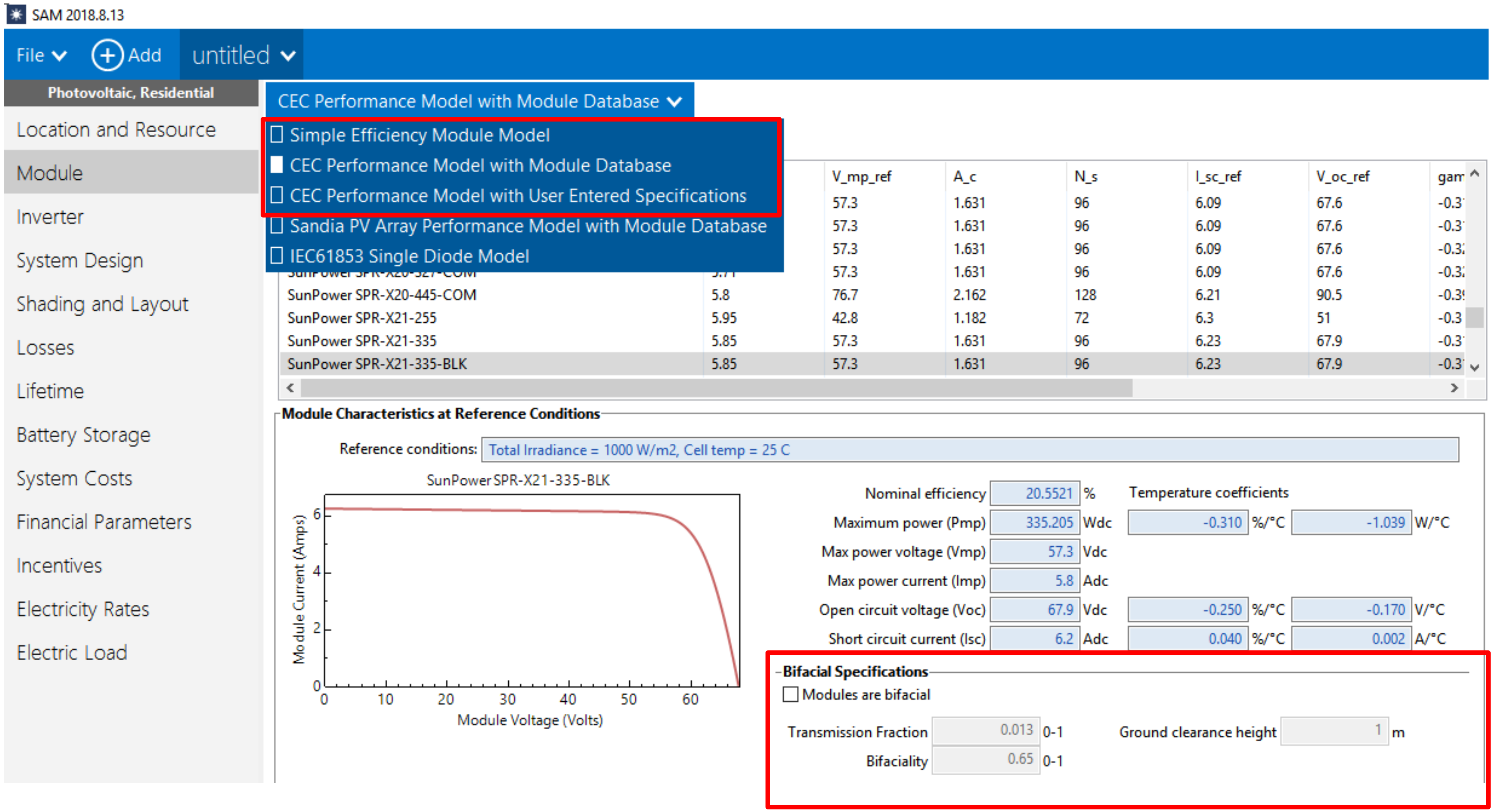
https://www.nrel.gov/docs/fy17osti/67847.pdf



https://github.com/NREL/bifacialvf

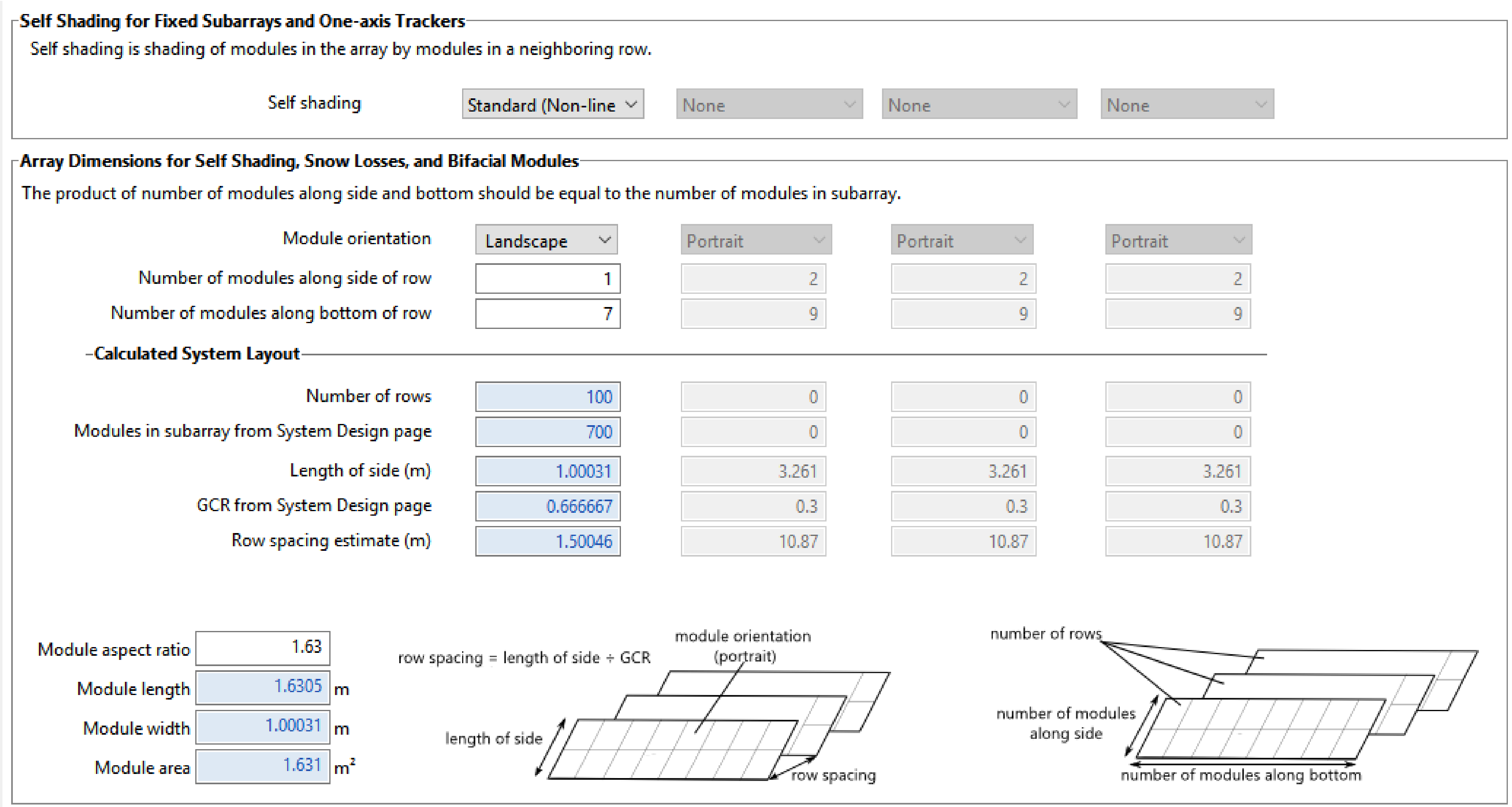
SAM Implementation
https://github.com/NREL/ssc

Bifacial model in SAM



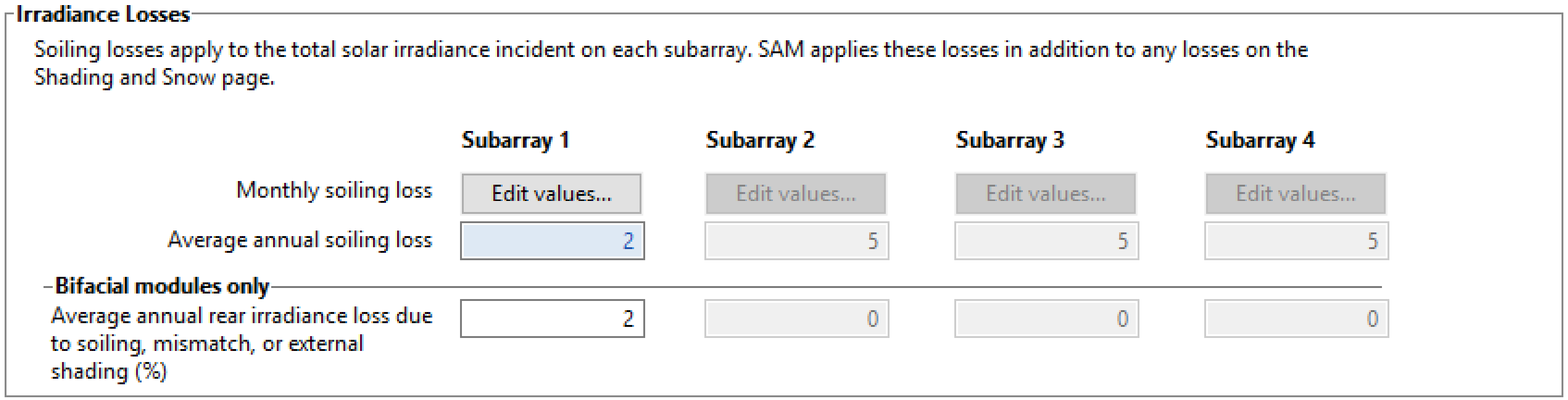
- Bifacial model available for module models which do not require test data

Bifacial system layout



Shading and Layout – Important to turn on self-shading model and configure the geometry of the layout for correct calculation of front-side and rear-side irradiance!

Bifacial losses

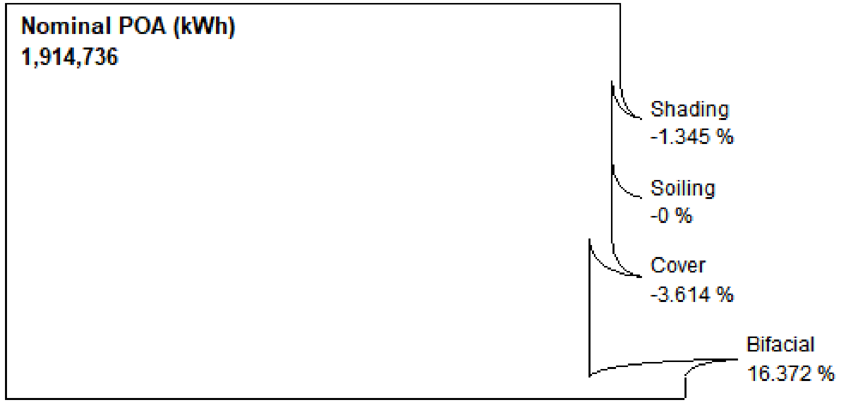


Additional rear-side irradiance losses can input to approximate:

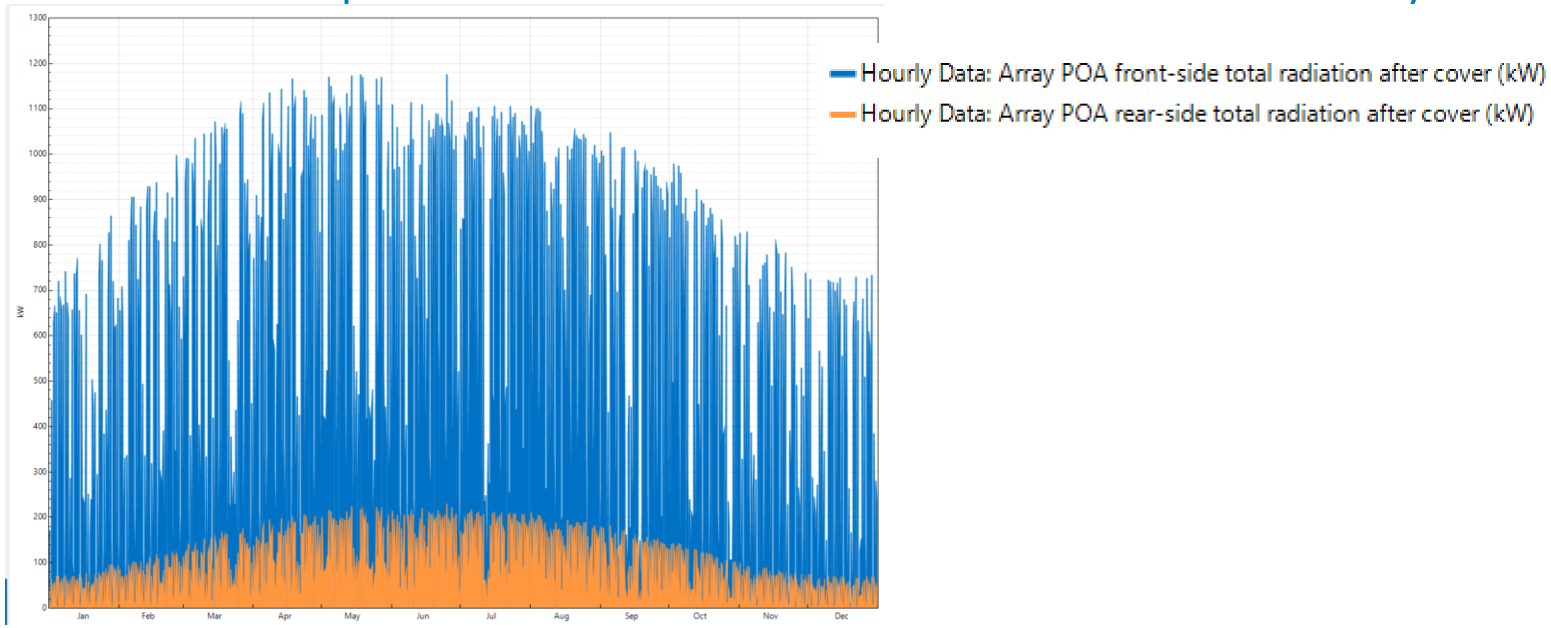
- Mismatch loss between front and rear-side
- Shading due to mounting structure or tracking system
- Soiling on the rear-side

Bifacial model outputs

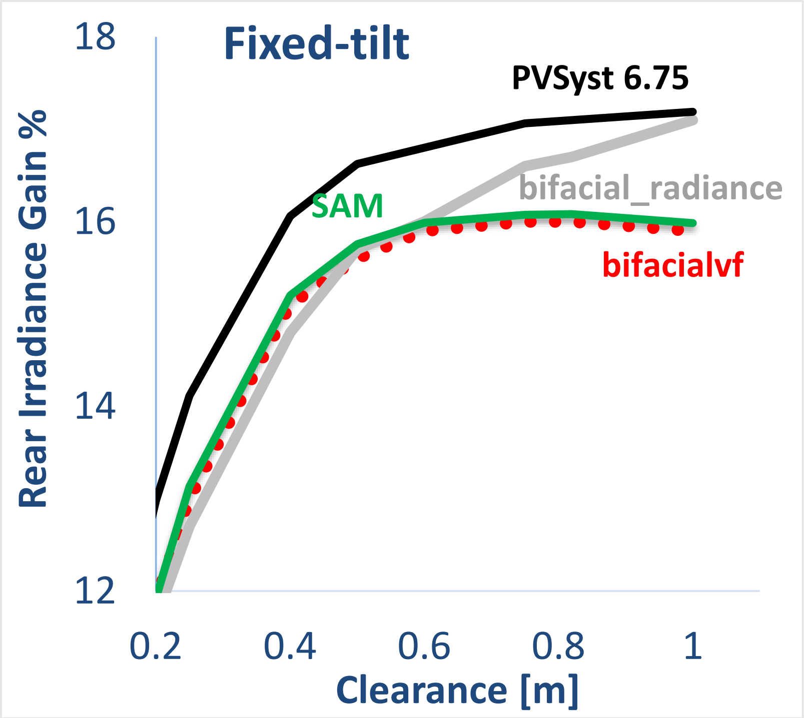
Updated loss diagram, showing bifacial irradiance gain

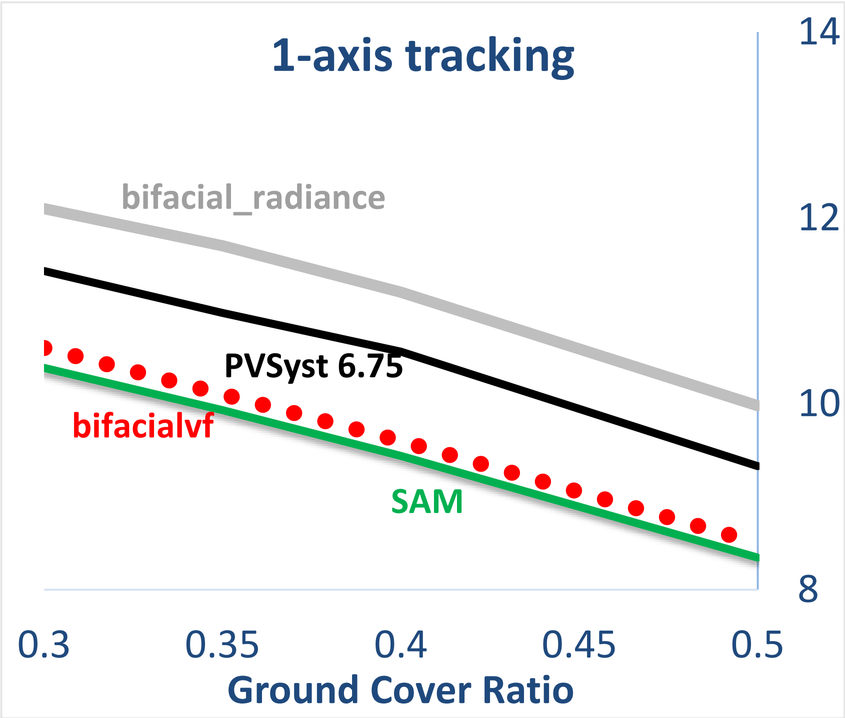


Time series outputs for front and rear-side irradiance for each subarray and total array



Model comparison



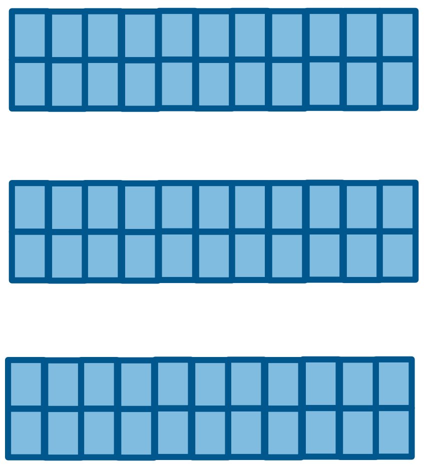


Preliminary results

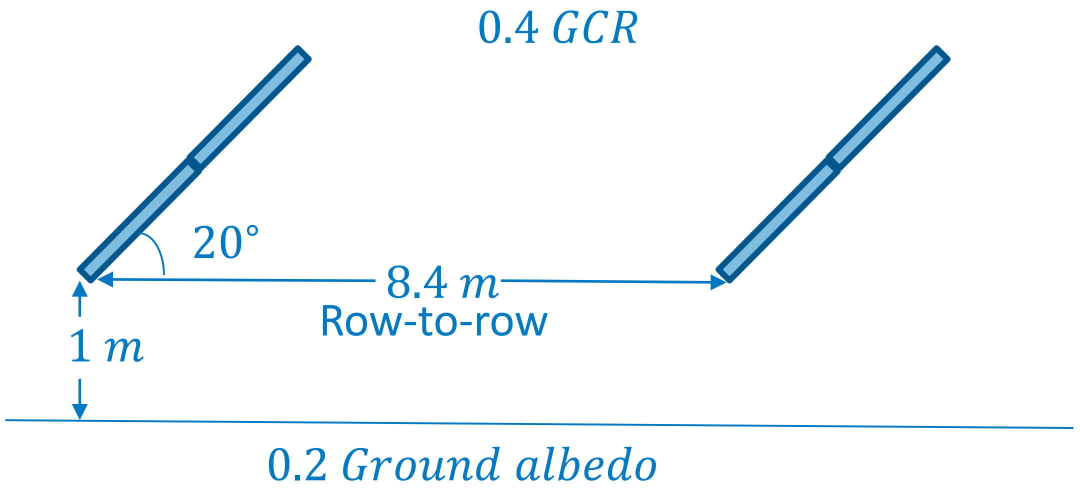
- SAM implementation closely tracks with bifacialvf prediction
- SAM tracks bifacial_radiance model at low ground clearances.
- SAM consistently predicts approximately 1-2% less rear-side irradiance than PVSyst
- For tracked systems bifacial_radiance predicts higher gain

Example analysis

- **Evaluate the boost in energy production with bifacial modules compared to monofacial modules with and without tracking systems.**



3 rows of 22 modules



Example results

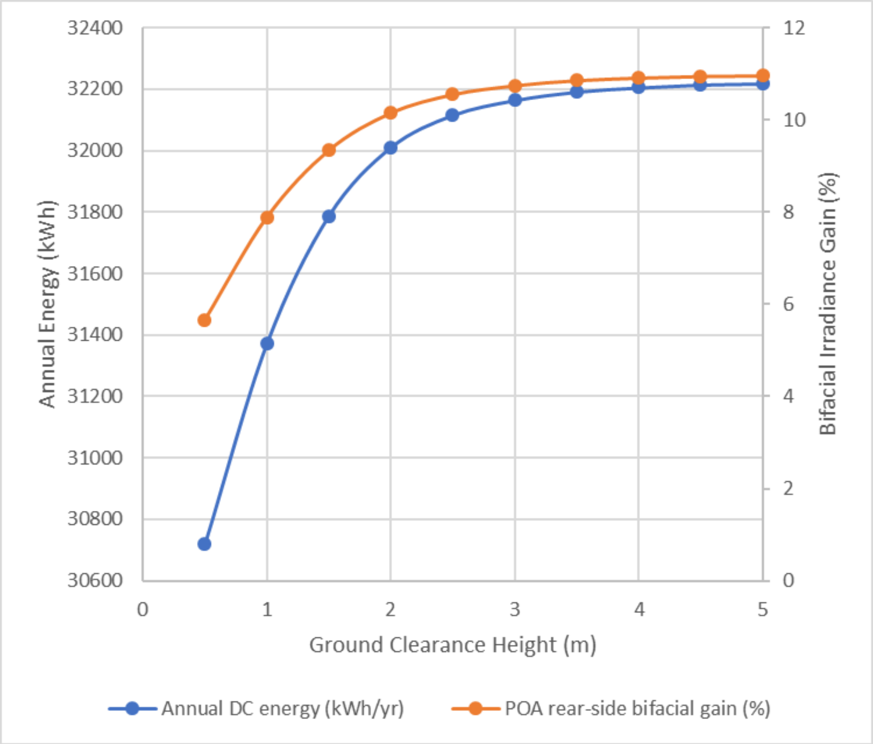
	Monofacial Fixed-tilt	Bifacial Fixed-tilt	Monofacial 1-axis track	Bifacial 1-axis track
POA Annual Irradiance (kWh)	190,961	206,030	254,943	265,187
Irradiance Gain	0%	7.9%	33.5%	38.9%
DC Annual Energy (kWh)	29,051	31,372	36,614	38,130
Energy Gain	0%	8.0 %	26.0%	31.3%

*Gains calculated relative to monofacial fixed-tilt system

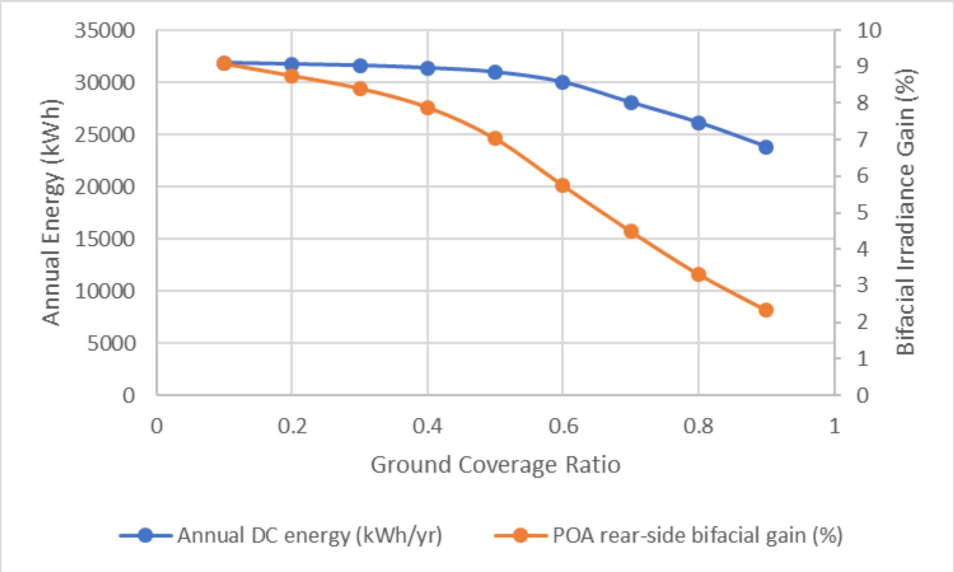
- DC energy gain is different from irradiance gain due to non-linear module response
- Installing 1-axis tracker on monofacial results in higher gain than installing bifacial (in this case).
- Installing bifacial modules with 1-axis trackers boosts annual DC energy by 31% over fixed monofacial system.

Sensitivity analysis of key variables

Ground Clearance Height



Ground Coverage Ratio



Key Variables:

- Ground Clearance Height
- Ground Coverage Ratio (row spacing)
- Albedo
- Tilt

Bifacial Summary and Future Work

Summary

- **Bifacial model added to SAM to calculate rear-side irradiance.**
- **Implementation tracks closely with other bifacial irradiance models**

Future Work

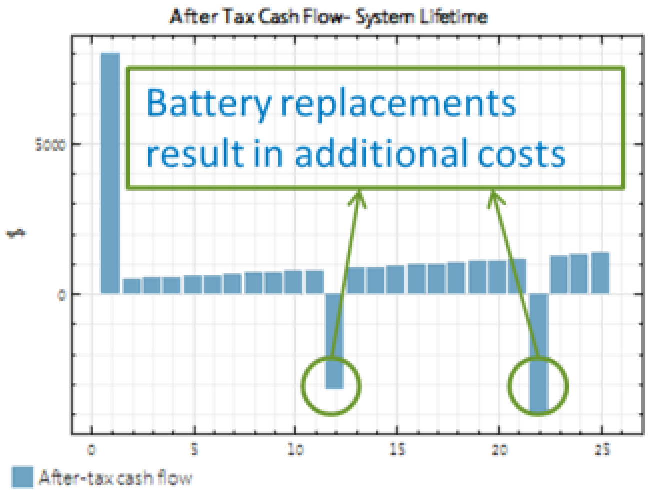
- **Model improvement and validation as part of upcoming NREL and Sandia projects:**
  - NREL installation of tracked bifacial PV
  - Impacts on bifacial PV shading from rack equipment
  - Research on mismatch from rear irradiance gradient.

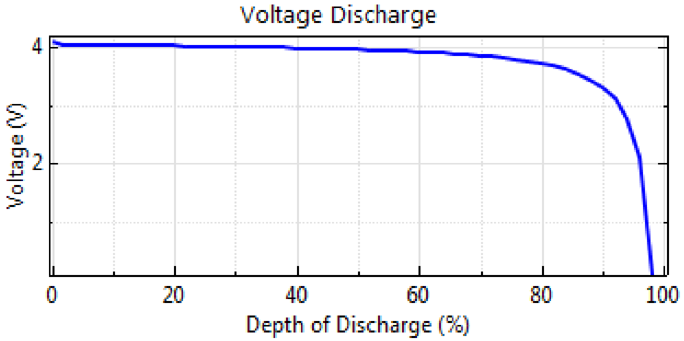
SAM Battery Outline

- Battery model introduction
- Dispatch
- Controlling charge source

Model Overview

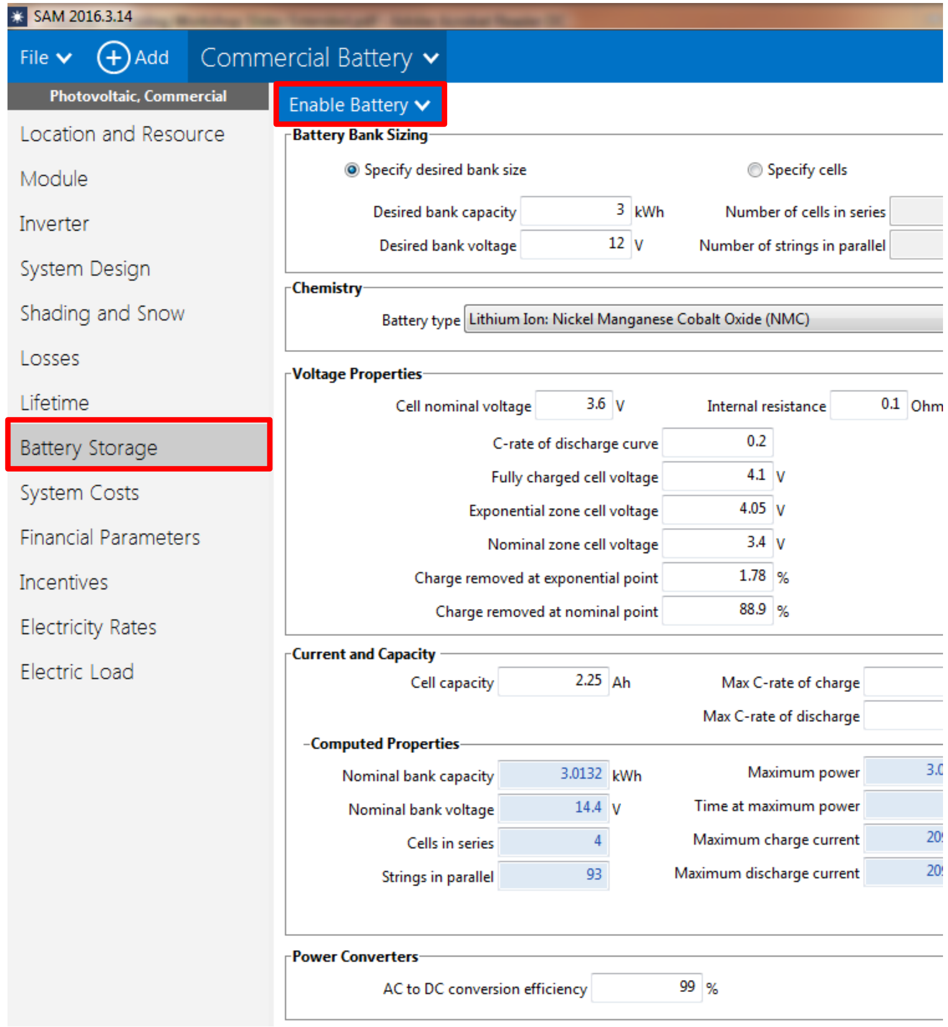
- **Techno-economic model for behind-the-meter and front-of-meter scenarios.**
  - Lead acid, lithium ion and flow battery chemistries
  - System lifetime analysis including battery replacement costs
  - Models for terminal voltage, capacity, temperature
  - Multiple dispatch controllers available





Detailed Battery Model

Photovoltaic (detailed)



Ability to configure

- Battery size
- Battery voltage
- Cell properties
- Chemistry type
- Max charge, discharge rates
- Battery configuration
- Power electronics efficiencies
- Battery operational limits
- Battery dispatch
- Battery lifetime properties
- Battery replacement preferences
- Battery thermal properties

Battery Financials

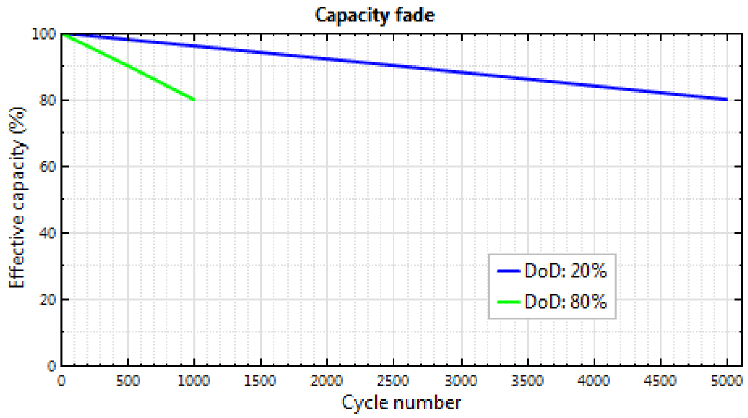
- **Lifetime**

PV simulation over analysis period

PV Array Performance Degradation

Module degradation rate | 0 | %/year

Applies to the array's hourly DC output.



Battery capacity fades with cycling, depends on depth-of-discharge

- **System Costs**

Direct Capital Costs

Module	928	units	0.2	kWdc/unit	199.8	kWdc	0.71	$/Wdc
Inverter	5	units	36.0	kWac/unit	180.0	kWac	0.21	$/Wdc
				Battery bank	3.0	kWh dc	600.00	$/kWh dc

- **Battery Bank Replacement (Battery Storage page)**

Battery Bank Replacement

- (•) No replacements
- ( ) Replace at specified capacity
- ( ) Replace at specified schedule

Battery bank replacement threshold | 20 | % capacity

Battery bank replacement schedule | Edit data...

Battery bank replacement cost | 600 | $/kWh

Battery cost escalation above inflation | 0 % | %/year

SAM applies both inflation and escalation to the first year cost to calculate out-year costs. See Help for details.

Battery Dispatch Behind the Meter

Storage Dispatch Controller

Choose Dispatch Model

- ( ) Peak shaving: 1-day look ahead
- ( ) Peak shaving: 1-day look behind
- ( ) Automated grid power target
- (•) Manual dispatch

Charge Limits and Priority

Minimum state of charge 30 %

Maximum state of charge 95 %

Minimum time at charge state 10 min

Automated Grid Power Target Model

Enter single or monthly powers

Single or monthly [Edit values...] kW

Time series [Edit data...] kW

Manual Dispatch Model

	Charge from PV	Charge from grid: Allow	Charge from grid: % capacity	Discharge: Allow	Discharge: % capacity
Period 1:	☑	☐	25	☐	25
Period 2:	☑	☑	25	☐	25
Period 3:	☑	☐	25	☑	25
Period 4:	☐	☐	25	☐	25
Period 5:	☐	☐	25	☐	25
Period 6:	☐	☐	25	☐	25

To activate the manual dispatch model, choose Manual Dispatch under "Choose Dispatch Model" above. These inputs are inactive for the automated dispatch options.

The manual dispatch model aims to minimize purchases from the grid. It first tries to meet load with PV, then battery, then grid. Choose whether PV should meet the load or charge the battery below. Use the timing controls to constrain the battery controller. See help for details.

- (•) PV meets load before charging battery
- ( ) PV charges battery before meeting load

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Feb	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Mar	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Apr	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
May	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Jun	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Jul	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Aug	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Sep	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Oct	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Nov	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
Dec	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1

Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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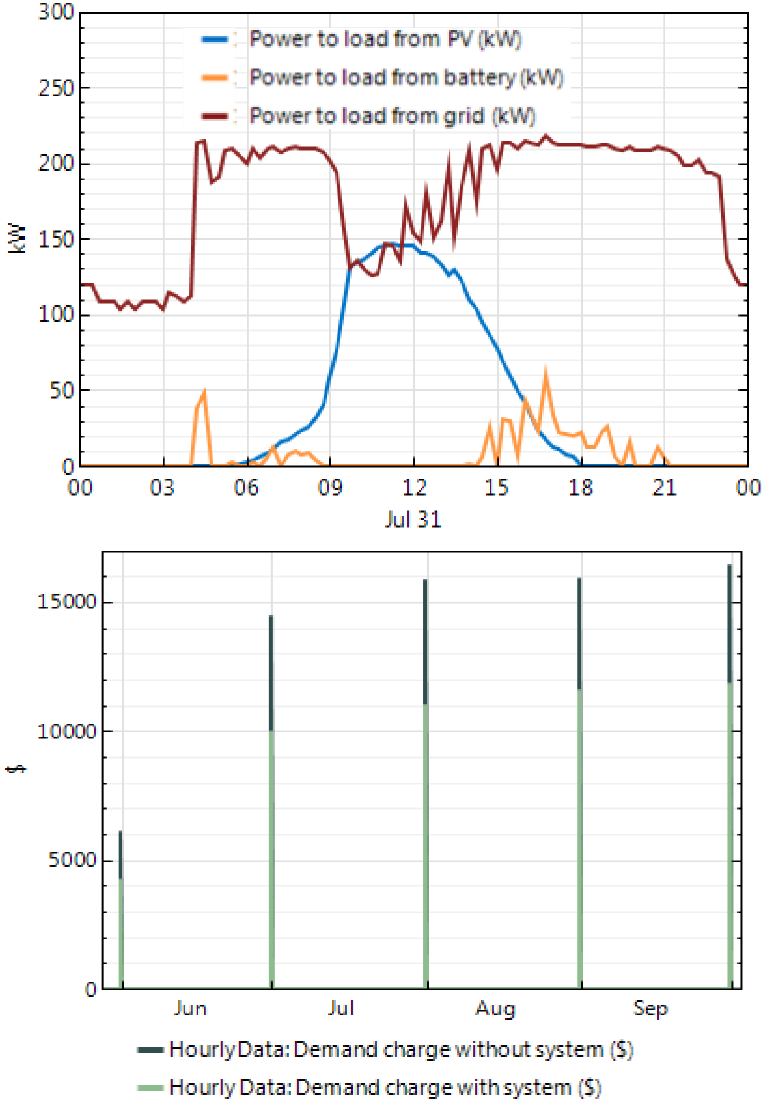
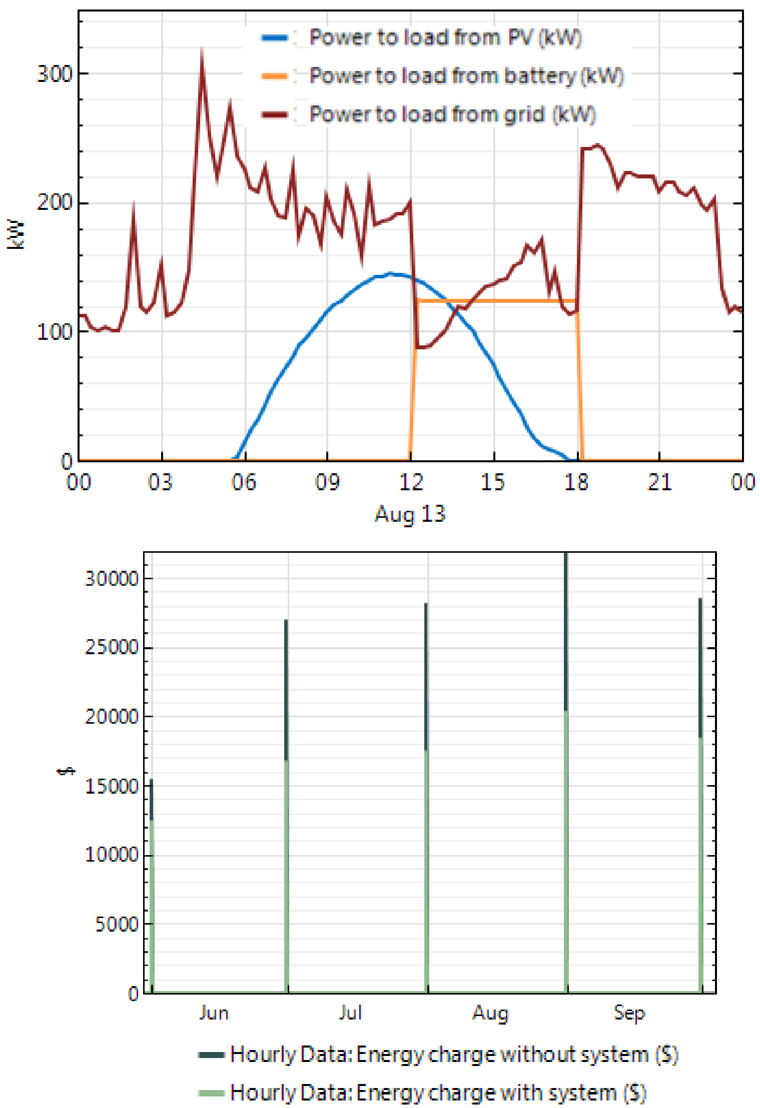
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Dispatch Visualization

Peak shaving for demand charge reduction



Manual dispatch for energy arbitrage



Example Case Study

- **Evaluate economics of installing PV-coupled battery system for demand-charge reduction:**
  - Los Angeles, CA
  - 27,625 ft^2 building with 247 kW peak load
  - Southern California Edison TOU-GS-2 Option B

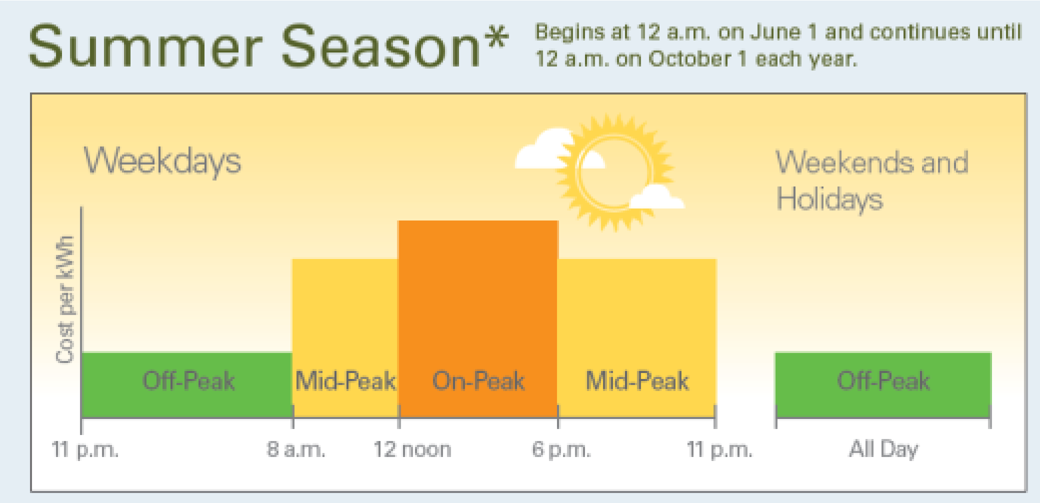


Image from SCE TOU-GS-2 Option B datasheet

Lithium Ion Battery System

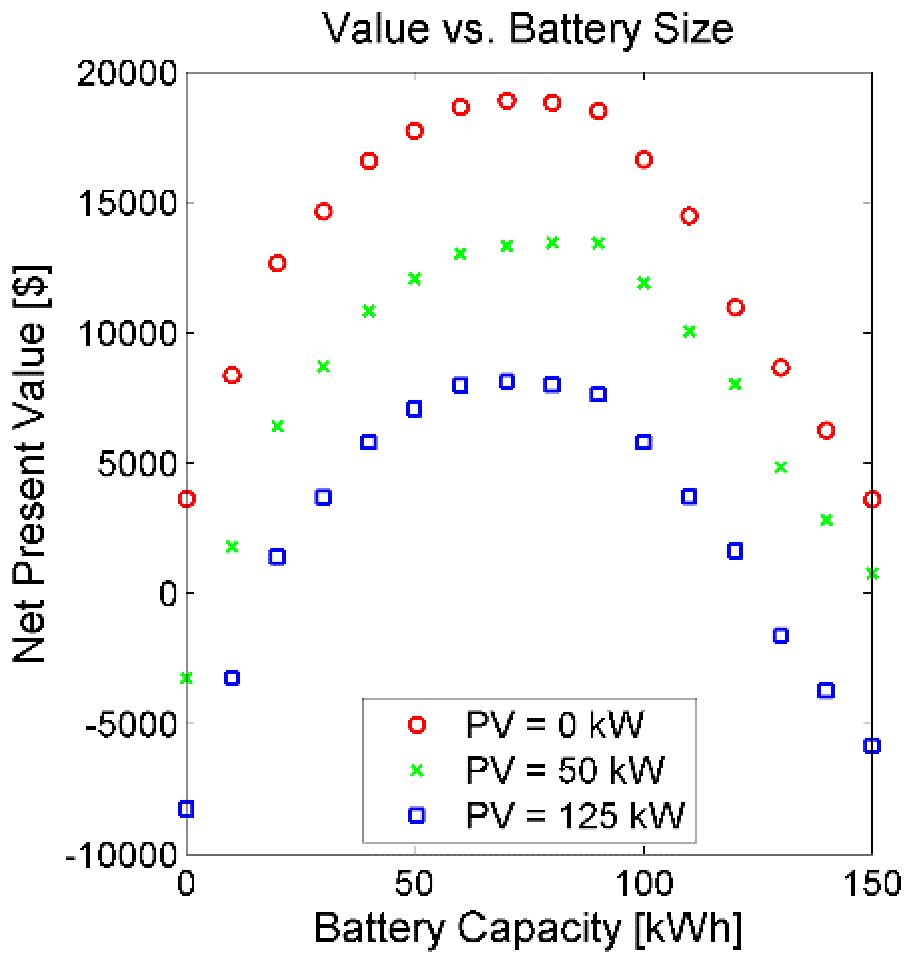
- **Model battery similar to Tesla Powerwall**
  - Lithium-ion nickel manganese cobalt
  - Assumed can cycle full 7 kWh down to 30% of state-of-charge, for a full capacity of 10 kWh.
  - Price given as ~$300/kWh before balance of system costs.
  - Assumed lifetime of 10-15 years before degrading to 70% of original capacity

Table 3: Tesla Powerwall Specifications [13]

Property	Value
Price	$3000
Capacity	7 kWh
Power	2.0 kW continuous, 3.3 kW peak
Efficiency	92%
Voltage	350 – 450 V
Current	5.8 A nominal, 8.6 A peak
Weight	100 kg
Dimensions	1300 mm x 860 mm x 180 mm

Image from teslamotors.com/powerwall

Parametric sizing results



- NPV maximized for no PV system, battery bank capacity of 70 kWh
- Illustrates simulation-based method to approximate ‘optimal’ sizing.

Modeling different system topologies

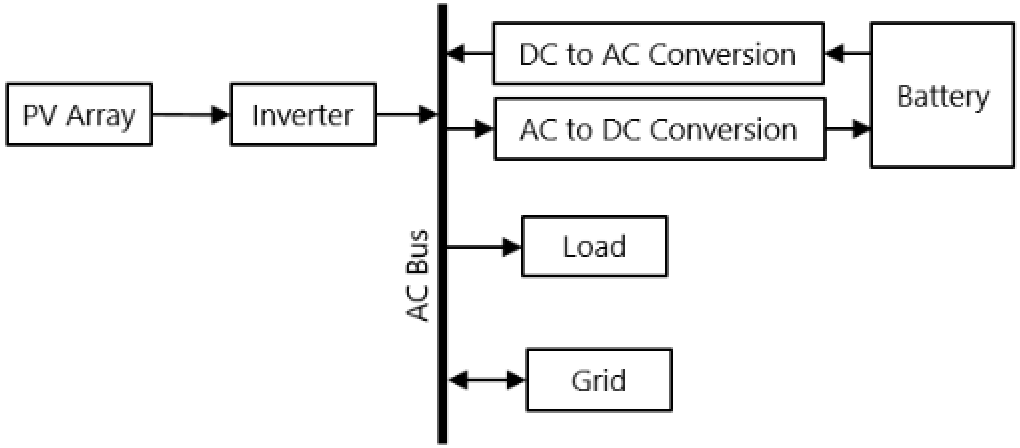


Diagram 1: Battery Connected to AC Side of Photovoltaic System

- AC-Coupled battery systems are solutions packaged with their own power electronics
- Can couple at common point of AC connection

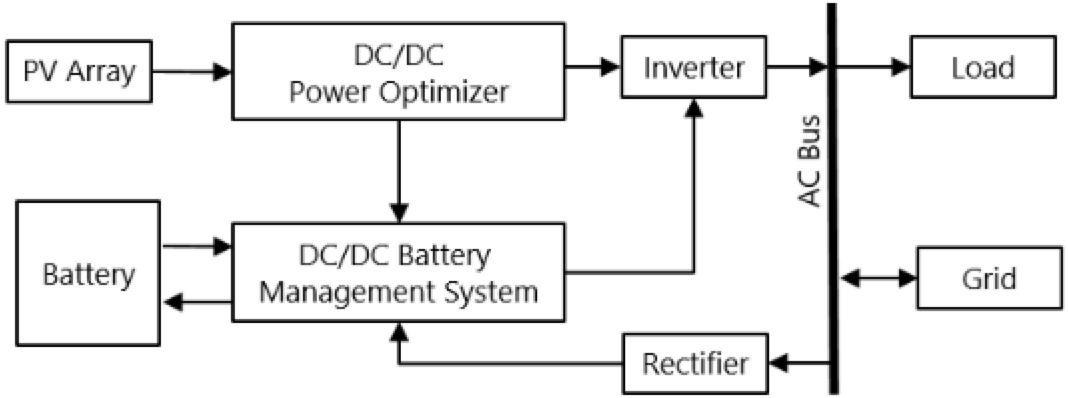
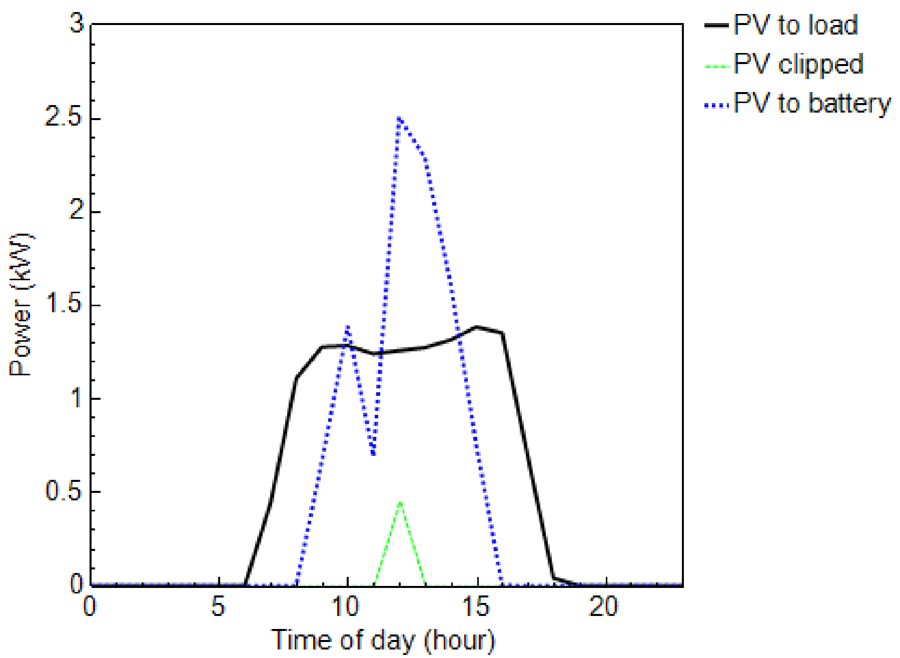


Diagram 2: Battery Connected to DC Side of Photovoltaic System

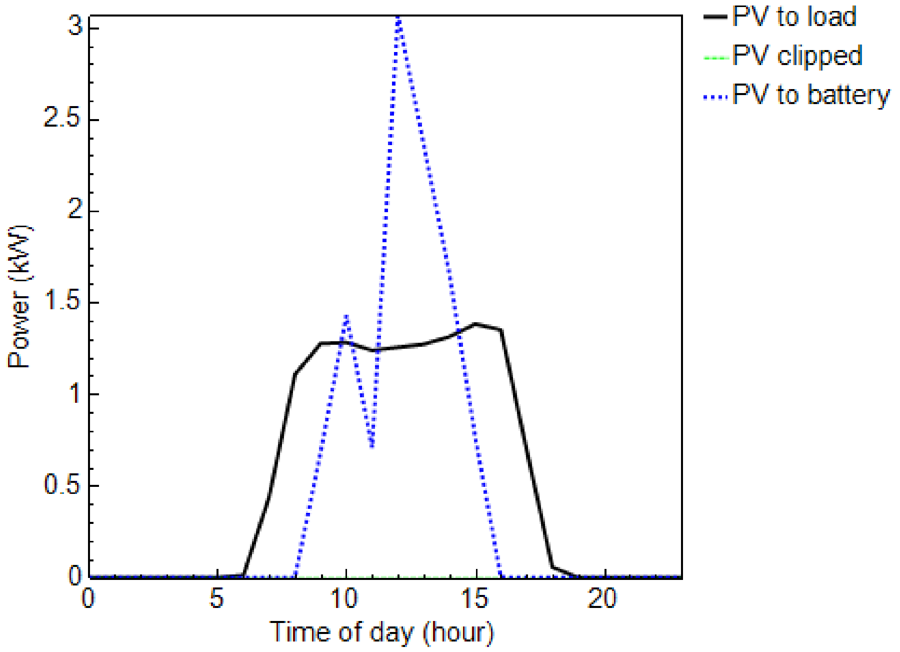
- DC-Coupled battery shares the PV inverter
- PV power can charge the battery without going through the inverter

DC-connected batteries to capture clipped power

PV + AC-Connected Battery

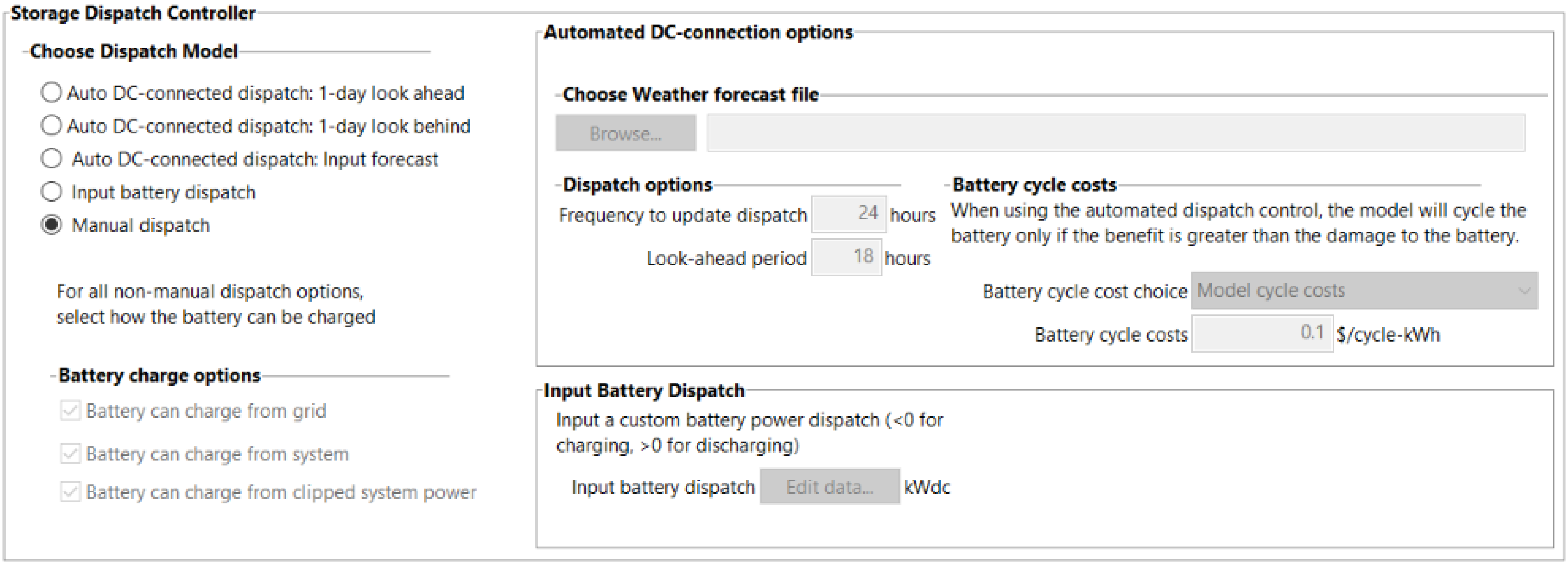


PV + DC-Connected Battery



- When the PV DC power output exceeds the inverter DC power input, excess power is clipped
- In an AC connected system, even if PV power is dumped to the battery, it doesn't reduce clipping, since PV power must still pass through the inverter before going to the battery
- In a DC connected system, PV power can be dumped to the battery before passing through the inverter

Battery Dispatch Front-of-meter

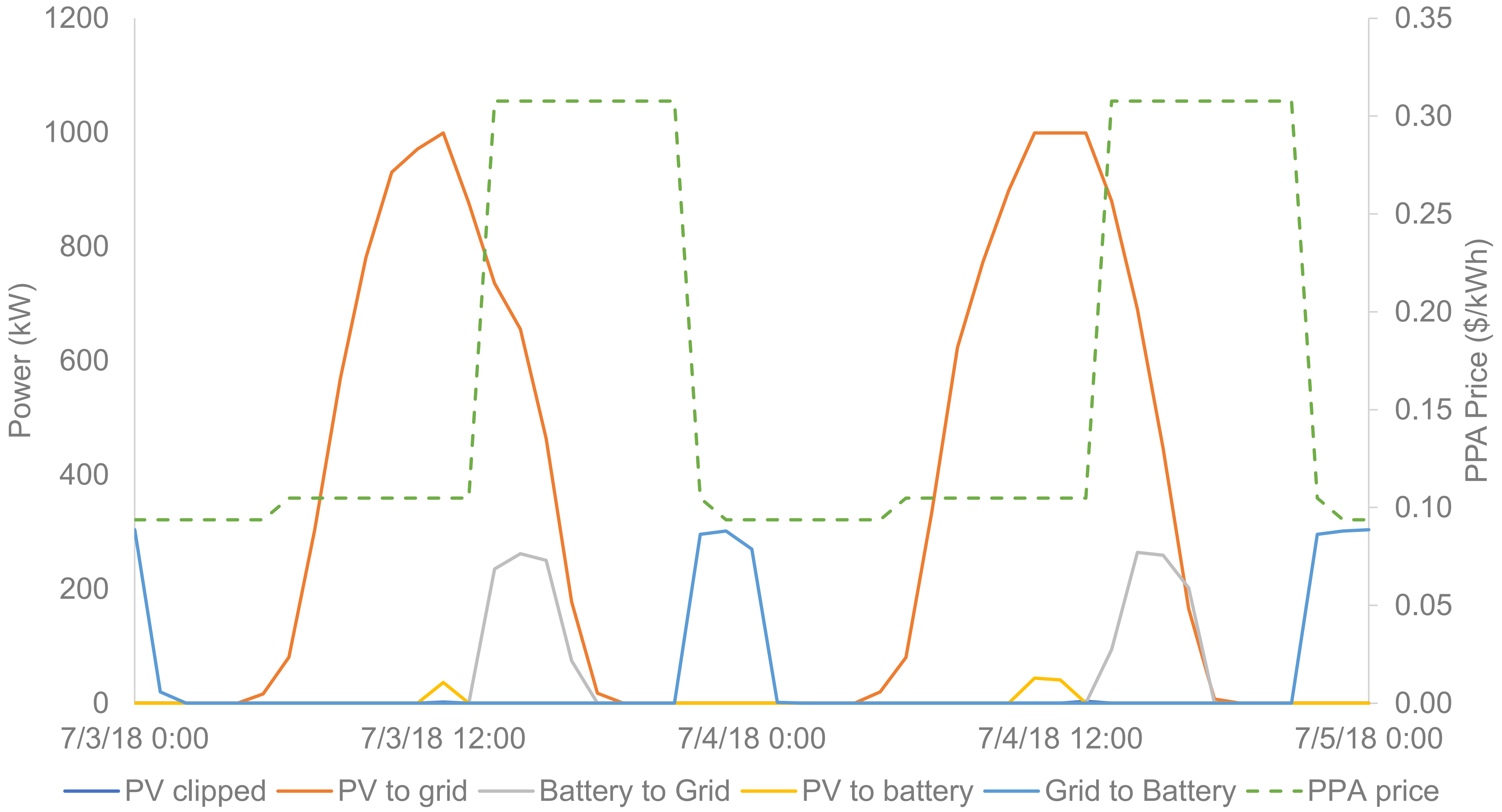


- Recently added automated control strategies for large plants with DC-connected battery systems
- Optimize dispatch to charge from PV, capture clipping, and maximize value
- Will be released publicly in October.

Controller development

- **Develop a controller that at every time, looks ahead 18 hours and decides:**
  - Whether to charge from the grid
  - Whether to charge from PV
  - Whether to charge from PV power which would otherwise be clipped.
  - Whether to discharge
- **Factor in the PV production forecast, the PPA time-of-delivery factors, and estimated wear cost of the battery**

Example peak summer day operation



Battery charges from PV minimally during peak operation to reduce clipping, otherwise charges mostly from grid.

Example Results Summary

Variable	PV Only	DC-Connected Battery
Annual Energy (year 1)	1,912 MWh	1929 MWh
Year 1 Energy Clipped	44.0 MWh	11.2 MWh
Year 1 Battery Energy Charged	0 kWh	107 MWh
Year 1 Battery Energy Charged from PV	0 MWh	35 MWh
Year 1 Battery Energy Charged from Grid	0 MWh	72 MWh
Year 1 Battery Energy Discharged	0 kWh	92 MWh
Net Present Value	$118,080	$107,570

- PV is cost effective, and installing a battery slightly reduces this value
- DC-connected battery reduces clipping by 75%.
- In this case, the battery mostly charges from the grid to take advantage of the difference in buy rate vs. sell rate

Tools That You Can Use

PV analysis tools take into account the factors that impact project potential

Publicly available tools can be used to gauge initial potential, optimize system sizing & refine project economics

	Expertise and Effort needed	Required Inputs	Key Outputs
Distributed Generation Screening Maps	Low	• Location	• Map interface with geospatial layers • High-level economics
PVWatts Calculator	Low	• Location • System configuration	• PV energy generation (no economics)
REopt Lite Web Tool	Medium	• Location • Energy Consumption • Rate tariff	• Optimized system size and dispatch • High-level economics
System Advisor Model (SAM)	High	• Energy Consumption • Rate tariff • Detailed system configuration • Financing inputs	• Detailed technology performance • Detailed economic modeling

Thank you! Questions?

Janine Freeman - project lead, photovoltaic and wind models
Nick DiOrio - code architecture, battery storage models
Nate Blair - emeritus lead, financials, costs, systems
Steve Janzou - programming, utility rate structures (subcontractor)
Paul Gilman - user support and documentation (subcontractor)
Ty Neises - concentrating solar power models
Mike Wagner - concentrating solar power models
Matt Boyd- concentrating solar power models

www.nrel.gov
http://sam.nrel.gov

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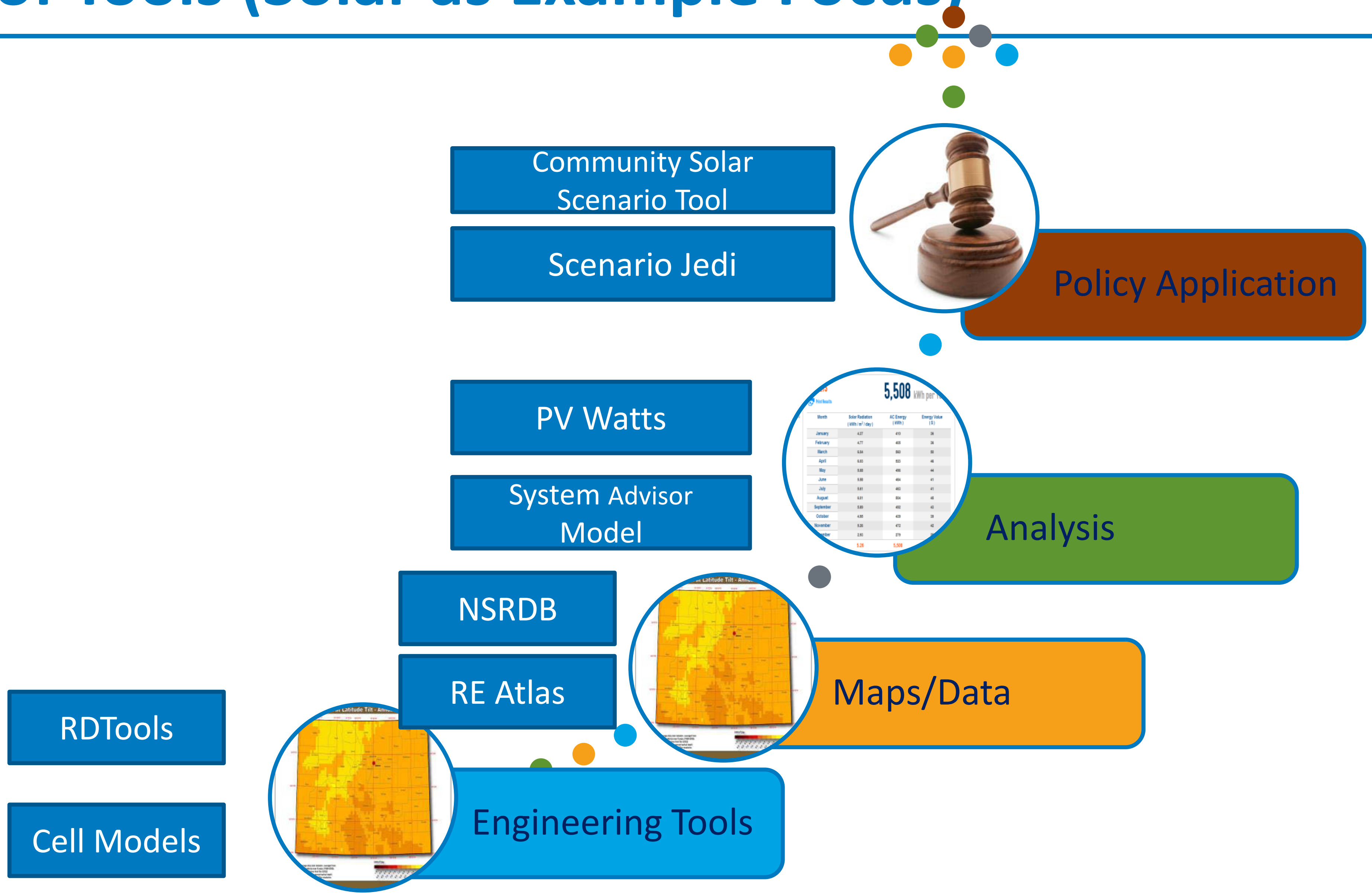
Additional Solar Tools

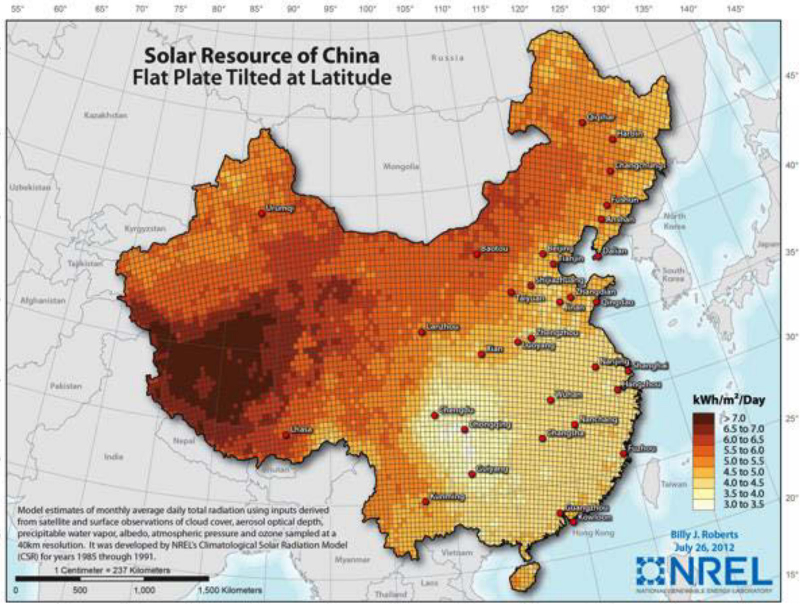
Nate Blair

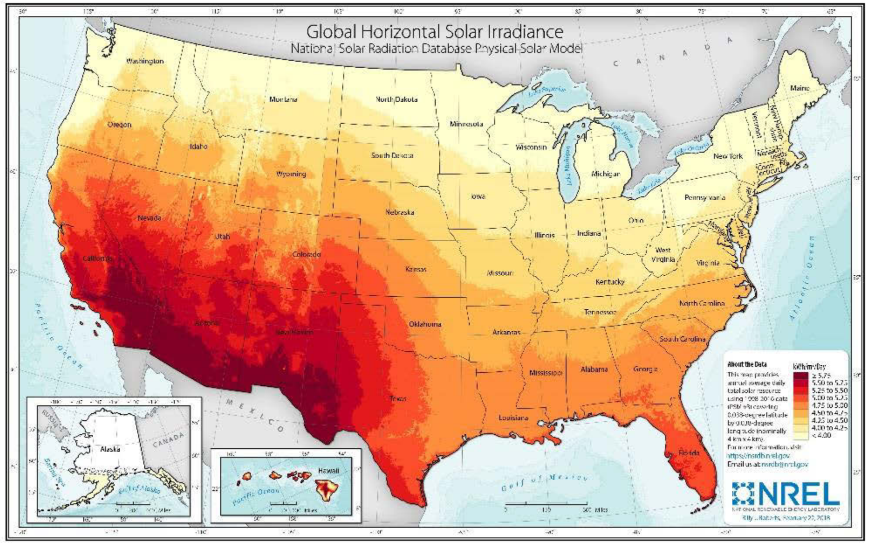
Group Manager

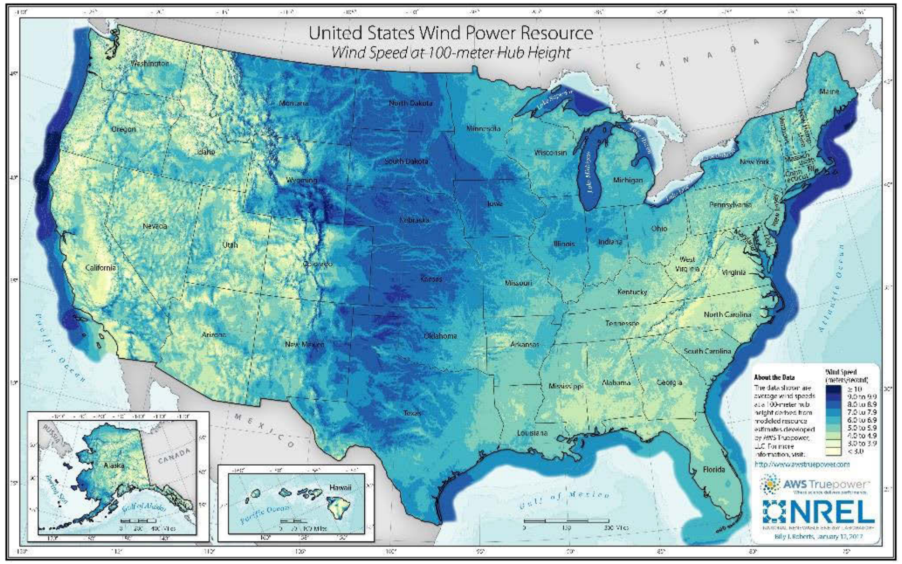
Range of Tools (Solar as Example Focus)

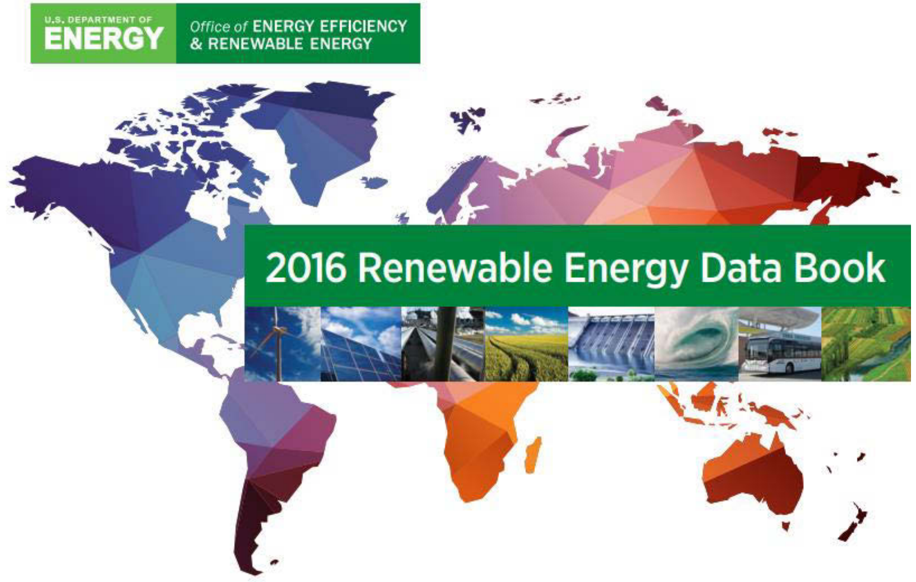


Clean Energy Models and Tools begin with high resolution, high quality Data

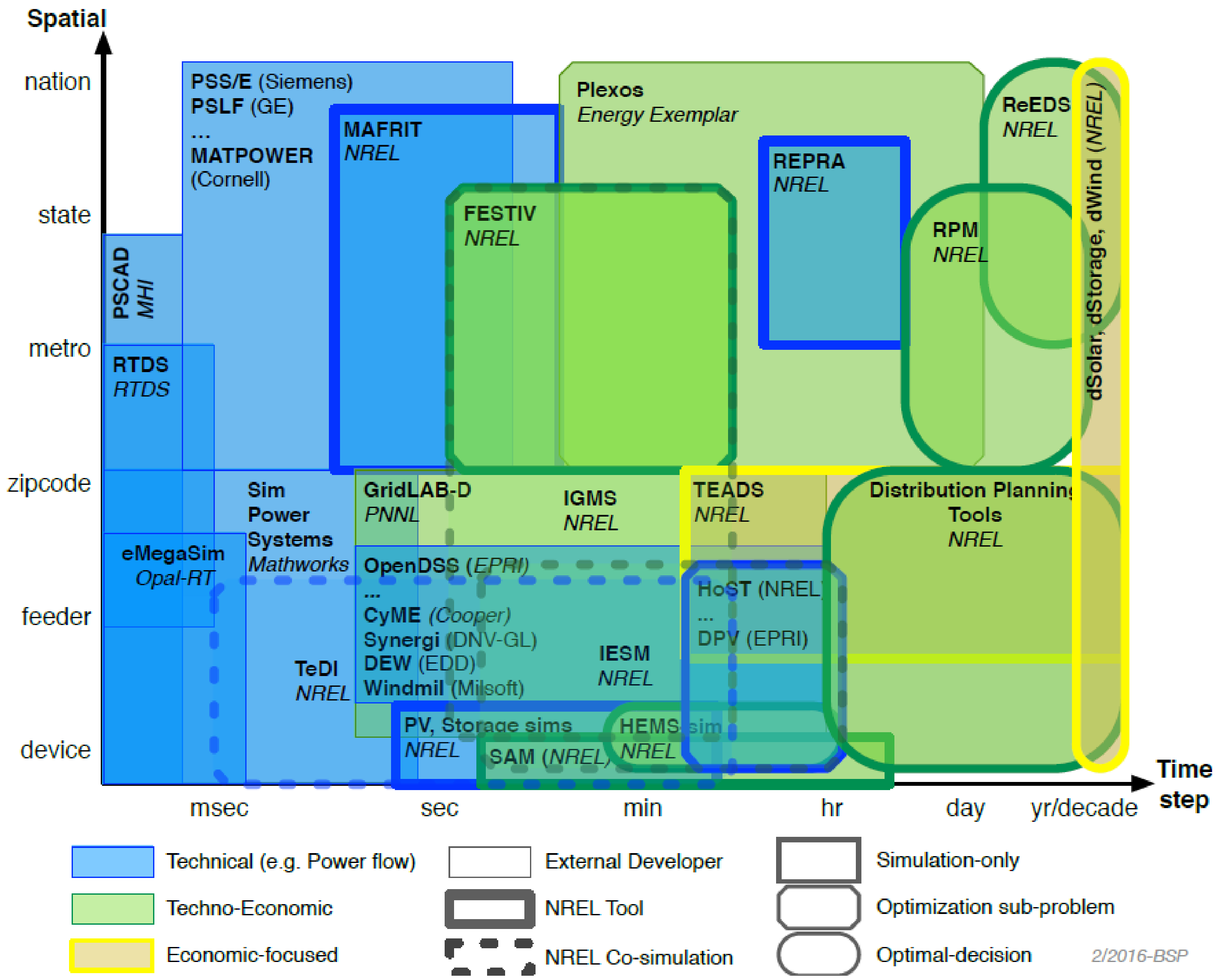




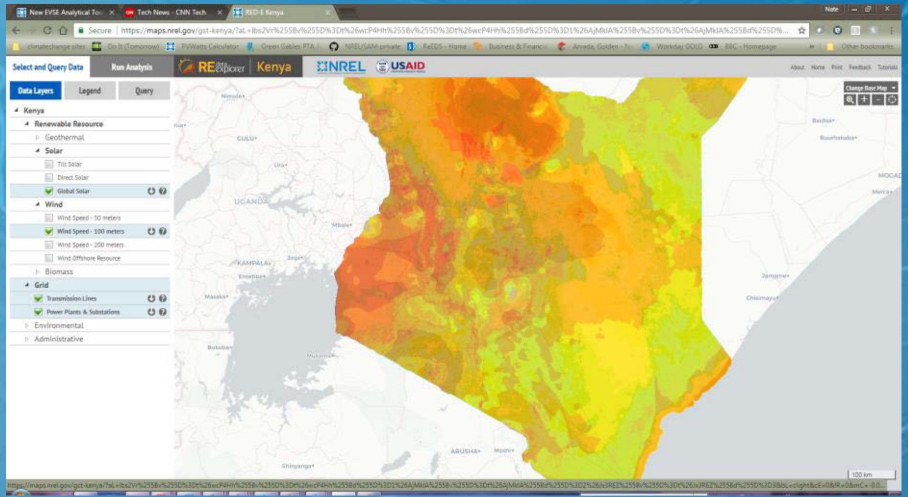




Power System Model Map



Mexico, Ghana, Kenya, Kazakhstan, Afghanistan, Pakistan, India, Nepal, Bangladesh, the Lower Mekong region, Indonesia, and the Philippines



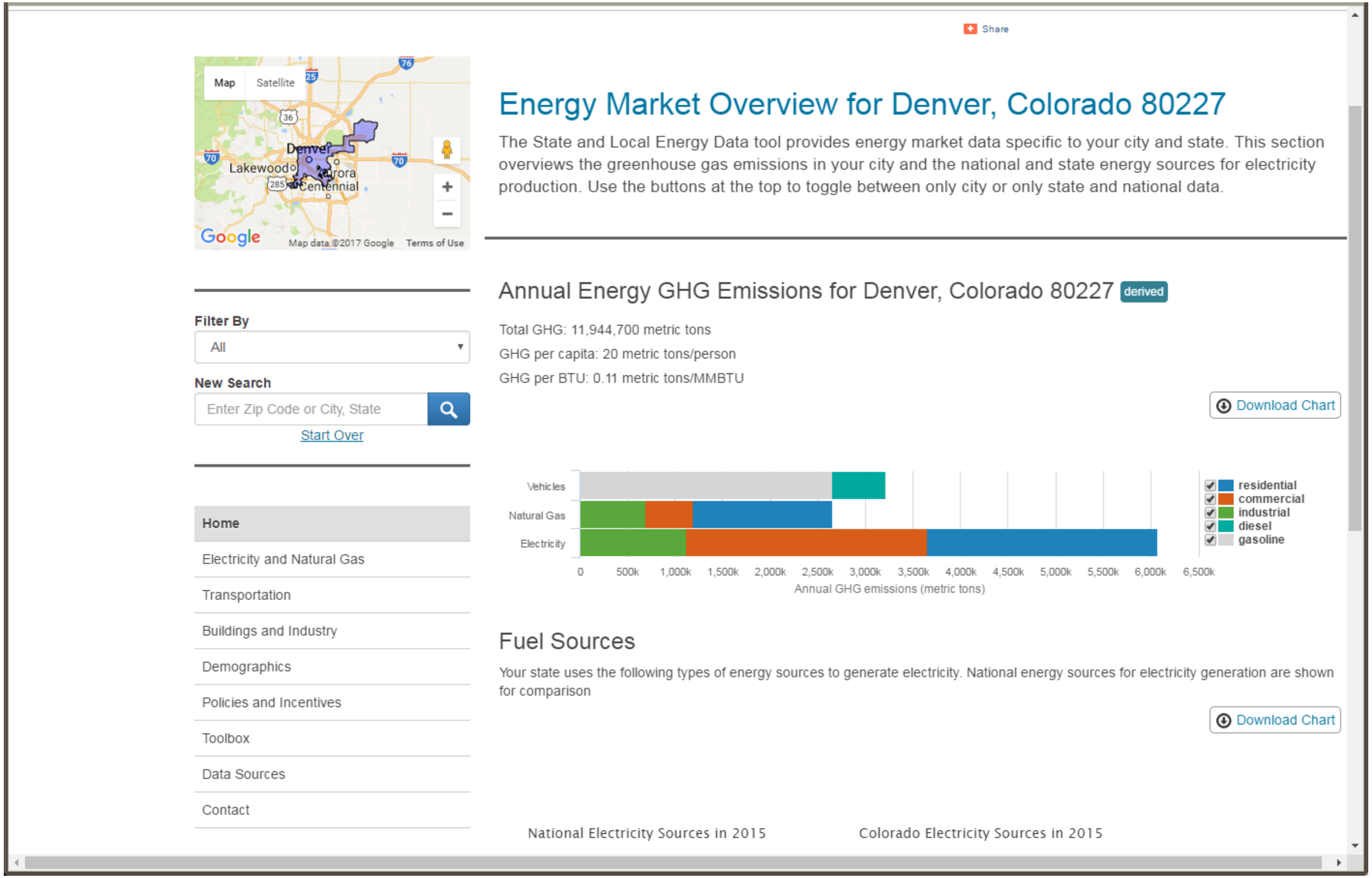
REexplorer
MAPPING OUR ENERGY FUTURE

Types of questions the RE Data Explorer can help answer

- High-level prospecting and integrated resource planning questions
- Where are the most appropriate areas to site utility-scale solar and wind facilities based on:
  - Resource quality?
  - Proximity to load centers, transmission lines, and/or roads?
  - Site suitability? (e.g., terrain, protection status, current land use?)
- How does resource potential vary at the province level?
- Which sites may offer the best possibilities for investment in long-term measurement stations?

www.re-explorer.org

State & Local Energy Data (SLED)



https://apps1.eere.energy.gov/sled

JEDI PV – Jobs and Economic Development

- **NOTE: JEDI models exist for wind, biofuels, Solar CSP, Coal, Hydropower, Geothermal, Marine Hydrokinetic, Petroleum, Transmission as well as PV**
- **PURPOSE:** Estimate the economic impacts of constructing and operating photovoltaic power generation at the local and state levels.
- **TYPE:** Spreadsheet-based impact model (PV has a web version as well)
- **TAKEAWAY:** Economic impacts for one, or, a portfolio of projects
- **CONTACT:** JEDISupport@nrel.gov

Local Economic Impacts - Summary Results

During construction and installation period	Jobs	Earnings ($000 (2010))
Project Development and Onsite Labor Impacts [?]		
Construction and Installation Labor	4.2	$275.11
Construction and Installation Related Services [?]	6.7	$313.85
Subtotal	11.0	$588.97

http://www.nrel.gov/analysis/jedi/download.html

Community Solar Scenario Tool

NEW

- **PURPOSE:** Evaluate economics of a community solar project from a customer's perspective as well as the sponsoring utility
- **TYPE:** Spreadsheet-based model
- **TAKEAWAY:** "First cut" analysis of different community solar options for utility, state and local advocates.
- **CONTACT**: john.nangle@nrel.gov

System Information		
Number of Shares		400
Project Lifetime [yrs]		25
Subscriber Discount Rate		0.00%
System Size [kW]		400
First Year Generation [kWh/kW]		1,418
Average Annual Generation [kWh]		533,290

Utility Perspective		
Costs per kWh		
Real LCOE or PPA Price [$/kWh]	$	0.158
Administrative Costs [$/kWh]	$	-
TOTAL COSTS [$/kWh]	$	0.158
Annual Costs		
Average Annual Cost of Production [$]	$	84,315
Administrative Costs [$]	$	-
TOTAL COSTS [$]	$	84,315
Cost per Share		
Average Annual Cost per Share [$]	$	210.79
Average Monthly Cost per Share [$]	$	17.57

Utility Charges per Share	No Credit
Average Annual Charge per Share [$]	210.79
Monthly Average Charge per Share [$]	17.57
Average Monthy Charge per Share [$/kWh]	0.16

		Average Monthly Bill Credit
No Bill Credit		17.57
Bill Credit Rate [$]	$	5.56
Average Energy Credit [kWh]		

www.nrel.gov/tech_deployment/tools_community_solar.html

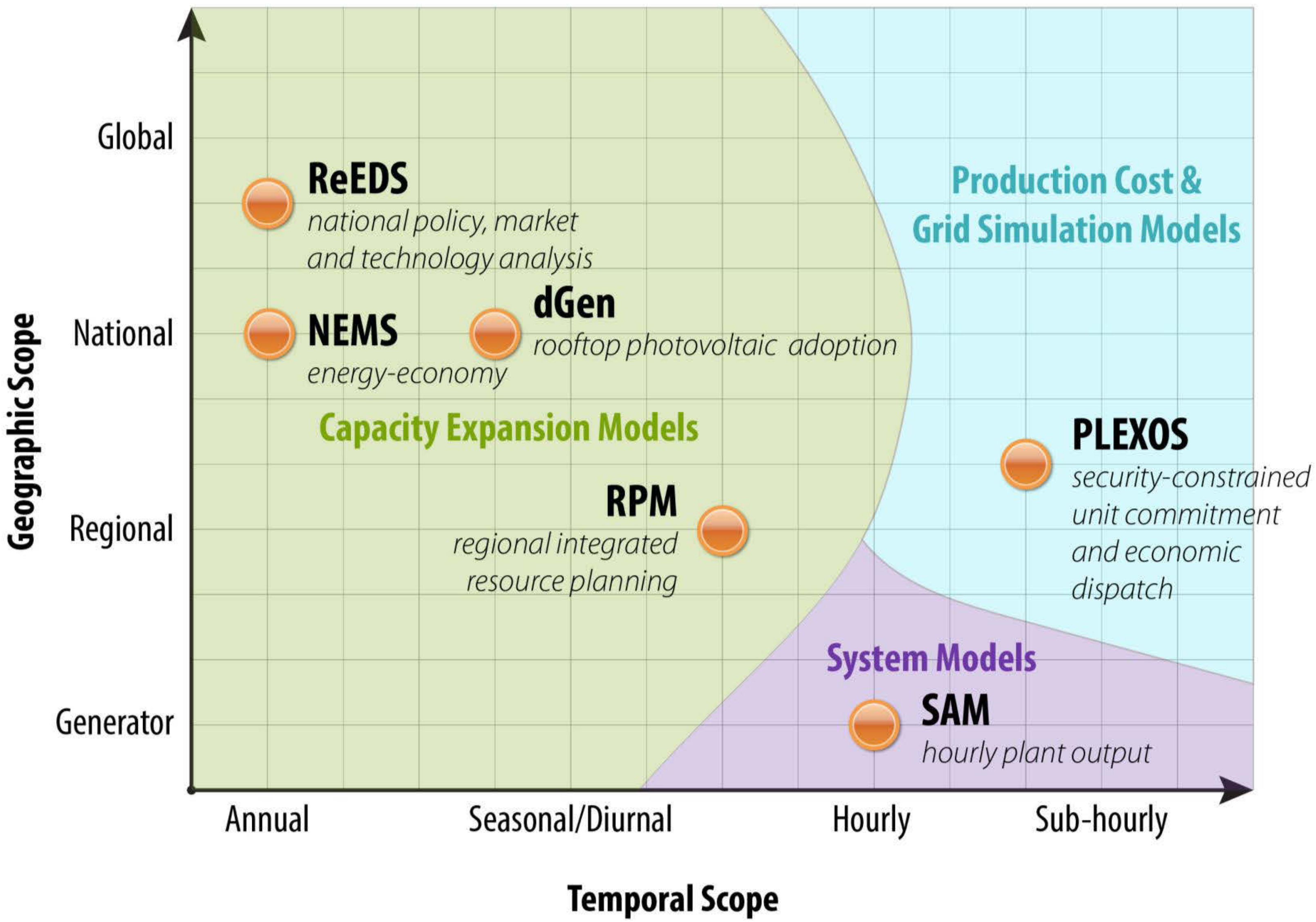
Developer Network at NREL *developer.nrel.gov*

Making data and analysis tools available to developers via web services / APIs *including PVWatts API*

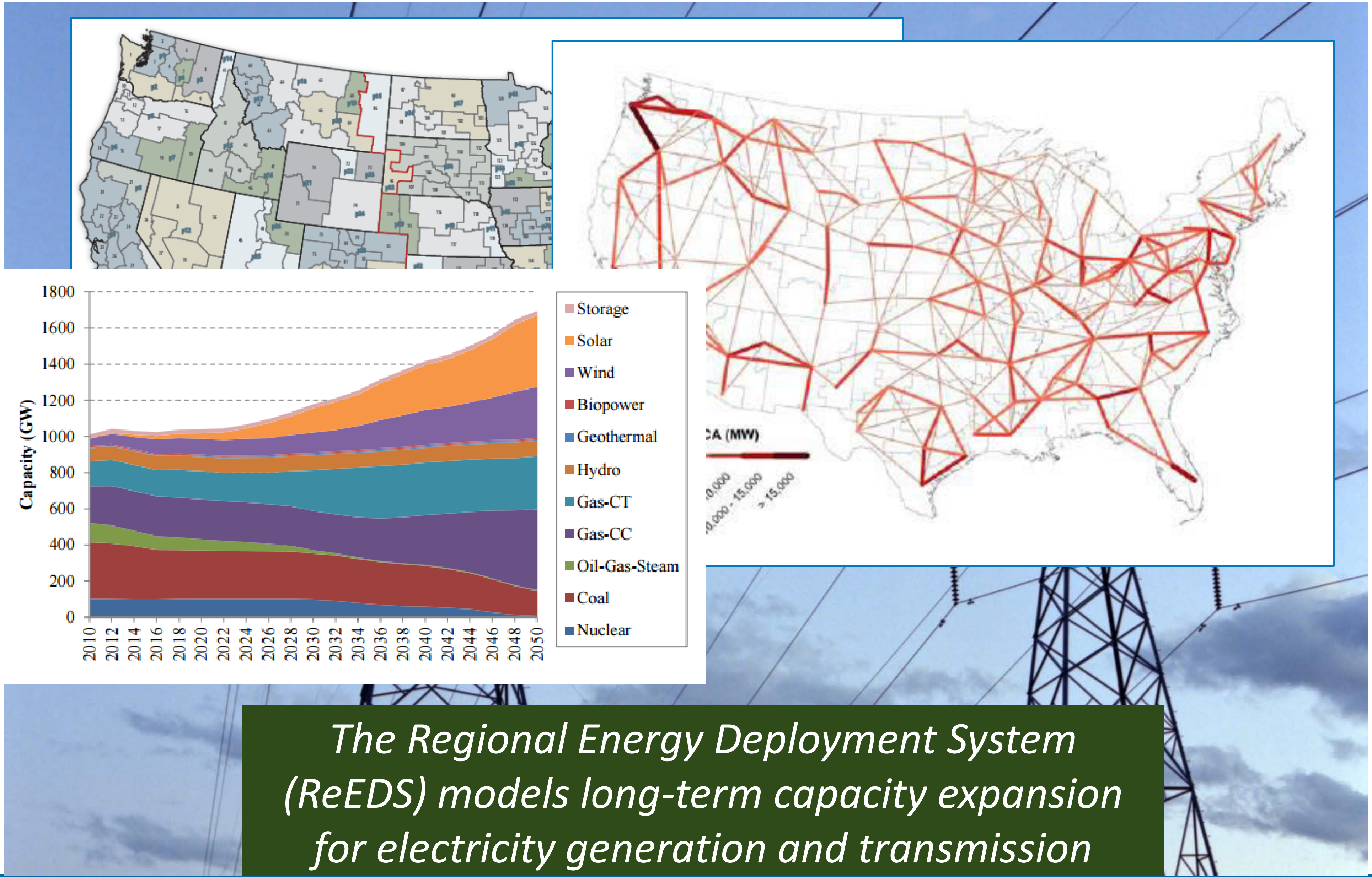
1. Public access to data/models/tools via Web Services
2. Increased access to real-time/dynamic data
3. Eliminates repeated downloads of data snapshots
4. Shifts NREL application development to platform development

Connects data with those who will increase its visibility

Interoperability



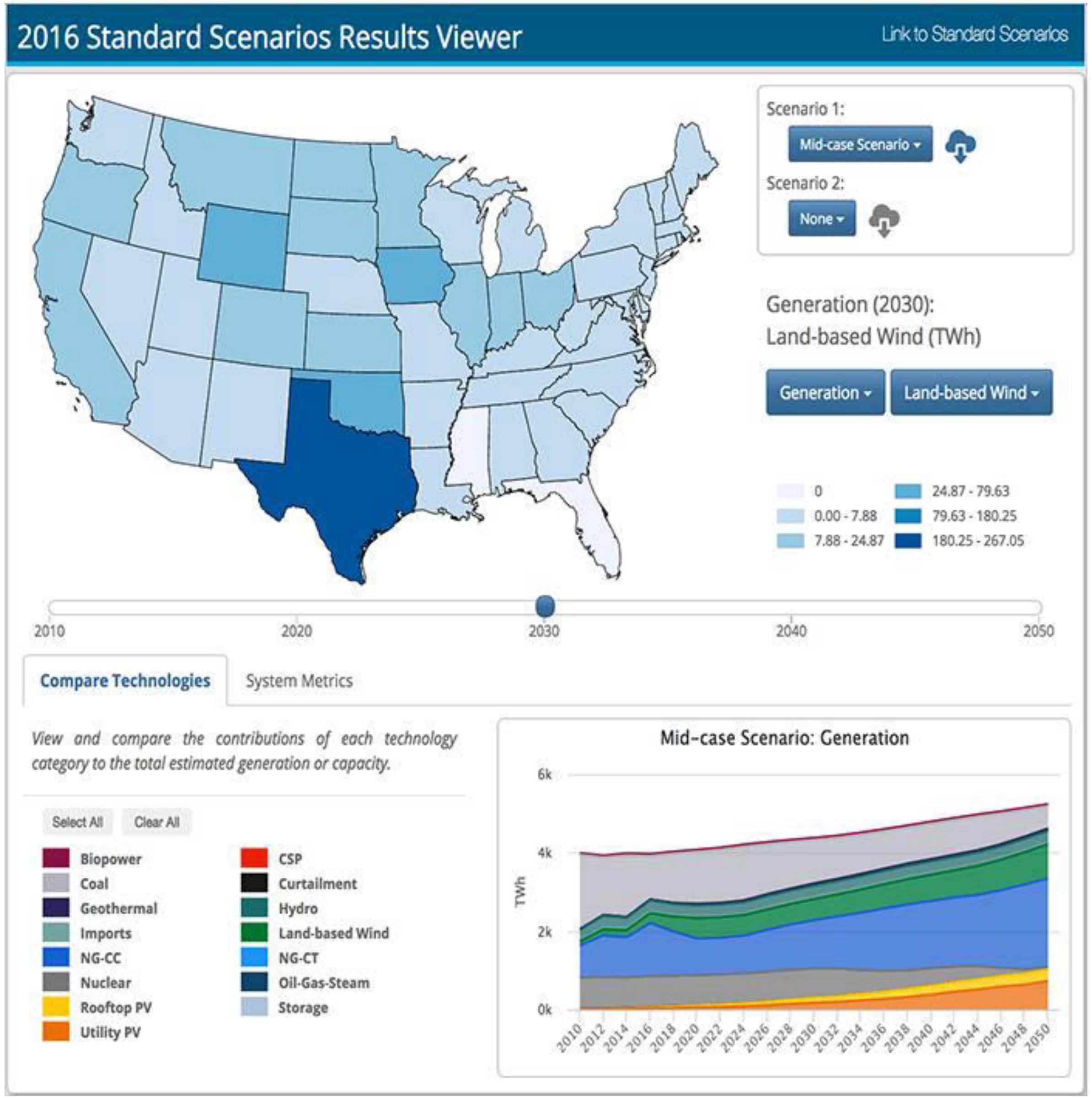
Tools: Modeling the Electric System



The Regional Energy Deployment System (ReEDS) models long-term capacity expansion for electricity generation and transmission

NREL Standard Scenarios Results Viewer

- 19 Scenarios Exploring Different future Electric Sector Scenarios
- Published annually for last 3 years
- Output of our ReEDS electric sector forecast model
- Results by state and year for each scenario
- Aggregate metrics including capacity, generation, emissions, electricity price, etc.
- http://en.openei.org/apps/reeds/
- Report at: https://www.nrel.gov/analysis/data-tech-baseline.html



Questions?

Tools you want us to build?

Thank you

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