GENERATING MODULE FILES IN PLANTPREDICT

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First Solar®

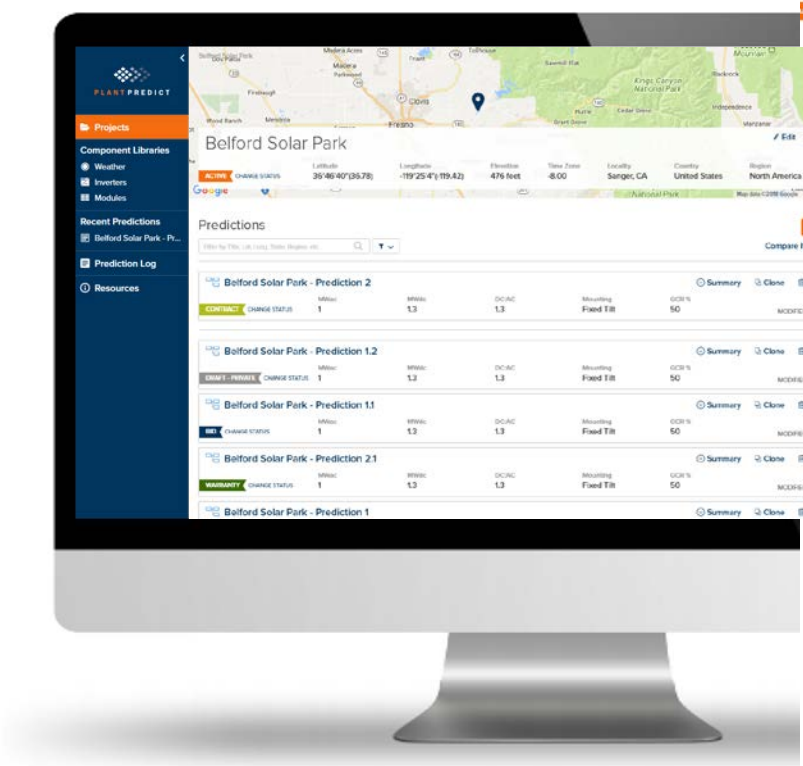
LEADING THE WORLD'S
SUSTAINABLE ENERGY FUTURE

TOPICS OF DISCUSSION

- PlantPredict Introduction
- New & Upcoming Features
- **Generating Module Files in PlantPredict**

INTRODUCING PLANTPREDICT

- Free, cloud-hosted, energy prediction software for **utility-scale** PV power plants
- Used in over 350 MWAC of contracted utility-scale PV projects
- All algorithms documented and published on www.plantpredict.com
- *End-to-end utility-scale modeling*
  - Sub-hourly and multi-year predictions
  - Built-in spectral correction
  - No need for pre- or post-processing
  - Pre-loaded with industry-standard weather, module, and inverter files
- API available for automation
- Independently reviewed and benchmarked against over 1 GW of operating facilities



Reviewed by: DNV·GL, leidos, ICF

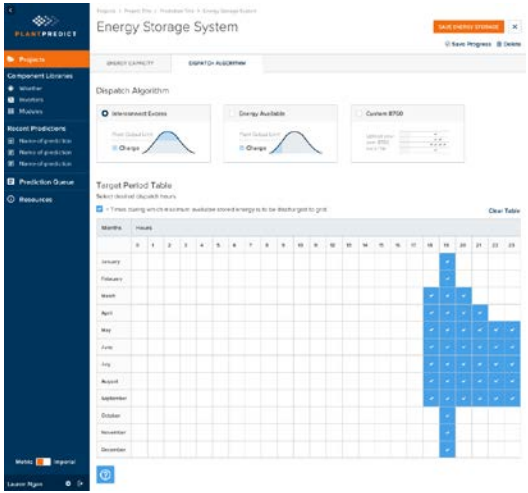
NEW FEATURES IN PLANTPREDICT

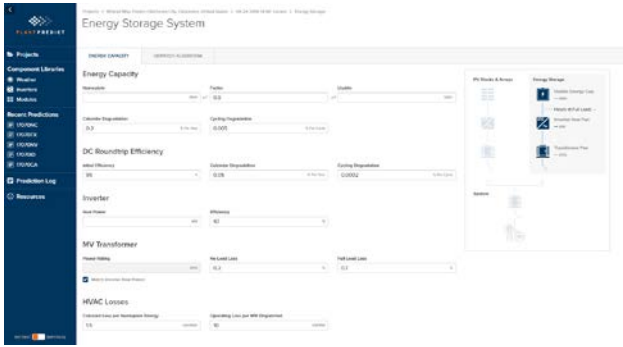
Recently-Added Features

PV Energy Storage

Module File Generator

Bifacial PV





Charging/Dispatch Options

1. LGIA Excess
2. Energy Available
3. Custom

AC-coupled storage systems

More storage modeling features planned for release in September 2019.

Recently-Added Features

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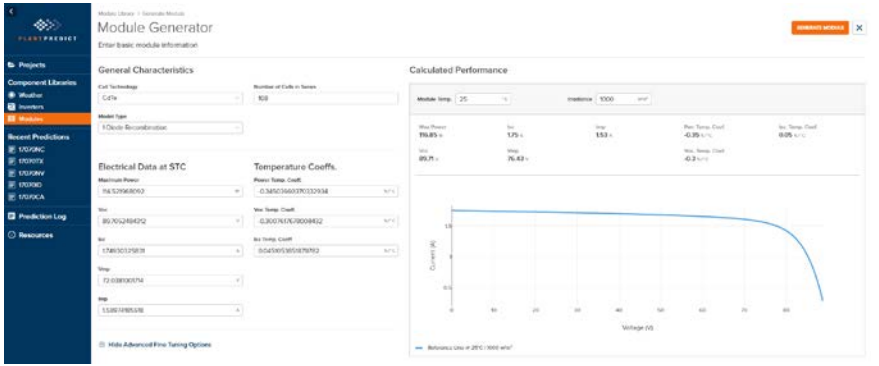

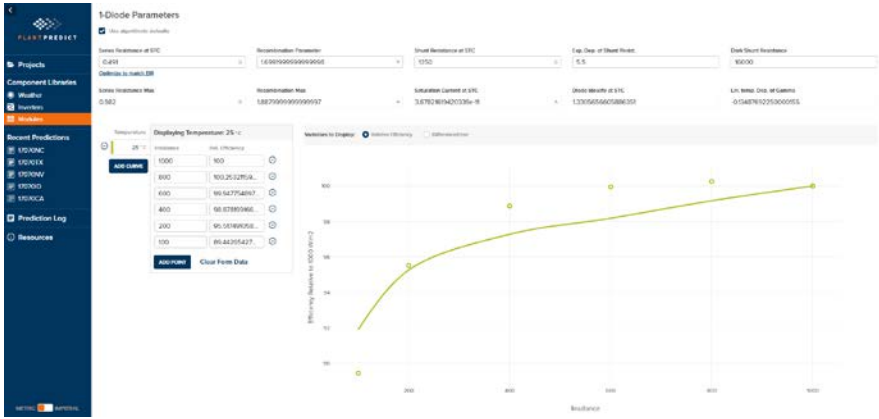

Recently-Added Features

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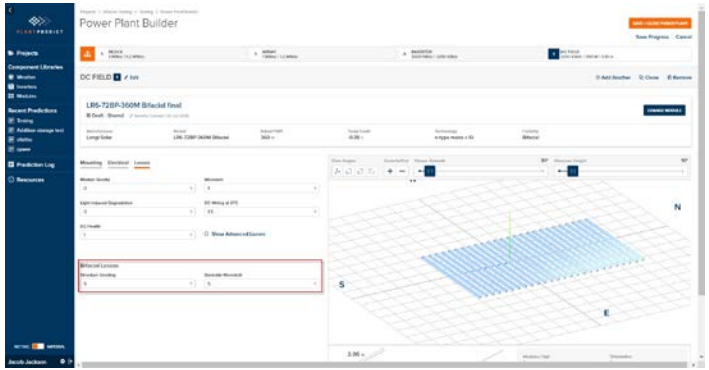
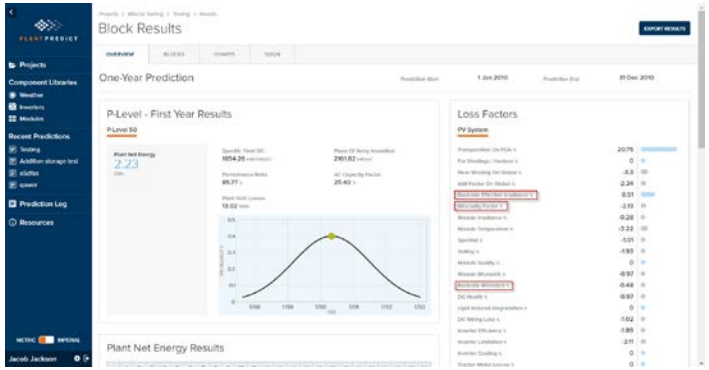




Model

NREL 2D View Factor Model

New Module Properties

"Bifaciality"

Transmission Factor

New DC Field Properties

Structure Shading

Backside Mismatch

Post Height

COMING SOON TO PLANTPREDICT

Upcoming Features in 2019

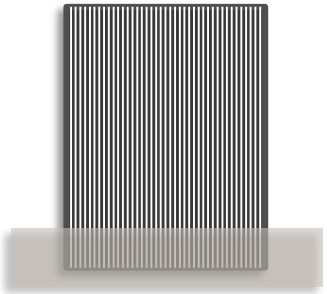
Electrical (c-Si) Shading

New Time Series Inputs

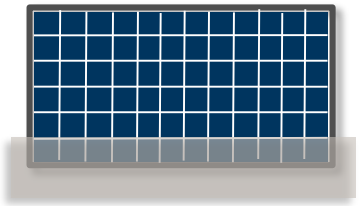
- Tracker Angle
- Plant Output Limit
- Inverter Set Point
- Module Surface Temperature
- Albedo (?)

Sloped Tables

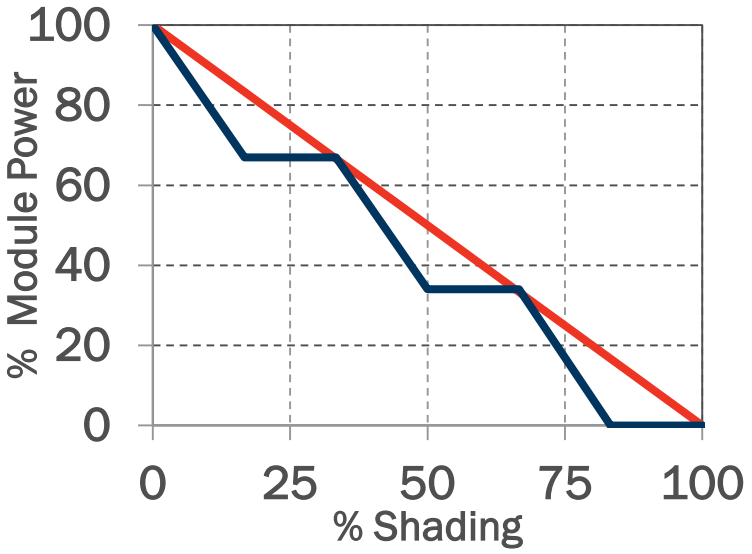
Object Shading



CdTe – linear shading



c-Si – nonlinear shading
(bypass diodes)



Upcoming Features in 2019

Electrical (c-Si) Shading

New Time Series Inputs

- *Tracker Angle*
- *Plant Output Limit*
- *Inverter Set Point*
- *Module Surface Temperature*
- *Albedo (?)*

Sloped Tables

Object Shading

	A	B	C	D	K	L	M	N	O
1	Station Type	Latitude (dd)	Longitude (d	Time Stamp	Mounting Technolo	Rotational Limits Mi	Rotational Limts Max	Tracking Method	Tilt Angle
2	NREL	15.84	78.03	IntervalBegi	Tracker	-60	60	True-Tracking	
3	MM/DD/YYYY	hh:mm:ss	GHI (W/m^2)	Temp (°C)	POAI (W/m^2)	Tracker Angle (°)	Plant Output Limit (kWh)	Inverter Set Point (kW)	Module Surface Temp. (°C)
4	1/1/2010	0:00:00	0	5.7	0	-60	0	0	0
5	1/1/2010	1:00:00	0	5.8	0	-60	0	0	0
6	1/1/2010	2:00:00	0	5.9	0	-60	0	0	0
7	1/1/2010	3:00:00	0	7	0	-60	0	0	0
8	1/1/2010	4:00:00	0	5	0	-60	0	0	0
9	1/1/2010	5:00:00	0	6	0	-60	0	0	0
10	1/1/2010	6:00:00	0	6	0	-60	0	0	0
11	1/1/2010	7:00:00	71	5	67.21342852	-55	1000	800	50
12	1/1/2010	8:00:00	238	7	238.1915783	-45	1000	800	51
13	1/1/2010	9:00:00	395	8	421.4376151	-40	1000	790	52

Image: NextTracker "TrueCapture"

Upcoming Features in 2019

Electrical (c-Si) Shading

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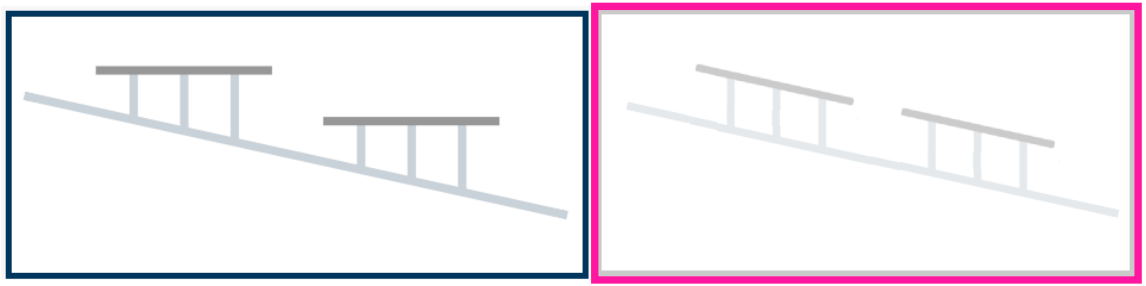

Available in PlantPredict

Coming Soon!

Upcoming Features in 2019

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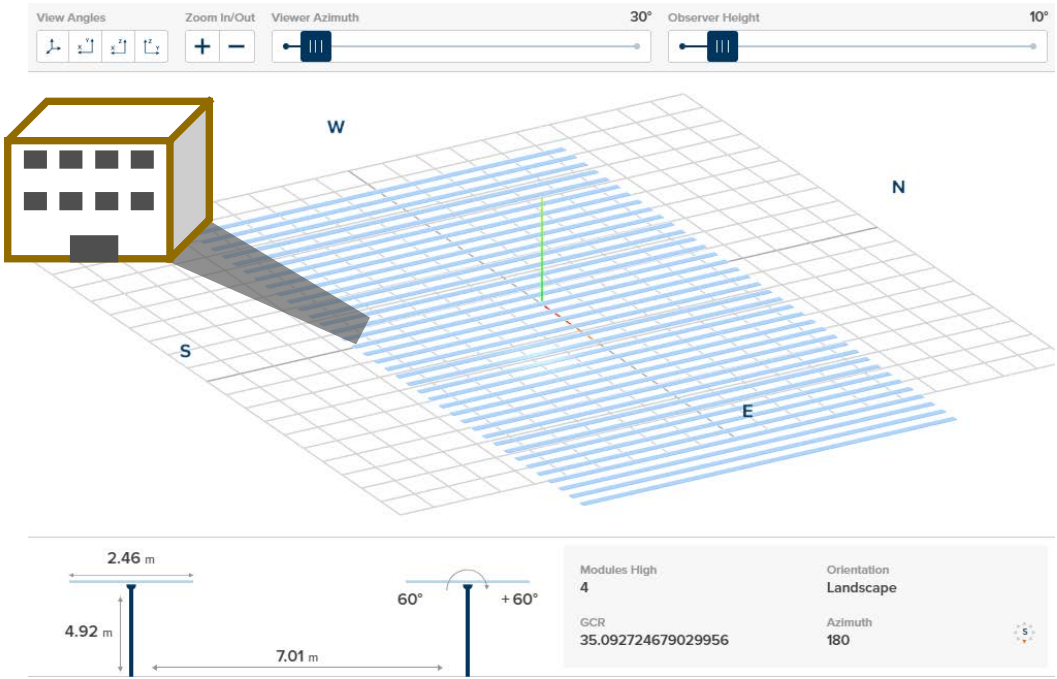


GENERATING MODULE FILES IN PLANTPREDICT

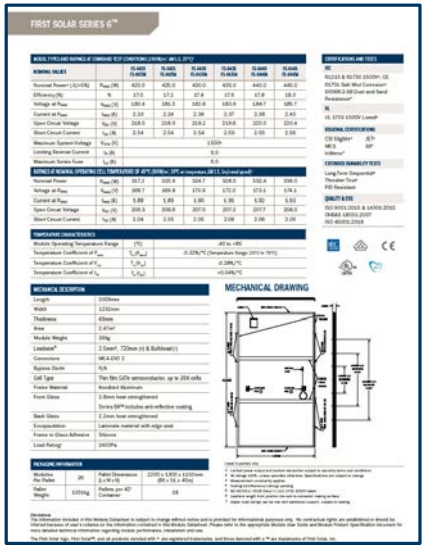
Comparing Existing PV Module Modeling Tools

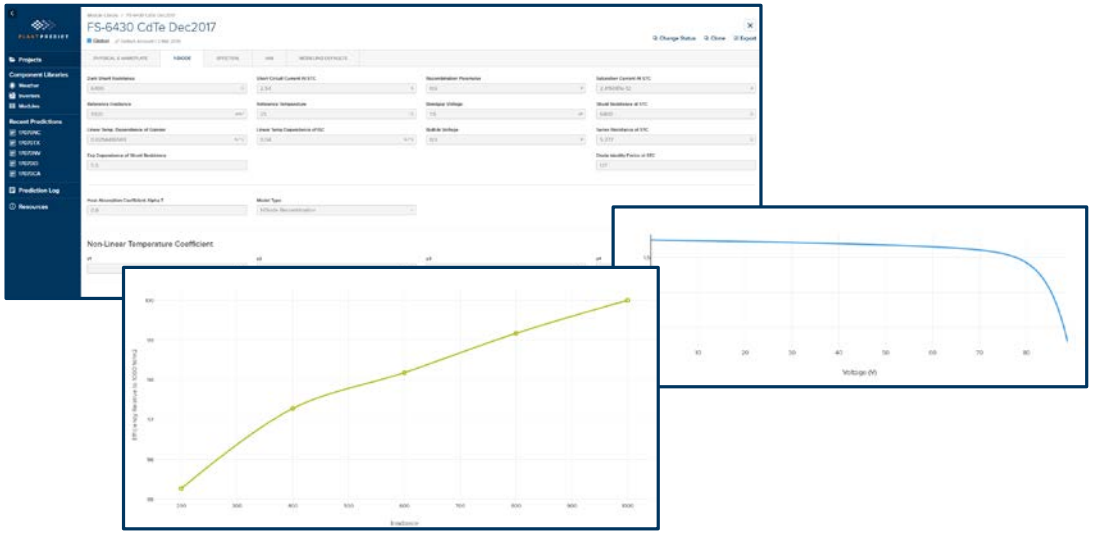
	PVLIB	NREL SAM	PVsyst	PlantPredict
Open-Source/Free	✓	✓		✓
Software Library (SDK)	✓	✓		✓
IEC-61853-1 Data Input		✓		✓
IV Curve Input			only @ STC	✓
Optional Recombination Term?	Only for explicit IV curve calculation		✓	✓
Performance Optimization Tools		limited	✓	✓
Graphics/Visualization		✓	✓	✓
	https://pvpmc.sandia.gov	https://sam.nrel.gov/	http://www.pvsyst.com	https://www.plantpredict.com

Problem Statement

I know how a module performs based on laboratory measurements…

How can I take a limited set of module electrical characteristics and generate a model that accurately represents the expected performance?





Modeling a PV Module

What is a "module file"? The entity used in PlantPredict to model a PV module.

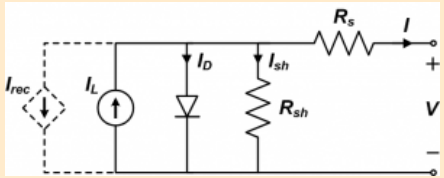
INPUTS

- STC Electrical Characteristics
- non-STC performance (low-light efficiency, temperature coefficients)
- # Cells in Series

*describe expected performance but not used by simulation engine to calculate DC field power

MODEL

- Single Diode Equivalent Circuit Model
- optional recombination term
- linear temperature dependence on the diode ideality factor ("μ_γ")
- DeSoto 5-parameter model for temperature/irradiance adjustment



OUTPUTS (1-diode params)

- Series Resistance
- Shunt Resistance
- Diode Saturation Current
- Diode Ideality Factor (and temperature coefficient)
- Recombination Parameter
- Light-Generated Current

*single diode parameters are used by prediction engine and determine actual performance; "model-calculated" MPP, etc.

Resources

"Performance Assessment of a Simulation Model for PV Modules of Any Available Technology" (Mermoud et al.)

"Improvement and validation of a model for photovoltaic array performance" (De Soto et al.)

"Parameter Estimation for Single Diode Models of Photovoltaic Modules" (Hansen)

"Handbook of Photovoltaic Science and Engineering" (Gray et al.)

"Single Diode Equivalent Circuit Models" – PVPMC Website (https://pvpmc.sandia.gov)

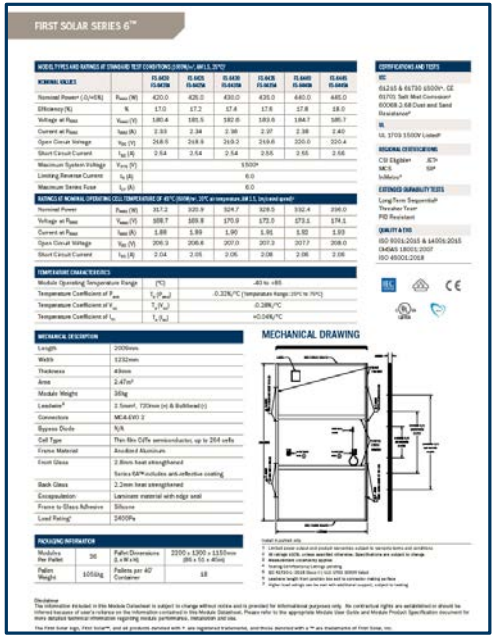
Algorithms fully documented at www.plantpredict.com

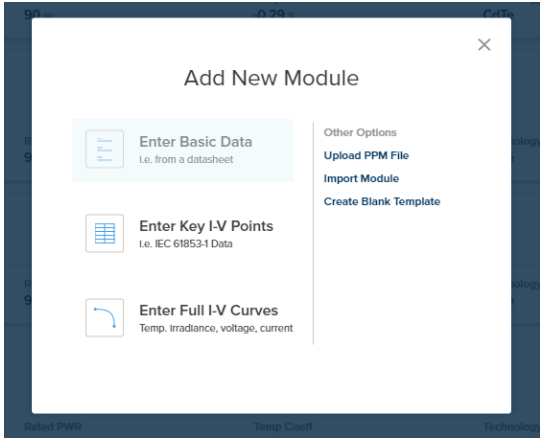
Manufacturer Datasheet as Input

Data Sources/Inputs
- Manufacturer Datasheet
- IEC-61853-1 Test Matrix
- I-V Curve Data

Generating a Module File
- Initial Calculation with Defaults
- Matching Expected Performance

What if I am given a module datasheet?





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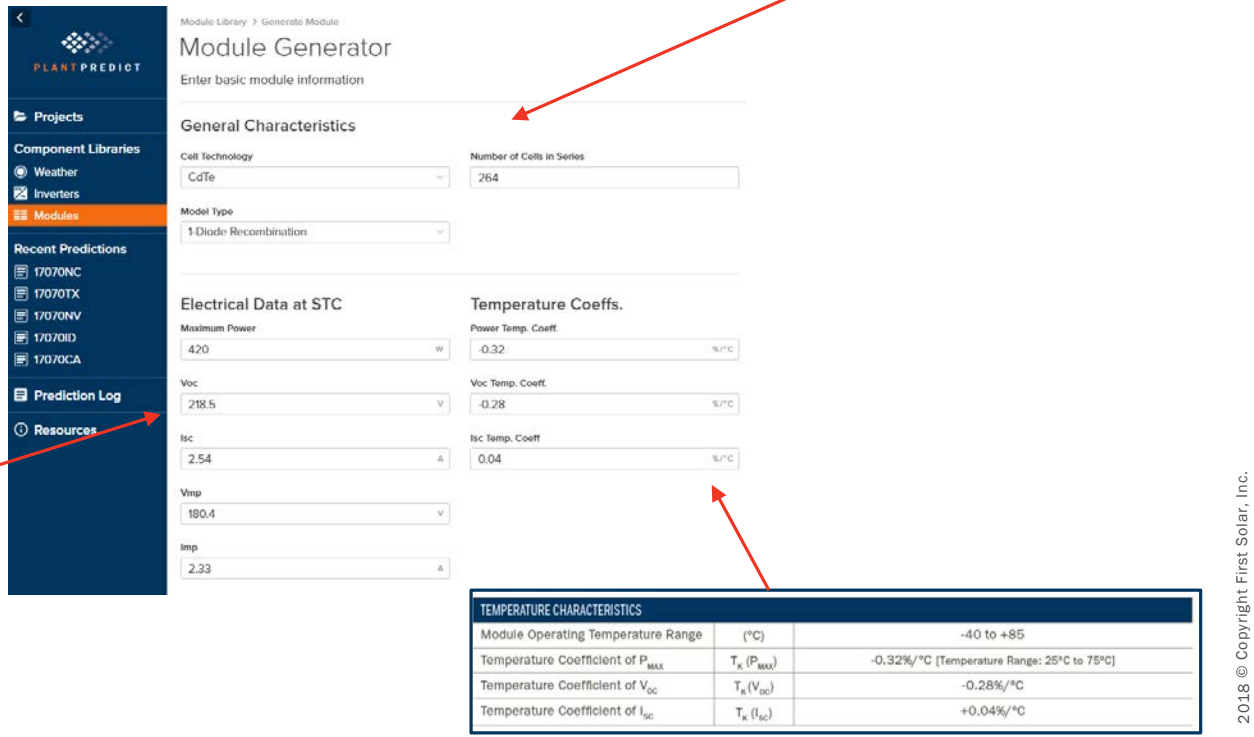
What if I am given a module datasheet?

Cell Type	Thin film CdTe semiconductor, up to 264 cells



MODEL TYPES AND RATINGS AT STANDARD TEST CONDITIONS (10		
NOMINAL VALUES		**FS-6420 FS-6420A**
Nominal Power[3] (-0/+5%)	P_{MAX} (W)	420.0
Efficiency (%)	%	17.0
Voltage at P_{MAX}	V_{MAX} (V)	180.4
Current at P_{MAX}	I_{MAX} (A)	2.33
Open Circuit Voltage	V_{OC} (V)	218.5
Short Circuit Current	I_{SC} (A)	2.54

TEMPERATURE CHARACTERISTICS		
Module Operating Temperature Range	(°C)	-40 to +85
Temperature Coefficient of P_{MAX}	$T_K(P_{MAX})$	-0.32%/°C (Temperature Range: 25°C to 75°C)
Temperature Coefficient of V_{OC}	$T_K(V_{OC})$	-0.28%/°C
Temperature Coefficient of I_{SC}	$T_K(I_{SC})$	+0.04%/°C

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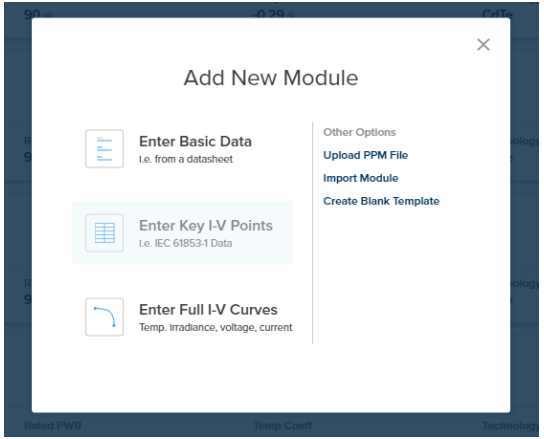
What if my only source of data is an IEC-61853-1 test matrix?

Temperature [C]	Irradiance [W/m2]	Isc [A]	Voc [V]	Imp [A]	Vmp [V]	Pmp [W]	FF [%]	Eff [%]	Ix [A]	Ixx [A]
15	100	0.174	83.71	0.150	70.28	10.56	72.42	14.67	0.169	0.122
15	200	0.349	86.41	0.310	72.80	22.57	74.93	15.67	0.342	0.248
15	400	0.698	88.97	0.628	74.38	46.72	75.25	16.22	0.683	0.491
15	600	1.046	90.46	0.948	74.66	70.74	74.79	16.38	1.027	0.726
15	800	1.395	91.51	1.268	74.51	94.52	74.05	16.41	1.377	0.955
15	1000	1.743	92.29	1.586	74.21	117.68	73.14	16.34	1.722	1.173
25	100	0.175	80.95	0.151	67.75	10.24	72.36	14.23	0.170	0.122
25	200	0.350	83.67	0.311	70.32	21.88	74.78	15.19	0.343	0.248
25	400	0.700	86.27	0.630	71.92	45.29	75.05	15.73	0.685	0.490
25	600	1.049	87.75	0.951	72.25	68.68	74.59	15.90	1.031	0.725
25	800	1.399	88.85	1.272	72.20	91.85	73.88	15.95	1.380	0.952
25	1000	1.749	89.71	1.590	72.04	114.52	72.98	15.91	1.726	1.168
25	1100	1.924	90.04	1.747	71.86	125.55	72.48	15.85	1.898	1.274
50	100	0.177	73.83	0.153	61.08	9.32	71.47	12.95	0.172	0.121
50	200	0.354	76.77	0.314	63.77	20.01	73.72	13.89	0.347	0.246
50	400	0.707	79.55	0.636	65.41	41.58	73.90	14.44	0.694	0.489
50	600	1.061	81.06	0.957	65.84	62.98	73.25	14.58	1.042	0.720
50	800	1.414	82.14	1.279	65.83	84.19	72.48	14.62	1.393	0.944
50	1000	1.768	83.05	1.599	65.71	105.07	71.55	14.59	1.745	1.160
50	1100	1.945	83.40	1.756	65.59	115.19	71.01	14.54	1.918	1.263
75	100	0.179	65.50	0.155	52.94	8.22	70.10	11.42	0.175	0.120
75	200	0.358	68.74	0.317	55.57	17.62	71.60	12.23	0.352	0.243
75	400	0.717	71.87	0.637	57.60	36.69	71.20	12.74	0.701	0.478
75	600	1.075	73.80	0.960	58.46	56.12	70.76	12.99	1.055	0.706
75	800	1.433	75.10	1.283	58.72	75.33	69.99	13.08	1.412	0.926
75	1000	1.791	76.10	1.602	58.70	94.04	69.01	13.06	1.766	1.140
75	1100	1.970	76.76	1.763	58.87	103.77	68.61	13.10	1.944	1.246



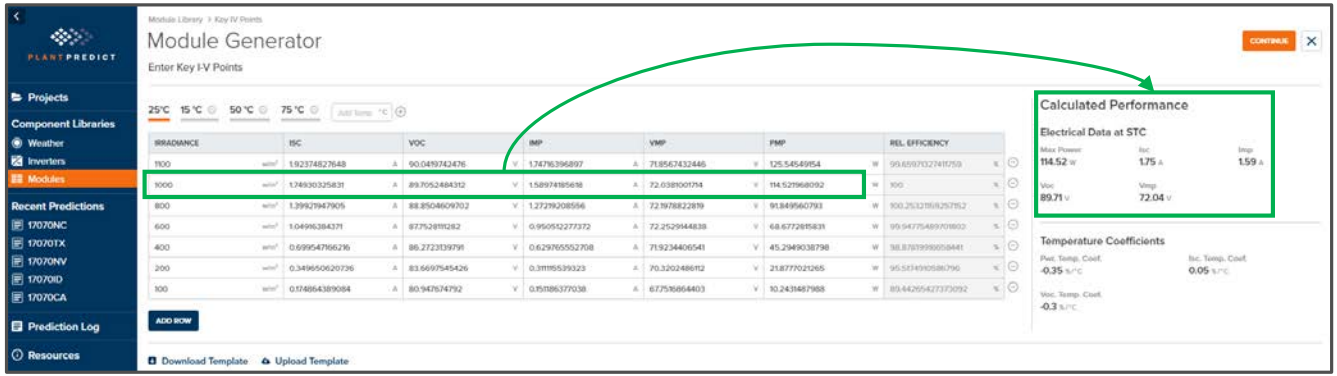
Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating, IEC 61853-1 Ed. 1.0, 2011.

IEC-61853-1 Test Data as Input

Data Sources/Inputs
- Manufacturer Datasheet
- IEC-61853-1 Test Matrix
- I-V Curve Data

Generating a Module File
- Initial Calculation with Defaults
- Matching Expected Performance

What if my only source of data is an IEC-61853-1 test matrix?



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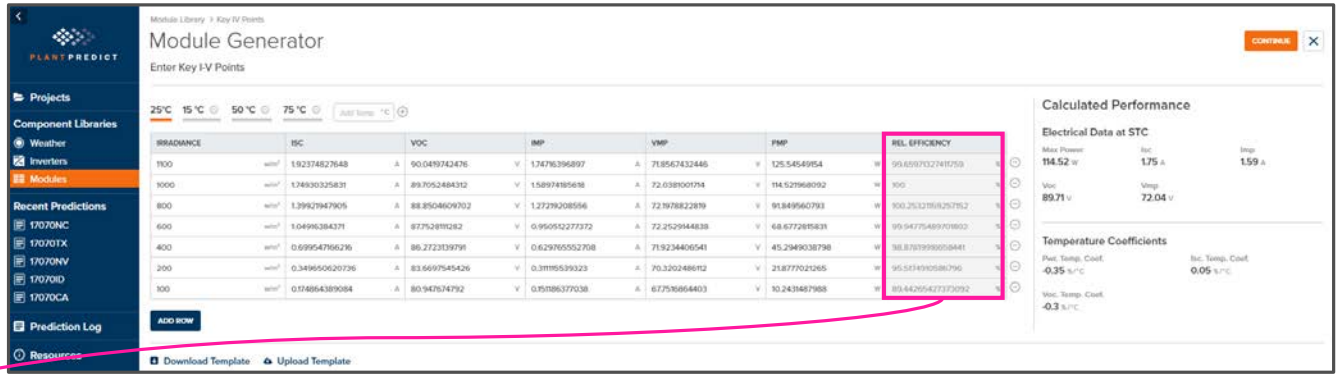

$$EIR_i = \frac{P_{mp,i}}{P_{max,norm}}$$

$$P_{max,norm} = P_{mp,1000}\frac{i}{1000}$$

Relative Efficiency Calculation

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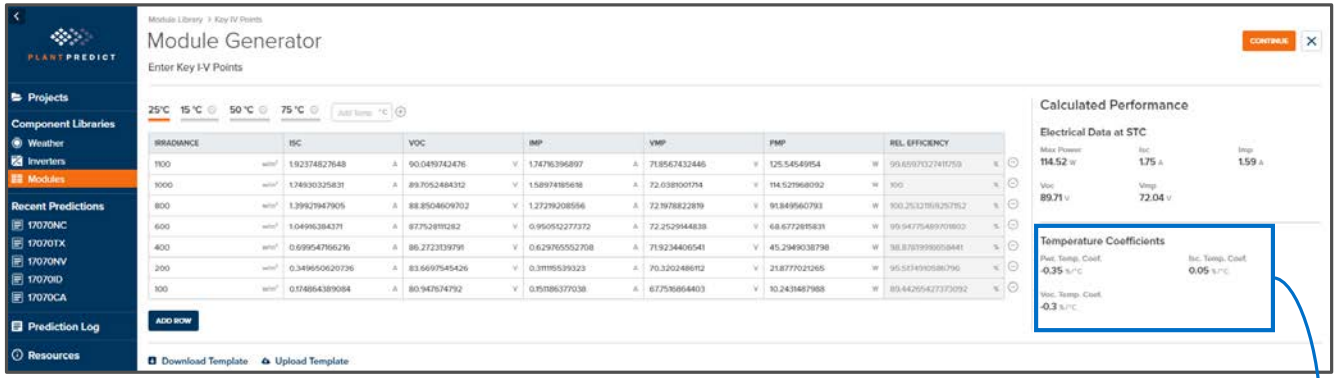

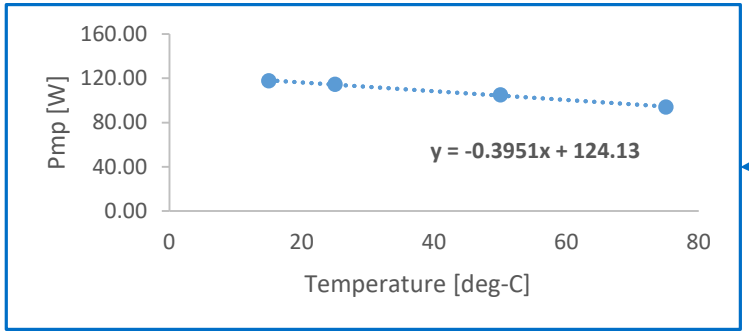

Temperature Coefficient Calculation (Linear Regression)

Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating, IEC 61853-1 Ed. 1.0, 2011.

I-V Curve Test Data as Input

Data Sources/Inputs
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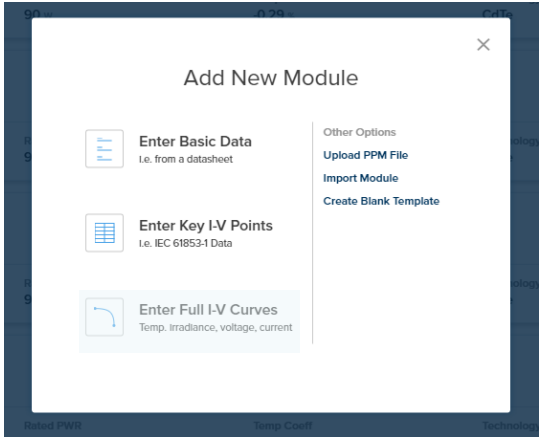
What if I only have I-V curve data?

Temperature [deg-C]	Irradiance [W/m2]	I [A]	[V]
25	1000	9.43	0
25	1000	9.4279	1.271
25	1000	9.4258	2.5419
25	1000	9.4236	3.8129
25	1000	9.4215	5.0838
25	1000	9.4194	6.3548
25	1000	9.4173	7.6257
25	1000	9.4152	8.8967
25	1000	9.4131	10.1676
25	1000	9.4109	11.4386
25	1000	9.4088	12.7095
25	1000	9.4067	13.9805
25	1000	9.4046	15.2514
25	1000	9.4025	16.5224
25	1000	9.4004	17.7933
25	1000	9.3982	19.0643
25	1000	9.3961	20.3352
25	1000	9.394	21.6062
25	1000	9.3918	22.8771
25	1000	9.3897	24.1481
25	1000	9.3874	25.419
25	1000	9.385	26.69
25	1000	9.3823	27.9609
25	1000	9.3789	29.2319



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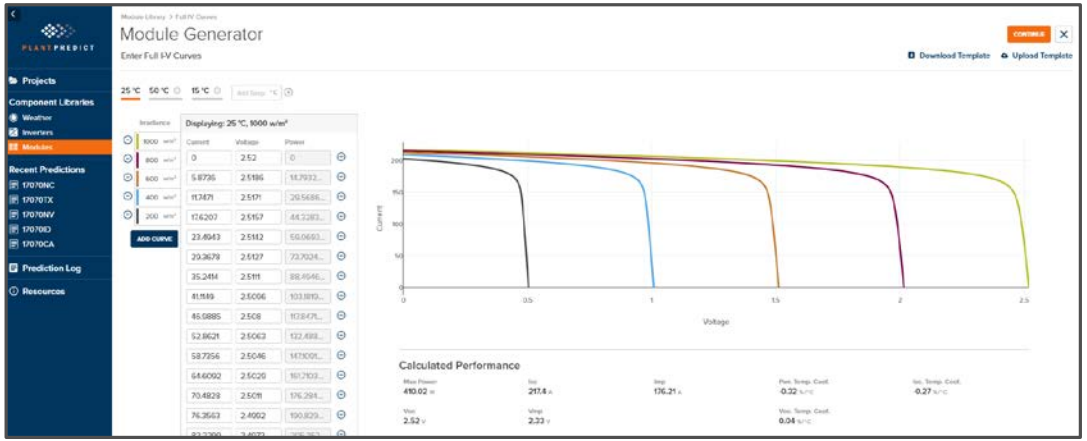

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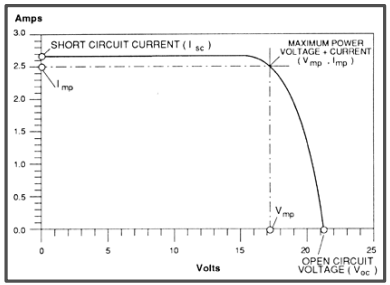


For each I-V curve at a given Temperature and Irradiance,
I_{sc} / V_{oc} / I_{mp} / V_{mp} / P_{mp} extracted via graphical methods.

2

Resulting dataset processed like IEC-61853-1 data to generate:

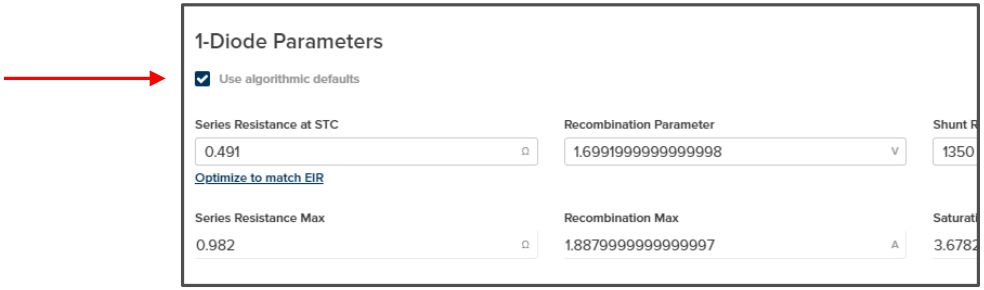
1. Electrical Characteristics @ STC
2. Temperature Coefficients
3. Relative efficiencies at low-light

Initial Calculation with Default Assumptions

Data Sources/Inputs
- Manufacturer Datasheet
- IEC-61853-1 Test Matrix
- I-V Curve Data

Generating a Module File
- Initial Calculation with Defaults
- Matching Expected Performance

What if I want to generate a module file as quickly as possible?



Automatically calculates a set of 1-diode parameters based on technology-dependent (ie. cSi vs. CdTe) generalizations, such as:

- low-light relative efficiency at 200 W/m^2 is ~97% (cSi)
- Series Resistance is ~50% of maximum series resistance (CdTe)
- Recombination Parameter is ~90% of maximum recombination parameter (CdTe)
- etc.

Initial Calculation with Default Assumptions

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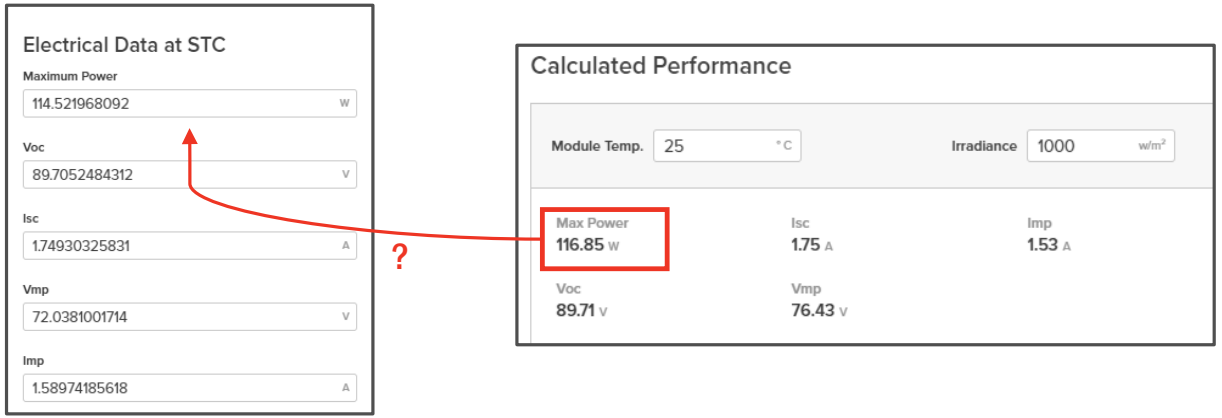
Disadvantages of Using Default Assumptions

Making single assumptions for ALL c-Si or ALL CdTe modules is a bad idea!



1

Significant error between nameplate power and maximum power calculated from resulting single-diode parameters.

Initial Calculation with Default Assumptions

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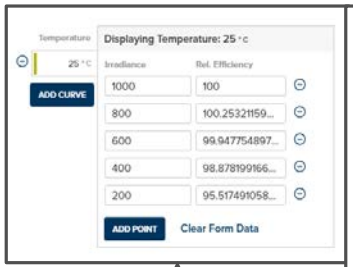
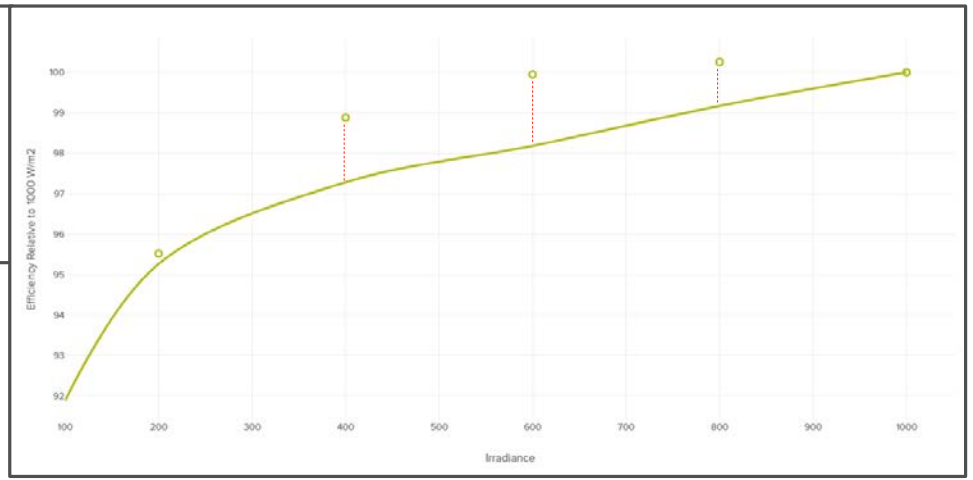


Effective Irradiance Response calculated from measured performance data. **This is the expected/target performance.**



2

Low-light performance does not match expected performance from measured test data (IEC-61853-1).

Matching Expected Module Performance

Data Sources/Inputs
- Manufacturer Datasheet
- IEC-61853-1 Test Matrix
- I-V Curve Data

Generating a Module File
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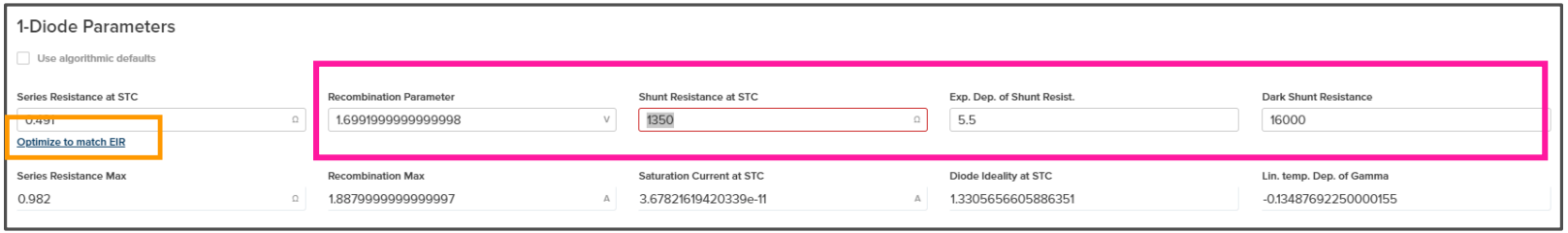
How do I "tune" the module to perform as expected?

1. Manually adjust key single-diode parameters.
2. Use automatic series resistance optimization.



Matching Expected Module Performance

Data Sources/Inputs
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Generating a Module File
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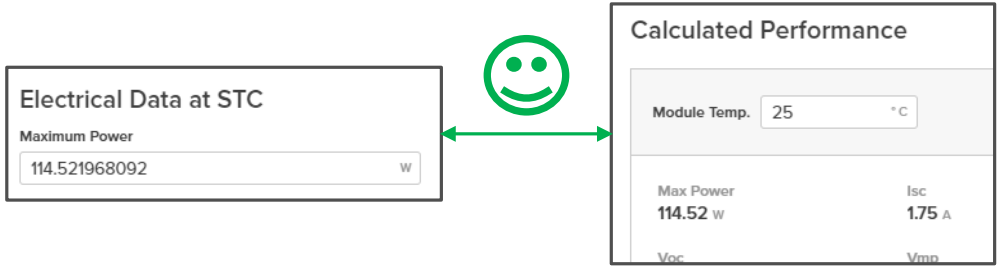
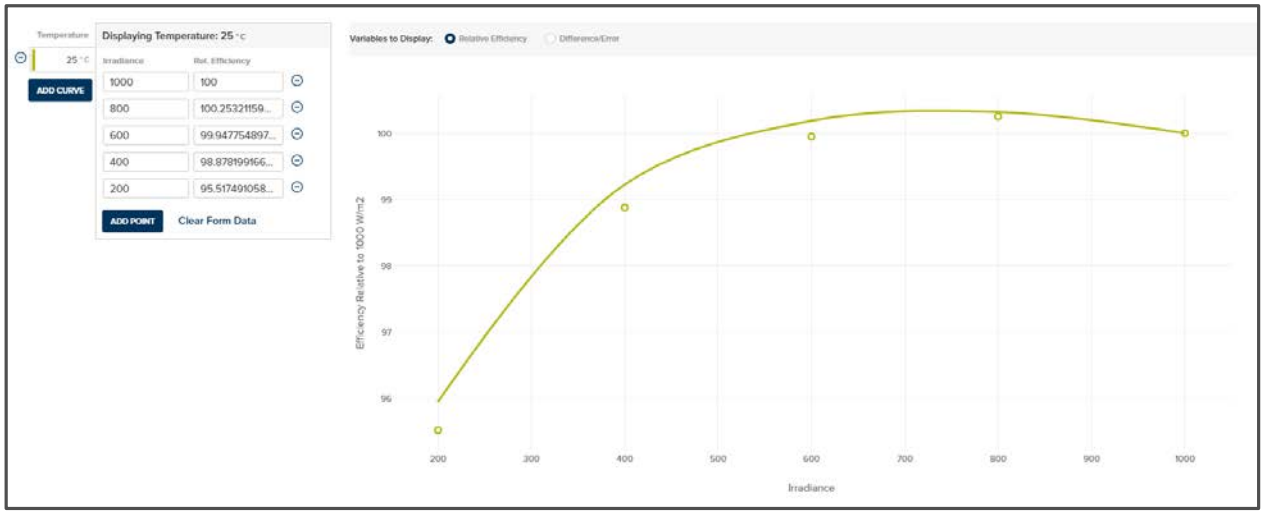
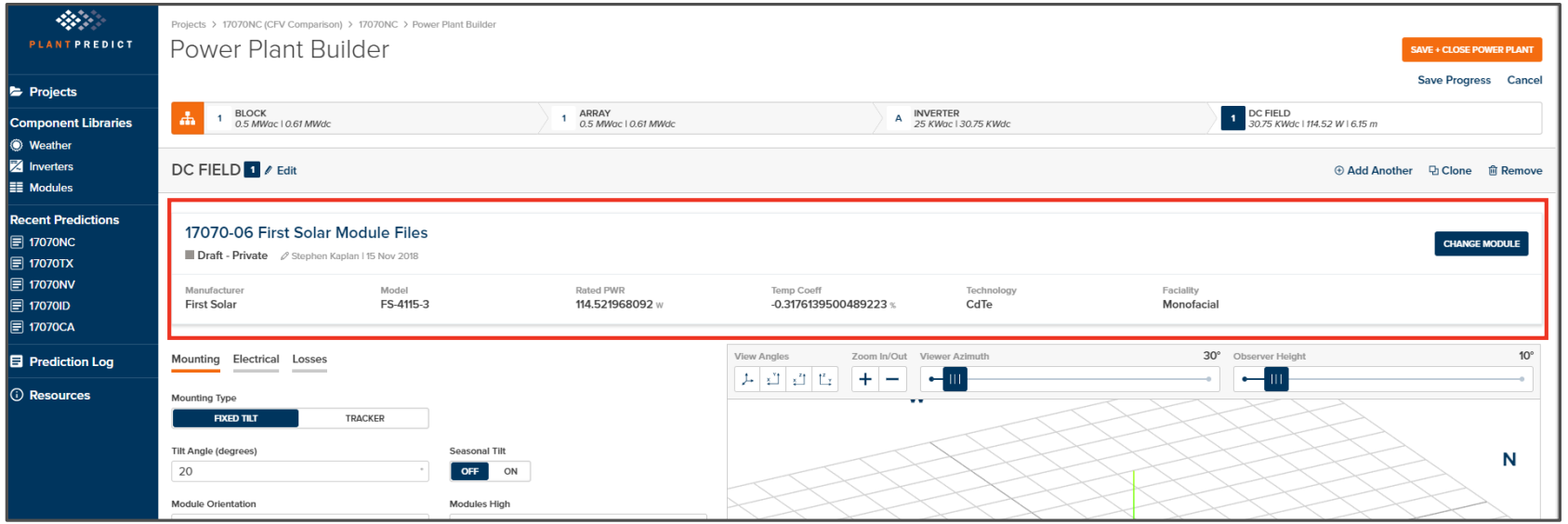
Module performance tuned successfully!





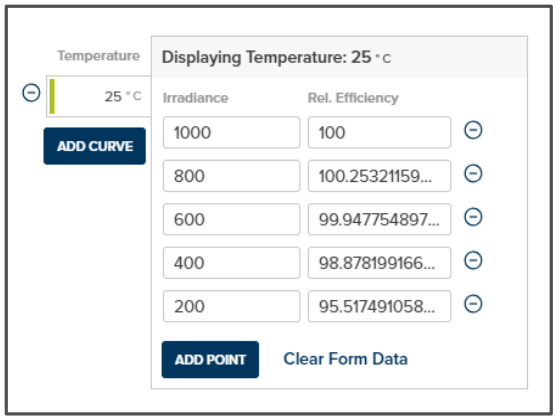
Module File Ready for Simulation



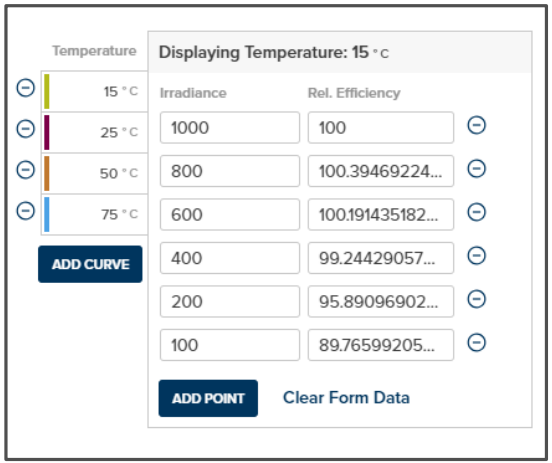
Algorithm Limitations & Potential Improvements

Limitation: ***Automatic*** Series Resistance Optimization currently only uses relative efficiency data at 200, 400, 600, 800 W/m^2 (@ 25ºC)

- Potential Improvement: Implement a more sophisticated model to match measured performance at *any* temperature/irradiance condition.
- Potential Strategy: Dobos/MacAlpine method as published in "Procedure for applying IEC-61853 test data to a single diode model." *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)* (2014): 2846-2849.



Limited Performance Tuning Target (Current)

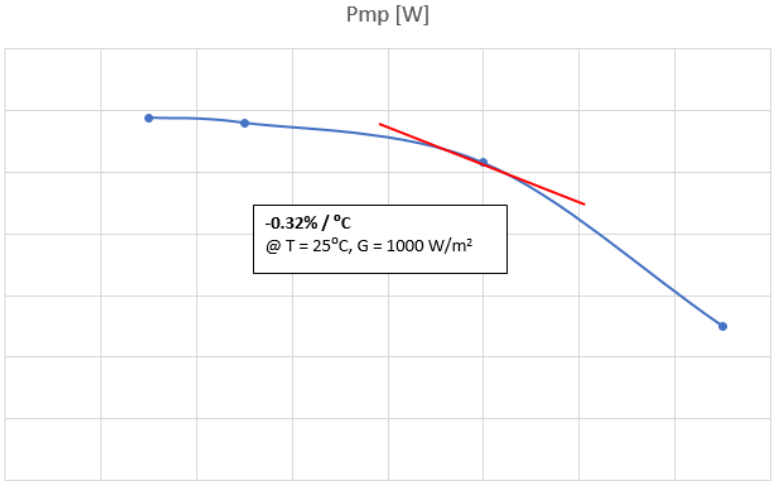


Comprehensive Performance Tuning Targets (Future)

Algorithm Limitations & Potential Improvements

Related Limitation: Algorithm assumes a linear temperature coefficient of power, calculated via linear regression. Therefore, the resulting model's performance does not match measured data at non-STC conditions.

- Potential Improvement: Treat temperature dependence as non-linear. The nameplate (datasheet) "linear" temperature coefficient should be interpreted as the **derivative** of the measured non-linear trend at STC.



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