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PV Performance Modeling: A 10-Year Retrospective

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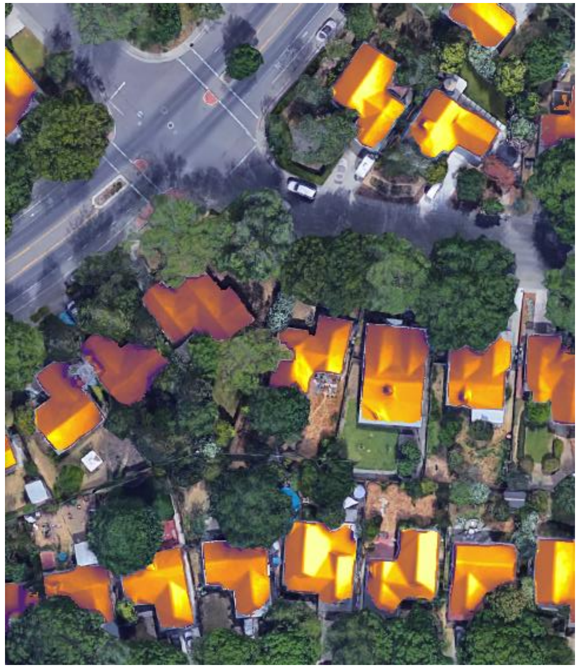
Ben Bourne | May 2, 2018

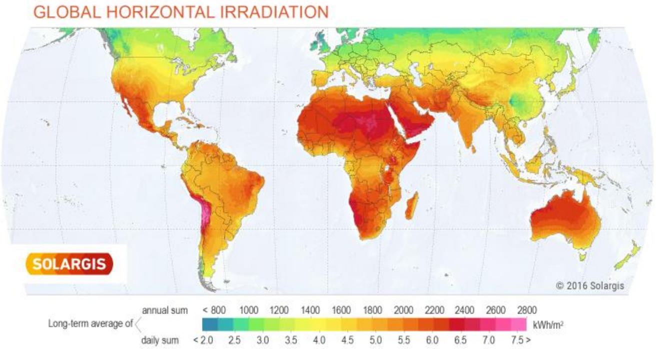
PV Performance Modeling: A 10-Year Retrospective

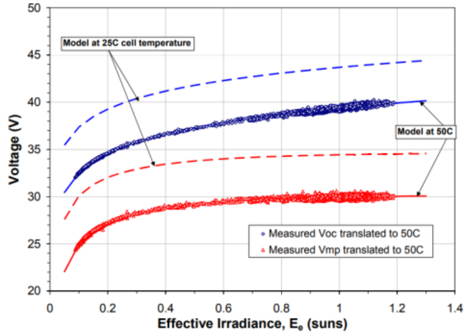
- Objectives of the PV modeling community
  - Minimize modeling bias error for valuating PV project investments
  - Minimize uncertainty to improve customer confidence and financing terms
- State of PV performance modeling in 2007
- Where we focused our efforts between 2007 & 2018
- Most impactful gains during the past 10 years
- Remaining gaps that need our attention



PV Performance Modeling: A 10-Year Retrospective

- Solar Resource Data
- Environmental Losses
- PV Module & Array Models
- Balance of System Losses
- PV Performance Characterization & Data Management
- PV Modeling & Design Tools





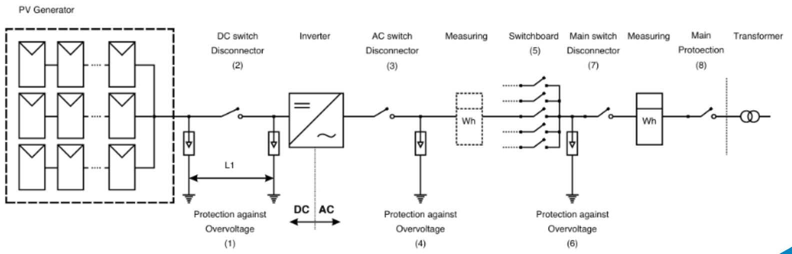
aurora

PVWatts® Calculator

PVComplete

HelioScope

PLANTPREDICT



Solar Resource Data

	Synthetic TMY	Ground TMY	Satellite TMY/TS	Sky Models
2007	- Meteonorm	- National Solar Resource Database (NSRDB)/TMY2 (US) - European Solar Resource Atlas (ESRA)	- PVGIS (Monthly) - 3Tier - Solar Radiation Data (SoDa) - SolarGIS	- Radiative transfer clear sky models (Bird, SMARTS, Rest2, ESRA) - Direct beam models (DISC, DIRINT) - Attenuation (Linke turbidity, Air Mass, AOD, water vapor) - Diffuse transposition (Perez, Hay-Davies)
↓	- Emergence of satellite data for model improvement	- Increasing number of prospecting stations - Growing fleet of commercial PV ground met stations	- Improved satellite resolution - More ground calibration data	- IR channel in satellite data used to improve albedo interpretation - Improved NWP models - Aerosol depth (AOD) ground measurements
2018	- Meteonorm (enhanced by satellite data)	- NSRDB/TMY3 Site-Adapted TMY	- 3Tier - SolarGIS - PVGIS - SolarAnywhere - NSRDB - NEDO (Japan) - HelioClim/SoDa	- Sufficient model accuracy (annual) - Seasonal bias remains - Uncertainty in data limiting continued backcast & forecast accuracy (ground data, satellite resolution & coverage, atmospheric scattering & absorption)

Environmental Losses

	Soiling Losses	Snow Losses	Shade Losses
2007	- Fixed-rate soiling - Dynamic model (Kimber *et al.*)	- No models available	- PVSyst – Inter-array shade tool - PVWatts - Shade vs. GCR response curves (from SunPower) - No diffuse shade models
↓	- GW of PV fleet data in arid and wet climates - Soiling measurement devices - Robotic washing - Anti-soiling coating research - Analytical diagnostic methods	- GW of PV fleet data in winter climates - Snow accumulation tests & publications	- 3D data & tools becoming publicly available for use & integration - Diffuse shade understanding & model development - Shade-resistant technologies (micro-inverters, cross-tied cSi modules, etc.)
2018	- Soiling well understood in most NA/EU locations (wet & dry) - Rain data critical in dry climates - Still very few publicly-available dynamic soiling models - Challenges in desert climates	- In-house industry calculators • DNV-GL snow model • SunPower dynamic model (PVSim) - Snow data critical for effective model accuracy	- Many industry tools with shade capabilities - Still little-to-no technology-specific shade response distinction among the most prominent tools - High uncertainty from site conditions

Optical Models & Surface Treatments

	Angular Response	Bifacial Models	Anti-Soiling Coating
2007	- Fresnel model - Sandia polynomial AOI modifier function – f(AOI) - PVSyst point/interpolation model	- Early bifacial modules in production - No bifacial models available	- No anti-soiling solutions available
↓	- Technologies with cell-surface texturing and/or anti-reflective glass coatings no longer follow basic Fresnel equations	- Limited but emerging interest in BF technologies - Ray-tracing models used to characterize BF response - View factor (VF) models for speed - IEC 60904 updated for BF testing	- Increasing PV development in high-soiling environments (Middle East + isolated soiling environments) - Anti-soiling coating technologies emerging - Anti-soiling studies (NREL, TUV, ASU)
2018	- Models have the ability to distinguish between PV cell/glass/laminate designs - Need to accommodate f(AOI) > 1	- Bifacial models being offered and implemented in modeling tools • Open source – NREL, SunPower • PVSyst - Validation work still needed	- Production coatings - Promising results – with cost trade-off

PV Module & Array Performance Models

	PV Model	Thermal Model	Spectral Response
2007	- Diode-equivalent models - Sandia Array Performance Model (SAPM) - 5-Parameter - PVWatts constant-efficiency model	- Energy balance methods (Fuentes, PVSyst) - Empirical methods (Sandia)	- EQE - Sandia Air Mass Modifier – f(AMa)
↓	- Loss Factors Model (Steve Ransome / Gantner) - Analytical methods for quantifying system degradation	- Very little focus on thermal model improvements	- Impact of atmospheric water content on cell spectral response (First Solar)
2018	- Degradation element accounts for changing voltage & current electrical response over time - Still no "perfect" PV model	- Poor industry guidance for modeling product-specific thermal performance *- Need a test standard for deriving thermal response coefficients* - High uncertainty in wind speed data and model use	- First Solar's precipitable water model - Sandia f(AMa) does not accurately characterize module spectral response in all locations

Balance of System Losses

	DC Wiring Losses	Inverter Model	AC Collection Losses	Grid Interaction
2007	- Constant wiring loss - Simple dynamic wiring loss model	- Constant efficiency - Simple η(P, V) - Simple operating limits	- Constant AC wiring loss - Constant transformer loss - Combined xfmr losses - No nighttime & aux load losses	- No models available - Unavailability not factored into energy models
↓	- Complex configurations - Optimized stringing - DC Optimizers - Combine-as-you-go DC harnessing	- Microinverters - Temperature-dependent capacity - Multiple MPPTs - Power Factor control	- TL inverters - Storage integration	- Reactive power control - Grid curtailment - Grid interconnection limits - Storage integration
2018	- Constant wiring loss - Simple dynamic wiring loss model - Design-specific dynamic loss model	- Many in-house post-processors for handling complex array/grid interaction - Need updated general modeling approach	- Constant AC wiring loss - Constant transformer loss - Combined xfmr losses - Nighttime & aux load losses considered - Most tools don't provide all grid-interaction dynamics	- Grid control schemes need to be implemented - System downtime and external curtailment always difficult to predict – *timing, duration, magnitude*

PV Performance Characterization & Data Management

	Characterization Methods	Characterization Data	Data Management
2007	- STC (indoor, outdoor) - PTC (indoor) - Sandia outdoor performance test to support SAPM	- Diode model coefficients • Lab measurements • best-fit - SAPM coefficients - CEC/PTC ratings	- Sandia/SAM DB - Photon - CEC
↓	- IEC 61853 1-4 • Efficiency vs. irradiance • Temperature coefficients • Spectral response • Angular response - IEC 60904 update for Bifacial	- Methods for deriving model coefficients from IEC matrix data - Split-cell technologies change the efficiency profile of c-Si technologies	- PV_LIB Toolbox established by Sandia – *open-source, documented, peer-reviewed model code for industry use, collaboration and standardization*
2018	- IEC 61853 test suite adopted by accredited labs - Need to extend 61853 efficiency characterization to bifacial test standard	- IEC 61853 matrix-to-model conversions • PAN file generation • Sandia coefficient generation	- IEC 61853 test data need an owner and QC/use standards - IEC 61853 standard needs to be supported & required by industry tools

PV Modeling & Design Tools

	Desktop Energy Tools	Web-Based Energy Tools	Design Tools	Open-Source/API
2007	- PVSyst - SAM - SolarPro - PVGrid	- PVWatts - PVGIS	- None	- None
	Challenge: Feature development vs. Model Integration, Validation & Uncertainty Reduction			
↓	- Slower growth & development than industry growth	- Tool feature advancement - Web-based for access & scalability - 3D shading functionality - Simple residential calculators	- Design feature plug-ins • Shade • CAD Drawings • BOM	- Creation of modeling collaboration, open-source models & code, simulation & database APIs
2018	- **PVSyst** - SAM - SolarPro - RdTools (Degradation)	- PVWatts - Helioscope - Aurora - PVSim - PlantPredict - Google Project Sunroof	- Helioscope - Aurora - PVComplete - SolarPro	- SAM/PVWatts (NREL) - SimEng/PVAPI - SolarGIS - PVWatts - PlantPredict

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PV Performance Modeling: Biggest Gains & Remaining Gaps

- Biggest 10-year gains
  - Satellite-based solar Resource data accuracy & accessibility, but at significantly higher cost
  - Web-based energy modeling, design tools, & shading calculators
  - Quantitative methods for degradation analysis
  - IEC 61853 test standard
  - PV_LIB Toolbox
- Environmental loss gaps
  - Dynamic soiling and snow models need to be implemented in leading industry tools
  - Tools need to account for technology-specific performance: shade-response, low-light response, thermal behavior, etc.
  - Long-term Shade losses are dependent on long-term site conditions – tree management, future development, etc.
- Thermal model gaps
  - Need to establish use standards for wind speed in energy modeling
  - Need a test and derivation standard for thermal response coefficients
- Data management gaps to support test standards
  - Tool developers need to require lab test data and to distinguish all attributes of various technologies
  - PV industry needs an IEC 61853 data warehouse owner

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Thank You

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