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# PV Performance Modeling: A 10-Year Retrospective

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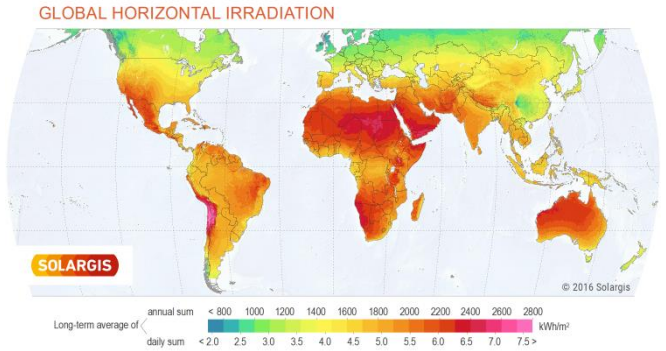
# PV Performance Modeling: A 10-Year Retrospective

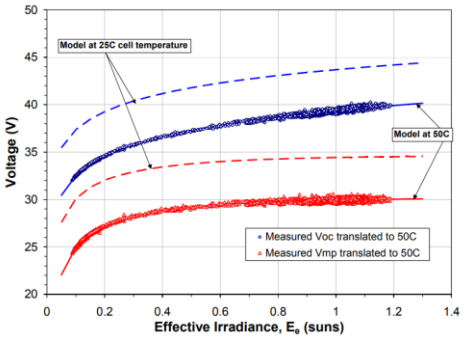
- Objectives of the PV modeling community
  - Minimize modeling bias error for valuating PV project investments
  - Minimize uncertainty to improve customer confidence and financing terms
- State of PV performance modeling in 2007
- Where we focused our efforts between 2007 & 2017
- Most impactful gains 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







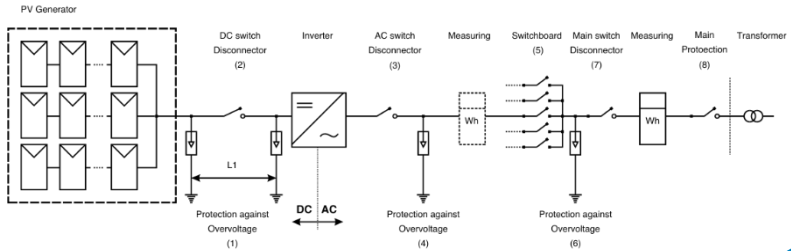

aurora

PVWatts® Calculator

PVCOMPLETE

HelioScope

PLANT PREDICT

# Solar Resource Data

| | Synthetic TMY | Ground TMY | Satellite TMY/TS | Sky Models |
|---|---|---|---|---|
| 2007 | - Meteonorm | - National Solar Resource Database (NSRDB)/TMY2 (US)<br>- European Solar Resource Atlas (ESRA) | - PVGIS (Monthly)<br>- 3Tier<br>- Solar Radiation Data (SoDa) | - Radiative transfer clear sky models (Bird, SMARTS, Rest2, ESRA)<br>- Direct beam models (DISC, DIRINT)<br>- Attenuation (Linke turbidity, Air Mass, AOD, water vapor)<br>- Diffuse transposition (Perez, Hay-Davies) |
| ↓ | - Emergence of satellite data for model improvement | - Increasing number of prospecting stations<br>- Growing fleet of commercial PV ground met stations | - Improved satellite resolution & coverage<br>- More ground data for satellite model calibration | - IR channel in satellite data used to improve albedo interpretation<br>- Improved NWP models<br>- Aerosol depth (AOD) ground measurements |
| 2017 | - Meteonorm (enhanced by satellite data) | - NSRDB/TMY3<br>Site-Adapted TMY | - 3Tier<br>- SolarGIS<br>- PVGIS<br>- SolarAnywhere<br>- NSRDB<br>- NEDO (Japan)<br>- HelioClim/SoDa | - Sufficient model accuracy (annual)<br>- Seasonal bias remains<br>- 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<br>- Dynamic model (Kimber *et al.*) | - No models available | - PVSyst – Inter-array shade tool<br>- PVWatts - Shade vs. GCR response curves (from SunPower)<br>- No diffuse shade models |
| | - GW of PV fleet data<br>- Soiling measurement devices<br>- Analytical diagnostic methods<br>- Robotic washing<br>- Anti-soiling coating research | - GW of PV fleet data in winter climates<br>- Snow accumulation tests & publications | - 3D data & tools becoming publicly available for use & integration<br>- Diffuse shade understanding & model development<br>- Shade-resistant technologies (micro-inverters, cross-tied cSi modules, etc.) |
| 2017 | - Soiling well understood in most NA/EU locations (wet & dry)<br>- Challenges still in Middle East<br>- Still very few publicly-available dynamic soiling models<br>- Rain data critical in dry climates | - In-house industry calculators<br>  • DNV-GL snow model<br>  • SunPower dynamic model (PVSim)<br>- Snow data critical for effective model accuracy | - Many industry tools with shade capabilities<br>- Still little-to-no technology-specific shade response distinction among the most prominent tools<br>- High uncertainty from site conditions |

# PV Module & Array Performance Models

| | PV Model | Thermal Model | Spectral Response | Reflective Response |
|---|---|---|---|---|
| 2007 | - Diode-equivalent models<br>- Sandia Array Performance Model (SAPM)<br>- 5-Parameter<br>- PVWatts constant-efficiency model | - Energy balance methods (Fuentes, PVSyst)<br>- Emperical methods (Sandia) | - EQE<br>- Sandia Air Mass Modifier – f(AMa) | - Fresnel model<br>- Sandia polynomial AOI modifier function – f(AOI)<br>- PVSyst point/interpolation model |
| ↓ | - Loss Factors Model (Steve Ransome / Gantner)<br>- Bifacial models under development | - Very little focus on thermal model improvements | - Impact of atmospheric water content on cell spectral response (First Solar) | - Technologies with cell-surface texturing and/or anti-reflective glass coatings no longer follow basic Fresnel equations |
| 2017 | - Degradation element accounts for changing electrical response over time<br>- Bifacial models need to be vetted | - Poor industry guidance for modeling product-specific thermal performance - *Need a test standard for deriving thermal response coefficients*<br>- High uncertainty in wind speed data and model use | - First Solar's precipitable water model<br>- Sandia f(AMa) does not accurately characterize module spectral response in all locations | - Models have the ability to distinguish between PV laminate designs<br>- Need to accommodate f(AOI) > 1 |

# Balance of System Losses

| | DC Wiring Losses | Inverter Model | AC Collection Losses | Grid Interaction |
|---|---|---|---|---|
| 2007 | - Constant wiring loss<br>- Simple dynamic wiring loss model | - Constant efficiency<br>- Simple η(P, V)<br>- Simple operating limits | - Constant AC wiring loss<br>- Constant transformer loss<br>- Combined xfmr losses<br>- No nighttime & aux load losses | - No models available<br>- Unavailability not factored into energy models |
| ↓ | - Complex configurations<br>- Optimized stringing<br>- Combine-as-you-go DC harnessing | - Microinverters<br>- Temperature-dependent capacity<br>- Multiple MPPTs<br>- Power Factor control | - TL inverters<br>- Storage integration | - Grid control<br>- Grid interconnection limits<br>- Storage integration |
| 2017 | - Constant wiring loss<br>- Simple dynamic wiring loss model<br>- Design-specific dynamic loss model | - Many in-house post-processors for handling complex array/grid interaction<br>- Need updated general modeling approach | - Constant AC wiring loss<br>- Constant transformer loss<br>- Combined xfmr losses<br>- Nighttime & aux load losses considered<br>- Most tools don't provide all grid-interaction dynamics | - Grid control schemes need to be implemented<br>- System downtime always difficult to predict – *timing, duration, magnitude* |

# PV Performance Characterization & Data Management

| | Characterization Methods | Characterization Data | Data Management |
|---|---|---|---|
| 2007 | - STC (indoor, outdoor)<br>- PTC (indoor)<br>- Sandia outdoor performance test to support SAPM | - Diode model coefficients<br>  • Lab measurements<br>  • best-fit<br>- SAPM coefficients<br>- CEC/PTC ratings | - Sandia/SAM DB<br>- Photon<br>- CEC |
| | - IEC 61853 1-4<br>  • Efficiency vs. irradiance<br>  • Temperature coefficients<br>  • AOI/IAM<br>  • Spectral response | - Methods for deriving model coefficients from IEC matrix data<br>- 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* |
| 2017 | - IEC 61853 test suite<br>- Still no reliable standard characterization for spectral response & bifacial products | - IEC 61853 matrix-to-model conversions<br>  • PAN file generation<br>  • Sandia coefficient generation | - IEC 61853 test data need an owner and QC/use standards<br>- IEC 61853 standard needs to be supported & required by industry tools |

# PV Modeling & Design Tools

| | Desktop Energy Tools | Web-Based Energy Tools | Design Suite Tools |
|---|---|---|---|
| 2007 | - PVSyst<br>- SAM<br>- SolarPro<br>- PVGrid | - PVWatts<br>- PVGIS | - None |
| ↓ | - Slower growth & development than industry growth | - Tool feature advancement<br>- Web-based for access & scalability<br>- 3D shading functionality<br>- Simple residential calculators | - Design feature plug-ins<br>• Shade<br>• CAD Drawings<br>• BOM |
| 2017 | - **PVSyst**<br>- SAM<br>- SolarPro | - PVWatts<br>- Helioscope<br>- Aurora<br>- PVSim<br>- PlantPredict<br>- Google Project Sunroof | - Helioscope<br>- Aurora<br>- PVComplete<br>- SolarPro |

**Challenge: Feature development vs. Model Integration & Uncertainty Reduction**

# 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
  - IEC 61853 test standard
  - PV_LIB Toolbox
- Environmental Losses
  - Need better understanding of soiling & snow losses, and dynamic model implementation in 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
  - Need to establish use standards for wind speed in energy modeling
  - Need a test and derivation standard for thermal response coefficients
- Data management standard to support test standards
  - PV industry needs an IEC 61853 data warehouse owner
  - Tool developers need to require lab test data and to distinguish all attributes of various technologies

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# Thank You

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