International Photovoltaic Reliability Workshop II
Removing Barriers to Photovoltaic Technology Adoption:
Reliability, Codes/Standards, and Market Acceptance

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Outline

• The Definition of DOE’s Key Solar Program Metric: Levelized Cost Of Energy

• Overview of DOE’s Solar Advisor Model

• Levelized Cost of Energy Analysis Examples
  – LCOE is not just performance and cost

• Current Efforts to Evaluate and Validate PV Performance Models
  – Preliminary Results

• Future Work
Levelized Cost of Energy (LCOE)

**Cash Flow (M)**

Financials
- Loan term, rate, fraction
- Income tax, depreciation
- Incentives $/w or $/kWh
- Discount rate \( (d) \)
- Inflation
- PPA, Escalation
- Required IRR...

Installed Price
- Modules ($/W)
- Inverters ($/W)
- BOS ($/m², $/unit)
- Installation ($/m², $/unit)
- Project Development, Permits, Design, Systems Monitoring ($’s)

Operations & Maintenance
- Weed control, washing… ($/m² – yr)
- Lube tracker, change inverter filter ($/unit-yr)
- Replace inverter ($/unit by year)
- Property taxes, insurance (% first cost)
- Monitoring ($/system)

**System Lifetime N (yrs)**

Energy Flow (Q)

Location
- Solar Resource (kWh/m²)
- Temperature, Wind, Snow…

System Design
- Orientation, Tracking or Fixed
- Mounting: BIPV, Open Rack…

Module Characteristics
- Efficiency (%)
- Temperature Coefficient (%/°C)
- Degradation Rate (%/yr)

Inverter Characteristics
- Efficiency (%)
  - Location (array vs. string vs. module)
  - Nighttime Tare Loss

Derates
- Mismatch
- Diodes & Connections
- AC & DC Wiring Losses
- Transformer
- Soiling and Shading
- Tracking Error
- Availability

\[
LCOE = \frac{\sum_{n=0}^{N} I_0 + M_n}{(1 + d)^n} \div \sum_{n=0}^{N} Q_n \div (1 + d) ^ n
\]
DOE’s Solar Advisor Model (SAM)

Vision

– Combine PV, CSP, thermal solar technologies into a single model
– Make high-quality performance models developed by NREL, Sandia, and other partners available to a wider audience
– Facilitate comparison by handling performance, costs and financing consistently across technologies
– Facilitate calculating the impact of R&D on LCOE, NPV, etc. in various markets.
– Sensitivity analysis and graphing capabilities
– Over 6000 downloads
  • Download (no cost) at: https://www.nrel.gov/analysis/sam

Thanks to Nate Blair and his colleagues at NREL for developing SAM
A Quick Tour of SAM

Program Tab:
- Select technology
  - Photovoltaics
  - Concentrating Solar Power
  - Generic
  - To be added
    - Solar Water Heating
    - Other renewables
- Select market
  - Central Generation
  - Distributed (Buildings)
A Quick Tour of SAM

Environmental Tab:
- Select climate
- Enter financial inputs
- Enter incentives

Default values
- Included in example files
- Values specific to project should be used!
A Quick Tour of SAM

System Tab:
- Configuration
- Array characteristics
- Module and model
- Inverter and model
- Cost Data
Select Module Model and Accompanying Database

- Sandia Array Performance Model
  - Empirical model for modules in database
    - Coefficients Derived from Outdoor Testing on 2-axis Tracker
    - Testing Technology being Transferred to TUV Rhineland PTL
  - Also used in SolarDesignPro and Internal Industry Models
- CEC/Wisc. 5-parameter model
  - Diode model
    - Built from spec. sheet or independent test data
    - Includes modules in CEC database
  - Also used for CA New Solar Homes Partnership

OR

- Enter module area, efficiency and $P_{mp}$ temperature coefficient
A Quick Tour of SAM

Select Inverter Model and Accompanying Database

• Sandia Inverter Model
• Empirical model
  • Performance Data from a Nationally-Recognized Testing Laboratory
• Data Published by California Energy Commission
• All CEC-listed data is analyzed by Sandia and added to the SAM inverter database

OR

• Enter inverter efficiency and size

Other inverter and system models may be added, e.g. PVWatts
A Quick Tour of SAM

Enter Array Parameters
- Array Layout and Orientation
- Tracking Type
- Degradation Rate
- Derate Factors
  - Often Estimated
  - Need to Understand and Document Derate Factors in Installed Systems

[Diagram of array parameters with specific values and formulas]

Note: Inverter efficiency handled on inverter page.
Cost Tab:

- Enter component, BOS, and installation costs
- Enter indirect costs
- Enter O&M costs
- An Excel-based systems cost model that can be linked to SAM is being developed by Navigant Consulting, Inc.

This example includes:

- O&M Schedule, e.g. for inverter replacement
- Parametric analysis of other O&M costs

A Quick Tour of SAM
A Quick Tour of SAM: Results Page
LCOE is about more than initial cost and performance

CAUTION! Financial, performance, and cost assumptions will impact results.
PV Performance Model Validation

• Two Activities Underway in Collaboration with Industry
  – Evaluate/Validate Models Used to Predict PV System Performance
    • In Choosing Between Technologies or Designs
  – Evaluate/Validate Models Used to Monitor System Performance
    • Determine When Performance is Less than Expected Given Weather and Solar Resource → O&M Needed
    • Also Relevant to Acceptance Testing

• Goal – Understand Accuracy and Uncertainty
  – More accurate models may require more accurate input data (components and solar resource)
System Model Validation Using Hourly Averaged Data

- **Weather Instruments**
  - Average
  - TMY Format
  - \( \text{DNI} \times \cos(I_A) = \text{Inc DNI} \)
  - \( \text{POA} - \text{Inc DNI} = \text{Inc Diff} \)
  - Compare \( \text{Inc DNI}, \text{Inc Diff}, \text{POA} \)

- **ARRAY**
  - Average Module T
  - Average Vmp
  - Average DC Output
  - Compare Module Temp
  - Compare Vmp
  - Compare DC Output

- **INVERTER**
  - Average AC Output
  - Compare AC Output

- **Radiation Model**
  - Incident DNI and Diffuse

- **Module Model**
  - Array

- **DC Derate**
  - Inverter Model

- **AC Derate**
  - PV Model

- **Regression Analysis**
  - Sandia Module Measurements
  - Module Database
  - CEC/SNL Inverter Data
  - Inverter Database

**Equations:**

- \( DNI \times \cos(I_A) = \text{Inc DNI} \)
- \( \text{POA} - \text{Inc DNI} = \text{Inc Diff} \)
Model Validation Results, Lat. Tilt, ABQ
DC Output (kWh) by Month (no derate)

1.11 kW Crystalline Silicon Array

DC Measured
No Temp Coeff.
SNL: module
1 pt+TC
5-para
PVMoD
SNL: Array
PVWatts

On-sun measured module parameters input to all modules
When derate is applied, modeled monthly output is similar, but implied derate factors vary.
Model Results Differ for Other Technologies

Module Model Comparison, Portland, OR 18 deg tilt

All analysis based on same physical parameters.
For illustration only - not necessarily representative of current module technology.

Missing: error bars (uncertainty analysis) and comparison with measured data
Solar input to models is an hourly average

- Alternating clouds and bright sun is modeled as medium irradiance
- All modules have higher efficiency at medium irradiance
  - Lower cell temperature = higher efficiency
- Hourly-averaging may overemphasize impact of superior “low-light level performance”
- Hourly averaging may lead to undersizing the inverter

![Modeled Performance Differences with Varying Irradiance](image)

Ambient conditions held at T=20 C, wind speed = 1 m/s

Model output - (Ee*(power out at Ee=1)), (kW/kW @ Ee=1)

- Module 1 - a-Si c.1997
- Module 2 - CdTe c.2004
- Module 3 - Thin Film 2009
- Module 4 - mono c-Si 2006
- Module 5 - mono c-Si 2003
- Module 6 - poly c-Si 2006
Future Work

• Continue Validation and Evaluation of Models
  – Acquire cSi and thin-film data sets in bright and diffuse climates (Albuquerque; Golden, Co; DC; Cocoa, FL)
  – Conduct detailed evaluation vs. incident angle, solar radiation, temperature, wind speed…
  – No right answer: Requirement for accuracy may vary
• Perform robust uncertainty analysis
  – Incorporate stochastic analysis into models
  – Which parameters are most important?
• Improve understanding of derate factors
  – Develop Web-Based Photovoltaic (PV) Database
    • See eere.energy.gov/solar/upcoming_opportunities.html
• Complete evaluation of impact of hourly averaging
  – Can modeling be improved by synthesizing sub-hourly data from existing hourly-averaged data sets?
Questions
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Select Performance Models and Accompanying Databases

• Sandia Array Performance Model
  • Also used in SolarDesignPro
• CEC 5-parameter model
  • New Solar Homes Partnership
  • All modules in CEC database
• Sandia Inverter Model
  • All inverters in CEC database

OR

• Enter module area, efficiency and $P_{mp}$ temperature coefficient
• Enter inverter efficiency and size

OR

• Use Generic Energy Input

PV Watts to be added to SAM