ASES 2019

PV Modeling – As a Community Resource

The Energy Institute
Colorado State University

John Bleem, Research Associate
Outline

• Our Northern Colorado Community
• CSU PV-STEM Solar Model Review / Validation
• Applications & Projects
• Q & A / Discussion
Colorado State University – Powerhouse Energy Campus

Hub of energy-related research and a space welcoming to a diversity of ideas.

- Renewable energy
- Power systems
- Electric vehicles
- Green building design
- Sustainability
- Human health
- International collaboration
Colorado State University Climate Action

- American College and University President's Climate Commitment (2008)
- Climate Action Plan:
  - Carbon neutrality by 2050 – (via 16 strategies)
- Climate Reality Pledge (2017) –
  - 100% renewable electricity by 2030
City of Fort Collins Climate Action

GMP = gross municipal product (indicator of economic health)

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https://www.fcgov.com/climateaction/

100% RE electricity by 2030
Growth of PV Solar Systems

- **Commercial Feed-in Tariff**
- **120% Net metering & Rebates**

Fort Collins Customers

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<th>Year</th>
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<th>Capacity</th>
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<tr>
<td>2020</td>
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Fort Collins Solar Systems

- ~1 kW to 990 kW
- About 1,600 systems
- A new one every day (about 350 in 2018)
- Incentives:
  - Feed-in-tariff
  - Full net metering
  - Rebates

As of 12/31/2018

Very little generation data for residential systems (net metering only)

Need modeling to support future planning
PV Solar Performance Models

COMMERCIAL VS. EDUCATION OR RESEARCH FOCUS

ALL PROPRIETARY

PV Solar Performance Models

NREL’s PVWatts® Calculator
Estimates the energy production and cost of energy of grid-connected photovoltaic (PV) energy systems throughout the world. It allows homeowners, small building owners, installers and manufacturers to easily develop estimates of the performance of potential PV installations.

COMMERCIAL VS. EDUCATION OR RESEARCH FOCUS

aurora

HOMER

PRO

PV F-CHART
Photovoltaic Systems Analysis

pvPlanner

PV SYST
PHOTOVOLTAIC SOFTWARE

Solar Pro 4.3

RETScreen

SYSTEM ADVISOR MODEL

ENERGY INSTITUTE
COLORADO STATE UNIVERSITY
CSU PV-STEM Solar Model

“Goldilocks” Concept for Model Design / Goals

- Not too technical → hard to implement
- Not too simple → maintain good accuracy
- Not proprietary → open source
- Accessible → novice programmers
- Flexible → detailed coding (unique projects)
- Modest data requirements (inputs)
- STEM teaching:
  - Accompanying documentation ("manual")
  - Slides / training materials
  - “Education” and “Project” versions
CSU PV-STEM Model

**INPUTS**
- GHI
- $T_{\text{amb}}$
- Wind speed
- Sizing / ILR
- Tilt
- Orientation
- Efficiencies
- Temp. Factors
- Losses

**OUTPUTS**
- Estimated PV Solar Generation (kW AC)
- Intermediate Metrics for QA / QC (and education)

Model Engine

- Weather Data
- System Design Specs
- Performance Metrics
Modeling Steps – Overview

- Establish time conventions and alignments
- Determine extraterrestrial irradiance
- Split measured irradiance → beam & diffuse
- Adjust beam to plane of array (POA) magnitude:
  - Tilt, Azimuth & Ground reflectance
- Calculate total plane of array irradiance
- Use system-specific metrics to calculate kW:
  - DC & AC ratings / other design metrics
  - Efficiencies → modules, inverter, system
  - Temperature degradation metrics / algorithms
  - Losses → wiring, outages, snow, shading, soiling, etc.
CSU PV-STEM Modeling Resources

User’s Guide & Model Documentation

- Step by step
- Assumptions
- References
- Tied to Code
- Open Source

Updated 7/28/23

PV Solar Modeling Guidelines

Updated via CSU’s PVLib Model (Python code)

These calculations are implemented in CSU’s PVLib, an open-source Python code developed at Colorado State University’s Energy Institute for STEM education, university research, utility solar program analysis and other applications.

PLANAR ARRAY IRRADIANCE

A fundamental step in calculating PV performance is determining the irradiance incident at the plane of the array (POA) as a function of time. This POA irradiance is dependent upon several factors, including:

- Sun Position
- Array Orientation (fixed or tracking)
- Irradiance Components (Direct and Diffuse)
- Ground Surface Reflectance (albedo)
- Shading factors (e.g. obstacles, buildings, and trees)

Total POA irradiance, $I_{POA}$, can be defined as the sum of individual sources:

$$I_{POA} = I_{D} + I_{S} + I_{G}$$

where $I_{D}$ is the direct beam component, $I_{S}$ is the diffuse, or scattered, component, and $I_{G}$ is the ground reflected component.

Note that the data acquisition system (DAS) on older generation systems typically measure total global radiation on a horizontal surface (GHI) in W/m². A horizontal monitor does not “see” the ground, so the ground reflected component included in the measured value is typically assumed zero. However, panels that receive ground reflected solar energy depending on location, local ground reflectance and the shade model.

BEAM COMPONENT ($I_D$)

The plane of array (POA) beam component of irradiance is calculated by adjusting the direct normal irradiance (DNI) to account for the position of the sun on the sky. One way to do this is to use the concept of inclination (IOP):

$$I_D = O\!N\!I \times \cos(IOP)$$

The angle of incidence between the sun’s rays and the PV array can be determined as follows:

$$IOP = \cos^{-1} \left( \cos(\theta_s) \times \sin(\phi_s) - \sin(\theta_a) \times \cos(\phi_s) \times \cos(\theta_a) \right)$$

where $\theta_s$ and $\phi_s$ are the solar zenith and azimuth angles, respectively. $\theta_a$ and $\phi_a$ are the tilt and azimuth angles of the array, respectively. Note that the sine and cosine functions need to be applied consistently (degrees vs. radians).

Updated 7/28/23

SOLAR AZIMUTH ANGLE ($\phi_s$)

To complete the ACI calculation, we need to determine the solar azimuth angle and the solar zenith angle. In their “Modeling Sharp” documentation, Sandia does not include the equations for determining solar azimuth directly, though does provide the following reference = from work at NEIS:


The equations necessary to determine the solar azimuth angle are included here (extracted from the reference above). The “nominal azimuth attitude angle” $\phi$ is calculated from:

$$\phi = \arctan \left( \tan(\theta_s) \times \cos(\phi_s) \right) - \arctan \left( \sin(\theta_s) \times \cos(\phi_s) \right)$$

Note that in the reference, NEIS’s convention for variable offset is different than that of Sandia (used here). Also note that their angle in the reference is measured $\phi_{east} = 0$ (see page 11 of NEIS reference). Therefore, morning angles are negative and afternoon angles are positive. The ARCTAN function is an antilog function applied to the numerator and the denominator separately (rather than applying to the usual division), in order to maintain the correct quadrant of the result (in the range from $-\pi$ to $\pi$).
CSU PV-STEM Modeling Resources

Python Code

- “Serial” version (teaching focus)
- “Panda” version (projects)
- Open source
CSU PV-STEM Modeling Resources

Training Slides

- Tied to coding
- CSU class use
- STEM students
- Open source
- Includes "real system" modeling considerations
Model Validation
COMPARISON
PVSTEM model estimate vs. metered PV generation

10 Commercial Systems (sites with generation data)
20 kW to 632 kW
Model Validation – Solar Position

NOAA Solar Calculator
https://www.esrl.noaa.gov/gmd/grad/solcalc/

Solar Position Algorithm (SPA)
https://midcdmz.nrel.gov/solpos/spa.html

Utilities Office – First week of January
Model Validation – Solar Position

Solar Angles

Altitude

Azimuth

Angle of Incidence
Modeling Validation – Generation

Annual Differences – Actual vs. Estimated

Monthly Differences – Actual vs. Estimated

Snow season (highest differences)  Highest Generation (lowest errors)  Snow season (highest differences)
Modeling Considerations – Snow

Snow Hours (mostly)

CSU Powerhouse – 15° tilt
20.2 kW DC

Solar energy available
Modeling Considerations – Snow

Two approaches for snow:
• Assume GHI sensor is clear and compare estimated with actual
• Apply a loss factor for snow days based on tilt and other metrics

Unknown – how many days to “clear” snow off?
Modeling Considerations –

Example – City Office Building

Some DAS units provide $T_{\text{cell}}$ (most do not)

For system wide modeling we use wind speed and $T_{\text{amb}}$

Consider:
- Module materials
- Mounting design / air flow
- Wind speed
- Ambient temperature
- Irradiance (POA)
Modeling Considerations – Weather Data

Four Weather Sources plus TMY

Key Data:
- GHI (W/m²)
- Ambient Temp.
- Wind Speed

Ideal – Key data available at the generation site
Reality – Limited data at most generation sites
## Modeling Considerations – Losses

- PVWatts values as default (if no data available)
- PV-STEM – unique values used (if known)
- Snow is calculated from weather data
- Shading based on site conditions
- Age loss based on commercial operating data

### Losses Calculation

\[
\text{Losses} = 100\% \times \left[ (1.0 - (1 - 0.02)) \times (1 - 0.02) \times (1 - 0.02) \times (1 - 0.005) \times (1 - 0.015) \times (1 - 0.01) \times (1 - 0.0) \right] \\
= 8.68\% \text{ (first year operation)}
\]

+ Modify total loss based on age (0.5% per year)

Also apply part-load inverter losses based on individual system specs or generic “curve”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Shading (%)</td>
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<tr>
<td>Snow (%)</td>
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<td>Mismatch (%)</td>
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<td>Wiring (%)</td>
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<td>Nameplate Rating (%)</td>
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<td>Age (%)</td>
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<td>Availability (%)</td>
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</table>
Modeling Considerations – Outages

24.75 kW system – 2014 installation

2014-2015

2015-2016

2016-2017

2017-2018

2018-2019

Verification period selection challenges
Model Validation – Hourly

January

![Graph showing electricity consumption for January. The graph compares actual and estimated electricity consumption.](image)

June

![Graph showing electricity consumption for June. The graph compares actual and estimated electricity consumption.](image)
Model Validation Example

**20.6 kW DC system – 18° tilt / 185° azimuth**

2018 Data

**Annual Results:**

- Estimated Annual Energy: 29,731 kWh
- Actual Annual Energy: 30,526 kWh
- Estimate vs. Actual % Error: 2.6%
- Snow Loss Estimate: 3.4%
Model Validation Examples

Daily Generation Comparison

Estimate - Actual

Snow clearing (not captured)
Model Validation – Hourly

Actual vs. Estimated

Sum of annual generation values by hour

GEN Actual
GFN PVSTEM
## Model Validation – PVSTEM vs. PVWatts

<table>
<thead>
<tr>
<th>PVSTEM</th>
<th>PVWatts</th>
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<tbody>
<tr>
<td>• Uses long-term average weather data (TMY)</td>
<td>• Can use any available weather data</td>
</tr>
<tr>
<td>• Limited to hourly granularity</td>
<td>• Can model any time interval</td>
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<tr>
<td>• Runs one system at a time</td>
<td>• Can model many systems – with managed I/O</td>
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<tr>
<td>• GHI, DNI and DHI are input directly</td>
<td>• DNI and DHI determined from GHI &amp; Erbs curve fit</td>
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<tr>
<td>• Limited module inputs</td>
<td>• Flexible module inputs</td>
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<tr>
<td>• Includes tracking system model</td>
<td>• Fixed modules only</td>
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<tr>
<td>• Algorithms and assumptions outlined in PVWatts user’s manual (2015):</td>
<td>• Algorithms and assumptions outlined in CSU PVSTEM documentation:</td>
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<tr>
<td>o Cell temperature from Fuentes algorithm</td>
<td>o Cell temperature from Sandia algorithm</td>
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<tr>
<td>o Mid-hour adjustment used</td>
<td>o Mid-hour adjustment included for consistency</td>
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<tr>
<td>o Glass reflection losses include</td>
<td>o No glass reflectance adjustment</td>
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<tr>
<td>o Inverter part load – CEC curve fit</td>
<td>o Inverter part load – Simple curve</td>
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<tr>
<td>o Other minor differences</td>
<td>o Other minor differences</td>
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Model Validation – PVSTEM vs. PVWatts

Very clear

Very cloudy

Direct & Diffuse determined from GHI and Erbs curve fits

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<thead>
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<th>Month</th>
<th>Day</th>
<th>Hour</th>
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Direct & Diffuse fed directly into model (long-term TMY values)
Model Validation – vs. PVWatts

100 kW DC system – 30° tilt / 180° azimuth (SOUTH)
TMY 2016 Data

Annual Results:
PVSTEM Annual Energy: 157,131 kWh
PVWatts Annual Energy: 158,378 kWh
Difference: 0.8% (underestimated)
Model Validation – vs. PVWatts

Daily Generation Comparison

30° tilt / 180° azimuth (SOUTH)

Difference (PVSTEM – PVWatts)
Model Validation – vs. PVWatts

- 0° Tilt & 180° Azimuth (HOR)
- 30° Tilt & 90° Azimuth (EAST)
- 30° Tilt & 270° Azimuth (WEST)
- 30° Tilt & 0° Azimuth (NORTH)
Model Applications – Utility Studies

Load profile development – AMI net metering

Utility has advanced metering infrastructure (AMI) net metered data – but no sub-metering of solar generation

Load = PV – MR + MD

D – delivered
R – received
M_D
M_R

Before install
Without PV
Load < PV
Load > PV
Zero Energy
Energy provided from grid “Delivered”
Energy sent to grid “Received”

(after install)

Model Estimate

Load
PV

Model Applications – Utility Studies

Solar Size Limitation

“120% Rule” → Annual PV generation <= 120% of annual load

- How does actual generation compare with initial design?
- How many systems use more than 100% (net)?
- Implications for changes to rule?
Model Applications – Utility Studies

Time-of-Use Analysis

- 20%
- 0%
- 20%
- 40%
- 60%
- 80%
- 100%

Solar Output
City Load

Solar Peak
System Peak

~ 12-15% On-Peak (annual)
Model Applications – Feeder Limits
**Education Projects launched:**

- Green Building Analysis
- Freezer Consolidation
- Fort Collins Solar Co-op
- City of Fort Collins’ Multifamily Building Energy Challenge
- Bike Parking Shelter Solar PV
- College Avenue Parking Garage Solar
- Meridian Village Solar
- PV Solar Modeling & Analysis
- Commercial Energy Audits

[Go to coloradoC3E.org/Shes-in-Power](http://coloradoC3E.org/Shes-in-Power)
Community Solar Resource Monitoring

- **City Database**
  - Locations (address)
  - Max DC kW rating

- **Solar System Metrics**
  - Orientation
  - Shading
  - Efficiency

- **Solar Monitoring**
  - Global horizontal solar resource (Watts/m²)

- **On line surveys**
  - GHI / DHI / DNI Analysis
  - Mathematical Modeling
  - Solar model programming

- **Site surveys**
  - School solar MET

FUTURE GOAL:
Community Web Site with Real-Time Solar Generation (total for City)
Model Applications – CSU Education

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- **THESIS**

  DISAGGREGATION OF NET-METERED ADVANCED METERING INFRASTRUCTURE DATA TO ESTIMATE PHOTOVOLTAIC GENERATION

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**MECH 575 Solar and Alternative Energies**  Credits: 3 (3-0-0)

**Course Description:** Solar radiation, flat-plate collectors, energy storage, space heating and cooling, generation, applications, simulation.

**Prerequisite:** MECH 337 and MECH 342 and MECH 344.

**Term Offered:** Spring.

**Grade Mode:** Traditional.

**Special Course Fee:** No.
Model Applications – STEM Education

STEM CLUB COMPETITION
Design a system → Run it through the PVSTEM model
Best system wins!
QUESTIONS?
DISCUSSION?
Contacts

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Powerhouse_Info@Mail.Colostate.edu