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

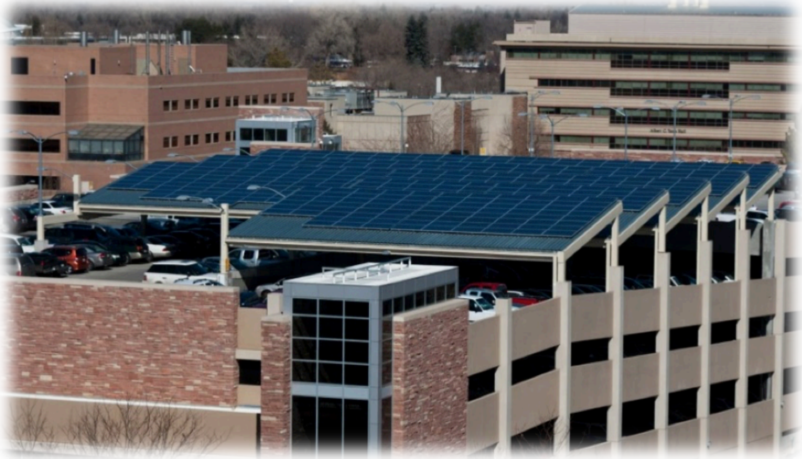
Colorado State University – Powerhouse Energy Campus

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*



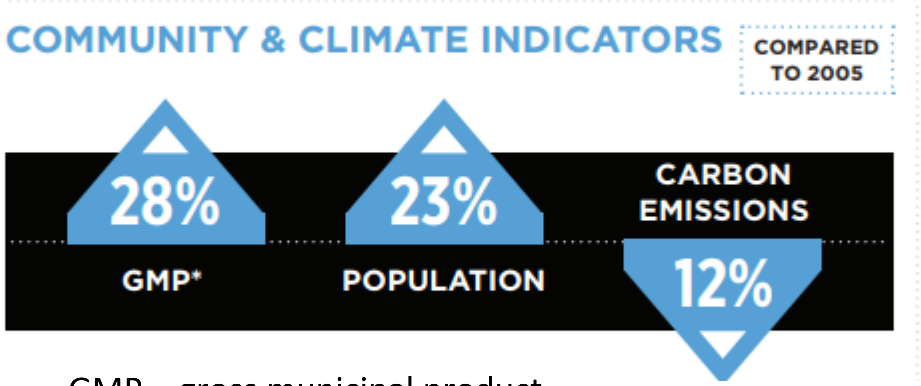
City of Fort Collins Climate Action

City of Fort Collins

Municipal Utility

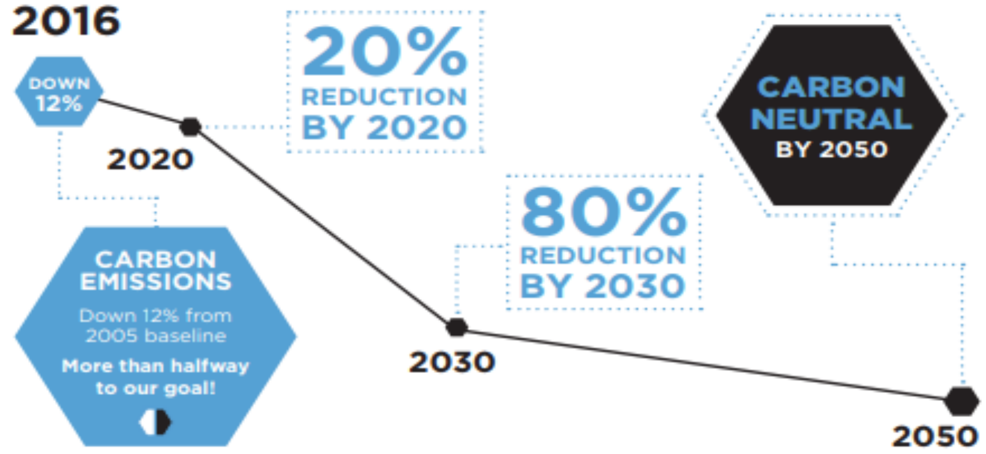
Platte River Power Authority

Electricity Supplier (Northern Colorado)



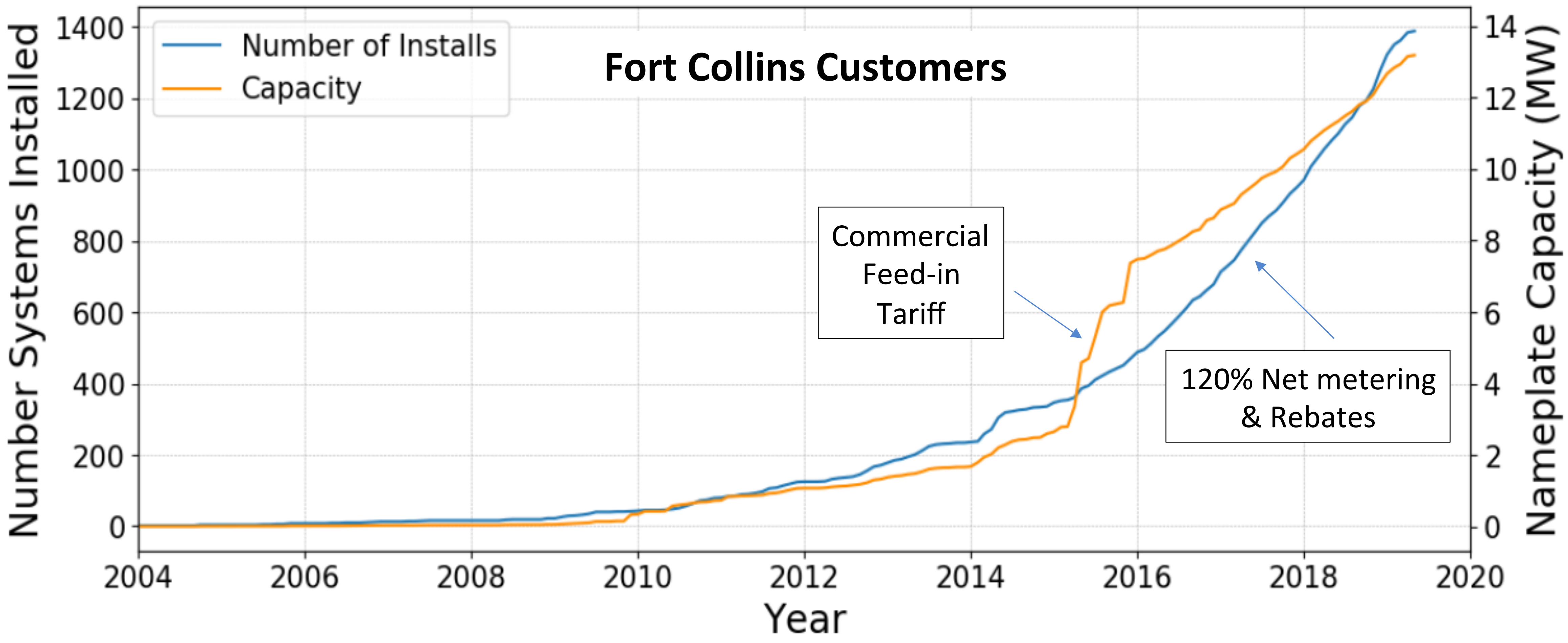
GMP = gross municipal product (indicator of economic health)

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



100% RE electricity by 2030

Growth of PV Solar Systems



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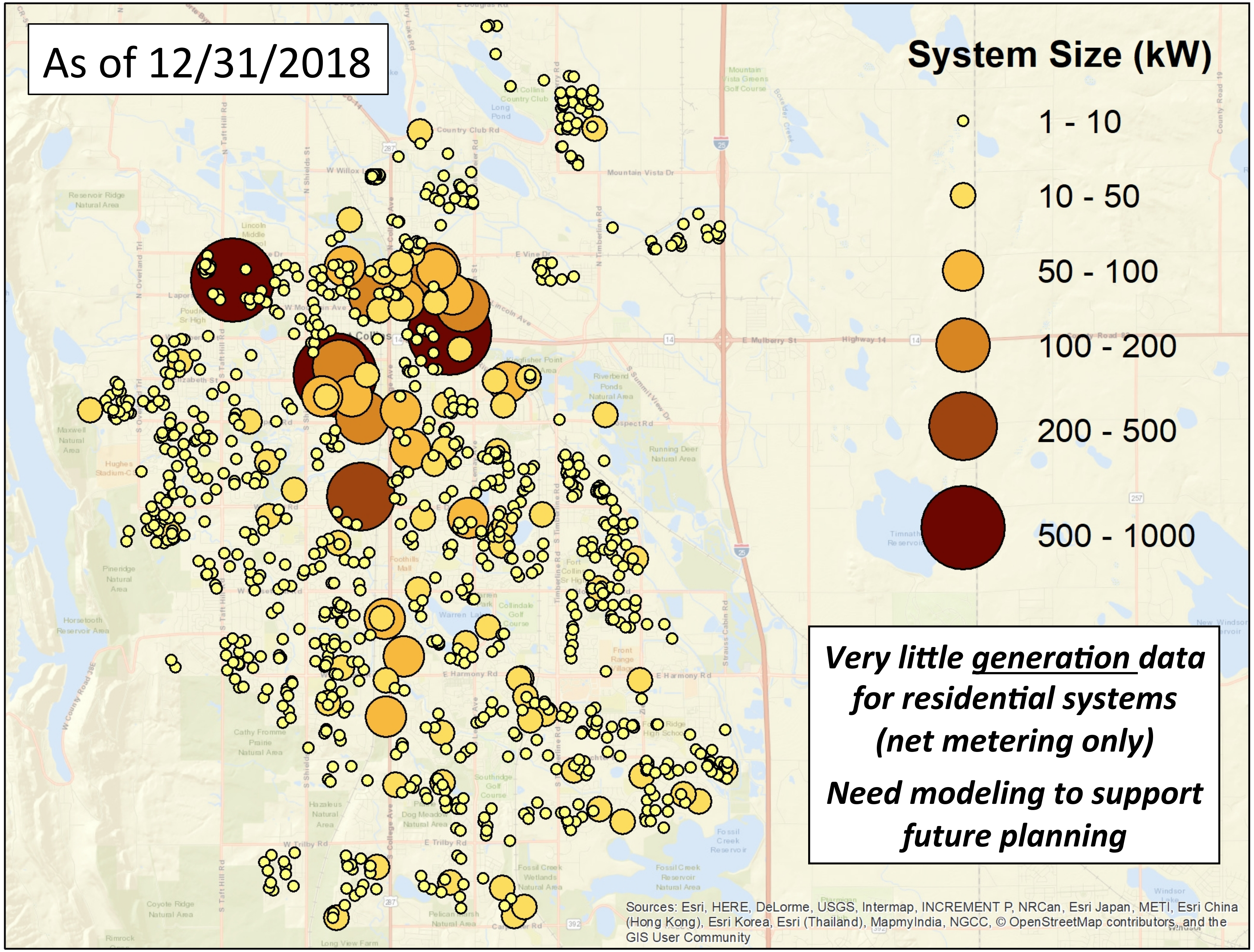
Fort Collins Solar Systems

- ~ 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



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

Need modeling to support future planning

PV Solar Performance Models

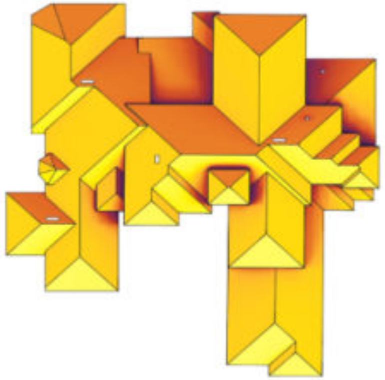
ALL PROPRIETARY

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

pvPlanner

PV F-CHART
Photovoltaic Systems Analysis

RETScreen

System Advisor Model

NREL

PVSYST
PHOTOVOLTAIC SOFTWARE

Solar Pro 4.3

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 – References

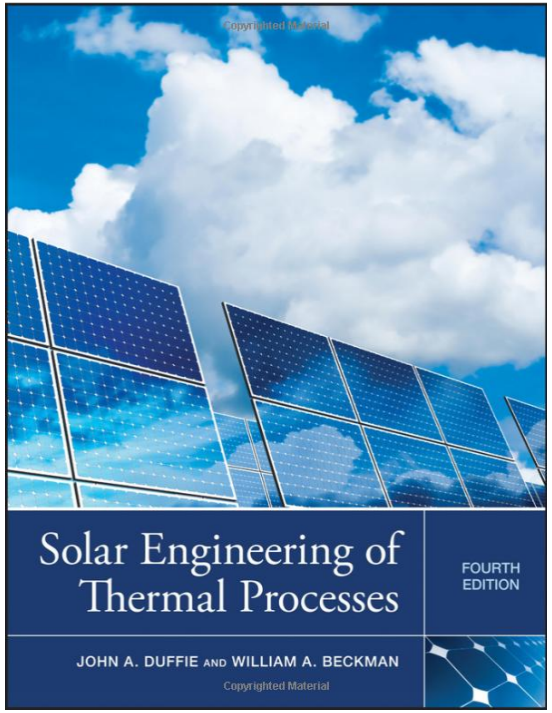
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Sandia National Laboratories

IEEE

CLIMATEDATA.US



CSU PV-STEM Model

INPUTS

- GHI
- T_{amb}
- Wind speed

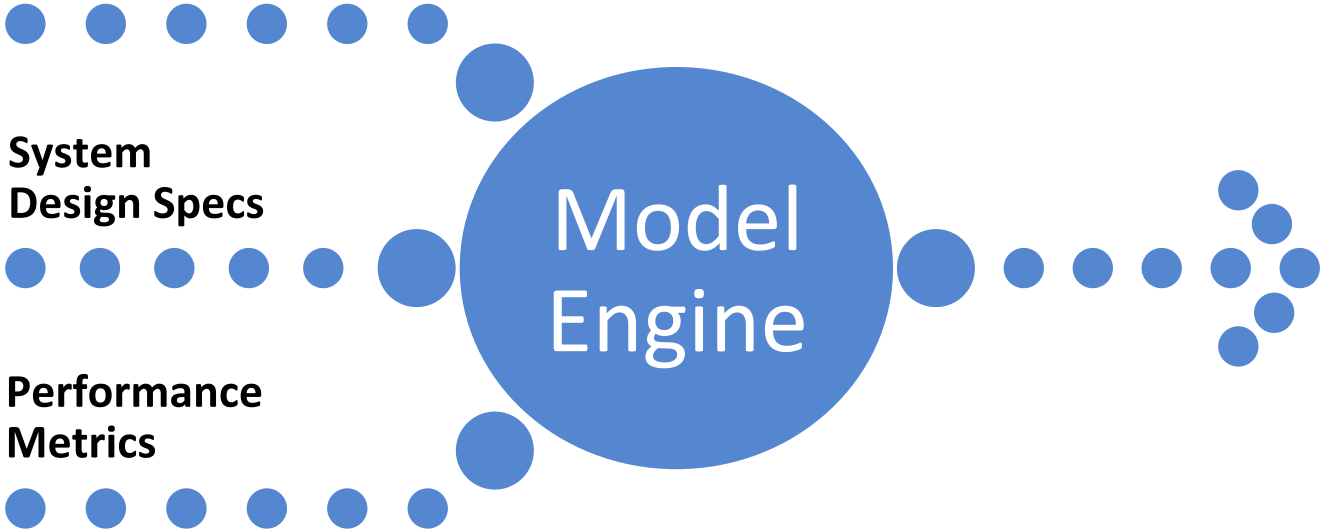
Weather Data

- Sizing / ILR
- Tilt
- Orientation

System Design Specs

- Efficiencies
- Temp. Factors
- Losses

Performance Metrics



OUTPUTS

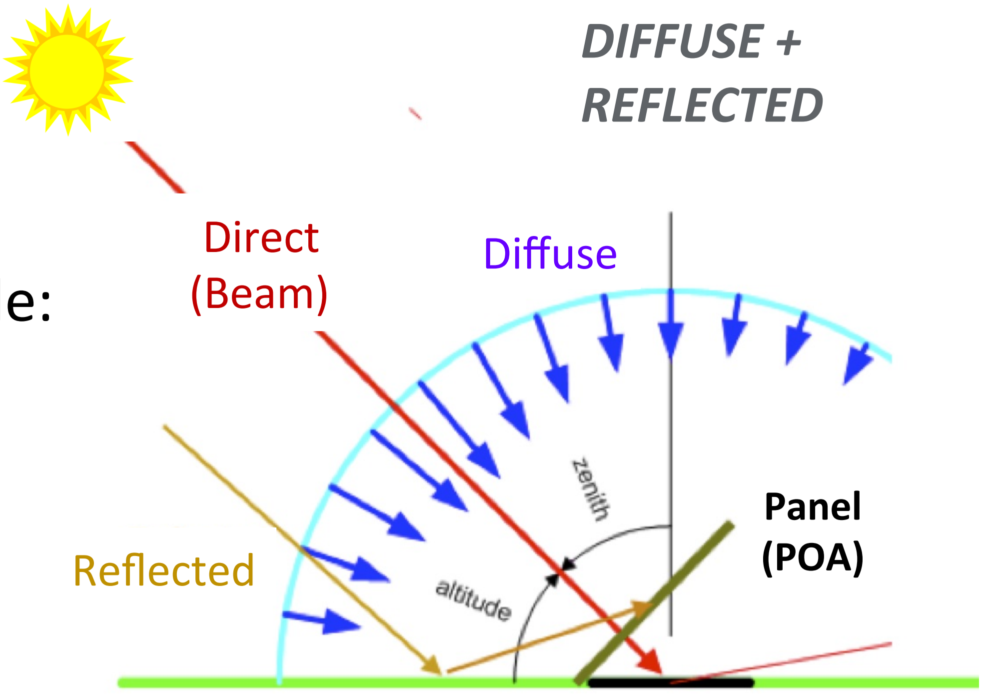
Intermediate Metrics for QA / QC (and education)

Estimated PV Solar Generation (kW AC)

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.

TOTAL = BEAM + DIFFUSE + REFLECTED



CSU PV-STEM Modeling Resources

User's Guide & Model Documentation

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

PV Solar Modeling Guidelines
Implemented via CSU's PVLib Model (Python code)

Steps for calculating solar generation from PV systems are outlined below, based on information from the Sandia National Labs PV Performance Modeling Collaborative (PVPMC)[1] website and other references.

[1] *https://pvpmc.sandia.gov/modeling-steps/*

These calculations are implemented in CSU-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.

PLANE OF ARRAY IRRADIANCE

A fundamental step in calculating PV performance is determining the irradiance incident on 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 Reflectivity (Albedo)
- Shading (near and far obstructions)
- Snow cover, soiling, shading, degradation (aging) and other losses

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

$$E_{POA} = E_b + E_g + E_d$$

where E_b is the POA beam component, E_g is the POA ground-reflected component, and E_d is the POA sky-diffuse component.

Note that the data acquisition system (DAS) on solar generation units typically measure total global radiation on a horizontal surface (GHI) in W/m^2. A horizontal monitor does not "see" the ground, so the ground reflected component included in the monitored value is typically assumed zero. However, panels may receive ground reflected solar energy depending on location, local ground reflectance and tilt.

BEAM COMPONENT – (E_b)

The plane of array (POA) beam component of irradiance is calculated by adjusting the direct normal irradiance (irradiance directly normal to the rays from the sun, or DNI) by the angle of incidence (AOI):

$$E_b = DNI * \cos(AOI)$$

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

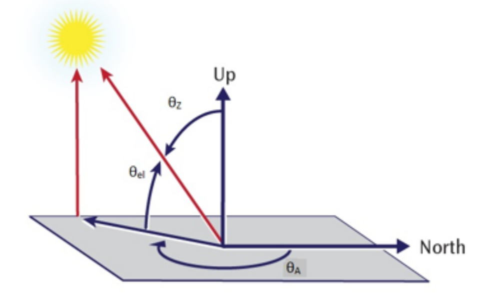
$$AOI = \cos^{-1} [\cos(\theta_Z) * \cos(\theta_T) + \sin(\theta_Z) * \sin(\theta_T) * \cos(\theta_A - \theta_{array})]$$

where θ_A and θ_Z are the solar azimuth and zenith angles, respectively. θ_T and θ_{array} 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).

The position of the sun relative to an observer on the surface of the earth is an important input needed to model PV system performance. The convention used to describe solar position includes the following:

- Zenith angle (θ_Z)
- Azimuth angle (θ_A)
- Solar elevation angle (θ_{el}); also equal to $90 - \theta_Z$ (this is sometimes called the solar altitude angle)

The figure below shows how these angles are defined.



θ_{el} = elevation angle, measured up from horizon

θ_Z = zenith angle, measured from vertical

θ_A = azimuth angle, measured from North

SOLAR AZIMUTH ANGLE (θ_A)

To complete the AOI calculation, we need to determine the solar azimuth angle and the solar zenith angle. In their "Modeling Steps" documentation, Sandia does not include the equations for determining solar azimuth directly, though does provide the following reference – from work at NREL:

[2] *I. Reda and A. Andreas, Solar position algorithm for solar radiation applications. Solar Energy, vol. 76, no. 5, pp. 577-589, 2004 (updated in 2008). https://www.nrel.gov/docs/fy08osti/34302.pdf*

The equations necessary to determine the solar azimuth angle are included here (extracted from the reference above). The "topocentric astronomers azimuth angle" (Γ) is calculated from:

$$\Gamma = ARCTAN2 \{ \sin(\theta_{hr}) / [\cos(\theta_{hr}) * \sin(\lambda) - \tan(\theta_d) * \cos(\lambda)] \} \quad (45)$$

Note that in the reference, NREL's nomenclature for variables differs from that of Sandia (used here). Also note that hour angle in the reference is measured **westward from south** (see page 11 of NREL reference). Therefore, morning angles are negative and afternoon angles are positive. The ARCTAN2 function is an arctangent function applied to the numerator and the denominator separately (rather than applying to the actual division), in order to maintain the correct quadrant of the result (in the range from – π to π).

CSU PV-STEM Modeling Resources

Python Code

- "Serial" version (teaching focus)
- "Panda" version (projects)
- Open source

```python
def calcTimevals(df):
    df['dayOfYear'] = df.index.dayofyear
    df['hour'] = df.index.hour
    df['minute'] = df.index.minute
    df['second'] = df.index.second
    df['tzOffsetHours'] = df.index.map(lambda x: x.utcoffset().total_seconds() / 3600.0)
    df['numDays'] = 365
    df.loc[df.index.is_leap_year, 'numDays'] = 366

def azimuth(df, lat, lon):                  # the weather dataframe is called as "df", along with latitude & longitude

    retDF = pd.DataFrame(index=df.index)   # sets up an output dataframe (retDF) with same index as input dataframe
    calcTimevals(retDF)                     # CalcTimevals above is applied and calculated columns are added below

    retDF['gamma'] = (2 * np.pi) / retDF['numDays'] * (retDF['dayOfYear'] - 1 + (retDF['hour'] - 12) / 24)

    retDF['eqtNOAA'] = 229.18 * ((0.000075 + 0.001868 * np.cos(retDF['gamma']) - 0.032077 * np.sin(retDF['gamma'])
                       - (0.014615 * np.cos(2 * retDF['gamma'])) - (0.040849 * np.sin(2 * retDF['gamma']))))

    retDF['timeOffsetMinutes'] = retDF['eqtNOAA'] + (4 * lon) - (60 * retDF['tzOffsetHours'])

    retDF['Tsolar'] = retDF['hour'] + retDF['timeOffsetMinutes'] / 60 + \
                      retDF['minute'] / 60 + retDF['second'] / 3600

    retDF['hr_angleD'] = np.degrees((np.pi / 12.0) * (retDF['Tsolar'] - 12.0))

    retDF['dec_angle'] = (0.006918 - 0.399912 * np.cos(retDF['gamma']) + 0.070257 * np.sin(retDF['gamma']) -
                          0.006758 * np.cos(2 * retDF['gamma']) + 0.000907 * np.sin(2 * retDF['gamma']) -
                          0.002697 * np.cos(3 * retDF['gamma']) + 0.00148 * np.sin(3 * retDF['gamma']))

    retDF['dec_angleD'] = np.degrees(retDF['dec_angle'])

    retDF['cos_zen'] = (sind(lat) * sind(retDF['dec_angleD']) +
                        cosd(lat) * cosd(retDF['dec_angleD']) * cosd(retDF['hr_angleD']))
```

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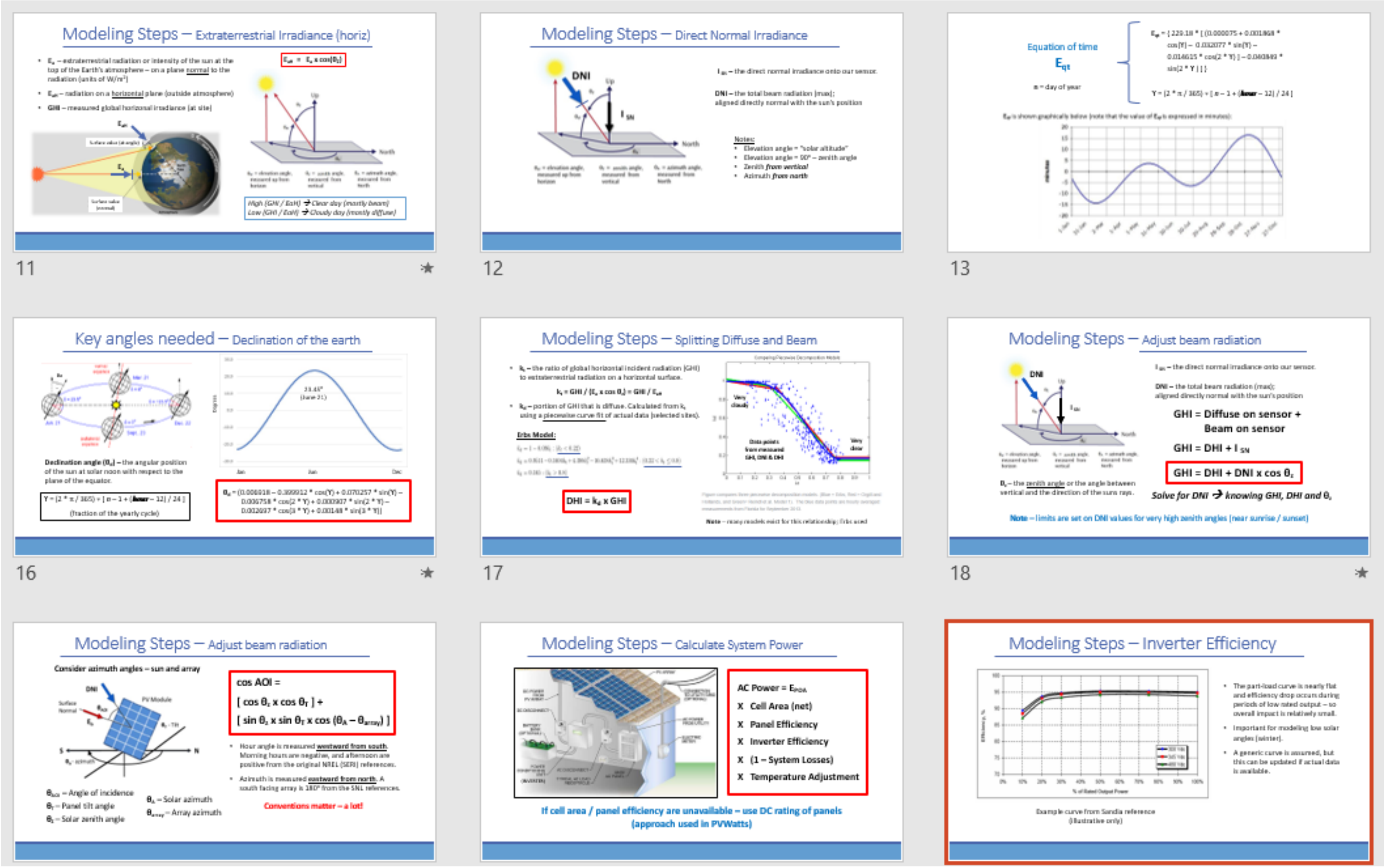
CSU PV-STEM Modeling Resources

Training Slides

- Tied to coding
- CSU class use
- STEM students
- Open source
- Includes "real system" modeling considerations



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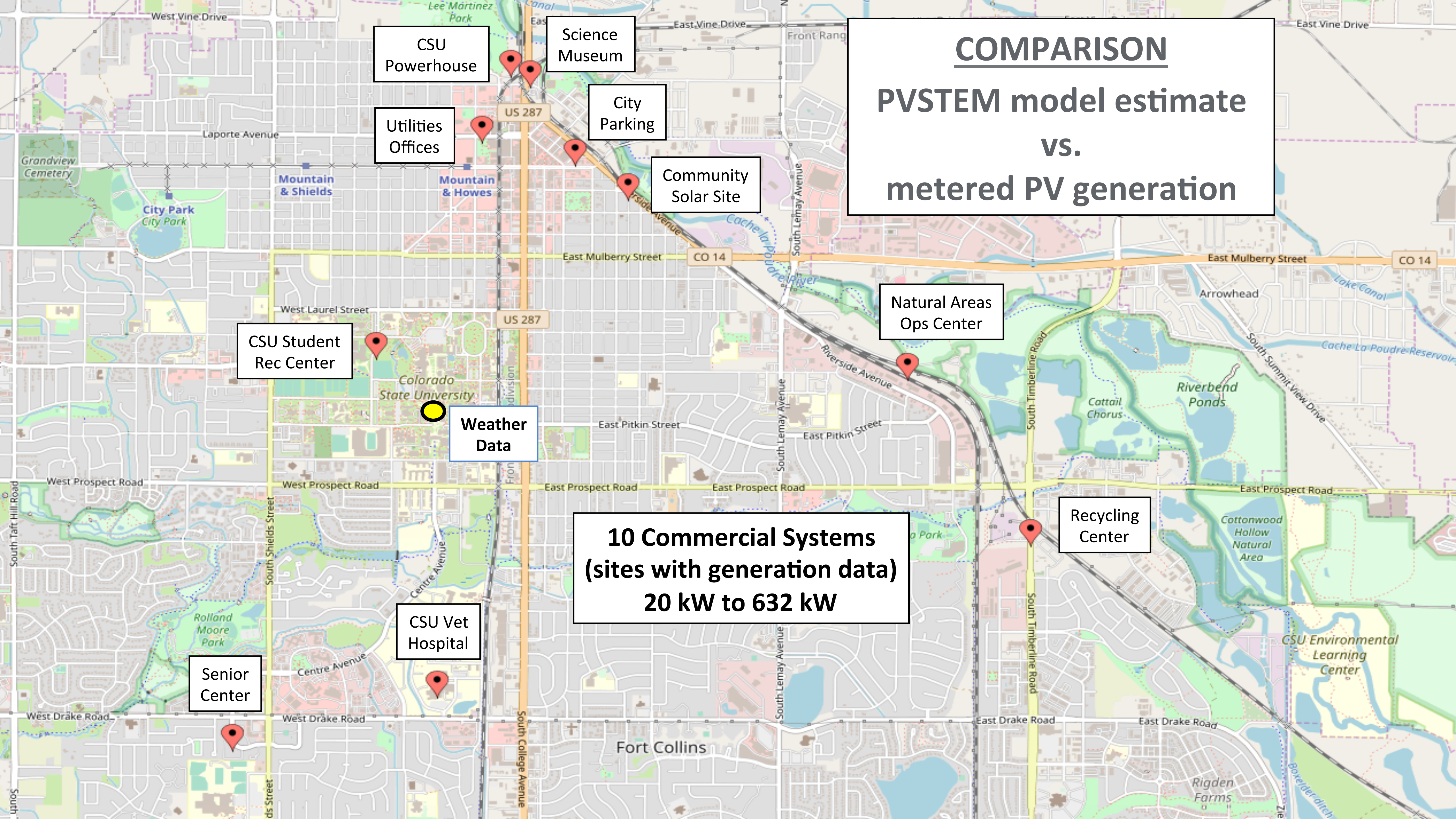
python™

Model Validation


COMPARISON
PVSTEM model estimate
vs.
metered PV generation
CSU Powerhouse
Science Museum
City Parking
Utilities Offices
Community Solar Site
Natural Areas Ops Center
CSU Student Rec Center
Weather Data
Recycling Center
10 Commercial Systems
(sites with generation data)
20 kW to 632 kW
CSU Vet Hospital
Senior Center
Fort Collins
Colorado State University
East Mulberry Street
East Prospect Road
West Prospect Road
West Drake Road
East Drake Road
South College Avenue
South Lemay Avenue
South Timberline Road
South Shields Street
Riverside Avenue
Laporte Avenue
West Vine Drive
East Vine Drive
US 287
CO 14

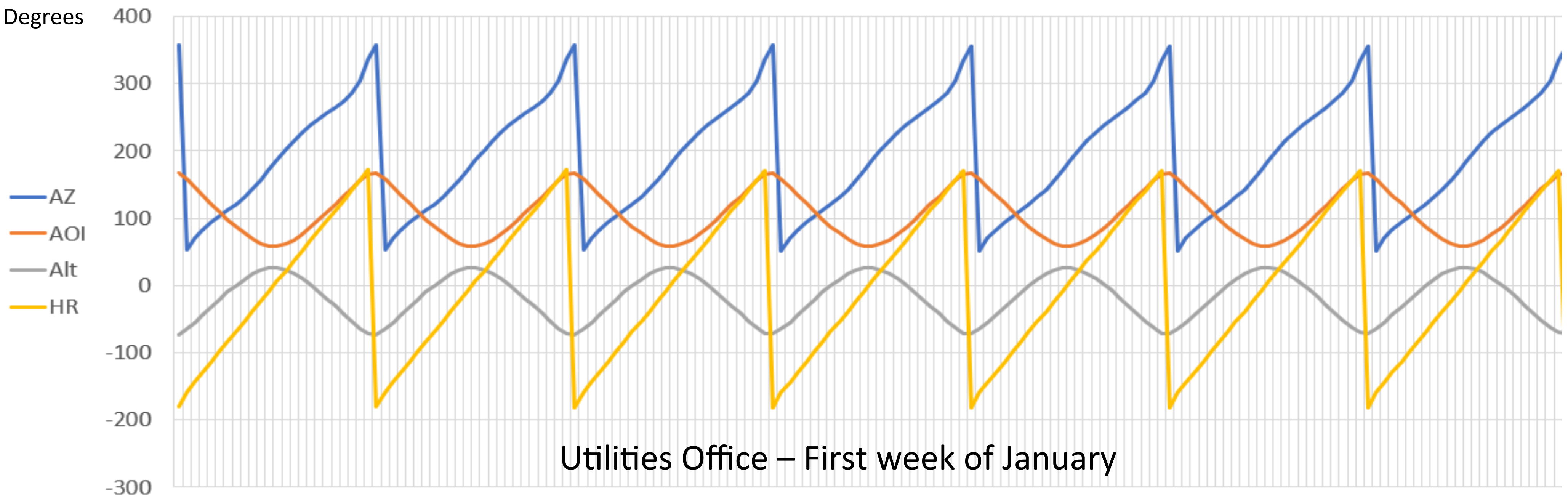
Model Validation – Solar Position

NOAA Solar Calculator

https://www.esrl.noaa.gov/gmd/grad/solcalc/

Solar Position Algorithm (SPA)

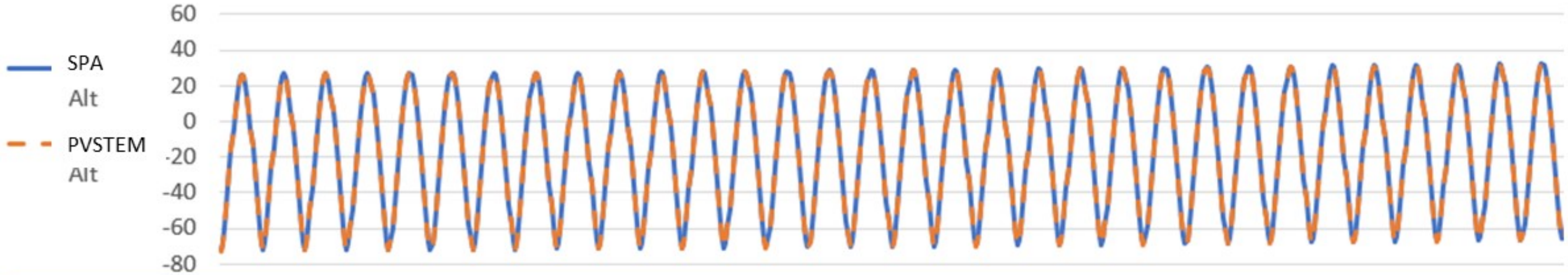
https://midcdmz.nrel.gov/solpos/spa.html



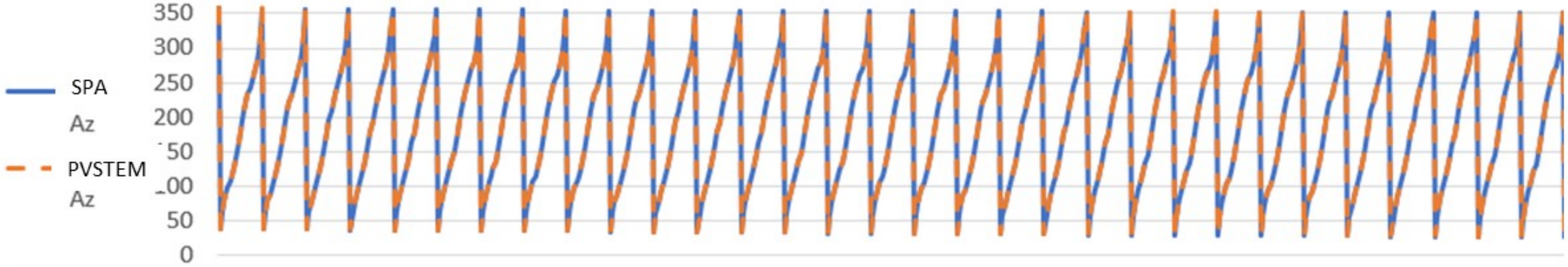
Model Validation – Solar Position

Solar Angles

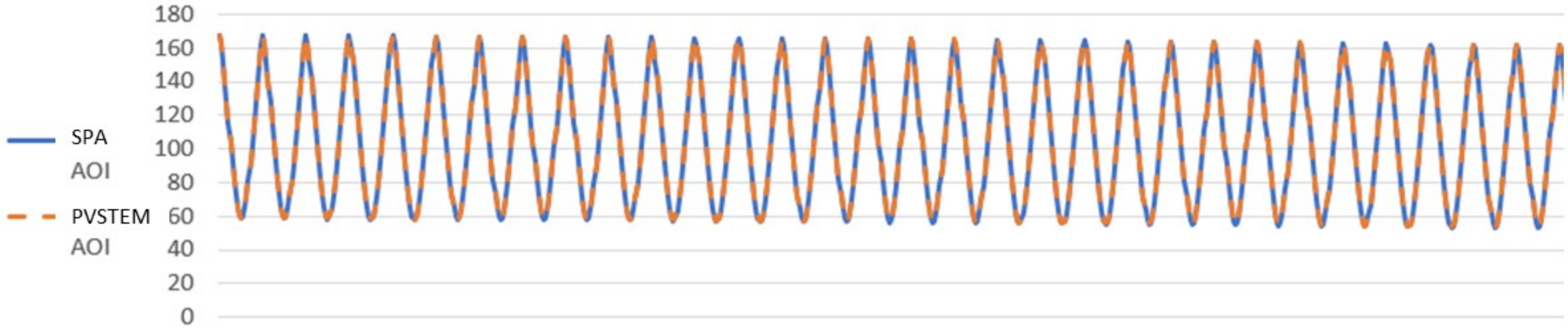
Altitude →



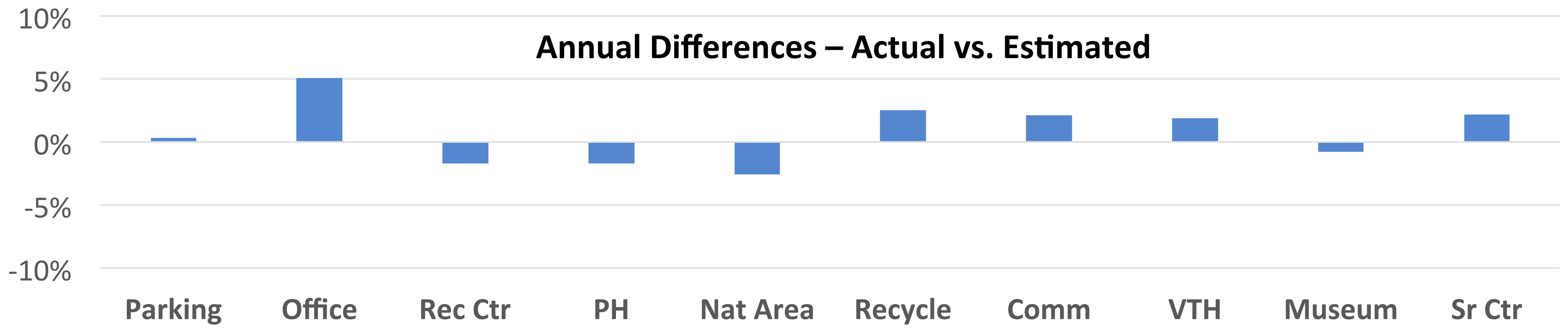
Azimuth →

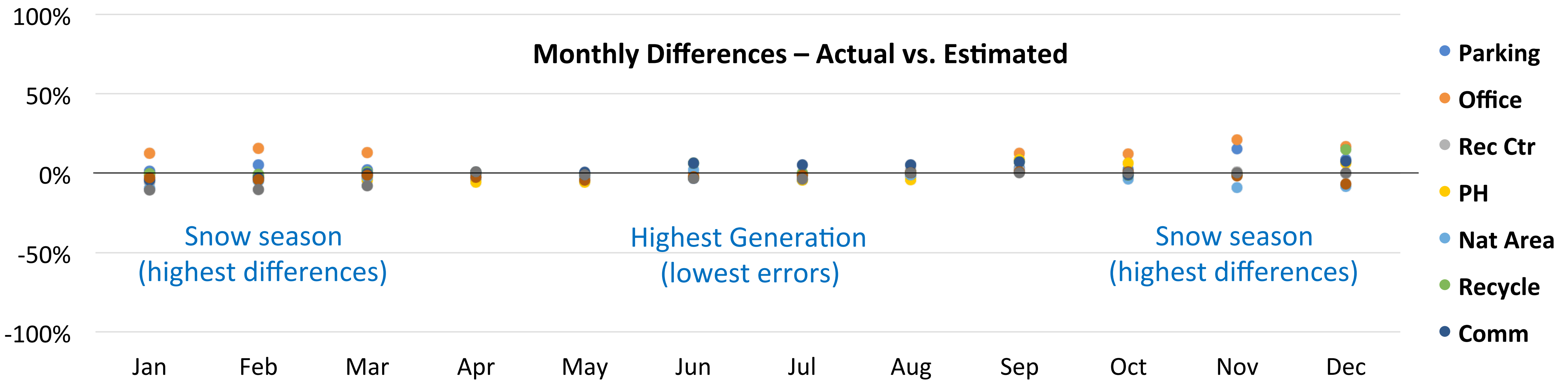


Angle of Incidence →



Modeling Validation – Generation





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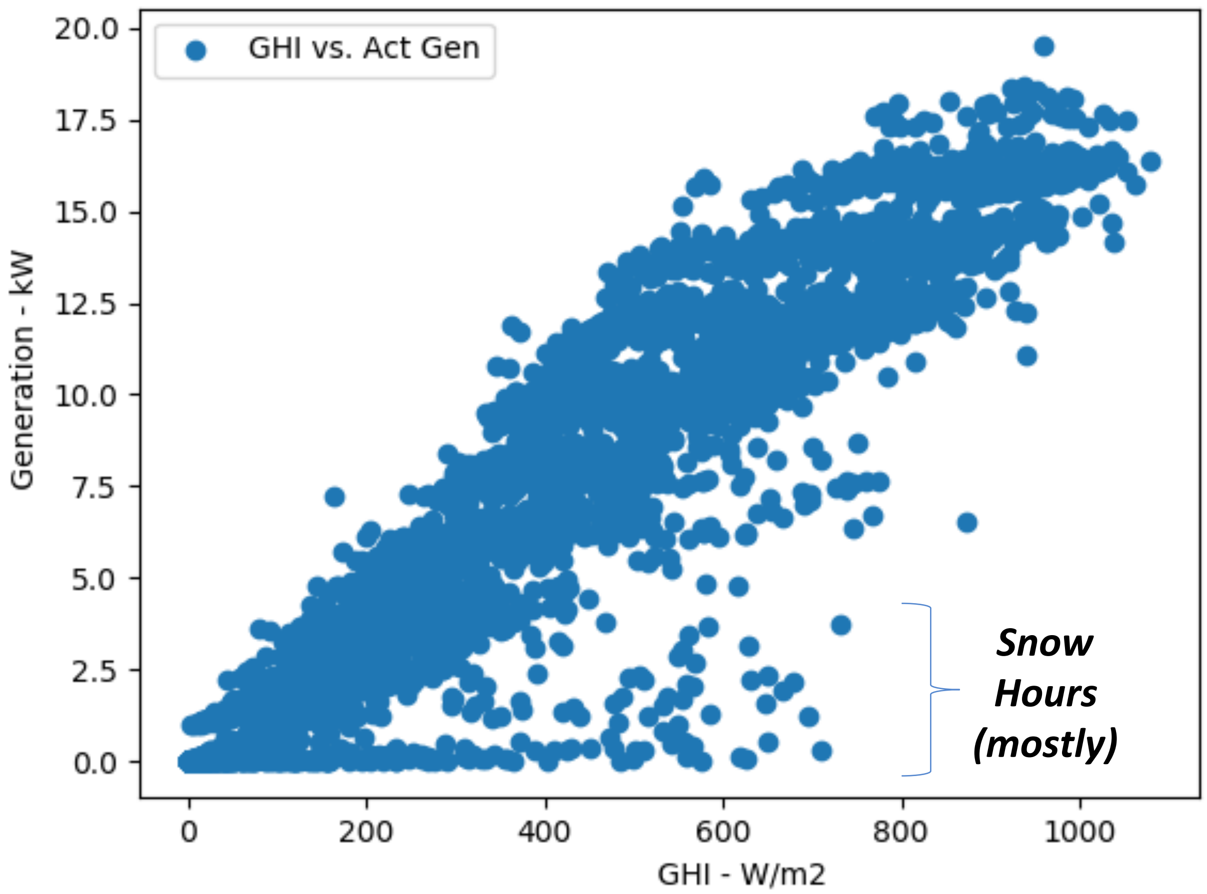
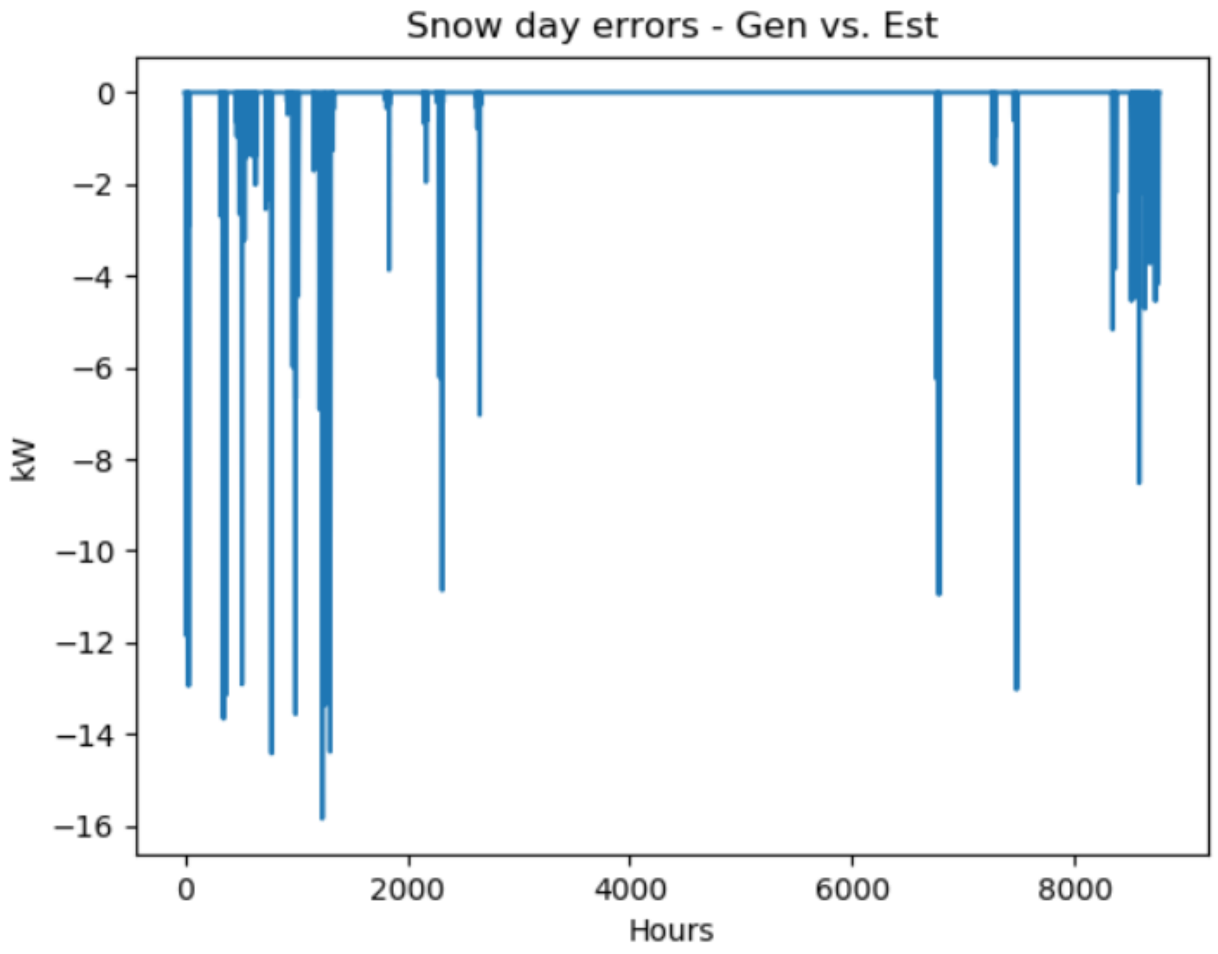
Modeling Considerations – Snow



Solar energy available

CSU Powerhouse – 15° tilt
20.2 kW DC

Modeling Considerations – Snow



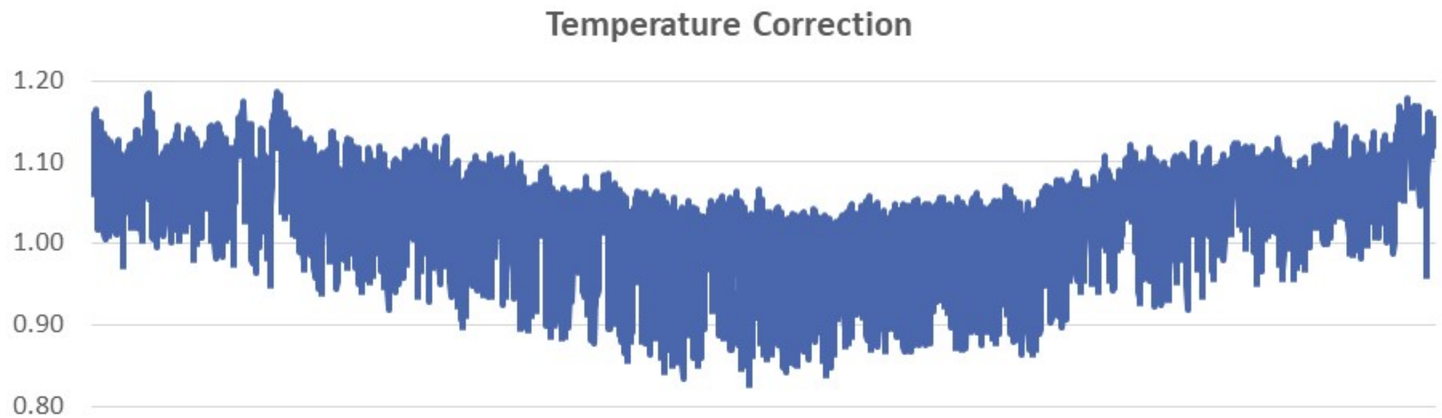
CLIMATEDATA.US

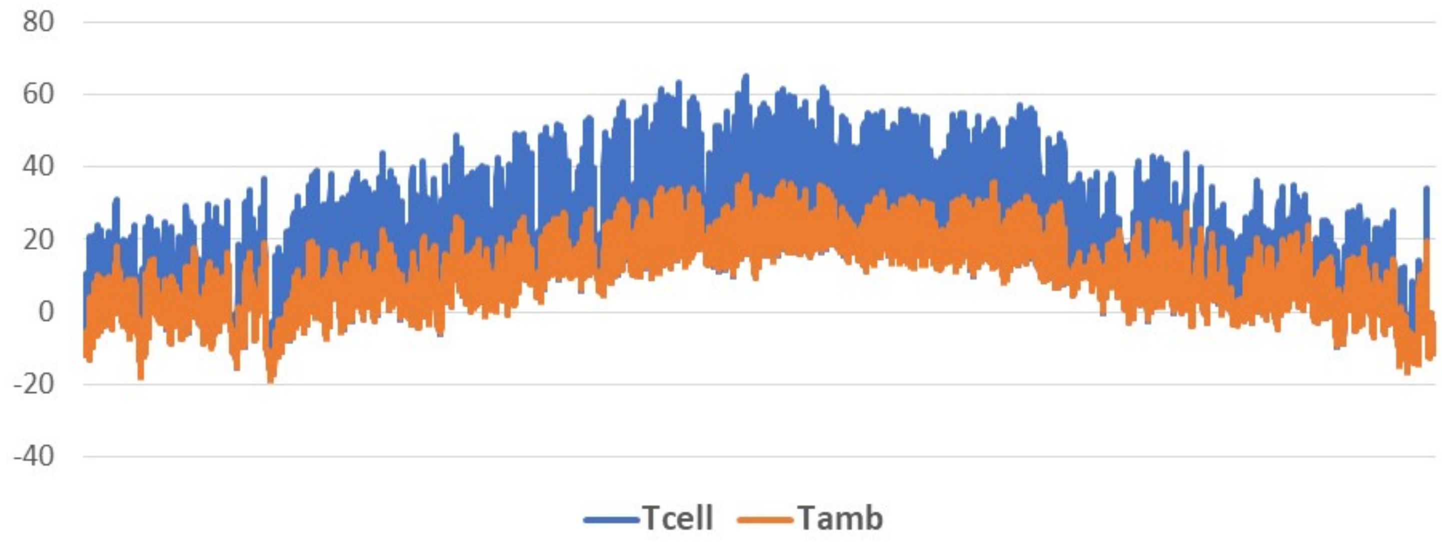
Two approaches for snow:

- 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

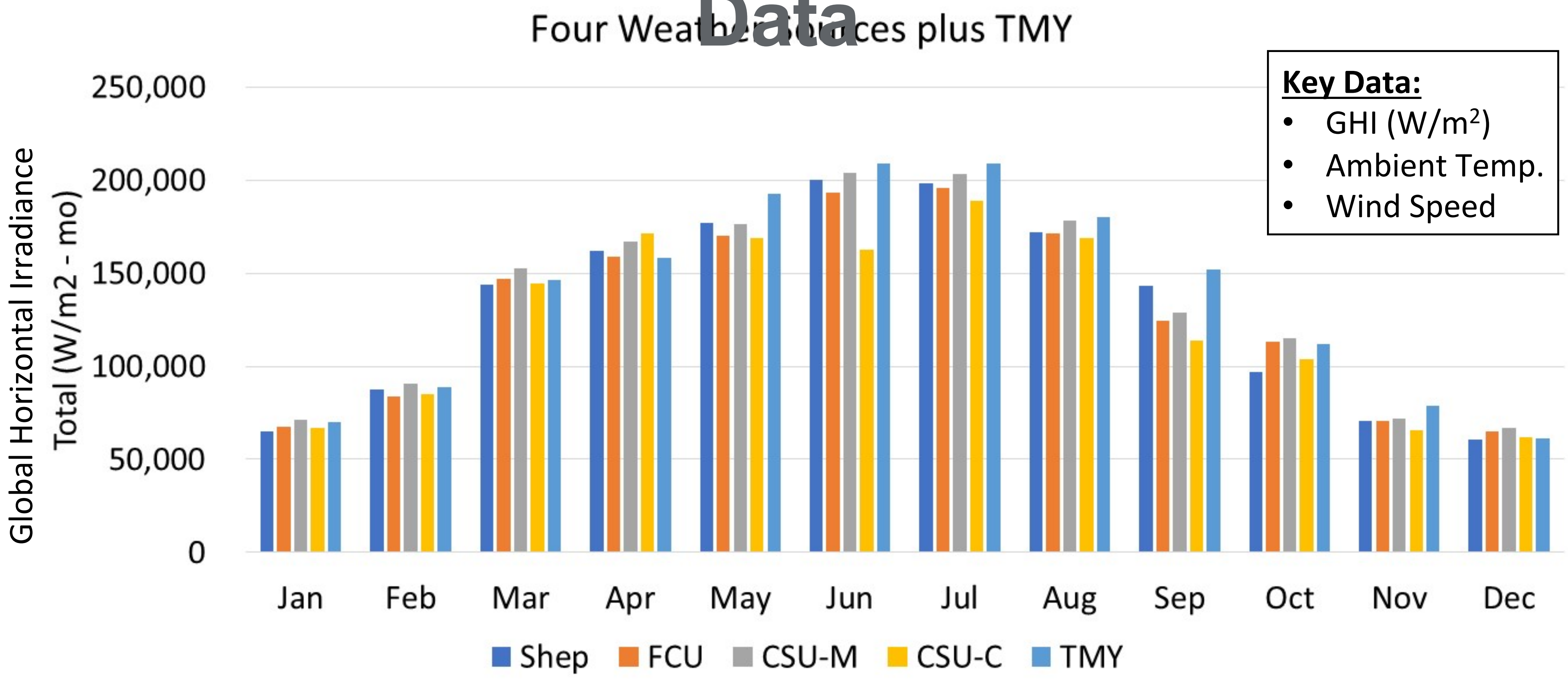
Some DAS units provide $\mathbf{T_{cell}}$ (most do not)

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

<u>Consider:</u>

- Module materials
- Mounting design / air flow
- Wind speed
- Ambient temperature
- Irradiance (POA)

Modeling Considerations – Weather Data



Key Data:

- GHI (W/m^2)
- Ambient Temp.
- Wind Speed

Ideal – Key data available at the generation site

Reality – Limited data at most generation sites

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Modeling Considerations – Losses

Soiling (%):	2
Shading (%):	0
Snow (%):	0
Mismatch (%):	2
Wiring (%):	2
Connections (%):	0.5
Light-Induced Degradation (%):	1.5
Nameplate Rating (%):	1
Age (%):	0
Availability (%):	0

- 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

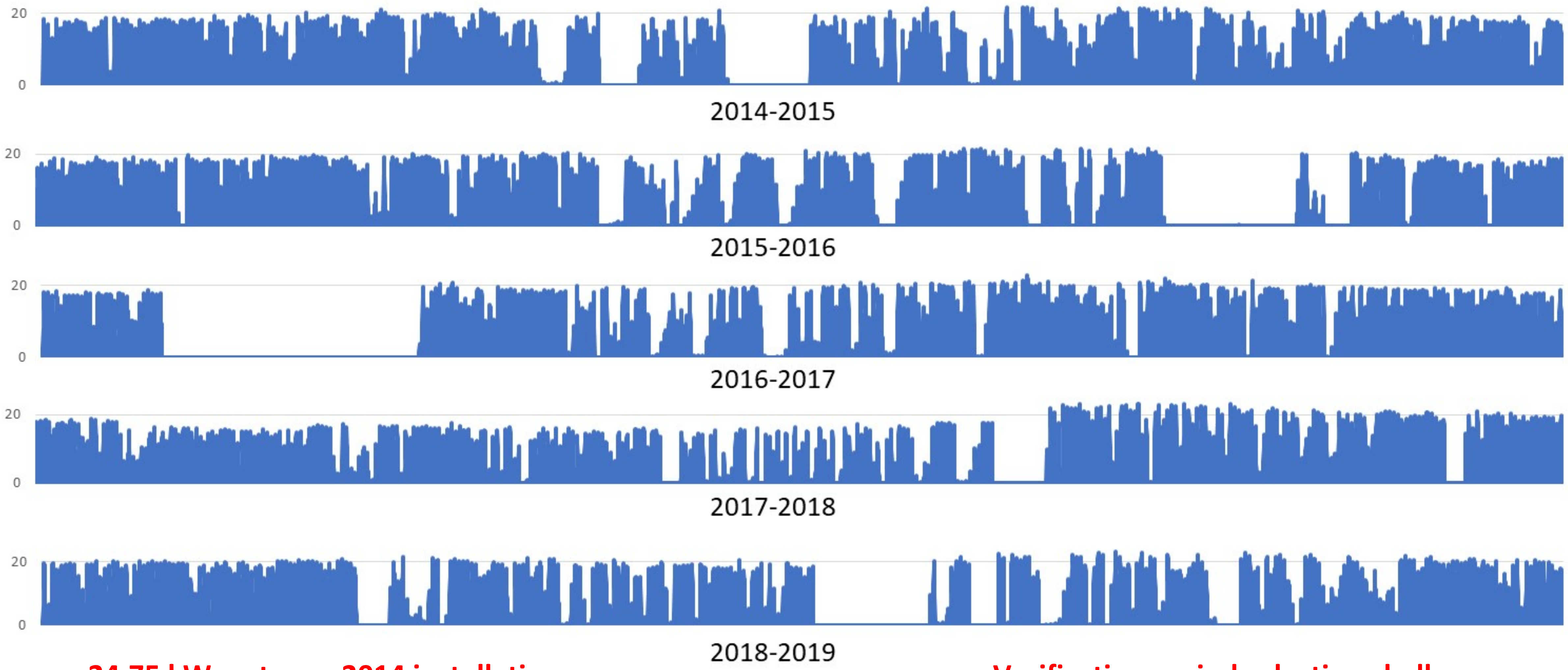
Losses $= 100\% \times [\,1.0 - (1 - 0.02) \times (1 - 0.02) \times (1 - 0.02) \times (1 - 0.005) \times (1 - 0.015) \times (1 - 0.01) \times (1 - 0.0)\,]$

$= \mathbf{8.68\%}$ (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"

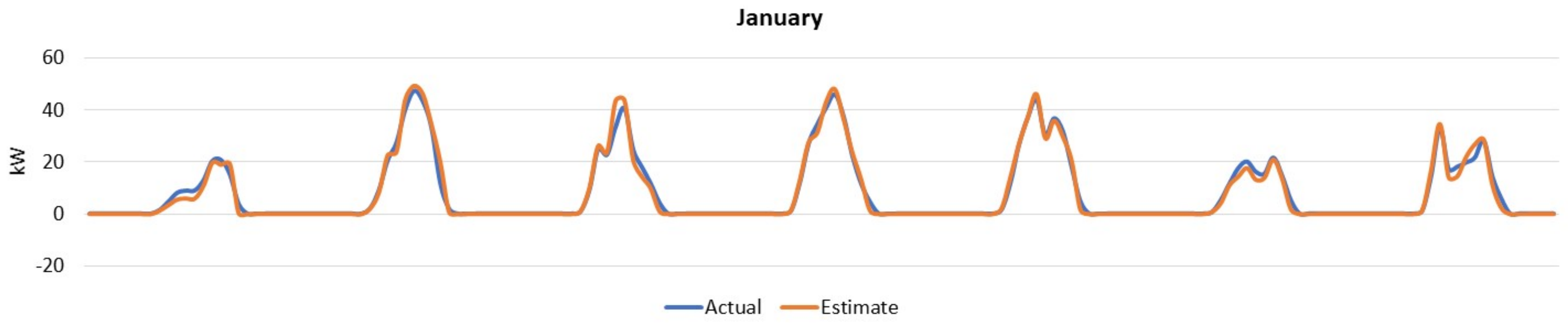
Modeling Considerations –

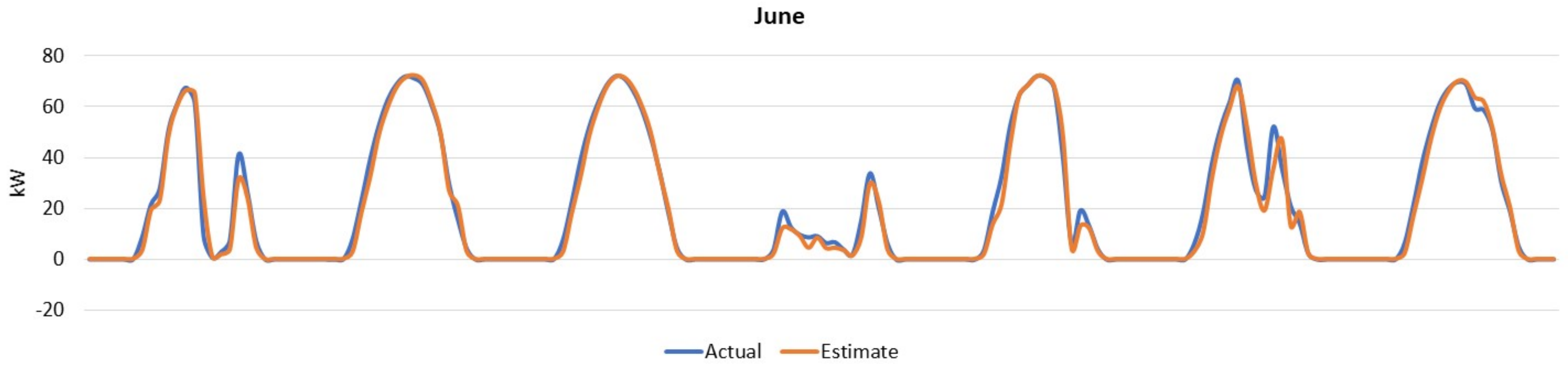


24.75 kW system – 2014 installation

Verification period selection challenges

Model Validation – Hourly





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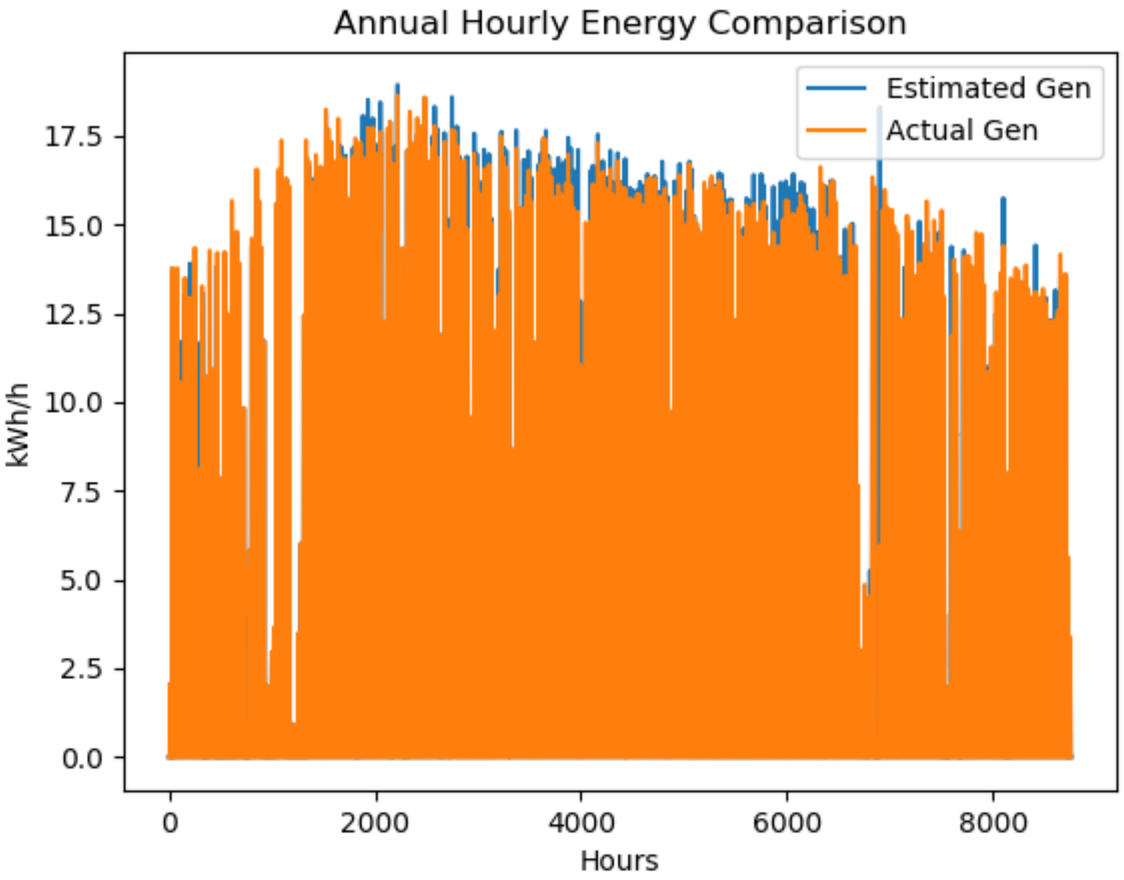
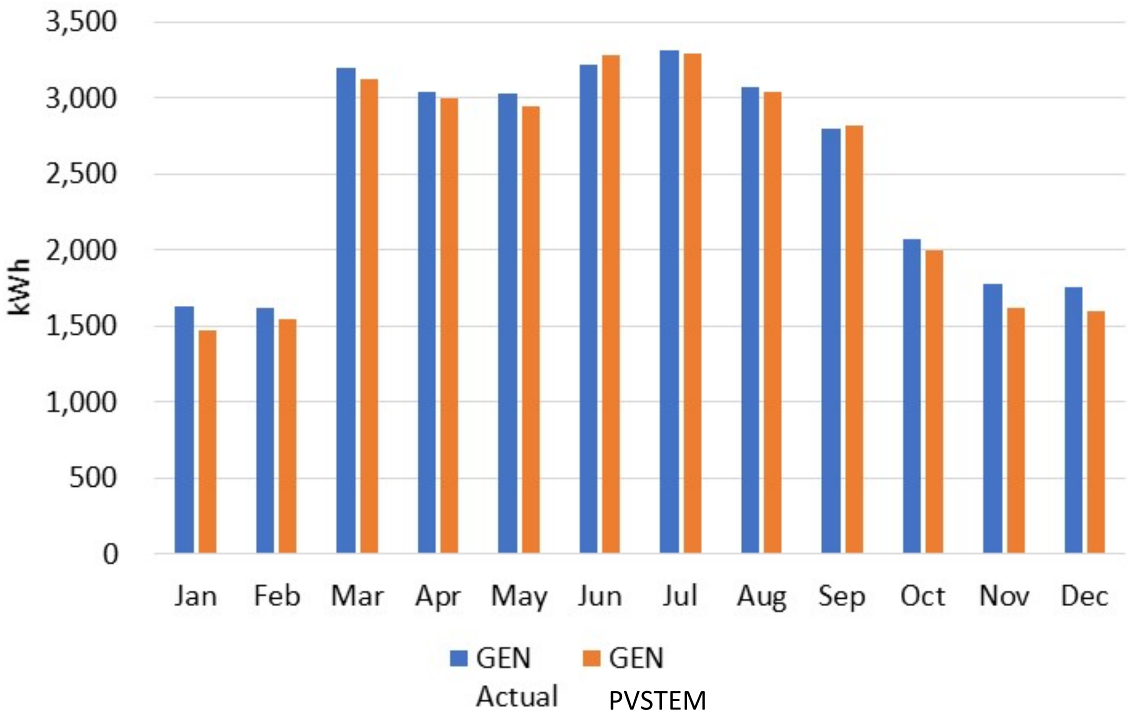
Model Validation Example



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: (underestimated)	2.6%
Snow Loss Estimate:	3.4%

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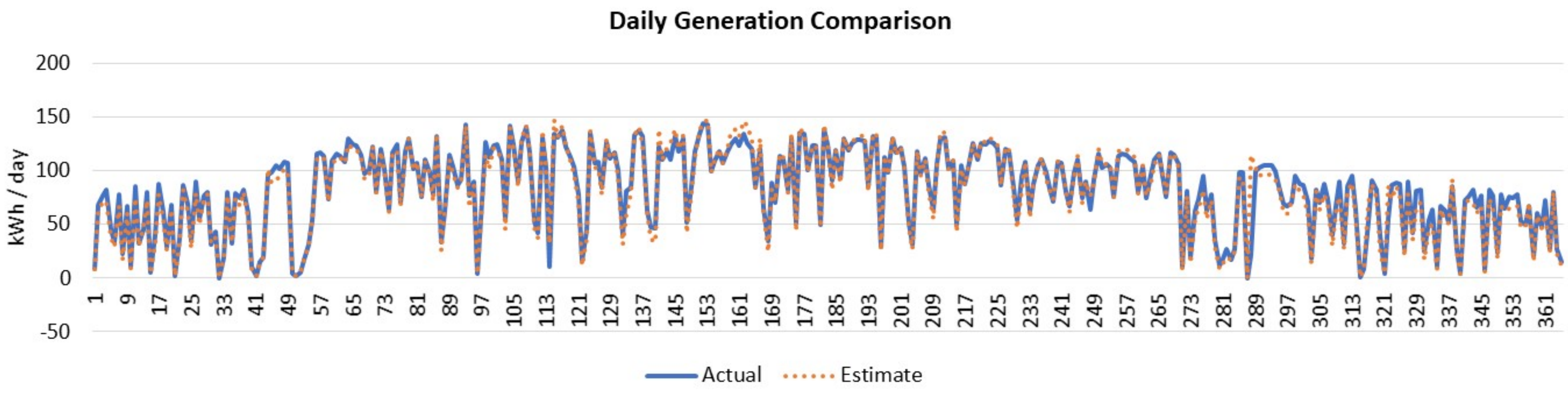
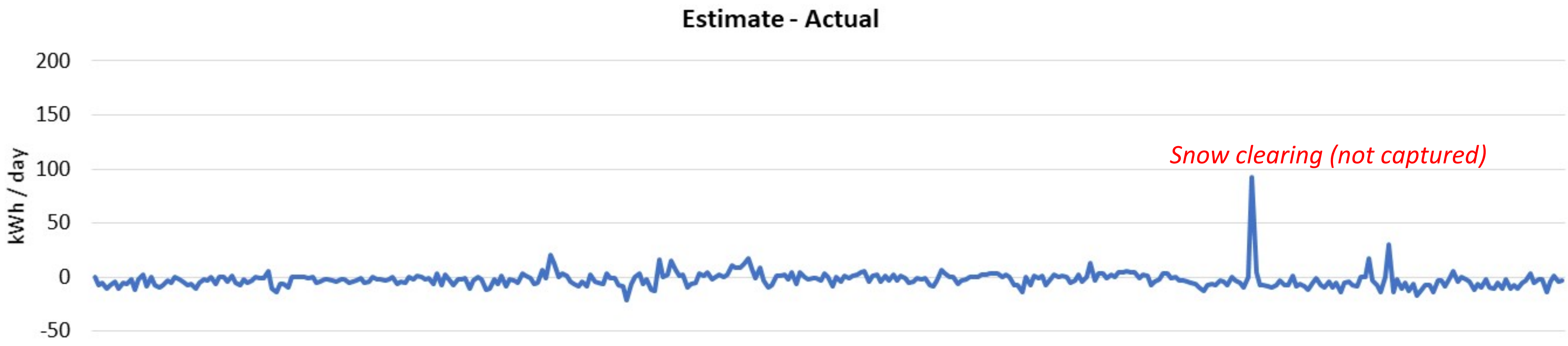
Model Validation Examples





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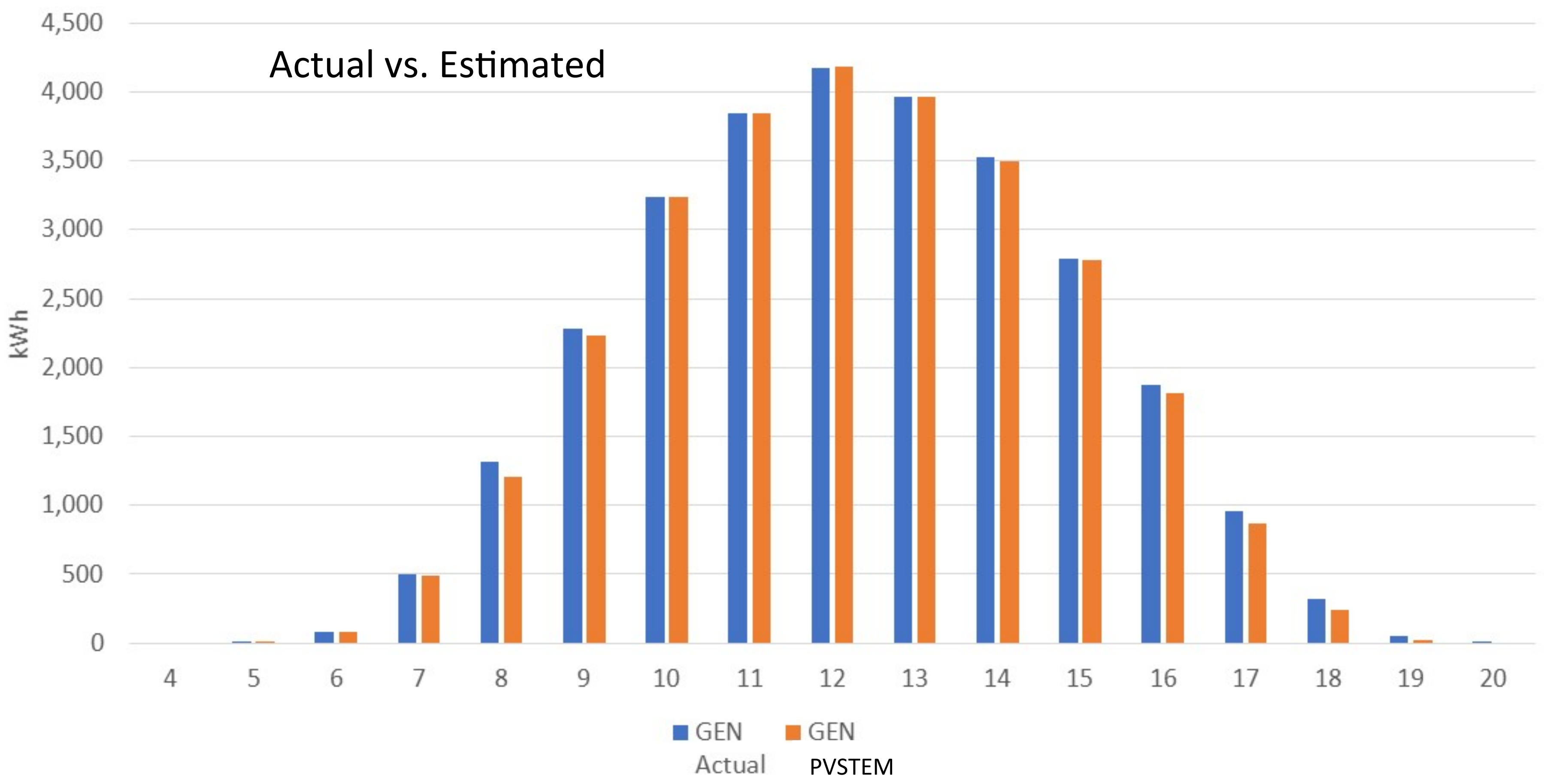
Model Validation – Hourly



Sum of annual generation values by hour

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Model Validation – PVSTEM vs. PVWatts

PVWatts	Colorado State University PV-STEM
Uses long-term average weather data (TMY)	Can use any available weather data
Limited to hourly granularity	Can model any time interval
Runs one system at a time	Can model many systems – with managed I/O
GHI, DNI and DHI are input directly	DNI and DHI determined from GHI & Erbs curve fit
Limited module inputs	Flexible module inputs
Includes tracking system model	Fixed modules only
Algorithms and assumptions outlined in PVWatts user's manual (2015):	Algorithms and assumptions outlined in CSU PVSTEM documentation:
○ Cell temperature from Fuentes algorithm	○ Cell temperature from Sandia algorithm
○ Mid-hour adjustment used	○ Mid-hour adjustment included for consistency
○ Glass reflection losses include	○ No glass reflectance adjustment
○ Inverter part load – CEC curve fit	○ Inverter part load – Simple curve
○ Other minor differences	○ Other minor difference

Model Validation – PVSTEM vs. PVWatts

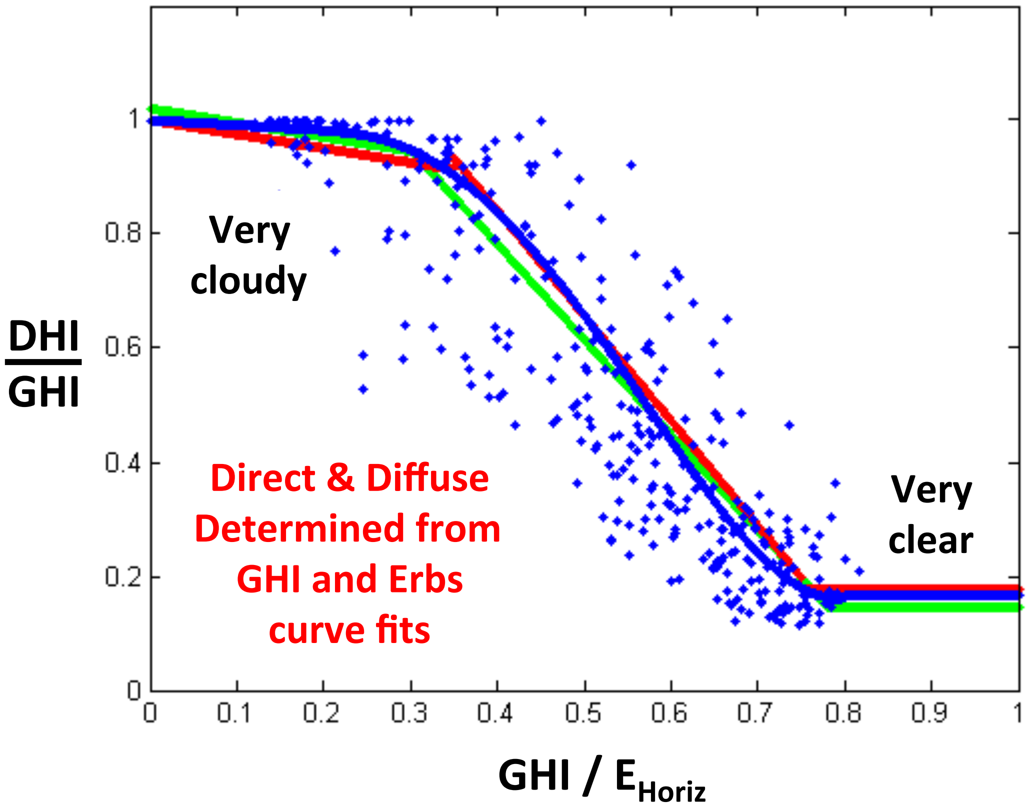
PVWatts™

Colorado State University

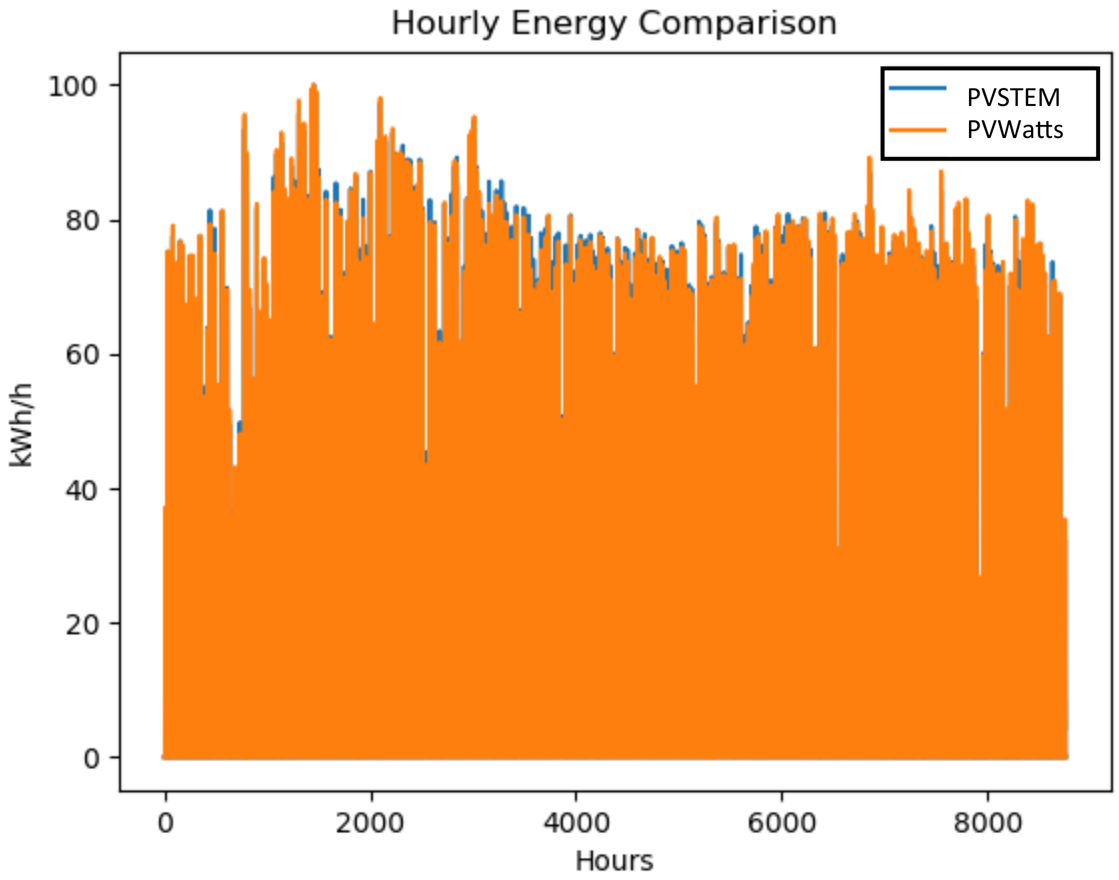
PV-STEM

Month	Day	Hour	Minute	Diffuse	Direct	Global
1	1	0	0	0	0	0
1	1	1	0	0	0	0
1	1	2	0	0	0	0
1	1	3	0	0	0	0
1	1	4	0	0	0	0
1	1	5	0	0	0	0
1	1	6	0	0	0	0
1	1	7	0	0	0	0
1	1	8	0	6	0	6
1	1	9	0	116	37	127
1	1	10	0	127	0	127
1	1	11	0	103	0	103
1	1	12	0	104	0	104
1	1	13	0	174	240	269
1	1	14	0	11	0	11
1	1	15	0	46	624	160
1	1	16	0	18	0	18
1	1	17	0	0	0	0
1	1	18	0	0	0	0
1	1	19	0			
1	1	20	0			
1	1	21	0			
1	1	22	0			
1	1	23	0			

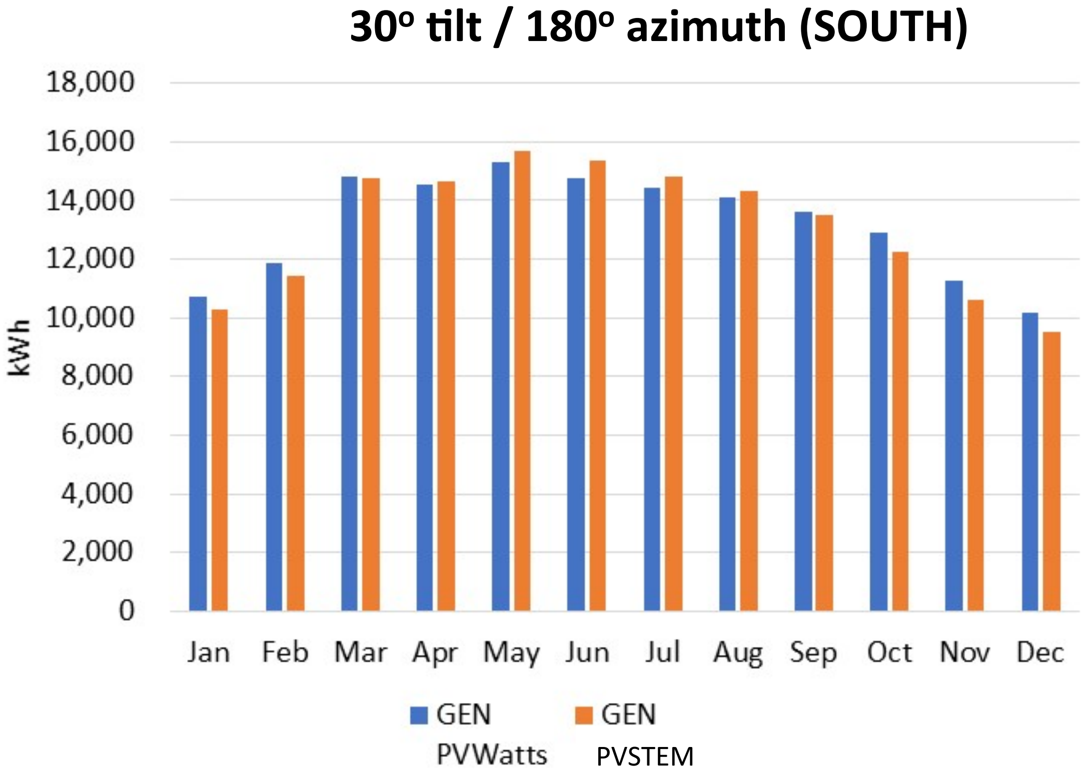
Direct & Diffuse fed directly into model (long-term TMY values)



Model Validation – vs. PVWatts



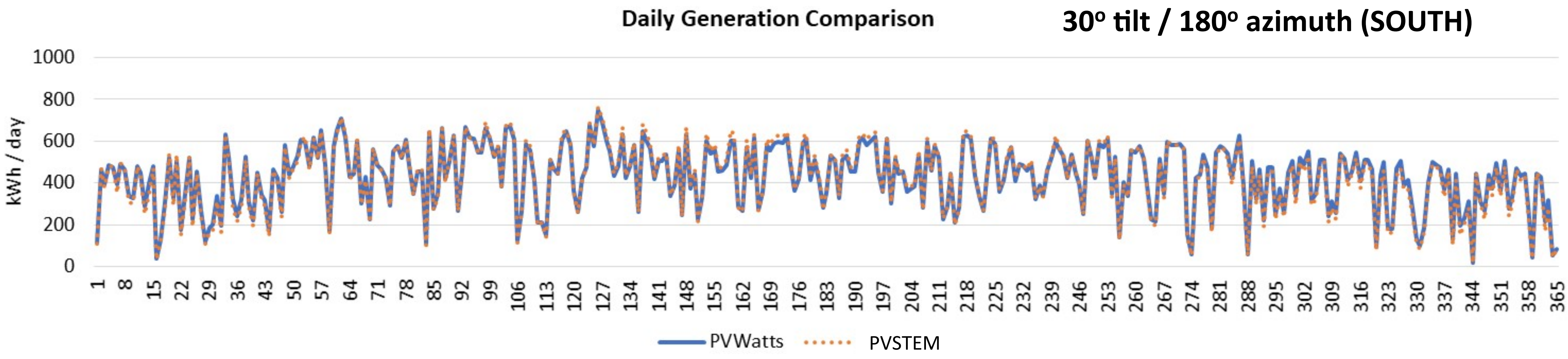
100 kW DC system – 30º tilt / 180º azimuth (SOUTH)
TMY 2016 Data

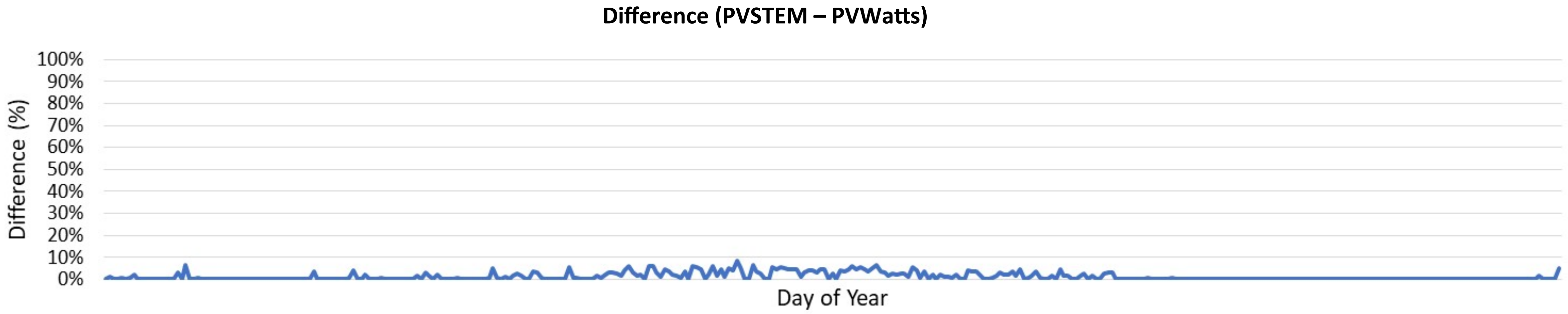


Annual Results:

PVSTEM Annual Energy:	157,131 kWh
PVWatts Annual Energy:	158,378 kWh
Difference:	0.8% (underestimated)

Model Validation – vs. PVWatts





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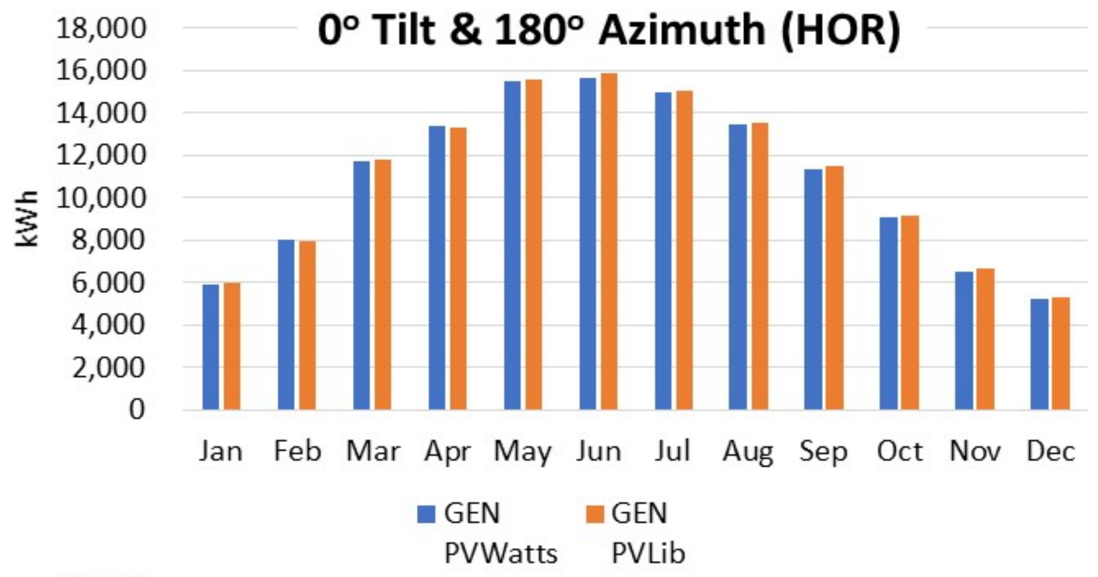
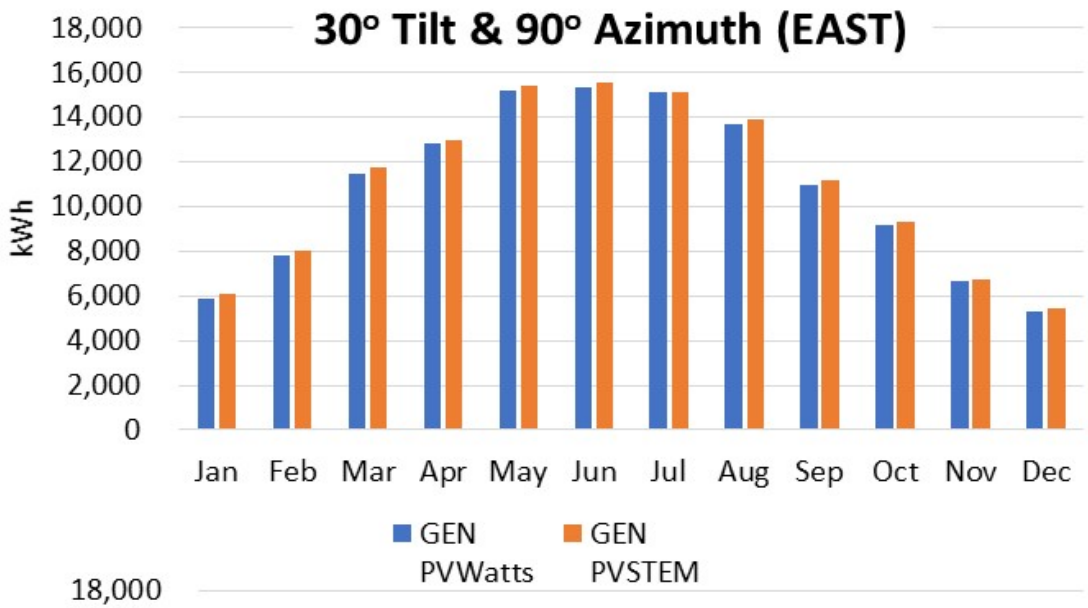
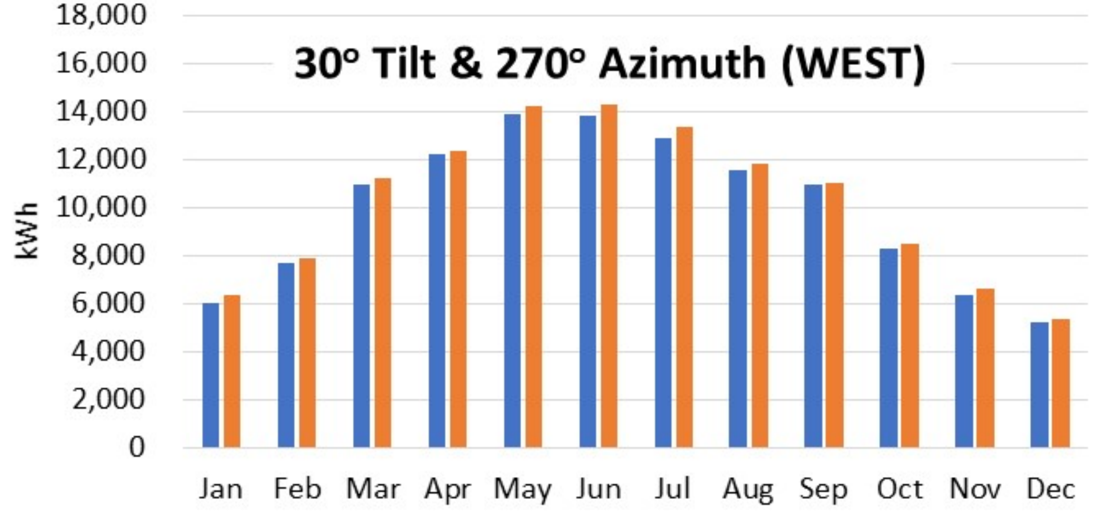
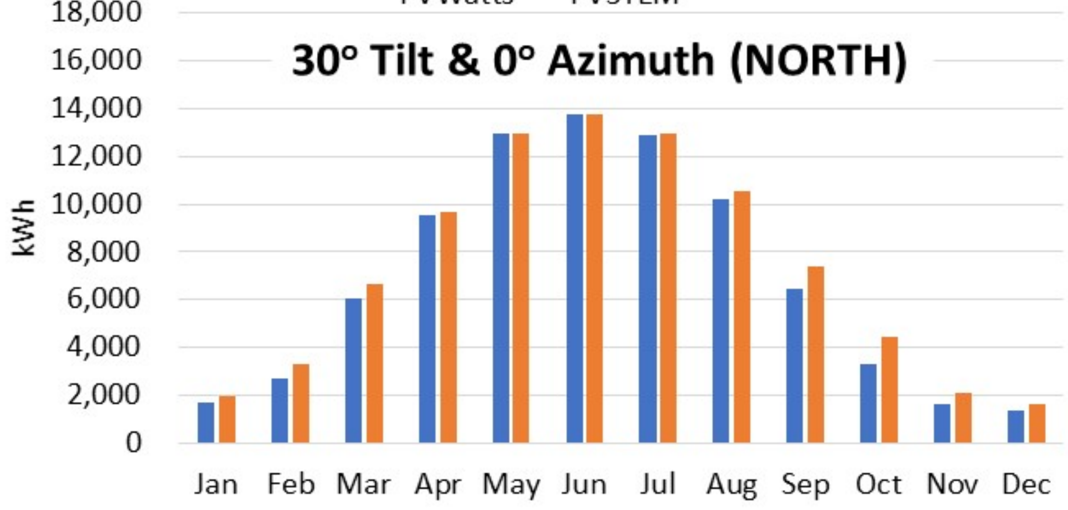
Model Validation – vs. PVWatts









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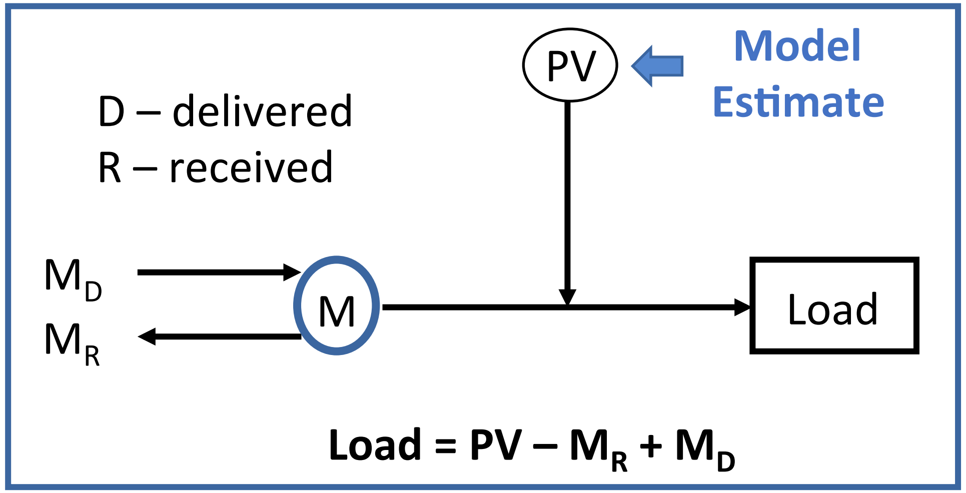
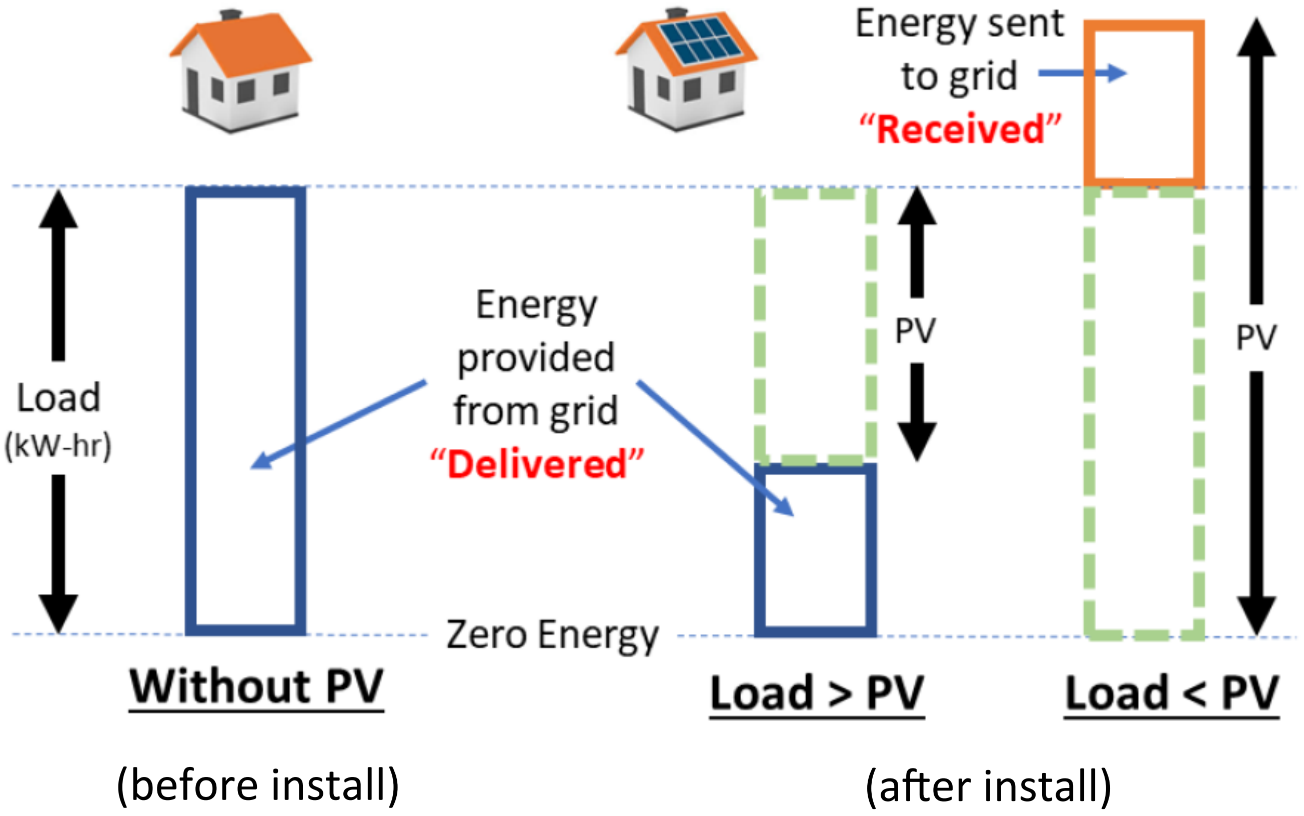
Model Applications – Utility Studies

Load profile development – AMI net metering



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



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Model Applications – Utility Studies

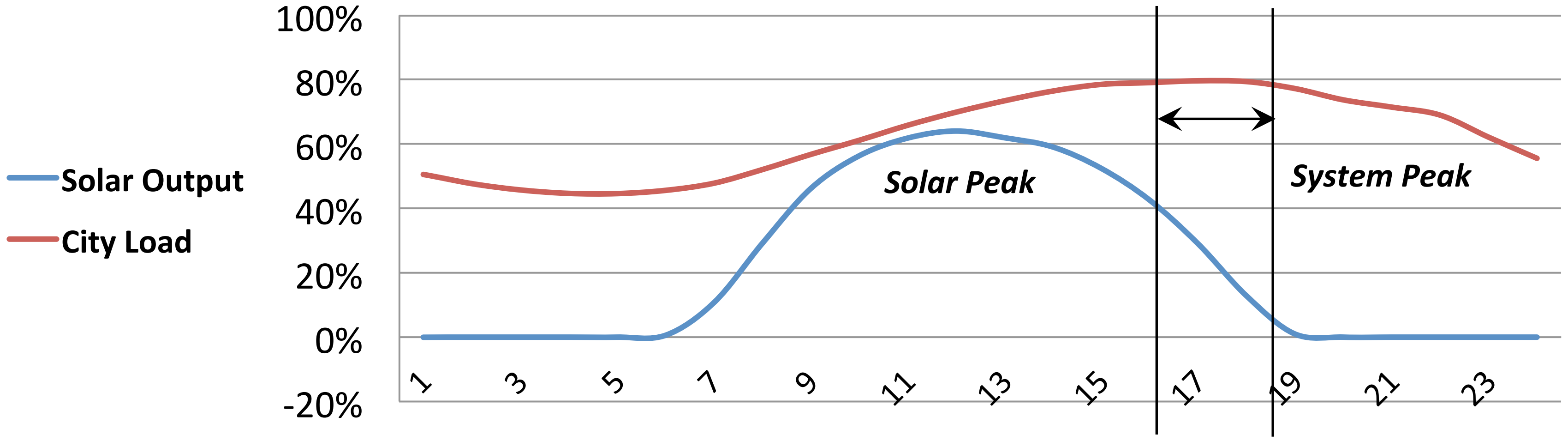
Solar Size Limit Evaluation

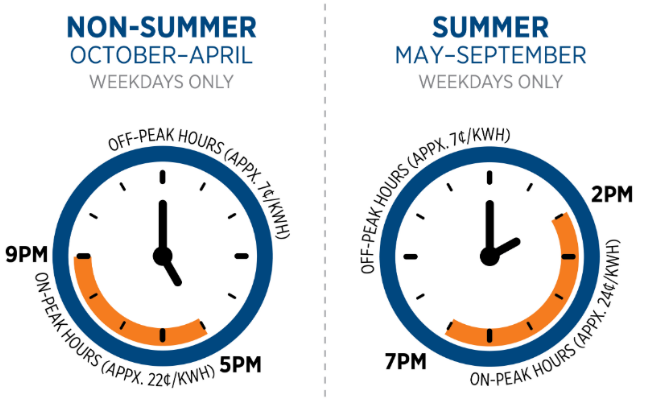
“120% Rule” → Annual PV generation <= 120% of annual load

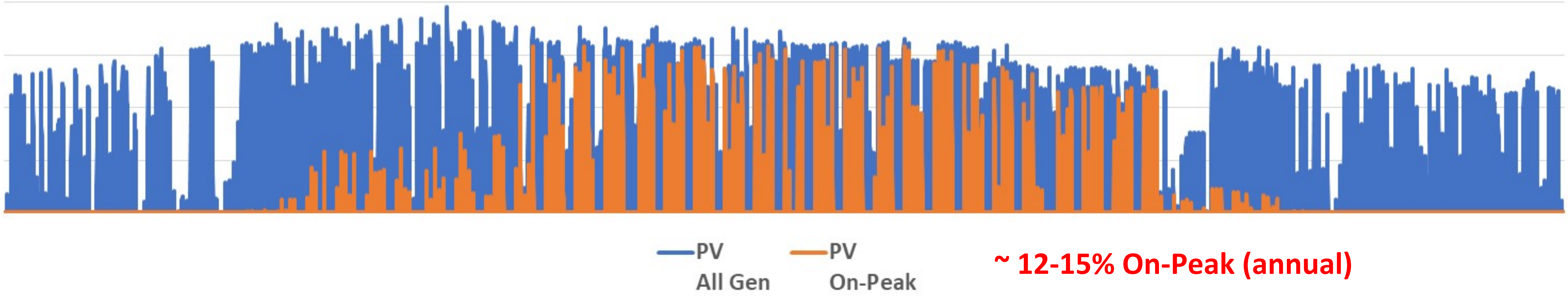
- How does actual generation compare with initial design?
- How many systems use more than 100% (net)?
- Implications for changes to rule?

Model Applications – Utility Studies

Time-of-Use Analysis







~ 12-15% On-Peak (annual)

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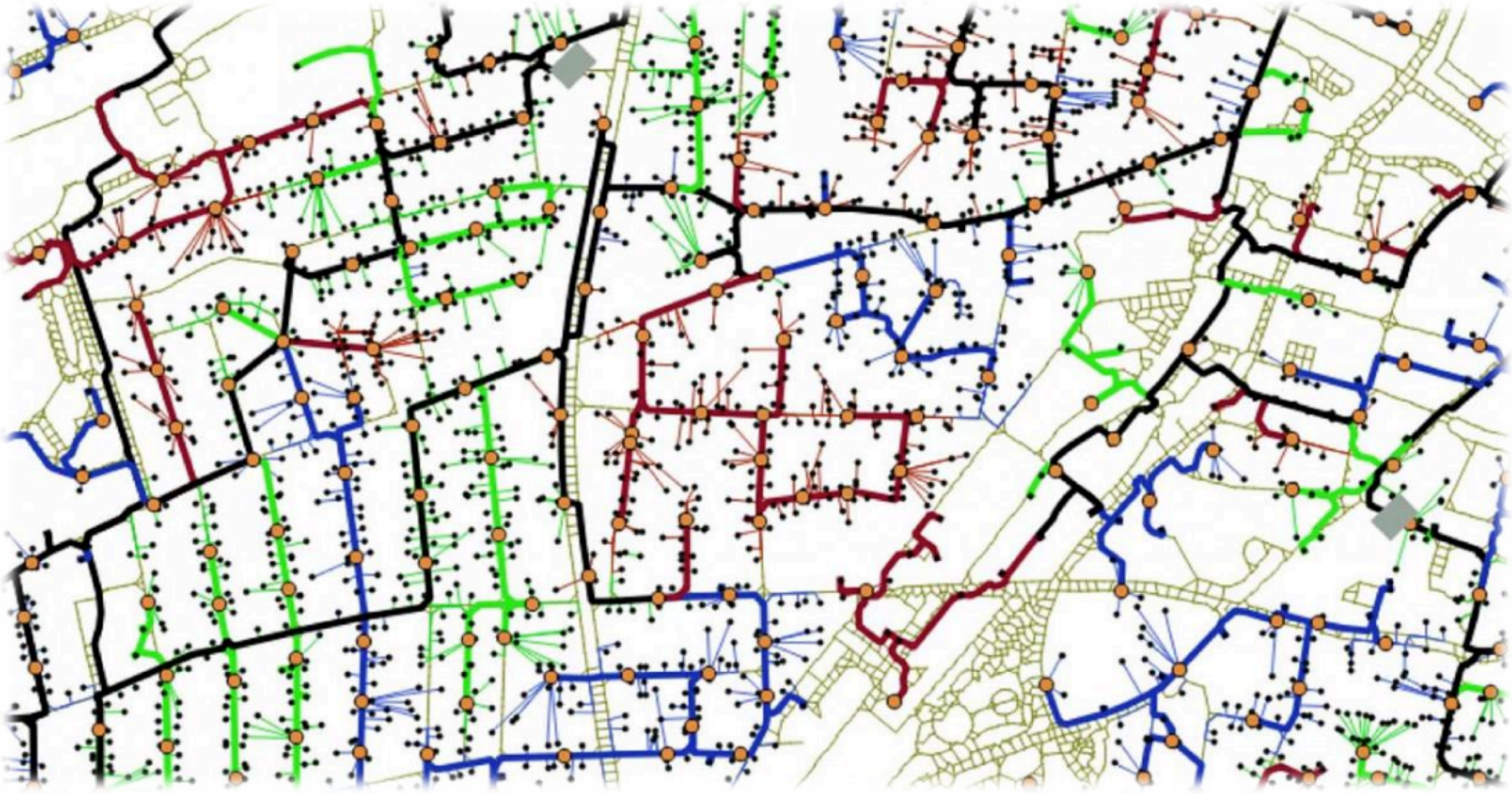
Model Applications – Feeder Limits



COLORADO C3E

Model Applications

She's IN POWER

10 PROJECTS 6 MONTHS 1 GOAL TO REDUCE GREENHOUSE GASES

She's IN POWER

coloradoC3E.org/Shes-in-Power

Solar Project

Energy Efficiency Project

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

Community Solar Resource Monitoring

City of Fort Collins Utilities

POUDRE SCHOOL DISTRICT

ENERGY INSTITUTE Colorado State University

Google earth

On line surveys

City Database

- Locations (address)
- Max DC kW rating

+

Solar System Metrics

- Orientation
- Shading
- Efficiency

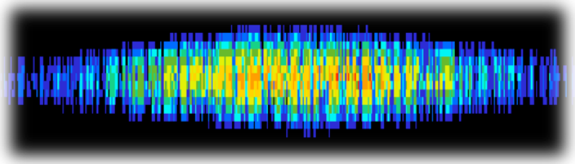
+

Solar Monitoring

- Global horizontal solar resource (Watts/m^2)

Site surveys

School solar MET

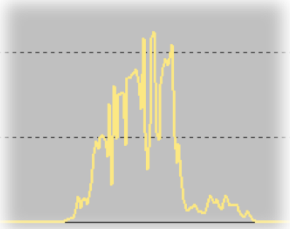


GHI / DHI / DNI Analysis

Mathematical Modeling

python™

Solar model programming



Community Solar Resource Monitoring

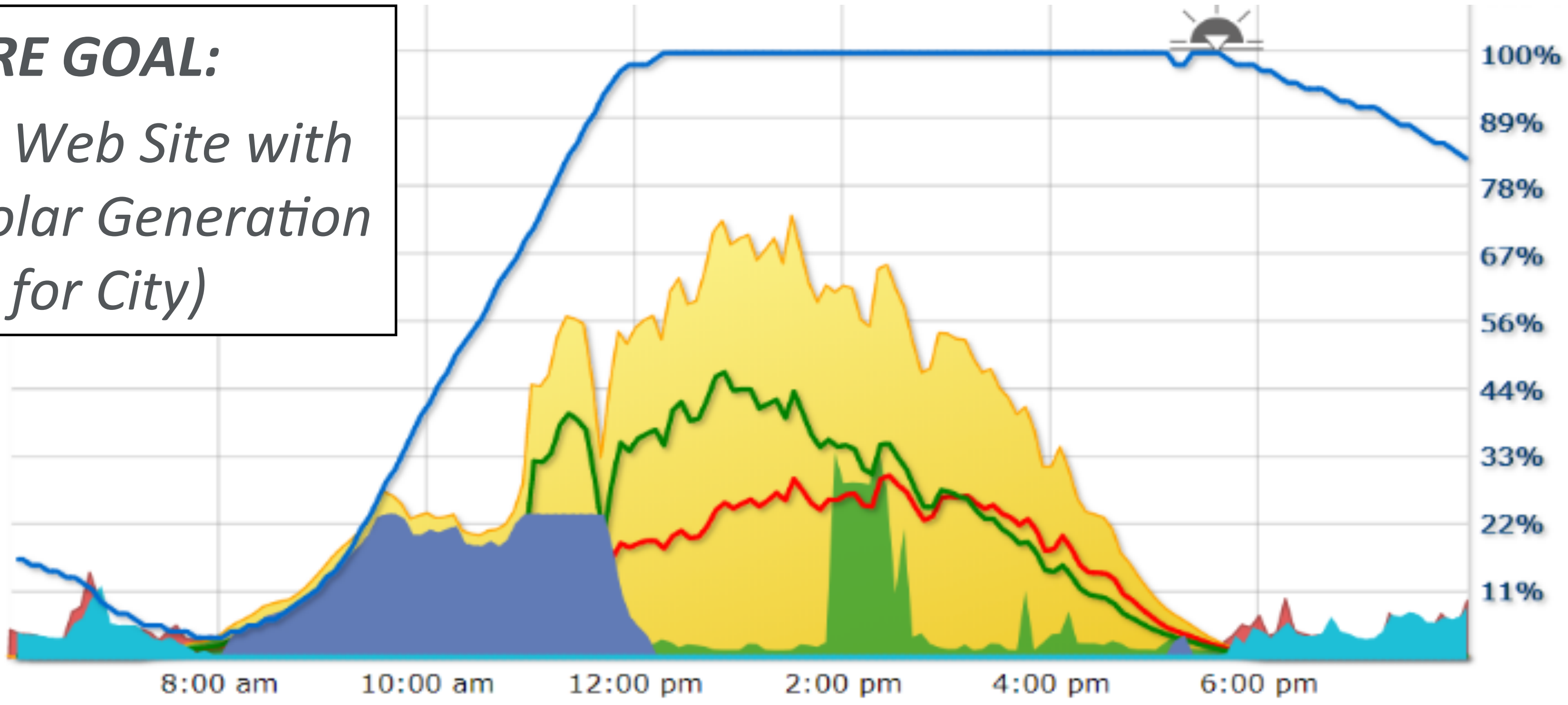
City of Fort Collins Utilities

POUDRE SCHOOL DISTRICT

ENERGY INSTITUTE Colorado State University

FUTURE GOAL:

Community Web Site with Real-Time Solar Generation (total for City)



Model Applications – CSU Education

– THESIS –

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

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.

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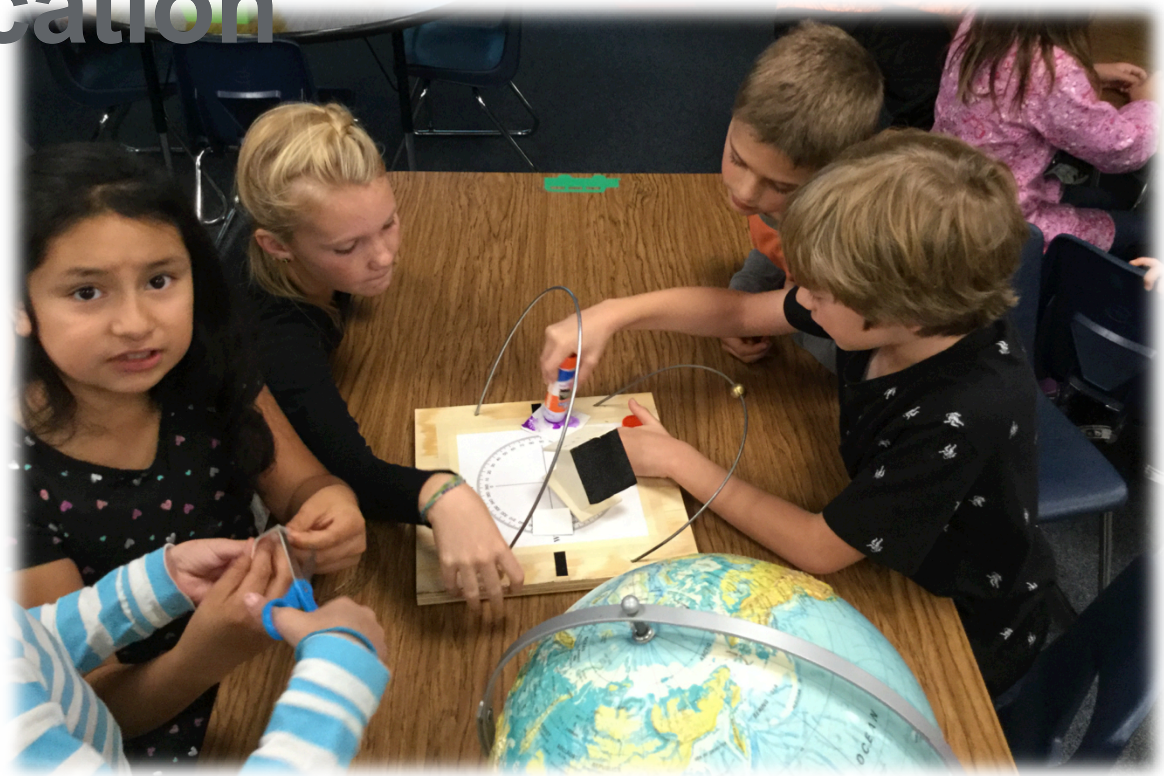
Model Applications – STEM Education



STEM CLUB COMPETITION

Design a system → Run it through the PVSTEM model

Best system wins!

QUESTION
S?
DISCUSSIO
N?

Contacts

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