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PV Modeling as a Community Resource

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Abstract

Northern Colorado communities have adopted policies that encourage utilities to implement 100% carbon free electricity by 2030. For example, Fort Collins is adding a new PV solar system nearly every day (350 in 2018) to support their climate and energy policy goals. Accurate PV modeling is well established, but often too complex to be readily employed in education or for use by municipal utility staff or energy researchers – the type of stakeholders needed to build community support for solar energy. Colorado State University has developed PV-STEM, a PV modeling tool that is both simple enough to teach solar engineering principals to STEM students and accurate enough to support local utility planning studies and university research. PV-STEM incorporates solar engineering principles developed by NREL, Sandia National Labs and NOAA into an open-source Python code accessible to novice software programmers that only requires commonly available PV system and local weather information. The model has been validated against ten operating PV systems and against PVWatts®. In addition to STEM education, the model has been used to enhance understanding of PV generation on the community's electric distribution system (generation profiles, PV customer load research, policy analysis, resource forecasting, etc.). User guidelines, teaching slides and open source Python code will be available for interested parties.

Keywords: *PV modeling, STEM education, community resource planning*

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1. Introduction

Colorado State University (CSU) is a major employer and a highly engaged member of the Fort Collins, Colorado community (City). Both CSU and the City have climate action plans with goals of carbon neutrality by 2050, including 100% renewable electricity use by 2030. These goals are being met in collaboration with the local electricity supplier (Platte River Power Authority), combining wholesale and distributed renewable resource additions. As of August 2019, about 1,600 residential photovoltaic (PV) solar systems have been installed on the City's distribution grid, encouraged by rebates, feed-in tariffs and net metering incentives (see Figure 1). A few large commercial systems were installed during 2015 (in response to the feed-in tariff program), but the vast majority of systems are installed on residential sites within the community. Though the City collects advanced metering infrastructure (AMI) data for all residential customers, very little PV system generation data is available for residential systems. AMI meters only provide net metered data regarding power flow (amounts delivered from the utility and amounts received by the utility from solar customers). By combining estimated generation from PV-STEM modeling with AMI data, estimated load profiles can be developed for residential solar customers (i.e. for the "solar" rate class in the City). Other projects that require estimated PV production, such as studies of high PV penetration in distribution systems, can also benefit from application of PV-STEM.

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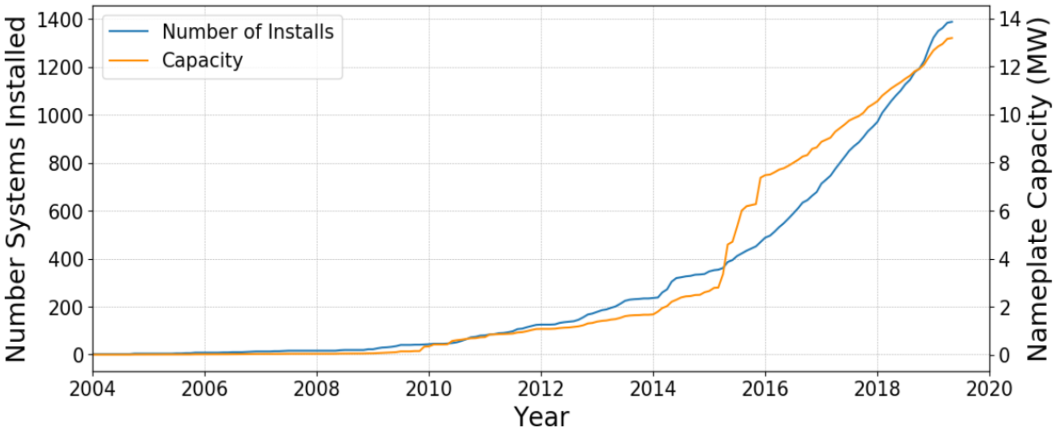

Figure 1: Growth of distributed PV solar systems in the City

A significant number of PV modeling programs exist, including PVWatts®, developed by the National Renewable Energy Laboratory (NREL). However, existing models have characteristics that make them unattractive for community-based PV modeling. These models typically: a) are proprietary, requiring a commercial license (with associated cost); b) use typical meteorological year (TMY) weather data, a long-term average rather than actual historical values; c) are limited to hourly time intervals (or longer); d) run one system at a time; and/or e) require detailed input data that is not available to community or educational users. These models are also somewhat limited in terms of use as an educational tool, since the source code is proprietary or complex, and difficult to change for either educational or project needs.

2. Modeling Methodology

The PV-STEM model is targeted at ‘community’ niche applications. It is neither too technical (hard to implement) nor too simple (able to maintain good accuracy), contains no proprietary software, is accessible to novice programmers, is flexible (allowing coding changes for unique projects), and requires modest data inputs that are likely to be available to community users. The tool is designed for STEM (science, technology, engineering, mathematics) teaching, as well as research and electric utility planning.

PV-STEM utilizes PV modeling algorithms available from the NREL, Sandia National Laboratories (SNL) and the National Oceanic and Atmospheric Administration (NOAA). Weather data from many sources can be used. For examples provided here, we use data from the National Climate Data Center and CSU”s main campus weather station. Other weather stations and monitoring data from other locations within the community may also be used for modeling. An overview of the modeling approach is provided in Figure 2.

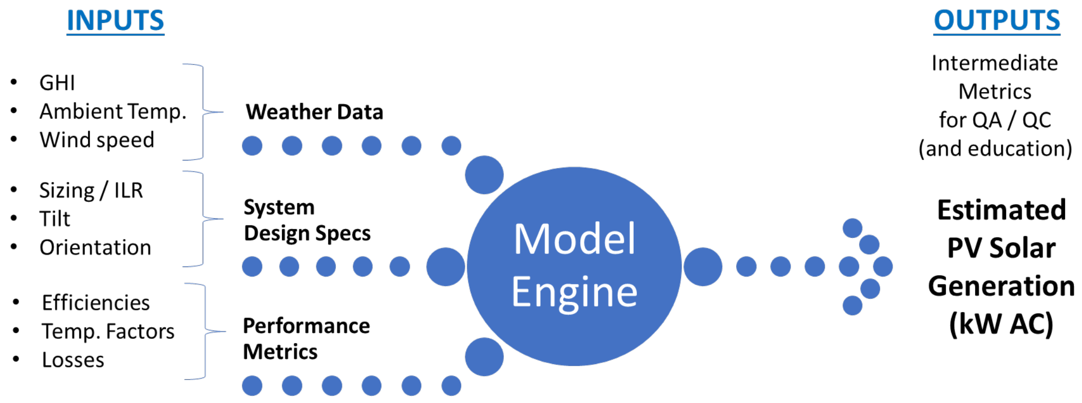

Figure 2: Overview of PV-STEM model

Key steps involved with the PV-STEM modeling process include:

- Establish time conventions and alignments
- Determine extraterrestrial irradiance – direct normal and horizontal – to support Erbs method
- Split measured irradiance (global horizontal) into beam and diffuse components
  - Erbs piecewise curve fitting used (see documentation)
- Adjust beam to plane of array magnitude:
  - Tilt, azimuth & ground reflectance
- Calculate total plane of array irradiance (beam plus diffuse plus ground reflected) – W/m^2
- Use system-specific metrics to calculate generation (kW):
  - DC & AC ratings and other design metrics
  - Efficiencies → modules, inverter, system
  - Temperature degradation metrics / algorithms
  - Losses → wiring, outages, snow, shading, soiling, etc.

Full details of the modeling approach are described in PV-STEM documentation, slides / training materials and source code. These materials will be available from the CSU Energy Institute (Powerhouse Campus), anticipating distribution by September 2019. See https://energy.colostate.edu/about/the-powerhouse/ for information.

3. Model Validation

PV-STEM has been verified through two approaches: (1) comparison with actual hourly generation from existing systems, and (2) comparison with PVWatts®. Though very few residential systems in the City have metered generation data available, this data has been gathered from commercial systems operating in the community. Ten existing systems were used to compare actual historical generation (provided by the solar unit's data acquisition system or DAS) with estimated generation from the PV-STEM model. For comparison with PVWatts®, several sets of tilt and orientation combinations were run with both models for a "generic" 100 kW PV solar system.

As an interim validation step for model verification, sun position values determined from PV-STEM were compared with values provided from two well established tools: (1) NOAA's Solar Calculator, and (2) NREL's Solar Position Algorithm. Results compare very favorably, with PV-STEM and existing models differing by only small fractions of a degree for each of the critical angles tested (zenith/altitude, azimuth and angle of incidence). Links to on-line versions of these tools are included below:

https://www.esrl.noaa.gov/gmd/grad/solcalc/ (NOAA) and https://midcdmz.nrel.gov/solpos/spa.html (NREL)

Existing PV systems used for verification (those having historical generation data available) range in size from 20 kW to 632 kW. System azimuth values range from 140° to 185° with system tilt values of 1.5° to 30°. All systems are located within a radius of approximately two miles from the weather site collecting historical global horizontal irradiance (GHI), ambient temperature and wind speed data (CSU's Main Campus Weather Station). Values for actual historical generation are provided by the data acquisition system (DAS) equipment associated with each PV solar system. System specifications (size, age, equipment performance metrics, etc.) were gathered from system owners and/or operators. Losses associated with system age were estimated assuming 0.6% loss per year (0.05% per month), from the initial commercial operating date to the mid-point of the analysis period, based on typical specifications from manufacturers of the systems modeled. Modeling data was available for all test systems in the time range of 2016 to 2018, with 12 months of consecutive hourly data used to validate each system. Acquired data sets were cleaned to remove missing or faulty generation data. As a result, not every system was run for the same 12-month period.

Annual comparisons between PV-STEM and actual generation are shown in Figure 3, and monthly comparisons in Figure 4 for all ten systems (sizes of the systems considered are also shown in Figure 3). Values for "Difference" in these figures are calculated as the PV-STEM estimated value less the actual value, divided by the actual value. Note that the largest deviations between actual and modeled generation occur during months when snow accumulates on the panels and generation is lowest (i.e. winter months). PV-STEM includes approaches to estimate snow losses (see documentation). Also, during winter months, weather is cloudier, and errors associated with the Erbs curve fit application for estimating direct vs. diffuse irradiance has more influence on results (see documentation for Erbs method). The model is most accurate during summer periods, when generation levels are highest. Overall, annual differences are small for the systems modeled (less than 5% on an annual energy basis).

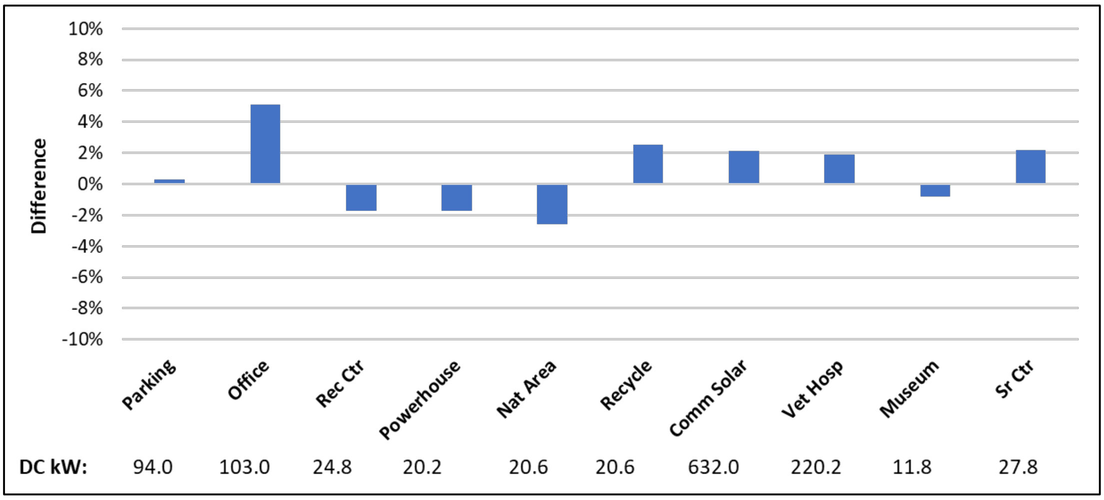

Figure 3: Annual generation differences

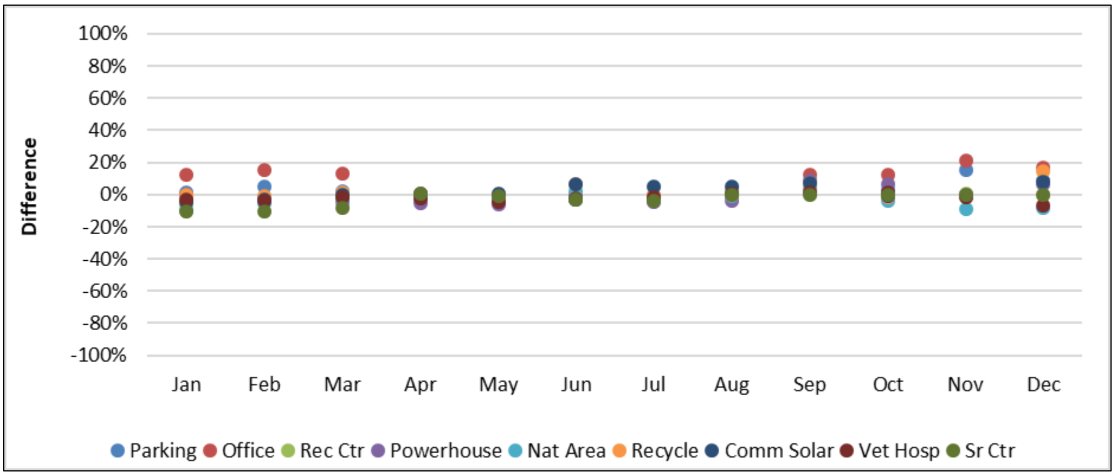

Figure 4: Monthly generation differences

Daily differences between the model and actual generation were also considered for verification. An example of this comparison is provided in Figure 5 (20.6 kW Nat Area site).

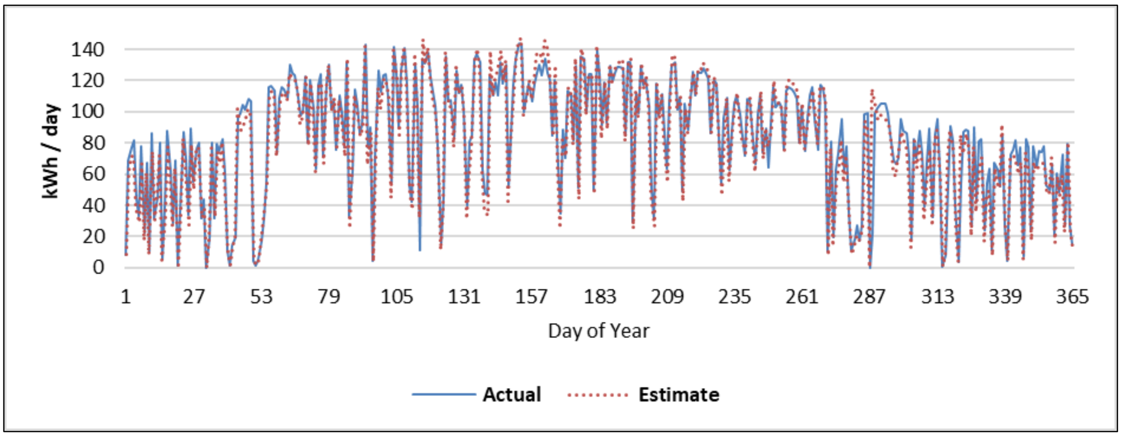

Figure 5: Example of daily generation comparison

Note that in this case, not all of the snow losses are captured by the model (snow clearing took longer than the model estimated). This is true for most of the comparisons. PV-STEM can be applied using two approaches for snow: (1) when comparing actual generation values with model estimates, and (2) when the model is used to directly estimated generation (no actual values available). For the first case, it is assumed that snow clears from the GHI sensor immediately and the model value is taken as the "no snow" value. Clearing of snow from the system is based on snow event data (snowfall and accumulation). Often, this approach shows that snow is not cleared from the systems even when snowfall data indicates no snow accumulation for the weather data site.

In the second case (when no actual generation data available), estimates of snow losses are addressed through additional model algorithms – based on tilt and other factors (see model documentation). Estimating snow is a challenge, particularly for shorter term time periods, and model errors associated with snow clearing can be significant for hourly / daily time increments.

Annual, monthly and daily values are summed from hourly values (actual and PV-STEM estimates). An example of the hourly comparison for the Natural Areas site (20.6 kW) is shown in Figure 6 (example week in May 2018).

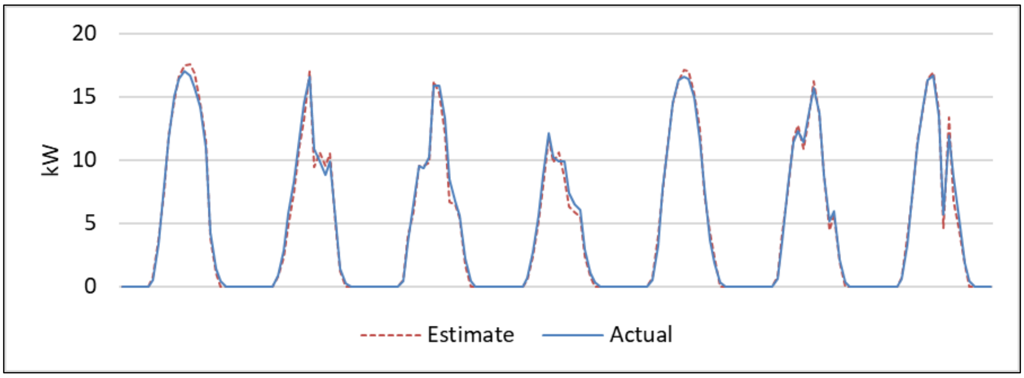

Figure 6: Example of hourly generation comparison

Hourly values (actual and modeled) were summed and compared for each system to further test validation of the PV-STEM model. Figure 7 shows an example of this summation.

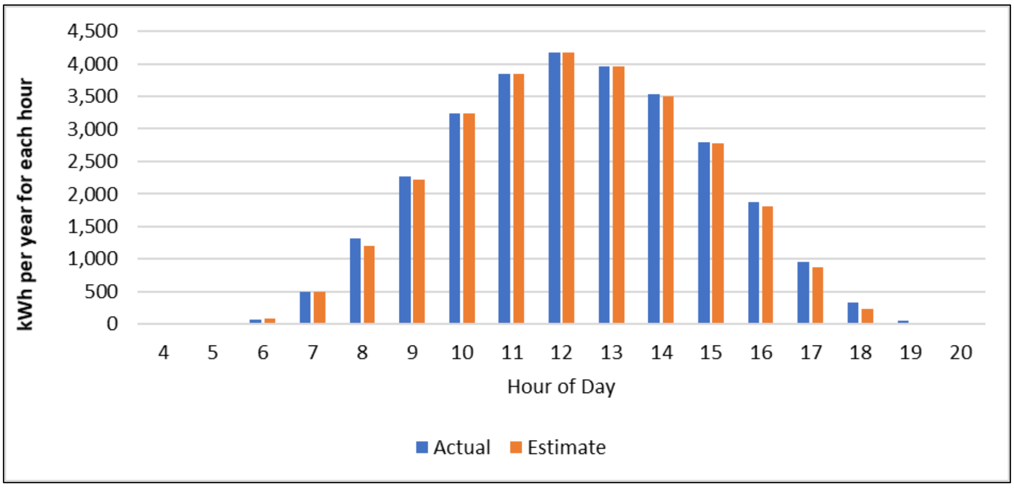

Figure 7: Example of hour-by-hour annual sum

Annual plots were also developed to track actual generation (measured by the specific PV system DAS) vs. estimated generation (from the PV-STEM model) for each hour of the entire year at each site modeled. An example is shown in Figure 8.

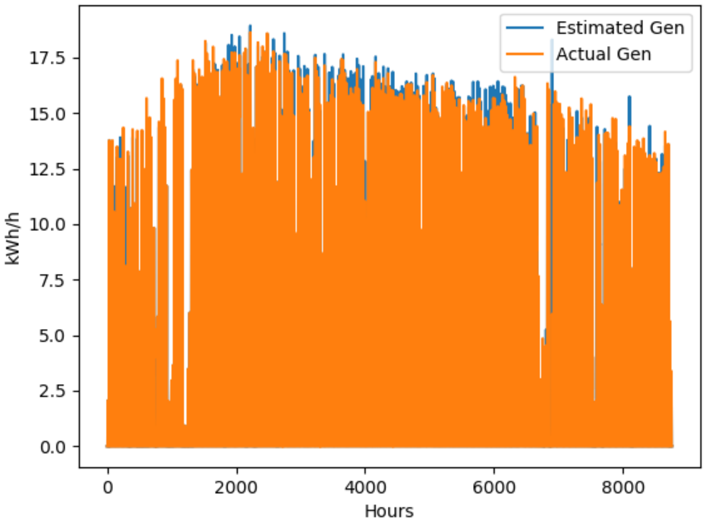

Figure 8: Example of full year hourly comparison for actual generation vs. PVSTEM estimated generation

As mentioned earlier, results from the PV-STEM model and PVWatts® runs were also compared. Fort Collins requires a PVWatts® run for estimating energy production from solar systems that are interconnected with the City's distribution system, so comparing these models was of interest to the PV-STEM team (and to the City). TMY weather data associated with the current version of PVWatts® were used as inputs to PV-STEM (global horizontal irradiance, ambient temperature and wind speed). The models were compared for a generic 100 kW system, having typical system parameters (defaults in the PVWatts® tool). Losses were handled identically in the two models, with losses for snow, aging and availability set to zero in both models. PVWatts® uses global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) values directly from the TMY data set to calculate total plane of array irradiance. PV-STEM estimates the split of GHI into DNI and DHI based on the Erbs piecewise curve fit approach (see details and references in model documentation).

Several sets of tilt / orientation values were analyzed using both models for the generic 100 kW system, with results provided below (annual comparison in Figure 9 and monthly in Figure 10). Results compare favorably and differences between PV-STEM and PVWatts® for these modeling sets were lower than those for the comparisons between actual generation and generation estimated by PV-STEM. These differences are attributed to handling of the following: GHI, DNI and DHI (as mentioned above), temperature-related losses, part-load inverter losses, and other differences between the models.

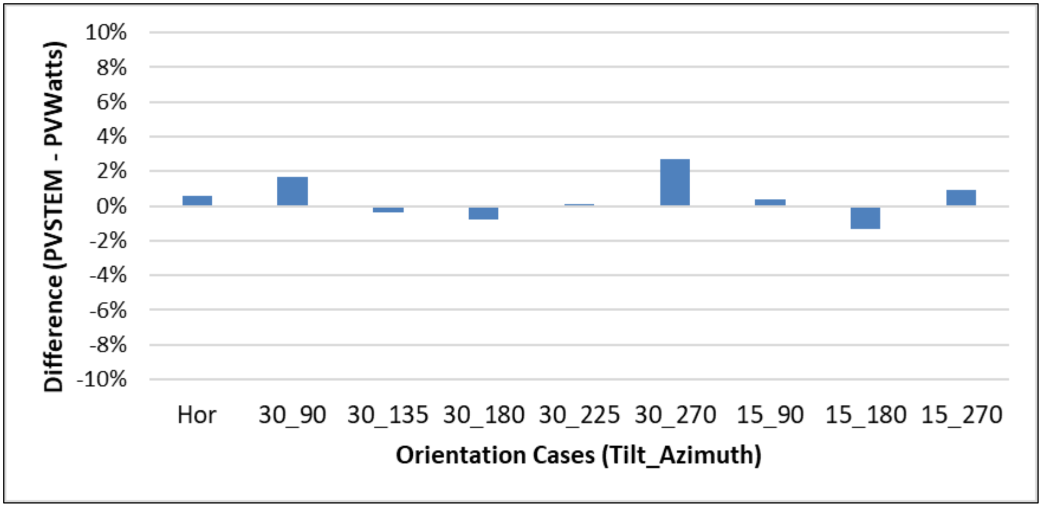

Figure 9: Annual PV-STEM vs. PVWatts® model comparisons

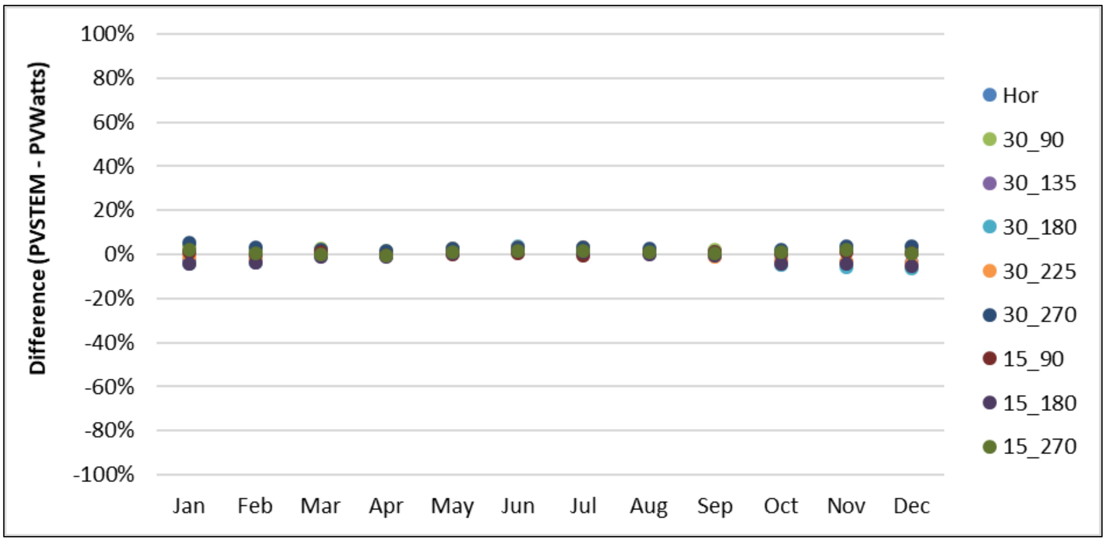

Figure 10: PV-STEM vs. PVWatts model comparisons (daily values)

PV solar systems in the community are typically mounted in parallel alignment with the roof, following standard practice for this region. Residential roof pitches in the City are typically in the range of 3/12 to 7/12 (14.0° to 30.3° tilt), so the PV-STEM model was run for cases in this range (to compare with PVWatts®).

As in the case of comparing actual generation with PV-STEM estimates, daily and hourly results were also compared for the PV-STEM vs. PVWatts® runs. Figure 11 provides example daily comparisons for the 30° tilt, 180° azimuth (30_180) case and Figure 12 shows an example of a full year hourly comparison. For this case, generation is highest in the spring and fall months. Systems with low tilt generate at their highest levels during summer periods (both models).

Note that a north facing case was also modeled, even though this is not ideal for this location (in the northern hemisphere). Differences in results for this case are similar, though daily and monthly errors are higher in the winter season for the north facing modeled case.

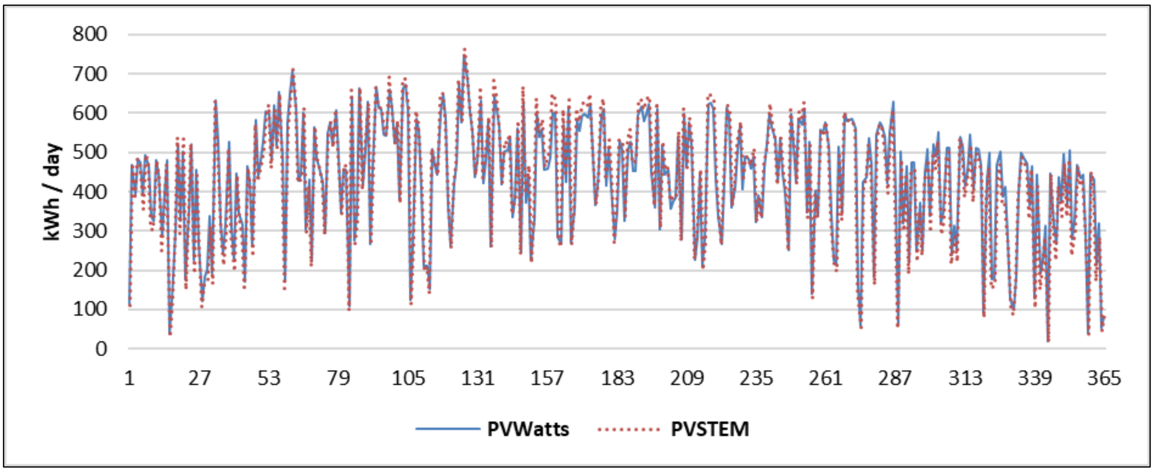

Figure 11: Example of Daily comparison for PV-STEM vs. PVWatts on 30° tilt, 180° azimuth (30_180 case)

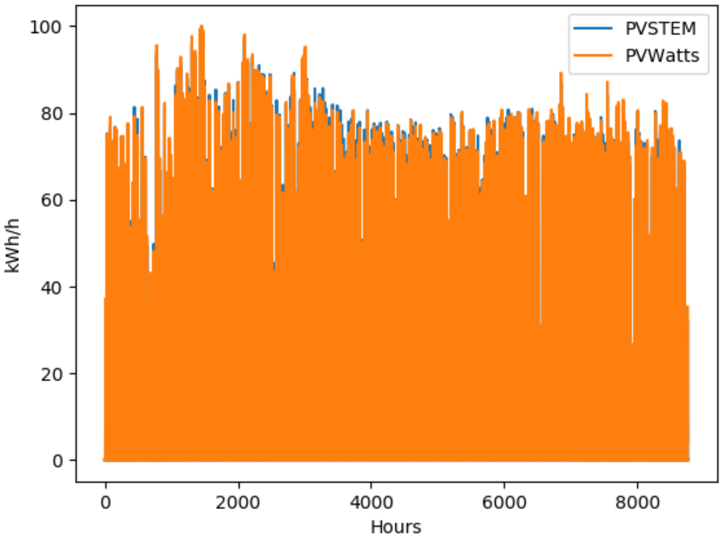

Figure 12: Example of full year hourly comparison for PV-STEM vs. PVWatts (30_180 case)

4. Model Applications

PV-STEM has been used to support several educational and planning activities in the community. A summary of applications to date is provided below:

- **Elementary school education** – the model supports solar design activities within STEM club and problem-based learning activities. Students are provided basic solar principles (through a lecture format), Then they design a system and install "panels" on small model buildings (non-operating replicas). PV-STEM is run for each of the systems and the system with the most production "wins" the design competition. Students are allowed to re-design and re-run the model with improved designs.

- **High school education** – high school students have been trained in Python coding and solar energy principles as part of extracurricular STEM activities. Students learn how to run the PV-STEM code in various configurations to gain experience in application of solar energy. The educational experience is enhanced through use of Google Earth® and Google Sunroof® online tools (also used by elementary students).

- **University education** – PV-STEM supported a thesis project at Colorado State University during 2019 and is available to support future graduate student work. It also is being integrated into solar-related research activities at the CSU Energy Institute and is reviewed as part of a graduate level mechanical engineering course at CSU.

- **Electric Utility research** – Fort Collins is a non-profit municipal utility, owned by the members of the community. Many collaborative projects have been conducted between CSU and the City. One recent project utilizing PV-STEM involves enhancing the understanding of residential PV solar generation characteristics in the City. Net electric load/generation (AMI) data is available in 15-minute increments for residential systems (from utility smart meters). A database of residential PV system characteristics is also being updated, which can provide input metrics for system modeling (size, tilt, azimuth, etc.). PV-STEM is being applied to provide estimates of generation patterns for individual customer installations at a granular level (15-minute metering increments). PV system output from the model can be combined with measured net load/generation data to estimate premise electricity use (shown graphically in Figure 13). Generation and usage estimates can also be aggregated to provide insights regarding PV generation operations across the City utility distribution network, supporting future planning efforts (rate design, limits on solar sizing, PV resource expansion, etc.).

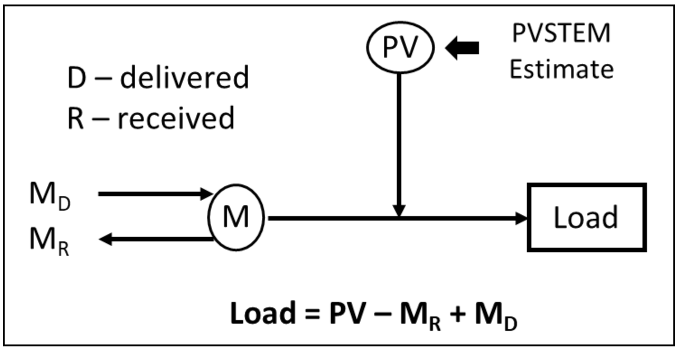

Figure 13: Schematic of approach for estimating solar customer load profiles

- **"She's In Power" program** – She's in Power is an initiative of Colorado Clean Energy Education and Empowerment (C3E), designed to grow and inspire the women who will be tomorrow's clean energy leaders and reduce greenhouse gases in the City, innovating a more sustainable community today and developing the diverse clean energy workforce of tomorrow. As a "Spark" in this program, students work with a project team to learn solar engineering principals and apply them through use of the PV-STEM model and other tools. This program provides student and Energy Institute staff to support the electric utility research mentioned above. Other projects and general information regarding the program can be viewed at this link: https://coloradoc3e.org/shes-in-power/.
- **Community-wide solar modeling** – PV-STEM is also being developed as a tool to provide estimates of total solar energy production occurring within the City (from distribution level PV systems), and to share this information with the community on a near real-time basis (e.g. every hour). Additional monitors, web site development / graphics and communications will be required to complete this effort.

Additional applications for PV-STEM will be identified as distributed solar energy continues to expand in the City and the region. Enhancements to the model are anticipated as it is applied to support future PV solar projects. Shading is a primary concern, which can be incorporated into the model using existing solar position algorithms and adding loss factors for solar positions related to shading obstacles at a given site. Additional work can also be done to improve the snow loss algorithms in the model. We hope to engage more students and educators in the ongoing process for improving the model over time (and finding new applications) – in order to continue supporting solar education, research and communications in our community.