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Simulation of Distributed PV Power Output in Oahu, Hawaii

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Simulation of Distributed PV Power Output in Oahu, Hawaii

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Abstract

Distributed solar photovoltaic (PV) power generation in Oahu has grown rapidly since 2008. For applications such as determining the value of energy storage, it is important to have PV power output timeseries. Since these timeseries of not typically measured, here we produce simulated distributed PV power output for Oahu. Simulated power output is based on (a) satellite-derived solar irradiance, (b) PV permit data by neighborhood, and (c) population data by census block. Permit and population data was used to model locations of distributed PV, and irradiance data was then used to simulate power output. PV power output simulations are presented by sub-neighborhood polygons, neighborhoods, and for the whole island of Oahu. Summary plots of annual PV energy and a sample week timeseries of power output are shown, and a the files containing the entire timeseries are described.

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1 Introduction

The state of Hawaii and specifically the island of Oahu has seen a significant amount of distributed solar photovoltaics (PV) installed in recent years [1]. Many distribution feeders have PV penetrations (installed PV capacity) exceeding 50% of daytime peak load [2]. These high PV penetrations can lead to challenges in grid operation.

One example challenge is the imbalance between PV production and electric demand. Around noon when solar production is highest, load demand is relatively low. Conversely, in the evening when load demand is high, PV production is small since the sun is setting. This can lead to a very sharp increase in net load (load minus PV production) in the early evening, and must be countered by injecting large amounts of power from other sources into the electric grid [3].

Another challenge is that solar irradiance is variable, especially in Hawaii where there are often many small clouds scattered across the sky. This variability leads to voltage fluctuations on distribution feeders, and at high PV penetrations, may cause voltage levels to exceed limits if no mitigation efforts are taken.

Incorporating energy storage into electric grid operations is one promising way to minimize the negative impacts of high penetrations of solar PV power output. To study and model potential value of energy storage, it is important to know how much power is being produced by distributed PV systems in each area and at each point in time. In nearly all cases, distributed PV is not measured; typically only net load is recorded. Thus, to allow for studies of the value of storage, in this work we simulate year-long timeseries of PV power output for the distributed PV systems that are spread across the island of Oahu.

2 Input Data

Irradiance, PV installation, and population data (Figure 1) was obtained from the following sources:

- **Satellite-Derived Solar Irradiance:** National Solar Radiation Database [1]
- **PV Installations:** Solar PV Installations in Honolulu (permit data) [2] and Honolulu Board of Realtors (neighborhood GIS data) [3]
- **Population by census block:** State of Hawaii Office of Planning [4]

PV installation data through the year 2014 was used, as it was the most recent available data that separated installations by neighborhood [1]. Irradiance data from 2014 was used, to match with most recent load measurements available for the storage integration study. Census data was from 2010 since that was the most recent data available.

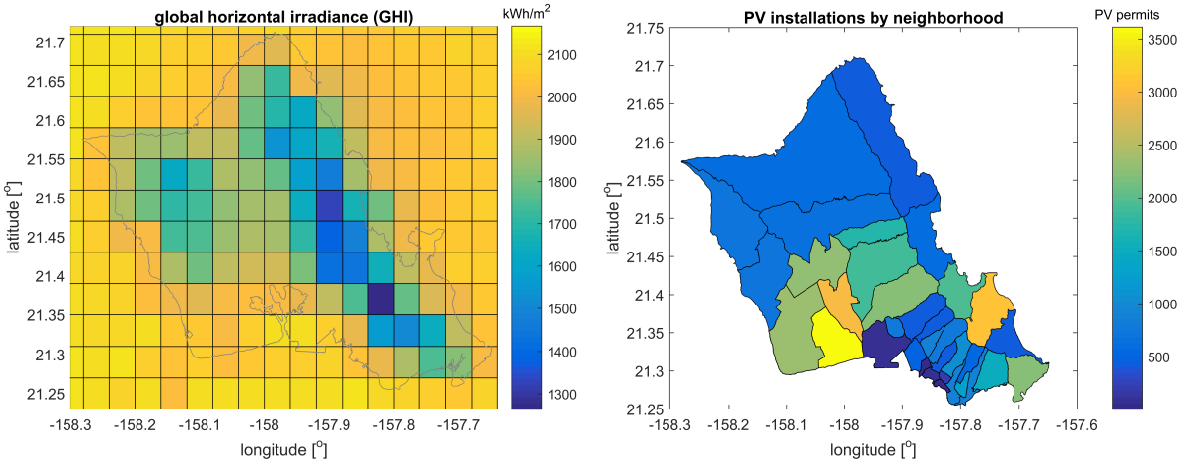
The irradiance year and the census year used should have little impact on the analysis, since there is not expected to be much inter-annual variation in weather population distribution across the island. The year used for PV installation data, however, will have a strong impact on the analysis: as distributed PV installations continue, the amount of power generated will increase. There may also be changes in the density of PV installations in each neighborhood as certain neighborhoods become saturated and have no new installations.

[1] https://nsrdb.nrel.gov/

[2] http://files.hawaii.gov/dbedt/economic/data_reports/briefs/Analysis_of_Solar_PV_Activities_in_Honolulu.pdf

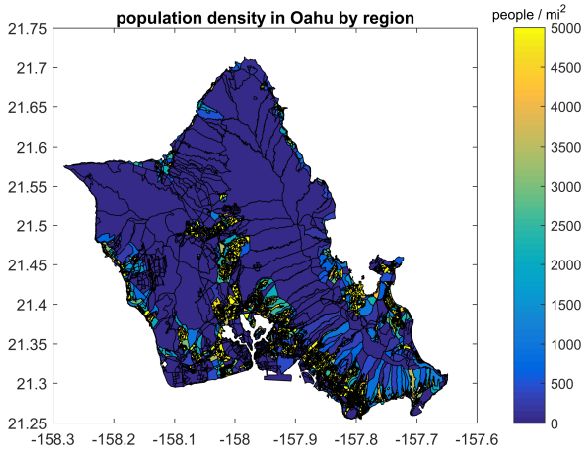
[3] http://gisftp.hicentral.com/gis_layer_list_by_topic_category.html

[4] http://planning.hawaii.gov/gis/download-gis-data/



(a) Solar resource data in a grid at 0.04 degree latitude and longitude resolution.

(b) PV permit data by neighborhood (35 neighborhoods in Oahu).



(c) Population density by census block (8460 blocks in Oahu).

Figure 1: Input data for distributed PV simulation.

3 Method

3.1 Merge Solar Resource and Demographic Data

Sub Neighborhood Polygons

To merge all this data, new polygons were created by finding unique combinations of solar resource grid cell and PV installation neighborhood. We call these sub-neighborhood polygons.

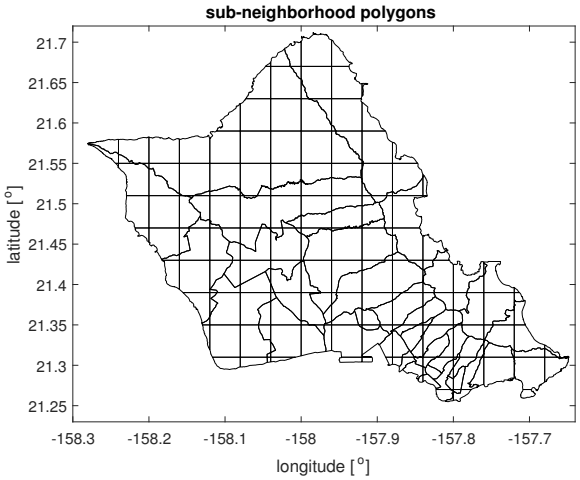
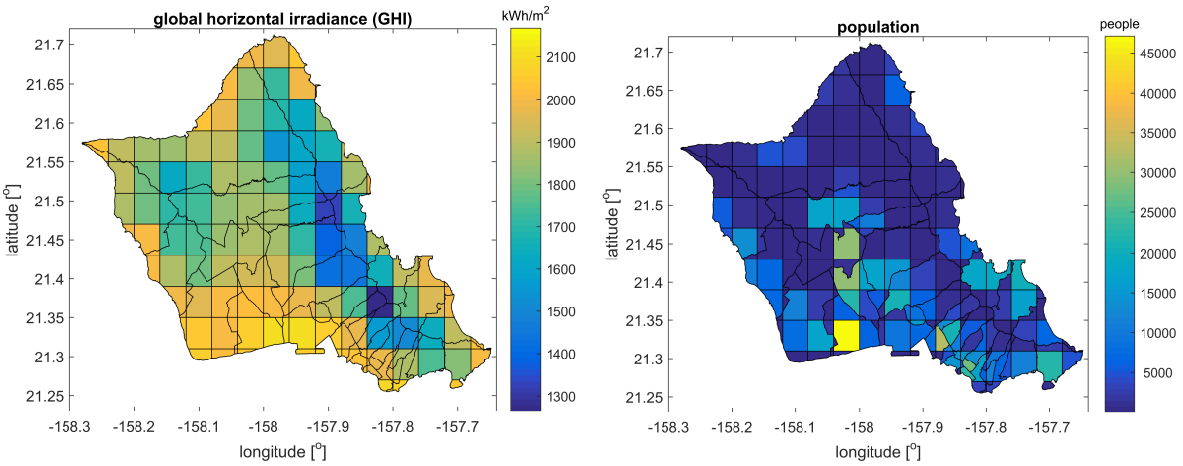


Figure 2: Sub-neighborhood polygons.

For each sub-neighborhood polygon, the solar resource and population were determined. The population was found by summing the population of all census blocks contained in the sub-neighborhood polygon. If a block was in two or more sub-neighborhood polygons, the population of that block was distributed evenly between the sub-neighborhood polygons.

PV Permits per Sub-Neighborhood Polygon

To approximate the number of PV permits per sub-neighborhood polygon, the PV permits in each neighborhood were scaled by the population. For example, if a certain sub-neighborhood polygon had 10% of the population in that neighborhood, it would be assigned 10% of the PV permits.



(a) Solar resource. **(b)** Population.

Figure 3: Solar resource and population partitioned by sub-neighborhood polygons.

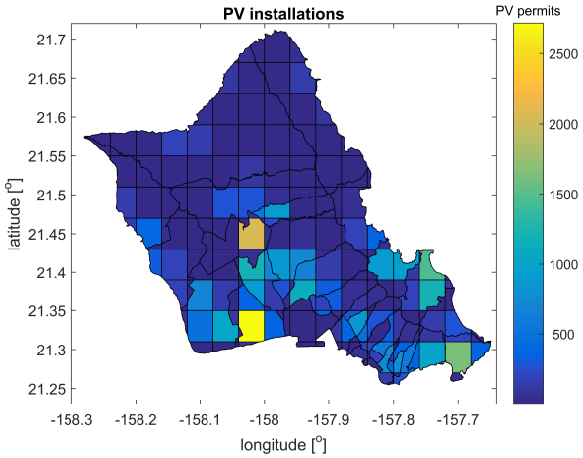


Figure 4: Approximated PV installations for sub-neighborhood polygons.

3.2 Simulate PV Power Output

To simulate PV power output, we followed four steps:

1. Obtain irradiance data.
2. Determine tilt and azimuth angles representative of residential PV in Oahu.
3. Determine the plane of array (POA) irradiance for each tilt and azimuth angle.
4. Convert the POA irradiance to PV power output.

Irradiance Data

Satellite-derived approximations of direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) for the year 2014 at half-hourly intervals were obtained from the National Solar Radiation Database [5]. These irradiance approximations are created using a Physical Solar Modem (PSM), as described in Sengupta, et al [4].

Tilt and Azimuth of PV Systems in Oahu

While latitude tilt and due south azimuth is generally considered the optimum orientation for PV modules, residential PV systems often vary from this due to different rooftop orientations and slopes. Although data on tilt and azimuth orientations of PV systems in Oahu was not available, this information was available for California systems using the California Solar Initiatives (CSI) Solar Statistics Database [6]. Tilt and azimuth distributions of 83,906 residential PV systems with valid tilt and azimuth data in the CSI database are shown in Figure 5.

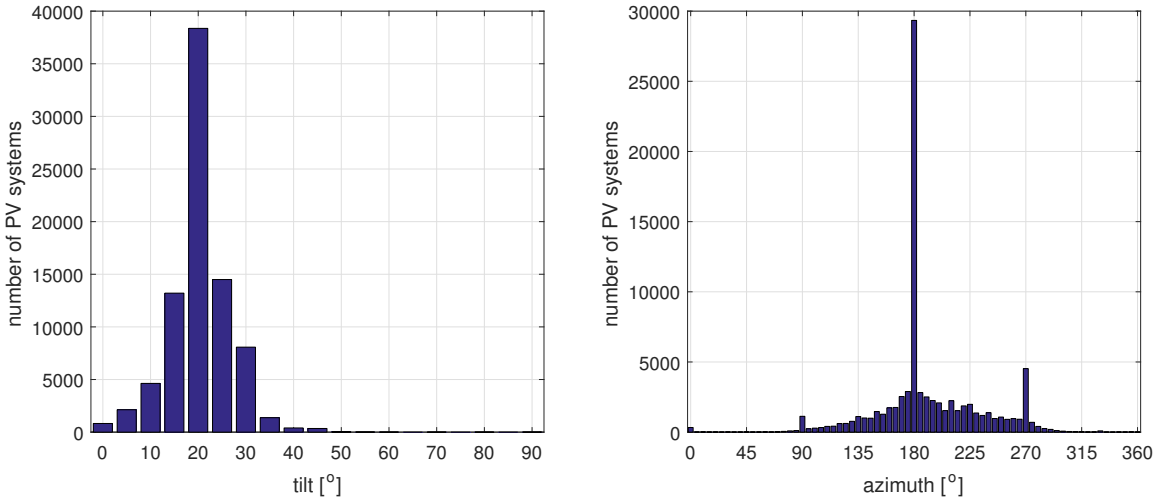


Figure 5: Tilt and azimuth of PV systems in the California Solar Initiative (CSI) database.

The azimuths of the CSI PV systems are mostly due south (180°), with some variation, and also a few systems are due west (270°) or due east (90°). We believe these azimuths will be representative of the azimuths of residential PV in Oahu.

[5] https://nsrdb.nrel.gov

[6] https://www.californiasolarstatistics.ca.gov/data_downloads/

The tilts of the CSI PV systems are generally less than latitude tilt (latitudes were between 32.5°and 41.3°). We assume that the tilt of these systems was determined by the tilt of the roof, such that they will be representative of Oahu tilts. However there are many CSI systems near latitude tilt. To represent the Oahu residential tilt angles of these types of systems (i.e., where tilt angle may be adjusted to optimize output), we modify the CSI tilt angles that fell within 5°of latitude tilt:

$$\text{if abs[CSI tilt - CSI latitude]} < 5^\circ$$

$$\text{set Oahu tilt = CSI tilt - CSI latitude + Oahu latitude}$$

For example, a PV system in San Diego (32.8°latitude) tilted 30°would be adjusted to be tilted 24.3°in Oahu (21.5°latitude). The modified tilt histogram representing Oahu is shown in Figure 6.

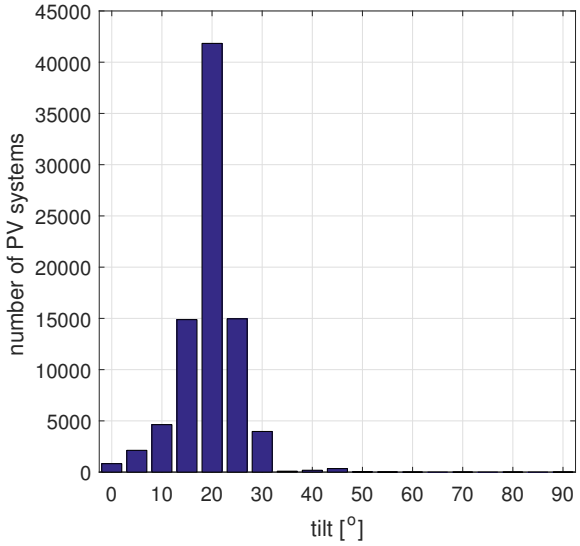


Figure 6: Modified CSI PV system tilts to represent tilts in Oahu

Plane of Array Irradiance

The DNI and DHI values were used with the Hay/Davies transposition model [5] to determine the plane of array (POA) irradiance in the plane of each PV module. For each sub-neighborhood polygon, we iterated through different combinations of tilt and azimuth, once per permit determined to occur in that polygon (based on Figure 4). For example, if 1500 permits were assigned to a certain polygon, 1500 different tilt and azimuth pairs, sampled from the CSI azimuths and modified tilts, were used to simulate 1500 different POA irradiance profiles.

PV Power Output

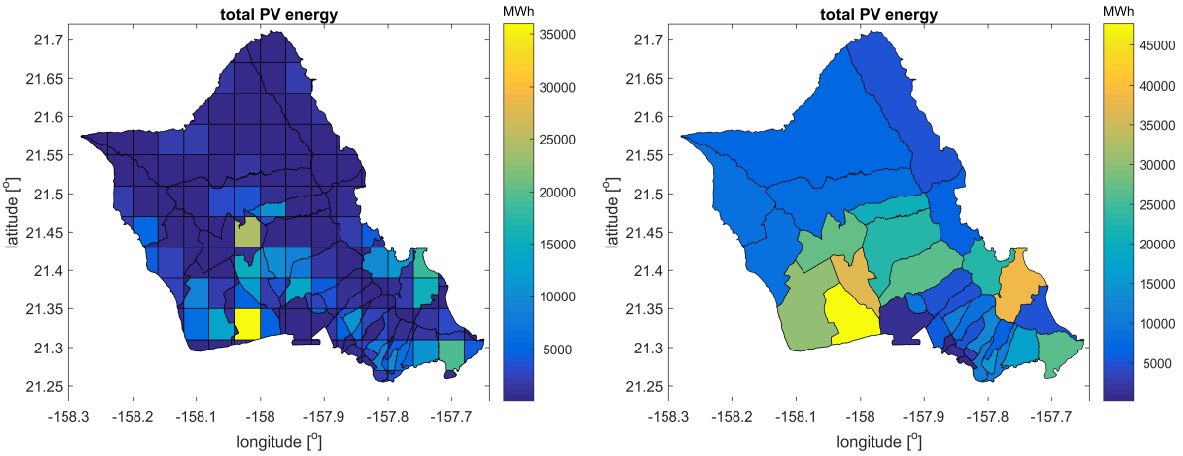
Each POA irradiance profile was converted to PV power output using the Sandia Array Performance Model [6] to simulate DC power production, and the Sandia Inverter Performance Model [7] to simulate conversion to AC power. A single (crystalline silicon) type of PV module and residential inverter was assumed for all simulations. Although true residential PV systems would have varying module technologies and inverter types, these differences are not expected to have a large impact on PV power output, and the assumed values should be representative of all models.

It was assumed that all PV systems were the same size. The total amount of distributed PV installed at the end of 2014 was assumed to be 272MW over 38,652 installations, or approximately 7kW per system. While this is probably larger than typical residential systems and smaller than typical commercial systems, based on the input data available, there was no way to segregate between residential and commercial systems. We expect this assumption of 7kW per system (rather than systems of varying sizes) to have very little impact on the simulated distribute PV power output for each region.

3.3 Aggregate Power Output by Region

PV power output simulations were aggregated by sub-area polygon, resulting in a year-long timeseries of PV power output for each sub-area polygon. The sum of each of these timeseries over the entire year of 2014 (i.e., the annual energy produced in 2014) are shown in Figure 7a. These power timeseries were subsequently aggregated by neighborhood (Figure 7b) and over the whole island of Oahu.

Figure 8 shows the first week (January 1-7) of PV power output values for each sub-neighborhood polygon, neighborhood, and for all of Oahu. The varying magnitudes seen in the sub-neighborhood and neighborhood plots in Figure 8 are due to the different amounts of PV in each region. These two plots also show the varying weather between the different regions: some locations are cloudy while others are clear.



(a) By sub-neighborhood polygon.

(b) By neighborhood.

Figure 7: Total annual PV energy.

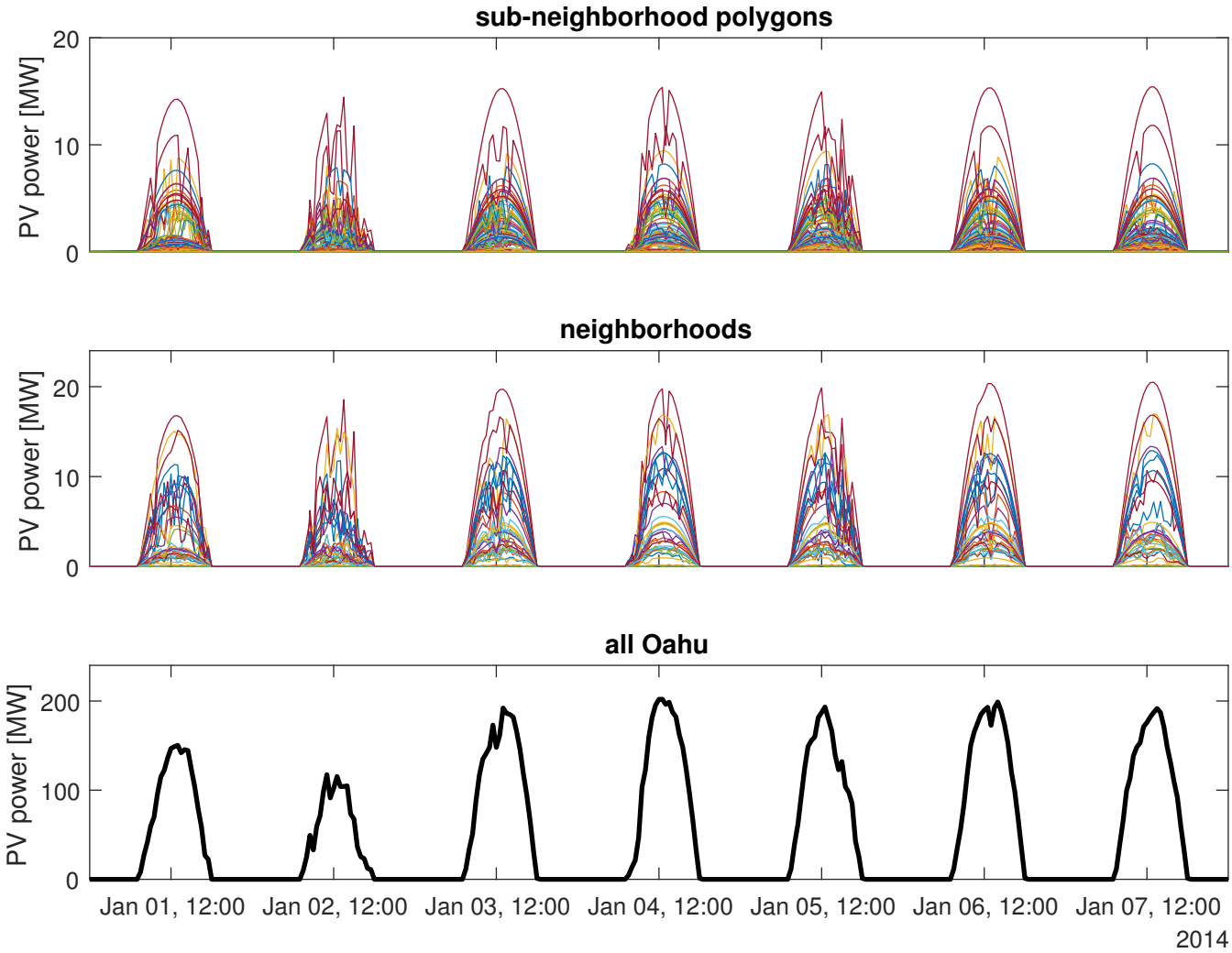


Figure 8: PV power output during first 7 days in January 2014 for the sub-neighborhood polygons, aggregated by neighborhood, and aggregated over all of Oahu. Sub-neighborhood and neighborhood PV power output intensities vary due to different installed capacities of PV in each area and due to different weather.

4 Data Format

PV power output data is supplied as *.csv files. Each file contains PV power output(s) in MWs for 1-year at 1-hour resolution (8760 data points). Two files are being supplied:

- **"PV_power_output_by_neighborhood.csv":** The PV power output timeseries for each neighborhood. The first 4 columns are year, month, day, and hour. The following columns are the PV power outputs for each neighborhood.
- **"PV_power_all_Oahu.csv":** The PV power output timeseries for the sum of all Oahu PV. Columns are year, month, day, hour, and PV power.

1	year	month	day	hour	Aiea	Airport	Ala moana	Aliamanu,	Diamond I	Downtow	Ewa
9	2014	1	1	7	0	0	0	0	0	0	0
10	2014	1	1	8	1.8073	0.023957	0.020088	0.40909	0.47194	0.02699	3.3999
11	2014	1	1	9	4.0558	0.071571	0.031587	0.88508	0.69289	0.033572	8.09
12	2014	1	1	10	4.6555	0.053404	0.043429	0.84915	1.5063	0	11.925
13	2014	1	1	11	7.2639	0.0611	0.082465	1.7986	1.0798	0.018234	14.811
14	2014	1	1	12	8.3311	0.11486	0.064275	2.084	3.2701	0.10056	16.387
15	2014	1	1	13	8.5163	0.062666	0.094074	2.0557	4.1697	0.091489	16.754

(a) PV power output by neighborhood.

	A	B	C	D	E	F
1	year	month	day	hour	all Oahu	
33	2014	1	2	7	0	
34	2014	1	2	8	24.966	
35	2014	1	2	9	32.953	
36	2014	1	2	10	71.332	
37	2014	1	2	11	117.4	
38	2014	1	2	12	102.02	
39	2014	1	2	13	104.1	
40	2014	1	2	14	104.82	
41	2014	1	2	15	67.689	
42	2014	1	2	16	25.311	
43	2014	1	2	17	12.278	

(b) PV power output for all of Oahu.

Figure 9: Samples from the supplied data files. All PV power values are in MWs.

References

[1] Research and State of Hawaii Economic Analysis Division (READ) of the Department of Business, Economic Development & Tourism (DBEDT). Solar PV Installations in Honolulu. Technical report, 2015.

[2] Hawaiian Electric. Oahu Locational Value Map, 2016.

[3] Jeff St. John. Hawaii's Solar-Grid Landscape and the 'Nessie Curve', 2016.

[4] M Sengupta, A Habte, P Gotseff, A Weekley, A Lopez, M Anderberg, C Molling, and A Heidinger. Physics-based goes product for use in nrels national solar radiation database. In *Preprint. Prepared for the European Photovoltaic Solar Energy Conference and Exhibition*, 2014.

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[7] D. King, S Gonzalez, G Galbraith, and W. Boyson. Performance model for grid-connected photovoltaic inverters. Technical Report SAND2007-5036, Sandia National Laboratories, 2007.

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