Assessment of Wind and Photovoltaic Technical Potential for the Hawaiian Electric Company

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List of Acronyms

AC	Alternating Current
DC	Direct Current
DOD	Department of Defense
CF	Capacity Factor
GW	Gigawatt
GWh	Gigawatt Hours
GCR	Ground Cover Ratio
IGP	Integrated Grid Planning
KM^2/SQ KM	Square Kilometer
kW	Kilowatt
kWh	Kilowatt Hours
LCOE	Levelized Cost of Energy
LiDAR	Lidar Detection and Ranging (also Lidar)
MW	Megawatt
MWh	Megawatt Hours
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
PSIP	Power Supply Improvement Plan
PV	Photovoltaics
R^2	Coefficient of Determination
reV	Renewable Energy Technical Potential (v) Model
SAM	System Advisor Model
TMK	Tax Map Keys
TMY	Typical Meteorological Year
TWh	Terrawatt Hours

Executive Summary

This report by the National Renewable Energy Laboratory (NREL) presents the findings of the utility-scale solar and wind and distributed rooftop solar technical potential for Hawaiian Electric's service territory on the Hawaiian Islands of Oʻahu, Maui, Lānaʻi, Molokaʻi, and Hawaiʻi. The technical potential provides an upper boundary estimation of available land, potential capacity, and potential electricity generation for sites across the five islands. This is not meant to imply achievable market potential or cost-effectiveness, but rather limits of what is physic ally possible. This analysis does not take into consideration already existing sites, or economic or market considerations for siting new solar and wind power generating assets. Sites where both solar and wind could be deployed were examined separately and not exclusively. Techno-economic potential represents the economic costs associated with renewable generation that is available in a given geographic area. Economic potential, which is not addressed in this study, considers the costs of a technology and revenues to assess the economic viability of its development.

This work was conducted to support Hawaiian Electric's Integrated Grid Planning (IGP) process. It creates geographically specific estimations of developable capacity and generation across Oʻahu, Maui, Lānaʻi, Molokaʻi, and Hawaiʻi, where previous renewable energy technical potential assessments focused exclusively on Oʻahu, Maui, and Hawaiʻi[1]. Multiple scenarios were considered for the utility-scale solar and wind technical potential results. The scenarios considered differing technological choices, as well as considerations for different land use and land category restrictions.

Table ES-1-4 below illustrate the results of the utility-scale solar, utility-scale wind, and distributed-scale rooftop solar technical potential in Hawaiian Electric service territory within developable areas by island. The utility-scale technical potential results are presented in terms of capacity (maximum power output measured in megawatts [MW]). Under this analysis, the technical potential for utility-scale solar with one-axis tracking arrays ranges between 16,284 (PV-1-3 scenario) and 193,656 (PV-2-HS scenario) MW, utility-scale solar with fixed-tilt arrays ranges between 18,306 (PV-1-3 scenario) and 217,706 (PV-2-HS scenario) MW, and utility-scale land-based wind ranges between 2,633 (WIND-3-20 scenario) and 5,031 (WIND-2-HS scenario) MW. Distributed-scale rooftop solar potential exceeds 7,000 MW.

Future work based on these technical potential analyses should consider additional validation between measured resource data and modeled data from the WIND Toolkit and National Solar Radiation Database as well as of Lidar data sources. The precision of rooftop solar technical potential analysis is significantly reduced by the overall quality and coarseness of the Lidar data sources used, which are under contract to be updated with at least Quality Level 2 coverage for all of Hawaii by the United States Geological Survey in 2020 with publication expected in 2021. These technical potential analyses provide insight into the availability of high-quality wind and solar resources for Hawaii. Using the results, maps, and data layers made available to the public, additional investigations into identifying available lands can be conducted to find the best

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[1] Brancucci Martinez-Anido et al. 2016

suitable land for new renewable energy development. While the technical potential analysis does not substitute on-the-ground investigations, state policies, community engagement, collaborative planning efforts, and other practical realities, it does allow for efficiency in focusing on lands with high resource potential and favorable land use constraints.

Table ES- 1: Summarized installable capacity in MW for Utility-Scale 1-Axis Tracking PV Systems All Scenarios; Lands with Capacity Factors >= 0.10

Island	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
Oʻahu	907	1,954	9,634	1,412	2,794	13,965	561	1,008
Molokaʻi	1,225	3,016	13,387	1,225	3,016	13,387	1,177	2,918
Maui	1,038	2,669	26,728	1,038	2,669	26,728	508	1,411
Lānaʻi	697	1,478	9,599	697	1,478	9,599	557	1,199
Hawaiʻi	12,417	29,384	117,231	15,083	35,319	129,977	13,621	31,841

Table ES- 2: Summarized installable capacity in MW for Utility-Scale Fixed Tilt PV Systems All Scenarios; Lands with Capacity Factors >= 0.10

Island	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
Oʻahu	1,021	2,199	10,838	1,588	3,143	15,710	632	1,134
Molokaʻi	1,378	3,394	15,060	1,378	3,394	15,060	1,324	3,283
Maui	1,168	3,003	30,069	1,168	3,003	30,069	572	1,587
Lānaʻi	784	1,663	10,798	784	1,663	10,798	627	1,349
Hawaiʻi	13,955	33,024	131,729	16,954	39,701	146,069	15,309	35,788

Table ES- 3: Summarized installable capacity in MW for Utility-Scale Wind Systems All Scenarios; Lands with Wind Speeds >= 6.5 m/s

Island	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
Oʻahu	436	761	640	1,147	230	465	333	728
Molokaʻi	951	1,249	951	1,249	688	958	688	958
Maui	634	940	634	940	421	659	421	659
Lānaʻi	381	441	381	441	312	368	312	368
Hawaiʻi	1,189	1,254	1,189	1,254	982	1,039	982	1,039

Table ES- 4: Summarized installable capacity in MW for Distributed-Scale PV Systems Modeled and Imputed Roofs

Island	Area (km^2)	Capacity (MW)
Oʻahu	19,968	3,934
Molokaʻi	378	45
Maui	5,768	1,113
Lānaʻi	355	44
Hawaiʻi	15,560	2,163

Table of Contents

List of Figures

List of Tables

1 Introduction

Hawaiian Electric is in the process of updating their Power Supply Improvement Plan (PSIP) to support the state of Hawaii's 100% Renewable Portfolio Standard (RPS) by 2045. The National Renewable Laboratory previously provided Hawaiian Electric with an assessment of wind and solar energy potential on Hawai‘i, Maui, and O‘ahu[2]. This study serves to update and expand that previous analysis to assist Hawaiian Electric in revising their PSIP. The updates and expansions include assessment of rooftop potential for distributed PV generation, incorporation of spatiotemporal energy resource data rather than use of typical meteorological year data, narrowing of technologies to land-based utility-scale wind, utility-scale solar, and distributed-scale rooftop solar (omitting concentrated solar power technology), customization and scenarios for potential land development, and expanded spatial coverage to Hawai‘i, Lāna‘i, Maui, Moloka‘i, and O‘ahu. In conjunction with Hawaiian Electric's PSIP and current Integrated Grid Planning efforts, NREL is providing these data and analyses to Hawaiian Electric and stakeholders to help inform collaborative efforts in identifying the best options to affordably move Hawai‘i toward a reliable and resilient clean energy future.

2 Utility-Scale Technical Potential Analysis

2.1 Background

The purpose of this project was to conduct a high-level evaluation of areas of land that are potentially available for new solar and wind development. This analysis typically is called a "technical potential" analysis, as it seeks to find land that is technically-viable for new development. Considerations that would fall under the purview of this analysis includes areas with high quality solar and/or wind resources; are located in areas with limited population density to support the development of utility-scale power systems; do not exist in areas with land use and land cover restrictions; are on lands that are sufficiently flat to reasonably accept the technology; and various other similar considerations. It is important to note, however, that the technical potential analysis does not seek to consider all aspects of new solar or wind development, most notably the economic, community and societal, or market factors that would determine whether a project is viable or not. Figure 1 provides an overview of the different types of potentials analysis. Additional analysis after the completion of the technical potential analysis can help to identify the areas with the economic and market factors that would facilitate new solar and wind development. Additionally, on-the-ground evaluation of land and discussions with local stakeholders will be critical to identify the highest potential areas for new development.

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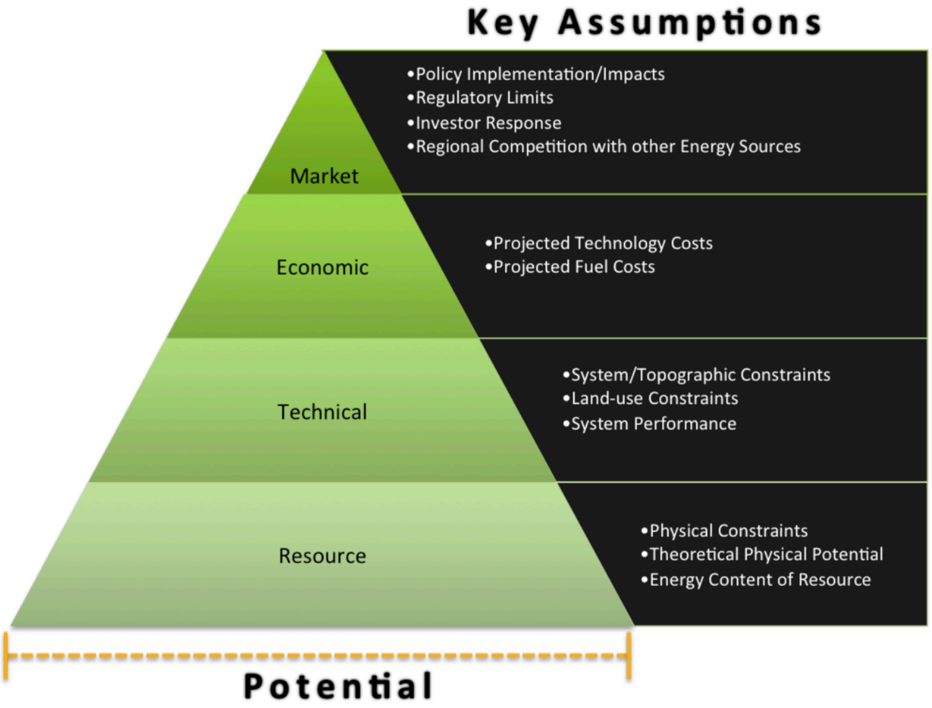
[2] Brancucci Martinez-Anido, C, B. Roberts, E. Chartan, A. Weekley, A. Lopez, B.-Mathias Hodge. 2016. "Technical Memo – Utility-Scale Onshore Wind, Utility-Scale PV, and CSP Potential Resource. Unpublished report.

Figure 1: Various Types of Potentials Analysis



Technical potential analysis like the type done for this project have been conducted for various geographic extents, including a previous iteration evaluating solar and wind development for Hawaiʻi. As part of the PSIP, the National Renewable Energy Laboratory (NREL) conducted a technical potential analysis in 2016 of three of the islands of Hawaiʻi: Hawaiʻi, Maui, and Oʻahu[3]. Similarly, a national-level technical potential analysis quantified available land area for various types of renewable energy technologies.[4] This analysis builds on the insights gained from these previous analyses, and in the case of the more recent PSIP effort, also includes the islands of Molokaʻi and Lānaʻi in the technical potential analysis.

A key development over the previous efforts to quantify available areas for solar and wind systems in Hawaiʻi is the development of the Renewable Energy Potential[5] (reV) model. The reV model allows for the rapid evaluation of different technical potential and supply curve scenarios. Since development of the reV model in 2017, technical potential and supply curve analyses have been conducted by NREL staff for numerous geographic areas including the United States, Canada, Mexico, South Africa, Southeastern Asia, India, and other regions. Using solar and wind system configurations and cost inputs defined by Hawaiian Electric, publicly-available

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[3] Brancucci et al. 2016

[4] Lopez, Anthony, Billy Roberts, Donna Heimiller, Nate Blair, and Gian Porro. "US Renewable Energy Technical Potentials: A GIS-Based Analysis," 2012. https://www.nrel.gov/docs/fy12osti/51946.pdf.

[5] Galen J Maclaurin et al., "The Renewable Energy Potential (ReV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling," 2019, https://doi.org/10.2172/1563140.

geospatial layers to designate land with competing uses, and feedback from local stakeholders, the reV model produced the technical potential results defined in this report.

2.2 Data Inputs

2.2.1 Spatiotemporal Resource Data

In order to evaluate the potential solar and wind electrical output of various generators, the historical weather patterns for Hawai‘i were evaluated using spatiotemporal resource datasets. These large-scale weather datasets are fed into the reV model in order to calculate yearly and multi-year average capacity factors and capacity factor profiles for pre-defined solar and wind generating technologies.

The National Solar Radiation Database[6] (NSRDB) was used for calculating the photovoltaic (PV) system output for a 1-axis tracking and fixed-tilt PV system. The NSRDB provides half-hourly temporal resolution and 4km nominal spatial resolution weather data for most of the northwestern hemisphere. Twenty-two years of data are available from the NSRDB, spanning years 1998 through 2019. By using multiple decades-worth of weather data, a long-term mean can be established for solar irradiance and other weather factors that would affect the performance of PV systems.

The WIND Toolkit[7] for Hawai‘i provides hourly temporal resolution and a 2km nominal spatial resolution for the islands and near offshore regions of Hawai‘i. The wind dataset used for this analysis includes twenty years of data, spanning years 2000 through 2019. Like the NSRDB dataset, using numerous years of wind data allows for the evaluation of a long-term average wind speed to increase the confidence in annual electrical generation of various wind generating technologies.

Maps of the solar and wind resources for Hawai‘i originating from the above datasets can be found in Appendix A.

2.2.2 Geographic Exclusions

Each scenario for the technical potential and supply curve analysis used differing geographic exclusion assumptions. For the evaluation of utility-scale solar and wind, geographic exclusions were selected to exclude land considerations including federal and state protected lands, wetlands, lava flow zones, areas with high slope, agricultural areas (including Land Study Bureau Agricultural lands), urban areas, and other considerations. The scenarios for the solar and wind technologies were developed in order to understand the impacts of various exclusion assumptions on available land, installable nameplate capacity, annual generation, and resource quality. As there is a high amount of uncertainty about the availability of land for new

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[6] Manajit Sengupta et al., “The National Solar Radiation Data Base (NSRDB),” *Renewable and Sustainable Energy Reviews* 89 (2018): 51–60, https://doi.org/10.1016/j.rser.2018.03.003.

[7] Caroline Draxl et al., “The Wind Integration National Dataset (WIND) Toolkit,” *Applied Energy* 151 (2015): 355–66, https://doi.org/10.1016/j.apenergy.2015.03.121.

development, the use of multiple scenarios allows for evaluating available lands under differing geographic constraints.

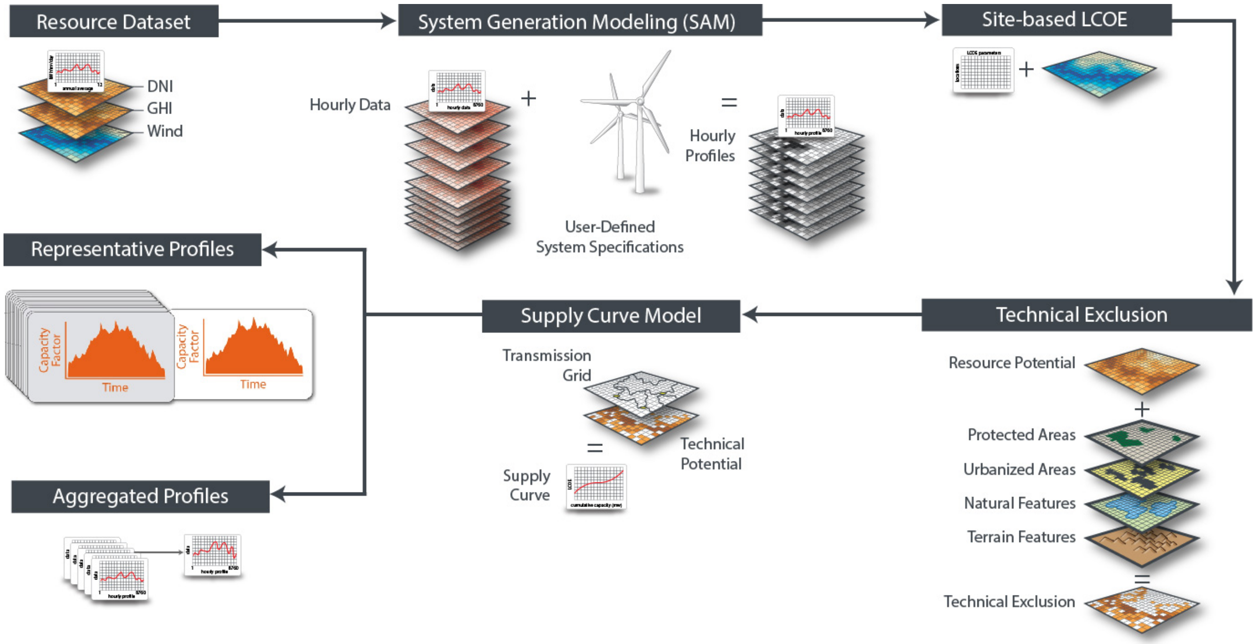
Once all geographic exclusion layers have been accounted for, an additional filter is applied to remove discrete clusters of available land pixels with too few adjacent pixels to support larger utility-scale PV systems. Each cluster of available land pixels are evaluated to determine the total available area of the cluster. For utility-scale PV systems, any clusters of land pixels that amount to less than 0.10 sq.km of available land are excluded from the available area calculations. Assuming a 32 MW/sq.km capacity density for 1-axis tracking systems, and 36 MW/sq.km for fixed tilt systems, the minimum system size would therefore be 3.2 MW and 3.6 MW respectively for the two PV technologies. This adjacent land pixel analysis was not applied to wind systems as the pad of the wind turbines are small when compared to utility-scale PV systems.

For a full list of all exclusions used for each solar and wind scenario, please see Appendix B.

2.3 Modeling Approach

The reV model allows for the rapid scenario-based analysis of solar and wind technical potentials and supply curves. The model progresses through a series of stages to calculate potential electrical output of solar and wind systems, calculate the site-based levelized cost of energy (LCOE), evaluate land areas that are potentially available for new development, and rank sites according to relative costs. A graphical depiction of the model is visualized in Figure 2 below.

Figure 2: reV Model Flowchart



Different system types were run for solar and wind systems. Table 1, Table 2, and Figure 3 below describe the configurations used for each system type during the System Generation Modeling phase of the reV model. These inputs affect the potential electrical output of the various solar or wind generating systems. It is important to note that guidance was given from Hawaiian Electric to use a smaller wind turbine for the island of Moloka‘i based on feedback received from community stakeholders. As a result, utility-scale wind turbines were used for modeling electrical generation for each island except Moloka‘i. Moloka‘i, on the other hand, used a smaller, distributed-scale wind turbine to produce nameplate capacity estimates, potential electrical generation, and site-based LCOE estimates.

Table 1. Solar System Configurations

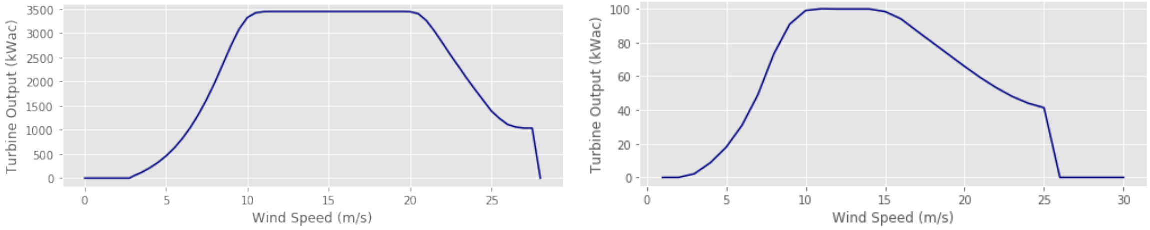
System Type	DC/AC Ratio	Azimuth	Tilt	GCR*	Inverter Efficiency	Losses
1-Axis Tracking	1.3	180°	0°	0.43	98%	12.15%
Fixed Tilt	1.5	180°	15°	n/a	98%	14.90%

*Ground Cover Ratio (GCR) is not considered for fixed tilt systems.

Table 2. Wind System Configuration

System Type	Capacity	Hub Height	Rotor Diameter	Turbulence Coefficient	Wind Shear Coefficient	Losses
Wind	3,450kW	105m	136m	0.132	0.31	16.70%
Wind (Moloka‘i)	100kW	40m	27.6m	0.132	0.31	16.70%

Figure 3: Utility-Scale (Left) and Distributed (Right) Wind Turbine Power Curves



Maps of the capacity factors resulting from the multi-year evaluation of electrical output for the solar and wind systems described above can be found in Appendix A.

To estimate the installable capacity for solar and wind, the capacity density estimates from previous studies was used.[8,9] The resulting capacity estimates in this study are a result of multiplying the available area by the capacity density values listed in Table 3

Table 3. Capacity Density for Utility-Scale Technologies

System Type	Capacity Density	Minimum System Size
1-Axis Tracking	32 MW/sq.km	3.2 MW
Fixed Tilt	36 MW/sq.km	3.6 MW
Wind	3 MW/sq.km	N/A

During the Site-based LCOE stage of the reV model outlined in Figure 2, the cost inputs listed in Table 4 were used for the LCOE calculation. The LCOE calculation used the Fixed Charge Rate method, and is described in **Equation 1**.

Table 4. System Cost Configurations

System Type	Capital Cost	Fixed O&M Costs	Fixed Charge Rate
1-Axis Tracking	$620/kWac	$15/kWac-yr	10.27%
Fixed Tilt	$575/kWac	$14/kWac-yr	10.27%
Wind	$2,017/kWac	$47/kWac-yr	10.27 %
Wind (Molokaʻi)	$6,231/kWac	$67/kWac-yr	10.27%

Equation 1: LCOE Calculation

$$LCOE = \frac{(CC * FCR) + FOM}{NetCF * 8760}$$

Once the potential electrical output and LCOE has been calculated for every site across Hawaiʻi, geographic exclusions are applied to remove areas from consideration for new solar and wind deployment. Geographic exclusions consider land categories including restricted federal lands,

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[8] Ong, S., et al. *Land-Use Requirements for Solar Power Plants in the United States*. 2013, doi:10.2172/1086349.

[9] Denholm, P., et al. *Land Use Requirements of Modern Wind Power Plants in the United States*. 2009, doi:10.2172/964608.

restricted state lands, wetlands, lava flow areas, flood zones, urban areas (for utility-scale modeling), setbacks to roads and buildings, and prohibitive slope.

2.4 Analysis Results

2.4.1 Solar

The scenarios for the solar technical potential were created using both a fixed tilt system and a 1-axis tracking system. The full list of exclusions used for each scenario are listed in Appendix B, but are summarized below:

1. PV-1-3: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 3%, and Dept. of Defense lands.
2. PV-1-5: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 5%, and Dept. of Defense lands.
3. PV-1-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 40%, and Dept. of Defense lands. This is a high slope scenario.
4. PV-2-3: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 3%, but include Dept. of Defense lands.
5. PV-2-5: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 5%, but include Dept. of Defense lands.
6. PV-2-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, most agricultural areas, slope > 40%, but include Dept. of Defense lands. This is a high slope scenario.
7. PV-3-3: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, agricultural areas and Land Study Bureau Agricultural lands at 90% area exclusion, slope > 3%, but include Dept. of Defense lands.
8. PV-3-5: Exclude some federal lands, urban areas, all state parks, wetlands, lava flow areas, flood zones, agricultural areas and Land Study Bureau Agricultural lands at 90% area exclusion, slope > 5%, but include Dept. of Defense lands.

The capacity estimates for each island are listed in the tables below, and plots describing the data are included in Appendix C.

2.4.1.1 1-Axis Tracking Utility-Scale Solar PV Technical Potential Results

Table 5: Utility-Scale Solar PV Potential (MWac - 1-Axis Tracking) for O‘ahu

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	907	1954	9634	1412	2794	13965	561	1008
>= 0.12	907	1954	9634	1412	2794	13965	561	1008
>= 0.14	907	1954	9634	1412	2794	13965	561	1008
>= 0.16	906	1949	8959	1411	2788	13283	561	1006
>= 0.18	899	1920	8238	1403	2759	11971	558	994
>= 0.20	886	1862	6672	1355	2612	8945	543	938

Table 6: Utility-Scale Solar PV Potential (MWac - 1-Axis Tracking) for Moloka‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	1225	3016	13387	1225	3016	13387	1177	2918
>= 0.12	1225	3016	13387	1225	3016	13387	1177	2918
>= 0.14	1225	3016	13387	1225	3016	13387	1177	2918
>= 0.16	1225	3016	13387	1225	3016	13387	1177	2918
>= 0.18	1225	3016	12948	1225	3016	12948	1177	2918
>= 0.20	1224	3010	12344	1224	3010	12344	1176	2915

Table 7: Utility-Scale Solar PV Potential (MWac - 1-Axis Tracking) for Maui

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	1038	2669	26728	1038	2669	26728	508	1411
>= 0.12	1038	2669	26728	1038	2669	26728	508	1411
>= 0.14	1038	2669	26678	1038	2669	26678	508	1411
>= 0.16	1038	2668	26153	1038	2668	26153	508	1411
>= 0.18	1037	2667	25815	1037	2667	25815	508	1410
>= 0.20	999	2496	22540	999	2496	22540	474	1264

Table 8: Utility-Scale Solar PV Potential (MWac - 1-Axis Tracking) for Lāna‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	697	1478	9599	697	1478	9599	557	1199
>= 0.12	697	1478	9599	697	1478	9599	557	1199
>= 0.14	697	1478	9599	697	1478	9599	557	1199
>= 0.16	697	1478	9599	697	1478	9599	557	1199
>= 0.18	697	1478	9599	697	1478	9599	557	1199

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.20	697	1478	9599	697	1478	9599	557	1199

Table 9: Utility-Scale Solar PV Potential (MWac - 1-Axis Tracking) for Hawai‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10								
>= 0.12	12417	29384	117231	15083	35319	129977	13621	31841
>= 0.14	12404	29355	117093	15070	35290	129839	13608	31811
>= 0.16	12395	29261	115697	15061	35196	128443	13599	31722
>= 0.18	11682	26886	100188	14348	32821	112935	13011	29879
>= 0.20	7607	16603	73121	10272	22537	85866	9186	20405

2.4.1.2 Fixed Tilt Utility-Scale Solar PV Technical Potential Results

Table 10: Utility-Scale Solar PV Potential (MWac – Fixed Tilt) for O‘ahu

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	1021	2199	10838	1588	3143	15710	632	1134
>= 0.12	1021	2199	10838	1588	3143	15710	632	1134
>= 0.14	1018	2185	9801	1586	3129	14649	631	1128
>= 0.16	1006	2139	8160	1549	3011	11328	617	1080
>= 0.18	88	134	660	261	331	1109	99	120
>= 0.20	0	0	0	0	0	0	0	0

Table 11: Utility-Scale Solar PV Potential (MWac - Fixed Tilt) for Moloka‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	1378	3394	15060	1378	3394	15060	1324	3283
>= 0.12	1378	3394	15060	1378	3394	15060	1324	3283
>= 0.14	1378	3394	14800	1378	3394	14800	1324	3283
>= 0.16	1377	3387	14030	1377	3387	14030	1323	3280
>= 0.18	1373	3375	12343	1373	3375	12343	1319	3268
>= 0.20	0	0	0	0	0	0	0	0

Table 12: Utility-Scale Solar PV Potential (MWac - Fixed Tilt) for Maui

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	1168	3003	30069	1168	3003	30069	572	1587
>= 0.12	1168	3003	30001	1168	3003	30001	572	1587
>= 0.14	1167	3002	29378	1167	3002	29378	572	1587
>= 0.16	1162	2961	25893	1162	2961	25893	567	1552
>= 0.18	938	2161	10078	938	2161	10078	423	1041
>= 0.20	0	0	372	0	0	372	0	0

Table 13: Utility-Scale Solar PV Potential (MWac - Fixed Tilt) for Lāna‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	784	1663	10798	784	1663	10798	627	1349
>= 0.12	784	1663	10798	784	1663	10798	627	1349
>= 0.14	784	1663	10798	784	1663	10798	627	1349
>= 0.16	784	1663	10798	784	1663	10798	627	1349
>= 0.18	273	554	6417	273	554	6417	244	499
>= 0.20	0	0	0	0	0	0	0	0

Table 14: Utility-Scale Solar PV Potential (MWac - Fixed Tilt) for Hawai‘i

NetCF	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5
>= 0.10	13955	33024	131729	16954	39701	146069	15309	35788
>= 0.12	13940	32868	128694	16940	39544	143033	15295	35644
>= 0.14	12063	26810	101290	15062	33487	115630	13646	30443
>= 0.16	5922	13251	58688	8602	19608	72707	7774	18065
>= 0.18	1819	4359	21369	3805	8875	31455	3790	8723
>= 0.20	0	4	764	0	4	766	0	4

2.4.2 Wind

The full list of exclusions used for each wind scenario are listed in Appendix B, but are summarized below:

1. WIND-1-20: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 20%, and Dept. of Defense lands.
2. WIND-1-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 40%, and Dept. of Defense lands. This is a high slope scenario.

3. WIND-2-20: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 20%, but include Dept. of Defense lands.
4. WIND-2-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 40%, but include Dept. of Defense lands. This is a high slope scenario.
5. WIND-3-20: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 20%, road, building, and transmission right-of-way setbacks, and Dept. of Defense lands.
6. WIND-3-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 40%, road, building, and transmission right-of-way setbacks, and Dept. of Defense lands. This is a high slope scenario.
7. WIND-4-20: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 20%, road, building, and transmission right-of-way setbacks, but include Dept. of Defense lands.
8. WIND-4-HS: Exclude some federal lands, urban areas, all state parks, wetlands, lave flow areas, flood zones, most agricultural areas, slope > 40%, road, building, and transmission right-of-way setbacks, but include Dept. of Defense lands. This is a high slope scenario.

The capacity estimates for each island are listed in the tables below, and plots describing the data are included in Appendix C.

Table 15: Wind Potential (MWac) for O‘ahu

WS (m/s)	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
>= 6.5	436	761	640	1147	230	465	333	728
>= 7.5	255	521	427	870	129	312	214	553
>= 8.5	164	359	317	681	89	224	167	450

Table 16: Wind Potential (MWac) for Moloka‘i

WS (m/s)	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
>= 6.5	951	1249	951	1249	688	958	688	958
>= 7.5	931	1226	931	1226	677	945	677	945
>= 8.5	562	766	562	766	389	576	389	576

Table 17: Wind Potential (MWac) for Maui

WS (m/s)	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
>= 6.5	634	940	634	940	421	659	421	659
>= 7.5	461	646	461	646	305	441	305	441
>= 8.5	308	434	308	434	200	293	200	293

Table 18: Wind Potential (MWac) for Lāna‘i

WS (m/s)	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
>= 6.5	381	441	381	441	312	368	312	368
>= 7.5	253	289	253	289	215	250	215	250
>= 8.5	109	118	109	118	83	90	83	90

Table 19: Wind Potential (MWac) for Hawai‘i

WS (m/s)	WIND-1-20	WIND-1-HS	WIND-2-20	WIND-2-HS	WIND-3-20	WIND-3-HS	WIND-4-20	WIND-4-HS
>= 6.5	1189	1254	1189	1254	982	1039	982	1039
>= 7.5	742	791	742	791	592	633	592	633
>= 8.5	538	570	538	570	415	441	415	441

2.4.3 Geospatial Data Layers

In order to allow for greater input from stakeholders and the public, web mapping applications were set up to allow for the visualization of the inclusion areas derived from the exclusion assumptions described above. The layers created for each of the PV and Wind exclusion scenarios can be visualized and evaluated by the public using the URLs below. Please note that in the case of the 1-axis tracking vs. fixed tilt PV systems, the inclusion areas do not change as the exclusion assumptions are not altered between the two PV system types. The capacity factors and installable capacity are different, as is apparent from the results tables above, but the actual areas of land included do not change, therefore there are only 1 set of PV exclusion layers listed in the web mapping applications below:

- Solar Inclusion Map Application: https://bit.ly/33pJ0ep
    - Full URL: https://nrel.carto.com/u/gds-member/builder/8f3209fc-76ba-41a7-9b3f-1947e056bf41/embed
- Wind Inclusion Map Application: https://bit.ly/34ncwkr
    - Full URL: https://nrel.carto.com/u/gds-member/builder/70be8a3c-7643-41c3-8169-0a11235136ba/embed

The layers visualized in the applications above can also be downloaded and viewed within open-source Geographic Information System (GIS) software including Quantum GIS, or within proprietary GIS software including ArcGIS:

- Maps and Data: https://bit.ly/34jAMUv
    - Full URL: https://app.box.com/s/qskohxbi5678g88iehi10msmq0vby2rv

2.5 Next Steps

The technical potential analysis described above provides insight into the availability of high quality wind and solar resources for Hawai‘i. Using the results, maps, and data layers made available to the public, additional investigation into available lands can be conducted to find the best suitable land for new solar and wind development. Though the technical potential analysis does not substitute on-the-ground investigation, community acceptance, and other policies, it allows for greater efficiency in focusing on lands with high resource potential and favorable land use considerations.

3 Distributed-Scale Technical Potential Analysis

3.1 Background

This section of the report focuses on quantifying the technical potential of photovoltaic systems deployed on existing suitable roof areas in the Hawaiian Electric service territory. Technical potential is a metric that quantifies the maximum generation available from a technology for a given area and does not consider the economic or market viability. Distributed-Scale technical potential refers to small-scale technologies to produce electricity (1 kW-100 MW) close to the end users of power, specifically rooftop-mounted solar photovoltaic panels in this case. Rooftops provide a large expanse of underutilized areas for solar energy generation. Rooftop solar can be stand-alone, particularly in the case of microgrids. Additionally, rooftop solar can reduce demand on the grid at peak times, minimizing congestion of power on the network. In cases such as Hawai'i, which is an evening peaking system, rooftop solar generation is most effective when paired with storage.

Several existing tools and methods can be used to estimate the solar energy potential of a single home or building, including Google's Project Sunroof and Mapdwell's SolarSystem. Although Project Sunroof has some detailed analysis in parts of Hilo, Kailua-Kona, Kihei, Wailea-Makena, Kahului, and other municipalities in southern Oʻahu, its coverage is incomplete while Mapdwell has not published any data products for the state of Hawaiʻi. NREL has not previously estimated rooftop solar technical potential in Hawaiʻi[10]. To fill these gaps, we provide a data-driven analysis of building and parcel level rooftop PV suitability and technical electricity-generation potential. This analysis expands upon previous NREL research investigating rooftop solar technical potential using light detection and ranging (LiDAR) scans of individual rooftops in 128 metropolitan regions in the continental United States[11].

3.2 Data Inputs

Assessing rooftop solar technical potential requires three primary data sets: continuous model of the built environment, building footprints, and solar resource data. The building environment model and building footprints are processed to determine the shading, tilt, and azimuth of each rooftop at a horizontal resolution between 0.5-2 square meters. A set of criteria is then applied to determine what roof area is suitable for PV deployment. Following delineation of suitable roof areas, those suitable roof areas are used to estimate electricity-generation using NREL's System

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[10] Gagnon, P., R. Margolis, J. Melius, C. Phillips, and R. Elmore. 2016. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65298. https://www.nrel.gov/docs/fy16osti/65298.pdf.

[11] Gagnon, P. R. Margolis, J. Melius, C. Phillips, and R. Elmore. 2018. "Estimating Rooftop Solar Technical Potential Across the US Using a Combination of GIS-Based Methods, LiDAR Data, and Statistical Modeling." *Environmental Research Letters* 13(2):024027. https://doi.org/10.1088/1748-9426/aaa/554,

Advisor Model[12]. These results can be aggregated to determine the total quantity of roof area suitable for PV systems at the building, parcel, island levels, and beyond.

3.2.1 Lidar Point Clouds

To model the built environment, primarily targeting building rooftop surfaces as well as shading obstructions, we use LiDAR scans to create high-resolution digital surface models. Rooftop surfaces models can also use photogrammetric surface models, such as Project Sunroof, or other 3D products. High resolution LiDAR scans allow for increased precision in mapping rooftop planes and features, including gutters, ridges, troughs, and appurtenances.

Light Detection and Ranging (LiDAR or Lidar) is an active remote sensing system that emits light quickly strobing from a laser light source. The light travels to the ground and reflects off of things in-between the sensor and the ground. A Lidar system measures the time it takes for emitted light to travel to the ground and back and calculates distance traveled for each pulse. This distance can be converted to elevation. These measurements are made using a Global Positioning System that identifies the X, Y, Z location of the light energy as well as an Internal Measurement Unit that provides the orientation of the sensor.

Lidar data attributes vary depending on how the data were collected and processed, which are typically listed in point cloud or survey metadata files. Most Lidar points have an intensity value (representing the amount of light energy recorded by the sensor), horizontal coordinates, and elevation. Some Lidar data are also classified before release, indicating the type of object that the laser return reflected off of. Classified data typically omit unwanted noise from the first-returns surface and reduce the overall data volume to be processed. However, they can sometimes omit usable data that indicate rooftop appurtenances. Unclassified data typically pass artifacts and systematic biases on to the released data product.

Table 20. 3DEP Lidar Point Cloud Quality Levels

Quality Level	Pulse Spacing (m)	Pulse Density (pls/m^2)	Overall Vertical RMSE	Minimum Derived Surface Resolution (m)
QL0	≤0.35	≥8.0	≤0.05	0.5
QL1	≤0.35	≥8.0	≤0.10	0.5
QL2	≤0.71	≥2.0	≤0.10	1
QL3	≤1.41	≥0.5	≤0.20	2

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[12] Blair, N., N. NiOrio, J. Freeman, P. Gilman, S. Janzou, T. Neises, and M. Wagner. 2018. *System Advisor Model (SAM) General Description (Version 2017.9.5)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70414. https://www.nrel.gov/docs/fy18osti/70414.pdf.

Assessing rooftop suitability for PV arrays requires a maximum first-returns surface model spatial resolution of 2 meters. This resolution requirement is based on the maximum pulse spacing and density and overall effects to accuracy (Table 3). As standards have changed in the past decade, current specifications from United States Geological Survey (USGS) and Federal Emergency Management Agency (FEMA) require Quality Level 2 (QL2) for most purposes[13]. Lidar data at Quality Level 3 may be used for non-essential mapping.

The Lidar data used in this analysis were obtained directly from the State of Hawaiʻi[14], USGS[15], or indirectly NOAA's Interagency Elevation Inventory[16]. In Hawaiʻi, most publicly available Lidar data was collected for the purpose of shoreline mapping, flood risk mapping, and bathymetric mapping by federal or state agencies. Bathymetric Lidar is not suitable for terrestrial mapping since the sensors operate in different wavelengths and capture different targets. The availability of Lidar for this study is biased to the coastlines except for the Island of Oʻahu, where most of the island was covered in a single collection from 2013 (Dewberry 2014). For this analysis, 15 separate Lidar datasets were processed to derive first-return surface (Table 2). These datasets were collected by contractors separately on behalf of federal and state agencies or by scholars and released by federal agencies. The datasets vary significantly in quality and accuracy. Each survey was processed and modeled using its minimum achievable resolution. The spatial distribution of aggregated survey statistics can be found in Table 20.

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[13] FEMA. 2016. "Guidance for Flood Risk Analysis and Mapping: Elevation Guidance." Guidelines and Specifications for Flood Hazard Mapping Partners and Procedure Memorandum 61 – Standards for LiDAR and Other High Quality Digital Topography, Appendix A.

[14] State of Hawaii GIS Program. 2002-2018. *Lidar Point Clouds Collection.* [LAZ compressed point clouds]. Retrieved from https://histategis.maps.arcgis.com/apps/webappviewer/index.html?id=7c22201923084f749e6626e3e195de71.

[15] USGS. 2020. *The National Map: 3DEP Lidar Point Clouds.* [LAZ compressed point clouds]. Retrieved from https://viewer.nationalmap.gov/basic/.

[16] NOAA. 2020. *United States Interagency Elevation Inventory*. [LAZ compressed point clouds]. Retrieved from https://coast.noaa.gov/inventory/.

Table 21. Lidar Surveys Processed for Rooftop Solar Technical Potential

Distributor	Island	Survey Name	Project Name	Classified	Cell Size	Collection Year
NOAA	Hawaiʻi	Big Island Extracted	FEMA Lidar: Hawaiian Islands	X	2	2006
	Lānaʻi	Lānaʻi Last Pulse Extracted	FEMA Lidar: Hawaiian Islands	X	2	2006
	Maui	Maui Last Pulse Extracted	FEMA Lidar: Hawaiian Islands	X	2	2006
	Oʻahu	Oʻahu 2013	NOAA Oʻahu	X	2	2013
State of Hawaiʻi GIS	Hawaiʻi	Kilaeuea A1	Kilaeuea Volcano		0.5	2018
		Kona Extract	DBEDT Lidar: Hawaiʻi Kona		2	2006
		Pelekane	Pelekane Watershed		0.5	2015
	Lānaʻi	Lānaʻi A1	Unknown	*	2	
	Maui	Central BE	Unknown		1	2015
		femafema	DBEDT Lidar: Maui (Kihei)		2	2005
		Prior1A Extract	DBEDT Lidar: Maui (Kihei)		2	2005
		Prior1B Extract	DBEDT Lidar: Maui (Kihei)		2	2005
		Maui PSC	Maui (West Coast) and Oʻahu (Ewa to Honolulu)		2	2005
		Upcountry	Maui County Lidar: Maliko to Nahiku		2	2005
USGS	Hawaiʻi	OT Puna	Kohala Peninsula	X	0.5	2013

3.2.2 Buildings

Building footprints data sets represent the planimetric extent and shape of a building in vector format. Building footprints do not represent building area except in the cases of single-story buildings. Microsoft's US Building Footprints data set for Hawai‘i was used for this analysis. This computer-generated building footprints data set uses semantic segmentation and polygonization to delineate building extent from high resolution true color aerial imagery (Microsoft 2019). The classifier is trained on 5 million labeled images, primarily for residential areas, in a diverse set of land cover settings. In the majority of cases, the quality of this data is at least as good as digitized buildings in OpenStreetMap. Its accuracy is diminished in dense urban areas.

In Hawai‘i, Microsoft has recorded 252,891 building footprints while the islands of Hawai‘i, Lāna‘i, Maui, Moloka‘i, and O‘ahu have a combined 234,036 building footprints. Of these building footprints on the five-island territory, 75% of these building footprints overlap with extant Lidar data (Table 21). These buildings constitute 51,889 square kilometers of rooftop area with built environment models. However, 16,281 square kilometers of rooftop area within the five-island territory do not have corresponding built environment models.

Table 22. Distribution of Buildings Relative to Available Lidar

	Hawai‘i	Lāna‘i	Maui	Moloka‘i	O‘ahu	Total
Buildings Count	65,224	1,182	31,641	2,027	133,949	234,023
Buildings with Lidar Data	16,848	27	30,306	-	129,692	176,873
Buildings without Lidar Data	48,376	1,155	1,335	2,027	4,257	57,150
Proportion of Buildings with Lidar	29%	5%	96%	0%	97%	
Square Kilometer of Building Footprint with Lidar	5,629	16	8,994	-	37,248	51,887

Even though the Microsoft buildings data set is not the most accurate buildings data set for all areas in Hawai‘i, it is one of the only statewide available data sets for buildings in Hawai‘i. Two municipal data sets, Building Footprints 2013 and Building Footprints (City and County of Honolulu), for O‘ahu only were found that are manually maintained and updated. County-maintained building data sets outside of O‘ahu and City and County of Honolulu were not publicly available at time of this analysis. Within the study area, 92% of buildings are considered small (≤ 5,000 square feet per footprint) with 7% and 1% considered medium (5,000-25,000 square feet per footprint) and large (25,000+ square feet per footprint) respectively.

3.2.3 Spatiotemporal Resource Data

Similar to the utility-scale PV analysis, NSRDB[17] was used for calculating the PV generation for a roof-mounted fixed-tilt solar system. The NSRDB provides half-hourly temporal resolution and

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[17] Manajit Sengupta et al., “The National Solar Radiation Data Base (NSRDB),” *Renewable and Sustainable Energy Reviews* 89 (2018): 51–60, https://doi.org/10.1016/j.rser.2018.03.003.

4-kilometer nominal spatial resolution weather data for most of the Northern hemisphere. Generation for years 2014 through 2018 was calculated for these prospective arrays on suitable roof planes.

3.3 Modeling Approach

3.3.1 PV Rooftop Model

This section presents an overview of our approach to (1) estimating the rooftop area that is suitable for rooftop solar and (2) estimation of building technical potential. These methods allow for accurate and flexible modeling of roof plane suitability for solar PV deployment and estimation of corresponding technical potential. This analysis builds on previous work by NREL (Gagnon et al. 2016) using Lidar data to model rooftop suitability for solar photovoltaics. Lidar first return surfaces can be used to infer the presence of individual buildings and their footprints, as well as the area, tilt, azimuth, and shading of each distinct geometric plane on a building's roof. Based on these characteristics, the technical performance for individual planes suitable for solar PV are estimated using the System Advisor Model, which are aggregated to building-level estimates.

3.3.1.1 Shading

Using the Lidar scans of areas within the Hawaiian Electric service territory, NREL developed a geospatial predictive model to identify rooftop panes suitable for rooftop-mounted solar PV given the roof's orientation (tilt and azimuth) and shading characteristics. Lidar scans, as opposed to aerial imagery, allow us to infer the building footprint and unshaded roof area, azimuth, and tilt for each distinct roof plane. To account for potential shading from adjacent buildings, vegetation, topography, and other obstacles, hourly shading models were generated using NREL's Solar Position Algorithm[18] and the Lidar first-returns digital surface models for roof pixel areas. The altitude and azimuth of the sun and local slope and aspect of the Lidar surface are used to calculate local illumination for a specific pixel as described by Equation 2 and illustrated by Figure 4, a value proportional to the direct solar energy that reaches the pixel. Local areas were defined as within three neighboring pixels for the purpose of this study, which may vary by proposed system size.

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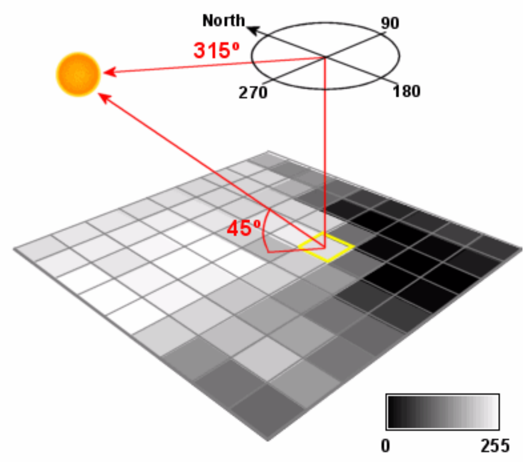
[18] Reda, I. and A. Andreas. 2008. *Solar Position Algorithm for Solar Radiation Applications.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-560-34302. https://www.nrel.gov/docs/fy08osti/34302.pdf.

Equation 2: Per-pixel illumination calculation using Lidar first-returns digital surface model

$$Illumination = 255 * \begin{pmatrix} \cos(90 - solar\ altitude) * \cos(local\ slope) \\ +(\sin(90 - solar\ altitude) * \sin(local\ slope) \\ * \cos\ (solar\ azimuth - local\ aspect) \end{pmatrix}$$

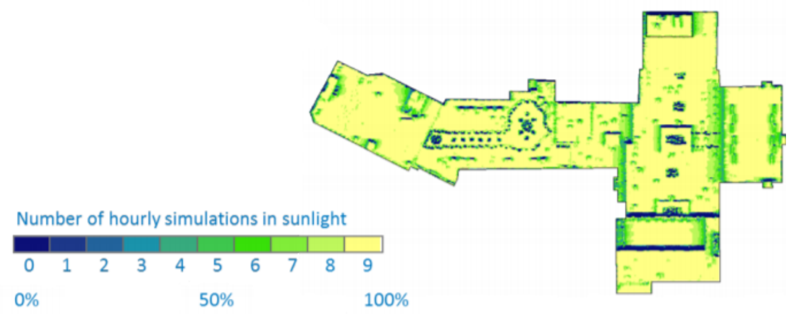
Figure 4: Scene model for calculating local illumination (0-255)



In addition to considering illumination, each hourly shading model considers a direct line-of-sight from each pixel to the sun. If a 3D line-of-sight from any given pixel to the sun is interrupted, whether from architecture, topography, vegetation, or other obstacle, the pixel is considered to be shaded in that hourly occurrence. Hourly shading models represent percent illumination for each pixel unless the pixel does not receive direct solar energy in that hour.

As shading varies seasonally, hourly shading models were generated for four days of the most recent analysis year – the vernal equinox (March 20), summer solstice (June 21), autumnal equinox (September 22), and winter solstice (December 21). These shading models result in the number of hours of sunlight each square meter of roof area received on those simulated days as shown in Figure 5. The hours of sunlight from the four representative days were used to determine the daily sunlight for each square meter, and this metric was used to exclude roof areas that are excessively shaded (≥ 20% total overall shading). Previous uses of the PV Rooftop model by Gagnon et al. 2016 considered excessively shaded areas to be areas not contributing towards meeting 80% of unshaded generation potential.

Figure 5: Visualization of roof plane irradiance based on plane tilt, azimuth, and shading. Replicated from Gagnon et al. 2016.



3.3.1.2 Azimuth and Tilt

The tilt (slope) and orientation (azimuth) of a roof plane is important for determining its suitability for PV as well as creating a generation profile. Using the first returns of the Lidar, we determine the average tilt and azimuth of each square meter of roof area. Each square meter was categorized into one of nine azimuth classes, shown in Figure 6, where tilted roof areas were assigned one of the eight cardinal and primary intercardinal directions. Planes with a slope less than 9.5° were classified as flat or open. For roof planes with slopes above 9.5°, we used five non-flat tilt classes. Roof planes that fall within the thresholds of a given class between 9.5° and 60° are assigned a midrange tilt for the tilt class. For example, any roof plane with a slope between 22.1° and 34.8° was considered to use an array tilt of 28.4° as shown in Figure 7. For roof planes classified as flat, an array tilt of 15° was assumed.

Figure 6: Azimuth classes of roof planes possible (left); azimuth classes considered suitable for solar PV deployment (right). Adapted from Gagnon et al. 2016.

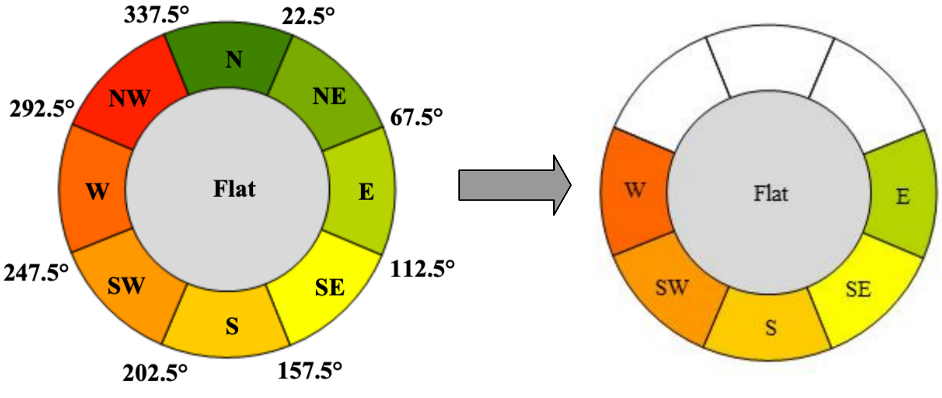
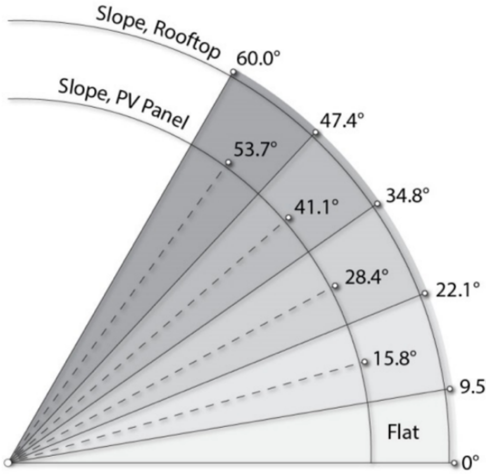


Figure 7: Roof plane slope and corresponding solar array tilt (Gagnon et al. 2016).



The tilt and azimuth values of the roof square meter to identify distinct roof planes, assuming contiguous areas of identical tilt-azimuth classes were a unique plane, aggregating each of the individual square meters of roof area into polygons representing contiguous roof planes. This results in a classification of tilt and azimuth for each unique roof plane. To identify developable surfaces for PV installment, a zonal mean neighborhood function was used to identify and remove data noise and complex features on roofs (e.g., peaks, edges, troughs, chimneys, appurtenances).

Finally, roofs were filtered for developable rooftop surfaces that met basic PV suitability requirements, such as being east-, south, or west-facing and having a contiguous minimum developable area (see Table 22). Excessively shaded areas were then excluded from these developable areas. The end result is a database of rooftop plane-level data with detailed attribution regarding the plane slope, array tilt, azimuth, and developable area of all suitable rooftops in the service territory.

Table 23. Criteria for Determining Roof Plane Suitability for Solar PV

Roof Plane Characteristic	Commercial Buildings	Residential Buildings
Shading	≤ 20%	
Azimuth	90° - 270°	
Tilt	≤ 60°	
Minimum Developable Area	≥3.63 m^2	≥1.63 m^2

3.3.1.3 System Performance

Once developable roof areas are delineated and classified, solar generation profiles were simulated for each distinct developable roof plane using the PVWatts7 model in the System Advisor Model (SAM). SAM[19] is a performance and economic model designed to facilitate decision making and analysis for renewable energy projects[20]. It uses time series meteorological data, a PV performance model, and user-defined assumptions to simulate the technical performance of a given solar installation. To simulate PV productivity, this study used a 5-year range of solar irradiance time-series data from the NSRDB, summarizing generation and capacity factor profiles for the 2014-2018 meteorological years. Using time-series data, as opposed to typical meteorological year (TMY) data, is preferable for grid integration studies since it captures variability and correlation of load and variable renewable resources. Table 23 summarizes the rooftop solar PV configuration parameters used in this analysis.

Table 24: Assumptions for PV Performance Simulations

PV System Characteristic	Commercial Buildings	Residential Buildings
Ratio of module area to roof area[21]	0.7 for flat roofs 0.98 for tilted roofs	
Module power density	170 W/m^2	172 W/m^2
Total system losses	14.08%	
Inverter efficiency	98%	
DC-to-AC ratio	1.0	

The capacity density values used in this analysis correspond to a commercial module with 19.3% efficiency and a residential module with 19.6% efficiency, both with an overall packing efficiency of 88%. These values were selected to represent an installed mixture of primarily monocrystalline-silicon systems based on early 2020 average benchmarks from the California Net Energy Metering Database and the most recent release of Lawrence Berkeley National Laboratory's *Tracking the Sun*[22]. The losses from soiling, shading, wiring, and other sources are captured in the total losses system parameter, which was chosen to remain at the SAM default value for this analysis. A DC-to-AC ratio of 1.0 was selected based on sizing of existing systems in the Hawaiian Electric service territory.

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[19] Documentation of the mathematical models used by SAM can be found internally within the program, under the "Help" section. For more information, see sam.nrel.gov.

[20] Blair et al. 2018

[21] For flat roofs, the ratio of module area to roof area was assumed to 0.7 to reflect the row spacing necessary to incur only approximately 2.5% losses from self-shading for south-facing modules at a 15-degree tilt. For tilted roofs, the value was assumed to be 0.98 to reflect the 1.27 cm spacing between each module for racking clamps.

[22] Barbose, G., N. Darghouth. 2019. *Tracking the Sun: Pricing and Design Trends for Distributed Photovoltaic Systems in the United States*. Berkeley, CA: Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/tracking_the_sun_2019_report.pdf.

3.3.2 Suitable Area Imputation

The Lidar datasets used for this analysis span 76% of the buildings in the Hawaiian Electric service territory. To estimate rooftop solar PV technical potential in these areas without Lidar coverage, a Random Forest statistical model was developed to impute the developable areas for the missing buildings. A suite of candidate variables (USCB 2018, USFS 2016, NSRDB 2014-2018) representing building, land attributes, solar resources, and population characteristics was explored to identify those with the greatest explanatory power for developable area by building.

For buildings where developable area was imputed, summarized generation and capacity factors for the same 5-year range was completed as was done for modeled roof planes. PV performance characteristics remained the same. Planes on these buildings were assumed to have a slope equaling the mean slope of their corresponding training samples, a 180° azimuth, and 8% shade (SAM default). This approach was taken to preserve local trends of solar resource data where imputation was necessary. Imputing generation per building alone instead of the built environment assumes that solar resources and variability are equivalent across sampling areas, which is not true in this case.

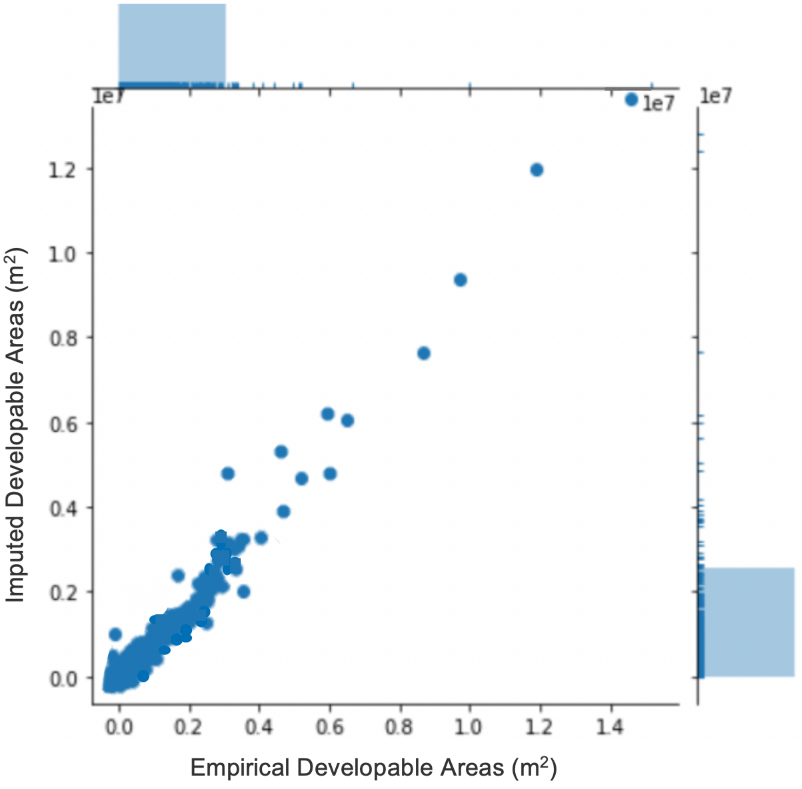
Table 25: Imputation and training set summary

Subset	Training Set Description	Sample Set Description	Training Set Size	Buildings Imputed	Accuracy (%)
A	Oʻahu: valleys (exclude Halawa Valley, UH campus)	Oʻahu: deep valleys	4,653	3,773	94
B	Oʻahu: Schofield Barracks	Oʻahu: Schofield Barracks	16,826	484	97
C	Hawaiʻi: Kailua-Kona	Hawaiʻi: Captain Cook, Kēōkea	12,120	3,568	95
D & E	Oʻahu: Waianae/Makaha Maui: Kula	Hawaiʻi: Southern Hawaiʻi Island, Milolii, Ocean View, Nāʻālehu	6,368	7,100	89
F	Maui: Haiku-Pauwela, Makawao, Pukalani, Kula, Keokea	Hawaiʻi: Hawaiian Paradise Park, Pāhoa	8,545	13,017	92
G	Oʻahu: Kaneohe	Hawaiʻi: Hilo	9,619	15,228	90
H & I	Maui: Pukalani, Makawao, Kula	Hawaiʻi: Waimea	7,905	8,136	95

J	Maui: North Kihei	Molokaʻi: Kanunakakai and surrounding area	6,533	3,482	93
K	Maui: Haiku-Pauwela	Molokaʻi: East Molokaʻi	5,585	1,269	91
L	Maui: Pukalani, Makawao	Lānaʻi: Lānaʻi City	5,587	1,093	92

The Random Forest statistical model was trained on an 80% subset of buildings with modeled developable areas from training areas provided by Hawaiian Electric. Table 24 references these training and sample sets. Various permutations of the Random Forest model were assessed against withheld training data subsets to inform optical hyper-parameterization. We evaluated the performance of the best trained model as determined by cross-validation against the remaining buildings in the training subset that were not used in model training. Overall, the training models were found to have a high degree of accuracy (R^2=0.92) between modeled developable area and imputed developable area (Figure 8). The goodness-of-fit comes from the building footprint areas, which are highly correlated with rooftop developable area and generation potential (R^2=0.88). Through model interrogation, the five most significant predictors of developable area were (in order of most to least significant) were building footprint area, building elevation, building aspect, canopy cover, and building footprint length-to-width ratio.

Figure 8: Scatter plot of modeled rooftop developable area and imputed rooftop developable area



3.4 Analysis Results

3.4.1 All Islands

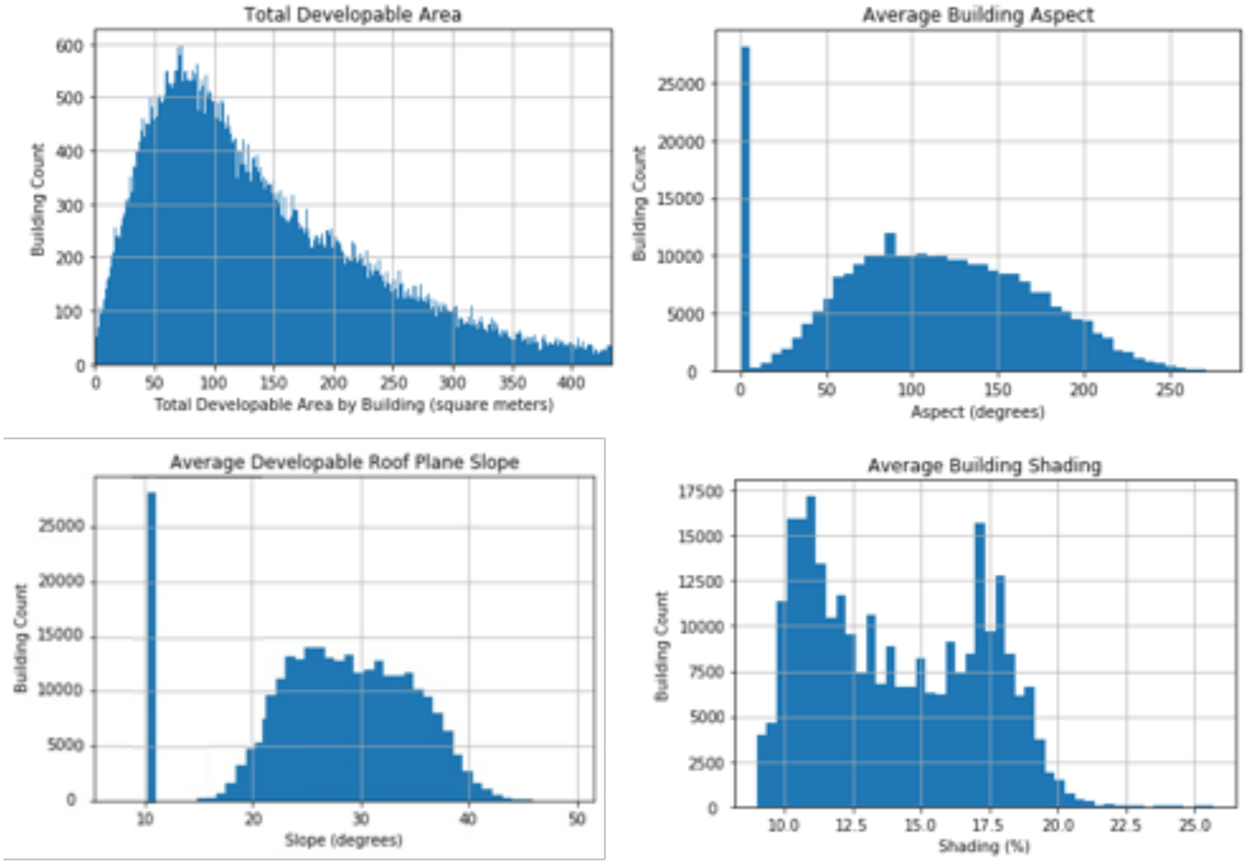
NREL estimates a total of 328,300 m^2 of developable area for rooftop solar on buildings in the Hawaiian Electric service territory (Table 25). Assuming the capacity densities given above, and adjusting for modeled shading, this corresponds to 7.3 GW_{DC} of capacity, or 14.608 TWh of annual generation. Of the 176,873 buildings that were modeled, 95% were deemed to be solar-suitable. The overall developable area of residential buildings is 23.76 km^2 while the overall developable area of commercial and industrial buildings is 17.970 km^2. Residential buildings (n = 156,843) have the highest rooftop potential at 4.124 GW while commercial and industrial buildings (n = 75,890) have 3.176 GW in rooftop potential. Potential annual generation for residential buildings is 7,448 GWh and 5,591 GWh for commercial and industrial buildings. This analysis modeled 79% of residential buildings and 69% of commercial and industrial buildings in the Hawaiian Electric service territory. The model found 18 residential buildings, typically multi-family dwellings, with the 1 MW or greater potential capacity; 99 commercial and industrial buildings also have 1 MW or greater potential capacity.

Table 26: Technical potential results by island and zone

Island	**Developable Planes** (thousands)	**Developable Plane Areas** (km^2)	**Capacity** (MW)	**Generation** (GWh)	**Capacity Factor** (%)
Hawaii	369	15,560	2,163	4,586	19.42
Commercial	*31,969 buildings*	*8,336*	*1,239*	*2,471*	*19.32*
Residential	*32,917 buildings*	*7,224*	*924*	*2,113*	*19.46*
Lanai	1	355	44	112	21.20
Commercial	*220 buildings*	*106*	*14*	*34*	*21.19*
Residential	*935 buildings*	*248*	*29*	*78*	*21.08*
Maui	643	5,768	1,113	1,858	21.05
Commercial	*10,654 buildings*	*2,878*	*559*	*932*	*21.10*
Residential	*20,347 buildings*	*2,889*	*553*	*925*	*21.02*
Molokai	-	378	45	112	20.05
Commercial	*1,198 buildings*	*240*	*28*	*71*	*20.22*
Residential	*772 buildings*	*138*	*17*	*41*	*19.80*
Oahu	1,750	19,968	3,934	6,369	21.23
Commercial	*31,849 buildings*	*6,408*	*1,334*	*2,082*	*21.17*
Residential	*101,872 buildings*	*13,260*	*2,599*	*4,287*	*21.25*
Total	**2,763**	**42,049**	**7,299**	**13,047**	**20.59**

Modeled roof planes and buildings in the Hawaiian Electric service territory regarded as suitable are generally southern-facing with low-to-moderately sloped roofs (78%). The majority of suitable roof planes for rooftop PV are < 10 square meters, which would not have been included in the technical potential assessment in previous versions of the PV Rooftop model that excluded all planes that did not have at least 10 square meters of contiguous developable area on a single plane. Average plane and building shading follow a bimodal distribution, illustrating clear priority on planes with low shading for rooftop solar deployment.

Figure 9: Summary distributions for roof plane and building models



Throughout the study area, building-level data were aggregated to Hawai‘i’s Tax Map Key (TMK) objects[23]. Appendix C.4 contains results from the rooftop solar technical potential analysis at the TMK level. A corresponding rooftop solar resource capacity factor map can be found in Appendix A.

3.4.2 O‘ahu

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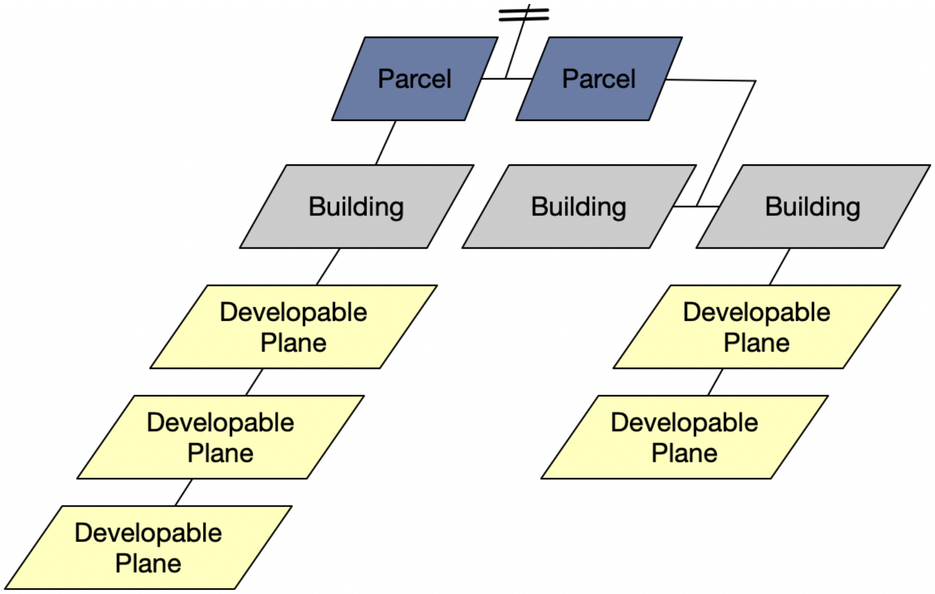
[23] State of Hawaii GIS Data Portal. 2018. *Tax Map Key Parcels*. [Shapefile]. Retrieved from https://geoportal.hawaii.gov/datasets/parcels-hawaii-statewide.

Hawaiian Electric requested that building-level results of the rooftop solar technical potential analysis be extended to existing Hawaiian Electric customers and infrastructure datasets, including node, circuit, and substation. Hawaiian Electric furnished these data for Oʻahu. Tables for these different entities are available as attachments to this report.

In joining distribution levels to building production data, customer addresses were geocoded using Mapquest Forward Geocoding API. Representative point geometries for these entities were compiled in a convex hull around shared nodes ("AccessNode"). Collected node polygons were compared to aggregated parcels with a node identifier. Node-aggregated parcels better corresponded to discrete areas in which DPV electricity generation could be directly connected. From the connections shown in Figure 9, generation is aggregated to node, circuit, and substation respectively. There is additional uncertainty in the relationship of individual customers to nodes, nodes to circuits, and circuits to substations due to the imperfection of geocoding accuracy as well as inconsistent data typing between these entities.

Figure 10: Hierarchical database model for DPV distribution



3.5 Next Steps

Several opportunities exist to improve the methods and data used in this section of the report. The geographic span of Lidar scans is restricted to predominantly Oʻahu and Maui with large gaps on Hawaiʻi, Lānaʻi, Molokaʻi. In fiscal year 2020, the United States Geological Survey is set to collect new Lidar scans at a sufficiently high quality (QL2) to update and complete this modeling effort[24]. Additional customer data and distribution network data would allow Maui, Hawaiʻi, Lānaʻi, and Molokaʻi rooftop solar generation estimates to be aggregated beyond parcels. Finally, while the methods of PV Rooftop model have been validated previously[25], validation of NSRDB time series against measured irradiance data as well as existing rooftop PV system performance against modeled performance are needed.

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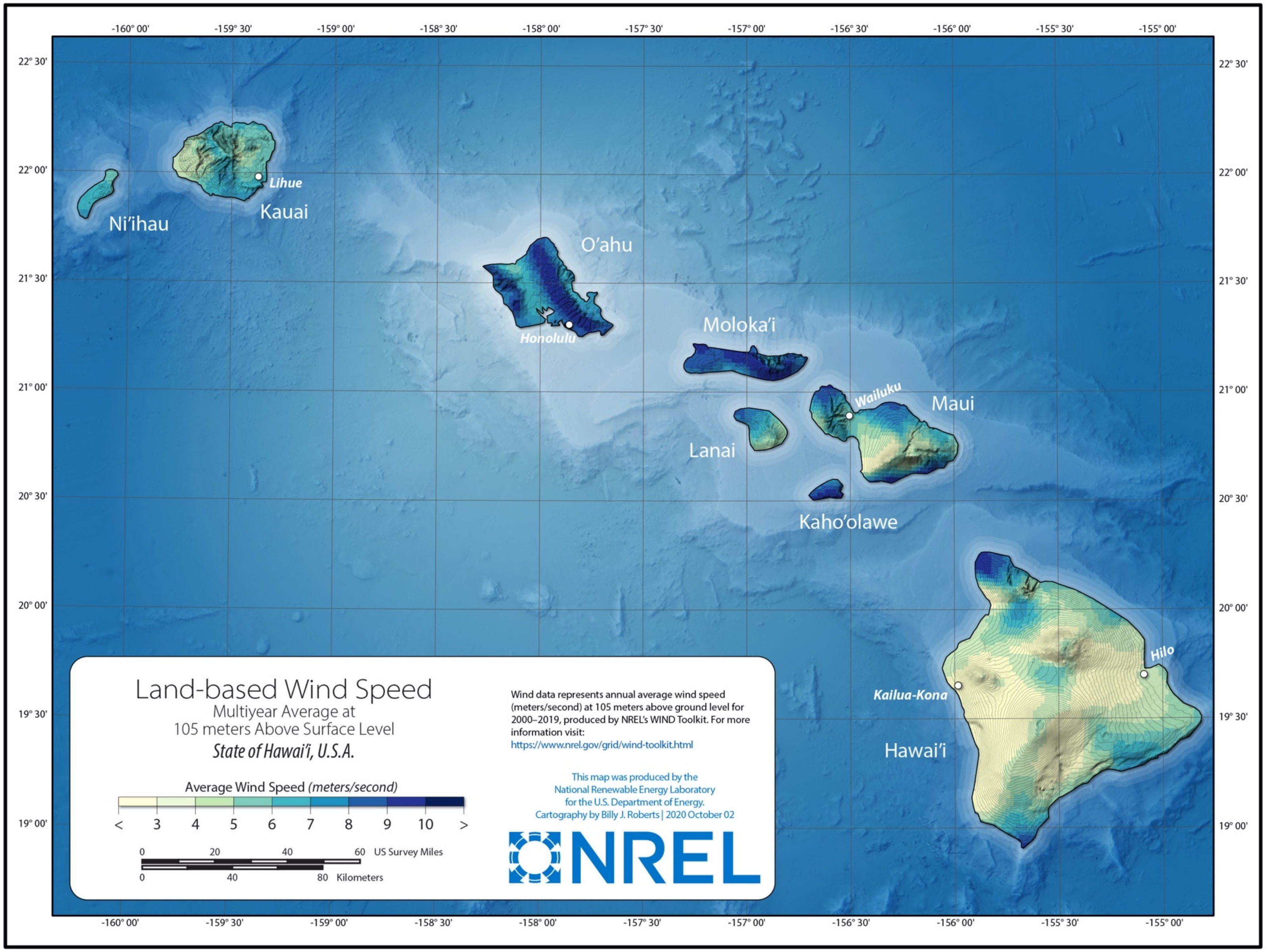
[24] USGS. 2019. "FY19/20 Broad Agency Agreements and Awards (Solicitation G19AS00124)." Online document. Accessed 10 June, 2020. https://www.usgs.gov/core-science-systems/ngp/3dep/3d-elevation-program-broad-agency-announcement-baa-2020-awards.

[25] Melius, J. R. Margolis, and S. Ong. *Estimating Rooftop Suitability for PV: A Review of Methods, Patents and Validation Techniques*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-60593. https://www.nrel.gov/docs/fy14osti/60593.pdf.

Appendix A. Solar and Wind Resource Maps



Land-based Wind Speed

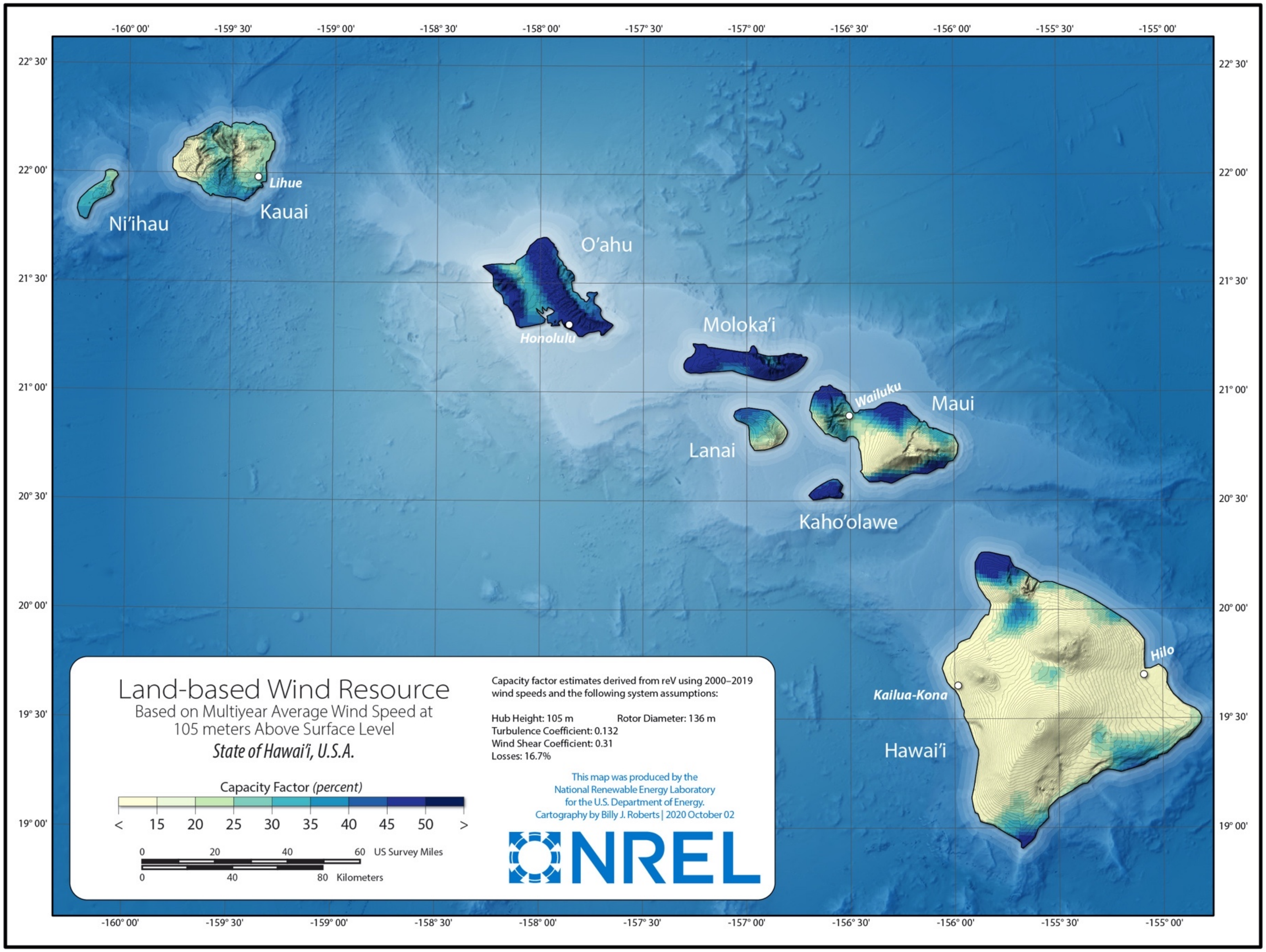
Multiyear Average at
105 meters Above Surface Level

State of Hawai'i, U.S.A.

Wind data represents annual average wind speed (meters/second) at 105 meters above ground level for 2000–2019, produced by NREL's WIND Toolkit. For more information visit:
https://www.nrel.gov/grid/wind-toolkit.html

This map was produced by the
National Renewable Energy Laboratory
for the U.S. Department of Energy.
Cartography by Billy J. Roberts | 2020 October 02

NREL

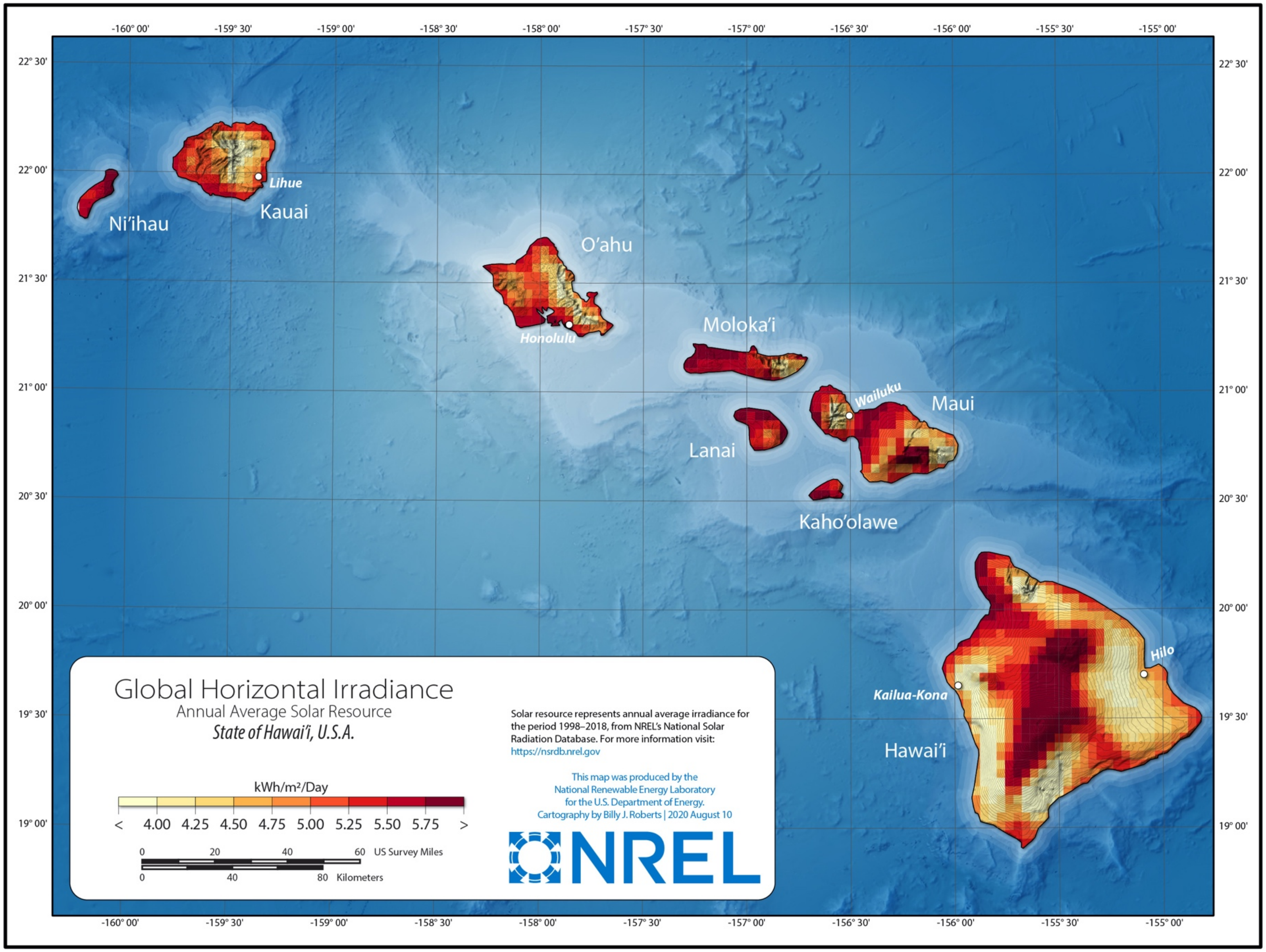


Land-based Wind Resource
Based on Multiyear Average Wind Speed at
105 meters Above Surface Level
State of Hawai'i, U.S.A.

Capacity factor estimates derived from reV using 2000–2019 wind speeds and the following system assumptions:

Hub Height: 105 m
Rotor Diameter: 136 m
Turbulence Coefficient: 0.132
Wind Shear Coefficient: 0.31
Losses: 16.7%

This map was produced by the
National Renewable Energy Laboratory
for the U.S. Department of Energy.
Cartography by Billy J. Roberts | 2020 October 02



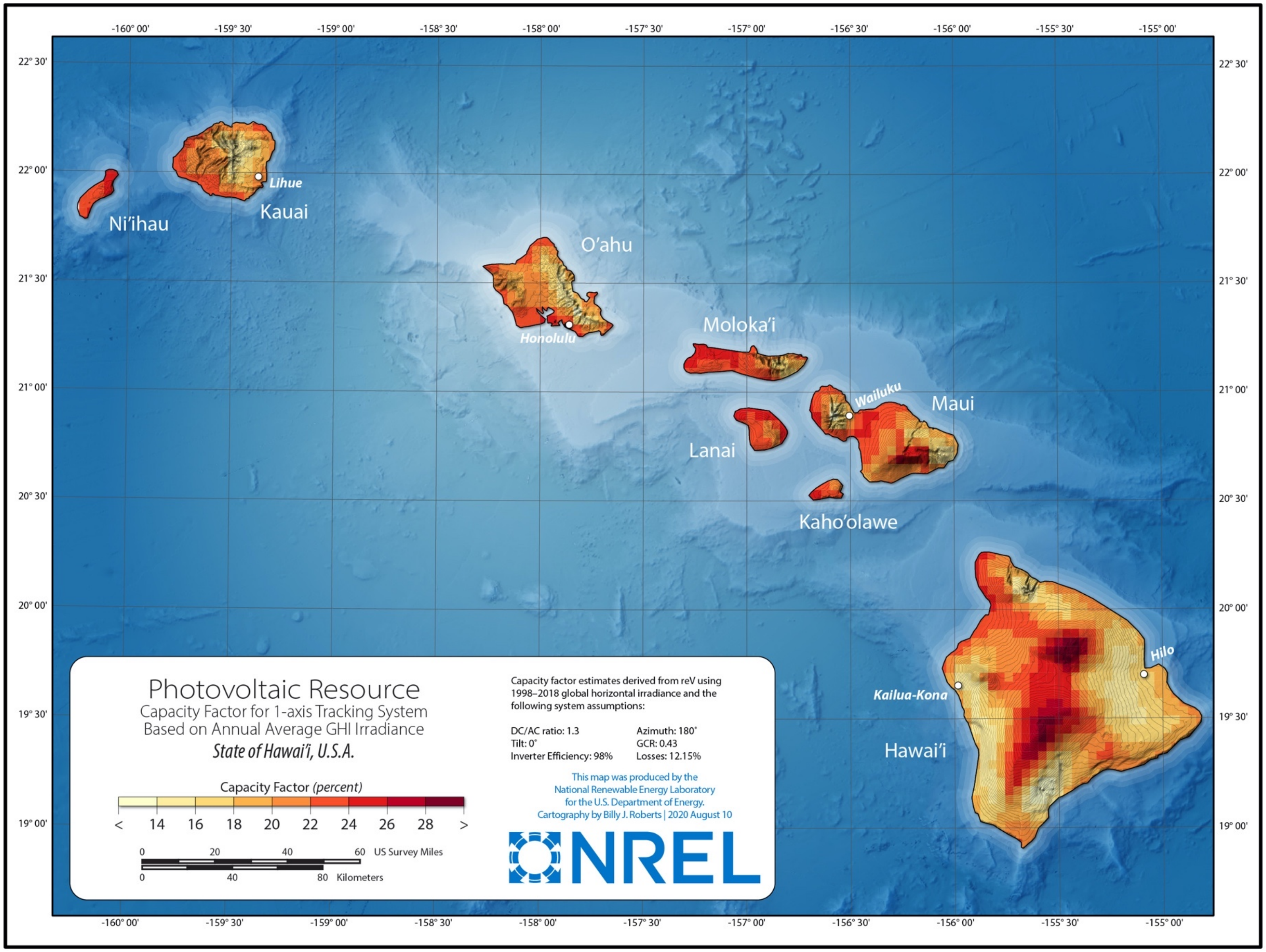
Global Horizontal Irradiance

Annual Average Solar Resource

State of Hawai'i, U.S.A.

Solar resource represents annual average irradiance for the period 1998–2018, from NREL's National Solar Radiation Database. For more information visit: https://nsrdb.nrel.gov

This map was produced by the
National Renewable Energy Laboratory
for the U.S. Department of Energy.
Cartography by Billy J. Roberts | 2020 August 10



Photovoltaic Resource

Capacity Factor for 1-axis Tracking System Based on Annual Average GHI Irradiance

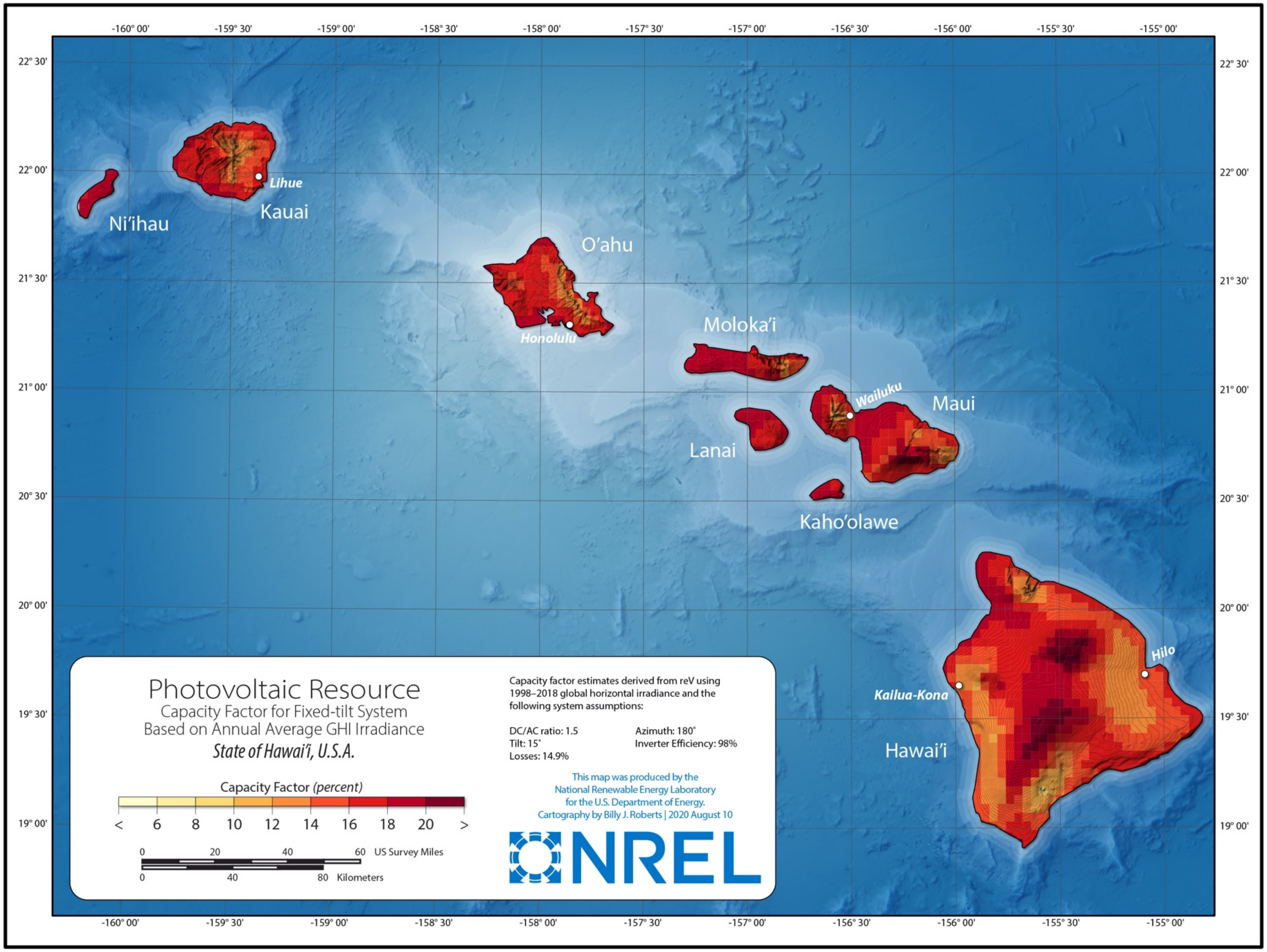
State of Hawai'i, U.S.A.

Capacity factor estimates derived from reV using 1998–2018 global horizontal irradiance and the following system assumptions:

DC/AC ratio: 1.3	Azimuth: 180°
Tilt: 0°	GCR: 0.43
Inverter Efficiency: 98%	Losses: 12.15%

This map was produced by the
National Renewable Energy Laboratory
for the U.S. Department of Energy.
Cartography by Billy J. Roberts | 2020 August 10

NREL



Photovoltaic Resource

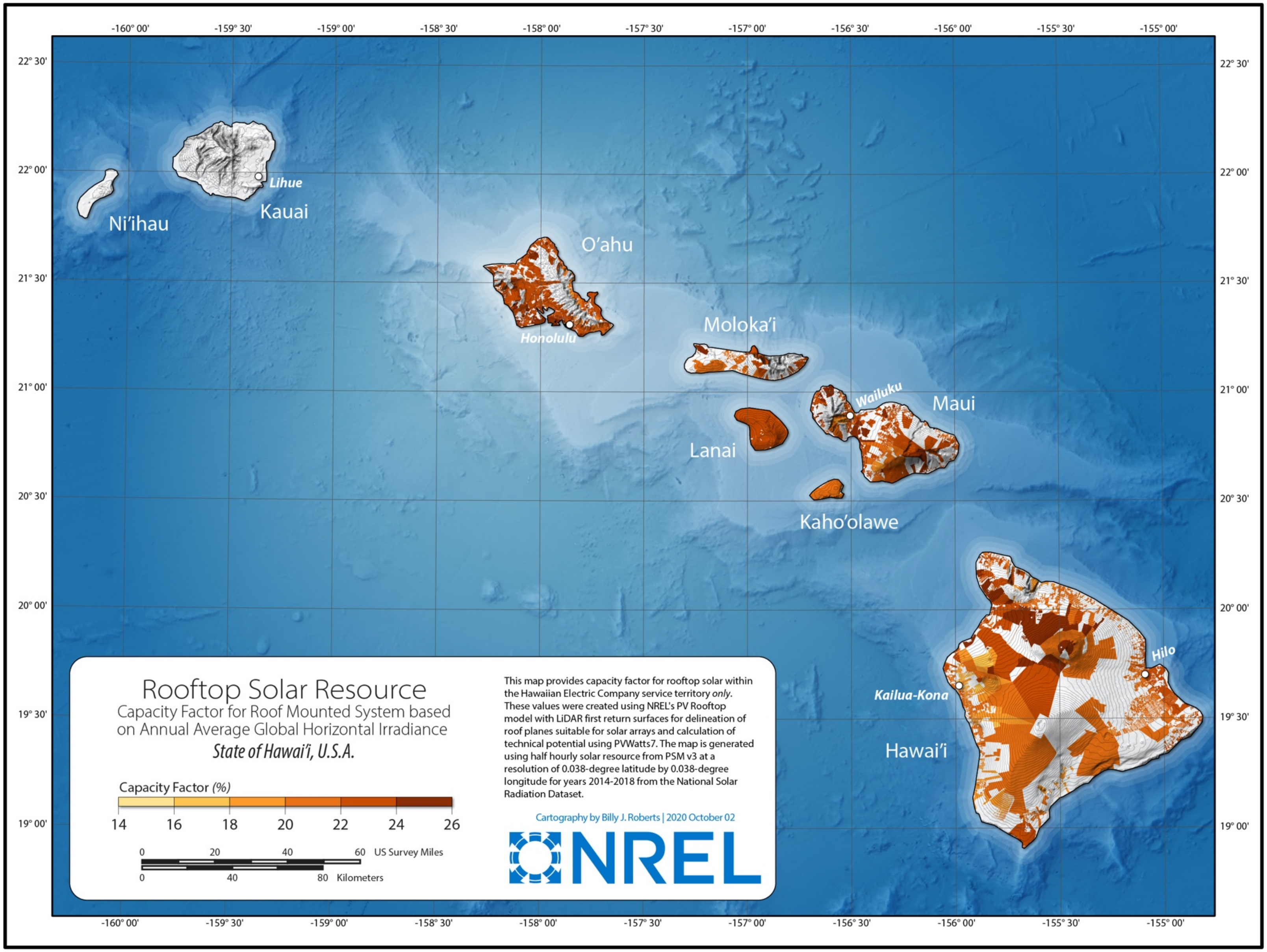
Capacity Factor for Fixed-tilt System
Based on Annual Average GHI Irradiance

State of Hawai'i, U.S.A.

Capacity factor estimates derived from reV using 1998–2018 global horizontal irradiance and the following system assumptions:

DC/AC ratio: 1.5
Tilt: 15°
Losses: 14.9%
Azimuth: 180°
Inverter Efficiency: 98%

This map was produced by the
National Renewable Energy Laboratory
for the U.S. Department of Energy.
Cartography by Billy J. Roberts | 2020 August 10



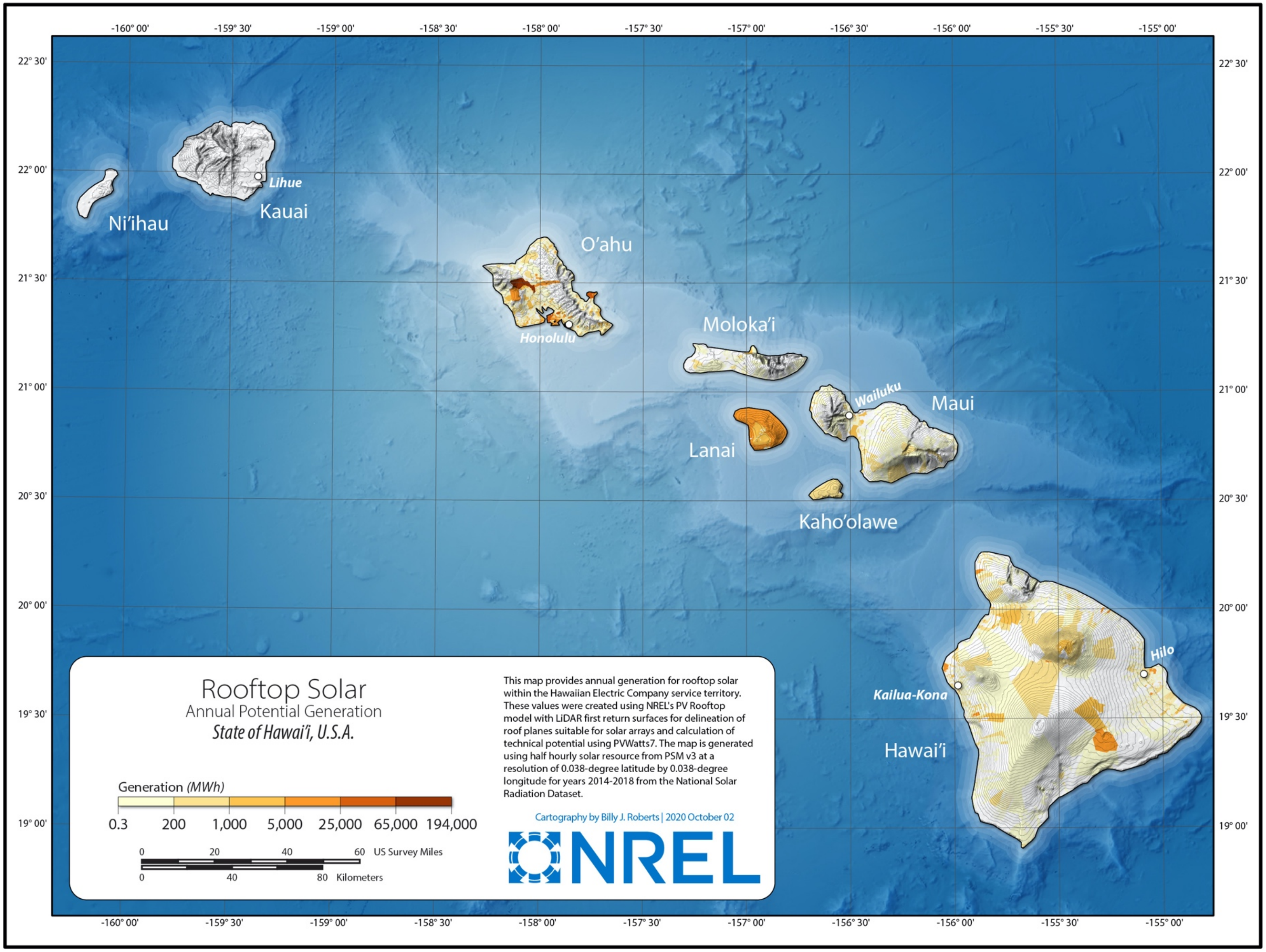
Rooftop Solar Resource

Capacity Factor for Roof Mounted System based on Annual Average Global Horizontal Irradiance

State of Hawai'i, U.S.A.

This map provides capacity factor for rooftop solar within the Hawaiian Electric Company service territory *only*. These values were created using NREL's PV Rooftop model with LiDAR first return surfaces for delineation of roof planes suitable for solar arrays and calculation of technical potential using PVWatts7. The map is generated using half hourly solar resource from PSM v3 at a resolution of 0.038-degree latitude by 0.038-degree longitude for years 2014-2018 from the National Solar Radiation Dataset.

Cartography by Billy J. Roberts | 2020 October 02



Rooftop Solar

Annual Potential Generation

State of Hawai'i, U.S.A.

This map provides annual generation for rooftop solar within the Hawaiian Electric Company service territory. These values were created using NREL's PV Rooftop model with LiDAR first return surfaces for delineation of roof planes suitable for solar arrays and calculation of technical potential using PVWatts7. The map is generated using half hourly solar resource from PSM v3 at a resolution of 0.038-degree latitude by 0.038-degree longitude for years 2014-2018 from the National Solar Radiation Dataset.

Cartography by Billy J. Roberts | 2020 October 02

Appendix B. Geographic Exclusions

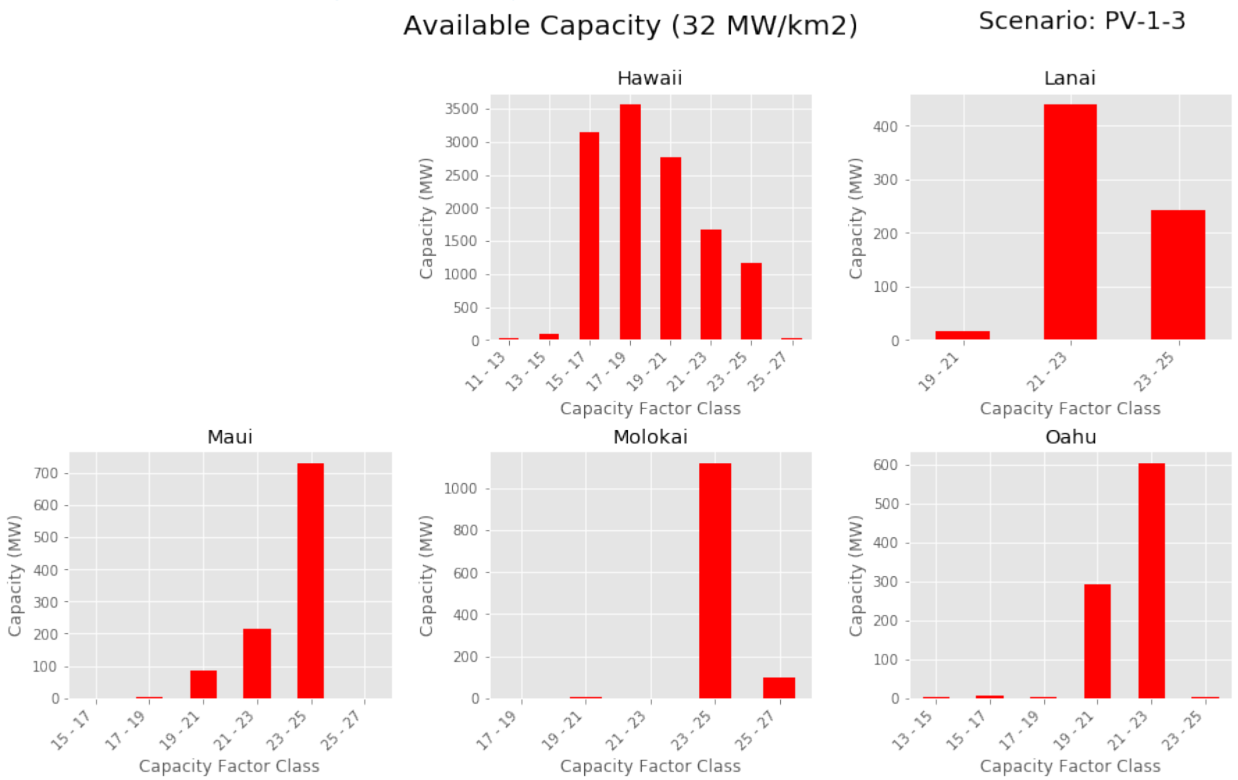
Table 27: Full Geographic Exclusions

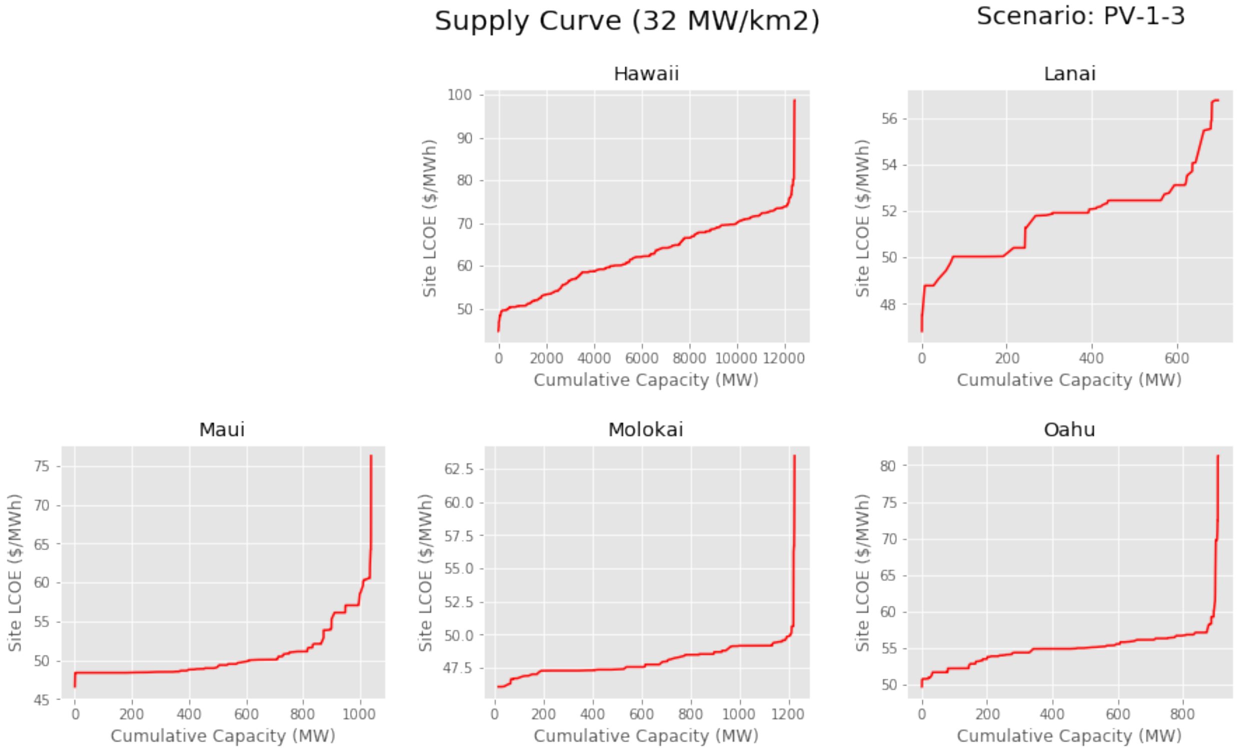
		PV								Wind							
Exclusion Category	Land Category	PV-1-3	PV-1-5	PV-1-HS	PV-2-3	PV-2-5	PV-2-HS	PV-3-3	PV-3-5	WIND-1-20	WIND-1-40	WIND-2-20	WIND-2-40	WIND-3-20	WIND-3-40	WIND-4-20	WIND-4-40
Federal Lands	National Guard	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include
	National Park Service	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Other Federal Lands	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include
	U.S. Department of Defense Lands	Exclude	Exclude	Exclude	Include	Include	Include	Include	Include	Exclude	Exclude	Include	Include	Exclude	Exclude	Include	Include
	U.S Fish & Wildlife Service	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
State Parks	State Park	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Bird Sanctuary	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Cultural/Historic Area	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Ecological Reserve	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Estuary Reserve	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Game Land	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Game or Wildlife Sanctuary	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Monument	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Nature Preserve/Reserve	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	State Wildlife Mgmt. Area	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Other State Lands	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Dept. of Defense	Dept. of Defense Lands	Exclude	Exclude	Exclude	Include	Include	Include	Include	Include	Exclude	Exclude	Include	Include	Exclude	Exclude	Include	Include
Wetlands	Estuarine and Marine Deepwater	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Estuarine and Marine Wetland	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Fresh. Emergent Wetland	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Fresh. Forested/Shrub Wetland	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Fresh. Pond	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Lake	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Riverine	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Lava flow	Highest	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Second Highest	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Kilauea Lava Flow (2018)	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Flood Zones	"A"	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Ag Areas	Important Agricultural Lands (IAG)	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Urban Zones	Urban Areas	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	HCDA Oahu Affordable Housing Prj	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Slope	Slope percent > 3%	Exclude	Include	Include	Exclude	Include	Include	Exclude	Include	Include	Include	Include	Include	Include	Include	Include	Include
	Slope percent > 5%	Exclude	Exclude	Include	Exclude	Exclude	Include	Exclude	Exclude	Include	Include	Include	Include	Include	Include	Include	Include
	Slope percent > 20%	Exclude	Exclude	Include	Exclude	Exclude	Include	Exclude	Exclude	Exclude	Include	Exclude	Include	Exclude	Include	Exclude	Include
	Slope percent > 40%	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Setbacks	Road Setback (173m)	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Exclude	Exclude	Exclude	Exclude
	Building Setback (173m)	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Exclude	Exclude	Exclude	Exclude
	Transmission ROW Setback (173m)	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Exclude	Exclude	Exclude	Exclude
Land Study Bureau Agricultural Lands	Class A Land	Include	Include	Include	Include	Include	Include	90% Exc.	90% Exc.	Include	Include	Include	Include	Include	Include	Include	Include
	Class B Land	Include	Include	Include	Include	Include	Include	90% Exc.	90% Exc.	Include	Include	Include	Include	Include	Include	Include	Include
	Class C Land	Include	Include	Include	Include	Include	Include	90% Exc.	90% Exc.	Include	Include	Include	Include	Include	Include	Include	Include
Sea Level Rise	SLR 6ft - 50yr	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	SLR 6ft - 100yr	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	SLR 6ft - 500yr	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
Tsunami Evacuations Zones	Tsunami Evacuation Zones	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude
	Extreme Tsunami Evacuation Zones	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include
RE Development Zones	Oahu, Molokai, Hawaii (x2)	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include	Include
Oahu Land Use Ordinance - Urban Zones	A-1, A-2, A-3, Aloha, AMX-1, AMX-2, AMX-3, Apart, ApartMix, B-1, B-2, BMX-3, BMX-4, I-1, I-2, I-3, IMX-1, Kak, MU, PU, Pub, R-10, R-20, R-3.5, R-5, R-7.5, ResMix, Resort, WI	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude	Exclude

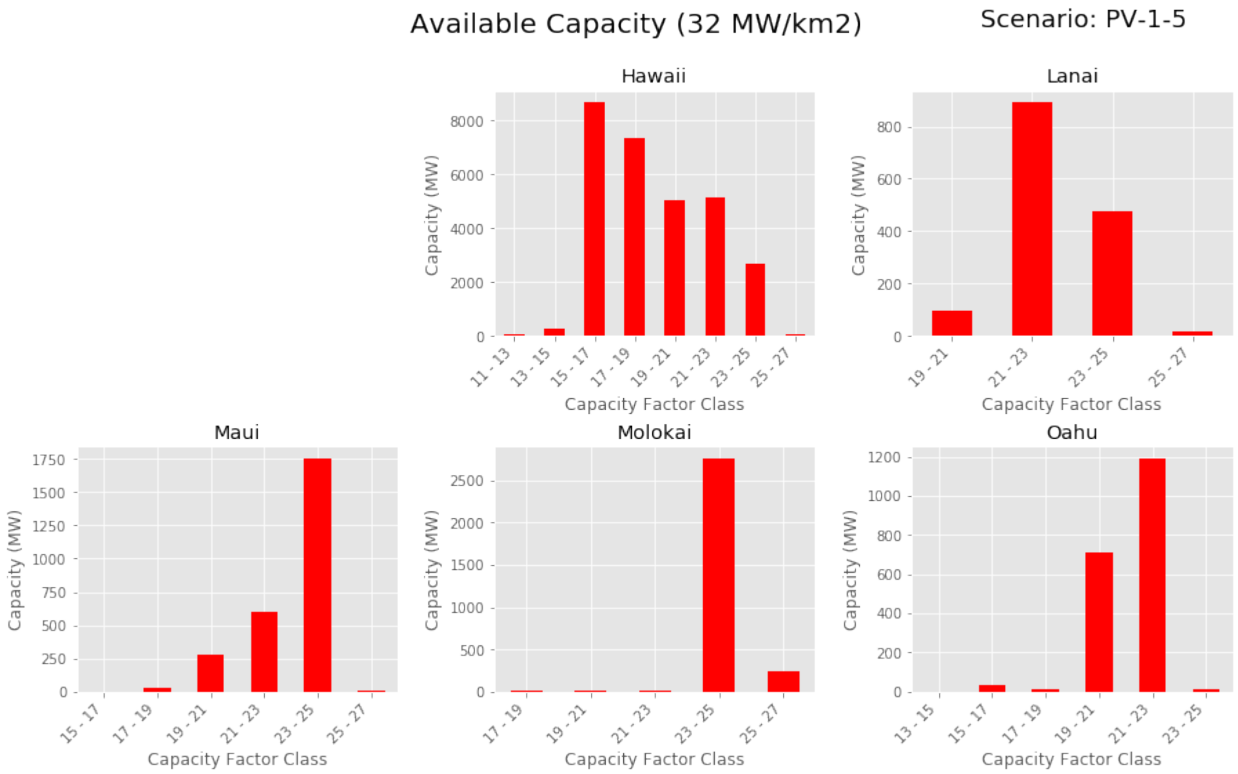
GIS Layer	Description	Source
Federal Lands	Vector locations of various federal land-classified areas	ESRI Federal Lands GIS Layer
State Parks	Vector locations of various state parks for Hawaii	HI Government Geoportal
Dept. of Defense Lands	Vector locations of Department of Defense lands	HI Government Geoportal
Wetlands	Vector locations of various wetland categories	HI Government Geoportal
Lava Flow Areas	Vector locations of various lava flow zones	HI Government Geoportal
Kilauea Lava Flow Footprint	Vector location of 2018 Kilauea lava flow	USGS ScienceBase-Catalog
Flood Zones	Vector locations of flood ones	HI Government Geoportal
Agricultural Areas	Vector locations of lands designated as Important Agricultural Lands (IAG)	HI Government Geoportal
Urban Zones	Vector locations of urban and suburban areas	Global Human Settlement - Settlement Model
Oahu Affordable House Projects	Vector locations of land designated for affordable housing projects	Hawaii Community Development Authority
Slope	Slope percent derived from continuous elevation digital elevation model data.	National Elevation Dataset
Roads	Vector roadways	HERE Street
Buildings	Vector buildings and structures	Microsoft building footprints
Transmission Right-of-Ways	Vector transmission lines	Homeland Security Information Network & Hawaiian Electric
Land Study Bureau Agricultural Areas	Vector locations of various agricultural land classes	HI Planning Data Portal
Sea Level Rise	Vector locations of areas under threat to sea level rise	Data Provided by Jupiter
Tsunami Evacuation Zones	Vector locations of tsunami evacuation zones	HI Government Geoportal
RE Development Zones	Vector locations of land designated for renewable energy development	Data Provided by Hawaiian Electric
Oahu Land Use Ordinance - Urban Zones	Vector locations of various land ordinance categories for Oahu	Data Provided by Hawaiian Electric

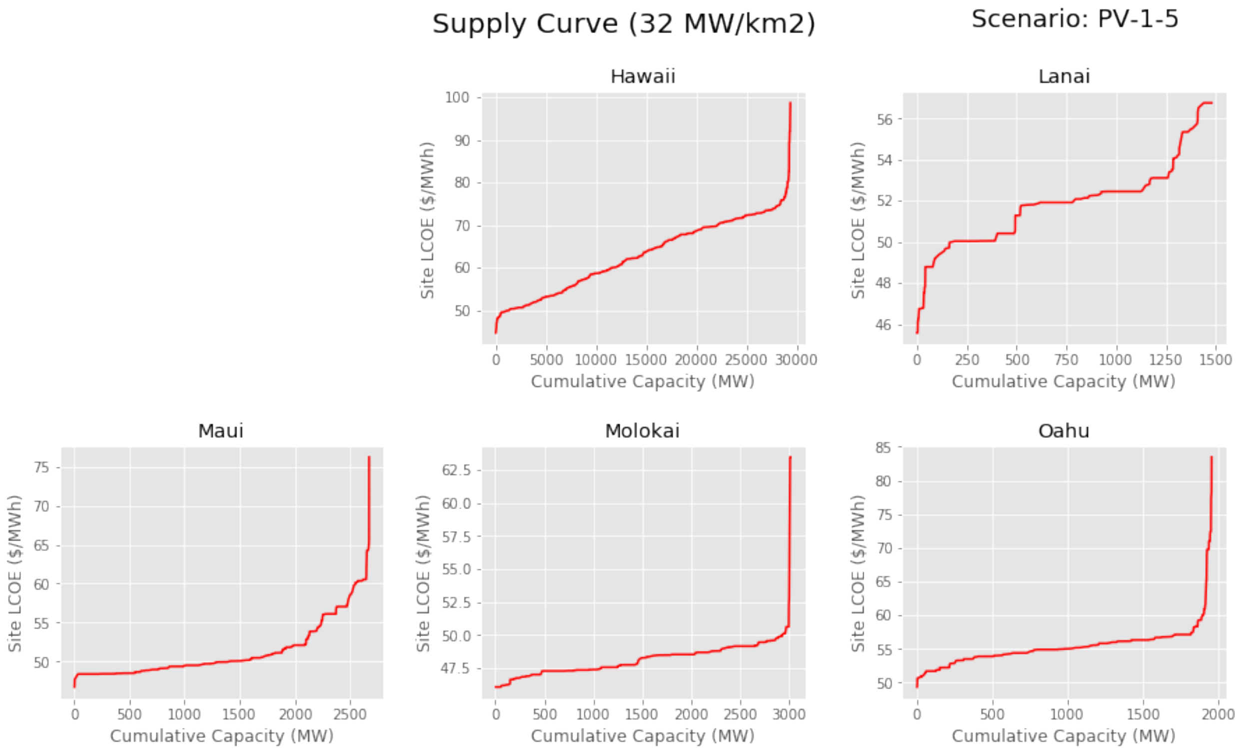
Appendix C. Technical Potential Summarizations

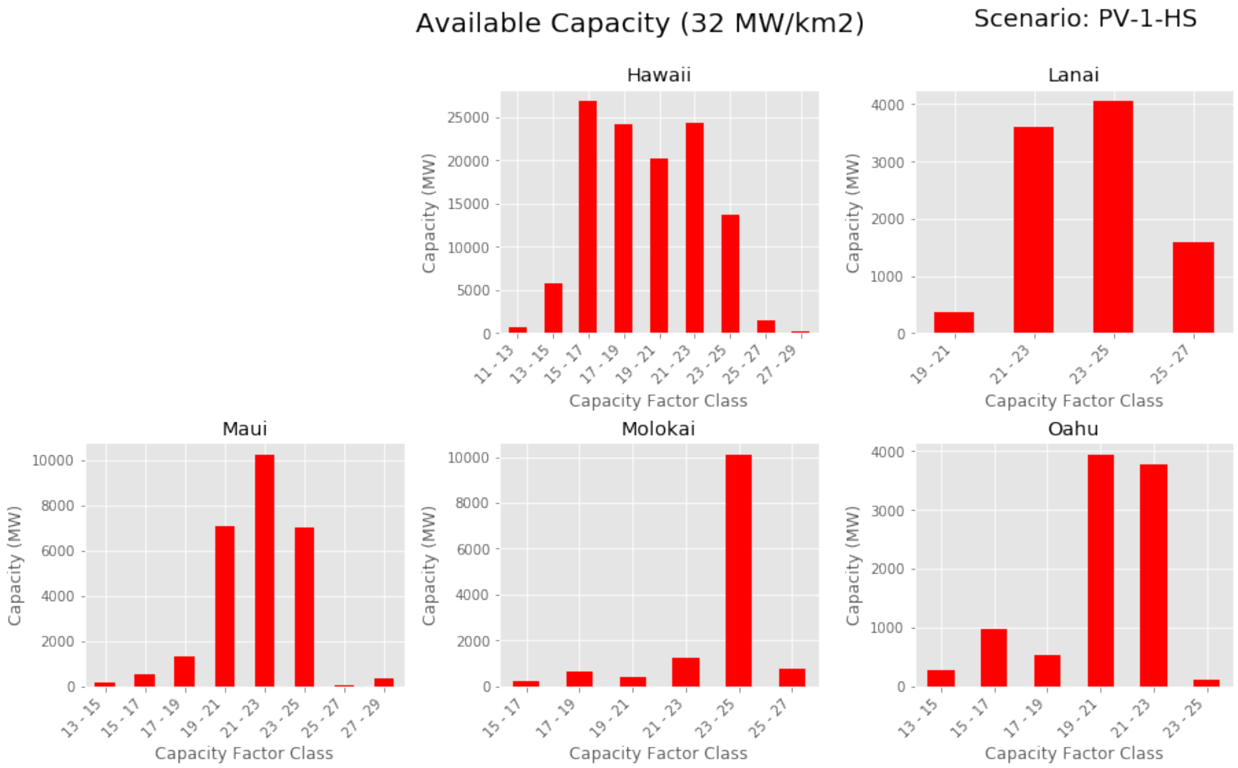
C.1 1-Axis Tracking Summary Results

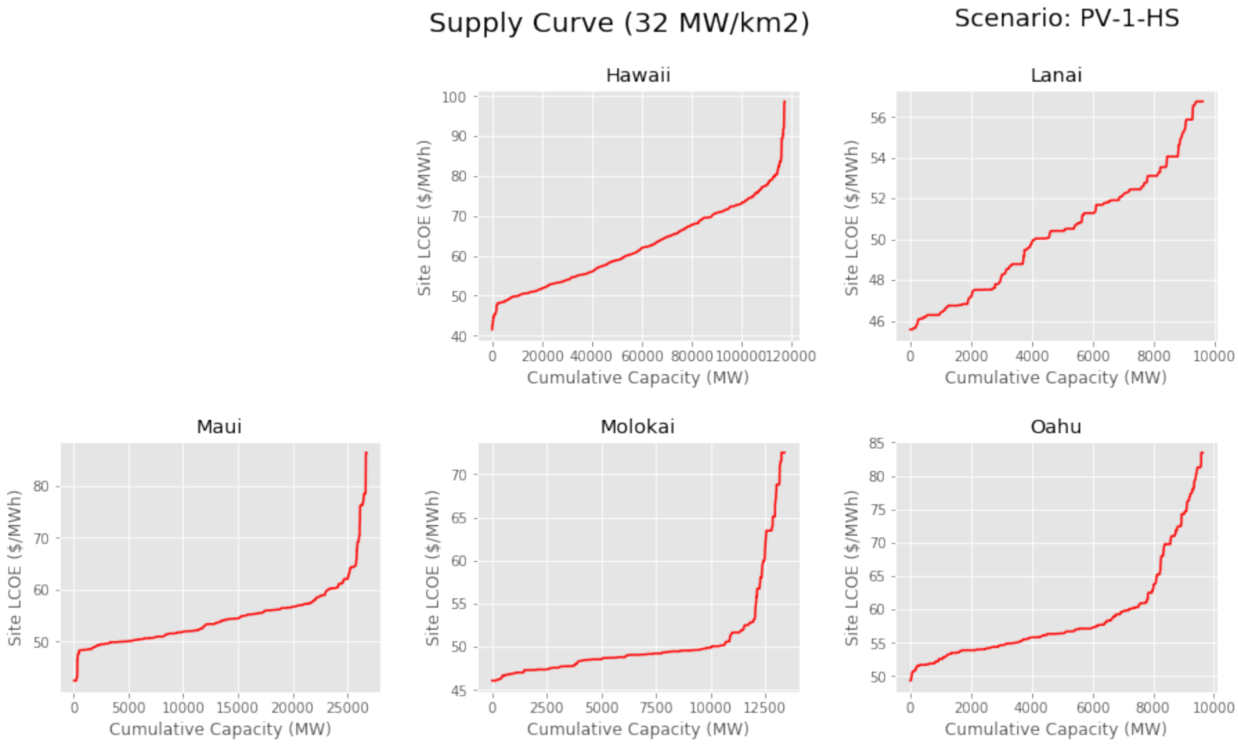


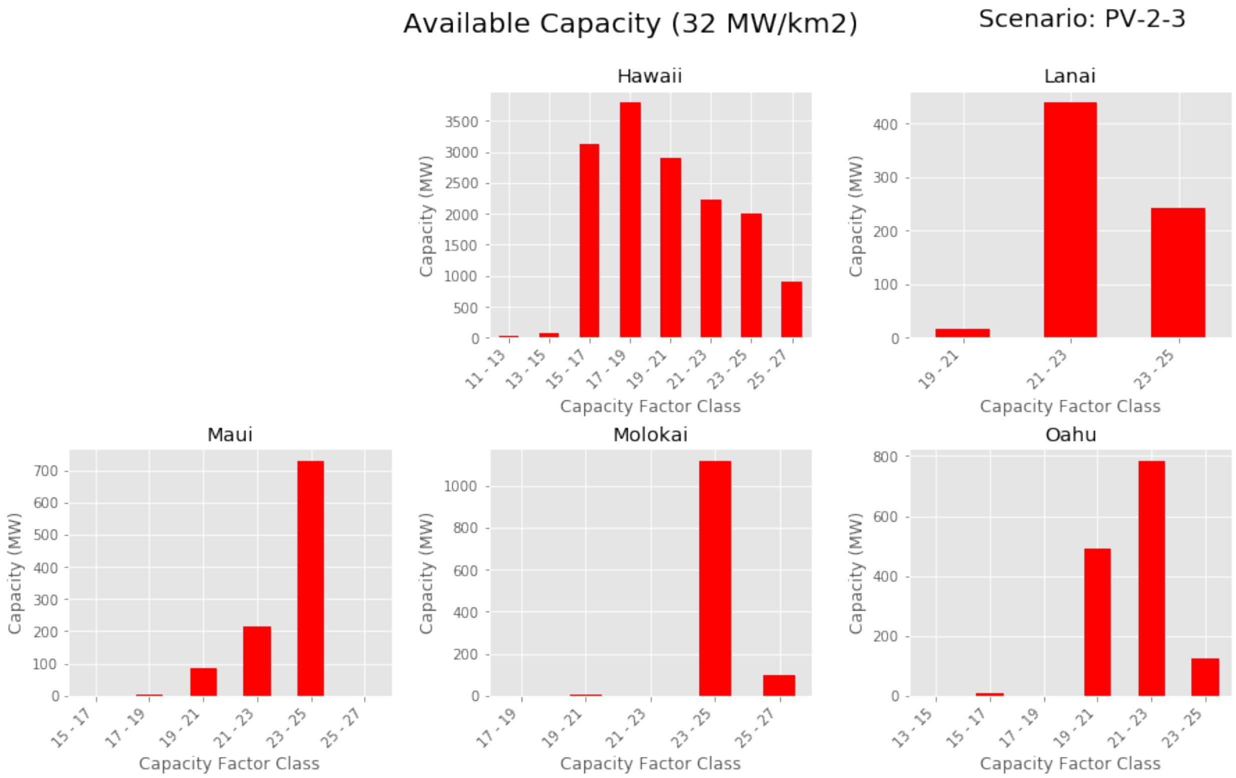



Available Capacity (32 MW/km2)
Scenario: PV-1-5
Hawaii
Capacity (MW)
0
2000
4000
6000
8000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Lanai
Capacity (MW)
0
200
400
600
800
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Maui
Capacity (MW)
0
250
500
750
1000
1250
1500
1750
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Molokai
Capacity (MW)
0
500
1000
1500
2000
2500
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
200
400
600
800
1000
1200
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class

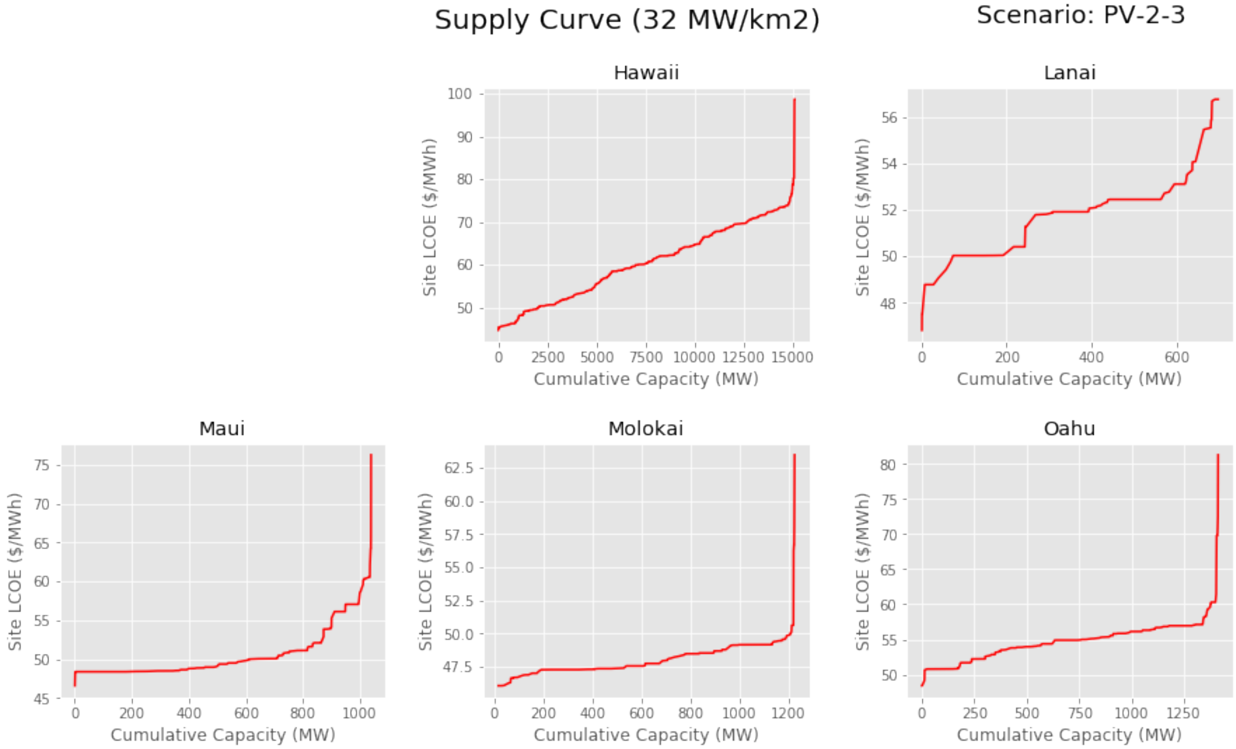

Supply Curve (32 MW/km2)
Scenario: PV-1-5
Hawaii
Site LCOE ($/MWh)
50
60
70
80
90
100
0
5000
10000
15000
20000
25000
30000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
46
48
50
52
54
56
0
250
500
750
1000
1250
1500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
50
55
60
65
70
75
0
500
1000
1500
2000
2500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
47.5
50.0
52.5
55.0
57.5
60.0
62.5
0
500
1000
1500
2000
2500
3000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
85
0
500
1000
1500
2000
Cumulative Capacity (MW)


Available Capacity (32 MW/km2)
Scenario: PV-1-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Capacity (MW)
Capacity Factor Class
0
5000
10000
15000
20000
25000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
27 - 29
1000
2000
3000
4000
2000
4000
6000
8000
10000

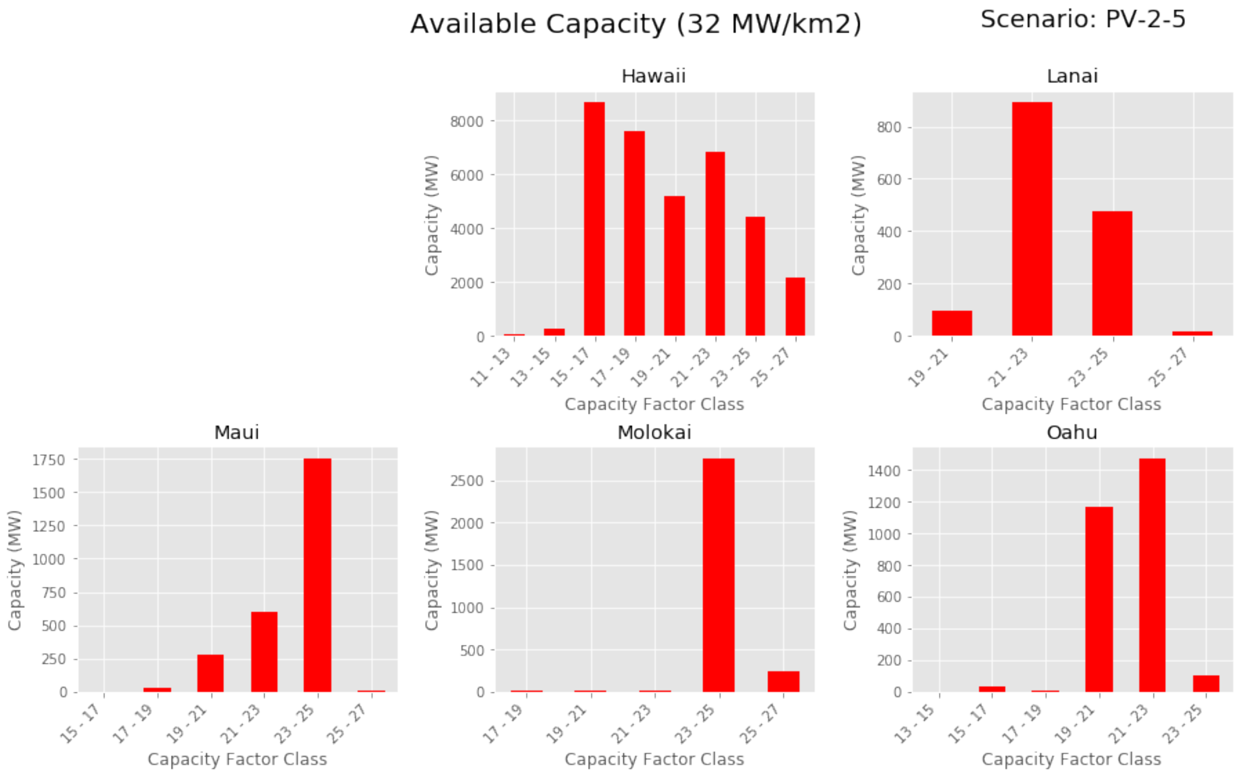

Supply Curve (32 MW/km2)
Scenario: PV-1-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Site LCOE ($/MWh)
Cumulative Capacity (MW)
40
50
60
70
80
90
100
0
20000
40000
60000
80000
100000
120000
46
48
50
52
54
56
2000
4000
6000
8000
10000
5000
15000
20000
25000
45
55
65
75
85
2500
7500
12500

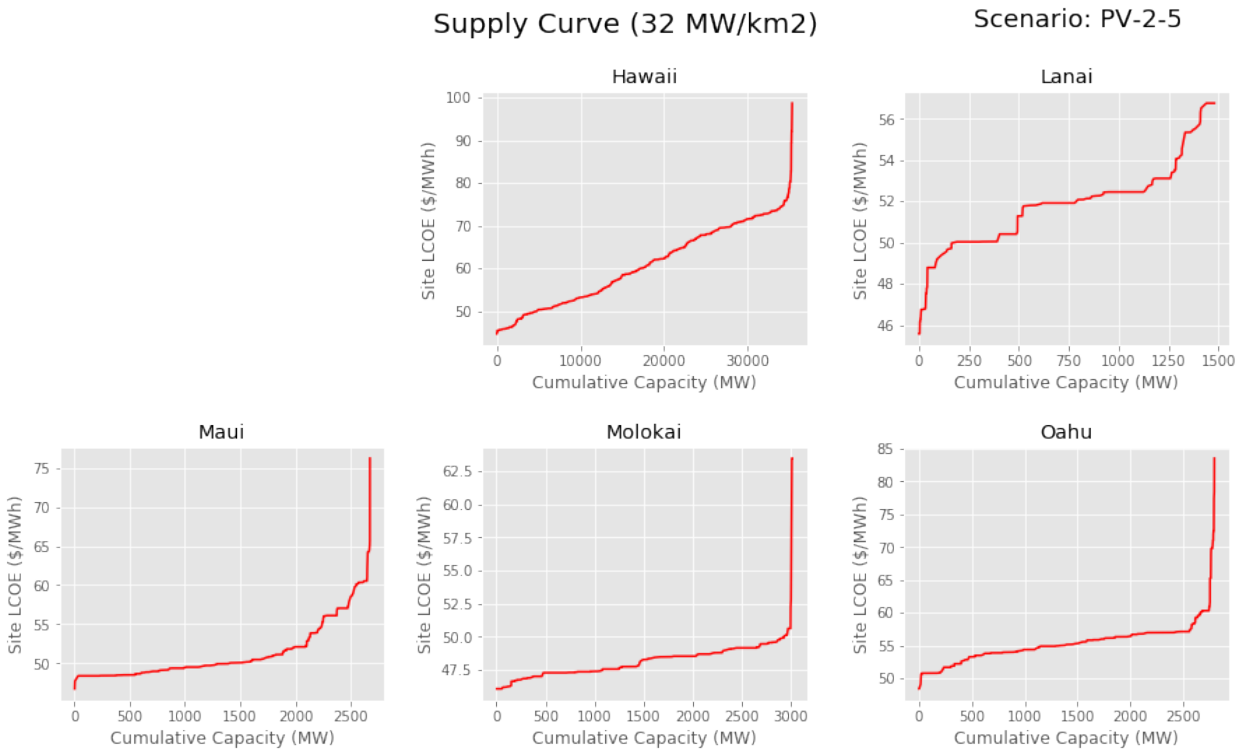


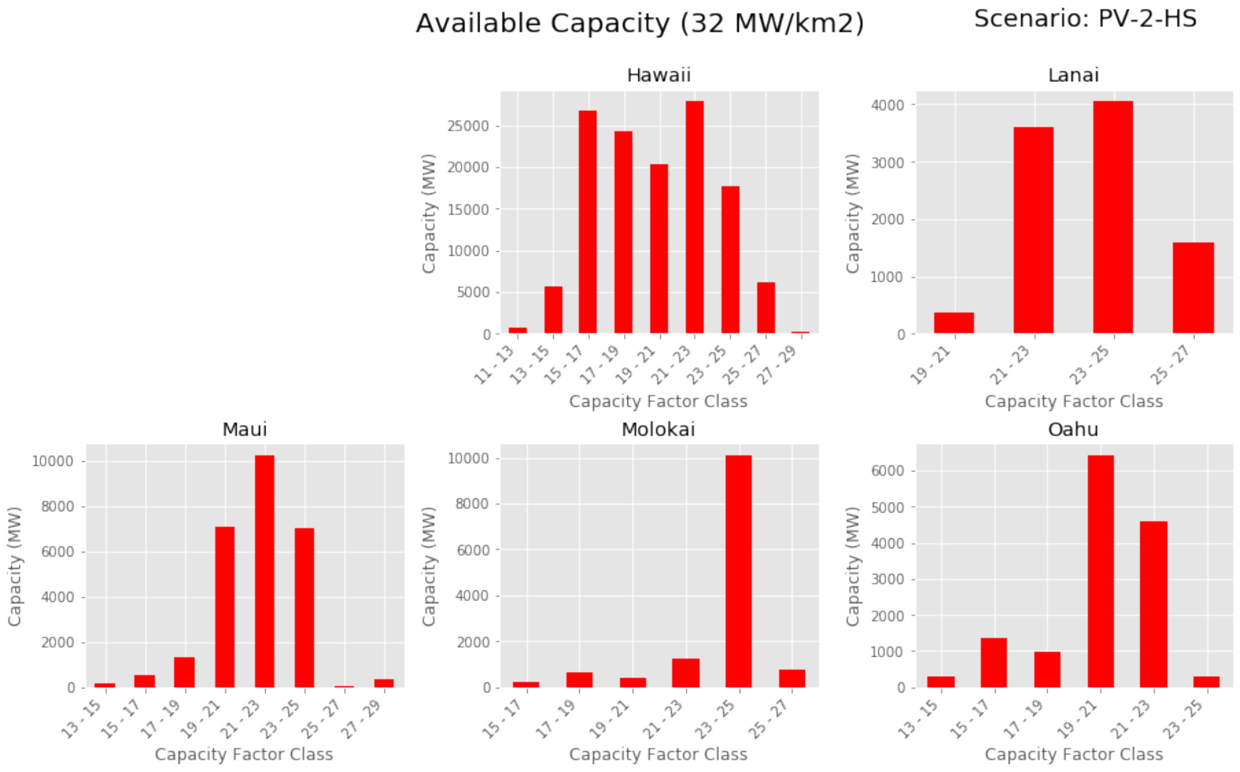
Available Capacity (32 MW/km2)
Scenario: PV-2-3
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
3000
3500
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Lanai
Capacity (MW)
0
100
200
300
400
19 - 21
21 - 23
23 - 25
Capacity Factor Class
Maui
Capacity (MW)
0
100
200
300
400
500
600
700
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Molokai
Capacity (MW)
0
200
400
600
800
1000
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
200
400
600
800
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class

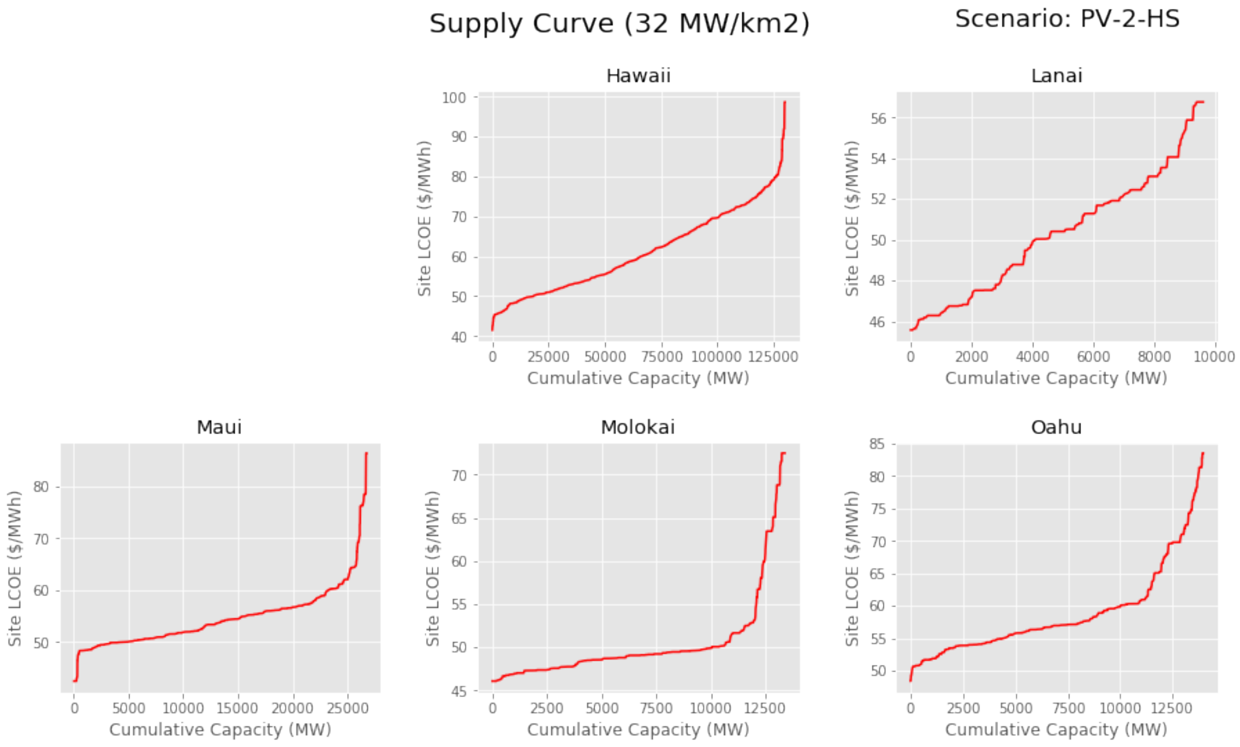


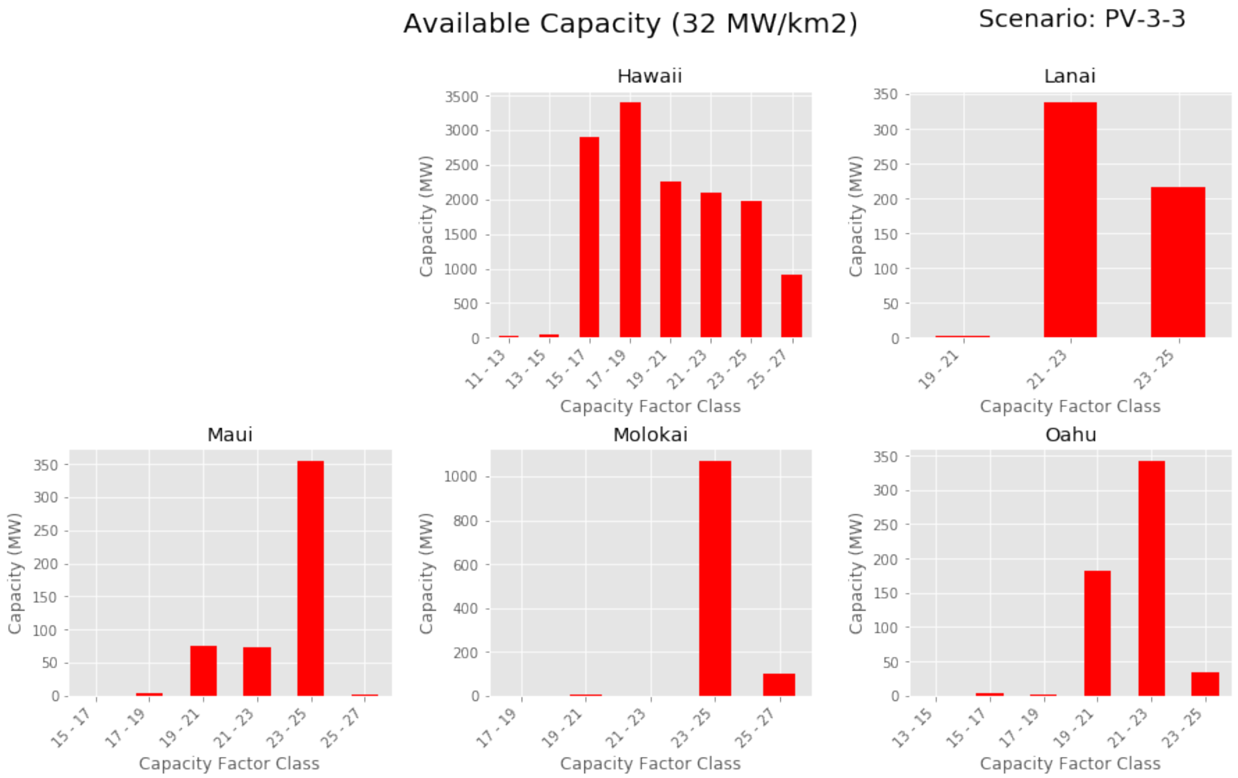
Supply Curve (32 MW/km2)
Scenario: PV-2-3
Hawaii
Site LCOE ($/MWh)
50
60
70
80
90
100
0
2500
5000
7500
10000
12500
15000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
48
50
52
54
56
0
200
400
600
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
45
50
55
60
65
70
75
0
200
400
600
800
1000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
47.5
50.0
52.5
55.0
57.5
60.0
62.5
0
200
400
600
800
1000
1200
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
0
250
500
750
1000
1250
Cumulative Capacity (MW)

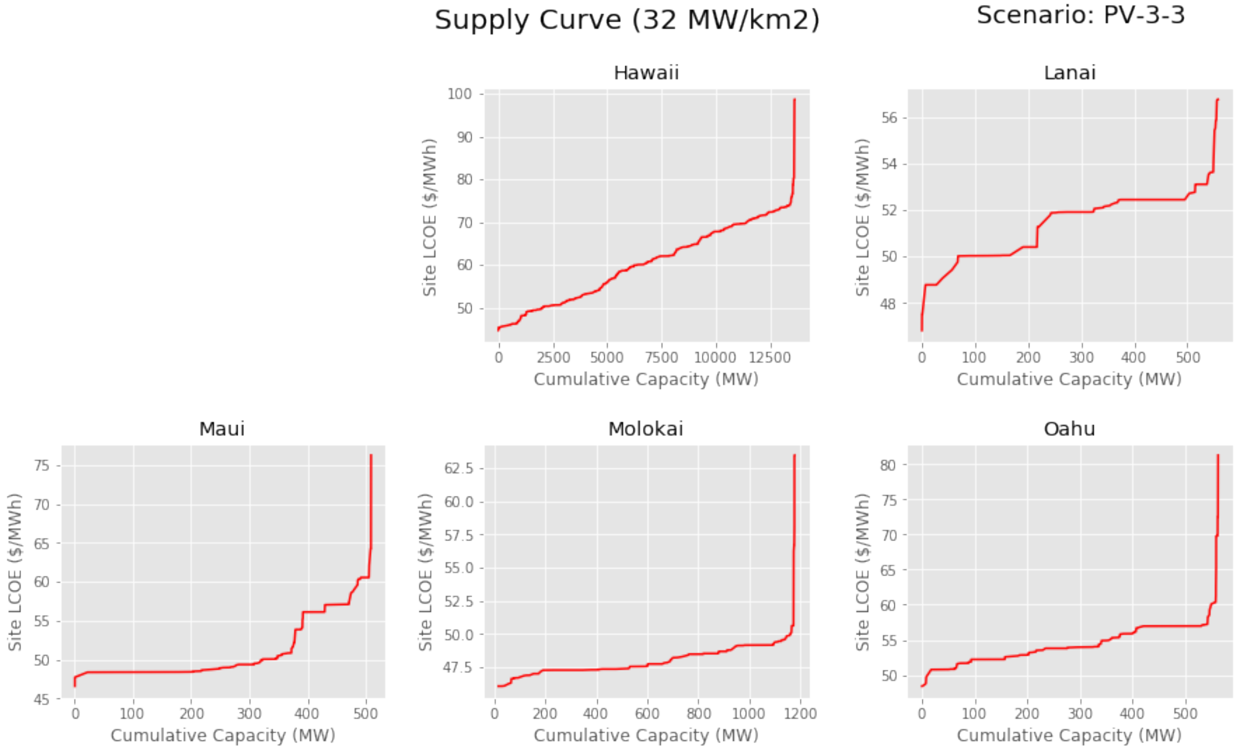

Available Capacity (32 MW/km2)
Scenario: PV-2-5
Hawaii
Capacity (MW)
0
2000
4000
6000
8000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Lanai
Capacity (MW)
0
200
400
600
800
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Maui
Capacity (MW)
0
250
500
750
1000
1250
1500
1750
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Molokai
Capacity (MW)
0
500
1000
1500
2000
2500
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
200
400
600
800
1000
1200
1400
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class

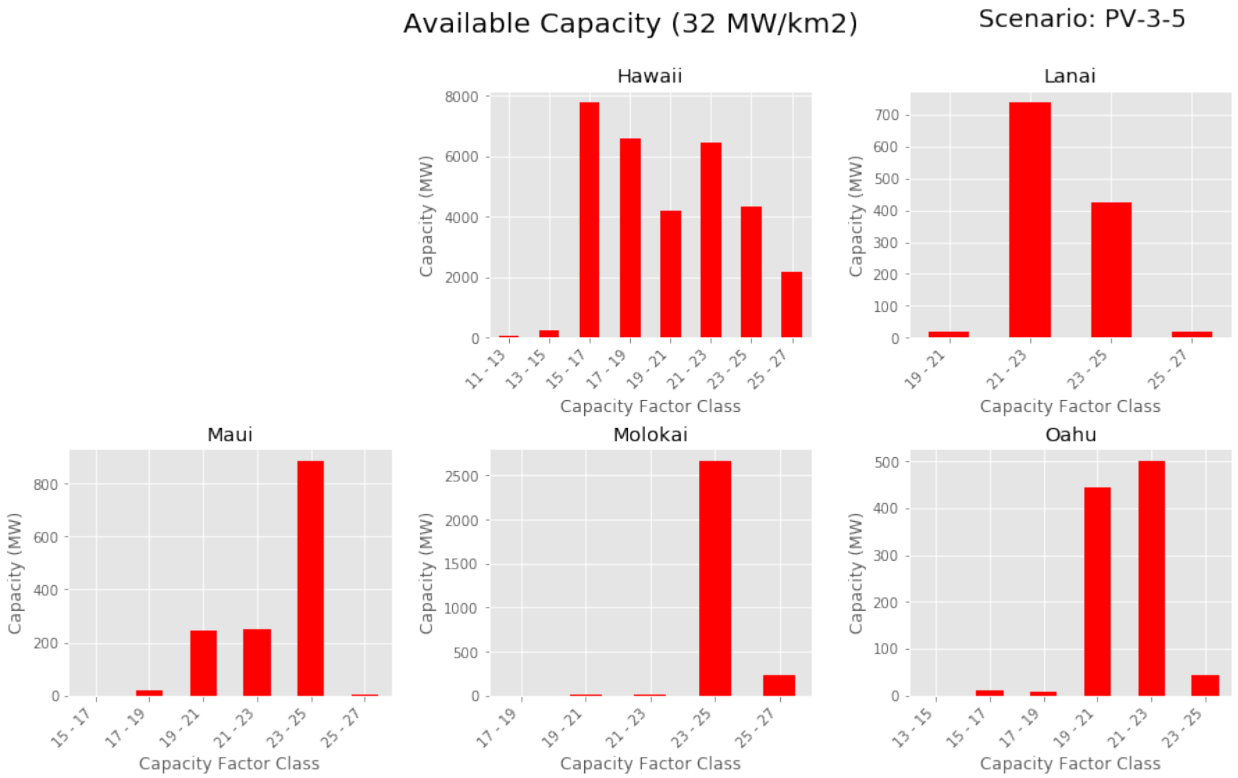

Supply Curve (32 MW/km2)
Scenario: PV-2-5
Hawaii
Site LCOE ($/MWh)
50
60
70
80
90
100
0
10000
20000
30000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
46
48
50
52
54
56
0
250
500
750
1000
1250
1500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
50
55
60
65
70
75
0
500
1000
1500
2000
2500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
47.5
50.0
52.5
55.0
57.5
60.0
62.5
0
500
1000
1500
2000
2500
3000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
85
0
500
1000
1500
2000
2500
Cumulative Capacity (MW)

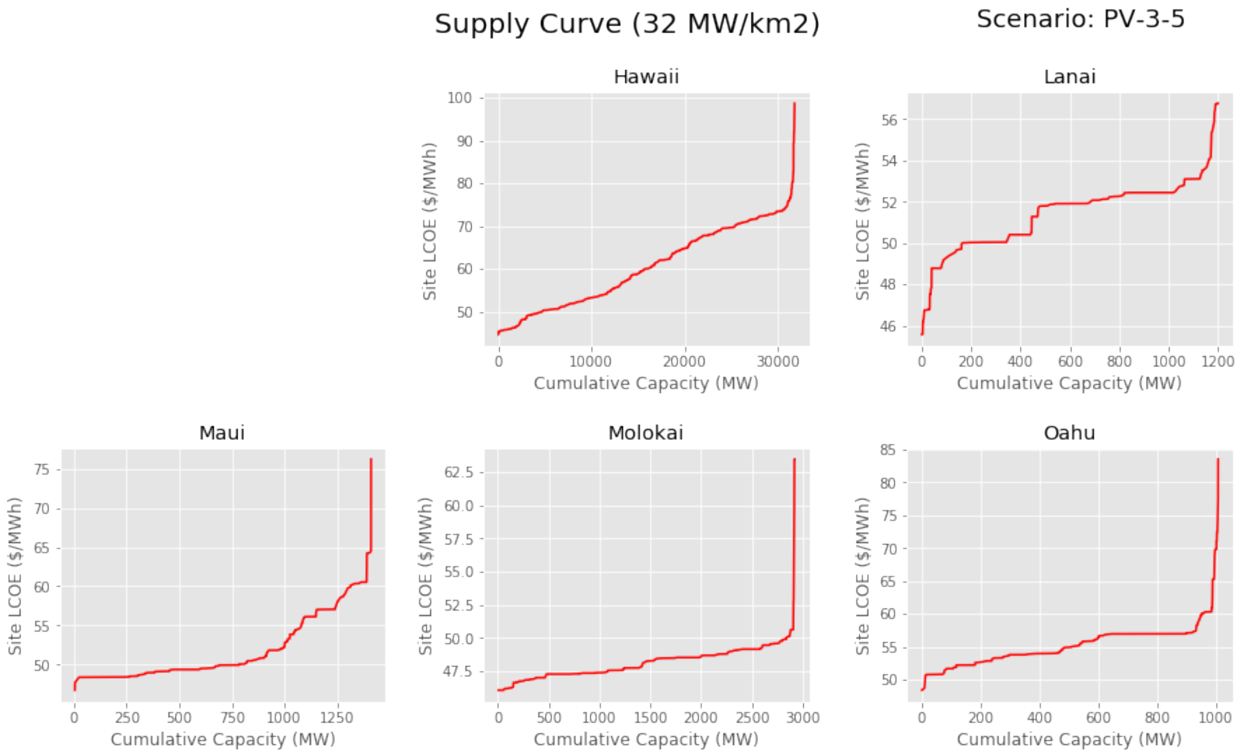

Available Capacity (32 MW/km2)
Scenario: PV-2-HS
Hawaii
Capacity (MW)
0
5000
10000
15000
20000
25000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
27 - 29
Capacity Factor Class
Lanai
Capacity (MW)
0
1000
2000
3000
4000
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Maui
Capacity (MW)
0
2000
4000
6000
8000
10000
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
27 - 29
Capacity Factor Class
Molokai
Capacity (MW)
0
2000
4000
6000
8000
10000
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
1000
2000
3000
4000
5000
6000
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class


Supply Curve (32 MW/km2)
Scenario: PV-2-HS
Hawaii
Site LCOE ($/MWh)
40
50
60
70
80
90
100
0
25000
50000
75000
100000
125000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
46
48
50
52
54
56
0
2000
4000
6000
8000
10000
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
50
60
70
80
0
5000
10000
15000
20000
25000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
45
50
55
60
65
70
0
2500
5000
7500
10000
12500
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
85
0
2500
5000
7500
10000
12500
Cumulative Capacity (MW)

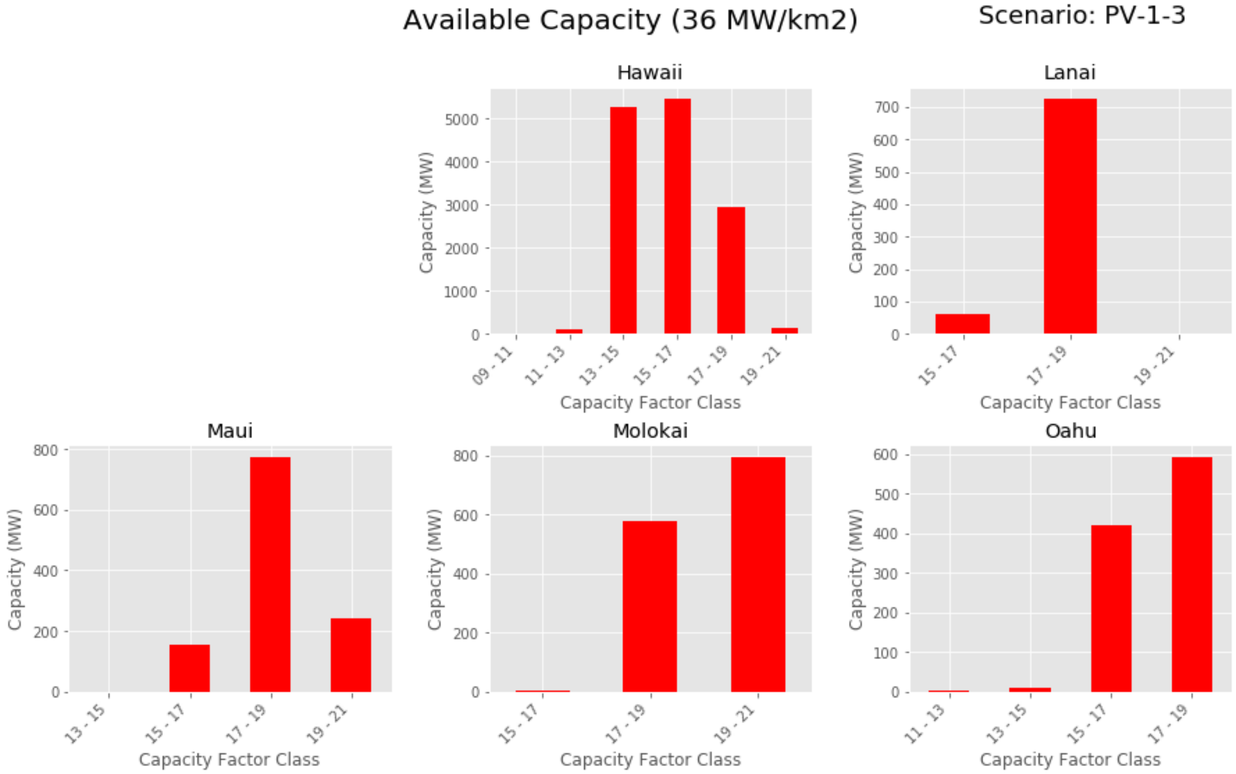

Available Capacity (32 MW/km2)
Scenario: PV-3-3
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
3000
3500
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Lanai
Capacity (MW)
0
50
100
150
200
250
300
350
19 - 21
21 - 23
23 - 25
Capacity Factor Class
Maui
Capacity (MW)
0
50
100
150
200
250
300
350
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Molokai
Capacity (MW)
0
200
400
600
800
1000
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
50
100
150
200
250
300
350
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class

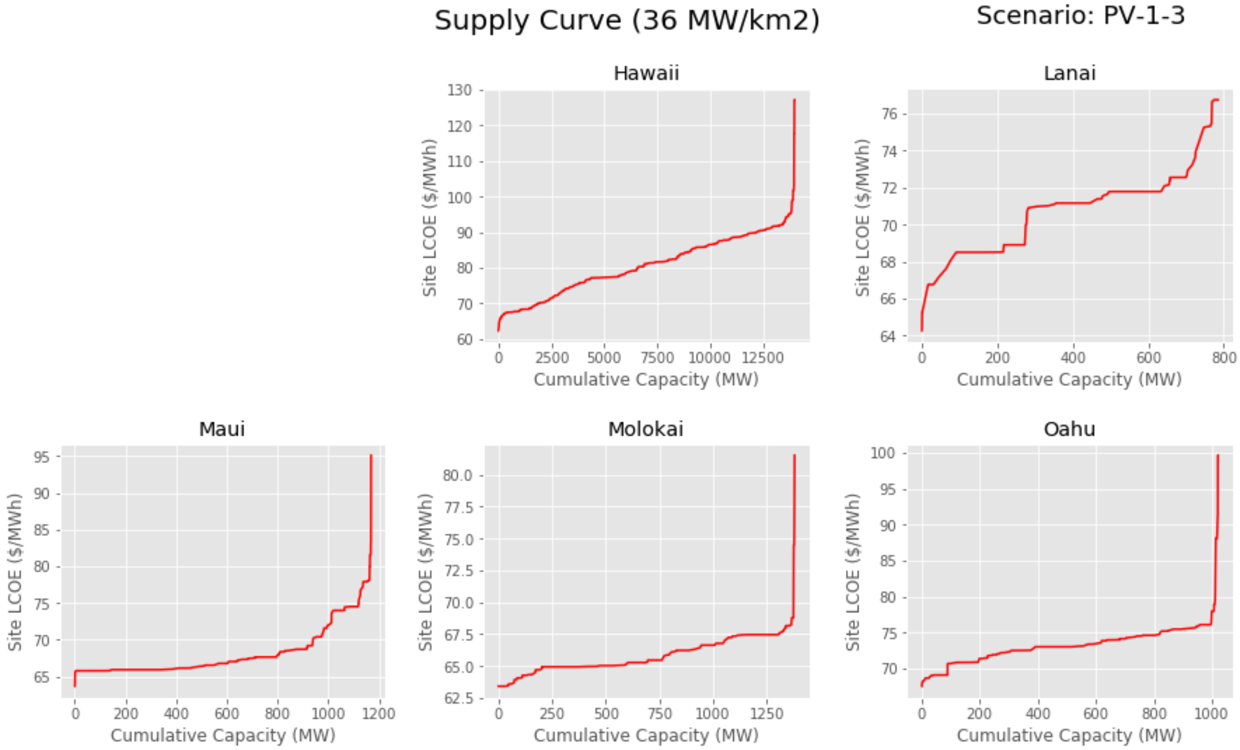

Supply Curve (32 MW/km2)
Scenario: PV-3-3
Hawaii
Site LCOE ($/MWh)
50
60
70
80
90
100
0
2500
5000
7500
10000
12500
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
48
50
52
54
56
0
100
200
300
400
500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
45
50
55
60
65
70
75
0
100
200
300
400
500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
47.5
50.0
52.5
55.0
57.5
60.0
62.5
0
200
400
600
800
1000
1200
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
0
100
200
300
400
500
Cumulative Capacity (MW)

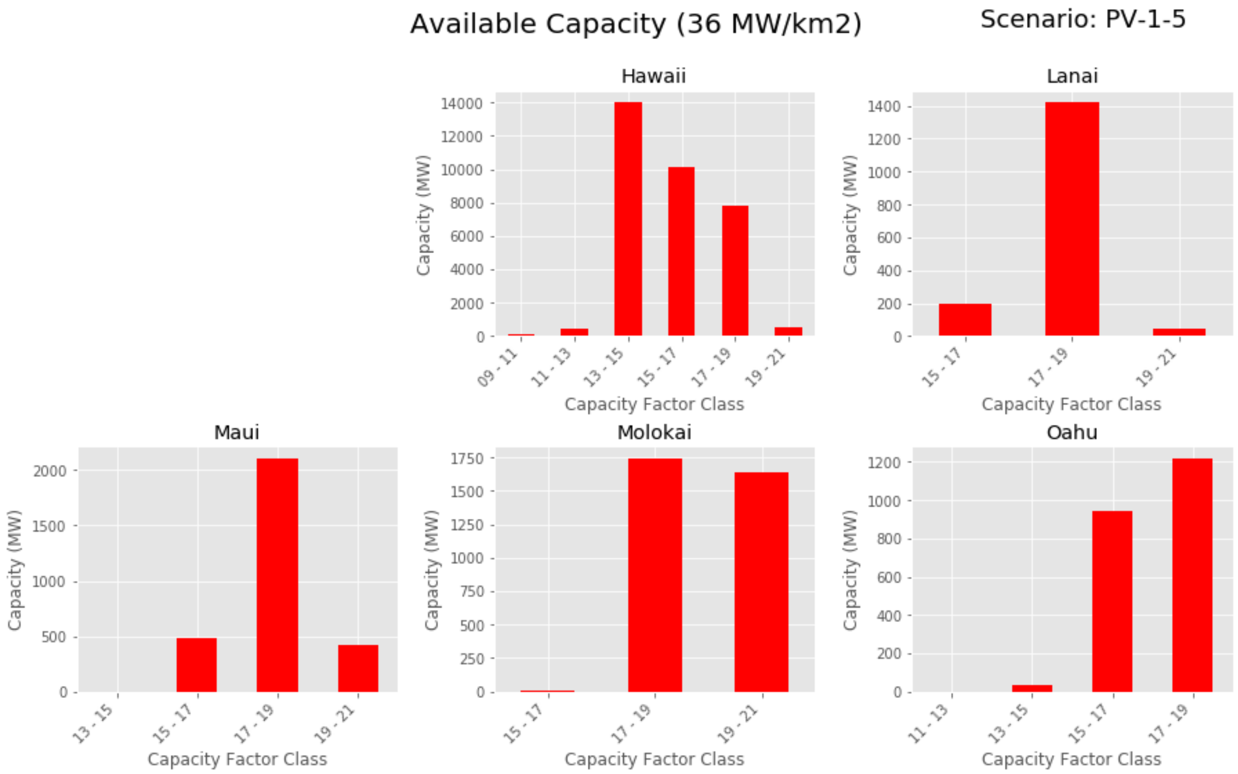

Available Capacity (32 MW/km2)
Scenario: PV-3-5
Hawaii
Capacity (MW)
0
2000
4000
6000
8000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Lanai
Capacity (MW)
0
100
200
300
400
500
600
700
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Maui
Capacity (MW)
0
200
400
600
800
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Molokai
Capacity (MW)
0
500
1000
1500
2000
2500
17 - 19
19 - 21
21 - 23
23 - 25
25 - 27
Capacity Factor Class
Oahu
Capacity (MW)
0
100
200
300
400
500
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
23 - 25
Capacity Factor Class

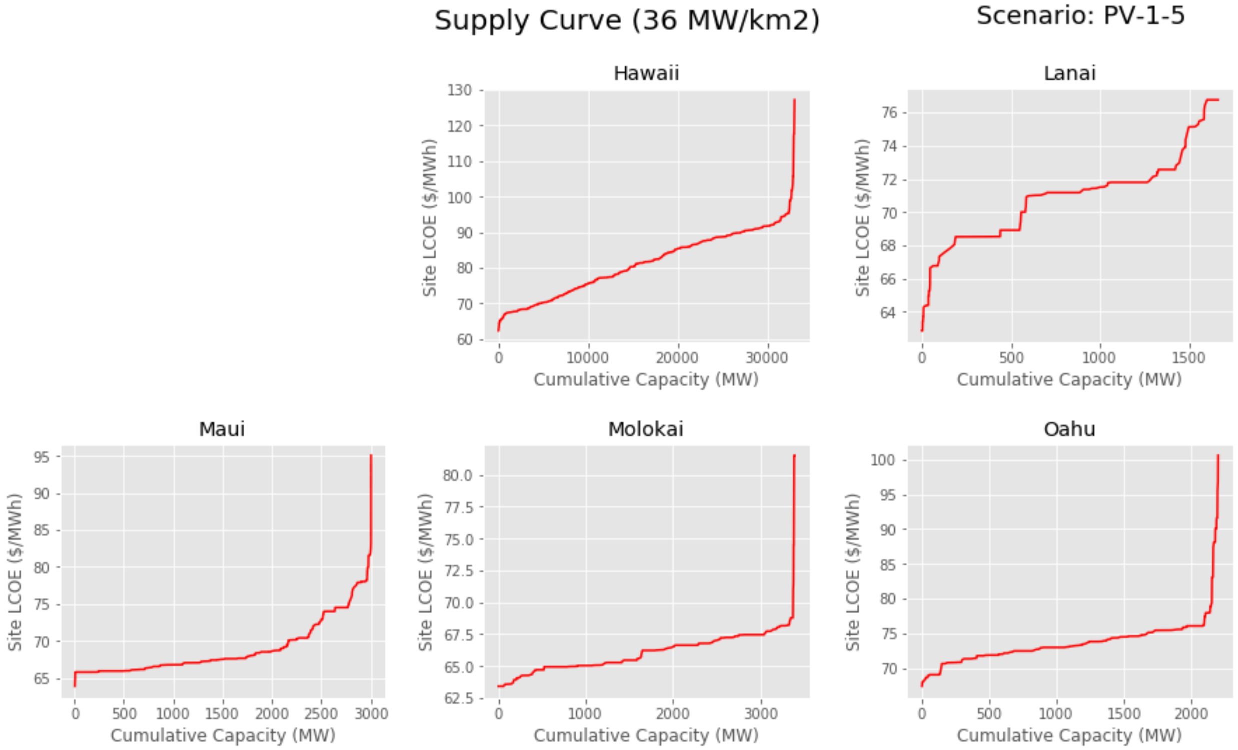

Supply Curve (32 MW/km2)
Scenario: PV-3-5
Hawaii
Site LCOE ($/MWh)
50
60
70
80
90
100
0
10000
20000
30000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
46
48
50
52
54
56
0
200
400
600
800
1000
1200
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
50
55
60
65
70
75
0
250
500
750
1000
1250
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
47.5
50.0
52.5
55.0
57.5
60.0
62.5
0
500
1000
1500
2000
2500
3000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
50
55
60
65
70
75
80
85
0
200
400
600
800
1000
Cumulative Capacity (MW)

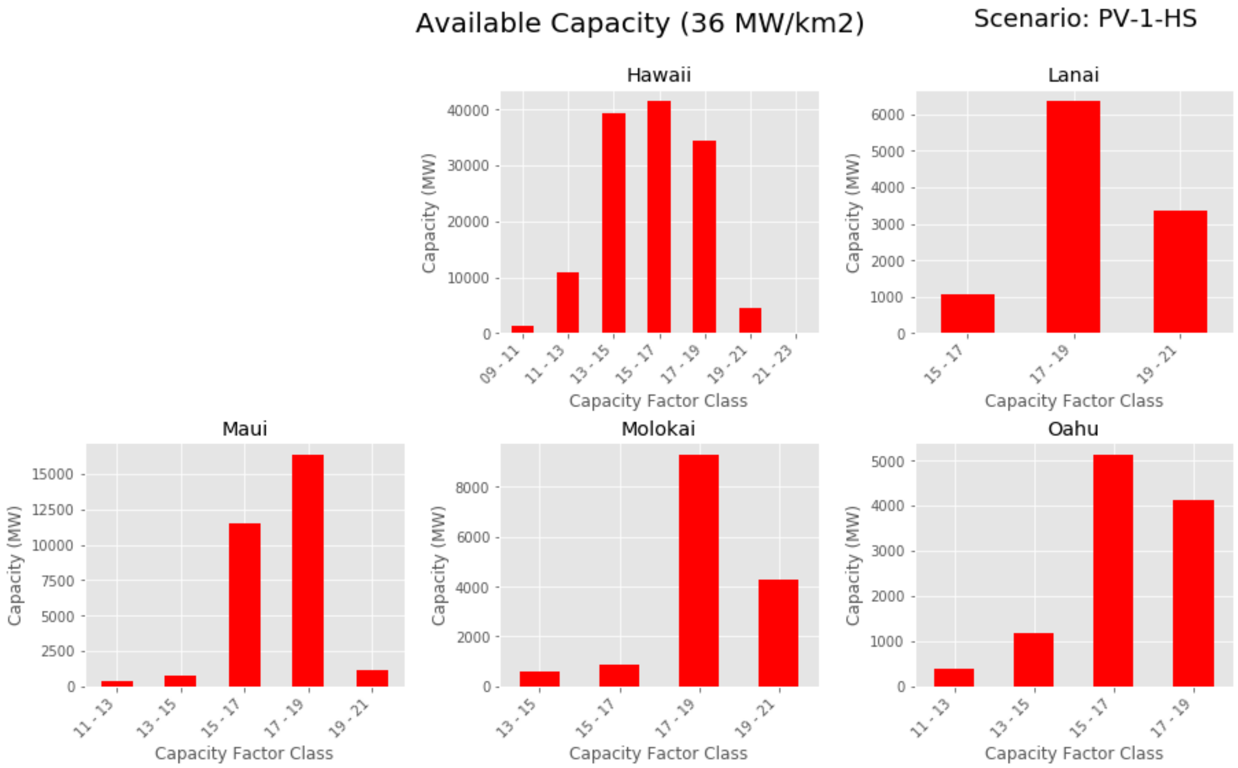
C.2 Fixed Tilt Summary Results

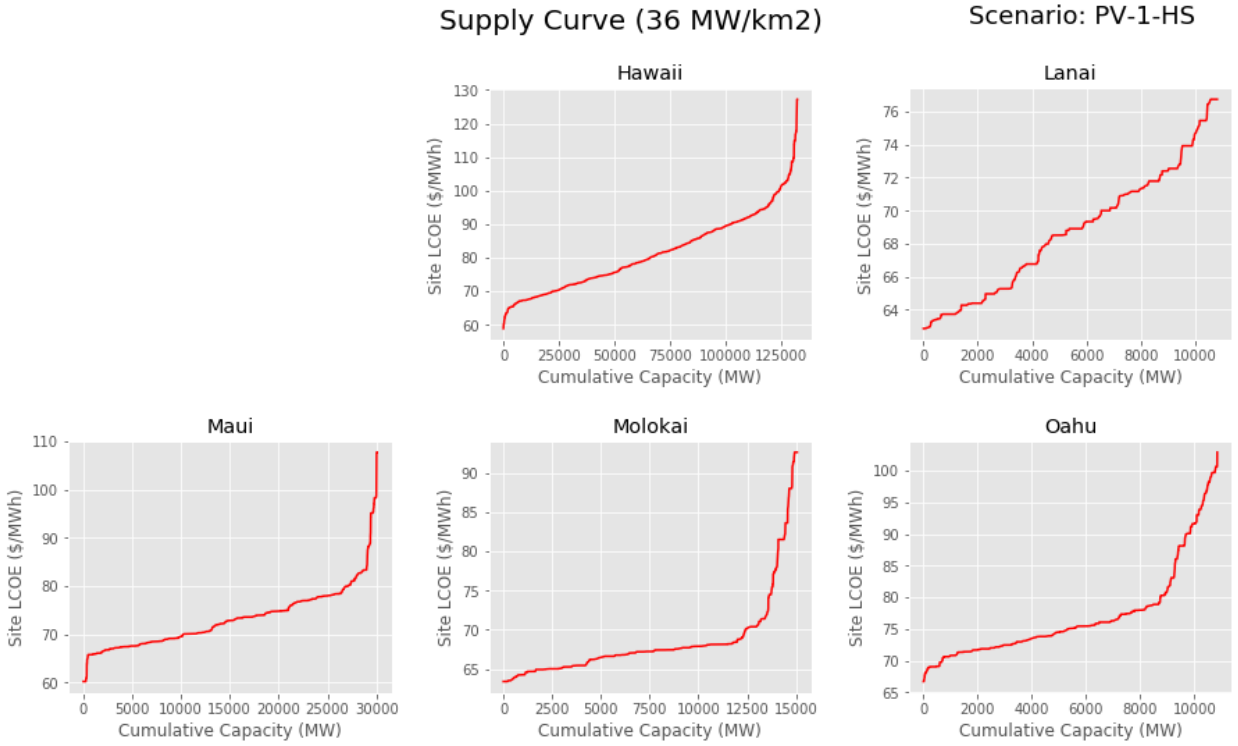


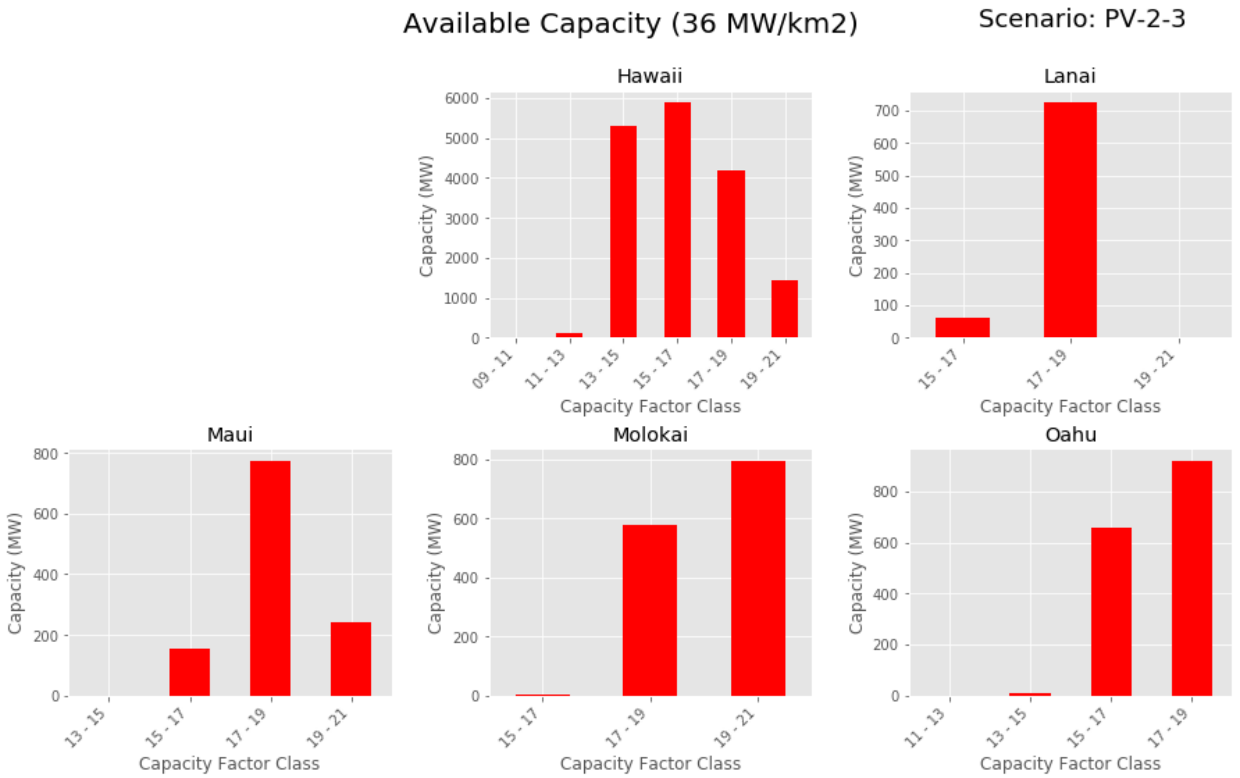


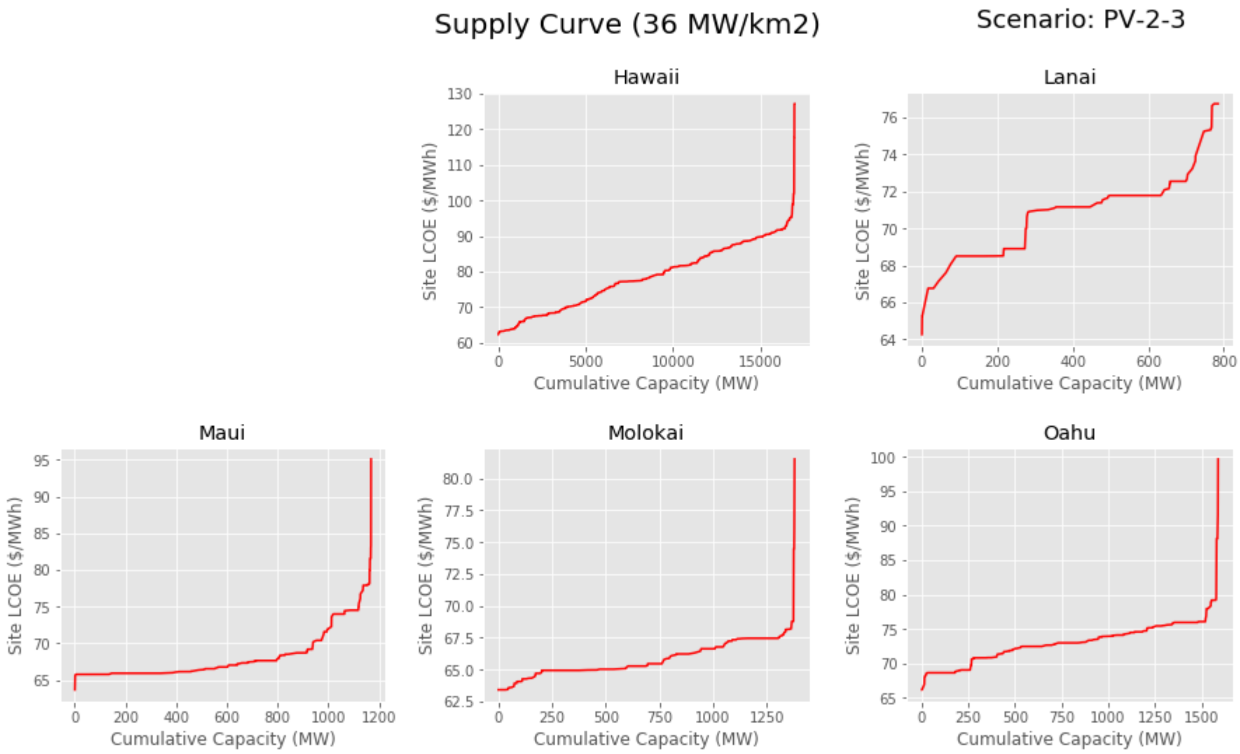

Available Capacity (36 MW/km2)
Scenario: PV-1-5
Hawaii
Lanai
Maui
Molokai
Oahu
Capacity (MW)
Capacity Factor Class
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
0
2000
4000
6000
8000
10000
12000
14000
200
400
600
800
1000
1200
1400
500
1500
2000
250
750
1250
1750

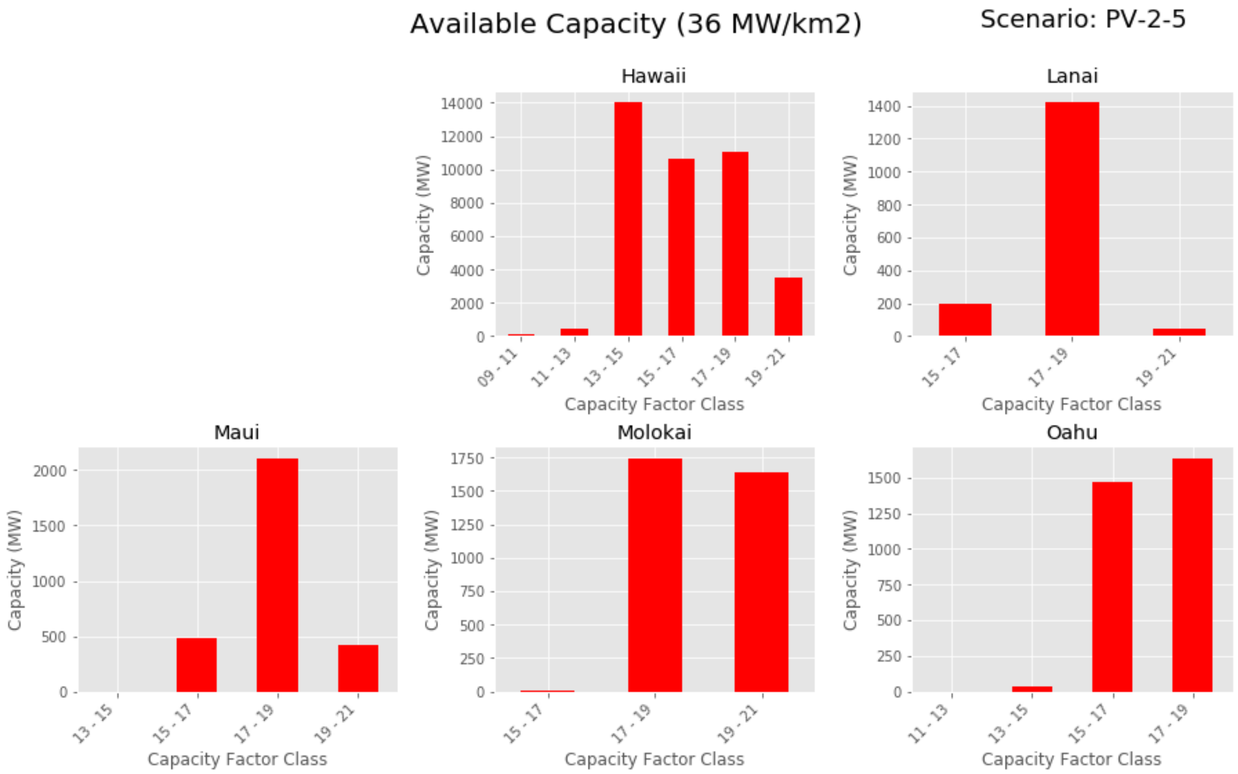

Supply Curve (36 MW/km2)
Scenario: PV-1-5
Hawaii
Lanai
Maui
Molokai
Oahu
Site LCOE ($/MWh)
Cumulative Capacity (MW)
0
500
1000
1500
2000
2500
3000
10000
20000
30000
60
70
80
90
100
110
120
130
64
66
68
70
72
74
76
65
75
85
95
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0

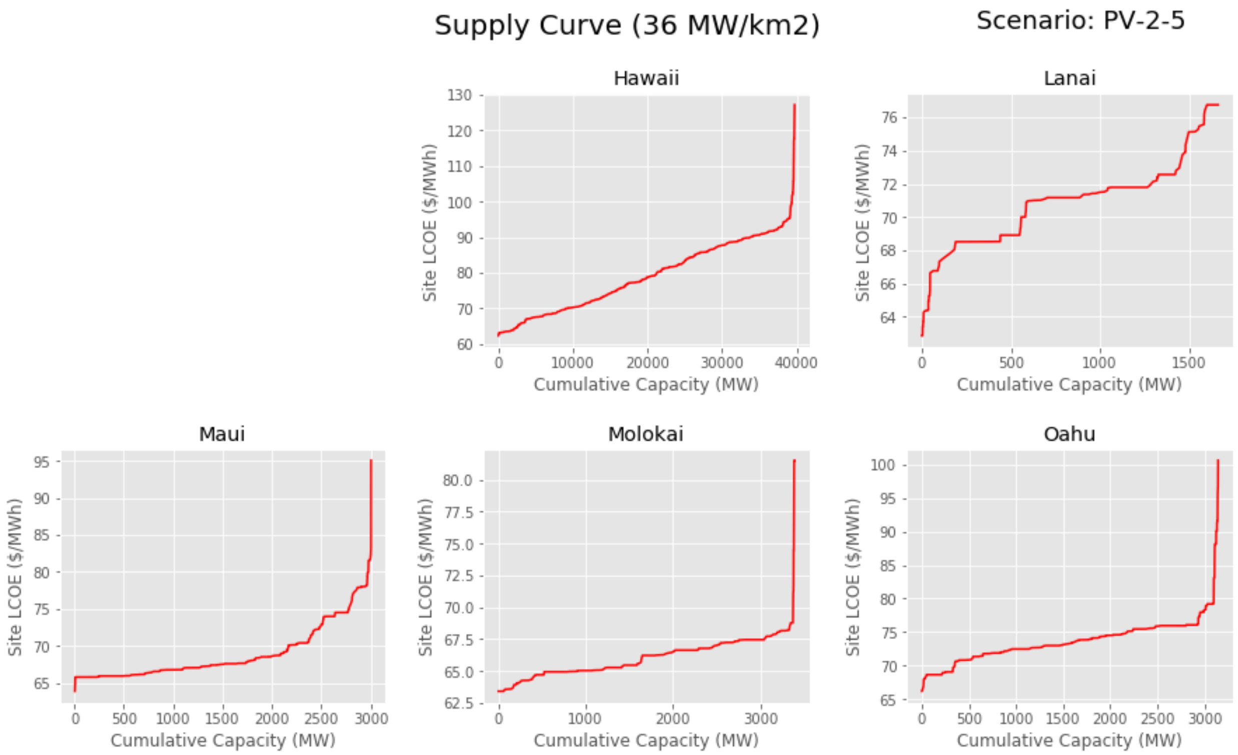

Available Capacity (36 MW/km2)
Scenario: PV-1-HS
Hawaii
Capacity (MW)
0
10000
20000
30000
40000
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
Capacity Factor Class
Lanai
Capacity (MW)
0
1000
2000
3000
4000
5000
6000
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Maui
Capacity (MW)
0
2500
5000
7500
10000
12500
15000
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Molokai
Capacity (MW)
0
2000
4000
6000
8000
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Oahu
Capacity (MW)
0
1000
2000
3000
4000
5000
11 - 13
13 - 15
15 - 17
17 - 19
Capacity Factor Class

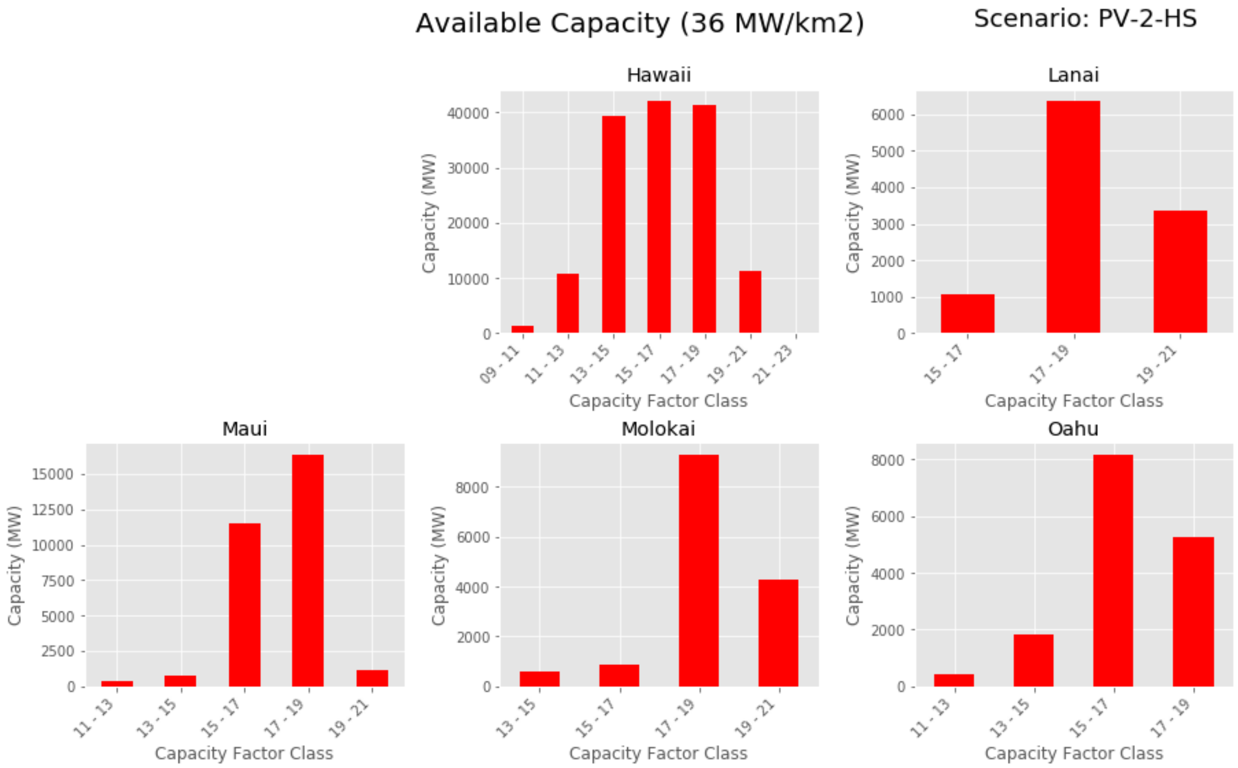

Supply Curve (36 MW/km2)
Scenario: PV-1-HS
Hawaii
Site LCOE ($/MWh)
60
70
80
90
100
110
120
130
0
25000
50000
75000
100000
125000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
64
66
68
70
72
74
76
0
2000
4000
6000
8000
10000
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
60
70
80
90
100
110
0
5000
10000
15000
20000
25000
30000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
65
70
75
80
85
90
0
2500
5000
7500
10000
12500
15000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
65
70
75
80
85
90
95
100
0
2000
4000
6000
8000
10000
Cumulative Capacity (MW)

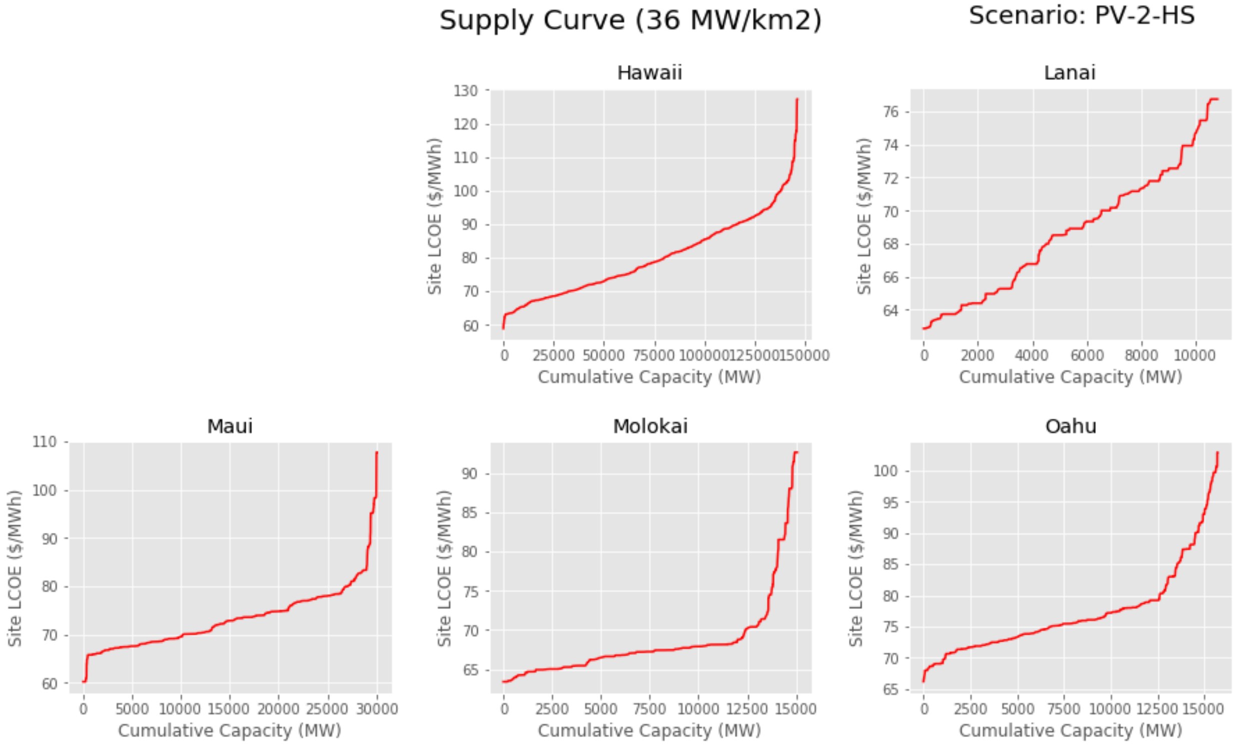

Available Capacity (36 MW/km2)
Scenario: PV-2-3
Hawaii
Capacity (MW)
0
1000
2000
3000
4000
5000
6000
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Lanai
Capacity (MW)
0
100
200
300
400
500
600
700
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Maui
Capacity (MW)
0
200
400
600
800
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Molokai
Capacity (MW)
0
200
400
600
800
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Oahu
Capacity (MW)
0
200
400
600
800
11 - 13
13 - 15
15 - 17
17 - 19
Capacity Factor Class

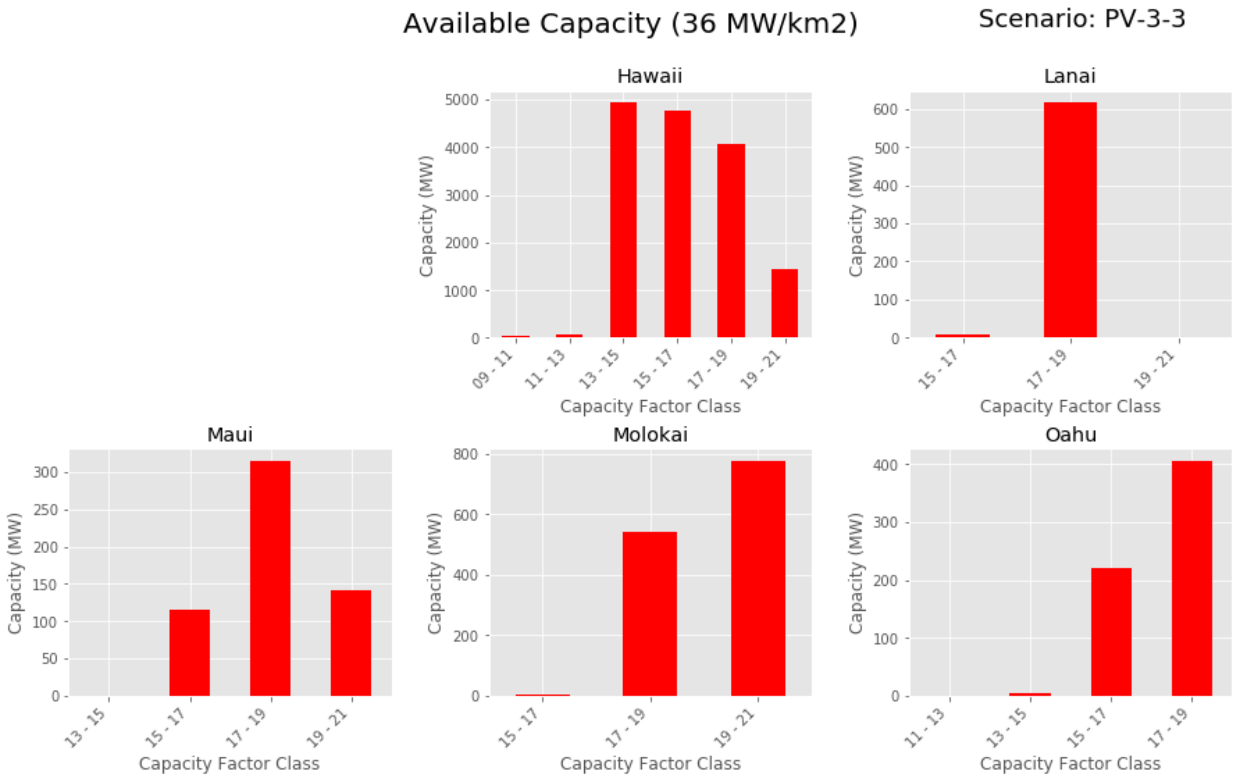

Supply Curve (36 MW/km2)
Scenario: PV-2-3
Hawaii
Site LCOE ($/MWh)
60
70
80
90
100
110
120
130
0
5000
10000
15000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
64
66
68
70
72
74
76
0
200
400
600
800
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
65
70
75
80
85
90
95
0
200
400
600
800
1000
1200
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
0
250
500
750
1000
1250
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
65
70
75
80
85
90
95
100
0
250
500
750
1000
1250
1500
Cumulative Capacity (MW)

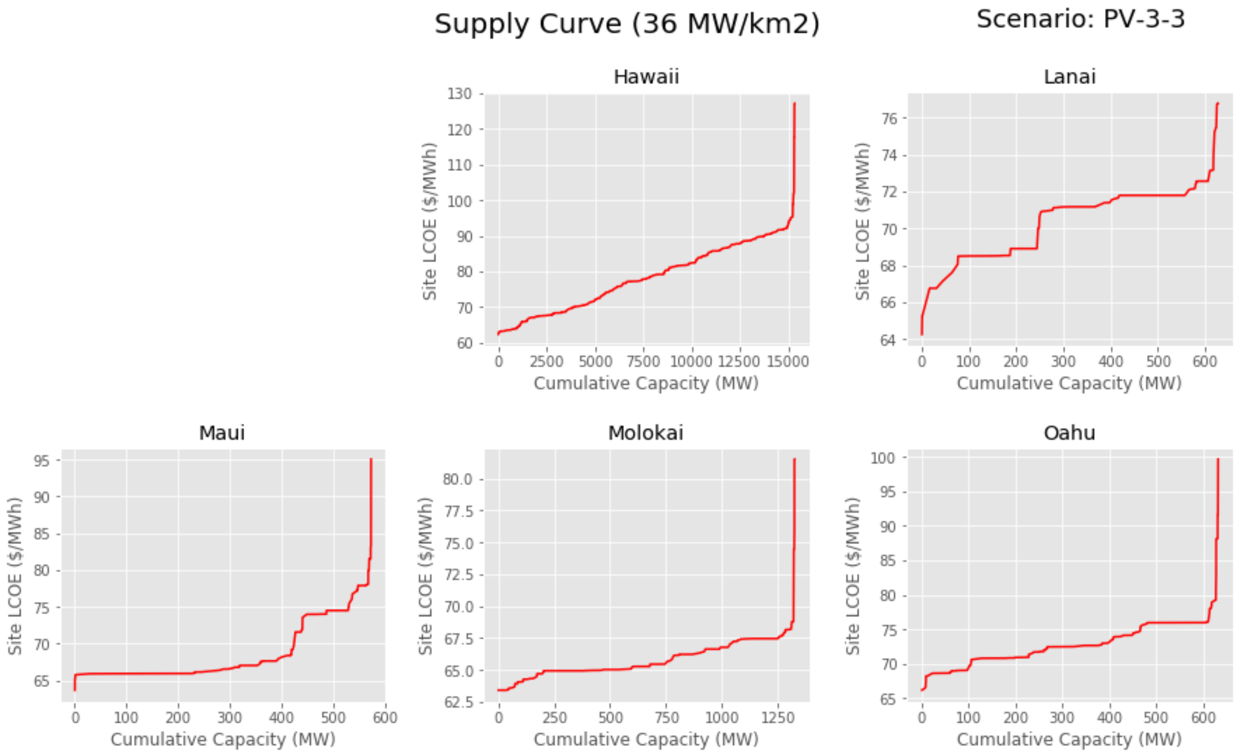

Available Capacity (36 MW/km2)
Scenario: PV-2-5
Hawaii
Capacity (MW)
0
2000
4000
6000
8000
10000
12000
14000
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Lanai
Capacity (MW)
0
200
400
600
800
1000
1200
1400
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Maui
Capacity (MW)
0
500
1000
1500
2000
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Molokai
Capacity (MW)
0
250
500
750
1000
1250
1500
1750
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Oahu
Capacity (MW)
0
250
500
750
1000
1250
1500
11 - 13
13 - 15
15 - 17
17 - 19
Capacity Factor Class

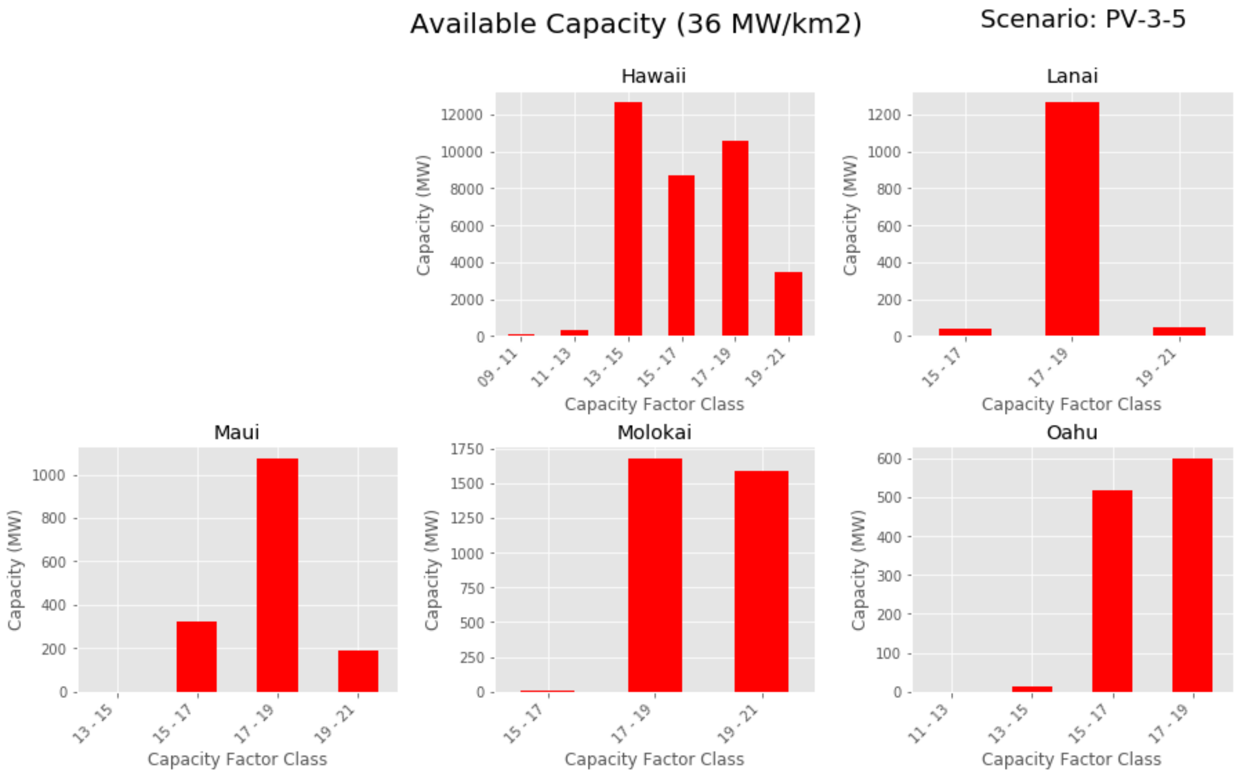

Supply Curve (36 MW/km2)
Scenario: PV-2-5
Hawaii
Site LCOE ($/MWh)
60
70
80
90
100
110
120
130
0
10000
20000
30000
40000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
64
66
68
70
72
74
76
0
500
1000
1500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
65
70
75
80
85
90
95
0
500
1000
1500
2000
2500
3000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
0
1000
2000
3000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
65
70
75
80
85
90
95
100
0
500
1000
1500
2000
2500
3000
Cumulative Capacity (MW)

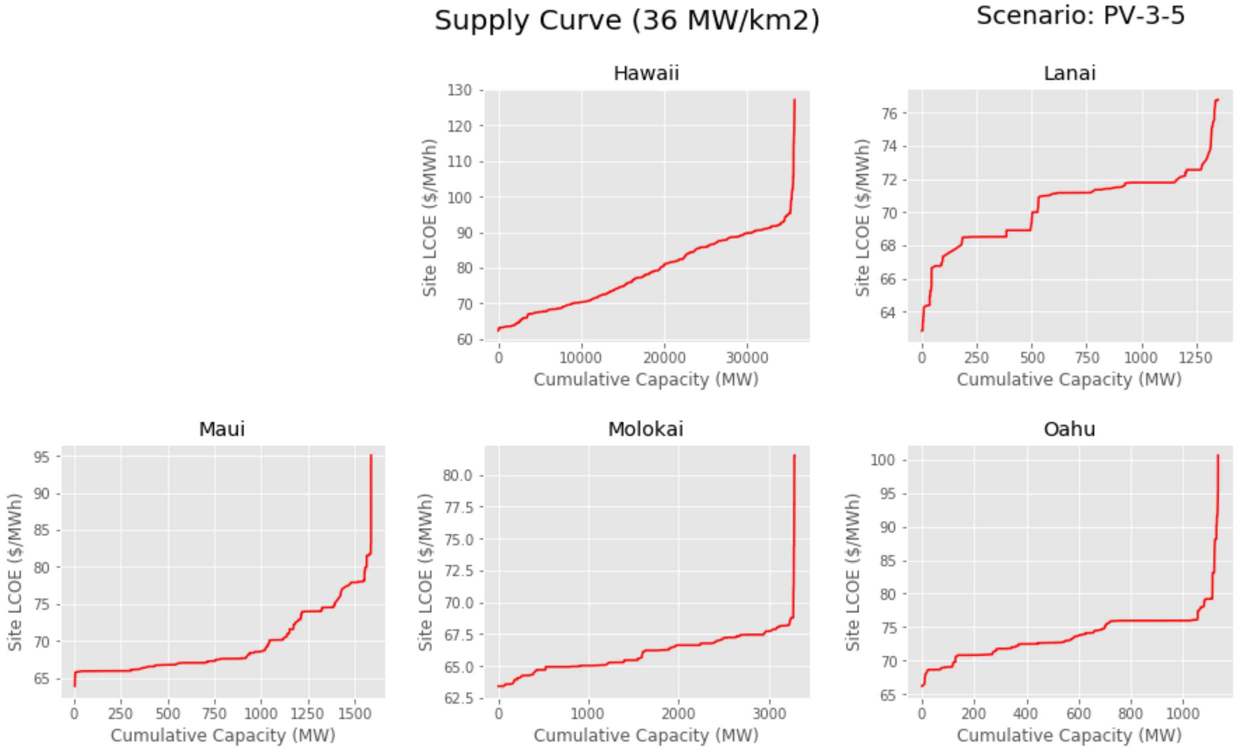

Available Capacity (36 MW/km2)
Scenario: PV-2-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Capacity (MW)
Capacity Factor Class
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
21 - 23
0
10000
20000
30000
40000
1000
2000
3000
4000
5000
6000
2500
5000
7500
10000
12500
15000
8000


Supply Curve (36 MW/km2)
Scenario: PV-2-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Site LCOE ($/MWh)
Cumulative Capacity (MW)
0
25000
50000
75000
100000
125000
150000
2000
4000
6000
8000
10000
5000
10000
15000
20000
25000
30000
2500
7500
12500
60
70
80
90
100
110
120
130
64
66
68
70
72
74
76
65
75
85
95

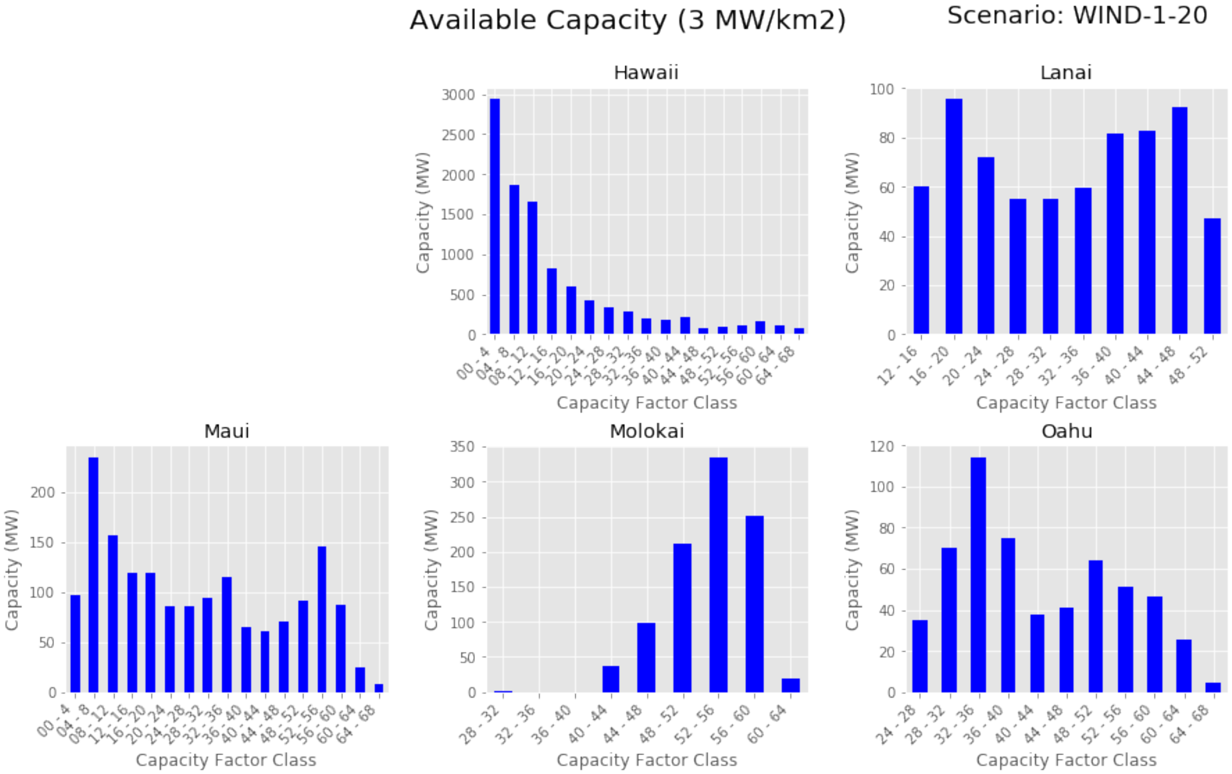

Available Capacity (36 MW/km2)
Scenario: PV-3-3
Hawaii
Capacity (MW)
0
1000
2000
3000
4000
5000
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Lanai
Capacity (MW)
0
100
200
300
400
500
600
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Maui
Capacity (MW)
0
50
100
150
200
250
300
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Molokai
Capacity (MW)
0
200
400
600
800
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Oahu
Capacity (MW)
0
100
200
300
400
11 - 13
13 - 15
15 - 17
17 - 19
Capacity Factor Class

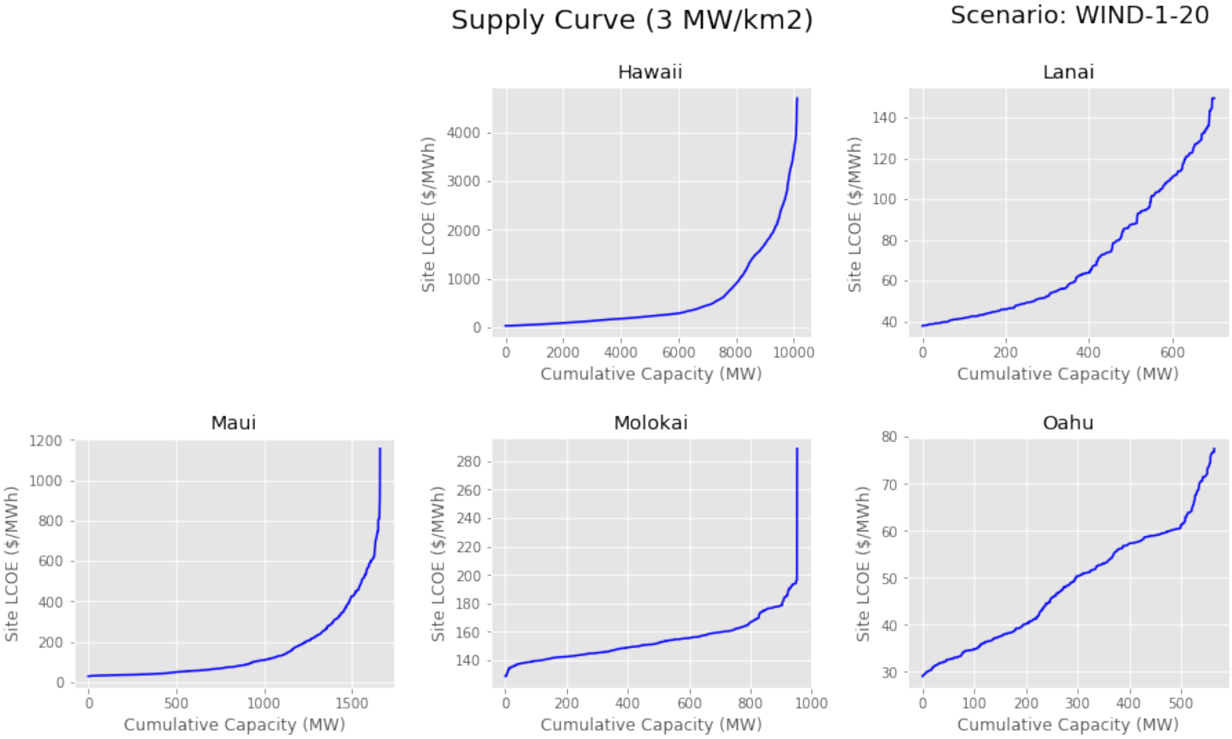

Supply Curve (36 MW/km2)
Scenario: PV-3-3
Hawaii
Site LCOE ($/MWh)
60
70
80
90
100
110
120
130
0
2500
5000
7500
10000
12500
15000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
64
66
68
70
72
74
76
0
100
200
300
400
500
600
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
65
70
75
80
85
90
95
0
100
200
300
400
500
600
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
0
250
500
750
1000
1250
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
65
70
75
80
85
90
95
100
0
100
200
300
400
500
600
Cumulative Capacity (MW)

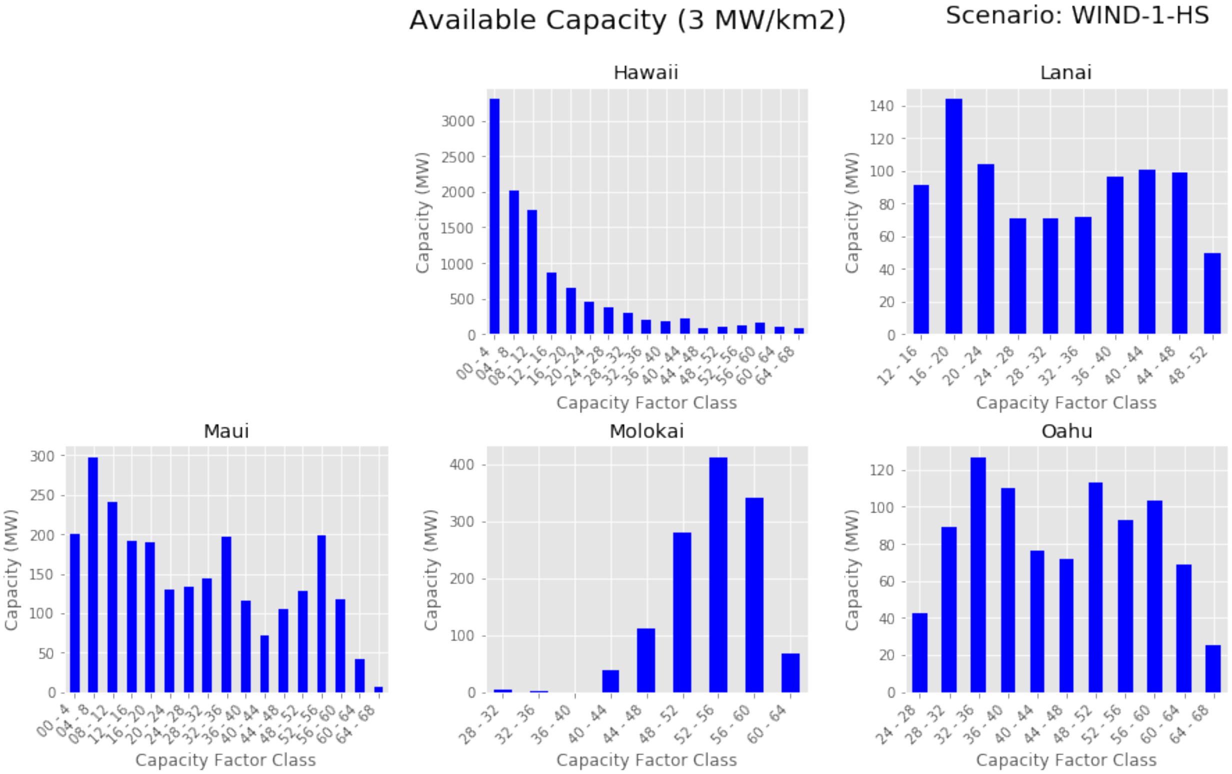

Available Capacity (36 MW/km2)
Scenario: PV-3-5
Hawaii
Capacity (MW)
0
2000
4000
6000
8000
10000
12000
09 - 11
11 - 13
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Lanai
Capacity (MW)
0
200
400
600
800
1000
1200
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Maui
Capacity (MW)
0
200
400
600
800
1000
13 - 15
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Molokai
Capacity (MW)
0
250
500
750
1000
1250
1500
1750
15 - 17
17 - 19
19 - 21
Capacity Factor Class
Oahu
Capacity (MW)
0
100
200
300
400
500
600
11 - 13
13 - 15
15 - 17
17 - 19
Capacity Factor Class

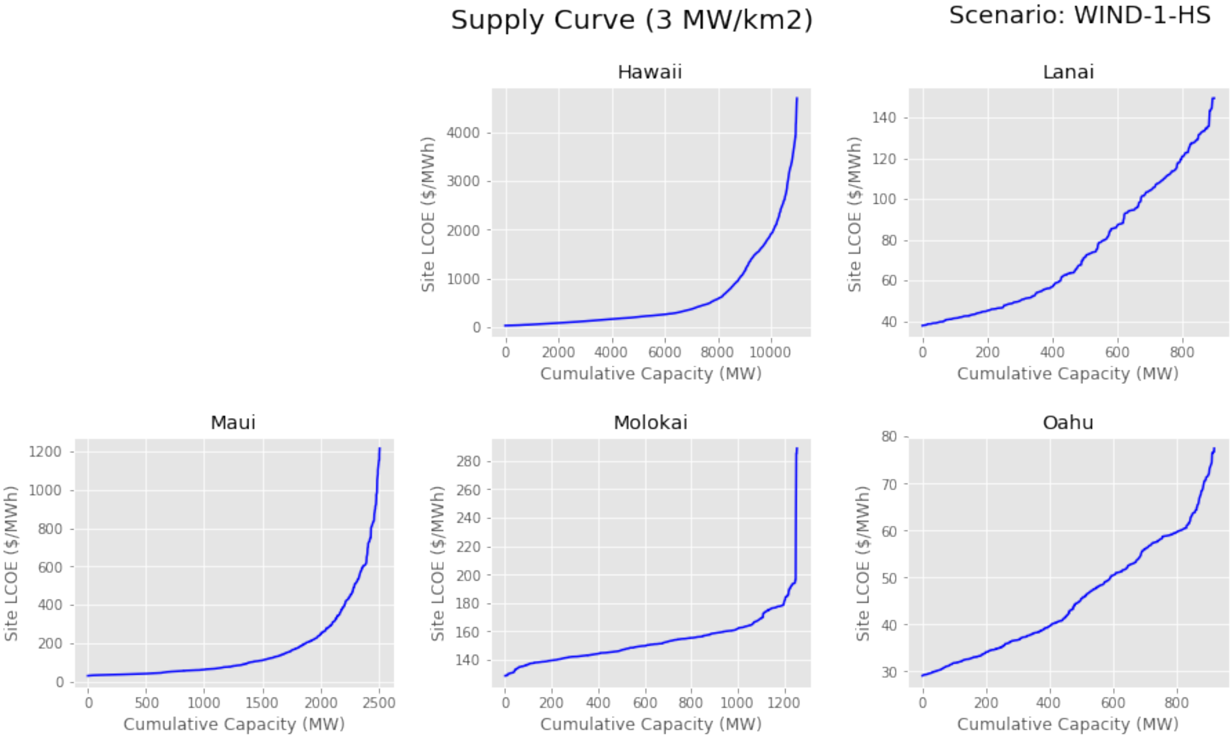

Supply Curve (36 MW/km2)
Scenario: PV-3-5
Hawaii
Site LCOE ($/MWh)
60
70
80
90
100
110
120
130
0
10000
20000
30000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
64
66
68
70
72
74
76
0
250
500
750
1000
1250
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
65
70
75
80
85
90
95
0
250
500
750
1000
1250
1500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0
0
1000
2000
3000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
65
70
75
80
85
90
95
100
0
200
400
600
800
1000
Cumulative Capacity (MW)

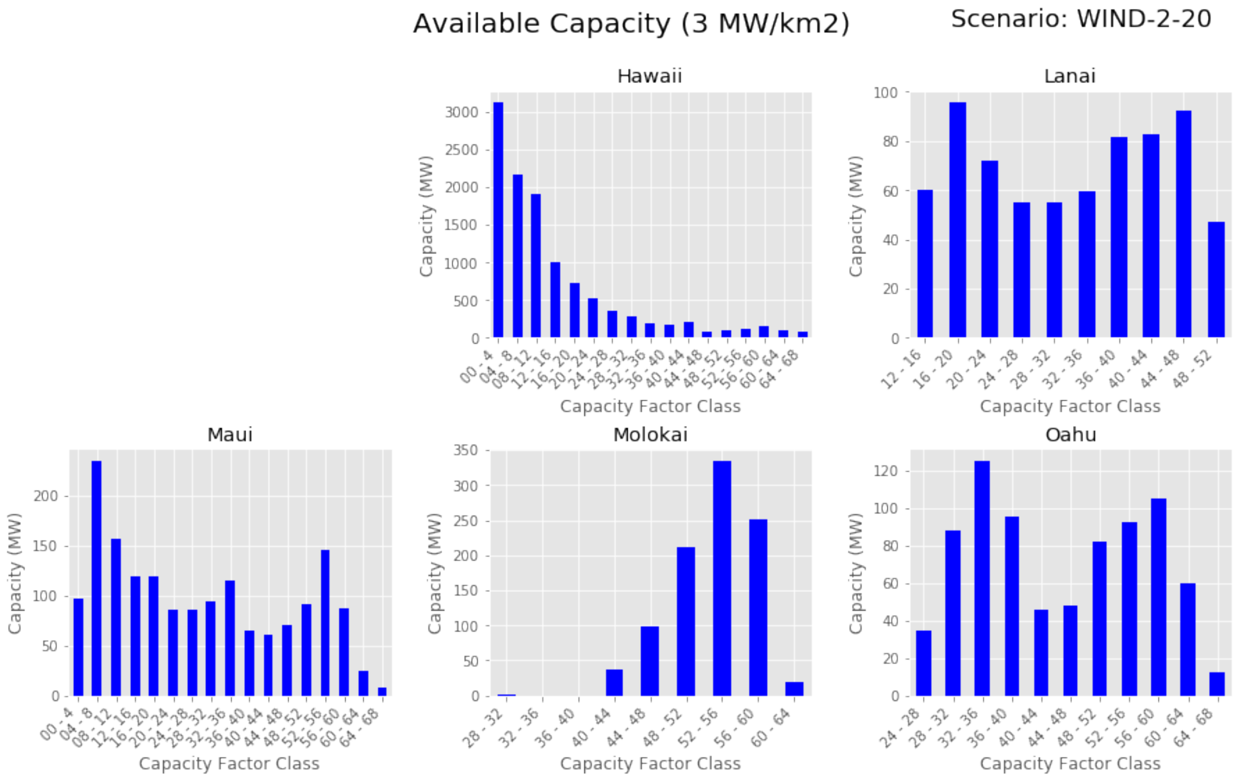
C.3 Wind Summary Results

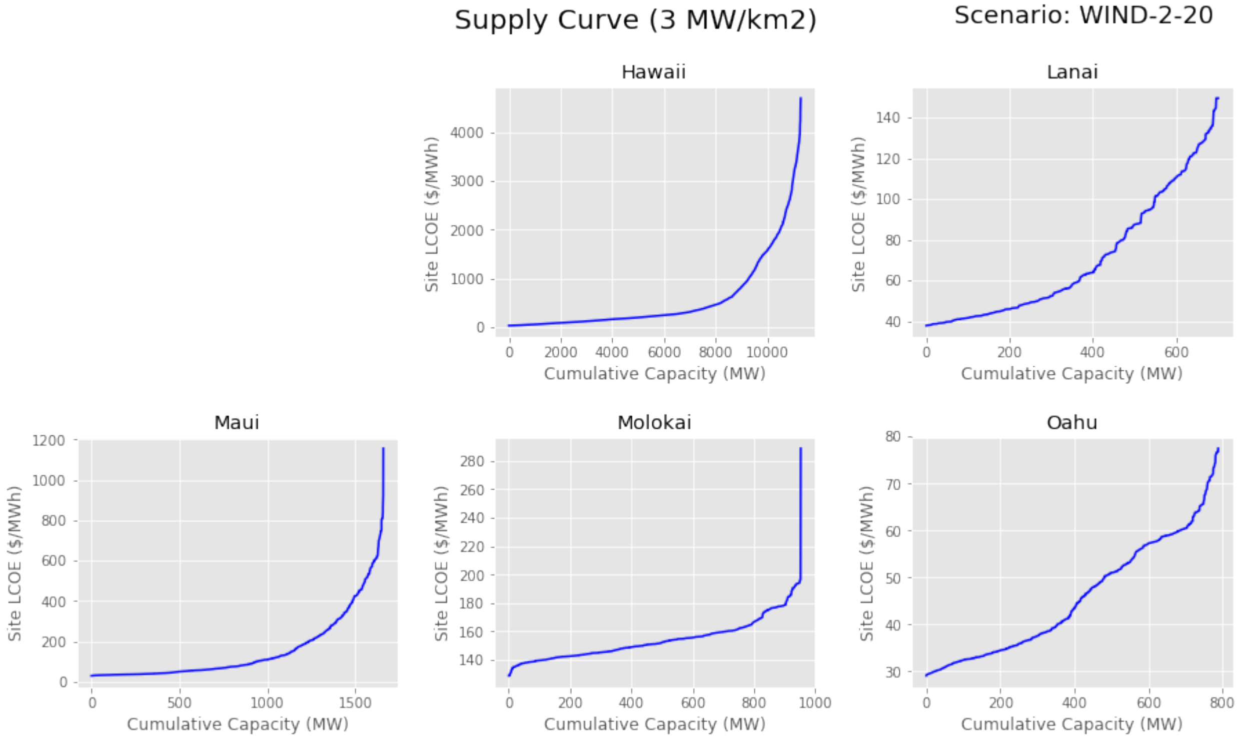





Available Capacity (3 MW/km2)
Scenario: WIND-1-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Capacity (MW)
Capacity Factor Class
0
500
1000
1500
2000
2500
3000
20
40
60
80
100
120
140
50
150
200
250
300
400
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68

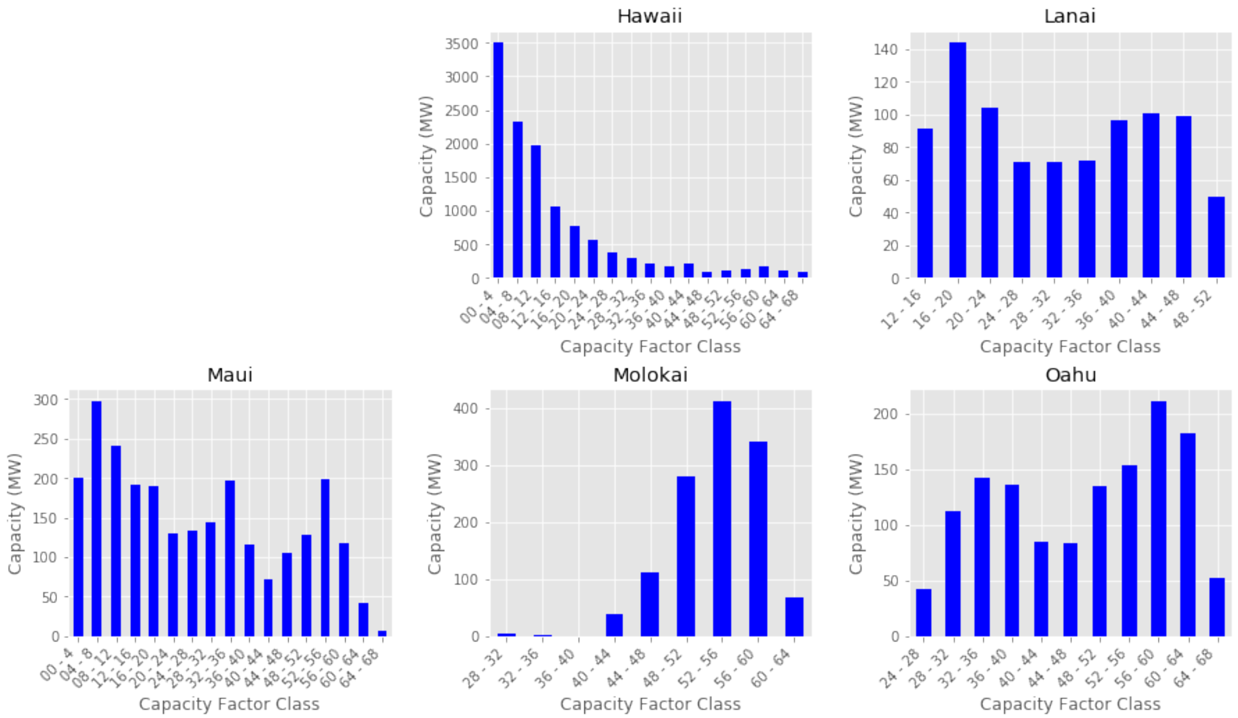

Supply Curve (3 MW/km2)
Scenario: WIND-1-HS
Hawaii
Lanai
Maui
Molokai
Oahu
Site LCOE ($/MWh)
Cumulative Capacity (MW)
0
1000
2000
3000
4000
6000
8000
10000
40
60
80
100
120
140
200
400
600
800
500
1500
2500
1200
160
180
220
240
260
280
30
50
70


Available Capacity (3 MW/km2)
Scenario: WIND-2-20
Hawaii
Lanai
Maui
Molokai
Oahu
Capacity (MW)
Capacity Factor Class
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
0
500
1000
1500
2000
2500
3000
20
40
60
80
100
50
150
200
250
300
350
120


Supply Curve (3 MW/km2)
Scenario: WIND-2-20
Hawaii
Lanai
Maui
Molokai
Oahu
Site LCOE ($/MWh)
Cumulative Capacity (MW)
0
1000
2000
3000
4000
6000
8000
10000
200
400
600
800
1200
1500
500
40
60
80
100
120
140
140
160
180
200
220
240
260
280
30
50
70

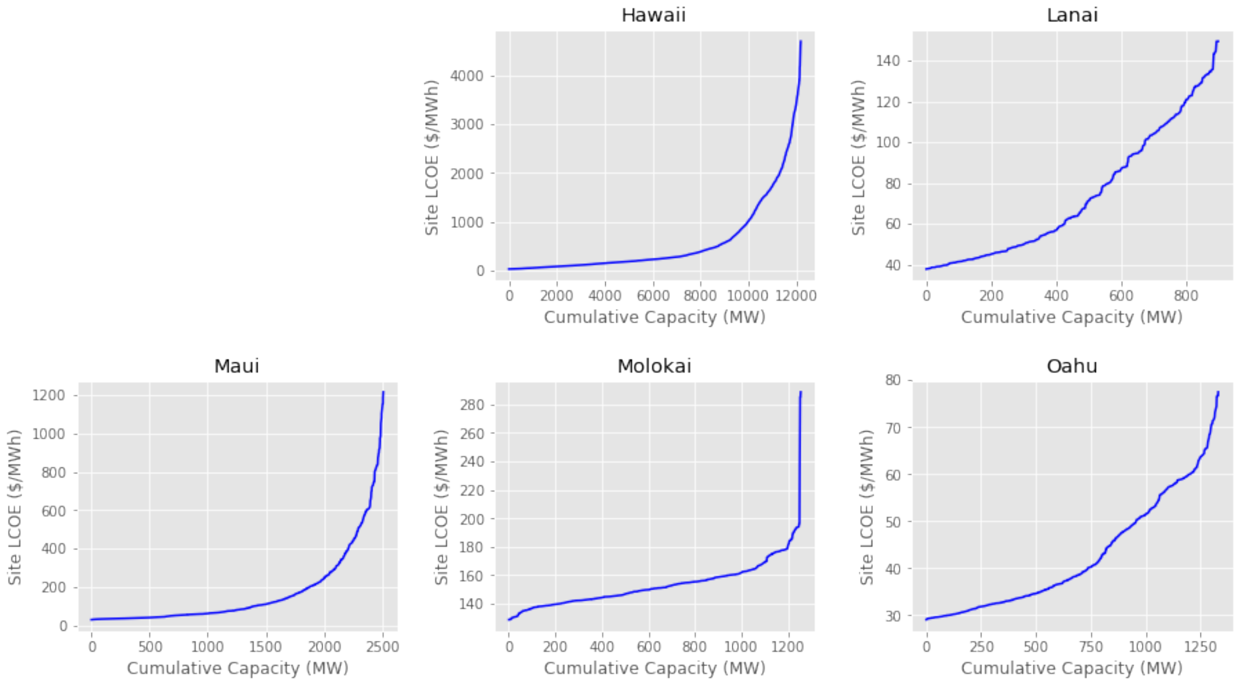
Available Capacity (3 MW/km2)

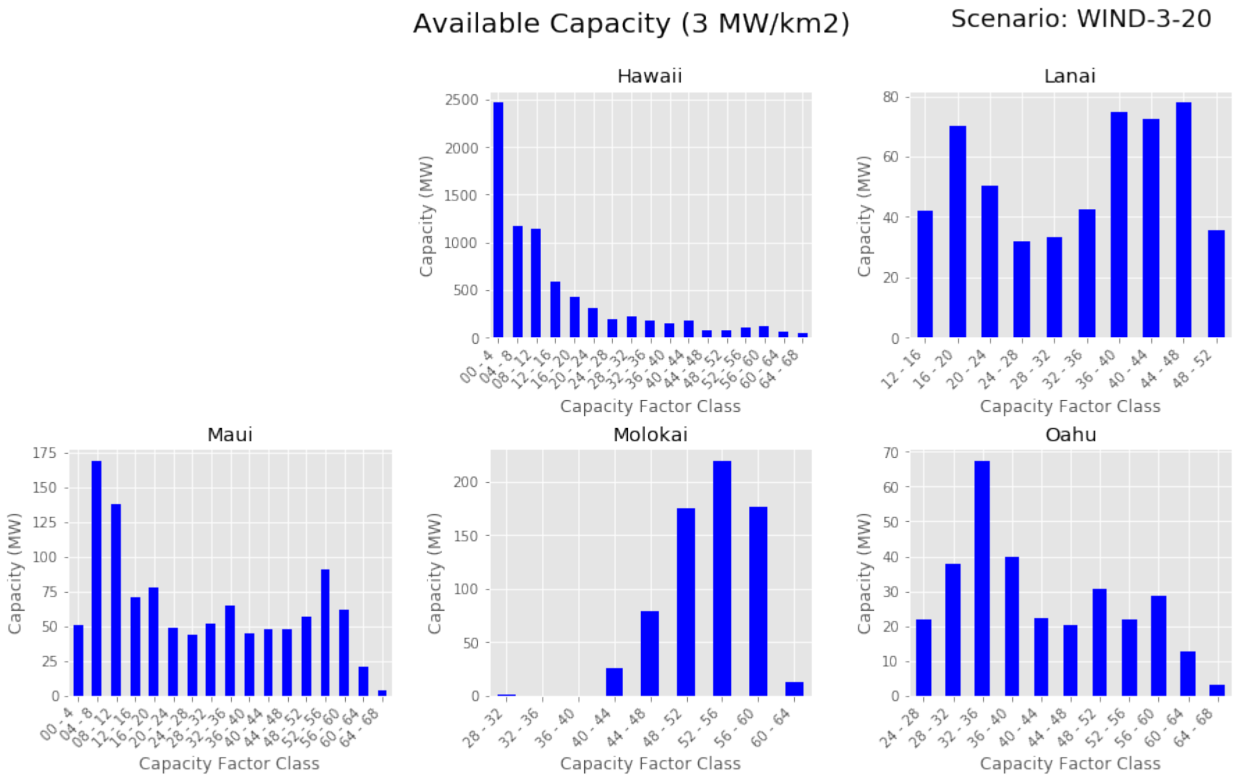
Scenario: WIND-2-HS

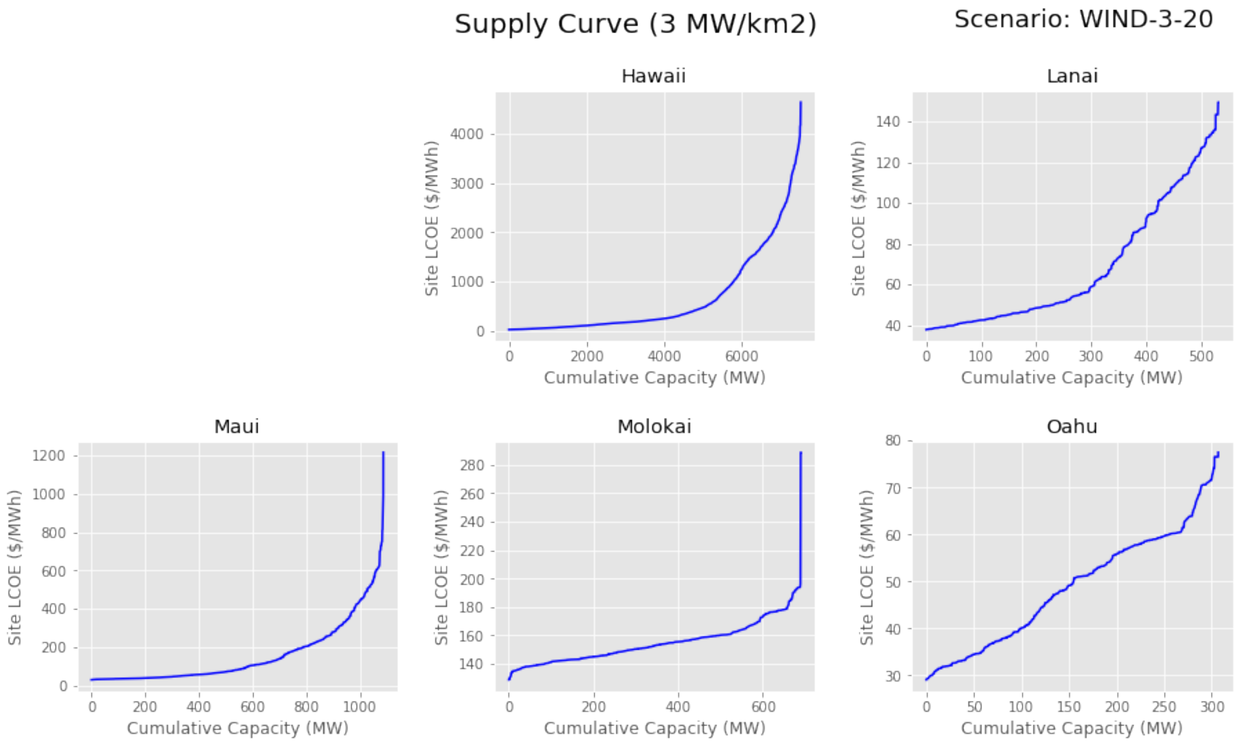


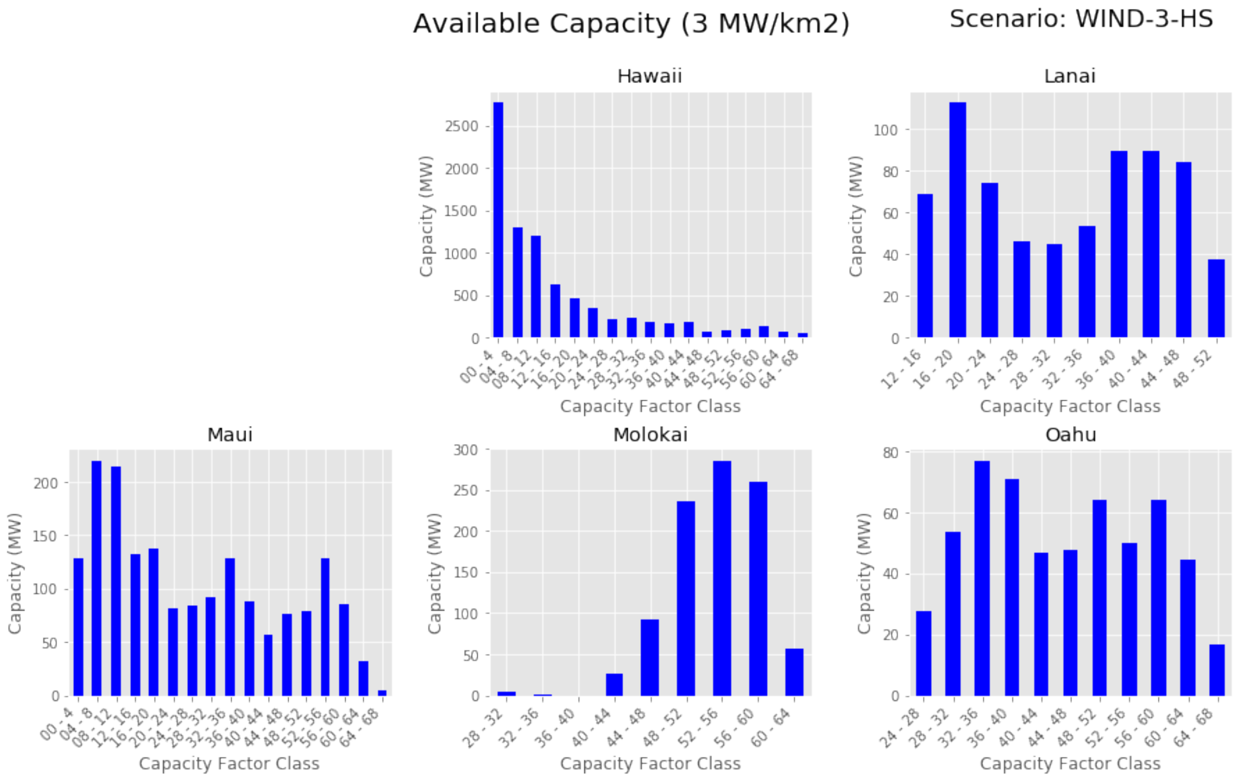
Supply Curve (3 MW/km2)

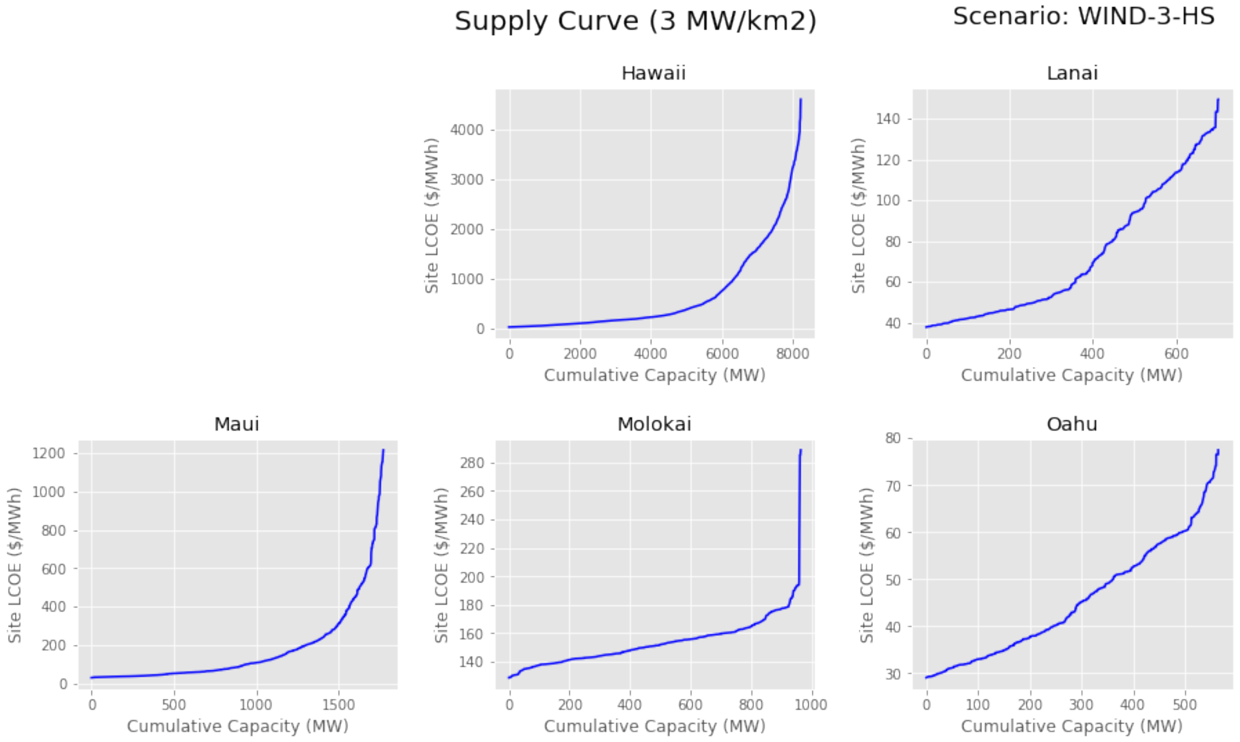
Scenario: WIND-2-HS

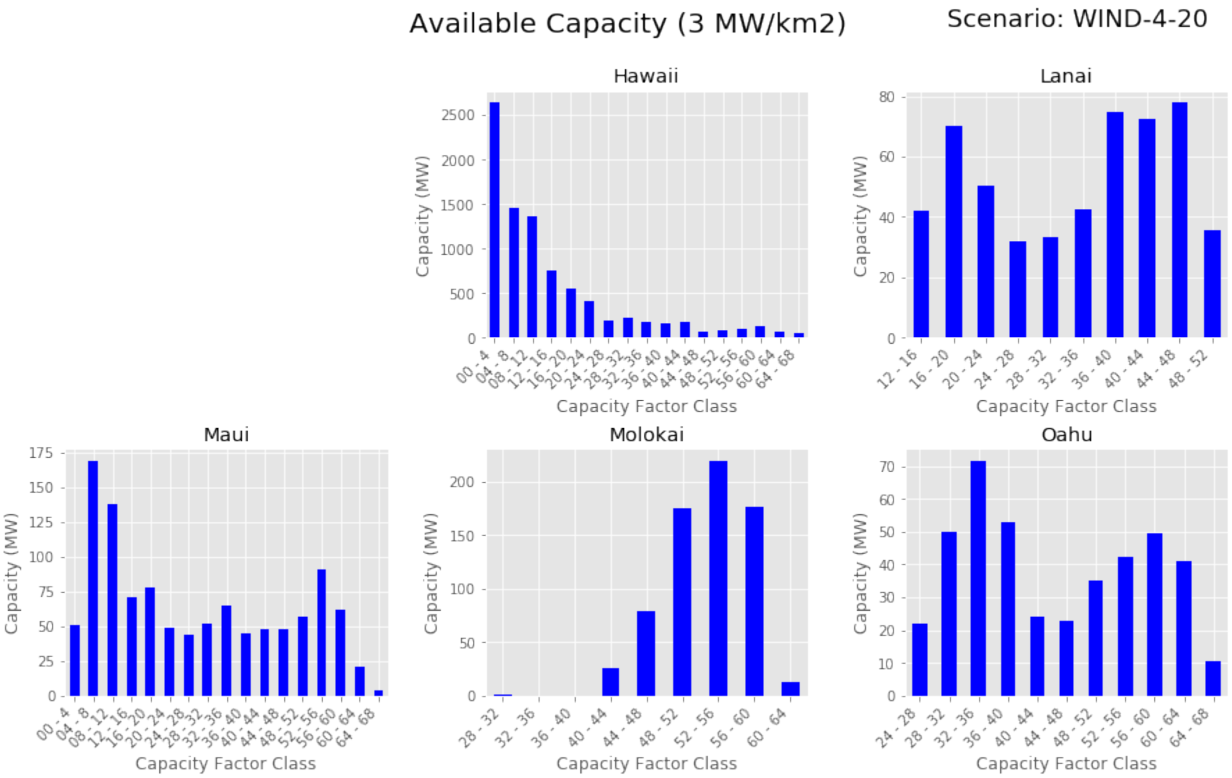


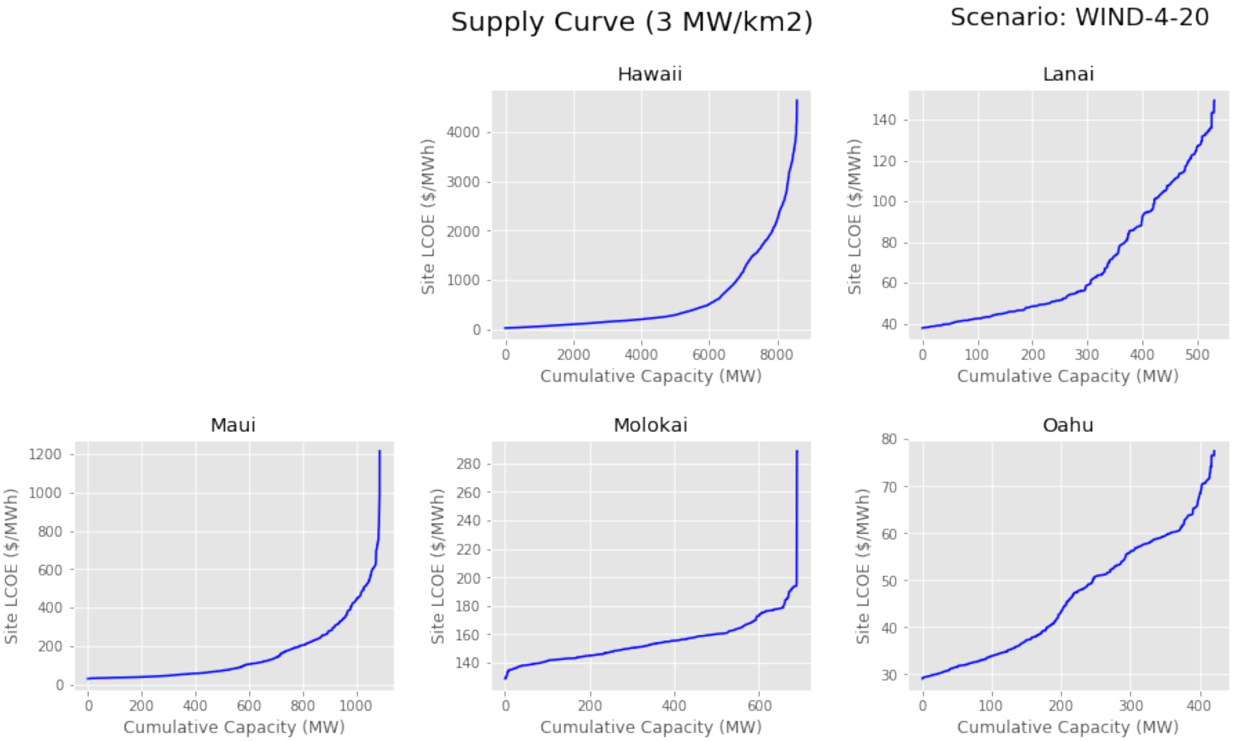

Available Capacity (3 MW/km2)
Scenario: WIND-3-20
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Lanai
Capacity (MW)
0
20
40
60
80
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
Capacity Factor Class
Maui
Capacity (MW)
0
25
50
75
100
125
150
175
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Molokai
Capacity (MW)
0
50
100
150
200
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
Capacity Factor Class
Oahu
Capacity (MW)
0
10
20
30
40
50
60
70
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class

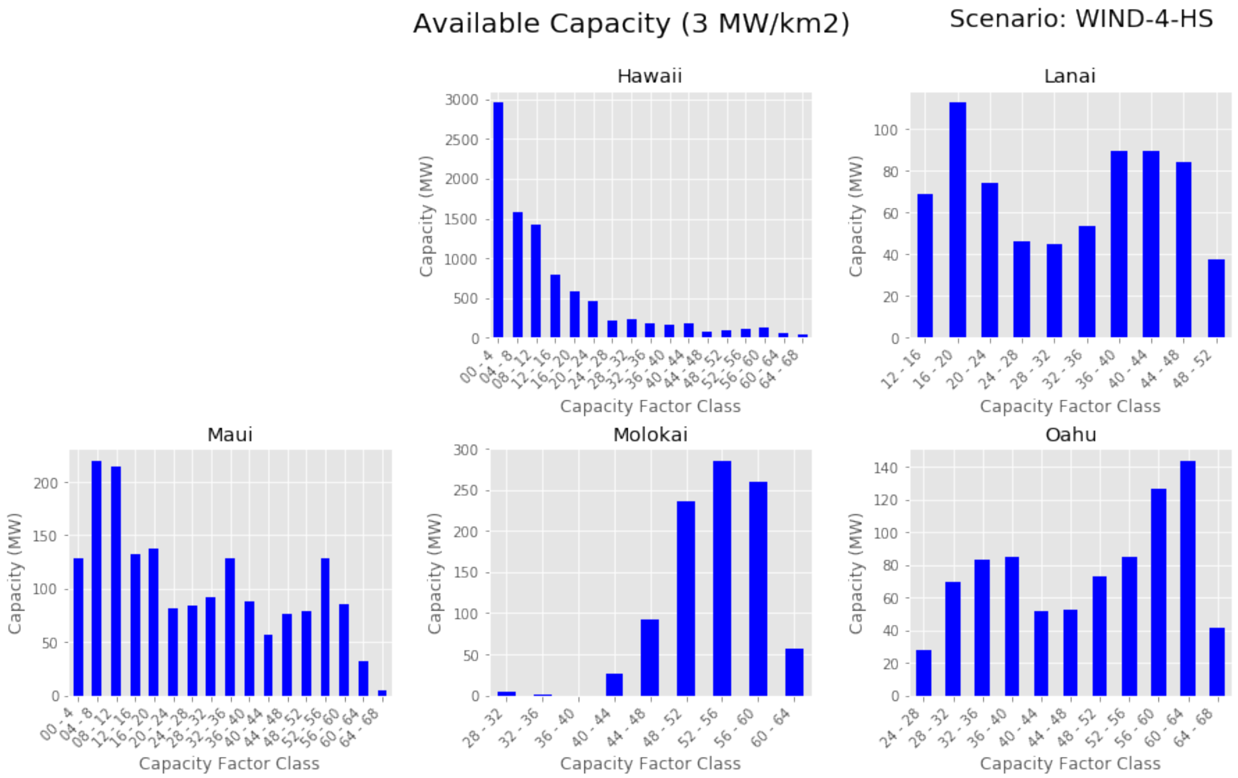

Supply Curve (3 MW/km2)
Scenario: WIND-3-20
Hawaii
Site LCOE ($/MWh)
0
1000
2000
3000
4000
0
2000
4000
6000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
40
60
80
100
120
140
0
100
200
300
400
500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
0
200
400
600
800
1000
1200
0
200
400
600
800
1000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
140
160
180
200
220
240
260
280
0
200
400
600
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
30
40
50
60
70
80
0
50
100
150
200
250
300
Cumulative Capacity (MW)

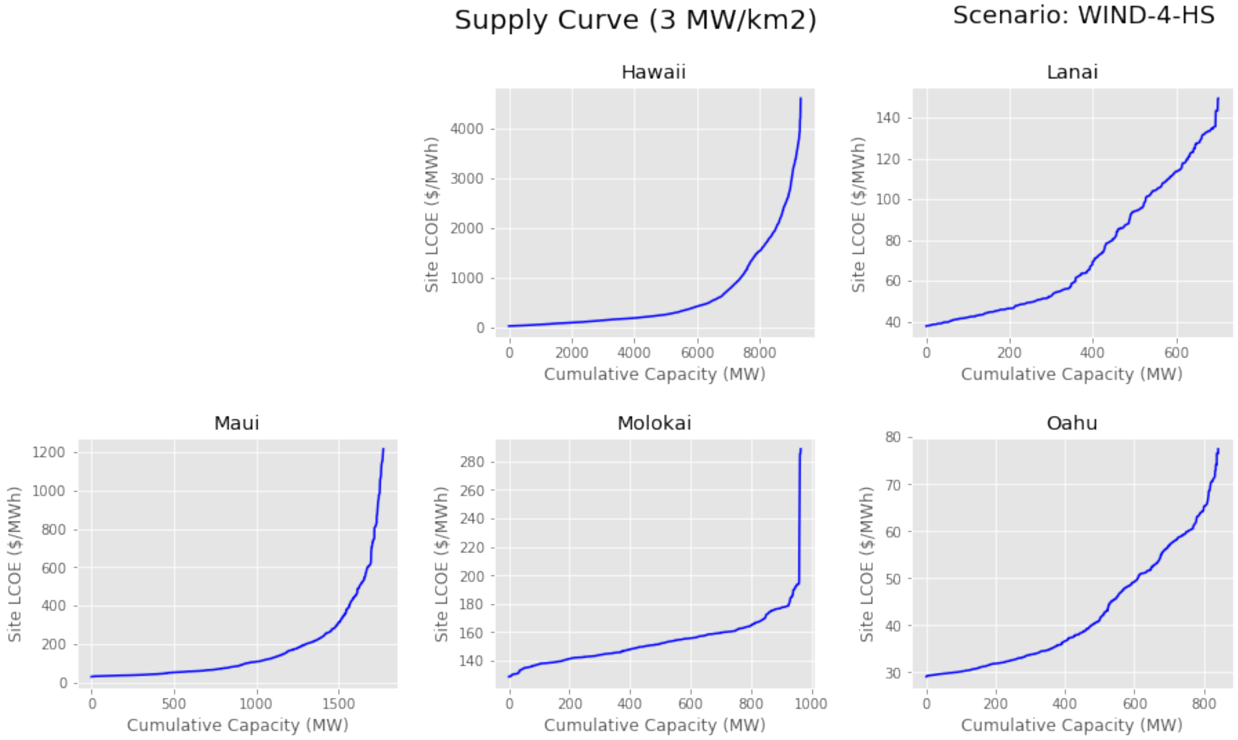

Available Capacity (3 MW/km2)
Scenario: WIND-3-HS
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Lanai
Capacity (MW)
0
20
40
60
80
100
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
Capacity Factor Class
Maui
Capacity (MW)
0
50
100
150
200
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Molokai
Capacity (MW)
0
50
100
150
200
250
300
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
Capacity Factor Class
Oahu
Capacity (MW)
0
20
40
60
80
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class


Supply Curve (3 MW/km2)
Scenario: WIND-3-HS
Hawaii
Site LCOE ($/MWh)
0
1000
2000
3000
4000
0
2000
4000
6000
8000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
40
60
80
100
120
140
0
200
400
600
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
0
200
400
600
800
1000
1200
0
500
1000
1500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
140
160
180
200
220
240
260
280
0
200
400
600
800
1000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
30
40
50
60
70
80
0
100
200
300
400
500
Cumulative Capacity (MW)


Available Capacity (3 MW/km2)
Scenario: WIND-4-20
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Lanai
Capacity (MW)
0
20
40
60
80
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
Capacity Factor Class
Maui
Capacity (MW)
0
25
50
75
100
125
150
175
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Molokai
Capacity (MW)
0
50
100
150
200
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
Capacity Factor Class
Oahu
Capacity (MW)
0
10
20
30
40
50
60
70
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class

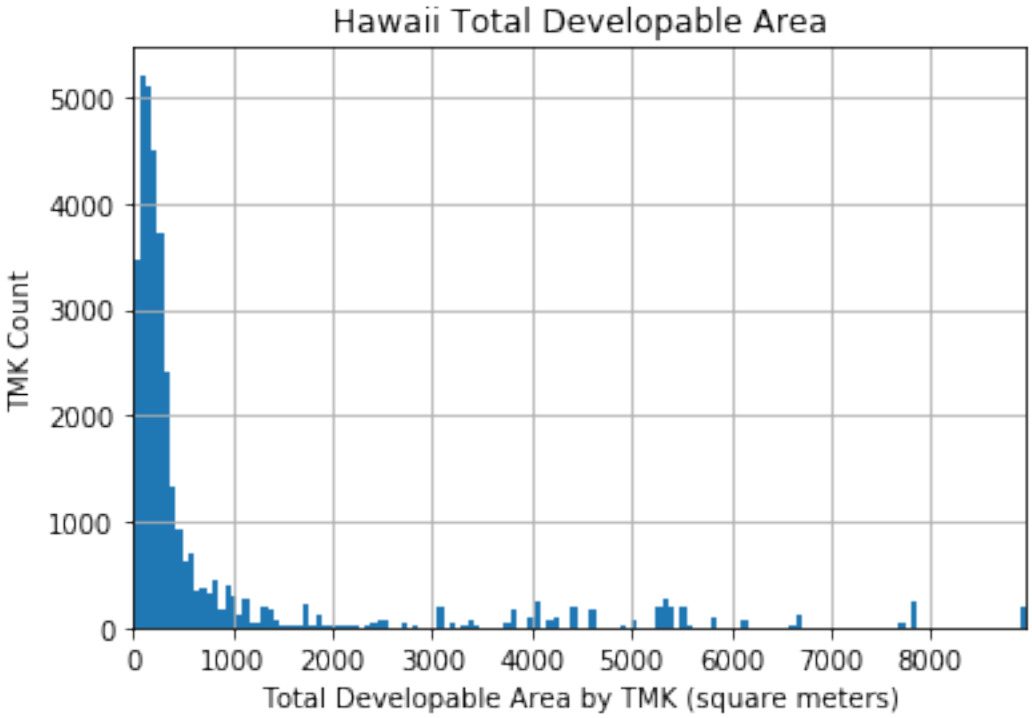

Supply Curve (3 MW/km2)
Scenario: WIND-4-20
Hawaii
Site LCOE ($/MWh)
0
1000
2000
3000
4000
0
2000
4000
6000
8000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
40
60
80
100
120
140
0
100
200
300
400
500
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
0
200
400
600
800
1000
1200
0
200
400
600
800
1000
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
140
160
180
200
220
240
260
280
0
200
400
600
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
30
40
50
60
70
80
0
100
200
300
400
Cumulative Capacity (MW)

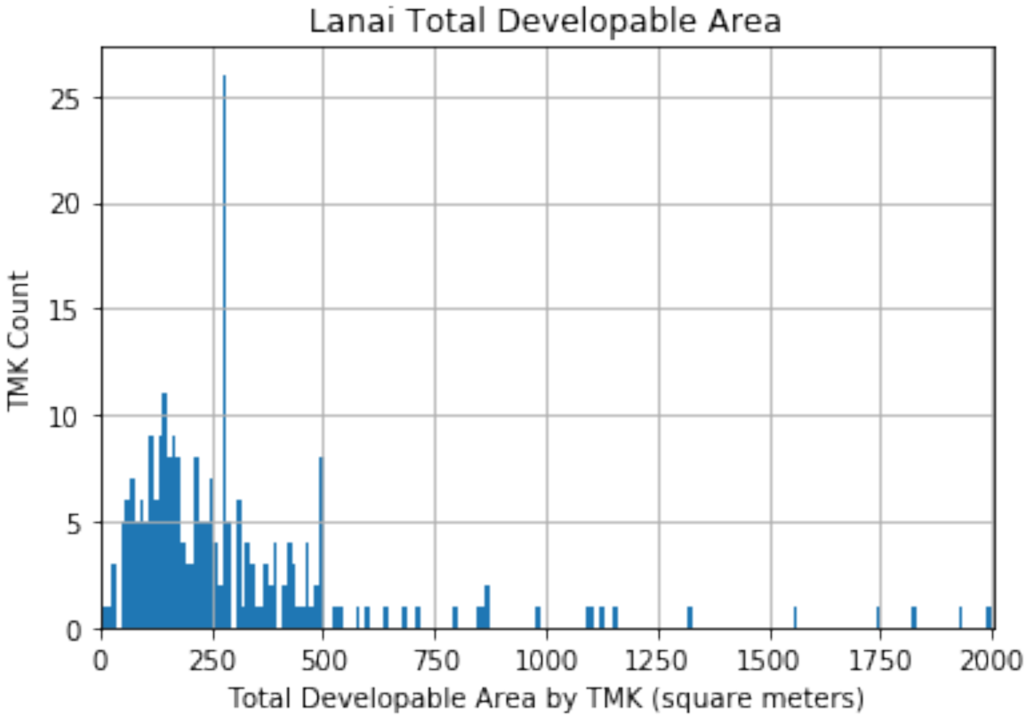

Available Capacity (3 MW/km2)
Scenario: WIND-4-HS
Hawaii
Capacity (MW)
0
500
1000
1500
2000
2500
3000
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Lanai
Capacity (MW)
0
20
40
60
80
100
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
Capacity Factor Class
Maui
Capacity (MW)
0
50
100
150
200
00 - 4
04 - 8
08 - 12
12 - 16
16 - 20
20 - 24
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class
Molokai
Capacity (MW)
0
50
100
150
200
250
300
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
Capacity Factor Class
Oahu
Capacity (MW)
0
20
40
60
80
100
120
140
24 - 28
28 - 32
32 - 36
36 - 40
40 - 44
44 - 48
48 - 52
52 - 56
56 - 60
60 - 64
64 - 68
Capacity Factor Class

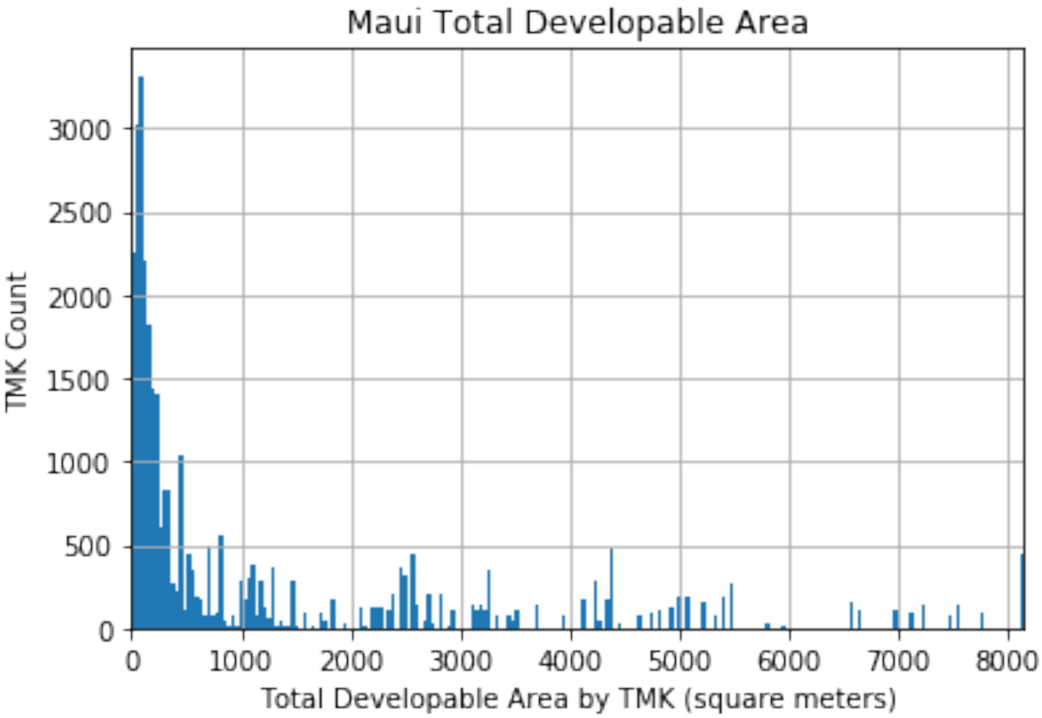

Supply Curve (3 MW/km2)
Scenario: WIND-4-HS
Hawaii
Site LCOE ($/MWh)
0
1000
2000
3000
4000
0
2000
4000
6000
8000
Cumulative Capacity (MW)
Lanai
Site LCOE ($/MWh)
40
60
80
100
120
140
0
200
400
600
Cumulative Capacity (MW)
Maui
Site LCOE ($/MWh)
0
200
400
600
800
1000
1200
0
500
1000
1500
Cumulative Capacity (MW)
Molokai
Site LCOE ($/MWh)
140
160
180
200
220
240
260
280
0
200
400
600
800
1000
Cumulative Capacity (MW)
Oahu
Site LCOE ($/MWh)
30
40
50
60
70
80
0
200
400
600
800
Cumulative Capacity (MW)

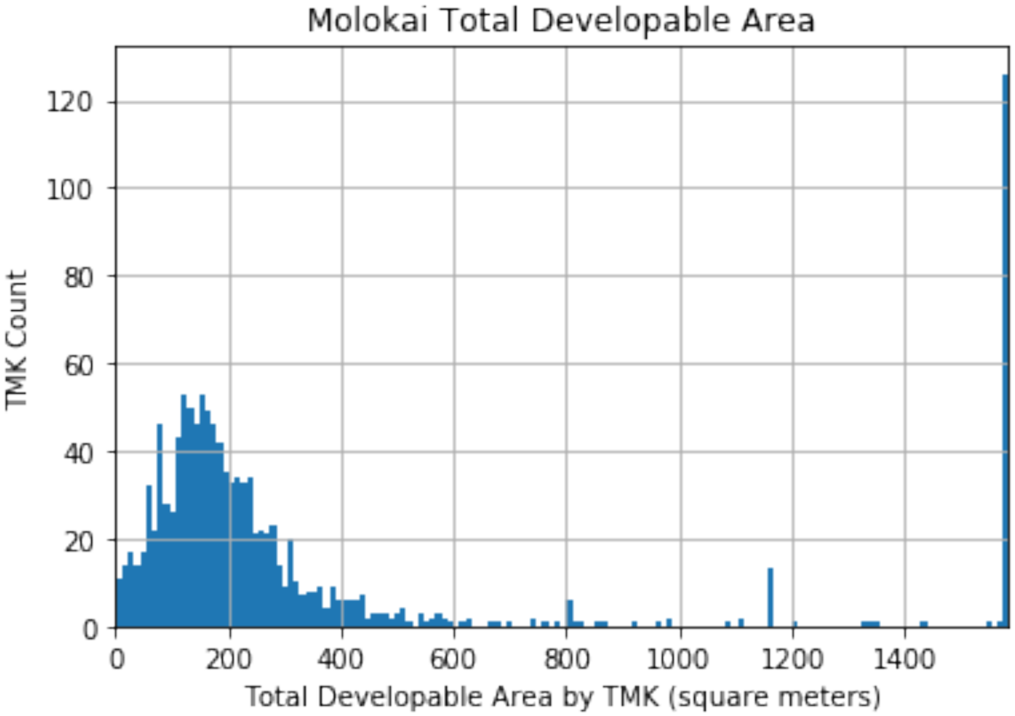
C.4 Rooftop Solar Summary Results

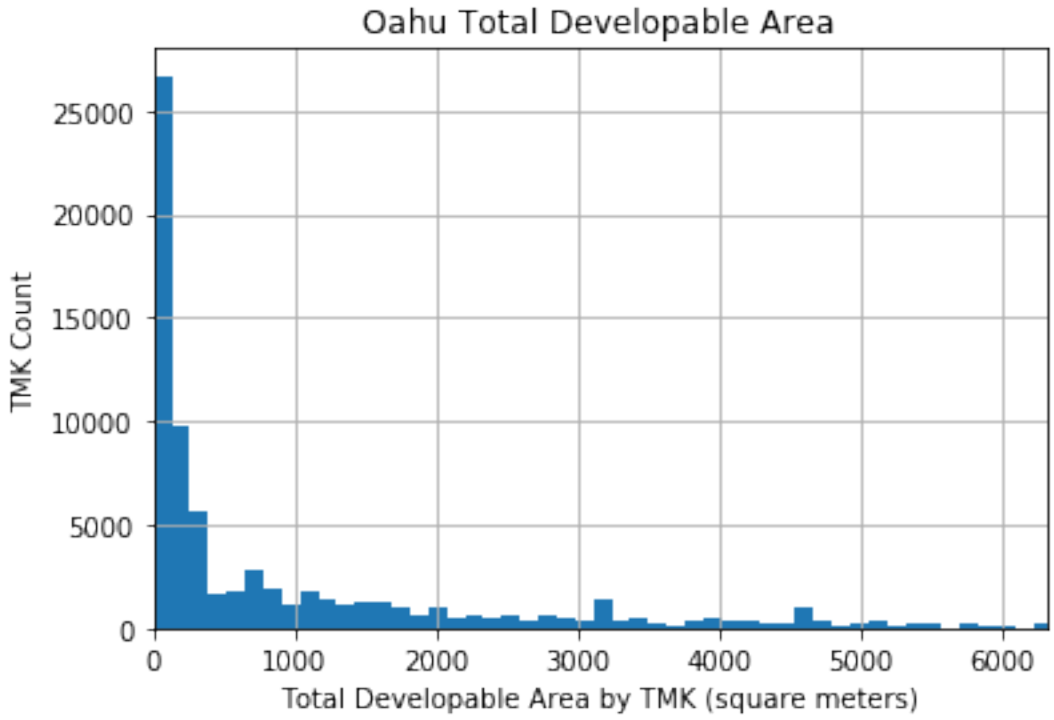
Developable Area





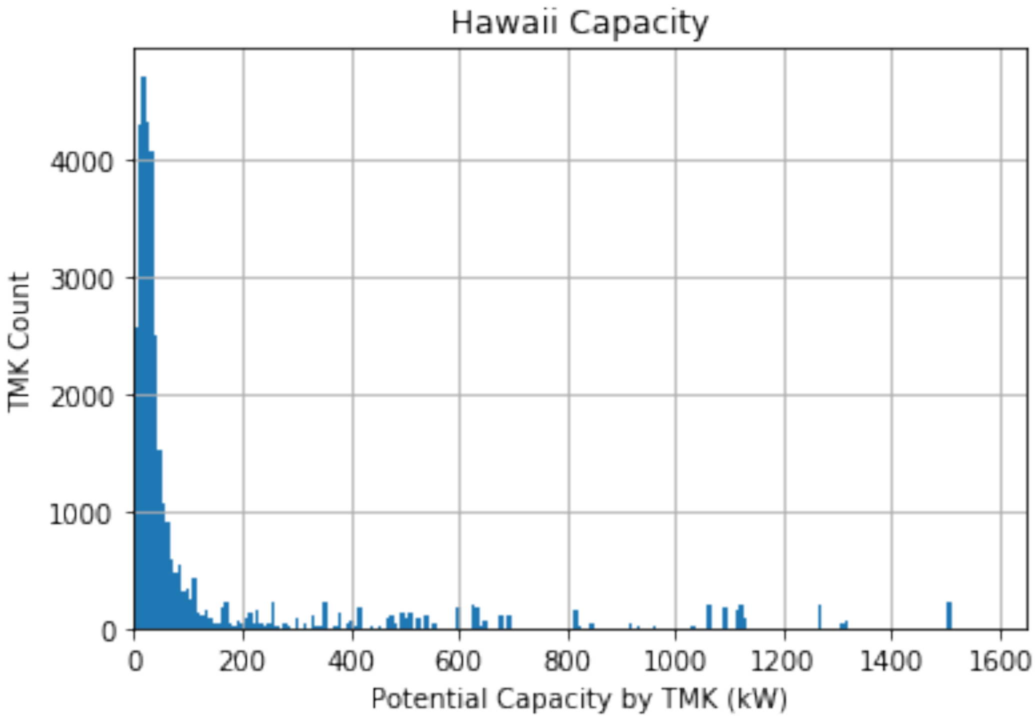

Maui Total Developable Area
TMK Count
0
500
1000
1500
2000
2500
3000
0
1000
2000
3000
4000
5000
6000
7000
8000
Total Developable Area by TMK (square meters)


Molokai Total Developable Area
TMK Count
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
1400
Total Developable Area by TMK (square meters)

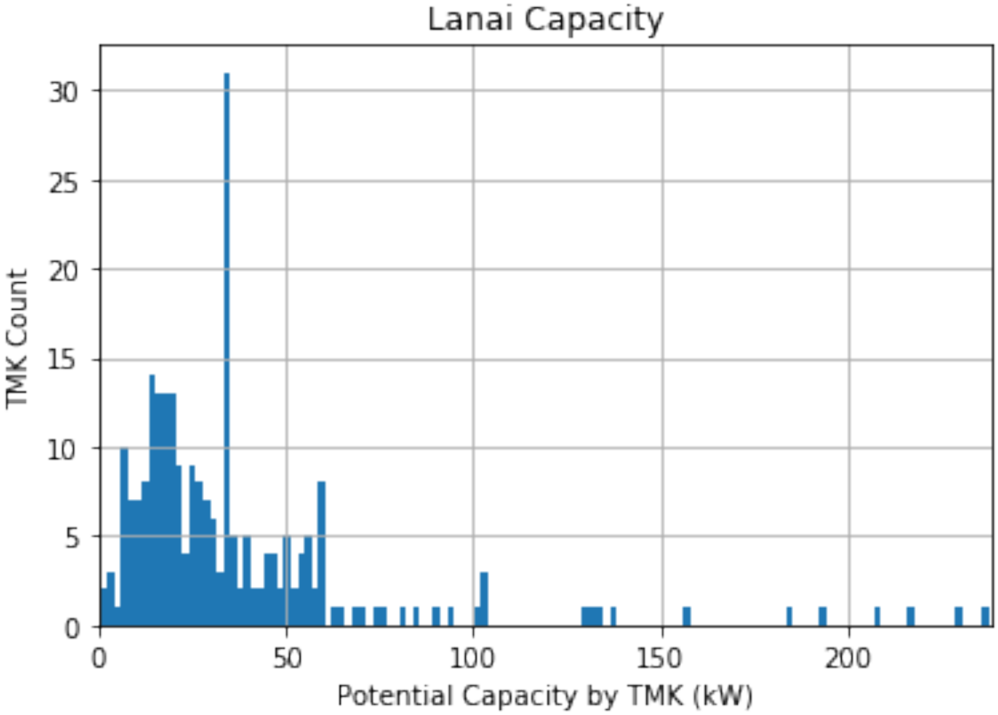


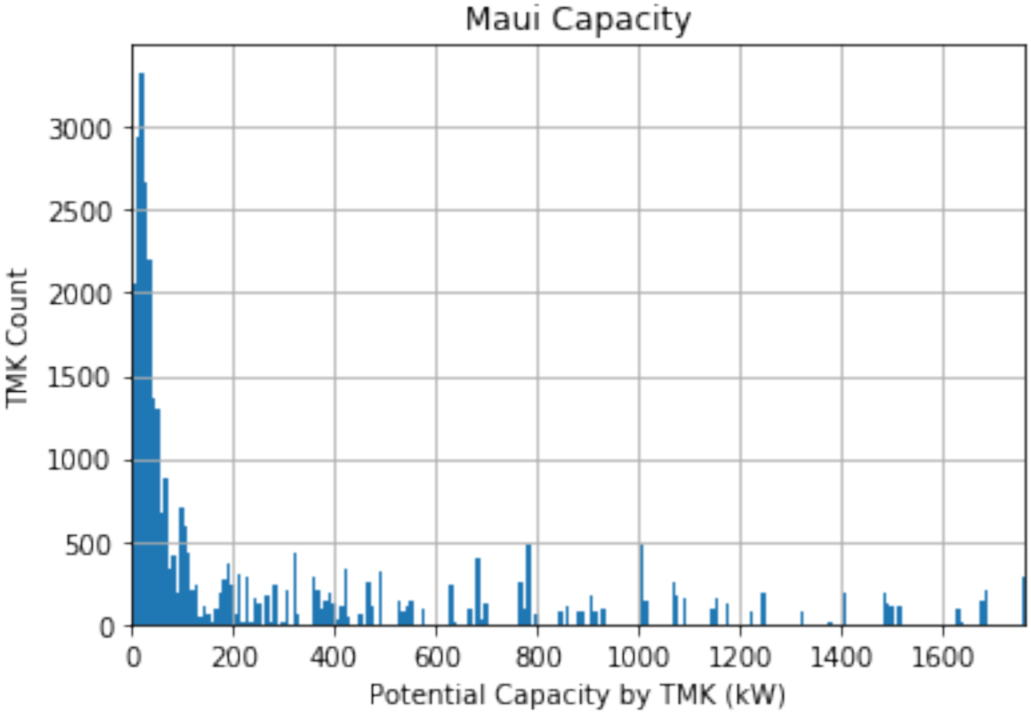
Oahu Total Developable Area
TMK Count
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
Total Developable Area by TMK (square meters)

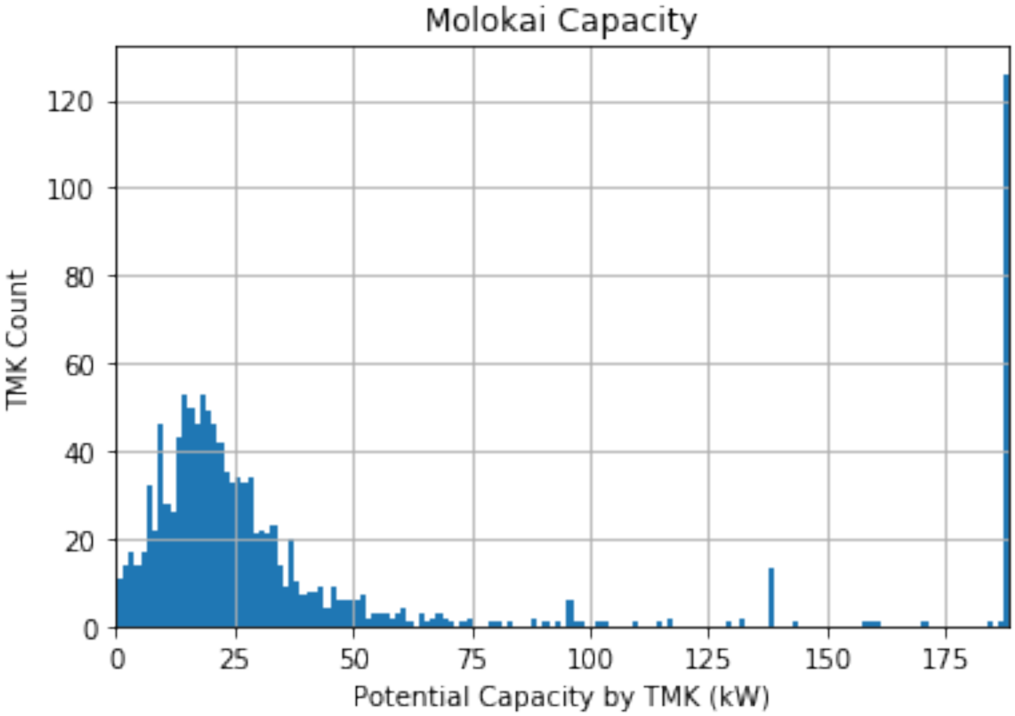
Capacity

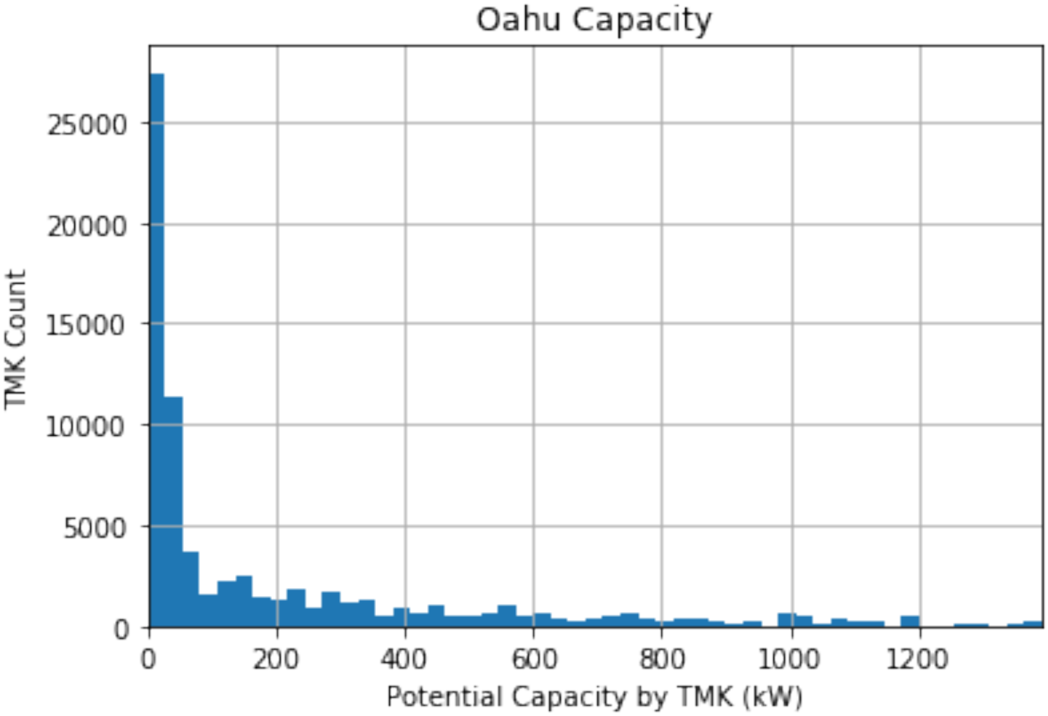


Hawaii Capacity
TMK Count
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
Potential Capacity by TMK (kW)

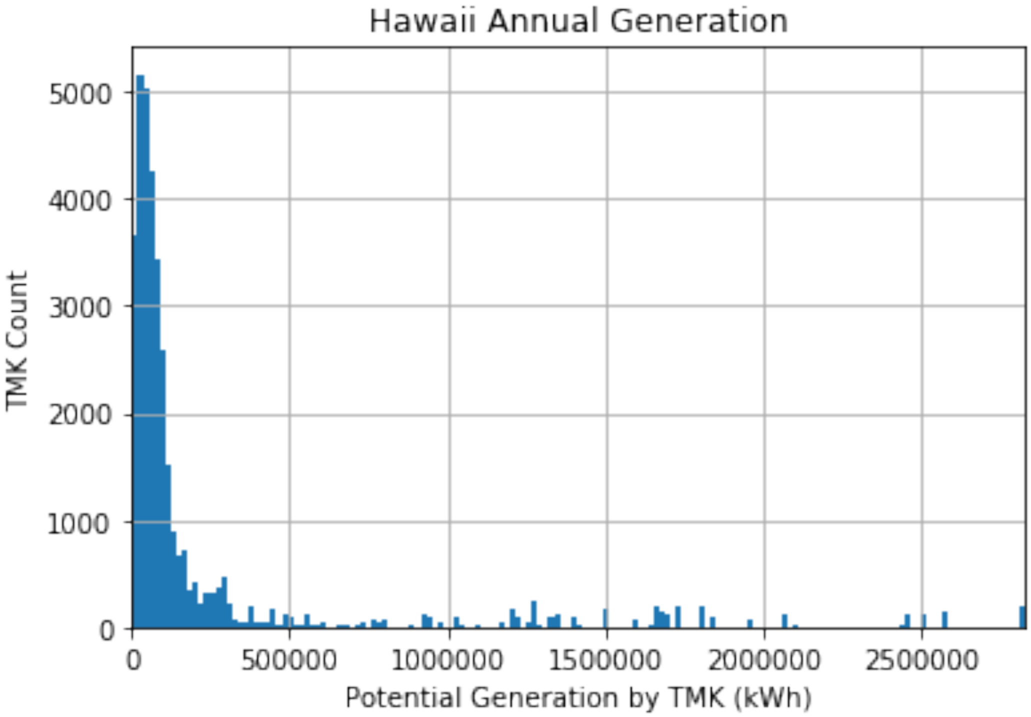

Lanai Capacity
TMK Count
0
5
10
15
20
25
30
0
50
100
150
200
Potential Capacity by TMK (kW)

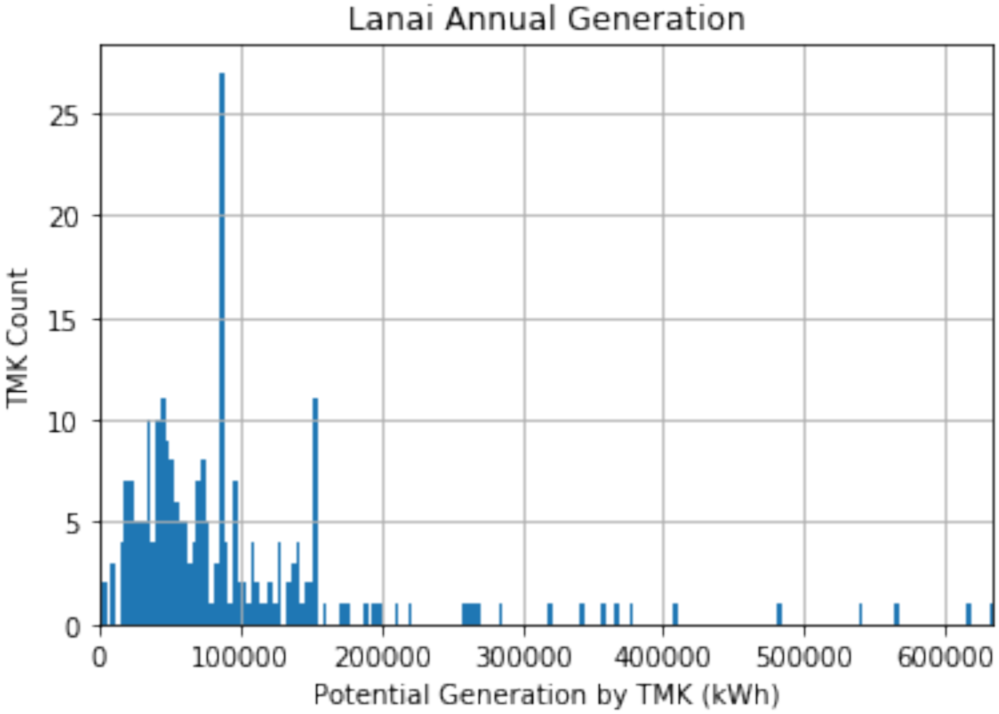

Maui Capacity
TMK Count
0
500
1000
1500
2000
2500
3000
0
200
400
600
800
1000
1200
1400
1600
Potential Capacity by TMK (kW)

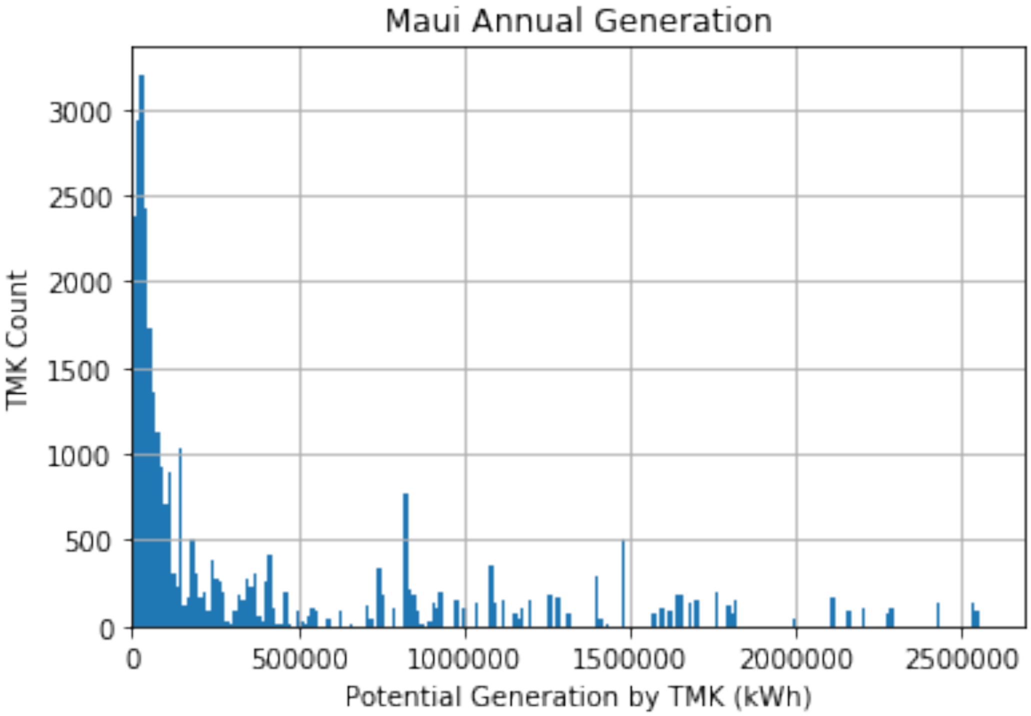

Molokai Capacity
TMK Count
0
20
40
60
80
100
120
0
25
50
75
100
125
150
175
Potential Capacity by TMK (kW)

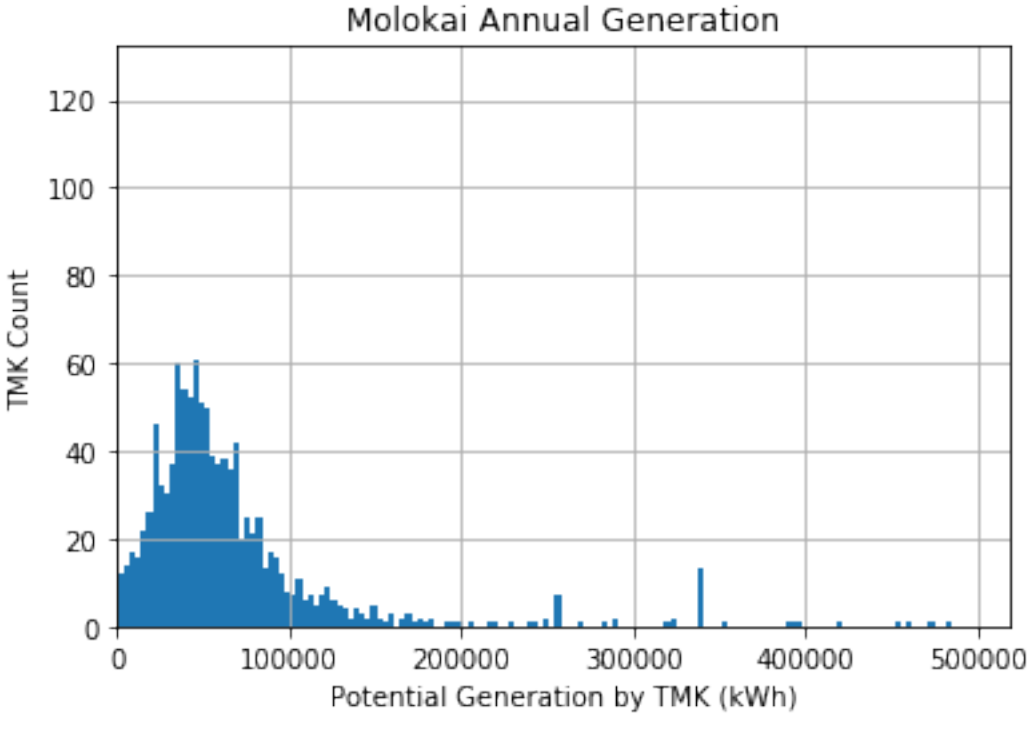

Oahu Capacity
TMK Count
0
5000
10000
15000
20000
25000
0
200
400
600
800
1000
1200
Potential Capacity by TMK (kW)

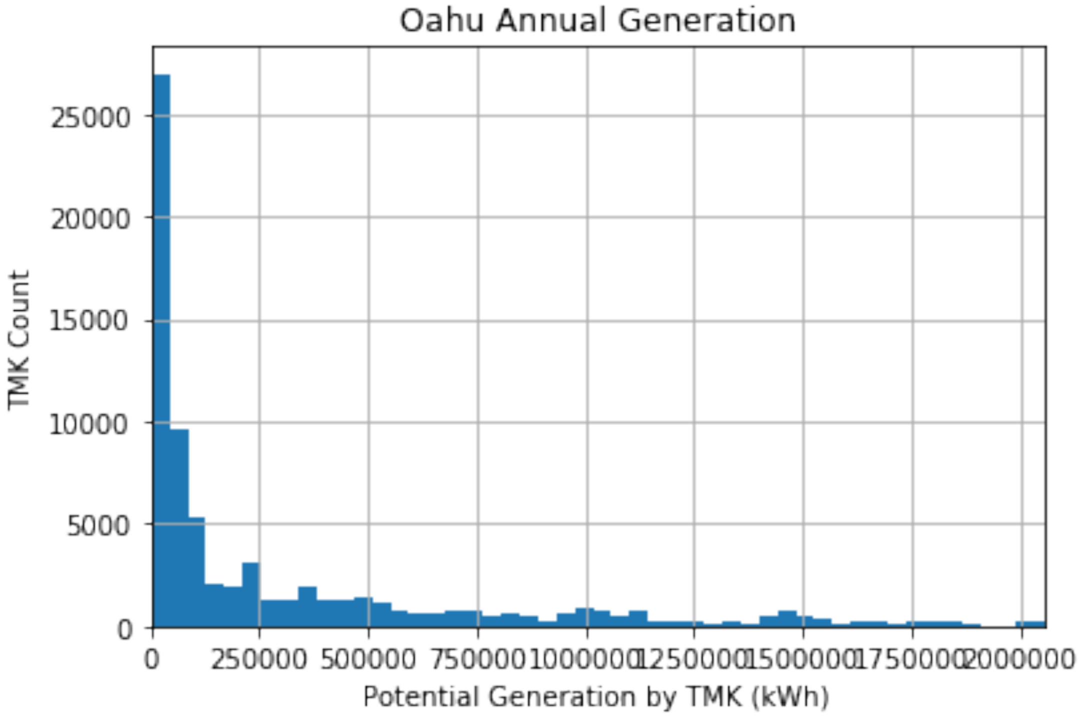
Annual Generation






Maui Annual Generation
TMK Count
0
500
1000
1500
2000
2500
3000
0
500000
1000000
1500000
2000000
2500000
Potential Generation by TMK (kWh)


Molokai Annual Generation
TMK Count
0
20
40
60
80
100
120
0
100000
200000
300000
400000
500000
Potential Generation by TMK (kWh)


Oahu Annual Generation
TMK Count
0
5000
10000
15000
20000
25000
0
250000
500000
750000
1000000
1250000
1500000
1750000
2000000
Potential Generation by TMK (kWh)