Renewable Energy Transition of Island Grids in Hawaii:
Applications for Remote Off Grid Regions

GridSTART

Grid System Technologies Advanced Research Team

Leon R. Roose, Esq.

Principal & Chief Technologist, Grid*START*

Hawaii Natural Energy Institute
School of Ocean & Earth Science & Technology
University of Hawaii at Manoa
1680 East-West Road, POST 109
Honolulu, Hawaii 96822

HNEI Hawai'i Natural Energy Institute

University of Hawai'i Manoa

APEC Workshop

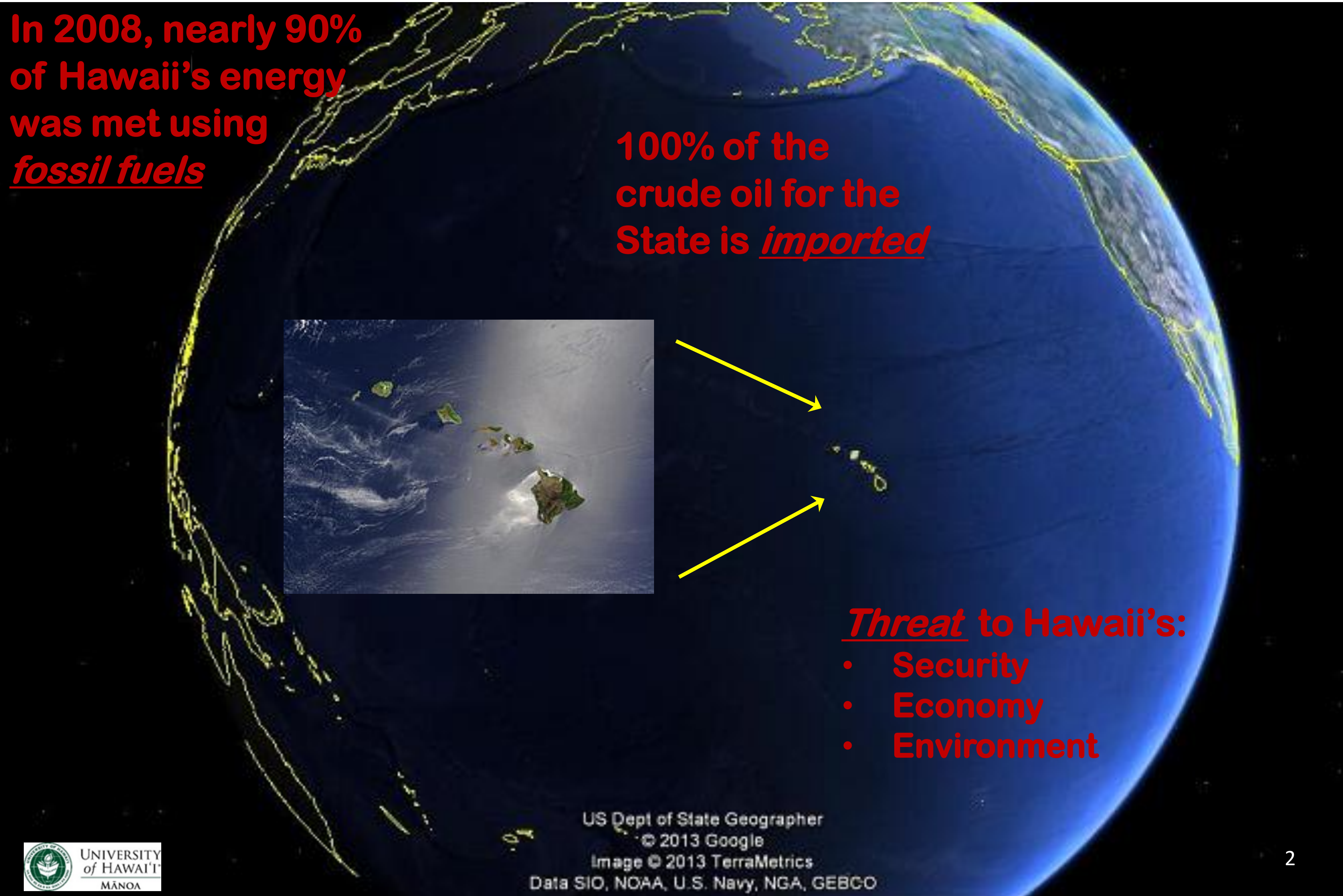
Off Grid Electrification Option for Remote Regions in APEC Economies

September 10, 2018
Chiang Mai, Thailand

Hawaii's Isolation Poses a Serious Challenge ….

In 2008, nearly 90% of Hawaii's energy was met using *fossil fuels*

100% of the crude oil for the State is *imported*

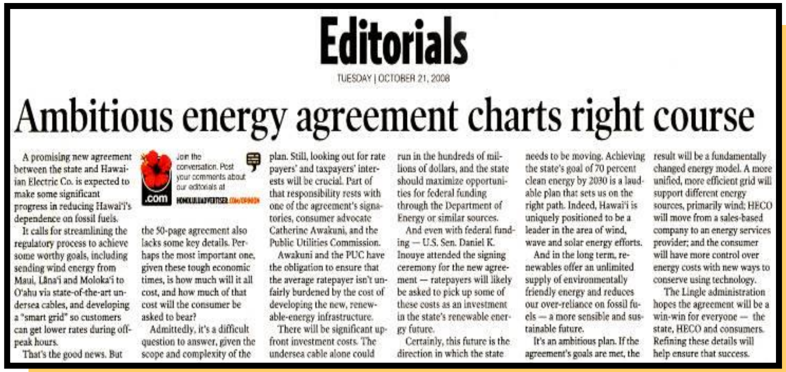


***Threat* to Hawaii's:**

- **Security**
- **Economy**
- **Environment**

UNIVERSITY of HAWAI'I MĀNOA

Hawaii's Progressive Leadership in Clean Energy Policy



Editorials

TUESDAY | OCTOBER 21, 2008

Ambitious energy agreement charts right course

A promising new agreement between the state and Hawaiian Electric Co. is expected to make some significant progress in reducing Hawai'i's dependence on fossil fuels.

It calls for streamlining the regulatory process to achieve some worthy goals, including sending wind energy from Maui, Lāna'i and Moloka'i to O'ahu via state-of-the-art undersea cables, and developing a "smart grid" so customers can get lower rates during off-peak hours.

That's the good news. But the 50-page agreement also lacks some key details. Perhaps the most important one, given these tough economic times, is how much will it all cost, and how much of that cost will the consumer be asked to bear?

Admittedly, it's a difficult question to answer, given the scope and complexity of the plan. Still, looking out for ratepayers' and taxpayers' interests will be crucial. Part of that responsibility rests with one of the agreement's signatories, consumer advocate Catherine Awakuni, and the Public Utilities Commission.

Awakuni and the PUC have the obligation to ensure that the average ratepayer isn't unfairly burdened by the cost of developing the new, renewable-energy infrastructure.

There will be significant up-front investment costs. The undersea cable alone could run in the hundreds of millions of dollars, and the state should maximize opportunities for federal funding through the Department of Energy or similar sources.

And even with federal funding — U.S. Sen. Daniel K. Inouye attended the signing ceremony for the new agreement — ratepayers will likely be asked to pick up some of these costs as an investment in the state's renewable energy future.

Certainly, this future is the direction in which the state needs to be moving. Achieving the state's goal of 70 percent clean energy by 2030 is a laudable plan that sets us on the right path. Indeed, Hawai'i is uniquely positioned to be a leader in the area of wind, wave and solar energy efforts.

And in the long term, renewables offer an unlimited supply of environmentally friendly energy and reduces our over-reliance on fossil fuels — a more sensible and sustainable future.

It's an ambitious plan. If the agreement's goals are met, the result will be a fundamentally changed energy model. A more unified, more efficient grid will support different energy sources, primarily wind; HECO will move from a sales-based company to an energy services provider; and the consumer will have more control over energy costs with new ways to conserve using technology.

The Lingle administration hopes the agreement will be a win-win for everyone — the state, HECO and consumers. Refining these details will help ensure that success.

Join the conversation. Post your comments about our editorials at .com

Hawai'i Powered

Hawai'i Clean Energy Initiative

Hawaii Clean Energy Initiative (HCEI)

The State of Hawaii, US DOE, and local utility launched HCEI in January 2008 to transform Hawaii to a 70% clean energy economy by 2030:

- *Increasing Hawaii's economic and energy security*
- *Fostering and demonstrating Hawaii's innovation*
- *Developing Hawaii's workforce of the future*
- *Becoming a clean energy model for the U.S. and the world*

Strong Hawaii Policies

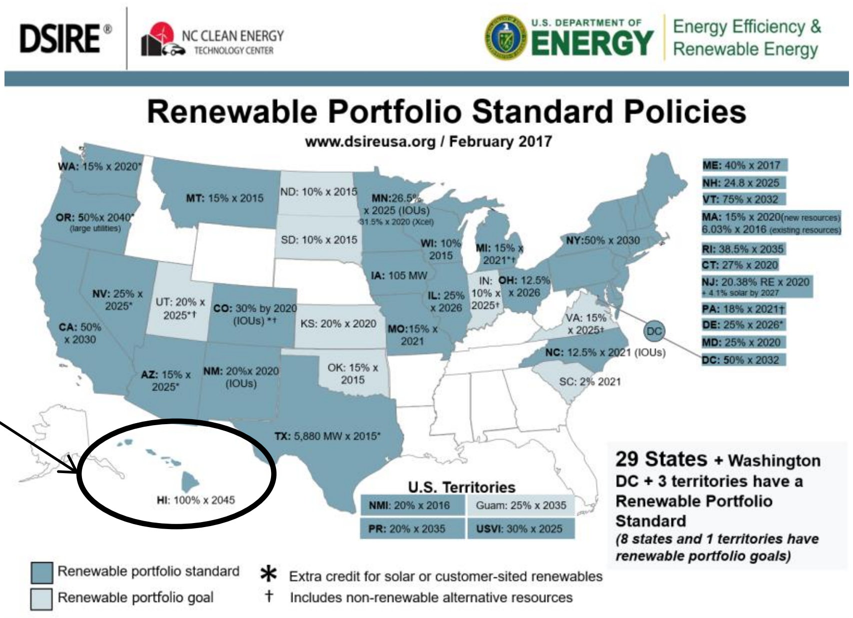
Highest RPS Target in the United States

100% by 2045

(2015 - 15%; 2020 - 30%, 2030 – 40%, 2040 – 70%)

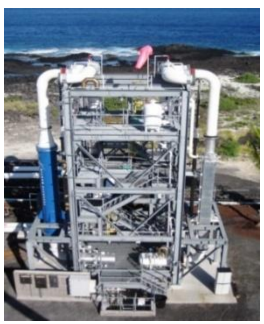
Other key policies:

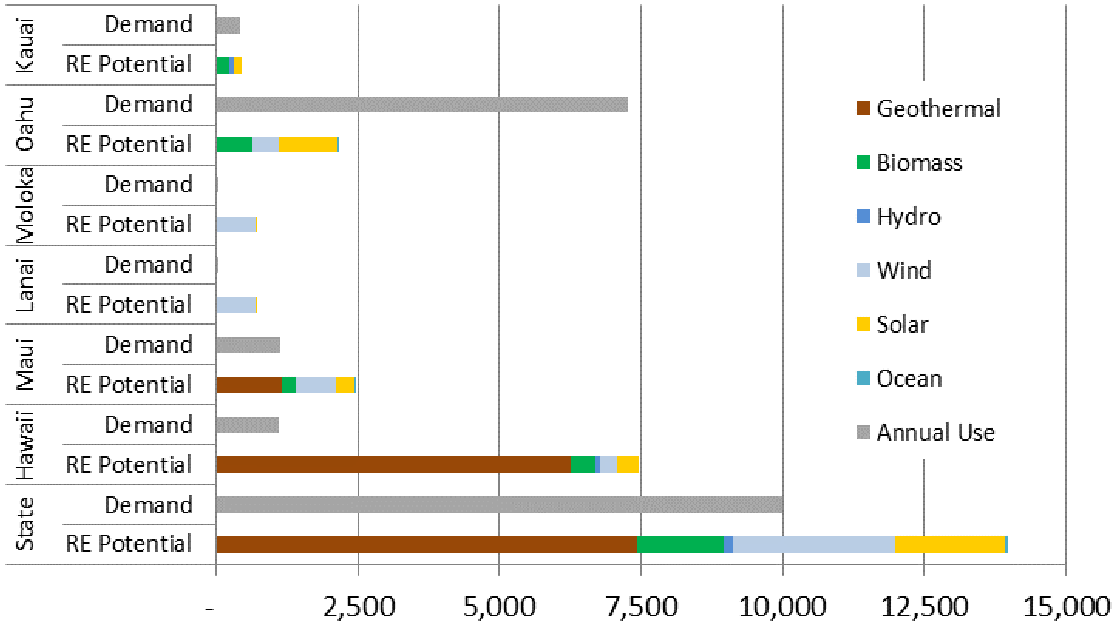
- **Tax incentives**
- **Net metering**
- **Feed in tariffs**
- **Decoupling**



UNIVERSITY of HAWAI'I MĀNOA

Opportunity for Sustainability in Hawaii is Abundant





Renewable Electricity Potential and Demand by Island, Gigawatt-hours

Source: National Renewable Energy Laboratory, Hawaii Clean Energy Initiative Scenario Analysis, 2012; and DBEDT

UNIVERSITY of HAWAI'I
MĀNOA

Exceeding Hawaii RPS Goals

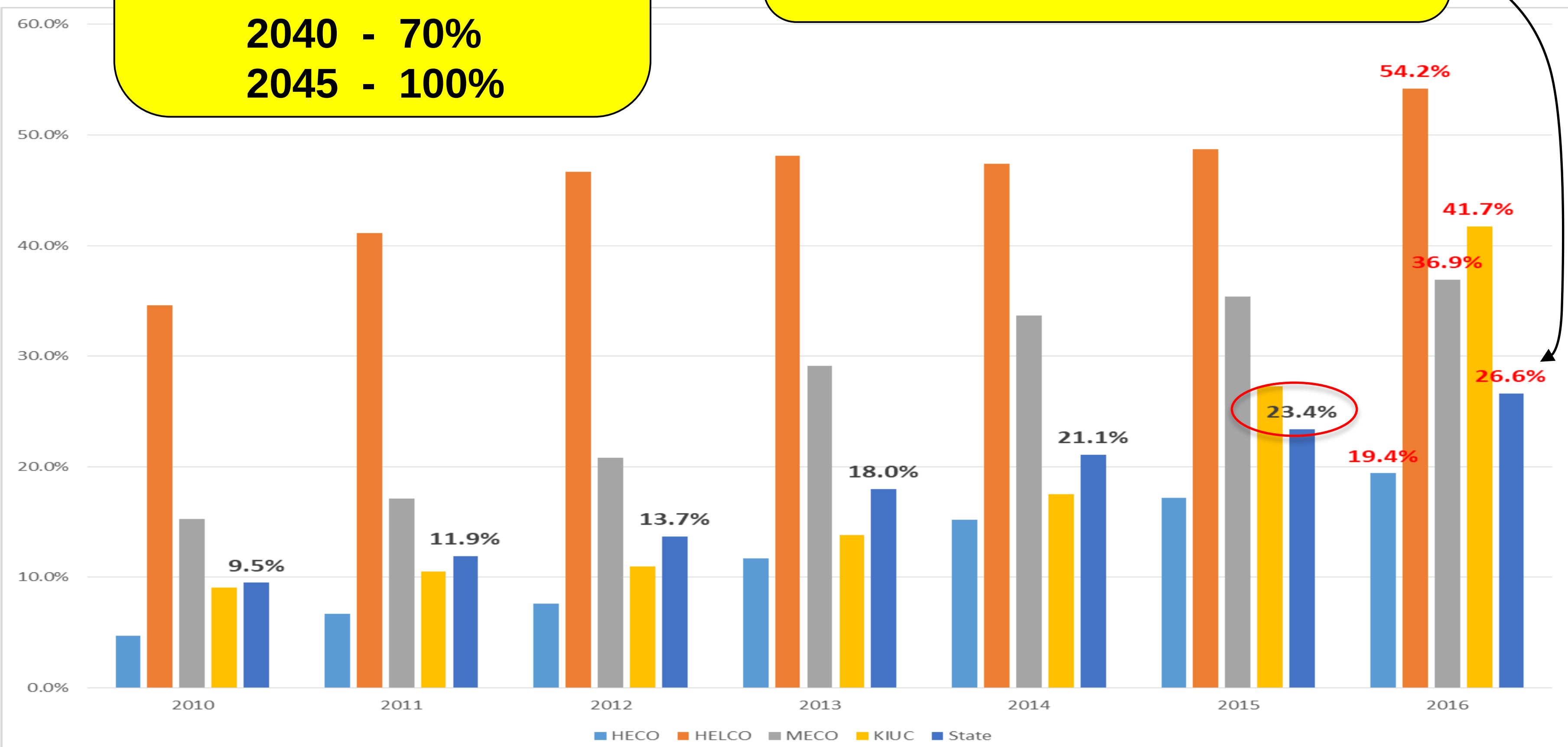
Hawaii RPS Goals

2015	15%
2020	30%
2030	40%
2040	70%
2045	100%

State-wide 2015 RPS Goal = 15%

RPS year-end 2016 @ 26.6%

(9.5% RPS at year-end 2009)



Source: State of Hawaii, "Hawaii Energy Facts & Figures," Hawaii State Energy Office, Honolulu, May 2017

University of Hawai'i
Mānoa

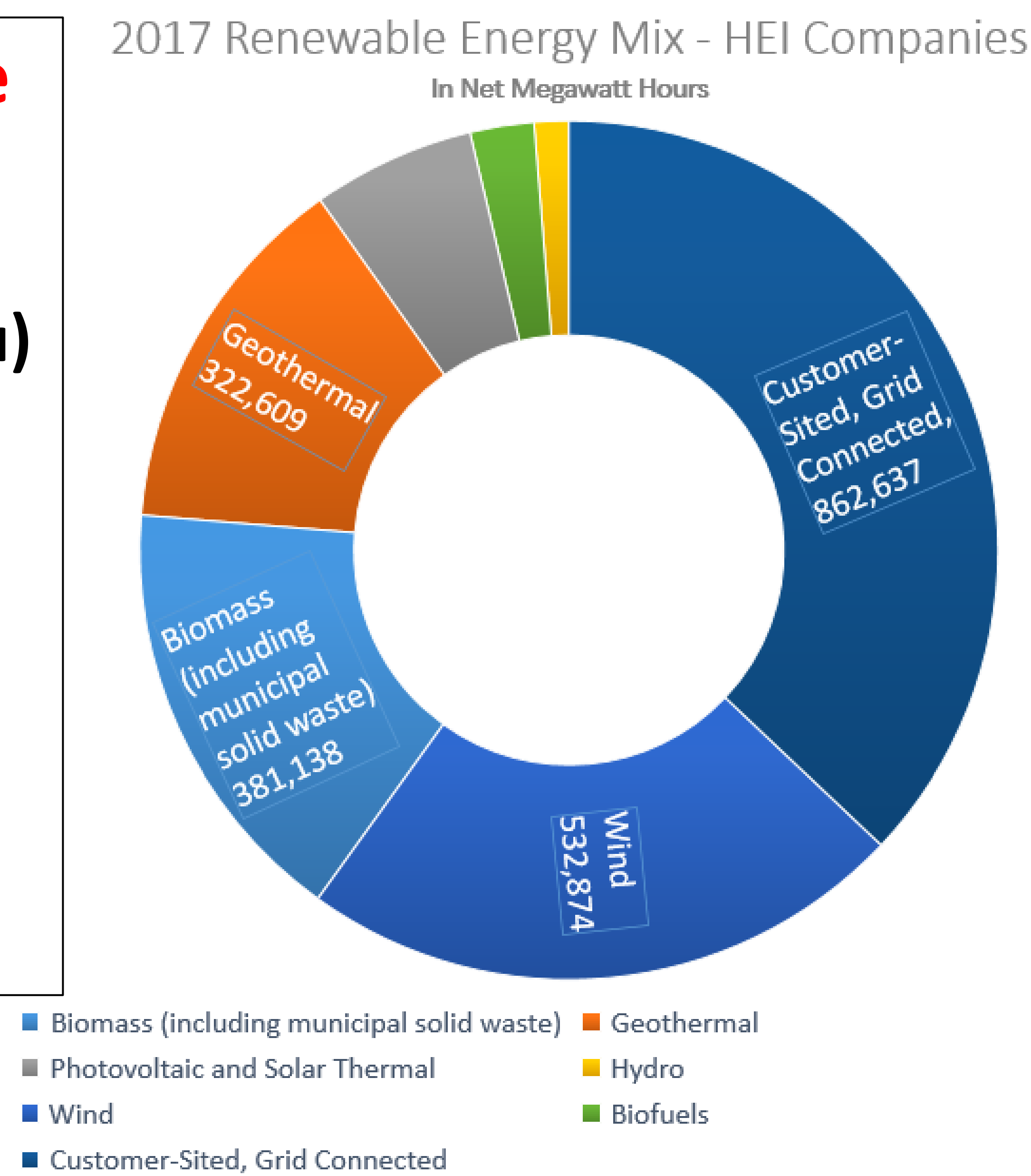
Hawaiian Electric Company RPS - 2017

27% Statewide

21% HECO (Oahu – Honolulu)

57% HELCO (Hawaii Island)

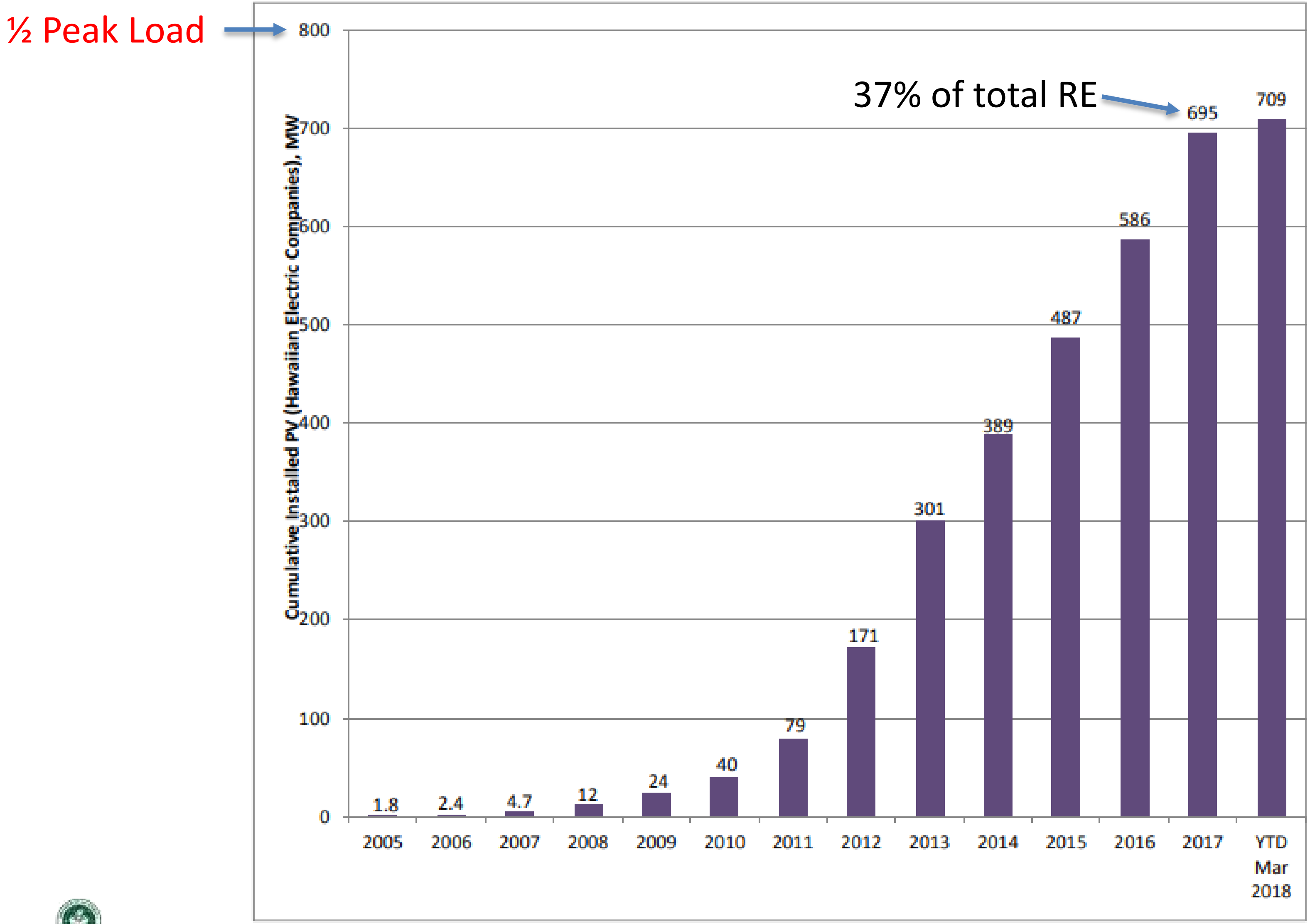
34% MECO (Maui, Molokai, Lanai)



University of Hawai'i Mānoa

Installed PV Capacity - HECO Companies

(2005 to 3/2018)



UNIVERSITY of HAWAI'I MĀNOA

Hawai'i Electric Systems –

4 Electric Utilities; 6 Separate Grids; % Renewable Energy

Kaua'i Island Utility Cooperative

System Peak: 78 MW

65.6 MW PV / 7 MW Biomass / 9 MW Hydro

Installed PV: 84% of System Peak

41.7% RE in 2016

Maui Electric

Maui System Peak: 202 MW

102 MW PV / 72 MW Wind

Installed PV & Wind:

86% of Sys. Peak

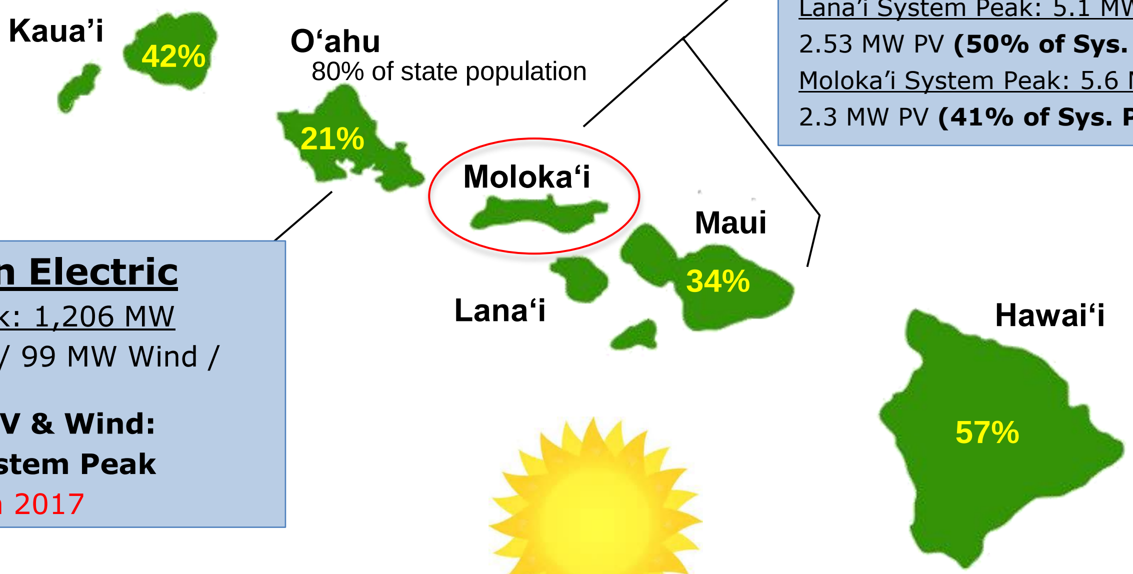
34.2% RE in 2017

Lana'i System Peak: 5.1 MW

2.53 MW PV **(50% of Sys. Peak)**

Moloka'i System Peak: 5.6 MW

2.3 MW PV **(41% of Sys. Peak)**



Hawaiian Electric

System Peak: 1,206 MW

512 MW PV / 99 MW Wind / 69 MW WTE

Installed PV & Wind:

50% of System Peak

20.8% RE in 2017

Hawaii Electric Light

System Peak: 192 MW

92 MW PV / 30 MW Wind /

38 MW Geothermal / 16 MW Hydro

Installed PV & Wind:

64% of System Peak

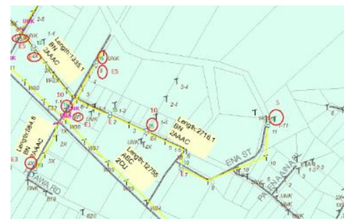
56.6% RE in 2017

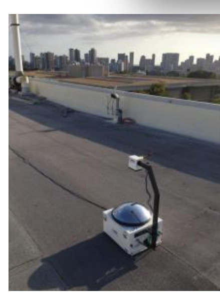
% Renewable Energy

University of Hawai'i Mānoa

Moloka'i Island 100% RE Grid Initiative

- **HECO Set Goal to be 100% Renewable by 2020**
- **HNEI RDTE Support**
  - ➢ System Data Collection
  - ➢ Load Flow & Midterm Dynamics Modeling
  - ➢ PV Hosting Capacity
  - ➢ Production Modeling
  - ➢ Battery Storage
    - ➢ 2MW, 375kWH
  - ➢ Dynamic Load Bank
  - ➢ PV Forecasting





- **Peak Load: 5.4 MW (2013)**
- **Daytime Min Load: 3 MW**
- **PV Installed: 1.07 MW (with 59.3Hz drop-out)**
- **PV Installed: 1.23 MW (with 57Hz drop-out)**
- **PV Planned: 0.6 MW in que**

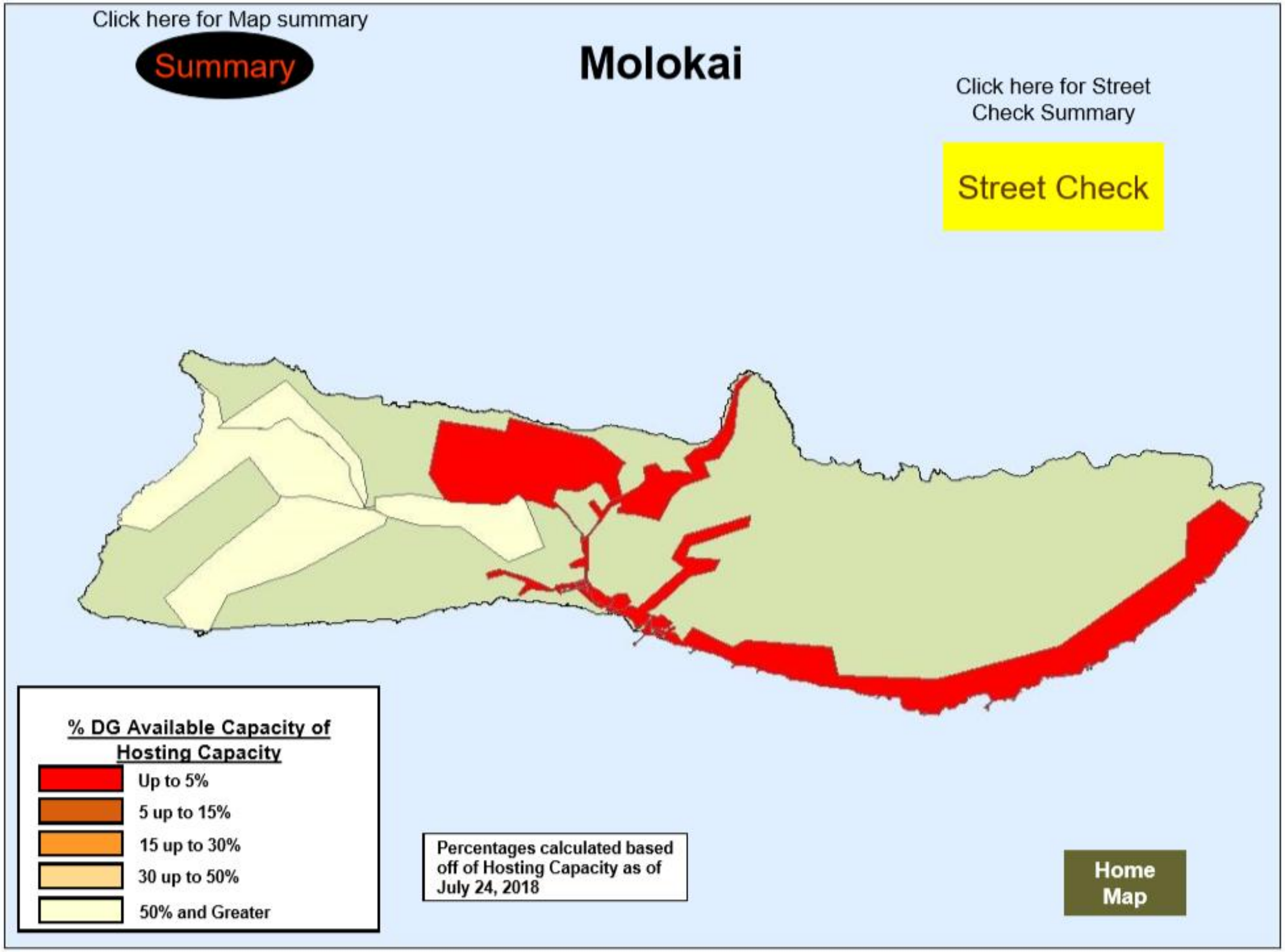
Hawaii ranks #1 in U.S. electric energy costs:

47.1 cents/kWh	**Molokai**
45.9 cents/kWh	**Lanai**
41.9 cents/kWh	**Hawaii**
37.8 cents/kWh	**Maui**
35.5 cents/kWh	**Oahu**
(Avg. residential rates for 2014)	
11 - 12 cents/kWh	**U.S. avg.**

Opportunity to extend this initiative as a scalable model to other Asia-Pacific regional sites

UNIVERSITY of HAWAI'I MĀNOA

Distributed PV Circuit Penetrations



Electrical Grid Risks

- All utilities are subject to unplanned events such as sudden loss of generation or transmission line interruptions.
- The impact of these events is more significant on smaller, isolated grids.
- Most events can be managed by adjusting other generation resources
- If the event is more significant, customer loads are automatically disconnected by the utility (at the feeder level), reducing power demand, to try to maintain generation-load balance and stable operation.
- While events can happen at any time of the day, significant events during the daytime can cause some or all PV on the island to stop operating (disconnect), increasing the risks on the entire grid.

The increase in PV generation has increased the need for new solutions to reduce the impact of this potential cascading loss of generation on the island

Potential Solutions

- Distributed Control Technology
  – Does not take up space on the grid when not needed
  – Requires grid-wide communication system and large number of coordinated distributed resources
  – Distributed batteries
    - Still involves significant costs
    - Relatively new and still in development
  – Distributed Load Control
    - Involves load shedding, but more selective (at customer level)
    - Response is less predictable

Some distributed solutions are still developing, especially in the response time needed

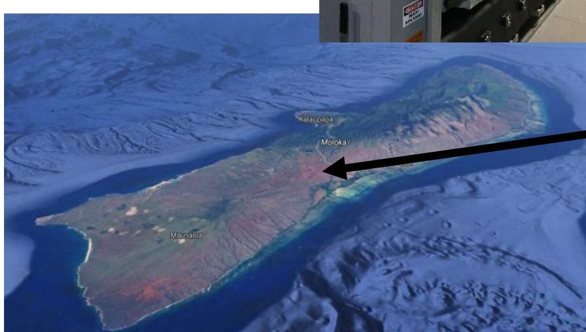
University of Hawai'i Mānoa

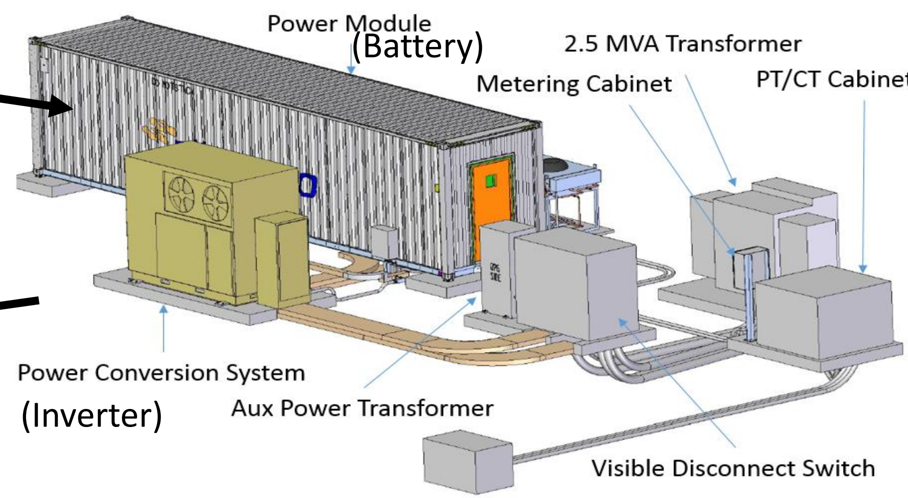
Selected Solution

- Install a *central* battery energy storage system (BESS)
  - Very high speed response
  - Significantly reduces the risk of customer load shedding and improves power quality
  - Does not take up room on the system when not needed, allowing for the addition of more renewable energy
  - Can be implemented relatively quickly
  - Easier maintenance versus a highly distributed customer sited BESS approach (modular battery units can be replaced when needed over time)
  - External funding was available

Molokai Grid Stability

- Even relatively small disturbances can trip PV units, increasing automatic load shedding customer outages on the system
- **Proposed solution** to increase grid reliability: a 2MW fast-acting BESS.
- **The challenge**: standard 250 ms response destabilizing to grid (models)
- **The solution**: re-engineer the way the BESS and the inverter computers collaborate to share computational burden in control





UNIVERSITY of HAWAI'I MĀNOA

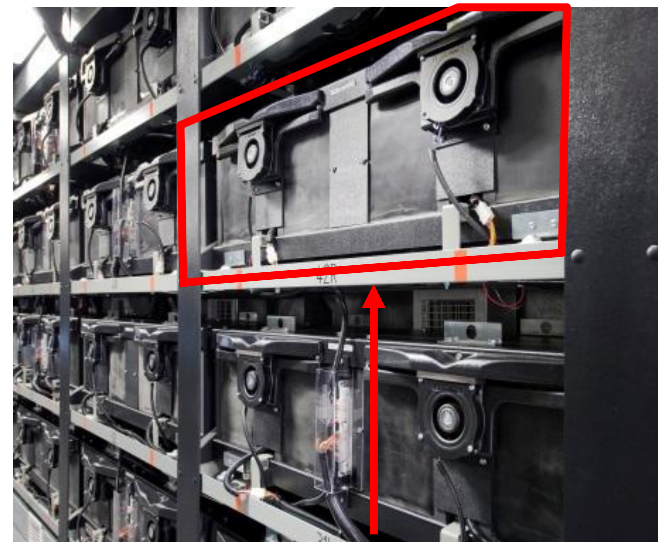
Molokai Island BESS Project

Altairnano Li-ion Titanate

Power Module

Power Conversion System

- Power module produces ± 2 MW
- Capacity of 375 kWH
- Inverter rated > ± 2 MVA
- Over 12,000 full charge / discharge cycles with minimal degradation in cell capacity



Interior View

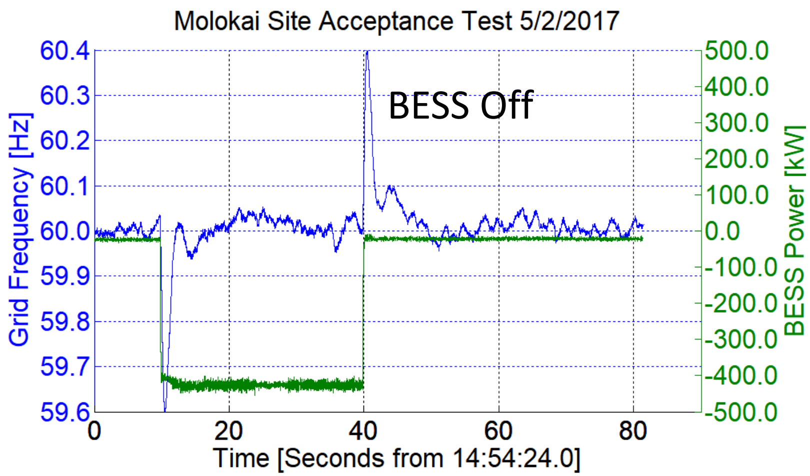
- Li-Ion Titanate 50 A-Hr Cells
- BESS has 2688 cells in 96 LRU

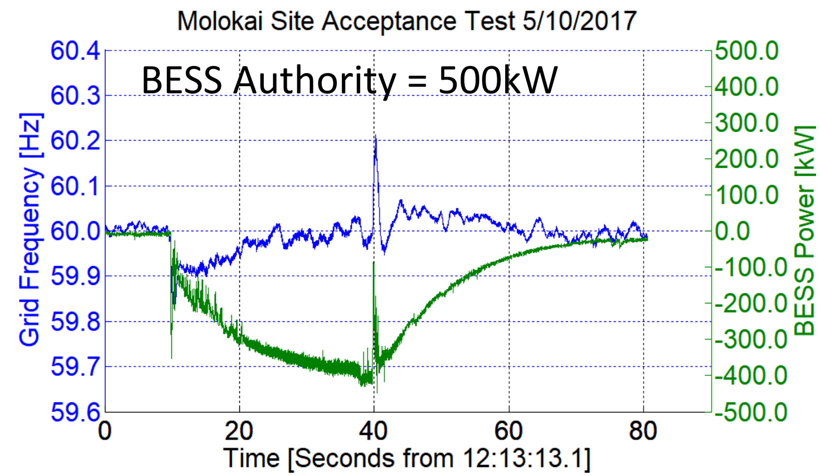
Designed for rapid charging and discharging

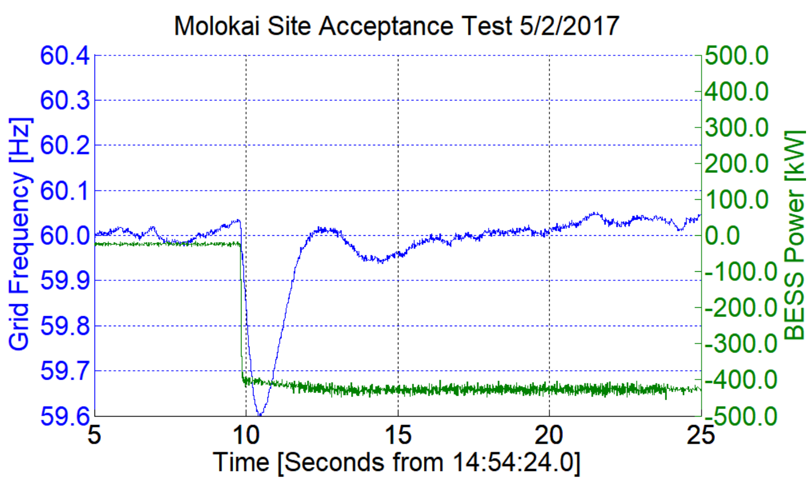
UNIVERSITY of HAWAI'I MĀNOA

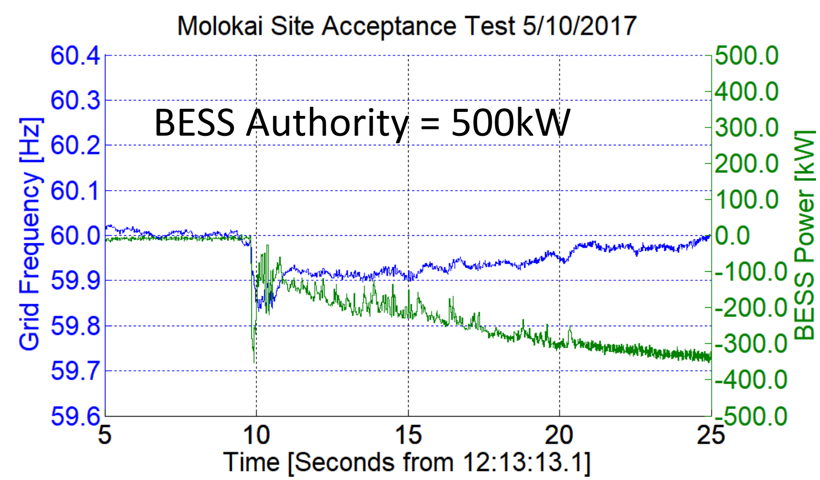
Impact of BESS with 500kW Authority and Fast Response

Expansions (bottom) show Down-Step





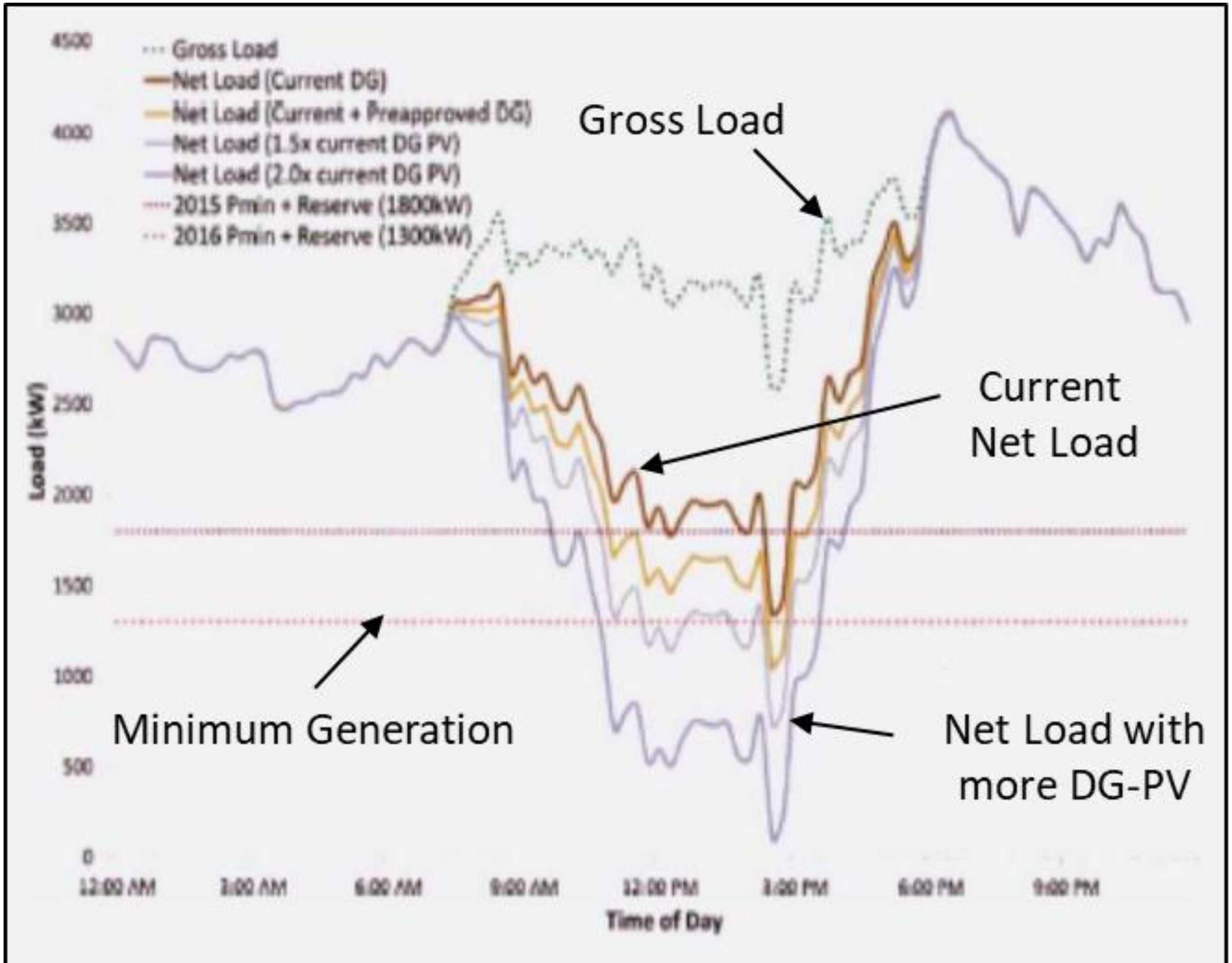




500kW fast response showed significant frequency improvement

UNIVERSITY of HAWAIʻI MĀNOA

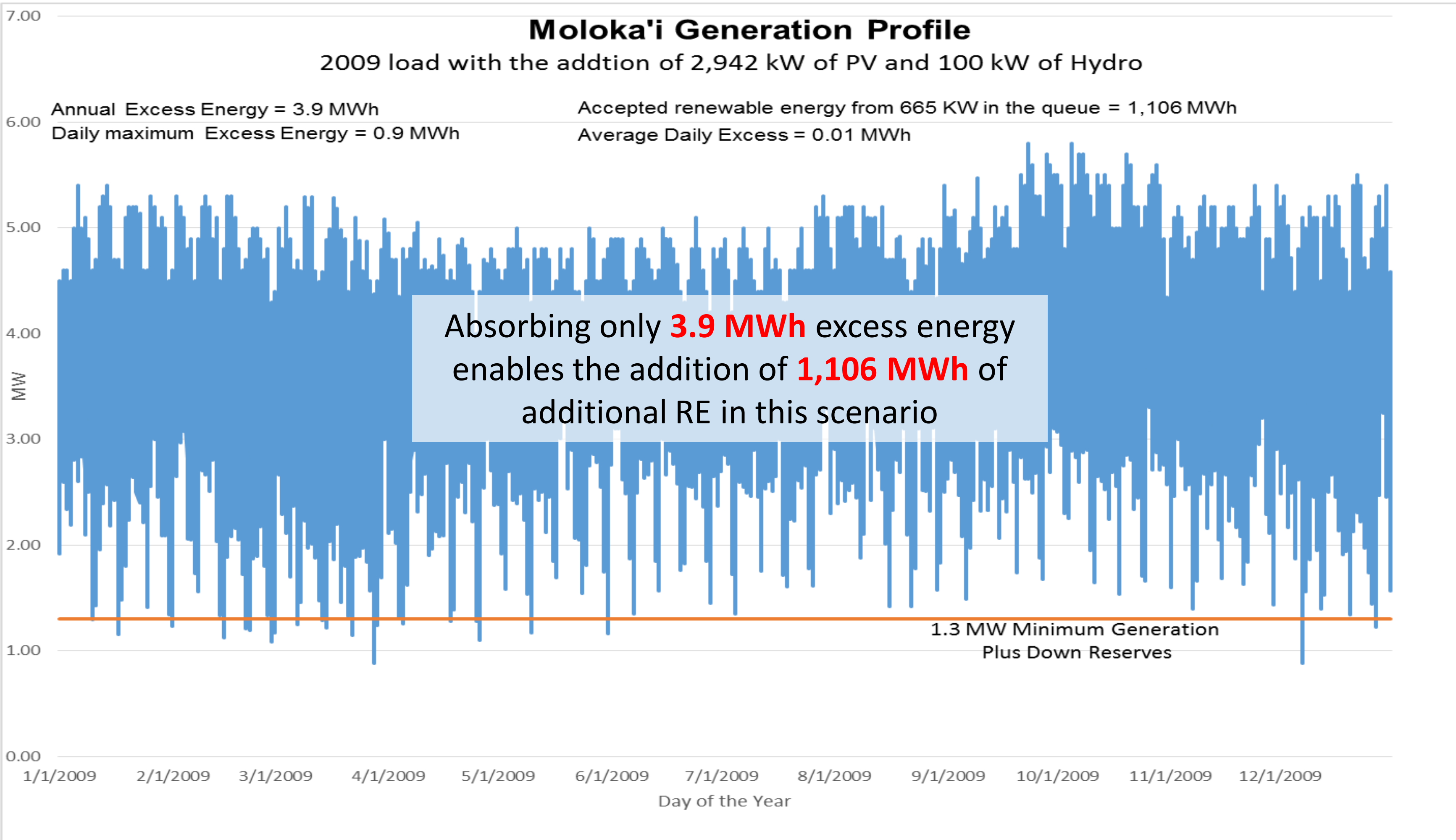
Excess Energy Potential Low Load Day



University of Hawai'i Mānoa

Alternatives to Storage

Dynamic Load Bank



Small to moderate amount of excess RE curtailment is a sound integration strategy

University of Hawai'i Mānoa

HNEI Solar Forecasting System - Overview

System provides solar resource and PV production estimates at a range of timescales from minutes to days ahead

Day ahead (DA) forecasts

- Regional numerical weather prediction model
- Regional forecasts - hours to days ahead
- Unit commitment planning

Hour ahead (HA) forecasts

- Satellite imagery
- Regional forecasts – 10 minutes to hours ahead
- Unit dispatch and operational reserve management

Minute ahead (MA) forecasts

- **Ground-based cameras**
- Local forecast - seconds to minutes ahead
- Grid stability and short ramp identification

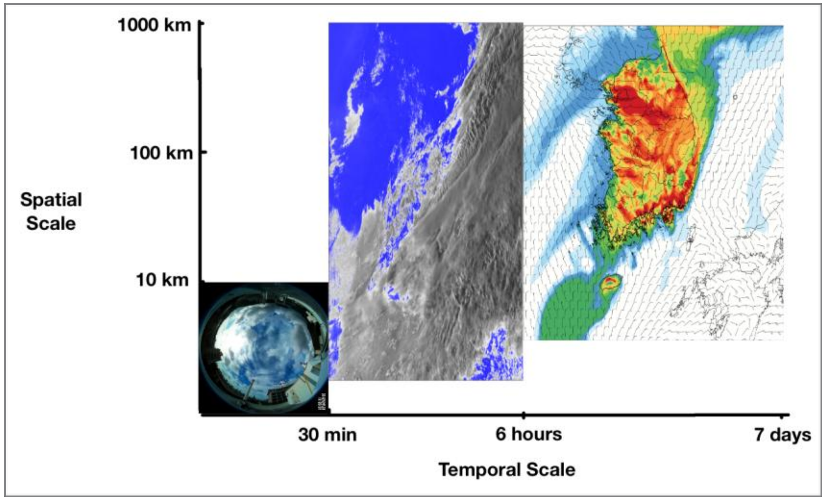


Figure: Forecasting time and space scales of the different components that make up the solar forecasting system.

University of Hawai'i Mānoa

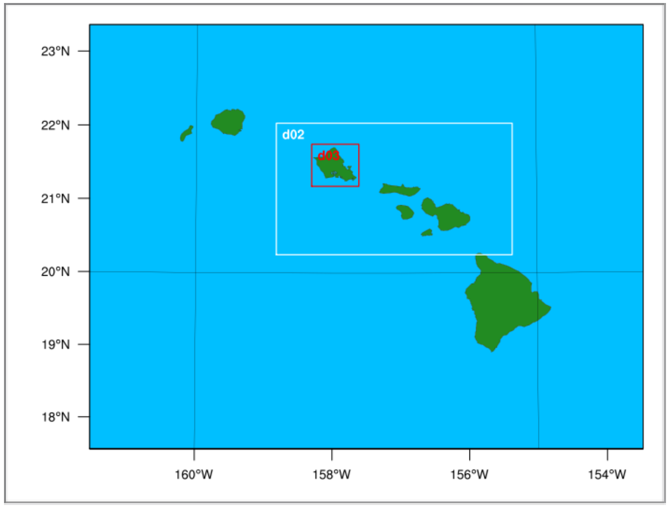
Day-ahead solar forecasting

Day-ahead (DA) forecasts are generated using a regional numerical weather prediction (NWP) model (mathematical model of the atmosphere)

- NWP based solar forecasts are most accurate for greater than 6 hours ahead

We utilize a specific version of the Weather Research and Forecasting (WRF) system designed for solar energy applications (WRF-Solar) recently developed at the National Center for Atmospheric Research (NCAR)

- WRF is a widely used, open source, mesoscale NWP system designed for both atmospheric research and operational forecasting applications
- WRF-Solar includes:
  - Improved representation of cloud-aerosol-radiation system
  - New aerosol parameterization
  - Direct computation of global, direct and diffuse components of irradiance
- We employ WRF in a nested grid configuration (domains shown right)
  - Parent domains are at 5 km resolution, first nest at 1 km, and second nest at 200 m



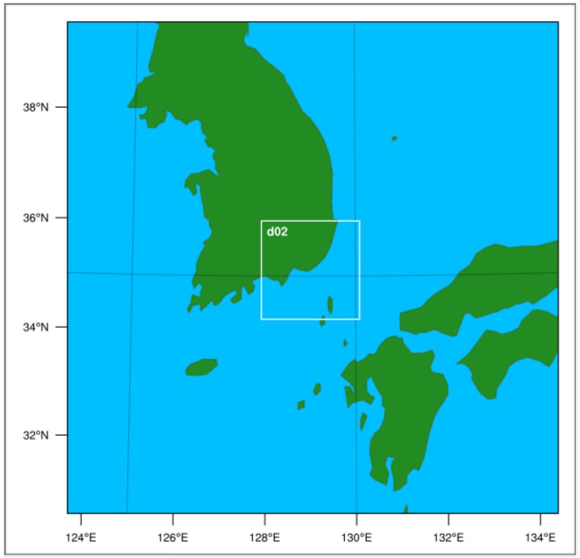


Figure: (TOP) WRF domains for Hawaiian region forecasts. (BOTTOM) WRF domains for KERI project.

University of Hawai'i Mānoa

Hour-ahead solar forecasting

Geostationary environmental satellites constantly monitor weather and cloud conditions, nominally providing a new set imagery every few minutes with full global coverage at lower latitudes

- Satellite image based solar forecasts are most accurate from 1 to 6 hours ahead

We have used the following satellites to generate operational solar forecasts:

- GOES-West: American satellite that monitors the eastern Pacific
- Himawari-8: Japanese satellite that monitors the western Pacific
- COMS-1: South Korean satellite that monitors eastern Asia

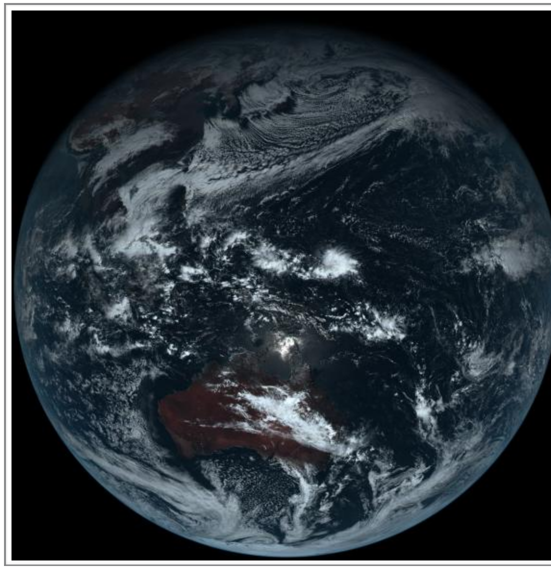
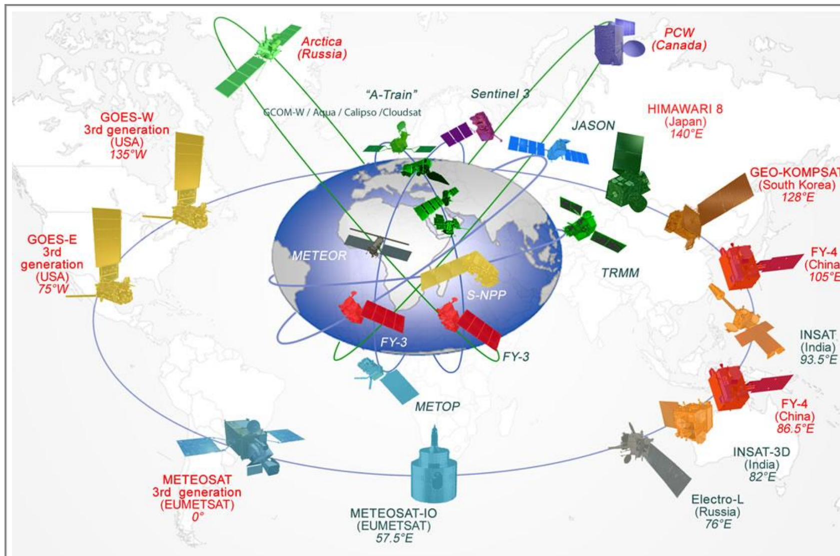


Figure: (RIGHT) Full disk image from Himawari-8. (BELOW) Earth environmental satellite coverage - geostationary satellite orbit along the equator at a greater distance than polar orbiters (image from the World Meteorological Organization http://www.wmo.int).



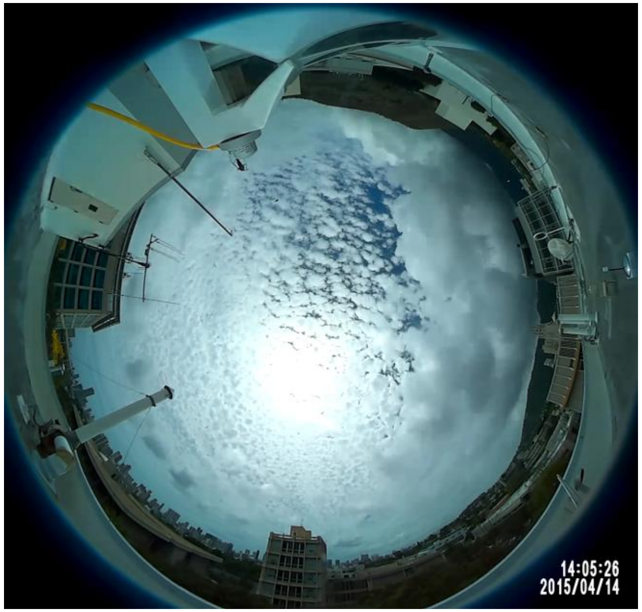
Minute-ahead solar forecasting

Upward looking sky imagers, supported with other instruments, are currently the best method to observe local cloud conditions at the time and space needed to predict short-term irradiance fluctuations

- Sky image based solar forecasts are most accurate from 1 minute to 1 hour ahead

HNEI is developing a novel prototype forecasting instrument - the Affordable High-Resolution Irradiance Prediction System (AHRIPS) is intended to be an alternative to the standard total sky imager, in a price range that can allow for multiple instrument, overlapping field of view deployment

- Low production cost - using off-the-shelf instrumentation and open-source single-board computing hardware
- Wireless communication - utilizing a Long-Term Evolution (LTE) modem
- Wireless power - using a small PV panel and sealed gel cell battery (or, if available, a power supply to convert 120V power)



UNIVERSITY of HAWAI'I MĀNOA

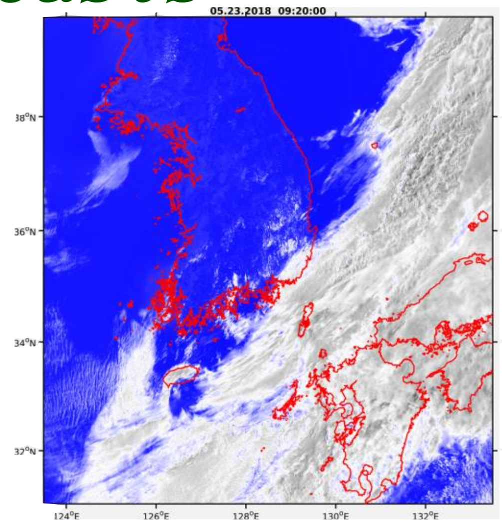
Generating irradiance maps from imagery – nowcasts

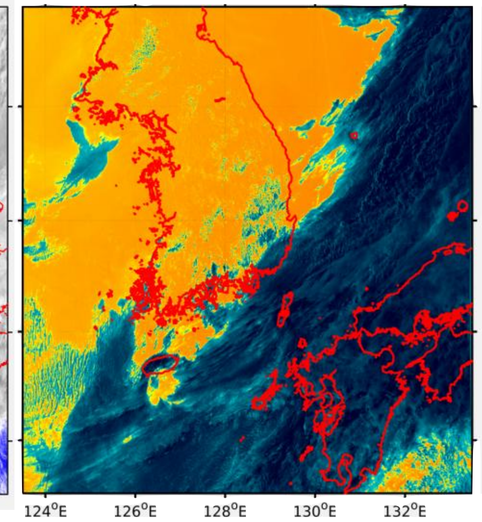
Satellite (HA) and ground (MA) imager based solar irradiance nowcasts and forecasts are generated using similar procedures

- Algorithms designed for computational efficiency - generate forecasts with minimal latency

Main steps:

- Identify cloud containing pixels
- Geolocate cloud containing pixels
- Estimate cloud attenuation levels
- Calculate sun position and clear sky irradiance levels
- Project cloud shadows to surface
- Generate irradiance map





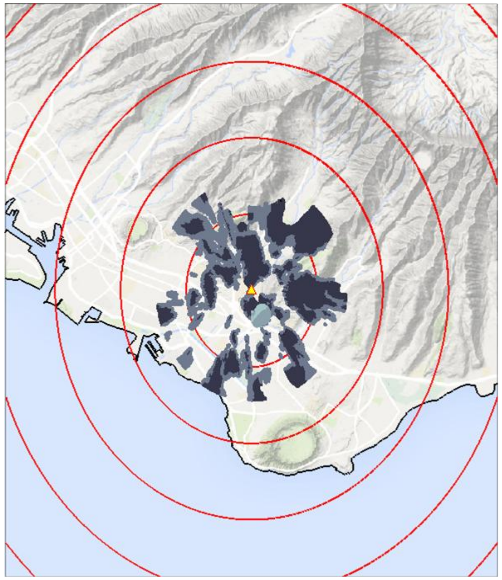


Figure: (TOP LEFT) Example visible image from Himawari-8. (TOP RIGHT) Cloud attenuation map derived from visible image. (LOWER LEFT) Example sky image from AHRIPS. (LOWER RIGHT) Georegistered cloud attenuation estimates from sky image.

UNIVERSITY of HAWAI'I MĀNOA

Generating irradiance maps from imagery – forecasts

HA and MA forecasting procedures are based on similar procedures

Main Steps:

- Determine cloud motion vectors using a pattern tracking algorithm applied to sequential images
- Predict future cloud conditions using a rapid fluid dynamics solver driven by the cloud motion vector field
- Update sun position and clear sky irradiance to the forecasting time
- Generate irradiance map forecasts using the methodology described on the previous slide

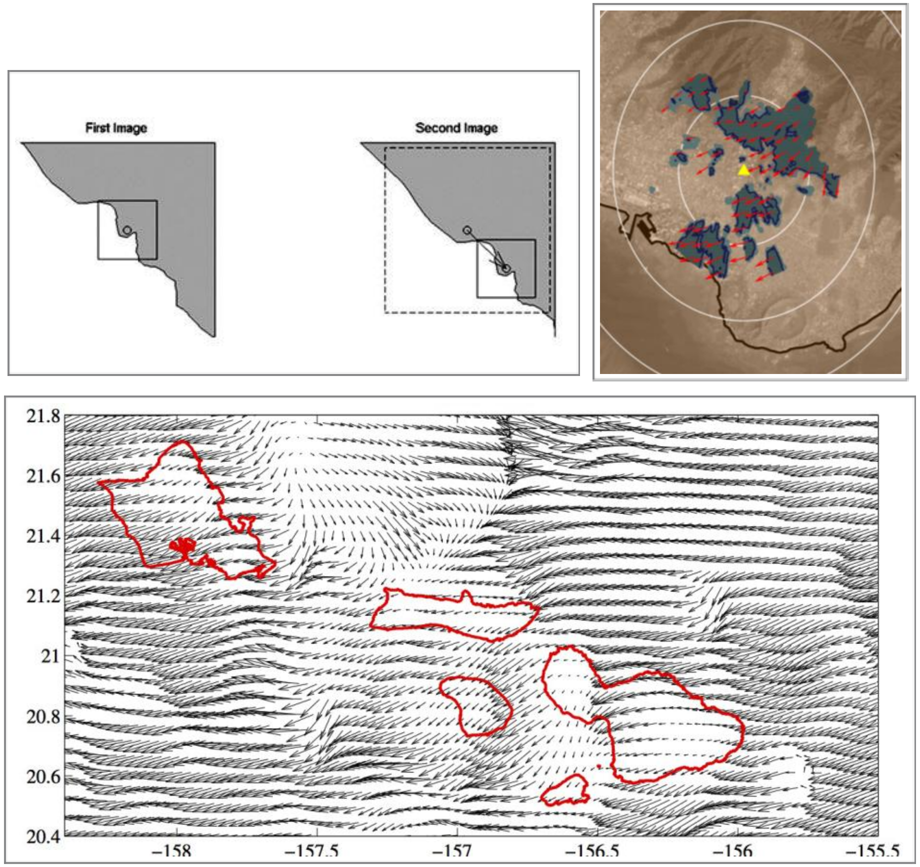


Figure: (TOP LEFT) Illustration of the pattern tracking algorithm called the Maximum Cross Correlation Method. (TOP RIGHT) Example cloud vectors derived from AHRIPS imagery. (LOWER) Cloud motion vector field derived from GOES-West imagery.

UNIVERSITY of HAWAI'I MĀNOA

Operational forecasting

Regional 2-day ahead WRF forecasts generated each night

Satellite and camera based forecasts start in early morning as sun rises

- GOES-West: Regional 6-hour ahead forecasts generated in ~15 minutes
- Camera-based: Local 30 minute ahead forecasts generated in ~3 minutes
  - Spatial coverage depends on cloud height and camera placement geometry - normally between 5-10 km

Final forecasts are generated using ensemble techniques - combining information from multiple forecasts

- Improve the accuracy of the forecasts
- Use forecasts population to estimate confidence and forecasts variability

System can then quickly estimate plane-of-array (POA) transmitted irradiance for a large number of PV panels with varying orientations

From POA irradiance - DC/AC power production is estimated from an energy systems model

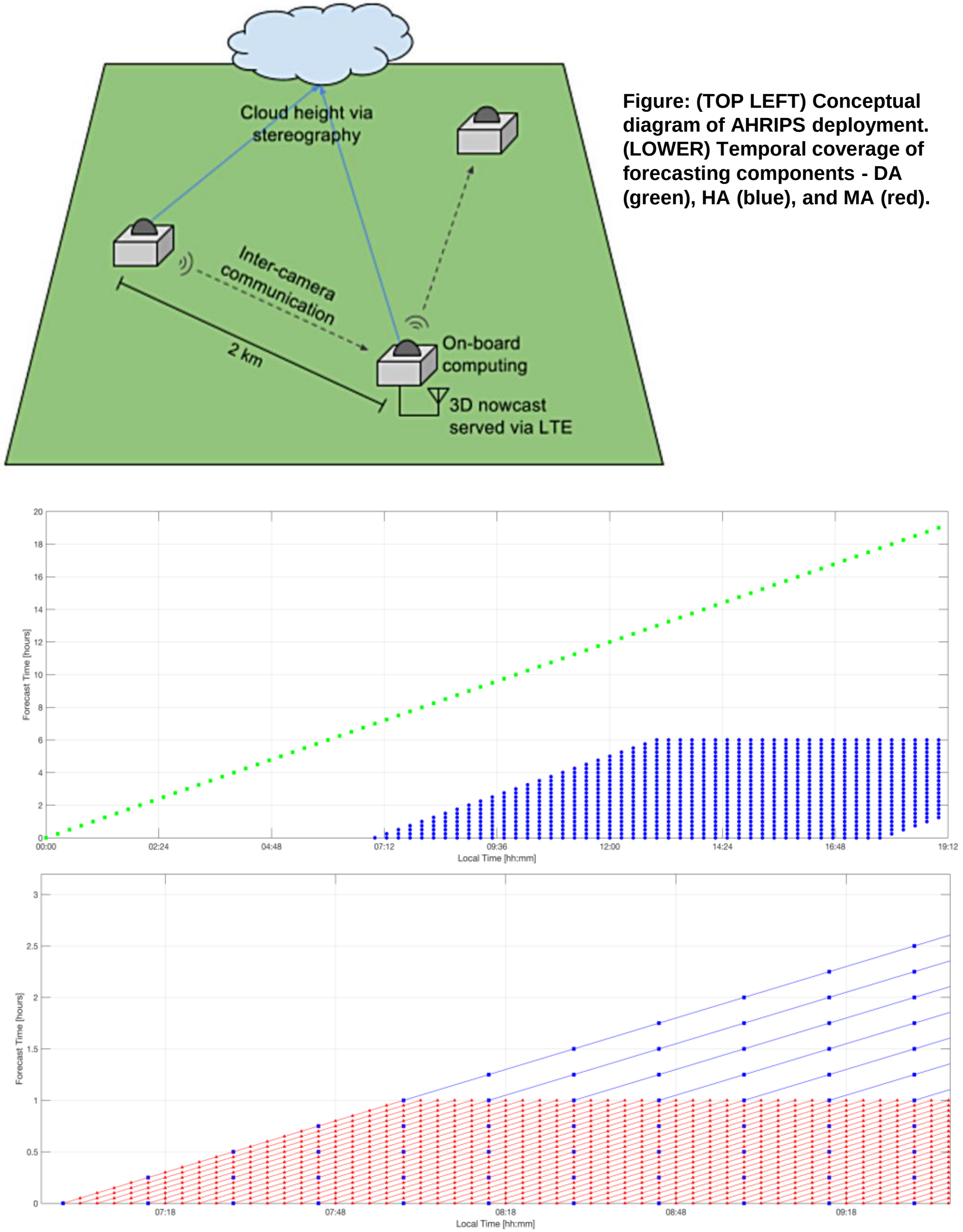


Figure: (TOP LEFT) Conceptual diagram of AHRIPS deployment. (LOWER) Temporal coverage of forecasting components - DA (green), HA (blue), and MA (red).

University of Hawai'i Mānoa

Calibration / Validation Hawaii System

To evaluate the accuracy of the forecasting system, plane-of-array irradiance and power production predictions are quantitatively compared against ground-based observations and measurements using four statistical performance metrics:

- **Root Mean Square (RMS)** difference - gives a measure of imperfection of the fit of the estimator to the data
- **Mean Absolute Bias (MAD)** - gives the statistical dispersion or mean difference
- **Correlation Coefficient (CC)** - gives the strength and the direction of the linear relationship
- **Mean Absolute Percent Error (MAPE)** - measures the prediction accuracy

Irradiance predictability

- Sky conditions
  - Cloudy skies are more difficult to forecasts
  - Small scale clouds may not be resolved by satellite data or numerical models
- Topography
  - Steep elevation changes can drive cloud formation/dissipation

Irradiance forecasts are compared against high quality thermopile pyranometers at two HNEI test locations

- Maui Economic Development Board (MEDB) test site located in Kihei, Maui
- Green Holmes Hall Initiative (GHHI) test site located at the UH Manoa campus on Oahu

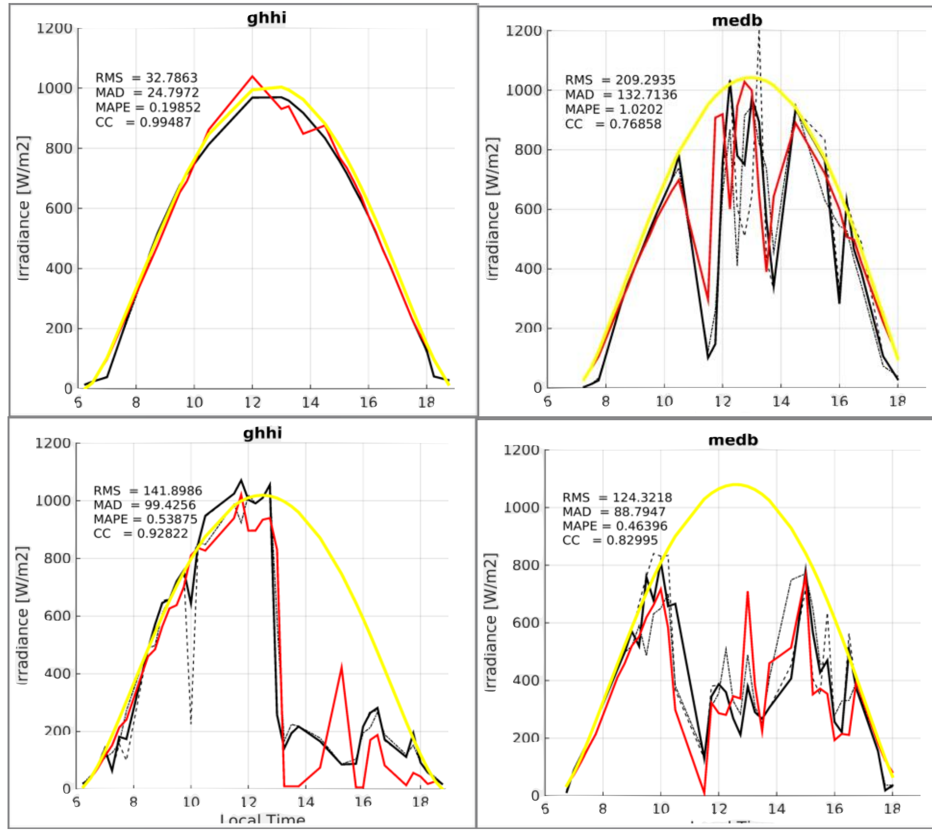
Figure: HNEI PV test platforms on Oahu (top) and Maui (bottom)

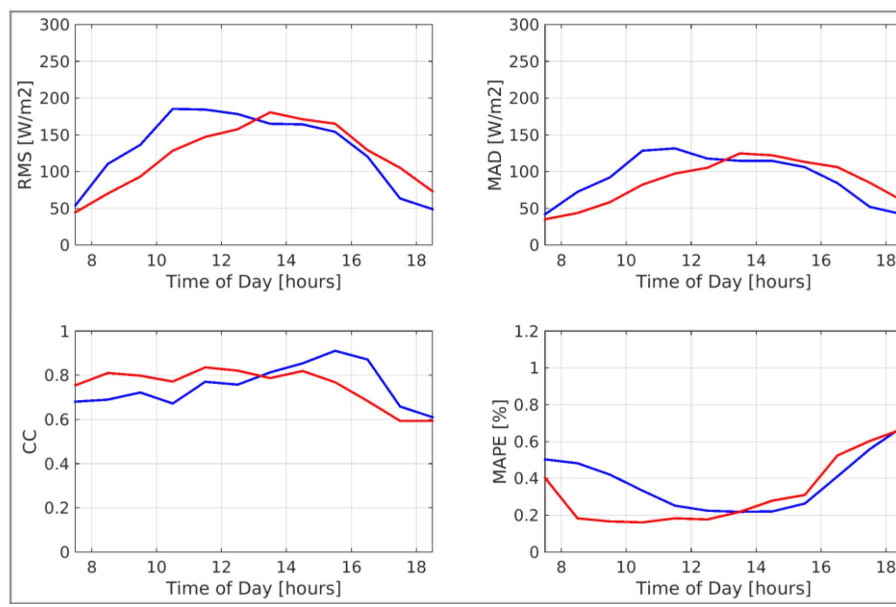
University of Hawai'i Mānoa

Calibration / Validation Hawaii System – Nowcasts

Nowcast irradiance maps are generated directly from the most recent satellite image within 15-20 minutes of real-time

- Coincident data shown (nearest 1 km pixel to pyranometer instrument)
- (Top) Time series of satellite irradiance nowcasts (red line) compared against ground-based observations (black line), with clear sky irradiance (yellow line)
- (Lower) Nowcasts statistics from one year of data - GHHI (red line) MEDB (blue line)
  - Statistics in lower figure are based on 1-year of data (May 2017 to June 2018) from two HNEI test sites
  - Results from one year of <u>*satellite*</u>-based forecasts without post processing ensemble methods





UNIVERSITY of HAWAI'I
MĀNOA

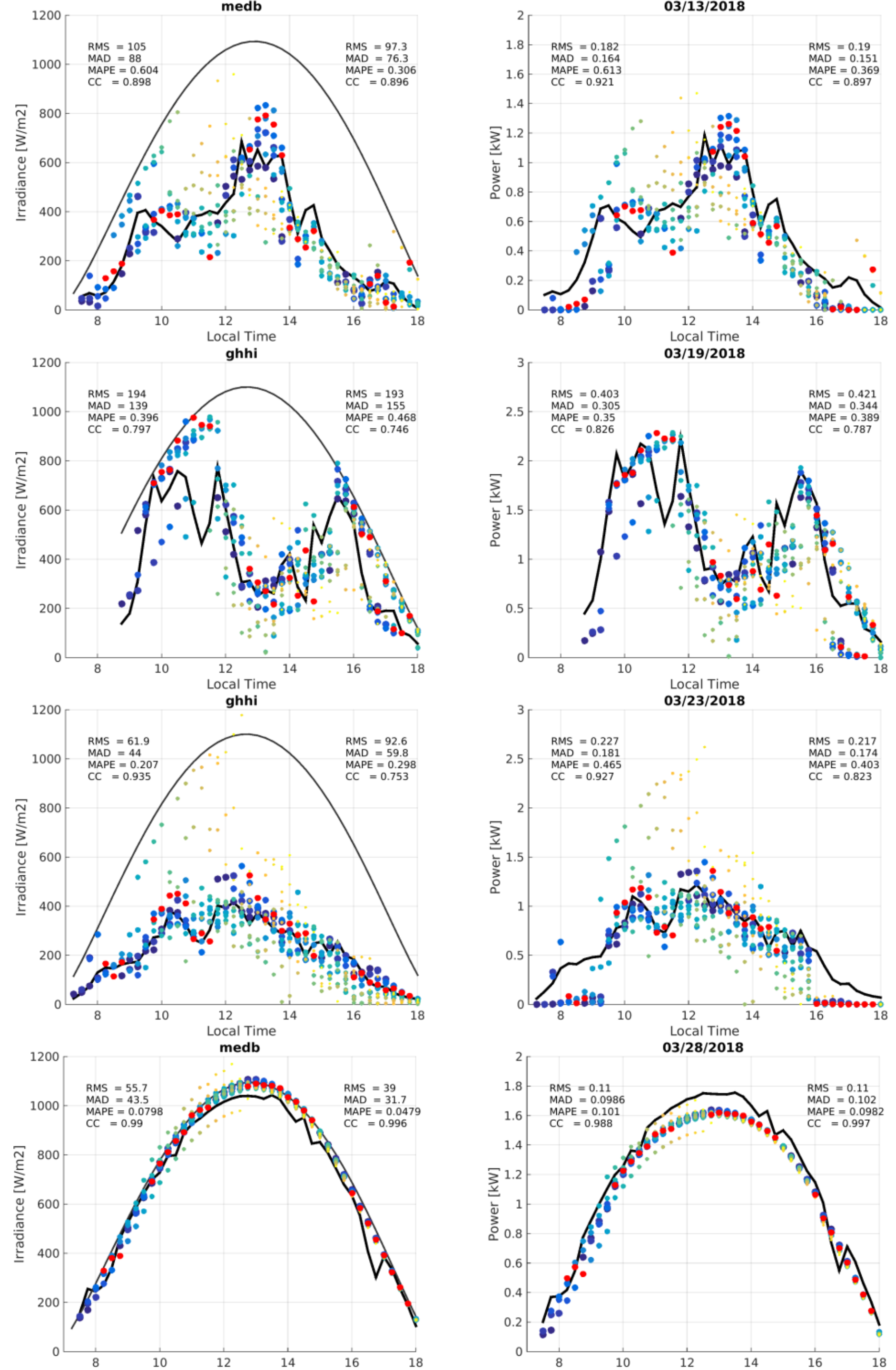
Calibration / Validation Hawaii System – daily forecasts examples

Example satellite forecasts from late March 2018

Left column irradiance forecasts compared against pyranometer data

Right column PV power forecasts compared against measured power output

- Black line - pyranometer observations
- Thin grey line - clear sky irradiance
- Solid dots - indicate forecasted values
  - Forecasting time is indicated by the size and color of dot
  - Short term forecasts blue larger dot
  - Long term forecasts smaller yellow dots
  - 1-hour ahead forecasts indicated by red dot
- Two sets of statistics
  - Left side - 1 hour ahead
  - Right side - 2 hours ahead

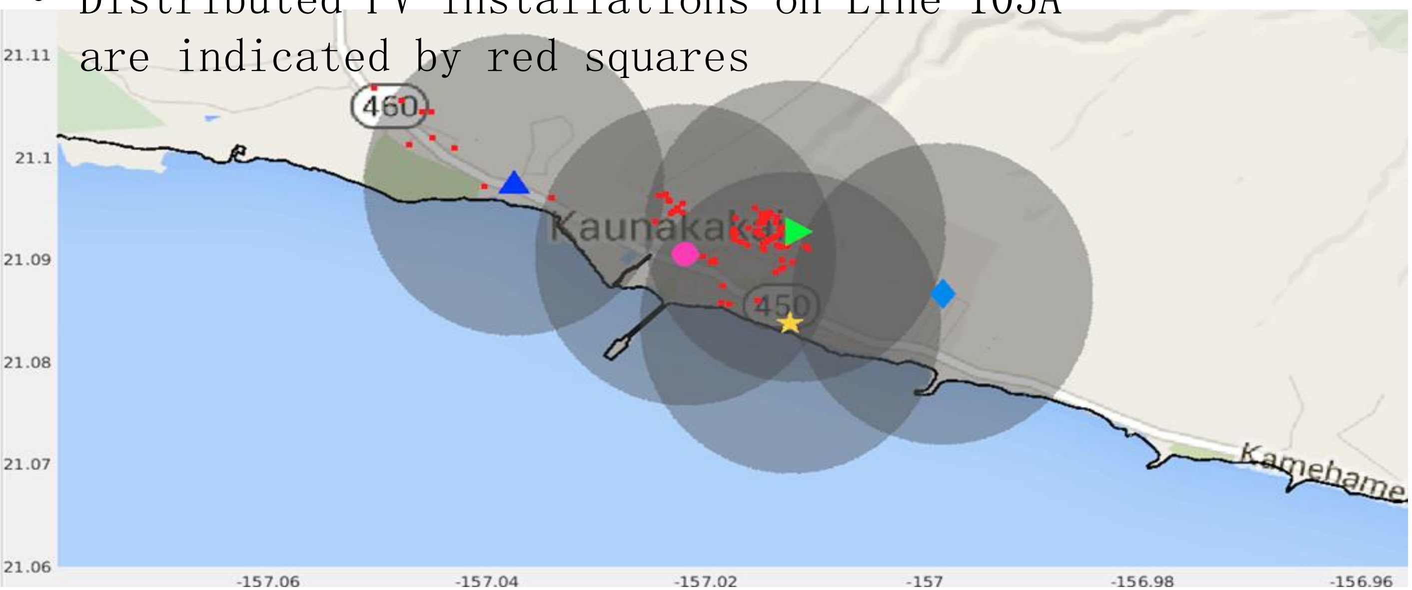


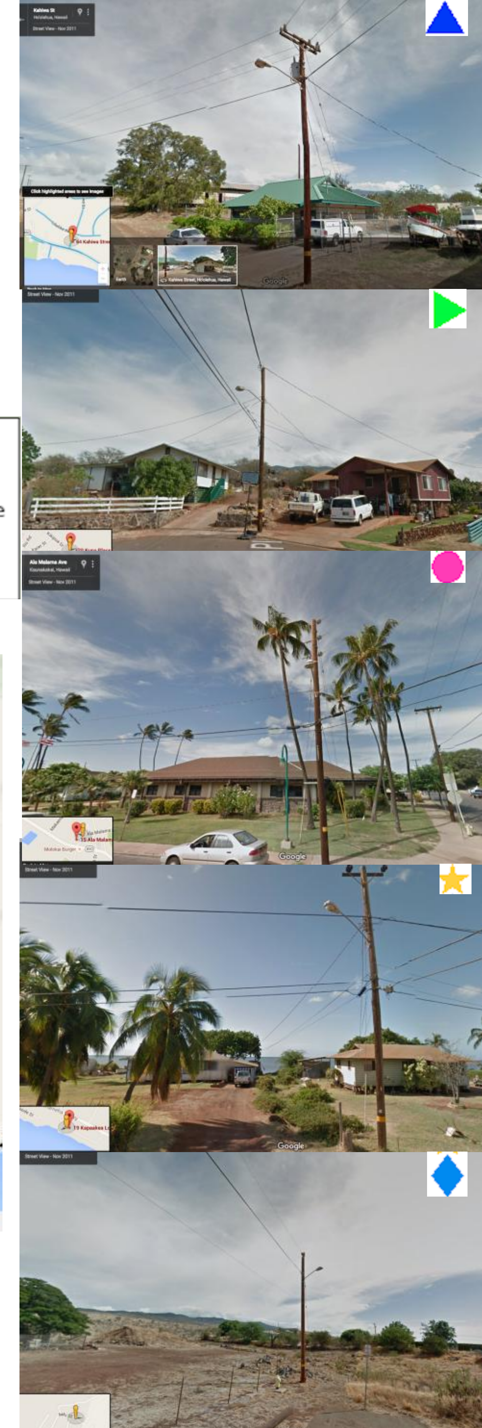
UNIVERSITY of HAWAI'I MĀNOA

Molokai Field Deployment

- Deployment focuses on Circuit 105A using 5 camera systems mounted on utility power poles
- Camera FOVs (shown by grey circles) are related to the cloud base height (CBH) – below, we use the regional mean atmospheric inversion height (900 m) to calculate FOV
- Distributed PV installations on Line 105A are indicated by red squares

64 Kahiwa St
370 Kupa Pl
15-47 Ala Malama Ave
19 Kapaakea Loop
246 Aahi St





UNIVERSITY of HAWAI'I
MĀNOA

GridSTART

Grid System Technologies Advanced Research Team

Established to develop and test advanced grid architectures, new technologies and methods for the integration of renewable energy resources, power system optimization and enabling policies.

- Diverse staff includes engineers, scientists, lawyers; students and postdoctoral fellows; visiting scholars
- Serves to integrate into the operating power grid other HNEI technology areas: biomass and biofuels, fuel cells and hydrogen, energy efficiency, renewable power generation
- Strong and growing partnerships with national and international organizations including Asia-Pacific nations.

Lead for many public-private demonstration projects

Mahalo!

(Thank you)

For more information, contact:

GridSTART

Grid System Technologies Advanced Research Team

Leon R. Roose, Esq.
Principal & Chief Technologist
Grid*START*

Hawaii Natural Energy Institute
School of Ocean & Earth Science & Technology
University of Hawaii at Manoa
1680 East-West Road, POST 109
Honolulu, Hawaii 96822

Office: (808) 956-2331
Mobile: (808) 554-9891
E-mail: lroose@hawaii.edu
Website: www.hnei.hawaii.edu