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# Integrating High Levels of Renewables into the Lanai Electric Grid

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**Technical Report**
NREL/TP-5500-50994
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Prepared under Task No. DP11.2000

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# EXECUTIVE SUMMARY

The Hawaii Clean Energy Initiative (HCEI) is working with a team led by the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (Sandia) to assess the economic and technical feasibility of increasing the contribution of renewable energy sources on the island of Lanai with a stated goal of reaching 100% renewable energy. NREL and Sandia partnered with Castle & Cooke, Maui Electric Company (MECO), and SRA International to perform the assessment.

## *The HCEI Lanai Study*

To assess ways to integrate high levels of renewable energy into the Lanai grid, NREL and the HCEI Technical Team conducted a three-phase study with support from DOE. The NREL team then compiled the final reports from each phase of the project into this report.

NREL and Sandia worked with MECO to gather the data necessary for modeling an initial base case of electricity production and use on Lanai. Phase 1 of this report evaluated renewable energy potential to meet the existing load. The initial analysis used solar and wind resource data and load data from 2005. This base-case model represents all generating units with efficiencies close to those seen in the field, but operating under an optimum control strategy. The controls allow the generators to shut down when load is met with renewable energy although the base load generators remain on (1.2 MW minimum load) to meet the system's stringent reliability requirements. The results indicated that the optimized use of localized wind turbines in conjunction with existing generators reduces the fuel usage significantly (37%) and reduces the Levelized Cost of Energy (LCOE) by 21%. However operational analysis is required to determine if this level of increased renewable energy integration could be supported with the Lanai existing electrical infrastructure, and whether additional upgrades would be required.

Phase 2 evaluated the cost comparison of photovoltaic (PV), Concentrated Solar Power (CSP), and wind turbines (all options included energy storage) to meet Lanai's 2008 load. Newer resource data from 2008 was also used in this study. NREL's 2008 solar data was used along with the wind resource data collected by Castle & Cooke in 2008. During this timeframe, Castle & Cooke installed a 1.5MW DC equivalent to 1.2MW AC PV system known as "La Ola" and MECO installed an 800 kW Combined Heat and Power (CHP) system. These projects were included in the analysis by calculating the adjusted load (the load remaining after the projected PV and CHP output were subtracted). Phase 2 highlighted a comparison of the three renewable energy technologies (CSP with thermal energy storage, PV with batteries, and wind with batteries). The results showed that a hybrid power system with 10.5 MW of wind power and 50.4 MWh sodium sulfur battery storage had the lowest LCOE. Although the wind-battery system had the lowest LCOE, it was the most problematic system to site, due to potential permitting issues.

In Phase 3, NREL evaluated pathways to 100% renewable energy for Lanai with a few near-term PV projects. Potential sites were evaluated for new PV systems without requiring storage or upgrades to the existing infrastructure. When considering non-dispatchable generation sources such as PV, the minimum load must be considered. Phase 3 showed that the minimum adjusted load, after the 800 kW CHP was added, is 1.7 MW. Through analysis it was determined that the island can support an additional 500kW of distributed PV without storage for excess energy or

discarding energy. This is in addition to the 1.2 MW existing PV system at La Ola. Integration feasibility and system impact studies would need to be conducted to support these projects.

Phase 3 also analyzed the data from irradiance sensors installed at the La Ola PV site. The data showed that PV system voltage/frequency trips cause large disturbance and rapid fluctuation with cloud cover. A more geographically spread PV system would be better to reduce variability due to clouds. Thus, a detailed evaluation using the NREL tool In My Backyard (IMBY) was conducted at various locations to determine the output of potential sites for the additional 500 kW of PV. The Solar SunEye instrument was used to measure shading for accurate calculation of energy production. The selected sites are distributed around the island in areas with sizable loads and transmission availability.

## *Future Research*

Developing a pathway to 100% renewable energy is challenging. Lanai has good solar and wind resources, but in order to reach 100% renewable energy, either energy storage must be used or potentially an interconnection to other islands to share resources. The energy storage could be in the form of bio-diesel fuel, batteries, or even pumped hydropower. The terrain of Lanai would lend itself to a pumped hydro storage option.

The existing power system will also need advanced control capabilities and energy storage if it is to operate with very high levels of renewable technologies. A large advanced battery is being installed at the La Ola PV site to limit the ramp rates of the PV system due to cloud cover. NREL is continuing with a final study to examine the impacts of increased amounts of renewable energy (specifically distributed PV) on the electric power system. This will be published as a separate report.

One additional option for reaching 100% renewable energy on Lanai would be to interconnect the existing power system with a planned large wind farm on the western portion of the island. The planned wind farm’s output would be much larger than the needs of Lanai and export power to the island of Oahu. If this wind farm was constructed, a connection to the local grid, possibly through an AC-DC-AC intertie, might be possible.

## List of Acronyms

| | |
|---|---|
| AC | alternating current |
| CHP | combined heat and power |
| CSP | concentrated solar power |
| DC | direct current |
| DER | distributed energy resource |
| DG | distributed generation |
| DNI | direct normal irradiance |
| DOE | U.S. Department of Energy |
| DS | distributed storage |
| EPS | electrical power system |
| FY | fiscal year |
| GIS | geographic information system |
| HCEI | Hawaii Clean Energy Initiative |
| HOMER | Hybrid Optimization Modeling Tool |
| IMBY | In My Back Yard |
| km | kilometer |
| kV | kilovolt |
| kW | kilowatt |
| kWh | kilowatt hour |
| LCOE | levelized cost of energy |
| MECO | Maui Electric Company |
| MWh | megawatt hour |
| MW | megawatt |
| NaS | sodium sulfur |
| NPV | net present value |
| NREL | National Renewable Energy Laboratory |
| O&M | operation and maintenance |
| PCC | point of common coupling |
| PV | photovoltaic |
| RE | renewable energy |
| SAM | System Advisor Model |
| VRB | vanadium redox flow battery |
| WWTP | wastewater treatment plant |

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# Introduction

## *Background*

The National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (Sandia) partnered with Castle & Cooke, Maui Electric Company (MECO), and SRA international to conduct a study that analyzed the technical and economic feasibility of increasing the renewable energy sources of electric generation on the island of Lanai. The study was supported by the Hawaii Clean Energy Initiative (HCEI) and focused on developing potential pathways for Lanai to reach 100% renewable electric energy. NREL conducted a three-part study supported by DOE. The NREL team then compiled the final reports from each phase of the study into this report.

- Phase 1 evaluated the renewable energy technologies that could meet the existing load on Lanai. NREL used a micro-power optimization modeling tool known as HOMER (Hybrid Optimization Modeling Electric Renewables) to conduct the preliminary hybrid power system assessment for the island. The renewable technologies that were modeled included PV, wind turbines and batteries.
- Phase 2 evaluated the cost comparison of photovoltaic (PV), Concentrated Solar Power (CSP) and wind turbines with energy storage to meet Lanai's reduced load. The new load included the production of a new Combined Heat and Power (CHP) system and a 1.2 MW PV array.
- Phase 3 analyzed the PV potential and located potential sites for rooftop, carport and ground mount PV systems. The analysis used the NREL tool In My Backyard (IMBY) to calculate the energy production at each site.

## *Lanai Site Overview*

The island of Lanai is approximately 14 miles long and 13 miles wide, with a land area of 140 square miles (approximately 90,000 acres). It is the sixth largest of the Hawaiian Islands and has a peak elevation of 3,379 feet above sea level. The island was formerly known as "Pineapple Island" due to the large Dole Pineapple plantation that has since been decommissioned. Lanai is currently owned by Castle & Cooke; they are reinventing the island into a vacation destination with two large luxury resorts at Manele Bay and near Lanai City.

Two maps of Lanai are shown in Figure I-1 and Figure I-2. Figure I-1 shows the entire island of Lanai. The northwest corner of the island is being considered for a large wind farm with an underwater cable to transmit power to other Hawaiian Islands. However, the large wind project is beyond the scope of work covered in this report and it is assumed for this analysis that this large wind project would not be tied to the Lanai electrical grid. The island's entire load is concentrated in the central and southern part of the island and highlighted in Figure 0-2. This figure shows the most populated areas on Lanai, which include Lanai City and Manele Bay Resort.

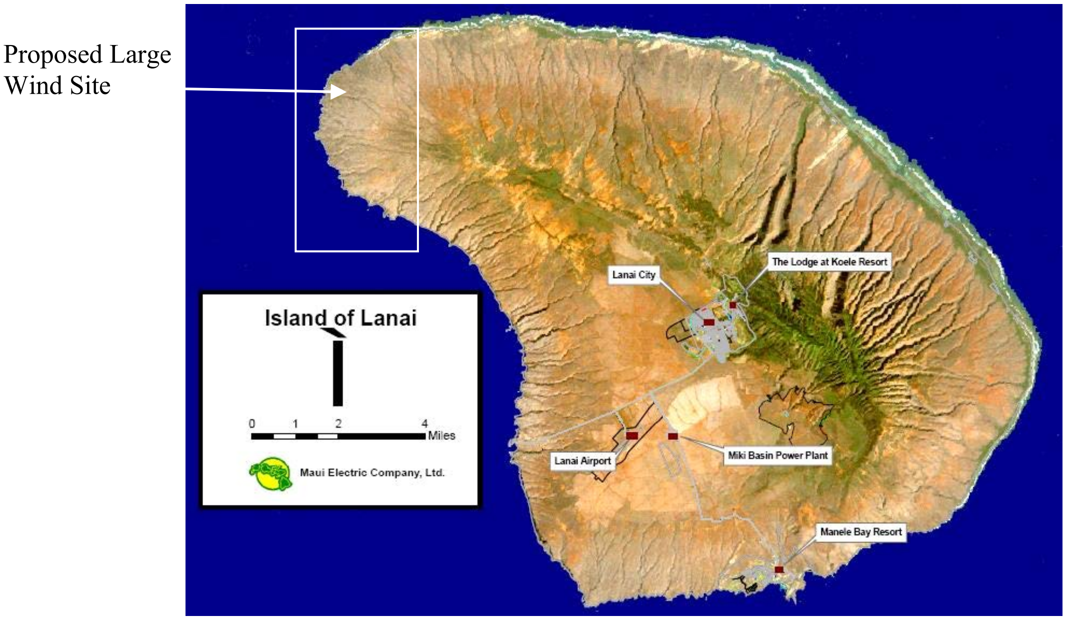


**Figure I-1. Lanai, Hawaii,**

Illustration from MECO

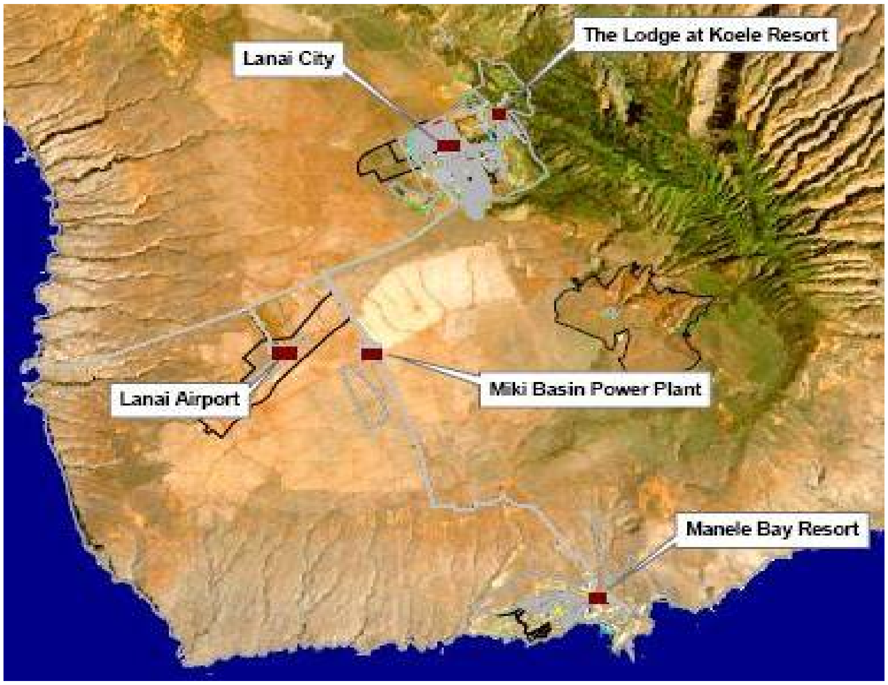


**Figure I-2. Load sites on Lanai**

Illustration from MECO

### *Lanai Energy Usage*

The power system on Lanai is owned and operated by the Maui Electric Company (MECO), which is a subsidiary of the Hawaiian Electric Company (HECO). The majority of the electrical loads on Lanai are attributed to the large resorts (the Lodge at Koele and Manele Bay), the well pumps for water on the island, and Lanai City. The Lanai electrical power system is supplied by two 2.2 MW diesel generators that typically run in a master-slave configuration. Six 1 MW diesel powered generators are used for peak power operations. The electric power system on Lanai does not have any high voltage transmission lines. It is a small distribution system with nominal voltages of 12.47 kV to bring electricity to customers. In 2004 Lanai’s energy production was approximately 30 MWh/year and increased less than 2.5% between 2004 and 2006. In 2007 Lanai’s energy consumption jumped over 6.0% to an average 32.88 MWh annually due to the new large hotels and has remained at this level.

### *Overview of Analysis Tools*

Three software tools, HOMER, System Advisor Model (SAM) and IMBY, were used to conduct the analysis of integrating high penetrations of renewables into the Lanai grid. Details of these tools are described in detail in the appendix.

# 1 Phase 1: Renewable Energy Potential

## 1.1 Background

Phase 1 used NREL's HOMER optimization model to analyze the technical and economical feasibility of adding wind and PV to reduce diesel use on the island. Phase 1 also analyzed what amount of wind and PV with batteries could meet the entire load.

## 1.2 Modeling Input Data

Modeling input data included solar and wind resource data, load data, and run time data from diesel generators.

### *1.2.1 Resource Data*

Resource data included both solar and wind resource data.

### *Solar Resource Data*

Hourly 2005 solar data (10 km grid point) from site 156952075 of the NSRDB/Perez satellite data set was used. Site 156952075 is the 10km grid shown highlighted in Figure 1-1. This figure also shows the direct normal irradiance (DNI) in kWh/$m^2$/day. The DNI value is useful in understanding the Concentrated Solar Power (CSP) potential for the island. Because CSP systems require flat land, the data has been filtered to remove slopes over 5%.

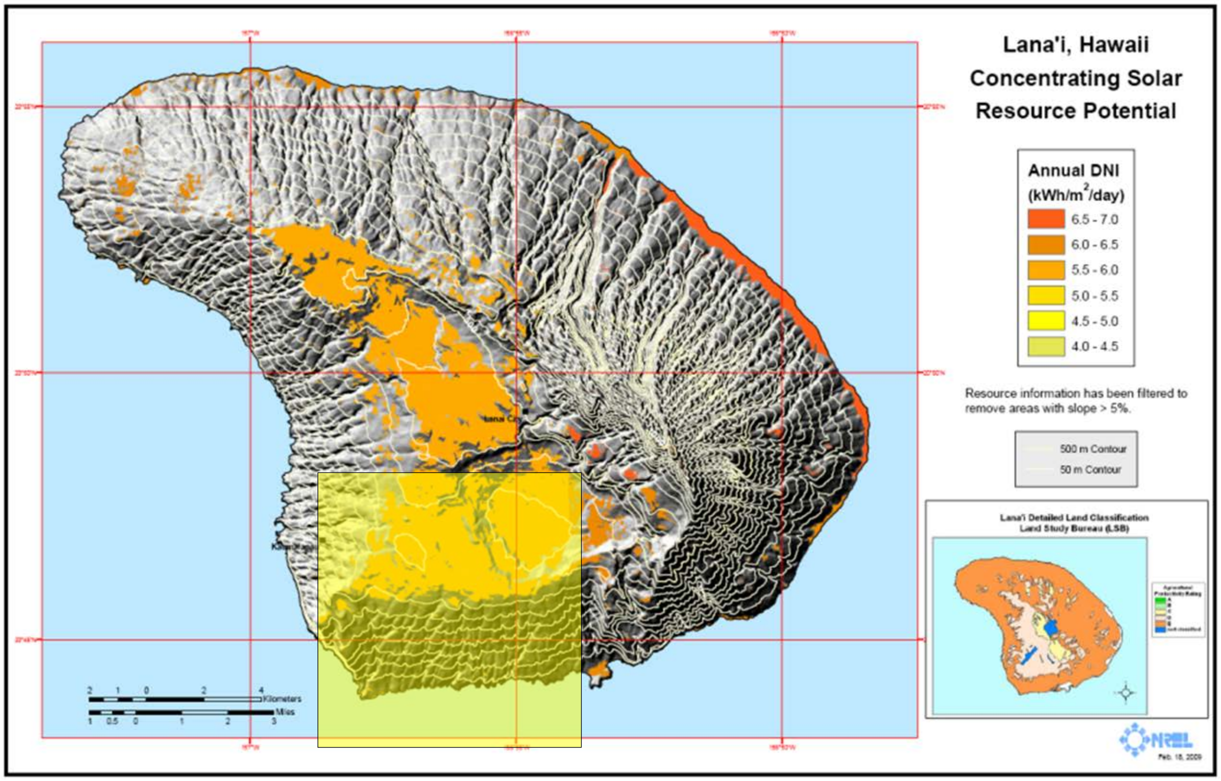


**Figure 1-1. Solar resource data map**

### Wind Resource Data

Figure 1-2 shows the wind resource map for Lanai. From this figure one can see the large wind resource on the northwest portion of the island. For this study, the 50 meter (in height) wind near the airport was used with additional information to evaluate the potential for a local wind farm located closer to the loads. Wind data from the weather service station at the Lanai airport was collected at a height of 6 meters. Wind patterns were created to match the wind characteristics from a coastal high wind site. Hourly wind data for 2005 was used for the site highlighted in the map below. The average annual wind speed at 6 meters was 4.51 m/s and the average power was 129 W/m$^2$. The 2005 data represent a low wind year at the airport, where the long-term mean wind speed is approximately 4.9 m/s. A revised data set adjusted for 50 meters average height provided an annual average wind speed of 8.00 m/s and wind power of 529 W/m$^2$.

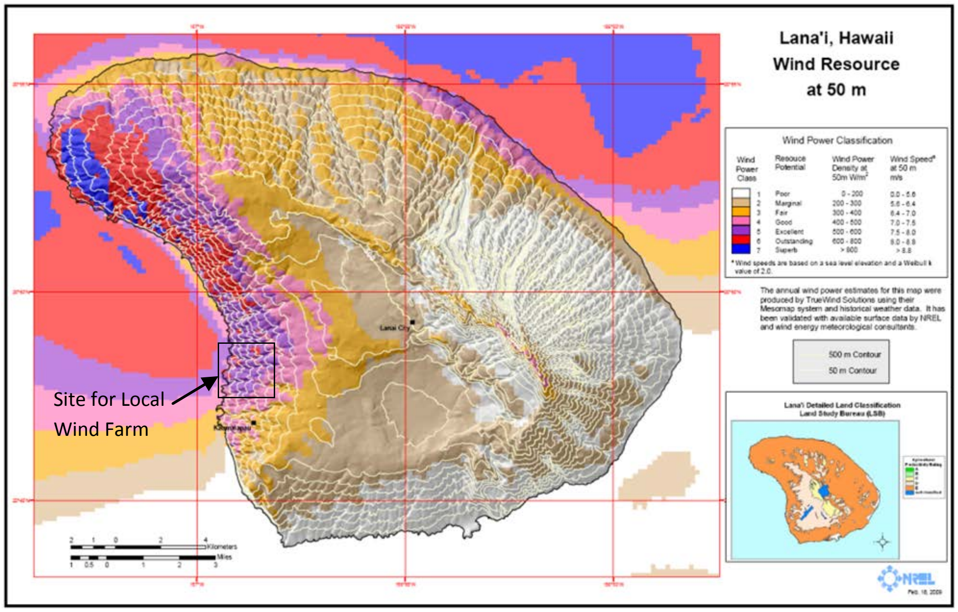


Figure 1-2. Wind resource data map

### 1.2.2 Load Data

The hourly load data used in Phase 1 to model Lanai was taken from 2005. The load profile on Lanai had a peak of around 5.4 MW and a minimum load of 2.1 MW. The peak and minimum loads on Lanai were fairly consistent over the period studied (see Figure 1-3). Because the load growth on Lanai has remained consistent, Phase 1 of this study assumed that the energy efficiency measures being implemented on the island would counteract any additional energy use and future load levels would be equivalent to historical levels.

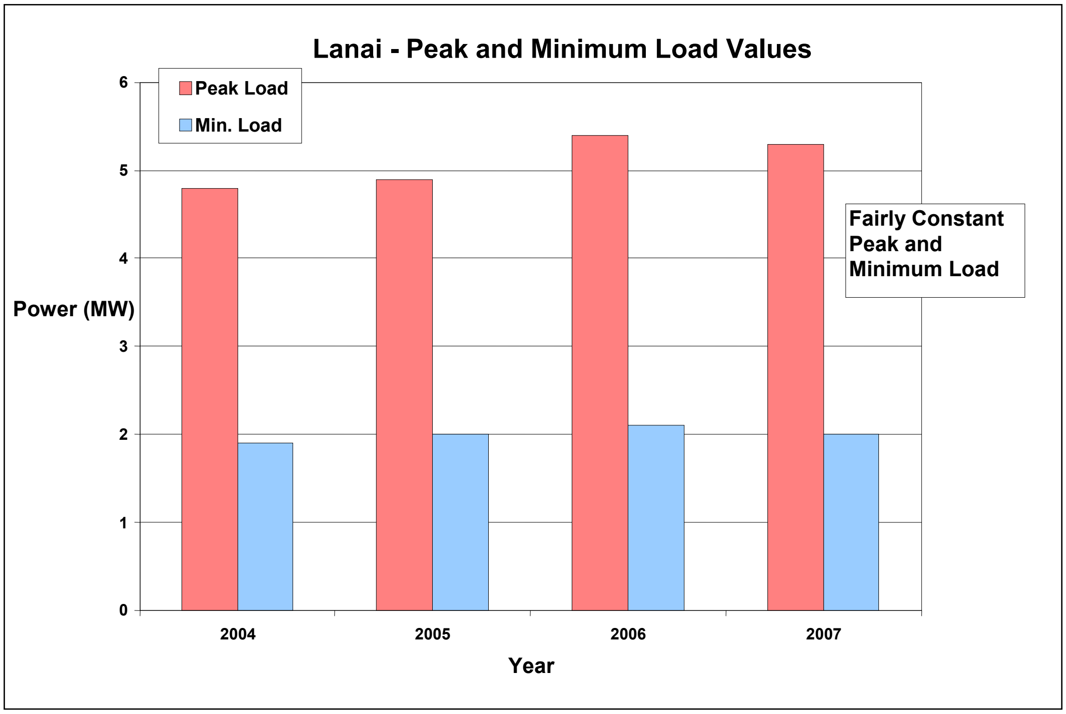


**Figure 1-3. Lanai peak and minimum loads (2004 through 2007)**

Lanai load duration curves for 2005 and 2007 are shown in Figure 1-4 with the peak power at approximately 5 MW. The 8760-hour load-duration curve allows us to see if the PV generation reduces peak loads. Peak load reduction is beneficial because it would allow the utility to reduce overall generation capacity and reduce spinning reserve.

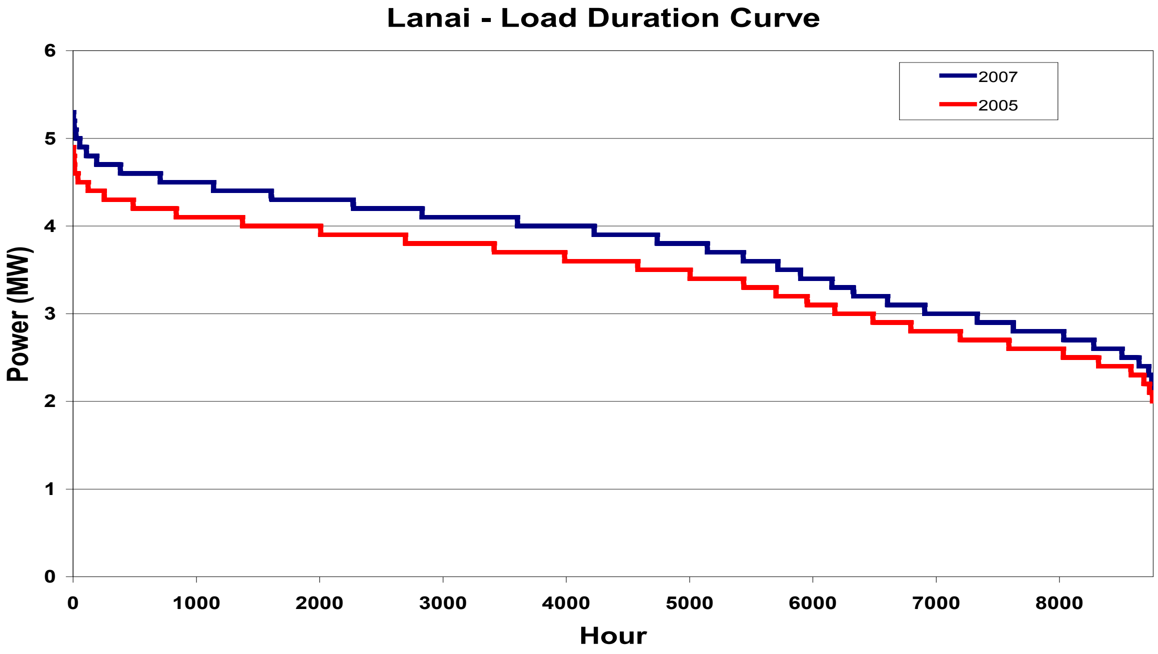


**Figure 1-4. Load duration curves (2005 and 2007)**

### 1.2.3 Diesel generators

The primary power on Lanai is currently provided by two 2.2 MW and six 1 MW standby diesel generators. During normal operation the two large generators are used to cover the majority of the load and the smaller generators are only operated during peak demand periods. Figure 1-5 and Figure 1-6 show photographs of the two sizes of generators. The two 2.2 MW diesels run in a master-slave configuration and for this analysis they are modeled as a single 4.4 MW generator. The six 1 MW units only run for peak load conditions and are individually turned on. Their use is rotated to reduce run hours on any single generator. Since the six generators do not operate concurrently they were modeled as one single generator.

**Figure 1-5. 2.2 MW diesel generator on Lanai, Photo by J. Keller, NREL**

**Figure 1-6. 1 MW diesel generators on Lanai, Photo by J. Keller, NREL**

## 1.3 Cost Inputs

The costs input to the model are summarized below. Except where indicated, these cost assumptions were developed at the time of study in 2008 and include increased estimated cost for installation on an island.

Diesel fuel cost

- A sensitivity analysis was performed determining the system effects if diesel costs $2.60/gal or $4.60/gal. These values were based on the average cost of diesel in 2007 and the highest cost during 2008.

2.2 MW generator:

- Capital cost: $0 (the equipment is already purchased and installed)
- Replacement cost: $440,000 (the equipment will be replaced when the generator has run for 20,000 hours)
- Operation and Maintenance cost: $8.76/operating hour

1 MW generator

- Capital cost: $0 (the equipment is already purchased and installed)
- Replacement cost: $400,000 (the equipment will be replaced when the generator has run for 20,000 hours)
- Operation and Maintenance cost: $1.58/operating hour

Photovoltaic panels (PV)

- Cost per watt: A sensitivity was performed determining the system effects if PV cost $6/W or $10/W
- Operation and Maintenance cost: $25/kW/yr

1.5 MW Wind Turbine

- Capital cost: $3,000,000/turbine. This cost is based on the national average wind turbine price of $2,000/kW at the time of this study
- Replacement cost: $3,000,000/turbine (the turbine will be replaced after 15 years of service
- Operation and Maintenance cost: $22,500/yr

Vanadium Redox Battery (VRB) Energy Storage System (NREL's estimated cost)

- Cell stacks
  - Capital cost: $1,030,000 for a 250 kW cell stack
  - Replacement cost: $750,000 (the cell stack will be replaced after 15 years of service)
- Electrolyte
  - Capital cost: $350/kWh of energy capacity

    - Replacement cost: $350/kWh of energy capacity (the electrolyte needs to be replaced after 125 years)
- Variable O&M cost: $0.005/kWh throughput

Converter (inverter/rectifier)

- Capital cost: $790/kW
- Replacement cost: $790/kW (the equipment will be replaced after 15 years of service)

## 1.4 Phase 1 Analysis

The hourly solar and wind resource data and load data were input into HOMER. Based on the inputs provided, HOMER allows for scenario analysis and cost optimization on the levelized cost of energy (LCOE). Four different scenarios are discussed in this chapter:

- Scenario 1: Base Case without renewable energy
- Scenario 2: Base Case + PV
- Scenario 3: Base Case + PV + Battery + Wind
- Scenario 4: Moving Lanai to 100% renewable energy

*For the analysis stated in this report, it is important to note that the LCOE only cover the cost of the fuel and operation and maintenance (O&M), which make up the cost of electricity. It does not include the capital cost of the existing diesel generation and does not cover and transmission and distribution system costs. The costs do include O&M of the exiting generation. The analysis does, however, provide a method to compare various future system options against each other on a LCOE basis.*

### *Scenario 1: Base Case – No Renewable Energy*

The base case of the system without any renewable energy is shown in Figure 1-7. The 2005 load profile was created using demand data provided by MECO staff on Lanai and resembles the electrical system, fuel use and energy production in that year. The total annual load is 30,244 MWh/yr with a peak demand of 4.9 MW.

The fuel curves for the generators were created also using data provided by MECO. This base-case model represents all generating units with efficiencies close to those seen in the field, but operating under an optimum control strategy. In this mode the generators are allowed to turn off and be replaced by renewable energy, although the base load generators remain on (1.2 MW minimum load) to meet the system's stringent reliability requirements. Due to the complexity of the real-world operation of the generators, the base case created in HOMER is indicative of the relative economics of similar options rather than a precise description of MECO's existing systems.

### *Scenario 1: Results*

The HOMER model base case electrical production indicates that 98% of the load (29,740 MWh) is met by the two 2.2 MW generators and 2% of the load (504 MWh) is met by the 1 MW auxiliary generators. The Base Case used 2,101,800 gal/year of diesel fuel.

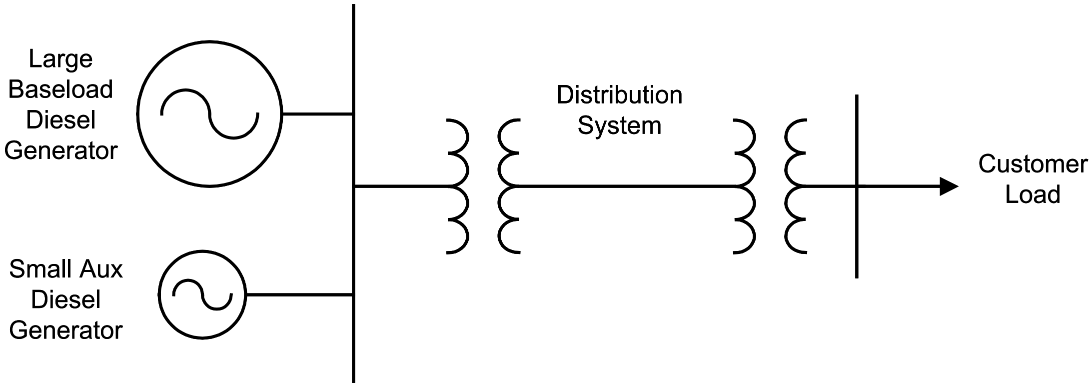


**Figure 1-7. Base case used in HOMER**

### *Scenario 2: Base Case + PV*

The second scenario shown in Figure 1-8 examined three potential PV sizes with the two separate PV costs and the two diesel prices. The PV sizes considered were 30%, 60% and 90% of the peak annual demand (1.5MW, 3.0MW and 4.5MW respectively).

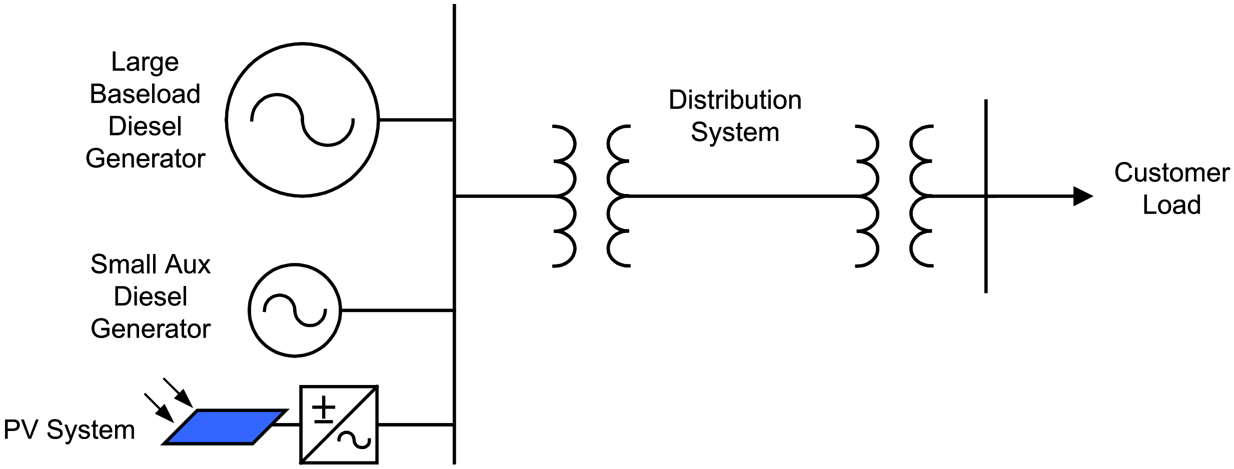


**Figure 1-8. Scenario 2: Base Case with PV**

### *Scenario 2: Results*

The LCOE for the various configurations in Scenario 2 are summarized in Table 1-1. For the low diesel cost ($2.60/gal), the optimized PV system based on LCOE for Lanai was a 1.5MW single-axis tracking PV system with 1,620 kW of converter capacity. This result is independent of PV price ($6/W or $10/W). The smallest PV system was optimal in terms of LCOE due to the high cost of PV relative to the cost of diesel. This system reduces the fuel use on Lanai by 9.3%, resulting in a fuel savings of 195,838 gallons/yr.

By adding 1.5 MW of PV the fuel cost savings is $ 504,103/yr (when diesel costs equal $2.60/gal) or $904,420/yr (when diesel costs equal $4.60/gal).

**Table 1-1. Comparison of LCOE**

| PV Size | System LCOE Diesel $2.60/gal | System LCOE Diesel cost $4.60/gal |
|---|---|---|
| 0 MW–Base case | 0% change | 0% change |
| | **Cost of PV = $6/W** | |
| 1.5 MW | 8.2% increase | 1.1% increase |
| 3.0 MW | 14.4% increase | 1.7% increase |
| 4.5 MW | 22.1% increase | 2.6% increase |
| | **Cost of PV = $10/W** | |
| 1.5 MW | 16.3% increase | 6.0% increase |
| 3.0 MW | 31.7% increase | 11.7% increase |
| **4.5 MW** | **47.6% increase** | **17.7% increase** |

Though the addition of PV reduced the fuel usage, the levelized cost of energy (LCOE) actually increased. At the lower diesel cost, the LCOE in Scenario 2 increases from 8.2% to 22.1% of the Base Case. Under the higher diesel cost ($4.60/gal), the cost for PV ranged from a 1.1% increase to a 2.6% increase.

Further sensitivity analysis was done to examine scenarios under which PV becomes cost-effective (i.e., a LCOE less than or equal to that of the base case). Figure 1-9 shows that PV becomes cost-effective at low PV costs ($6/W) and high diesel cost (above $1.30/liter or $4.92/gallon).

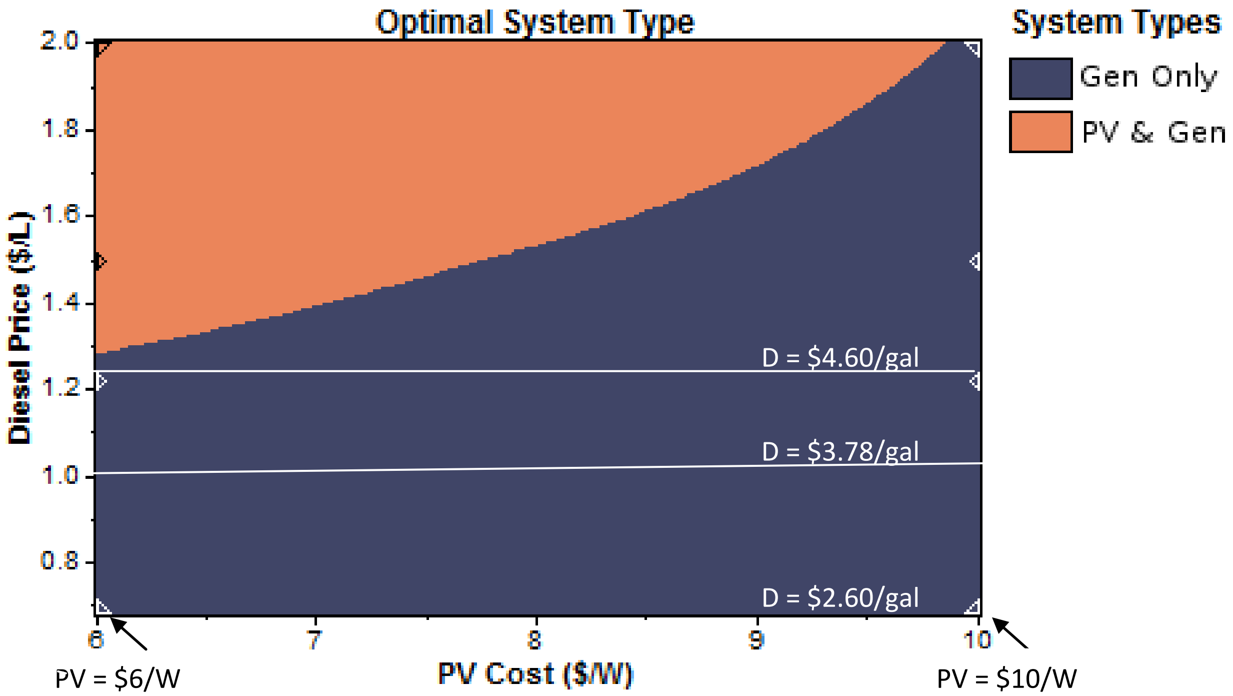
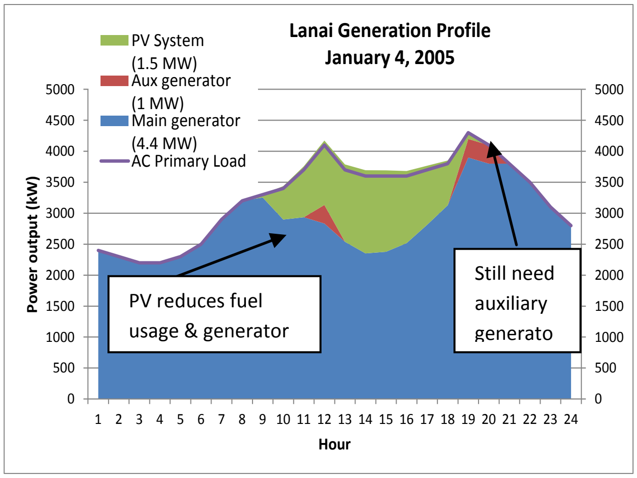


**Figure 1-9. Sensitivity analysis of PV cost vs. diesel price, Illustration by HOMER Energy, LLC**

Figure 1-10 and Figure 1-11 show the daily energy profile associated with two different sizes of solar PV systems. January 4, 2005 was chosen to represent an average load profile. In Figure 1-10, a 1.5 MW PV system produces energy during the daytime hours and is shown in green. The main generator energy is shown in blue and the auxiliary generator is shown in red. The system load is overlaid as a purple line. The 1.5 MW of PV reduces the fuel usage of the generator, but does not alleviate the need for the auxiliary generator(s). The auxiliary generator must come on in the late morning for system reliability; the PV does not provide firm capacity and the auxiliary generator must be available for fluctuations in the solar resource. The auxiliary generator also must turn on in the afternoon after the sun has set. In Figure 1-11, the PV size is increased to 4.5 MW. The 4.5 MW of PV produces excess power in the middle of the day; therefore, some form of storage should be considered. Both systems still require the use of the auxiliary generators to cover the evening peak load. Load management or storage also could be considered to eliminate the use of the auxiliary generator.



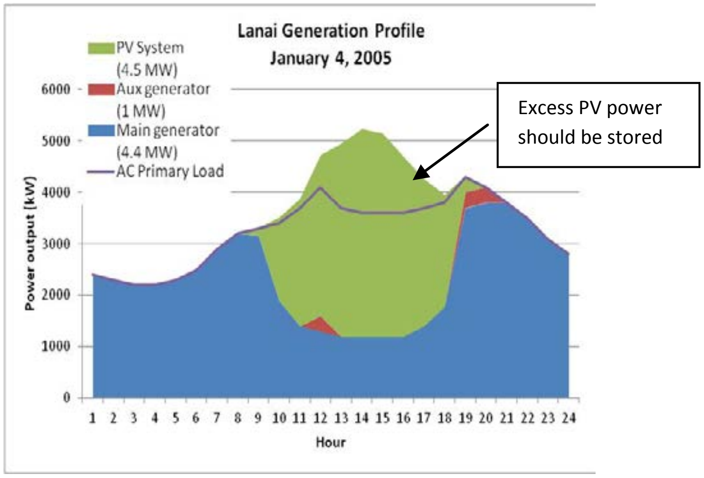


**Figure 1-10. Scenario 2: Base case + 1.5 MW PV, Illustration by HOMER Energy, LLC**

**Figure 1-11. Scenario 2: Base case + 4.5 MW PV, Illustration by HOMER Energy, LLC**

### *Scenario 3: Base Case + PV + Batteries + Wind*

This scenario analyzes the base case power production with the addition of PV, batteries and wind turbines. Again, three sizes of PV (1.5, 3, and 4.5 MW) were considered, along with 0 to15 MW of wind turbines and 250 kW of VRB batteries with 3, 4, or 8 hours of storage, for capital and replacement cost. A vanadium redox flow battery (VRB) was modeled in HOMER. The vanadium is used in a dilute sulphuric acid electrolyte that is pumped from separate storage tanks. The process is reversible, allowing the battery to be recharged. The VRB has a round-trip efficiency of 80%. There are a number of parameters that HOMER uses to model batteries that include maximum charge current and charge rate, minimum state of charge, annual throughput and expected life. All these factors are considered each hour of the operating power system to determine the optimal solution to meet demand.

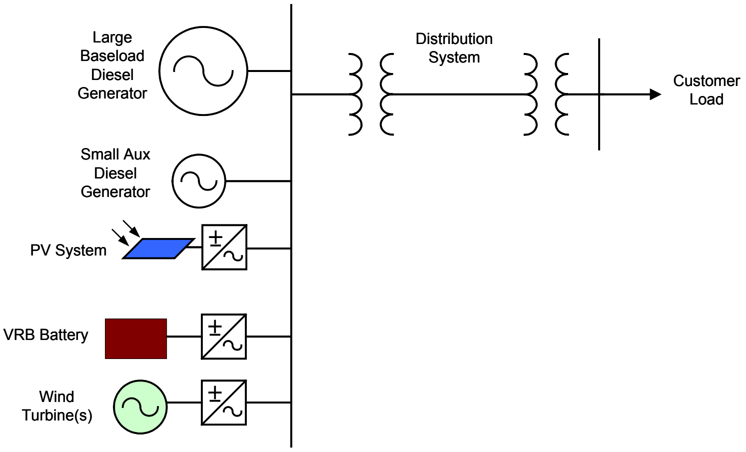


**Figure 1-12. Scenario 3: Base Case + PV, wind, and energy storage**

### *Scenario 3: Results*

Assuming a 6m/s average annual wind speed, under Scenario 3 the hybrid power system that had the least LCOE included:

- Three 1.5 MW (4.5MW total) wind turbines (diesel price equal $2.60/gal)
- Four 1.5 MW (6MW total) wind turbines (diesel price equal $4.60/gal).

The lowest cost solution did not include PV or batteries due to the high relative costs of batteries and PV. A solution with only wind turbines might not be realistic because the system would likely have very high ramp rates from the variability of wind. There would need to be additional controls to integrate the ramp rates of the wind turbines.

#### *Diesel Costs: $2.60/gal*

The three 1.5MW wind turbines reduced the fuel use to 1,400,304 gal/yr. This reduction results in a fuel saving of 33.5% or 705,211 gal/yr. When diesel costs $2.60/gal the reduction in fuel use amounts to a cost savings of $1,812,674/yr. The resulting LCOE decreases by 12.5%.

#### *Diesel Costs: $4.60/gal*

The four-1.5MW wind turbines reduced the fuel use to 1,320,838 gal/yr. which results in a fuel saving of 37.3% or 784,676 gal/yr. When diesel costs $4.60/gal the reduction in fuel use amounts to a cost savings of $3,618,614/yr. The resulting LCOE reduces 21.4% from the base case LCOE.

The sensitivity analysis for a cost of PV equal to $10/W indicates that the wind-diesel hybrid system tends to be the most cost effective at this PV cost. If the price of diesel reaches $8.70/gal ($2.30/L), PV may be cost effective, but only if the annual average wind speed is less than ~4 m/s.

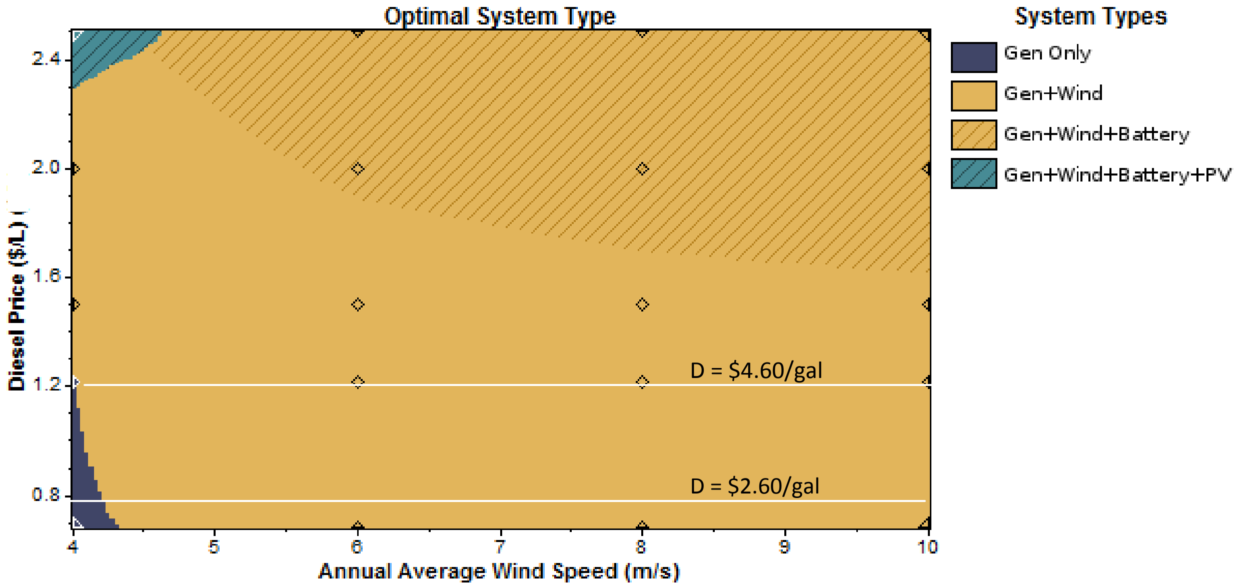


**Figure 1-13. Sensitivity analysis for Scenario 3 with PV = $10/W, Illustration by HOMER Energy, LLC**

As the cost of PV decreases to \$6/W, the sensitivity analysis shows in Figure 1-13 that at high fuel cost a PV, wind turbine, diesel generator hybrid system is cost effective. Battery storage is economical at very high diesel prices (approximately \$6/gal). The wind turbine/diesel generator system (yellow area) is the optimal system for the majority of the expected diesel prices and annual average wind speeds.

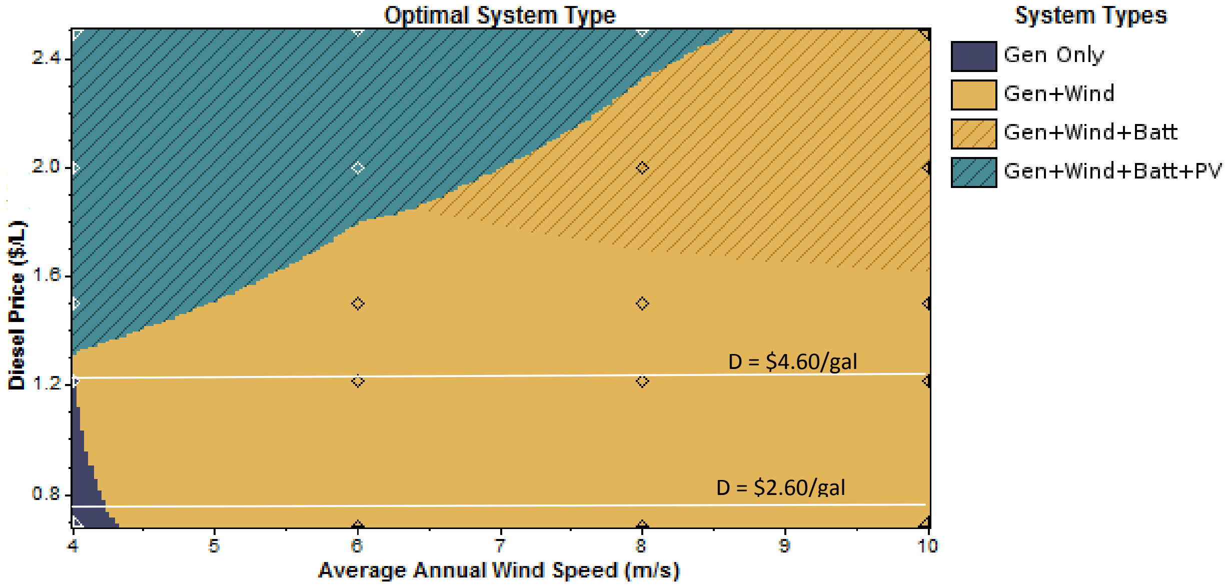


**Figure 1-14. Sensitivity analysis for Scenario 3 with PV = \$6/W, Illustration by HOMER Energy, LLC**

### *Scenario 4: 100% Solar/Wind*

The final scenario analyses at what amount of PV, wind turbines and batteries would be needed to bring Lanai to 100% renewable energy.

The first step is to determine approximately how much PV would be needed to meet the 2005 primary load of 30,245 MWh using basic solar calculations. Based on 2005 solar resource data, Lanai's solar resource equals 2.116 MWh/m$^2$/yr. Assuming that the PV system has 10% efficiency, the PV system produces approximately 0.2116 MWh/m$^2$. The amount of PV that needs to meet the load is approximately:

$$30{,}245 \text{ MWh} / 0.2116 \text{ MWh/m}^2 = 142{,}935 \text{ m}^2.$$

The PV produces 0.0001 MW/m$^2$. The minimum PV system is:

$$142{,}935 \text{ m}^2 * 0.0001 \text{ MW/ m}^2 = 14.3 \text{ MW}.$$

Adjusting for energy storage at approximately 75% round trip:

$$(75\% * 19 \text{ MW} = 14.3 \text{ MW})$$

The total amount of PV required is approximately 19 MW.

Note that the minimum PV system required to meet the load is approximately four times the peak load rating (5 MW). This is due to the capacity factor of PV, which is approximately 20% on Lanai. The PV system would need to greatly overproduce electricity during the daylight hours in order to storage enough energy to supply the nighttime loads.

During the course of this study the VRB flow battery was no longer available. Therefore, in Scenario 4, a sodium sulfur (NaS) battery was used to complete the analysis. Sodium sulfur batteries are one of the most promising candidates for energy storage applications. They are often referred to as thermal batteries or molten–salt batteries that usually operate at a relatively high temperature (300° to 400° C).

Figure 1-15 shows that on the minimum load day the system needs to store 58 MWh of unused power produced from the PV. Because one sodium sulfur battery is 6 MWh, a 19MW PV plant with 12 NaS batteries (72 MWh) would be needed to operate Lanai on a 100% PV/battery.

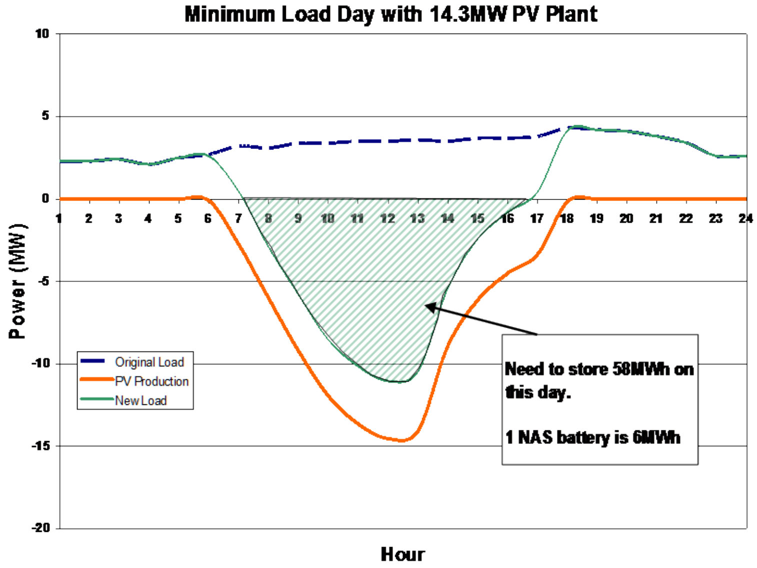


Figure 1-15. Minimum load day with 14.3MW PV

### *Scenario 4: Results*

Using the HOMER model and the actual 2005 solar resource data and primary load data, we can determine how large a PV/battery system is required to meet the entire load. The modeling results indicate that 25 MW of PV and 12 MW/100 MWh of batteries and a 2.2 MW generator would be required to meet the entire load at all times. The generator would be needed to maintain system reliability in the event that there were more than three cloudy days. Figure 1-16 shows the large PV system output in comparison to the load. This scenario would provide 90% of the power from PV and batteries at a LCOE of approximately three times the base case cost of electricity.

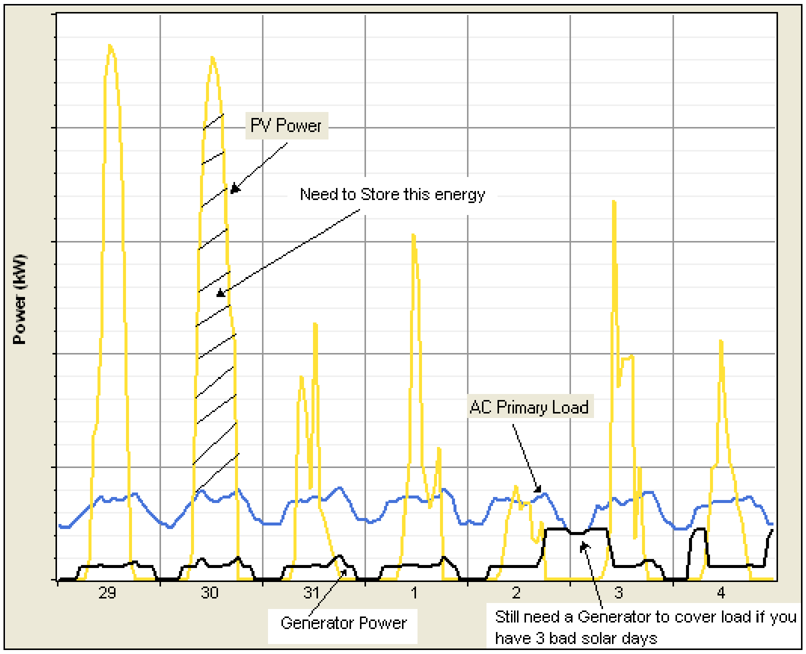


**Figure 1-16. PV/battery/generator hybrid system, Illustration by HOMER Energy, LLC**

Similarly, for a wind hybrid power system, 90 MW of wind turbines, 12MW/200MWh of batteries and 2.2MW diesel generator the load can be met nearly 100% of the time with renewable energy. The LCOE using wind and batteries would be quite high, nearly threefold increase.

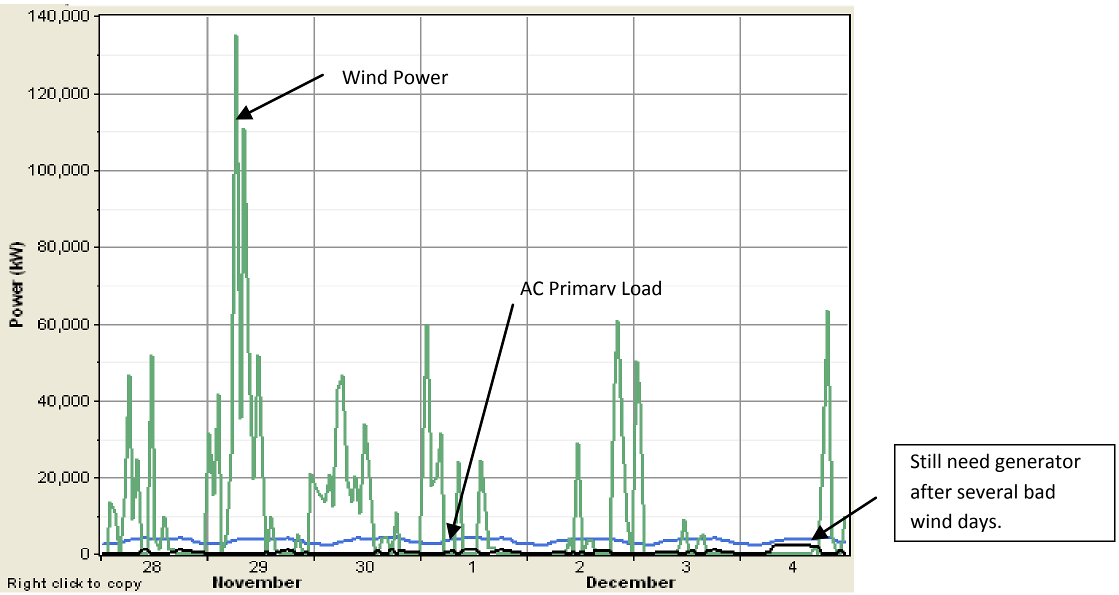


**Figure 1-17. Wind/battery/generator hybrid system, Illustration by HOMER Energy, LLC**

## 1.5 Summary of Findings

The results from the study indicate that the optimal hybrid power system with the lowest LCOE is a wind/generator system which was modeled in Scenario 3. Optimized use of wind turbines to the existing generators can reduce the fuel use by 56% and reduce the LCOE by 28%, when compared to the base case. Lanai should consider installing wind turbines into the grid with different dispatch strategies as variable renewable energy penetration increases. The sensitivity analysis done for Scenario 3 shows how the high cost of PV can drive up the LCOE. In order to supply 100% of the renewable energy with PV only, it needs to be sized four to five times the peak load (MW) with large amounts of storage. At the time of this analysis in 2008, batteries are not cost effective for long-term energy balancing with small renewable fractions or low diesel prices. The energy storage may be necessary for short-term grid stability and controlling ramp rates of the renewable energy. In this situation, the batteries with large kW rating and smaller kWh should be considered. For each scenario, operational analysis is required to determine if the level of increased renewable energy integration could be supported with the Lanai existing electrical infrastructure. Feasibility and system impact studies would need to be done to determine if additional upgrades are required.

This phase of the study showed that trying to provide 100% renewable energy with only solar/ wind/battery hybrid systems is very difficult and cost prohibitive without inclusion of generators for periods where there is little renewable resources. Lanai should consider hybrid systems with generators that use biodiesel or alternative energy options to get to 100% RE fraction. Figure 1-18 indicates a potential path forward for Lanai to achieve their goal of 100% renewables.

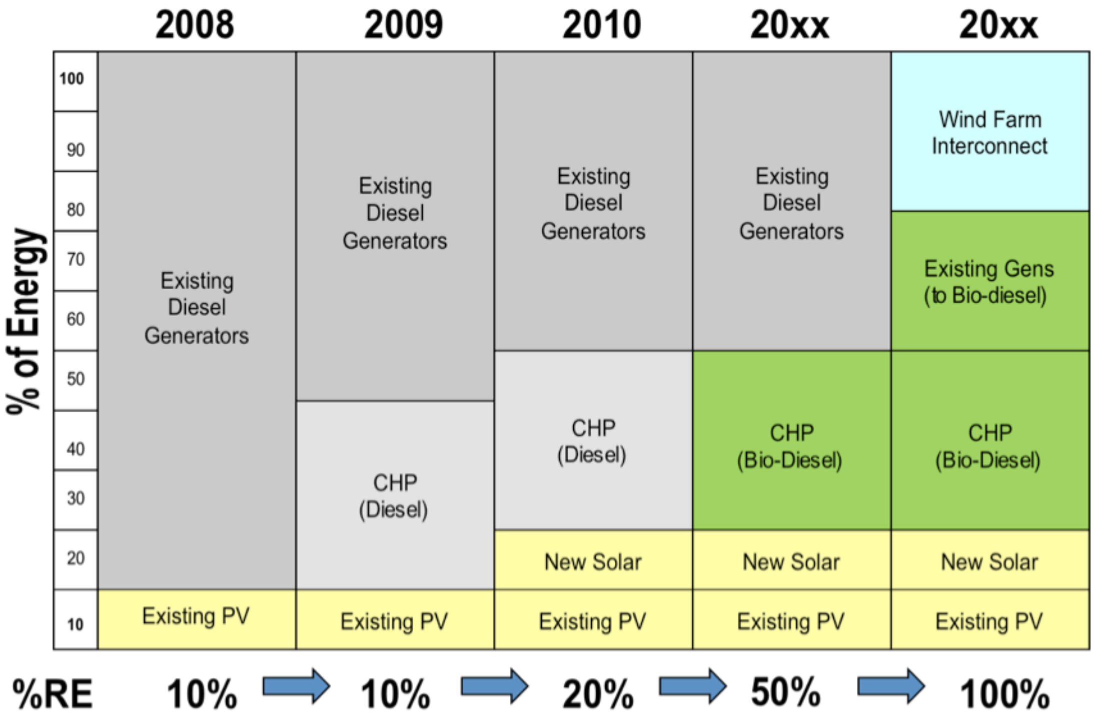


Figure 1-18. Potential Road Map to 100% Renewable Energy

# 2 Phase 2: Cost Comparison between CSP, PV & Wind

## 2.1 Background

Phase 2 of the electrical energy study in Lanai updated the original Base Case scenario with 2008 solar and wind resource data, as well as 2008 load data. NREL's 2008 solar data was used along with the wind data recently collected by Castle & Cooke. Since Phase 1 showed that supplying 100% of the energy requirement to Lanai with renewable energy was cost prohibitive, Phase 2 studied three options to provide 88% of the energy requirements with renewable energy. Concentrated solar power (CSP) that incorporated thermal storage, photovoltaics with battery energy storage and wind with battery energy storage were analyzed. The Solar Advisor Model (SAM) was used to analyze the performance of the concentrated solar power system while HOMER was used to optimize the PV/wind/battery/generator hybrid systems. Phase 2 examines which projects are most cost effective to bring Lanai closer to 100% renewable energy.

## 2.2 Modeling Inputs

The models built with SAM and HOMER used the same solar and wind resource data and hourly load data.

### *2.2.1 Resource Data*

Resource data included both solar and wind resource data.

*Solar Data*

The hourly solar resource data for Site 156952075 was obtained from the NREL's NSRDB/Perez Satellite data. The same location was used in Phase 2 as was used in Phase 1 of this project.

*Wind Data*

Hourly wind data for 2008 was obtained from the same site location used in the Phase 1 study. The average wind power at a height of 50m is 550 W/m$^2$ and average wind speed is 8.4 m/sec.

*Diesel generators*

In addition to the already-installed two 2.2 MW and six 1 MW diesel generator units on Lanai, an 800 kW combined heat & power (CHP) station was installed by HECO at the hotel complex. The reduction in the base load from the CHP was considered in this phase of the study. The diesel fuel cost assumed for Phase 2 was set at $2.60/gal (average for 2007).

### *2.2.2 Load Data*

Primary load data for 2008 was obtained from MECO. The "adjusted" hourly load profile for 2008 was used after subtracting out the hourly load data from the 800 kW CHP and the existing 1.2 MW PV system at La Ola. Note that the power output data received for the CHP unit had an average load of 825 kW power. The maximum and minimum power were 884 kW and 645 kW, respectively. For general purposes, we refer to the CHP power as ~800 kW. A comparison of the minimum and max load days are shown in Figure 2-1 through Figure 2-4 before and after the CHP and 1.2 MW PV systems were installed. The new "adjusted" load data was used throughout Phase 2 of this study, as it represents the actual load after the planned installation of these two systems (CHP and PV).

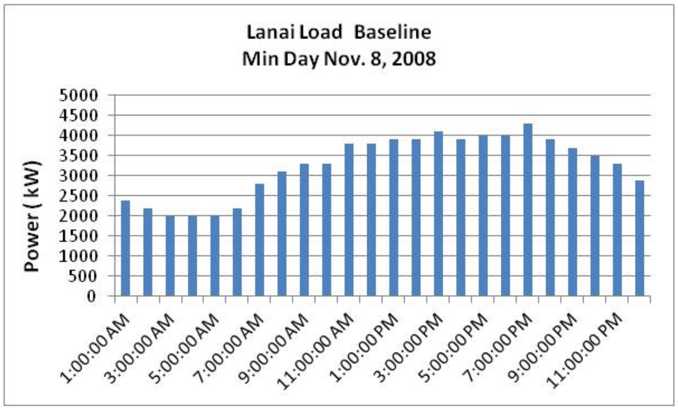


**Figure 2-1. Lanai min. load base case**

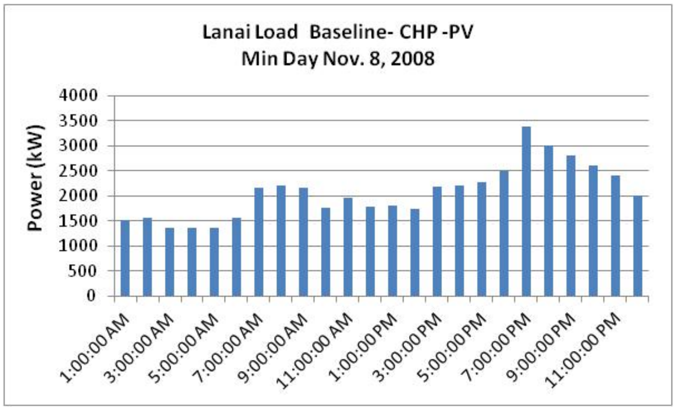


**Figure 2-2. Lanai min. adjusted load**

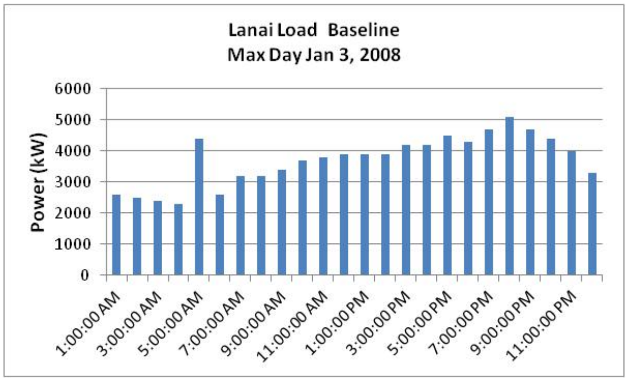


**Figure 2-3. Lanai max. load base case**

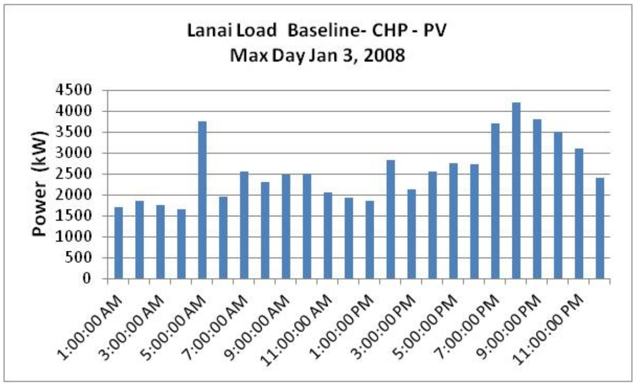


**Figure 2-4. Lanai max. adjusted load**

In addition to the 800 kW base load reduction from the CHP, Figures 2-1 through 2-4 show demand reduction from the PV system for minimum and maximum loads during the hours 10 AM and 3:00 PM. Figure 2-5 shows the 2008 load duration curves for Lanai. The adjusted load duration curve for 2008 indicates that the peak power (kW) for Lanai is reduced by 20% as a result of the planned CHP project and existing PV project. The figure also indicated that there is a minimum generator output. This means that the existing generation must operate at least at that level to maintain system stability.

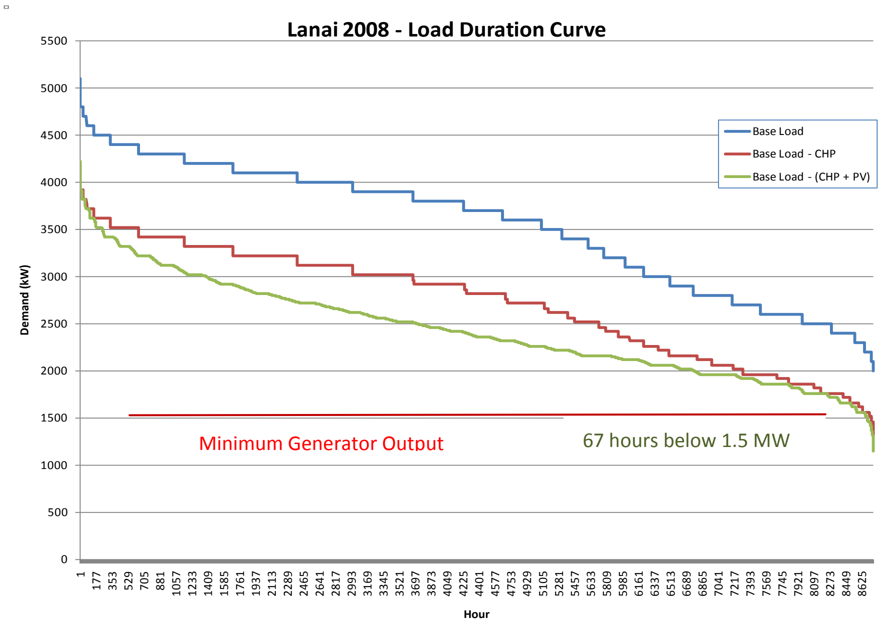


**Figure 2-5. Load duration curves for 2008**

## 2.3 Phase 2 Analysis

The Adjusted Base Case model in the HOMER analysis is shown in Figure 2-6. The adjusted base case load includes the 800 kW CHP and 1.2 MW PV systems. The adjusted system output is 62 MWh/day and 22,734 MWh/year. The diesel fuel use equals 1,616,858 gal/year. The LCOE for the adjusted base case is referred to as the “adjusted” base case (when diesel cost is $2.60/gal).

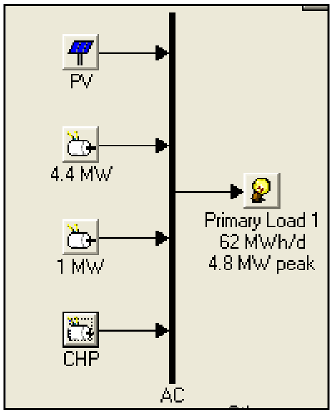


**Figure 2-6. “Adjusted” base case, Illustration by HOMER Energy, LLC**

### *Scenario 1: Adjusted Base Case and CSP*

The first Scenario is to model the Adjusted Base Case with CSP using SAM. The version of SAM used for this analysis was 2.5.0.2.

The method of modeling with SAM assumed a CSP system similar to the 1MW Saguaro Plant in Arizona. This plant uses Carloria HTF and an organic Rankine power cycle. The power block is available within the SAM library.

The solar multiple and storage hours in the parametric analysis were adjusted, as was the size of storage. The size of storage was set to cover the evening peak and the morning peak of the following day. This is approximately 9 to 12 hours total.

The average daily energy demand on an annual basis is 2.5 MWh with a standard deviation of 0.5 MW. The current version of SAM that was used does not allow for the modeler to stop the storage dispatch in the evening so the analysis assumes the excess evening power will be held and dispatched the next morning as indicated by the red arrow in Figure 2-7.

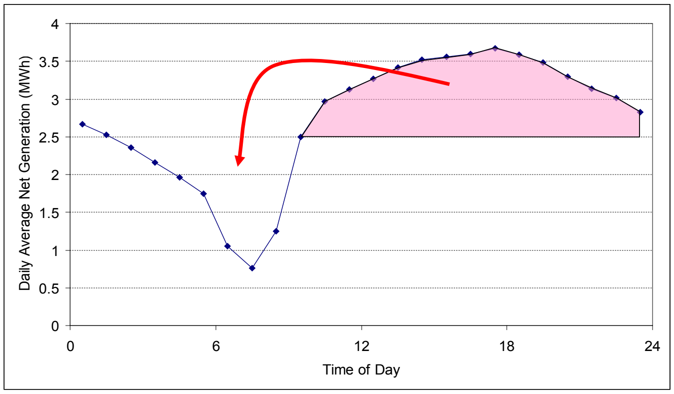


**Figure 2-7. Average daily CSP electric generation**

### *Results*

Even though the CSP plant is sized to provide the necessary power for the entire year, variations in weather and seasonal insolation will prevent meeting demand for every day. Figure 2-7 Figure 2-7 shows the average values for the entire year for Case 1. The lesser solar insolation from December through March means the uncovered load met by the CSP plant for only 44% of the days. In contrast, for April through November demand is met or exceeded for 75% of all days. A larger (and more costly) CSP plant could increase these percentages. For comparison, a CSP plant with expanded storage capacity of 30 hours is also modeled. This plant was assumed to meet demand in any day when the prior day had excess generation that exceeded the demand gap on the next day.

The results are summarized in the following Table 2-1.

**Table 2-1. Results from CSP Analysis**

| Parameter | Case 1<br>4 MW Organic Rankine | Case 2<br>4 MW Steam Rankine | Case 3<br>4 MW Steam Rankine |
|---|---|---|---|
| Solar field size ($m^2$) | 153,000 | 119,000 | 151,000 |
| Turbine efficiency | 20.7% | 30.6% | 30.6% |
| Collector cost ($\$/m^2$) | 400 | 400 | 400 |
| Annual power gen (MWh) | 22,500 | 22,200 | 23,100 |
| LCOE (% of adjusted base case) | 77% increase | 41% increase | 86% increase |
| Est. installed cost | $116M | $89M | $125M |
| Days meeting load | 64% | 64% | 88% |
| Thermal storage (hrs) | 15 | 15 | 30 |
| Solar multiple | 5 | 5.5 | 7 |
| Power block model | APS Sagauro<br>(1 MW) | SEGS III<br>(30 MW) | SEGS III<br>(30 MW) |

The results shown above indicate that it is possible to design a CSP system to supply most of the remaining load at Lanai, assuming that the system will have a large solar multiplier of 7, along with a relatively small turbine output of around 4MW. This assumes a steam Rankine cycle with and 30.6% efficiency. The CSP system would also need a large thermal storage system to cover the evening and morning peaks for the following day (30 hours). A CSP plant of this type would be able to meet the load 88% of the time. The economic feasibility of the CSP plant is dependent on the plant's ability to use excess electricity and heat generated by the plant during times of good solar insolation.

### *Scenario 2: Adjusted Base Case, PV and NaS Batteries*

The next step in the analysis used HOMER modeling tool to add PV and NaS batteries to the system. In order to compare the PV/battery systems with the CSP plant both were analyzed to meet the adjusted base load 88% of the time. The PV system sizes that were considered in HOMER varied from 1 to 30 MW in 1 MW increments. The cost of the PV system was assumed to be $7/W.

The NaS battery modules were modeled to produce 1.2 MW for 7 hours (8.44 MWh) at a cost of $3M/battery module. The diesel price assumed for this analysis was $2.60/gal.

### *Results*

The study varied the amount of PV from 1 to 30 MW and the amount of battery modules from 0 to 15. The various configurations were analyzed using HOMER and then the systems were plotted to determine the most economical combination of PV and batteries to meet the adjusted load 88% of the time.

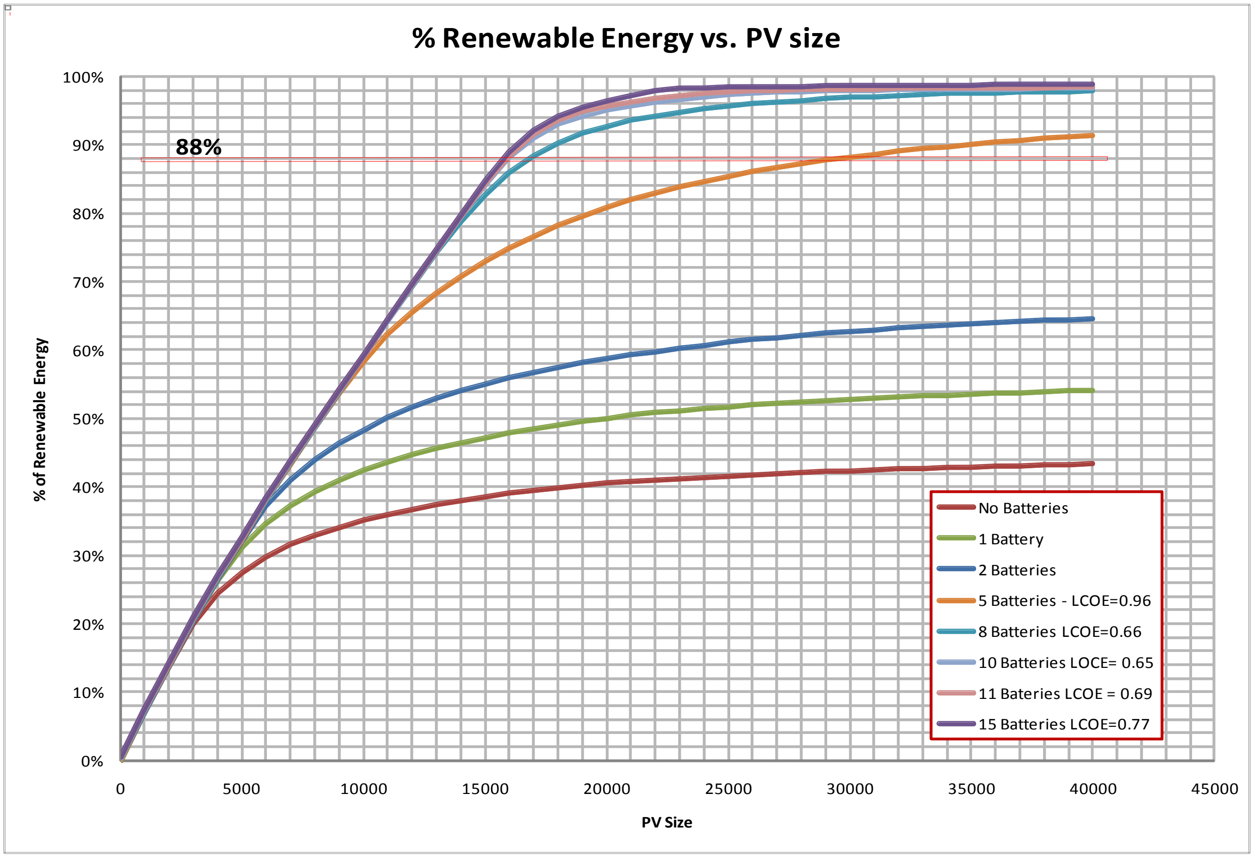


**Figure 2-8. Percent renewable energy vs. PV sizes**

The graph indicates that the optimal system for the lowest LCOE is 84 MWh of NaS batteries with 16 MW of PV, resulting in the lowest LCOE increase of 195% over the adjusted base case.

### *Scenario 3: Adjusted Base Case, Wind Turbines and NaS Batteries*

The final comparison in this analysis was to analyze the effects of adding wind turbines and NaS batteries to the adjusted base load to provide 88% of the electrical energy from renewables. The size of the wind turbine considered was 1.5 MW and varied in quantities from 0 to 10. The NaS batteries modeled were the same as in Scenario 2 (1.2MW for 7 hours at $3M/battery). Again, the diesel price was set to equal $2.60/gal.

### *Results*

The number of 1.5 MW wind turbines was varied from 1 to 10 and the number of batteries from 0 to 6. The systems were plotted to determine the most economical combination of wind turbines and batteries to meet the adjusted load 88% of the time.

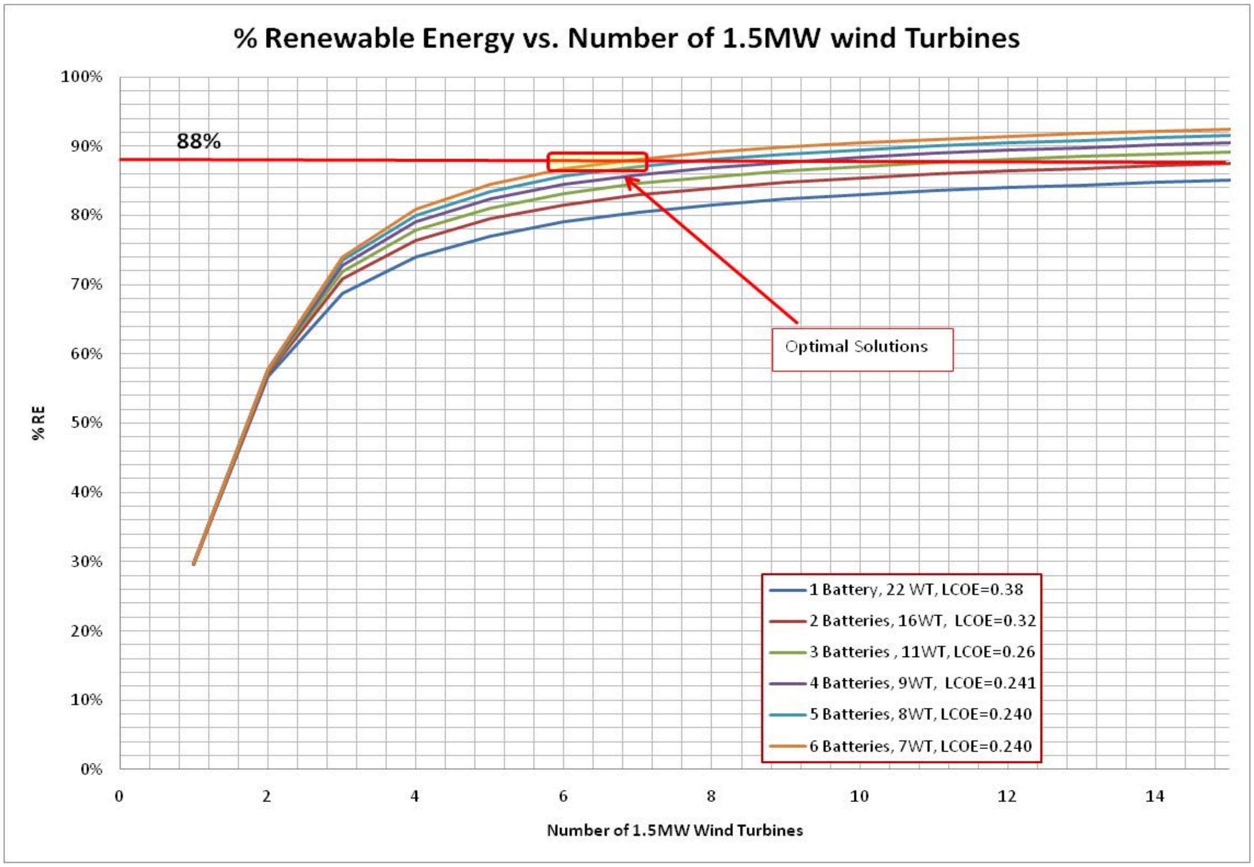


**Figure 2-9. % Renewable energy vs. number of 1.5 MW wind turbines**

From the graph the optimal system with the lowest LCOE included 10.5 MW of wind turbines and 50.4 MWh of storage. The optimal wind/battery system has a LCOE equal to a 9% increase over the adjusted base case.

## 2.4 Summary of Findings

Table 2-2 summarizes the results from the three scenarios: CSP, PV/batteries and Wind/batteries. The optimal system to reach 88% renewable energy based on lowest cost of energy using renewable technology is Scenario 3 with a LCOE equal to 9% increase over the adjusted base case using 10.5MW wind turbine power and 50.4 MWh (6 NaS batteries) storage.

**Table 2-2. Summary of Results**

| | PV (MW) | Wind (MW) | Main Gen (MW) | Backup Gen (MW) | NaS Modules (1.2 MW) | COE (% Adj. BC) | Additional RE Frac. (%) |
|---|---|---|---|---|---|---|---|
| Adjusted Base Case | - | - | 4.4 | 1 | - | Adj. BC | 0 |
| Scenario 1 | 4 (CSP) | - | 4.4 | 1 | - | 86 % increase | 88 |
| Scenario 2 | 16 | - | 4.4 | 1 | 10 | 195% increase | 88 |
| Scenario 3 | - | 10.5 | 4.4 | 1 | 6 | 9% increase | 88 |

# 3 Phase 3: Additional PV Potential & Location

## 3.1 Potential PV Amount on Lanai

A solar resource assessment of the island was performed using existing and new data with geographic information system (GIS) techniques to determine additional potential for PV on the island. The detailed analysis below determines favorable locations on Lanai for installing PV and calculates the potential amount of power each system will produce.

### *Interconnection of Distributed Generation— Rule 14h*

At the time of this study, Maui Electric Company (MECO), the electric power company that operates the grid on Lanai, required an interconnection study for DG systems that are greater than 10% of the load on the distribution feeder. Since the completion of this study, the limit that triggers an interconnection requirements study is 15%. Lanai is a small power system with three circuits. One of the circuits already contains the 1.2MW La Ola PV plant, and is thus above the 15% threshold. The other two circuits are currently under the 15% threshold.

## 3.2 Acceptable amount of PV

When integrating non-dispatchable generation sources such as PV at high penetrations, the minimum daytime load must be considered. This is because as the penetration of solar increases, the other generation will need to be reduced, but must be available to provide power in case clouds appear. The average minimum load for the island with the CHP and large PV installed is 1.7 MW (See Figure 3-1 for daily load profile in January). The minimum diesel generator loading at Lanai is 1 MW, therefore, the largest amount of additional PV that the island can support without storage or discarding energy is approximately 500 to 700 kW.

Ultimately, the amount of PV that a power system can safely accommodate is determined by the capabilities of the dispatchable generation and storage. If the controllers cannot support the inherent variability of PV generation, the amount of PV may need to be limited to maintain stability. Exporting can be prevented by sizing the PV system so that it never produces more energy than the site can use, or by adding hardware that disconnects the PV system or ramps down production if the load drops below a preset threshold (Coddington et al. 2009).

Minimum load with CHP and PV is 1.7 MW

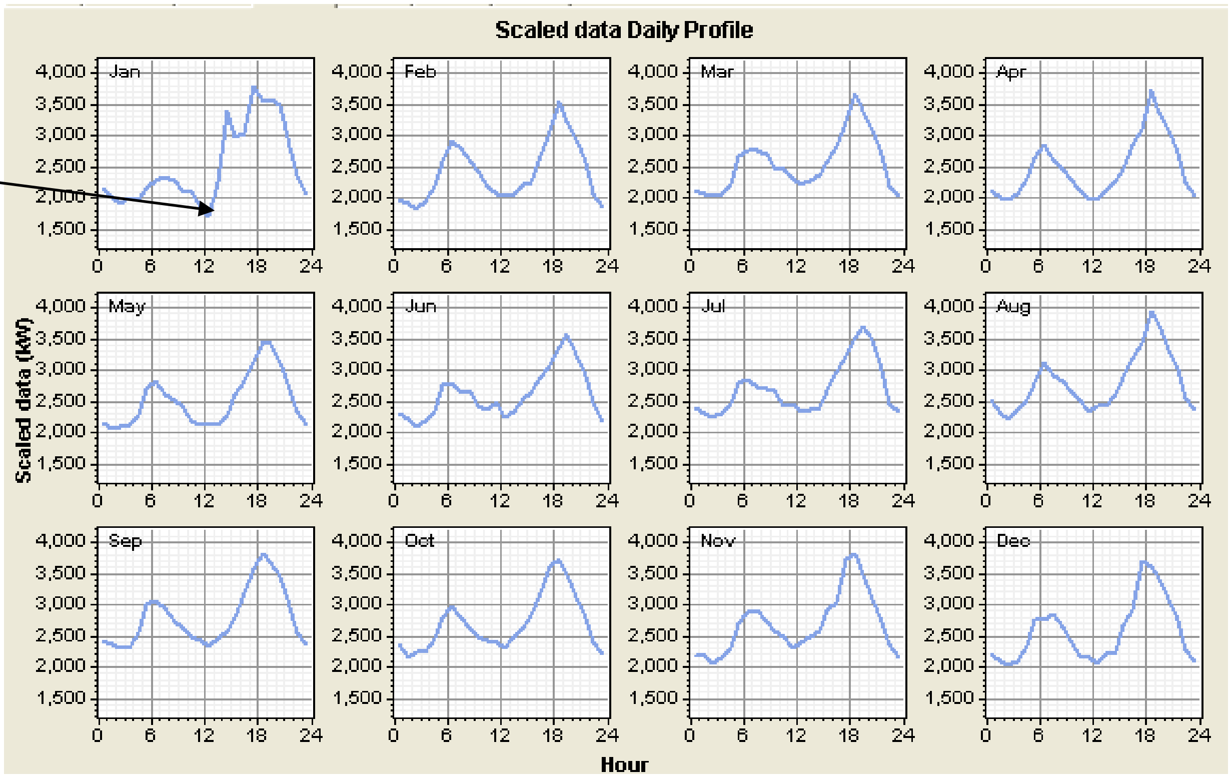


Figure 3-1. Scaled daily load profile, Illustration by HOMER Energy, LLC

### *Understanding PV variability due to Cloud Cover*

A rotating shadow radiometer was installed at the La Ola 1.2 MW PV power plant to collect high resolution solar data at the site. Figure 3-2 shows the rapid fluctuation of solar irradiance at the La Ola site. If this variability occurs at all the PV plants on the island, then the diesel generators may have a difficult time managing the ramp rates. The project team studied the variability due to clouds by examining the correlation between the La Ola site solar resource data and irradiance data from a site at the Lanai High & Elementary School located in Lanai City. Data from this system is collected every 15 minutes. A comparison of the solar irradiance at these two sites is shown in Figure 3-3 and Figure 3-4. The data illustrates the good correlation in solar irradiance at the two sites on a clear day, and the correlation is very poor on a cloudy day.

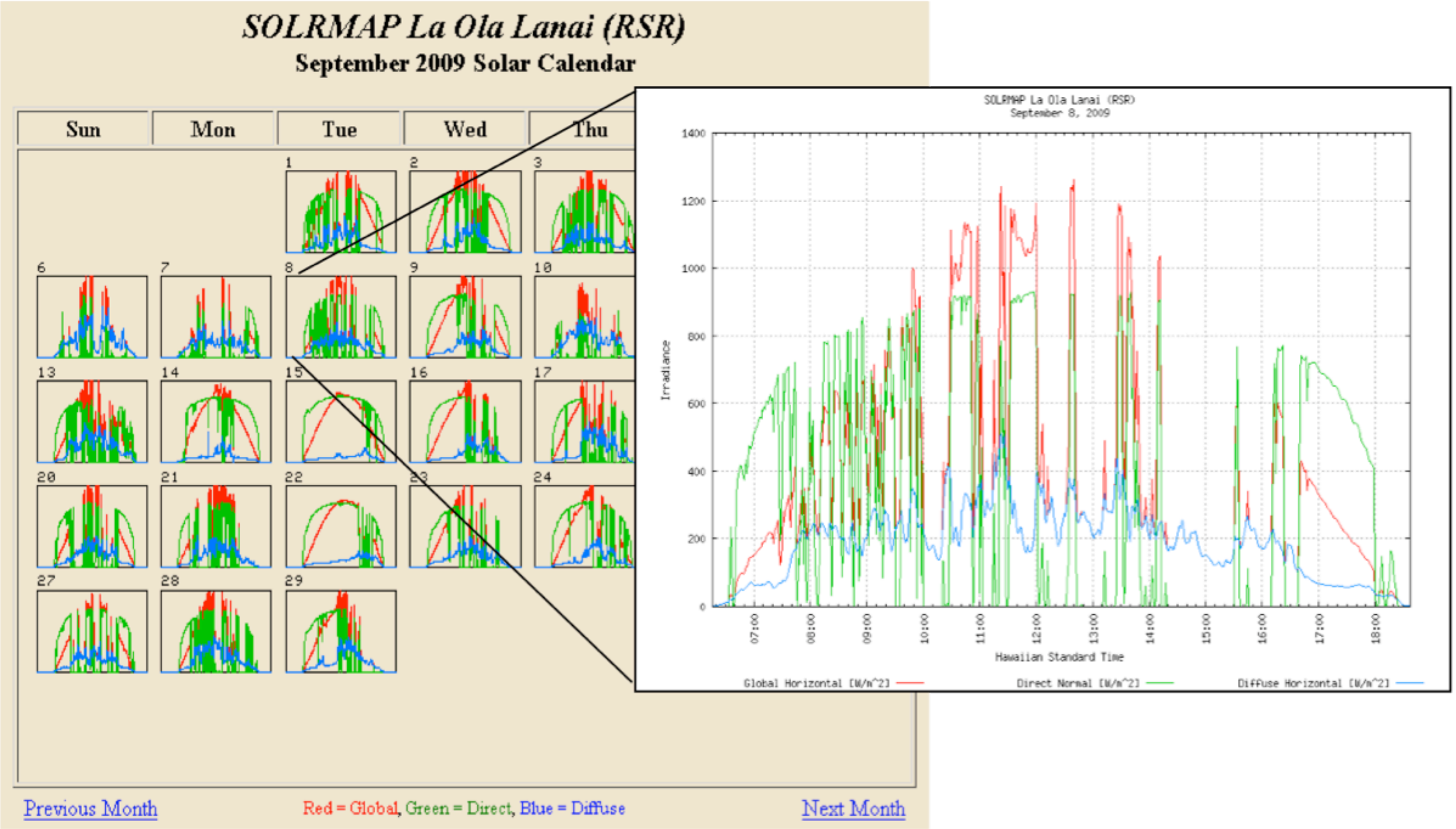


**Figure 3-2. Solar map of La Ola, Lanai in September 2009**

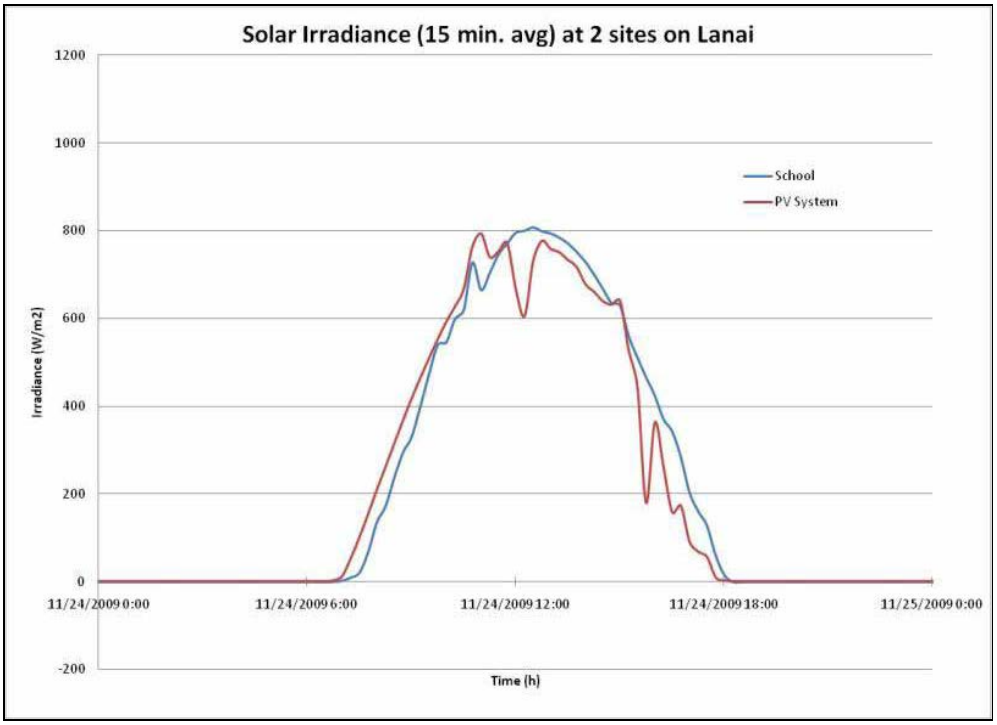


Figure 3-3. Solar irradiance at two sites on a clear day

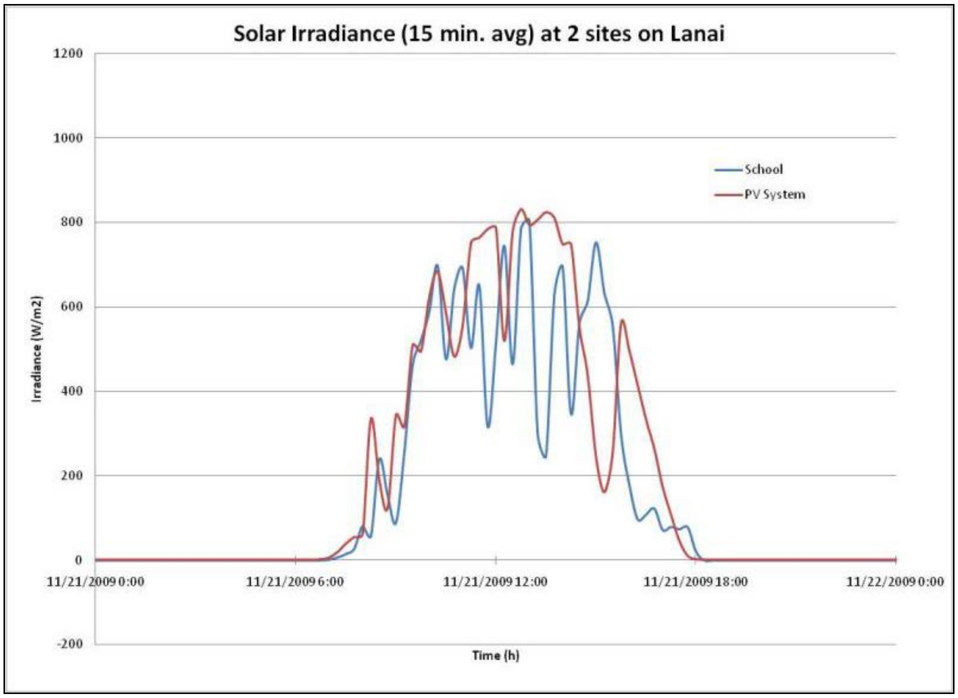


Figure 3-4. Solar irradiance at two sites on a cloudy day

## 3.3 Examination of Future Potential PV System Locations

Four locations were selected to analyze the potential for PV system installation. These sites were selected with input from interested PV installers. The sites considered PV on rooftops, ground mount, and parking lot structures. The first location is at Castle & Cooke facility headquarters and includes the administration, maintenance, and bakery building's rooftops. The second location is at Manele's Wastewater Treatment Plant, and the third location is at The Challenge at Manele Bay golf course parking lot. To support the PV system, covered carport structures will have to be constructed on both rows of the parking lot. The forth location is at Hulopoe' Park parking lot.

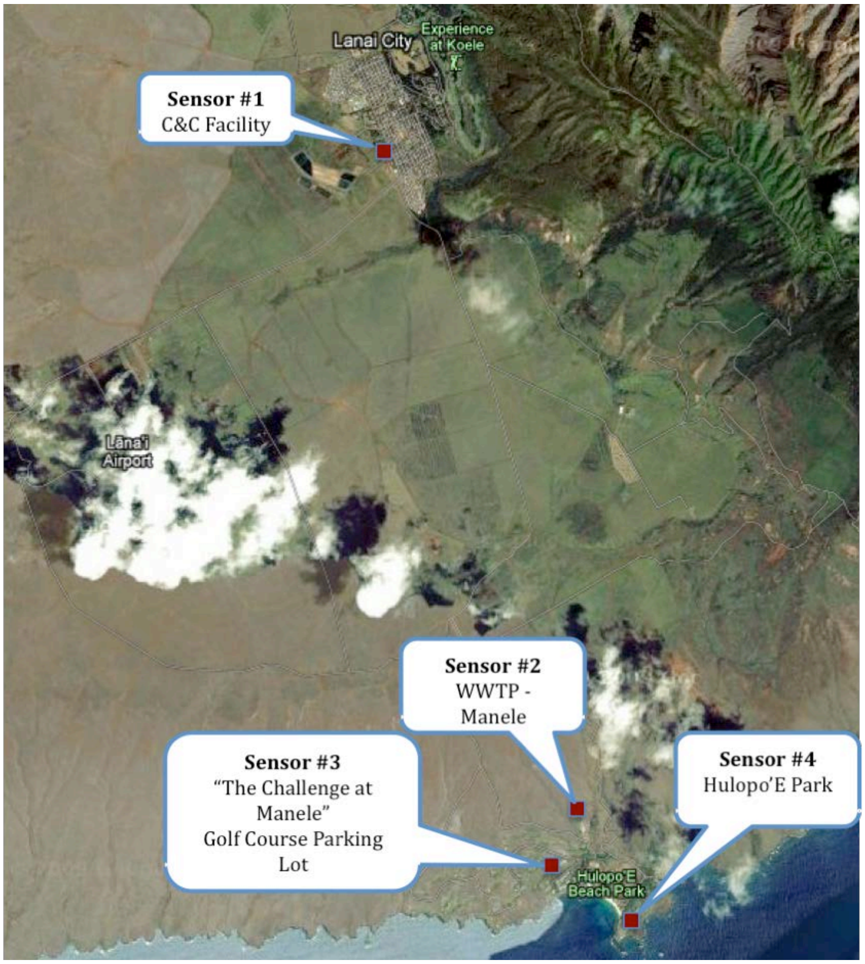


**Figure 3-5. Potential site locations for placement of irradiance sensors**

Each location was evaluated using NREL's In My Backyard (IMBY) tool and the Solmetric SunEye hand held device.

### *3.3.1 C&C Administrative Buildings Location 1*

The first location is located at the Castle & Cooke central service facility. Three buildings have the potential for PV rooftop installation. Figure 3-6 shows an aerial view of Castle & Cooke central service bakery, maintenance, and administration buildings. The shaded area represents the PV array size that IMBY estimates for each rooftop PV system. The buildings are oriented in a south-east direction. The PV power output at each rooftop location is outlined in Table 3-1.

**Figure 3-6. IMBY aerial view of the Castle & Cooke central services buildings**

*IMBY results:*

The total amount of rooftop AC PV power at the three Castle & Cooke central services buildings is approximately 140kW.

**Table 3-1. Proposed PV C&C Service Buildings**

| PV Location | NREL Estimate using IMBY (kW AC) |
|---|---|
| Bakery | 52 |
| Maintenance | 35 |
| Administration | 52 |

*SunEye results:*
The average annual solar production for all three Castle & Cooke facility buildings is 96%. All three buildings have a very clear sun path through each month of the year.

### *3.3.2 Wastewater Treatment Plant – Manele – Location 2*

The second location is near the Manele wastewater treatment plant (WWTP) embankment. The embankment footprint is roughly 60 x 700 ft with an approximate slope of 45%. Figure 3-10 shows an aerial view of the WWTP embankment area. Again, the shaded area represents the PV array size that IMBY will estimate for the PV system.

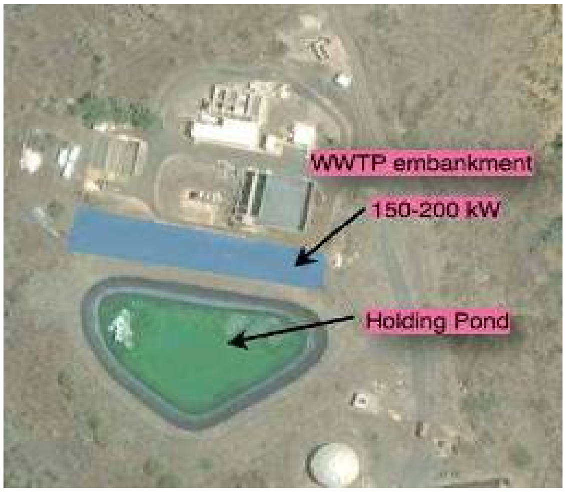


**Figure 3-7. IMBY-WWTP**

*IMBY results:*
The amount of AC PV output power located along the WWTP embankment was estimated by IMBY to be 150 to 200 kW.

*SunEye results:*
The average annual solar production for both sites is around 100%. Both locations have a very clear sun path through each month of the year.

### *3.3.3 "The Challenge at Manele" Golf Course Parking Lot – Location 3*

The third location was the "The Challenge at Manele" golf course parking lot (Figure 3-12). Figure 3-11 shows an aerial view of the parking lot area with the blue shaded area representing the PV array size that IMBY will estimate for the PV system. Figure 3-12 shows a picture of the parking lot.

**Figure 3-8. IMBY– "The Challenge at Manele" parking lot**

**Figure 3-9. "The Challenge at Manele" parking lot, Photo by J. Keller, NREL**

*IMBY results:*

The amount of AC PV output power each parking lot strip would yield approximately 75 kW (at latitude tilt, 21 degrees). The total parking lot would provide approximately 150 kW, according to estimates provided by IMBY.

*SunEye results:*

The average annual solar production for this site is 99%. Both locations have a very clear sun path through each month of the year.

### *3.3.4 Hulopoe' Parking Lot – Location 4*

Another possible site for PV is at the Hulopoe' Park parking lot (Figure 3-13 and Figure 3-14). Figure 3-13 shows an aerial view of the parking lot area. The blue shaded area represents the PV array area for which IMBY estimated the energy output. Figure 3-14 shows a picture of the Huolpoe' Park parking area.

Figure 3-10. IMBY – Hulopoe' Park parking lot

Figure 3-11. Hulopoe' Park parking lot, Photo by J. Keller, NREL

*IMBY results:*
The amount of AC PV output power each parking lot strip would yield approximately 20 kW (at latitude tilt, 21 degrees). The total parking lot would provide approximately of 40 kW, according to estimates provided by IMBY.

*SunEye results:*
The average annual solar production for this site is 97%. This location has a very clear sun path through each month of the year.

### 3.3.5 Total amount of PV to be added to Lanai system

The estimated capacity from the PV for each site is listed in Table 3-2.

**Table 3-2. Possible PV System Locations on Lanai**

| Location | NREL Estimate using IMBY (kW AC) |
|---|---|
| Castle & Cooke central services buildings | Bakery Building = 52 kW, Maintenance Building = 35 kW, Admin Building = 52 kW. Totaling 139 kW |
| WWTP – Manele | 150 to 200 kW |
| The Challenge parking lot | 75*2 = 150 kW |
| Hulopoe' park | 20*3 = 60 kW |
| Total amount of PV | 500 to 549 kW |

## 3.4 Summary of Findings

Phase 3 of this study determined that there is a potential for an additional 500 to 700 kW of PV to be integrated into the power system on Lanai without the requirement for storage. This was due to the fact that there was approximately 700kW of power that could be reduced from the minimum daytime load before the minimal operating parameters of the exiting diesel generator were reached. This phase also examined possible locations for potential PV systems. These systems will be used in a follow-on report that examines electrical impacts. In order to reduce cloud variability, geographically dispersed sites would be more optimal than a centrally located PV site for electrical interconnection.

## 4 Pathway Forward and Future work

A roadmap to move towards 100% renewable is outlined in the chart below. This is assuming that any growth in electrical load on Lanai will be offset by energy efficiency measures.

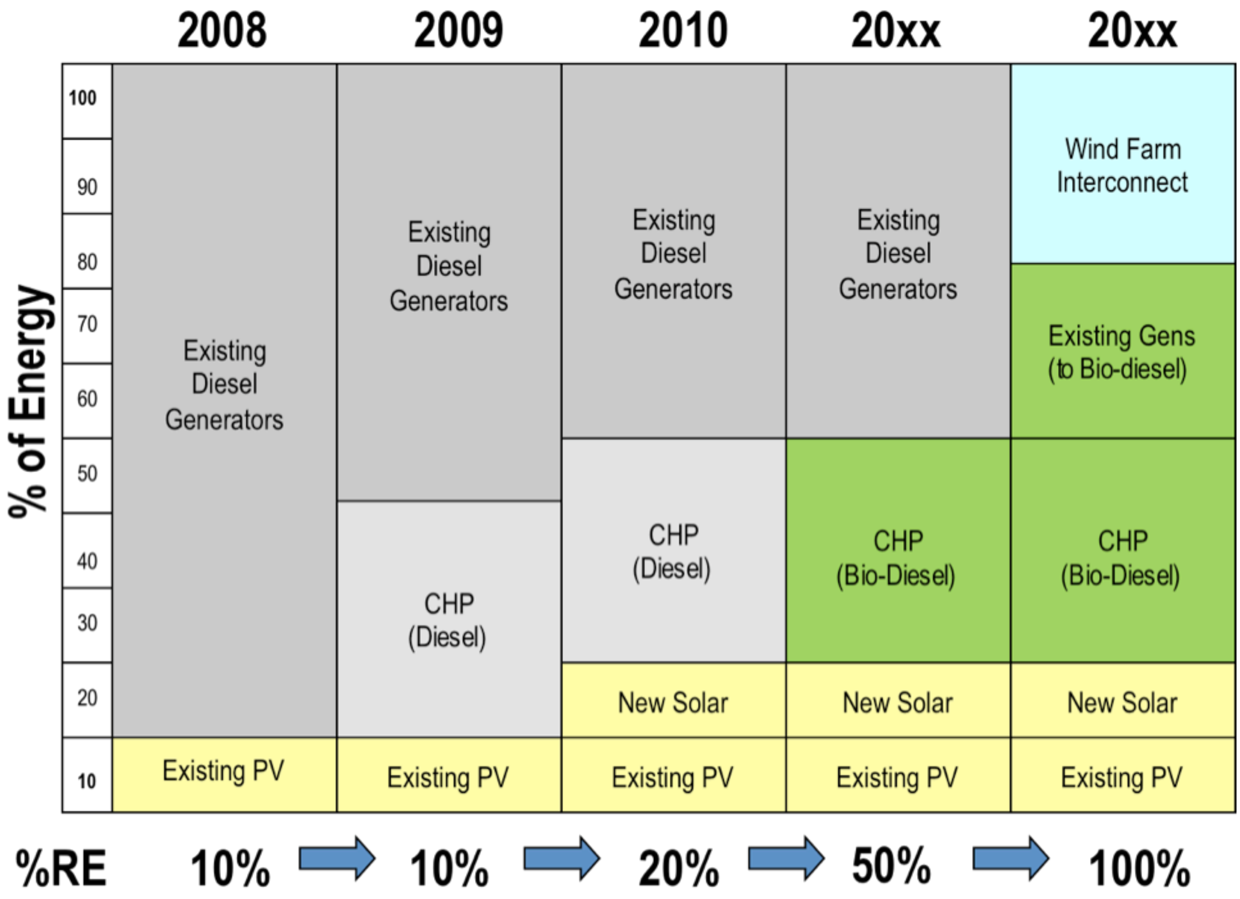


**Figure 4-1. Possible roadmap**

Though some additional PV may be added at this time, eventually more storage to time shift the power generation will be required. The path forward also suggests that wind should be considered in the renewable hybrid mix. Storage and wind are discussed in the following section for future studies.

## 4.1 Future Studies

Future studies on Lanai should include:

1. Storage options with batteries, flywheel and/or pumped hydropower to help smooth the ramp rate of the high penetration of PV and/or defer the loads
2. Integration of wind power options
3. Impact of high penetrations of photovoltaics on a number of circuits in Lanai's electric power systems through an island wide integration study.

## 4.2 Storage Options

As more renewable energy is integrated into the electric power system on Lanai, energy storage will play a more important role. Additional solar or wind generation would require larger amounts of energy storage to shift generation to morning and evening, as shown in Figure 4-2.

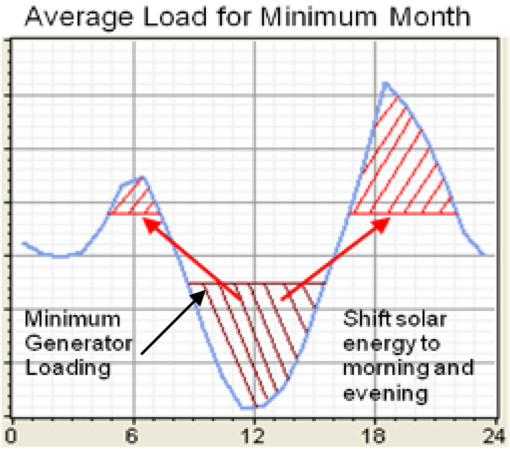


**Figure 4-2. Storage required**

### *4.2.1 Pumped Hydropower*

Batteries are still an expensive choice for large amounts of energy storage. The terrain on Lanai lends itself to the use of pumped hydro because of the natural mountains. If larger PV or wind systems are planned, then Lanai may want to consider a small (10 to 20MWh) pumped hydro system.

### *4.2.2 Flywheel*

A flywheel is a rotating disk that transforms electrical energy into kinetic energy and stores the rotational energy, which can later be converted back to electricity. Contained inside the housing of a flywheel is the power-coupling motor generator, spinning flywheel, shaft and advanced magnetic bearing. When the flywheel transforms the electrical energy into kinetic energy, the electrical motor accelerates a shaft until the working speed is reached. At the working speed, the electrical motor can be disconnected and the shaft will continue to spin storing the rotational energy. To capture the stored kinetic energy, the shaft moves like a conductor in the advanced magnet. Electronic controls are used to extract the power at the right frequency. To address the ramp rate issues with integrating renewable technologies a flywheel system should be examined. This would help smooth rapid power fluctuations and maintain grid frequency stability. The life expected of the flywheel is around 15 to 20 years, which is much longer than the 5 to 6 years for most batteries.

## 4.3 Wind Power Options

There are two options for adding wind power to the renewable energy mix. As is shown in Figure 4-3, Option A would connect the large wind farm on the northwest part of Lanai (200 to 400 MW total) to the power plant at Miki Basin. Option B would add small wind turbines (2 to 5 MW total) near the harbor and tie into Miki Basin. Option A will require more infrastructure because wind locations are further from the loads. It may also require an AC-DC-AC converter at the interconnection to deal with system frequency excursions at the large wind farm. Wind power is a good complement for solar since it is usually available at night on Lanai and solar power would be generated during the day. This would require the use of additional "dump" loads to dissipate high wind power conditions. Again, the pumps at the water wells could be considered in this scenario.

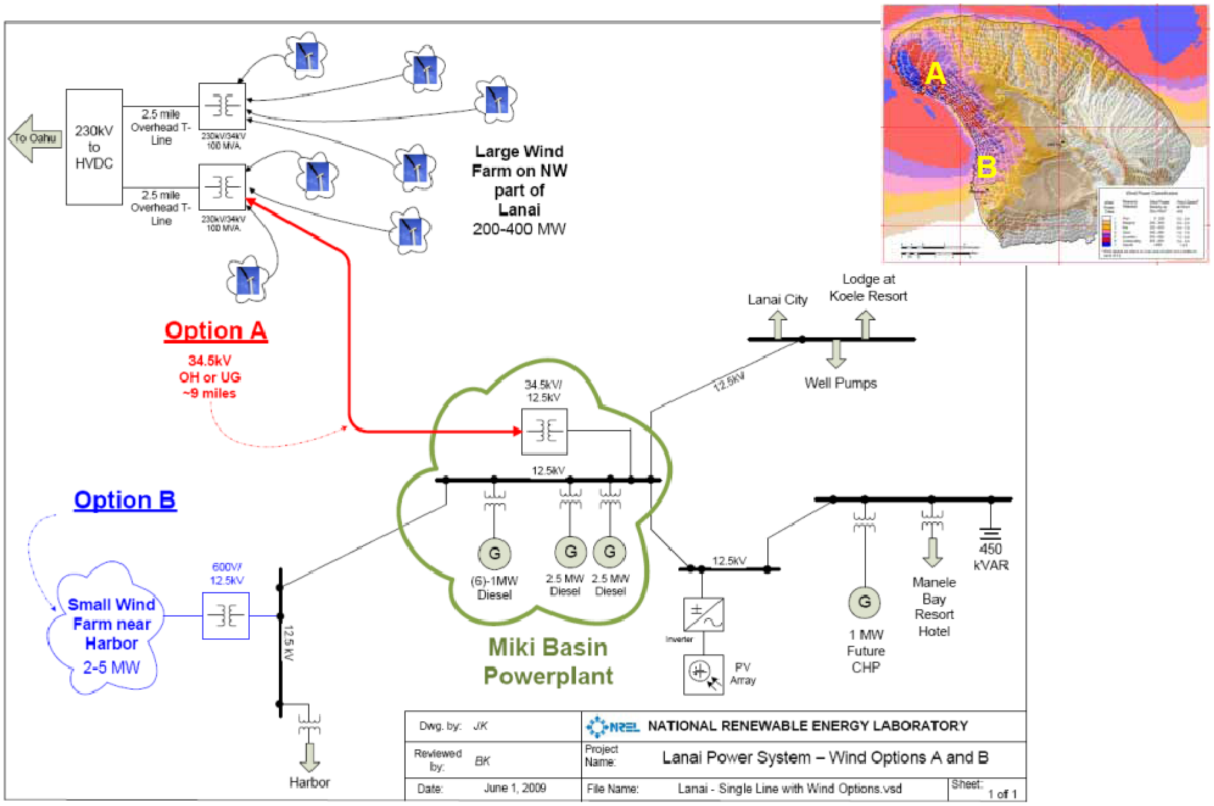


Figure 4-3. Two options for wind power

The distributed wind in Lanai near the existing load centers is still viable and economically attractive; however, there is a large uncertainty in the permitting process.

### 4.4 Island-wide Integration Study

A key to understanding the impacts of variable sources is the ability to accurately model the performance of PV systems. Analysis of the electrical distribution system must consider limits of penetration due to a number of factors (Keller and Kroposki, 2010). NREL will work to examine the impact of high penetrations of photovoltaics on a number of circuits in Lanai's electric power systems through an island-wide integration study. To accurately monitor the steady-state and transient response of these PV systems, nameplate data collection of electrical equipment at key points in distribution system— such as generation sites, energy storage, loads, distribution circuits, and transformers— will need to be identified to enable the development of high-fidelity models of an electric power system with a high penetration of renewable energy. Additional data acquisition may need to be added to capture highly sampled electrical and environmental data and will be helpful to validate the models that are developed. This research will use the PV inverter models that are currently being developed.

Based on renewable energy scenarios that were modeled in Phase 1 and Phase 2 of this study, NREL helped to refine the Roadmap for reaching 100% renewable energy on Lanai. This included overlaying the existing electrical grid with wind and solar resource data and developing an optimized generation mix to minimize net present cost of the generation system. Phase 3 of this study helped to determine the amount and location of new PV that can be added into the power system without additional energy storage. Continued analysis will examine the impact of larger penetrations of renewables into the Lanai grid by evaluating upgrades to the electrical grid needed to accommodate new RE scenarios through an island-wide integration study.

# 5 Conclusion

To support the Hawaii Clean Energy Initiative DOE provided MECO and Castle & Cooke technical assistance through NREL and Sandia to conduct a three-phase study that analyzed the potential pathways for Lanai to reach 100% renewable electric energy. This study looked at the technical and economical feasibility of adding a high penetration of renewables to the island. This final report compiled the work done in all three phases and is intended not only to document NREL's work in Lanai, but also assist other island utilities who want to increase their renewable portfolios.

Phase 1 evaluated the renewable energy potential that could meet the existing load on Lanai. Using the optimization tool, HOMER, NREL conducted the preliminary hybrid power system assessment for the island. The renewable technologies that were modeled included PV, wind turbines and batteries. The optimal solution recommended adding 1.5 MW wind turbine to the existing generators to reduce the fuel usage by 37% and reduce the LCOE by 21%. New system controls may be necessary to manage ramp rates of the wind turbines.

Phase 2 conducted a cost comparison of photovoltaic (PV), concentrated solar power (CSP) and wind turbines with storage to meet Lanai's reduced load due to new generation capacity. The adjusted load included a new CHP system and a 1.2 MW PV array at La Ola. The renewable energy hybrid system with the lowest LCOE used 10.5 MW of wind power, 4.4 MW generators with 7.2 MW of batteries. The LCOE would increase approximately 9% and would provide a renewable energy fraction of 88%.

Phase 3 used the NREL tool IMBY to calculate PV potential and located optimized sites for rooftop, carport and ground mount PV systems. Based on this analysis, a potential 500 to 700 kW of PV could possibly be added to the system without exceeding the minimum load and requiring storage. However, further analysis of overall system reliability and operations—including analysis of the impacts to the electrical distribution system that considers limits of penetration due to a number of factors—is required. NREL will work to examine the impact of high penetrations of photovoltaics on all three of the circuits of which the Lanai electric power systems is comprised through an island-wide integration study. The island-wide integration study will examine the impact of increasing penetrations of renewables into the Lanai grid by evaluating upgrades to the electrical grid and beneficial performance characteristics of the renewable resources needed to accommodate new RE scenarios.

# 6 References

Coddington, M., Kroposki, B., Basso, T., Lynn, K., Sammon, D., Vaziri, M., Yohn, T. (2009). *Photovoltaic Systems Interconnected onto Secondary Network Distribution Systems- Success Stories* (Report No. NREL/TP-550-45061). Golden: National Renewable Energy Laboratory.

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In My Backyard (IMBY), http://www.nrel.gov/eis/imby/

Keller, J., Kroposki, B. (2010), *Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources* (Report No. NREL/TP-550-46698). Golden: National Renewable Energy Laboratory.

NREL Solar Advisor Model (SAM), https://www.nrel.gov/analysis/sam/

Solmetric SunEye Shade Analysis Tool, http://www.solmetric.com/buy210.html

# Appendix A: Modeling Tools

## *Overview of HOMER Modeling Tool*

Hybrid Optimization Model for Electric Renewables (HOMER) is a software modeling tool used to assist in the design of micro-power system configurations with distributed generation (DG) applications. HOMER can be used to evaluate design options for both off-grid and grid-connected power systems. HOMER was designed by NREL in 1993 for a Village Power program and has grown to have over 25,000 users in 191 countries.

HOMER models both conventional and renewable energy technologies, including:

**Power sources**

- Solar photovoltaic (PV)
- Wind turbine
- Run-of-river hydropower
- Biomass power
- Generator: diesel, gasoline, biogas, alternative and custom fuels, co-fired
- Electric utility grid
- Microturbine
- Fuel cell

**Storage**

- Battery bank
- Flow batteries
- Hydrogen

**Loads**

- Daily profiles with seasonal variation
- Deferrable (water pumping, refrigeration)
- Thermal (space heating, crop drying)
- Efficiency measures

HOMER uses resource data, cost and performance data for various combinations of power sources, and storage provided as inputs to simulate different system configurations to meet a given load. The results are sorted by the lowest net present cost. HOMER can perform sensitivity analyses to determine the effects that economic conditions and resource availability might have on the cost of the different system configurations. An example of this is shown in Figure A-1, where the optimal combination of wind, PV, diesel generation, and batteries depends on the price of diesel and the wind resource.

In 2009, NREL executed a commercial license, giving HOMER Energy, LLC the exclusive rights to distribute and enhance the HOMER software.  Downloads of the software are available at [http://homerenergy.com/](http://homerenergy.com/).

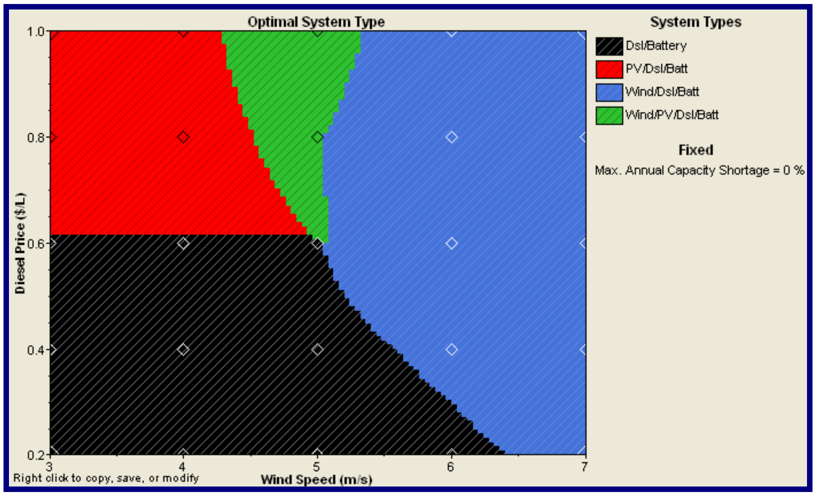


**Figure A-1. HOMER sensitivity analysis, Illustration by HOMER Energy, LLC**

## *SAM Modeling Tool*

The System Advisor Model (SAM) is a tool developed by NREL in 2010 to combine all of the solar technologies into one modeling environment: concentrating solar power (CSP), photovoltaics and solar heating (solar hot water, industrial process heat etc.). In addition to using HOMER to model the hybrid power system mix, the second phase of this study also used SAM to analyze specifically the technical and economical feasibility for implementing CSP on Lanai. SAM analyzes performance, costs and financing consistently across solar technologies for comparisons based on net present value (NPV) and levelized cost of energy (LCOE). SAM does not model the comparison between various hybrid systems as HOMER can, but it will provide a LCOE for solar energy systems. It is also capable of analyzing CSP systems, which HOMER is not. A block diagram of the SAM modeling tool is shown in Figure A-2 and the CSP trough component model internal to SAM is shown in Figure A-3. H. Price developed a CSP model for NREL using Microsoft Excel. This original CSP model, called Excelergy, is an empirical model that was programmed into SAM.

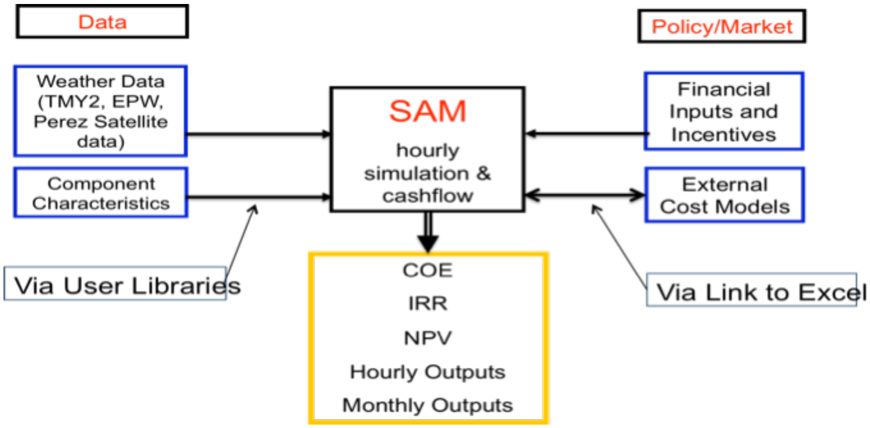


**Figure A-2. Block diagram of the SAM modeling tool -NREL**

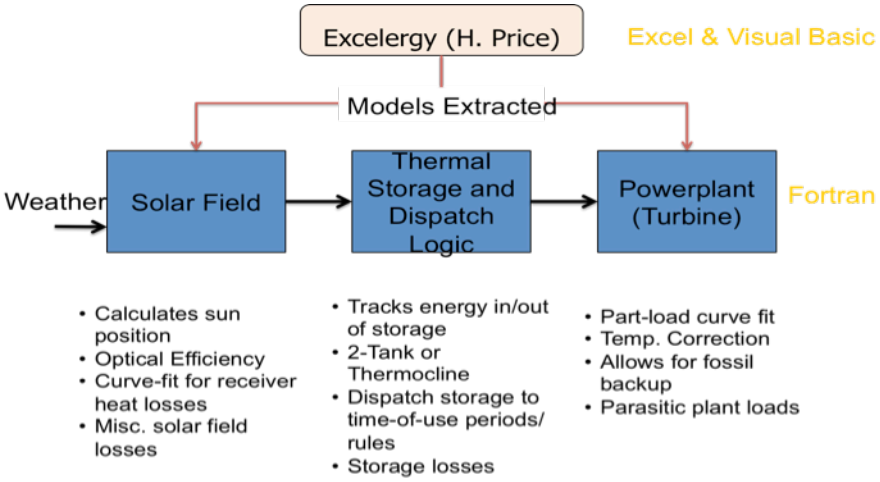
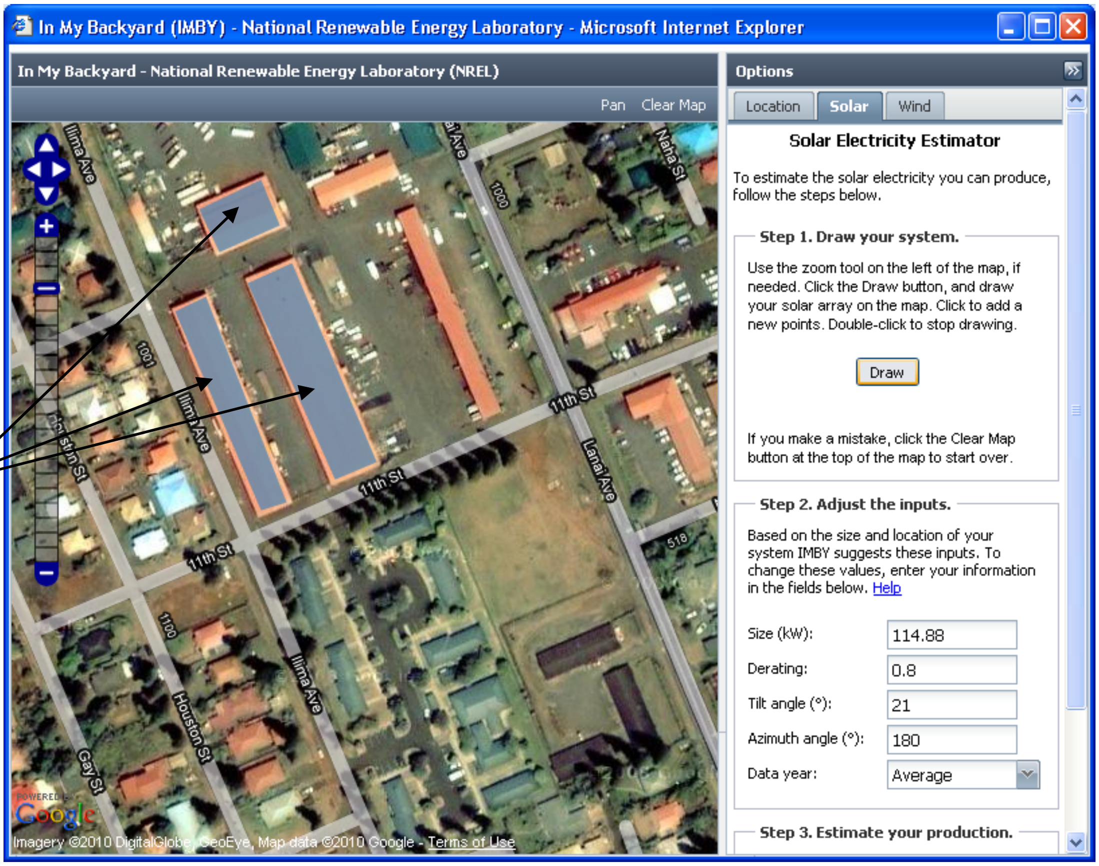


**Figure A-3. Parabolic trough model components**

### IMBY Modeling Tool

In My Backyard (IMBY) is an NREL-developed, web-based solar mapping tool that provides a user-friendly interface to estimate the hourly amount of electricity produced by a PV system in a year. IMBY provides a Google map-based interface where the user can locate an address or area in the U.S. and draw a potential PV system area. IMBY is available at http://www.nrel.gov/eis/imby/.



Solar Electricity Estimator

To estimate the solar electricity you can produce, follow the steps below.

Step 1. Draw your system.

Use the zoom tool on the left of the map, if needed. Click the Draw button, and draw your solar array on the map. Click to add a new points. Double-click to stop drawing.

If you make a mistake, click the Clear Map button at the top of the map to start over.

Step 2. Adjust the inputs.

Based on the size and location of your system IMBY suggests these inputs. To change these values, enter your information in the fields below. Help

Size (kW): 114.88
Derating: 0.8
Tilt angle (°): 21
Azimuth angle (°): 180
Data year: Average

Step 3. Estimate your production.

Blue area drawn using IMBY to estimate solar potential

**Figure A-4. Example of measuring rooftop area with IMBY**

IMBY calculates solar power potential using NREL's SUNY/Perez satellite-derived hourly data set. The SUNY/Perez data has a spatial resolution of 10 km. Based on the selected location, IMBY uses default values to calculate the expected hourly solar power production. The values that are populated include the PV size, derate value, tilt of the system and azimuth. The size is based on the area selected by the user and represents the DC rating. The derate value is the amount of energy lost in the DC to AC conversion of the system, and IMBY assumes a derate value of 0.80. The azimuth is a user input for the direction the PV system is facing ($180^0$ is south) and the tilt default value is the latitude of the chosen location. IMBY can model the following outputs:

- Initial cost, rebates, and tax credits ($)

- Simple PV payback period (years)
- Monthly production of electricity and respective dollar value of electricity produced (kWh/month and $/month)
- A load profile can be chosen and IMBY provides a bar graph of the monthly bill reduction after PV is added.

### *Solmetric SunEye Shade Analysis tool*

The Solmetric SunEye is a handheld electronic tool that is used during site visits and assessments to measure the effect of shading on a PV system at a given site. Measurements correct for the impact of shading due to shade-causing items such as trees or buildings in the immediate vicinity. The SunEye 110 has a digital camera with a fisheye lens. The output displays the skyline with the sun paths for each month and each hour of the day and solar access numbers. The output report displays the average monthly solar access as a percentage of the total and predicts how much electricity a PV system could generate in a typical year. This tool helps PV designers pick the optimal spot for installing a PV array.