




Renewable Power Options for Electrical Generation on Kaua'i: Economics and Performance Modeling

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November 2011

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NATIONAL RENEWABLE ENERGY LABORATORY

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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) to assess the economic and technical feasibility of increasing the contribution of renewable energy in Hawaii. This part of the HCEI project focuses on working with Kaua'i Island Utility Cooperative (KIUC) to understand how to integrate higher levels of renewable energy into the electric power system of the island of Kaua'i. NREL partnered with KIUC to perform an economic and technical analysis and discussed how to model PV inverters in the electrical grid.

Economic Model and Analysis

NREL worked with KIUC to gather the data necessary for modeling an initial base case of electrical production and use on Kaua'i. KIUC currently derives the majority of their power from diesel and naphtha (96%) and has about 7% renewable energy installed in their system. Their strategic plan calls for 50% of electricity from renewable energy by 2023. KIUC is well on their way to achieving this goal with current plans for adding renewable energy to the Kaua'i grid. KIUC has already put together a fairly extensive portfolio of potential renewable projects for the island. Their portfolio contains a variety of projects covering solar photovoltaics (PV), biomass, landfill gas, hydro and storage projects. The proposed projects increase the renewable energy percentage on Kaua'i from 7% to approximately 44% and reduce the consumption of diesel fuel for power generation on Kaua'i by over 37%. The various projects were modeled as Scenarios 1 and 2 outlined below.

Base case: Existing fossil generators + Existing 7 MW Hydro

Scenario 1: Base case + 6.7 MW Biomass + 4.2 MW PV

Scenario 2: Base case + 6.7 MW Biomass + 20 MW PV + 1.6 MW Landfill Gas + 2 Xtreme batteries + additional 15 MW hydro

The results are summarized in the Table E-1:

Table E-1. Summary of Modeled Results

Scenario	LCOE ($/kWh)	LCOE (% of Base case)	Simple Payback (years)	Total Renewable Energy Fraction	Variable Renewable Energy Fraction	Total Fuel Savings (Million gallons) % Savings
Base case	$0.149	n/a	n/a	7.1%	7.1%	n/a
1	$0.155	4.03 % increase	17.1	20.4%	8.7%	(4.3)/ 13.4%
2	$0.159	6.71% increase	13.5	44.3%	29.8%	(12.2)/37.4%

These findings depend on a number of assumptions, which are documented in this report.

Note: KIUC did not want to include wind generation in this analysis due to the environmental regulations for the protection of federally endangered sea birds.

Model Development for Power System Studies

In addition to understanding the financial impact of significant renewable energy on islanded electrical systems, it is critical to also understand how these systems will impact existing generation and distribution infrastructure. This report describes the need for and provides a general overview of power system models, specifically load-flow, stability, short-circuit, protection and coordination studies. Accurate model simulations are critical for planning overall grid quality and safety. The type of models required for the different studies are discussed. With the addition of distributed energy resources, including renewable energy generation and storage, these models are more complicated to develop. This section of the report focuses on understanding and accurately modeling inverters. Inverters are the key component to modeling high penetration of PV on the Kaua'i grid. Different types of PV inverter models are analyzed for each of the required power studies to ensure the stability of the electrical system during disturbances.

Future Research

NREL will continue to work with KIUC to accurately monitor the integration of high penetration levels of PV systems installed in the KIUC service territory. NREL will examine adding data acquisition to capture electrical and environmental data from the installed PV system. This type of data on the status and behavior of electrical equipment at key points, enables the development of high fidelity models of an electric power system with a high penetration of solar integration. The data collection will be used to validate the models. NREL's work will continue to help Kaua'i meet its goal of 50% of its electricity coming from renewable energy by 2023.

List of Acronyms

Btu	British thermal unit
CSP	concentrating solar power
DER	distributed energy resource
DG	distributed generation
DOE	U.S. Department of Energy
DPR	Dynamic Power Resource
DS	distributed storage
EPA	U.S. Environmental Protection Agency
EPS	electrical power system
ESS	energy storage system
HCEI	Hawaii Clean Energy Initiative
HE	high efficiency
HOMER	Hybrid Optimization Modeling Tool
HRSG	heat recovery steam generator
IC	internal combustion
IRP	Integrated Resource Plan
IRS	interconnection requirement study
KIUC	Kaua'i Island Utility Cooperative
KPS	Kapaia Power Station
kWh	kilowatt hour
LCOE	levelized cost of energy
LFG	landfill gas
MMBtu	million Btu
MPPT	Maximum Power Point Tracking
MVA	megavolt amperes
MW	megawatt
MWh	megawatt hour
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PCC	point of common coupling
PMRF	Pacific Missile Range Facility
PPA	power purchase agreement
PSC	Public Service Commission
PV	photovoltaic
RE	renewable energy
RFP	request for proposal
TES	thermal energy storage
THD	total harmonic distortion

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Introduction

In partnership with the U.S. Department of Energy (DOE), in 2008 the State of Hawaii established the Hawaii Clean Energy Initiative (HCEI) to facilitate the state's transition to 70% clean energy by 2030. To successfully achieve these long term goals, stakeholders throughout the islands are working together to reduce energy use, promote the development of renewable energy (RE), and support the transition to a more self-reliant Hawaii.

In response to these efforts, the National Renewable Energy Laboratory (NREL) partnered with Kaua'i Island Utility Cooperative (KIUC) in Hawai'i to examine the renewable energy resource potential on Kaua'i. For the initial stage of the analysis, NREL employed a micro-power optimization model known as HOMER (Hybrid Optimization Model for Electric Renewables) to conduct a preliminary analysis for KIUC. The model will be used to conduct an economic feasibility analysis for integrating high penetration of renewable energy on the KIUC grid. The objective of this study is to model the renewable energy projects being developed on the island and identify the scenarios that will meet KIUC's goal of 50% renewable generation by 2023. This report provides a background to the projects, the study methodology and the optimization model for renewable energy options. Analysis is presented to show fuel and cost savings and determine what mix of renewable energy will meet their growing electrical demand.

Following the economic analysis is a discussion of the model development for power systems studies. This section outlines the detail studies required for maintaining stability along with safe and reliable performance on electrical power systems. This section of the report will focus on power system models and studies required to analyze high penetration of distributed generation including non-dispatchable generation, specifically photovoltaics (PV).

1 Background

In late 2002, the sale of the Kaua'i Electric Company to the Kaua'i Island Utility Cooperative (KIUC) became official. This is a non-profit entity with cooperative by-laws. In 2005, KIUC was directed by the Hawaii Public Utilities Commission to update the Integrated Resource Plan (IRP) from the one developed in 1997. Recognizing the important role of energy diversity, KIUC developed an aggressive strategic plan for 2008 through 2023. In November 2007, KIUC committed to generate at least 50% of its electricity using renewable energy by 2023. To study the impact of increasing renewable energy levels to meet their IRP goals, KIUC requested that NREL provide assistance to develop a roadmap for integrating renewable energy technology onto their island grid.

Integrating renewable energy into an island grid results in a renewable-diesel hybrid electrical power systems (EPS). These systems have special planning and control requirements. This report covers some of the important considerations that go into technical design decisions for the EPS. A hybrid power system uses multiple types of energy production to supply the required loads. Components of a hybrid system may include fossil fueled generators, along with renewable energy such as, solar photovoltaics, wind, micro-hydro, and biomass generators. These components may be combined with storage devices, inverters, and charge controllers to meet the load demands on the island. Variable, or non-dispatchable, generation from photovoltaic and wind systems is more challenging to incorporate into small island systems than conventional generation that is dispatchable.

Renewable energy generally requires a larger capital expenditure compared with the standard engine generators, but result in reduced spending on fuel and maintenance. Renewable energy technologies, like PV, produce variable power that is not dispatachable. This adds to the complexity of the hybrid design and cost. This preliminary analysis conducted by NREL and HOMER Energy LLC identifies the conditions in which solar PV, concentrated solar, hydroelectric and biomass technologies become cost effective for the utility. This report presents the economic analysis followed by the development of power system models for technical studies.

1.1 KIUC Electrical Power System

1.1.1 Electrical Generation

Figure 1-1 shows the island of Kaua'i, its major generation stations and electrical power system. There are two main power plants on Kaua'i, Port Allen and Kapaia Power Station. Port Allen has 12 generating machines capable of producing 96.5 MW of power. They also have a heat recovery steam generator (HRSG). The HRSG uses the waste heat from two of the combustion turbines to produce steam for additional electrical generation. The Kapaia Power Station (KPS) has a 27.5 MW steam-injected gas turbine facility purchased in 2003 and is KIUC's more efficient and cleaner burning plant. This plant provides the majority of the power to the island. Currently KIUC derives 96% of their power from diesel and naphtha. KIUC also maintains the Waiahi hydro power plant, which includes the Upper and Lower Waiahi hydro-electric units, rated at 500 kW and 800 kW respectively. The combined island hydro plant provides approximately 7% renewable energy annually.

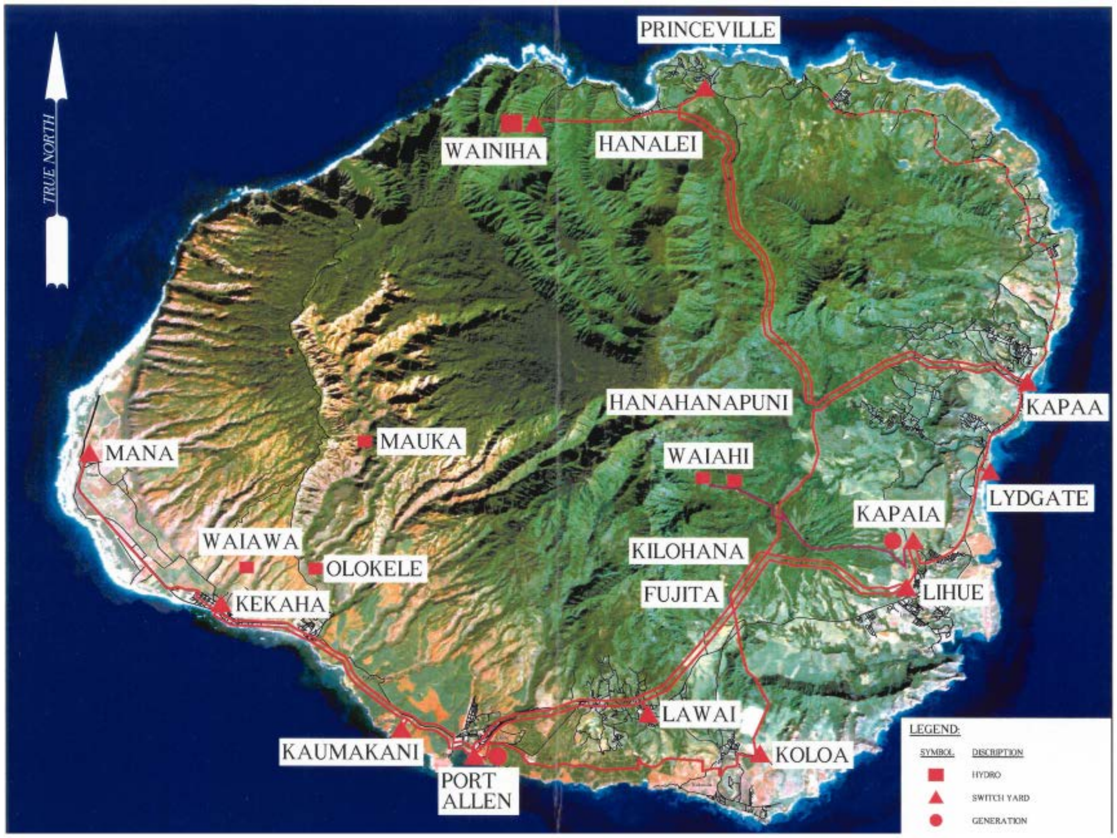

Figure 1-1. KIUC electrical generation and distribution map

Source: Kaua'i Island Utility Cooperative

1.1.2 Electrical Transmission and Distribution systems

The mainland power grid uses very high transmission voltages (130 to 765 kV). Islands are smaller and generally transmit electricity at a subtransmission levels (25 to 115 kV). The transmission system on Kaua'i is operated at 69 kV. Distribution substations around the islands contain transformers that reduce the voltage levels to the distribution voltage level of 13.8 kV. The distribution system was originally designed to deliver power in one direction— from the substation to the customer loads.

Bulk power producers are generally large (greater than 10 MW) and connected at the subtransmission voltage level. Distributed energy resources (DER) are sources of electric power that are usually interconnected near the load to the electric power distribution system. DER may include distributed generation (DG) and distributed storage (DS). DG can include fossil-fuel and renewable sources. Fossil-fuel based generation includes micro-turbines, small backup diesel generators and fuel cells. Renewable sources include photovoltaic (PV), wind turbines and biomass generators. Distributed storage may include battery technologies, flywheels, electric cars and compressed air. This report discusses a new dry cell technology from Xtreme Power because KIUC will be installing this type of DS on their island.

1.1.3 KIUC's Modeling Tools

KIUC's power modeling and simulation tools include Uplan and PSS/E. Currently they run Uplan for their planning activities and PSS/E for stability analysis and other electrical simulation needs.

NREL performed a simplified HOMER analysis of various renewable scenarios for KIUC. This analysis should give KIUC an economic evaluation of integrating renewable energy on Kaua'i to help KIUC develop a path forward for higher levels of renewable energy generation. Some of the important considerations in the design of adding DER to the electrical distribution systems will also be discussed. Because island grids are small, the impact of adding variable generation—either at the sub-transmission or distribution level—can have a negative impact on the central generating plants and the quality of power delivered to the customers.

One of KIUC's primary concerns with adding variable generation such as PV to their system is the coordination with the under-frequency load-shedding schemes. UL-listed inverters are designed to trip at the IEEE 1547 recommended settings of 59.3 Hz. KIUC would like the inverters to stay on line to coordinate with their load shedding scheme. KIUC is requiring that all systems stay on line down to 57 Hz as part of their interconnection agreements.

2 Economic Model and Analysis

2.1 Overview of HOMER Modeling Tool

The HOMER software optimization model used for the Kaua'i analysis was developed at NREL but is now supported by HOMER Energy, LLC. HOMER simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, standalone, and distributed resource (DR) applications. HOMER is a tool for comparing and evaluating hybrid-power systems and determining the most cost-effective mix of renewable energy and fossil fuel generation. In the optimization process, HOMER compares the energy supply and demand every hour of the year and simulates many different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. The model's optimization and sensitivity analysis algorithms enable evaluation of the economic and technical feasibility of a great number of technology options while accounting for variation in technology costs and energy resource availability. HOMER models both conventional and renewable energy technologies including the following:

- Power Sources
  - Solar photovoltaic
  - Wind turbine
  - Run-of-river hydro power
  - Generator: diesel, gasoline, biomass, alternative and custom fuels, co-fired
  - Electric utility grid
  - Micro-turbine
  - Fuel cell
- Storage
  - Battery bank
  - Hydrogen
- Loads
  - Daily profiles with seasonal variation
  - Deferrable (water pumping, refrigeration)
  - Thermal (space heating, crop drying)
  - Efficiency measures
- Resource Data—Local wind, solar, and hydropower resource data is used to characterize the magnitudes and timing of the renewable resources.

2.2 Levelized Cost of Energy (LCOE)

Economic factors are important when integrating renewable energy technology onto the electric power systems of Kaua'i. Renewable energy generally requires a large capital investment compared with the standard fossil fuel generators. However, some RE technology do not have fuel cost and require minimal maintenance. For the economic analysis, NREL compared the levelized cost of energy (LCOE) of the existing power production (base case) with renewable energy added into the mix of generation. The LCOE is a metric for evaluating the cost and energy production of a technology over its lifetime.

The LCOE is reported in $/kWh and it captures the following parameters:

- Capital costs, including replacement costs
- Operations and maintenance costs
- Fuel costs
- Electricity production.

The LCOE allows a comprehensive comparison of the true cost for alternative technologies. The LCOE reported in this analysis is the cost of energy delivered to the EPS; it does not include the cost for transmission, distribution and utility overhead costs.

2.3 Renewable Energy Projects

KIUC already has put together a fairly extensive list of potential renewable projects for the island. This list, summarized in this section, contains projects covering solar PV, biomass, landfill gas, battery storage and hydro-electric.

Photovoltaics

Solar photovoltaics (PV) are semiconductor devices that convert sunlight directly into electricity. They do this without any moving parts and without generating any noise or pollution. They must be mounted in an un-shaded area. Rooftops, carports, and ground-mounted arrays are common mounting locations. PV systems work very well on Kaua'i, where the average global horizontal annual solar resource is 5.5 $kWh/m^2/day$ (see Appendix A). This number, however, is not the amount of energy that can be produced by a PV panel. The amount of energy produced by a panel depends on several factors, including the type of collector, the tilt and azimuth of the collector, the temperature, the level of sunlight, and weather conditions. An inverter is required to convert direct current (DC) to alternating current (AC) of the desired voltage compatible with building and utility power systems. The balance of the system consists of conductors/conduit, switches, disconnects, and fuses.

Figure 2-1 shows the major components of a grid-connected PV system and illustrates how these components are interconnected.

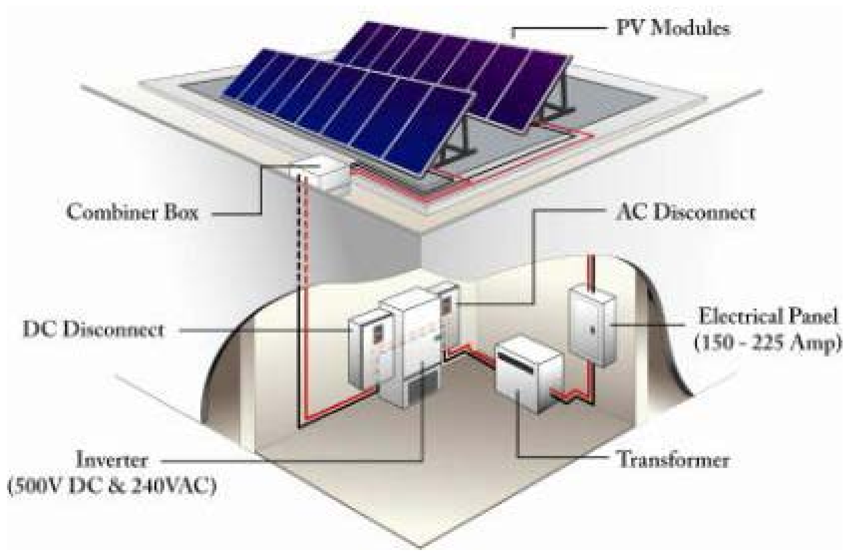

Figure 2-1. Major components of grid-connected PV system

Credit: NREL

Ground-mounted Systems

On a $/DC-Watt basis, ground-mounted PV systems are usually the lowest cost option to install. Several PV panel and mounting options are available, each having different benefits for different ground conditions. Table 2-1 outlines the power density values that can be expected from each type of system. Single-axis tracking systems require more spacing so have slightly less power density per square foot.

Table 2-1: Energy Density Values for Ground-Mounted PV Systems

System Type	Fixed-tilt Power Density (DC-Watts/ft^2)	Single-axis Tracking Power Density (DC-Watts/ft^2)
Crystalline Silicon	4.0	3.3
Thin Film	1.7	1.4
Hybrid HE[a]	4.8	3.9

[a] Because hybrid high efficiency (HE) panels do not represent a significant portion of the commercial market, they were not included in the analysis. Installing panel types that do not hold a significant portion of the commercial market would not be feasible for a large-scale solar generation plant.

HOMER optimization software can model both fixed and tracking systems. For the purpose of this analysis, all PV panels are crystalline silicon ground mount, fixed-tilt systems mounted at 21.88 degrees (latitude tilt).

There are three proposed large ground mount solar PV projects planned on Kaua'i:

- 1.2 MW at Kapaa (22° 04' 50" N and 159° 19' 54" W)
- 3 MW at Poipu (21° 53' 33" N and 159° 27' 29" W)
- 6 MW adjacent to Port Allen generation facility (21° 54' 07" N and 159° 35' 13" W).

All three systems are planned to be installed by the end of 2012.

KUIC is currently considering several additional PV farms not described above and expects the capacity to reach 20 MW.

Storage Systems

Dry cell or gel batteries are gaining popularity in power quality and bridging power storage markets. Gel batteries are included here, not as a renewable energy technology, but as a technology that enables higher penetration levels of non-dispatchable renewable energy. More advanced dry-cell batteries use fiberglass packing with sulfuric acid. The packing absorbs the acid to create a highly conductive gel-like substance. Recently, an advanced dry-cell battery using a solid-state design and chemistry was proposed by Xtreme Power of Kyle, TX[1]. These battery systems are marketed as Power Cells and can be assembled in massive parallel and series matrices, making them suitable for grid applications. A complete package is available in a containerized unit as a system called Dynamic Power Resource (DPR) with a microsecond response rated for 1.5 MVA/1 MWh (Figure 2-2). A few of these systems are being installed as part of wind and PV projects the other Hawaiian islands of Lanai, Maui and Kaua'i.

Figure 2-2. Xtreme Power DPR 15-100C system

Credit: Xtreme Power, Inc.

[1] www.xtremepower.com

Biomass

Biomass is generally defined as any organic feedstock available on a renewable basis. Typical biomass resources include wood and wood waste, landfill gas (LFG), agricultural and crop residues, human solid waste, and animal manures. In Kaua'i the direct burning of a feedstock (wood waste) with air is used to produce steam, which can then be used to create both heat and power. This is typically the most economical method of converting biomass fuel to combined heat and power (CHP). One of the primary benefits of biomass is that feedstocks can be stored, which allows for base load, dispatchable generation.

Green Energy Team LLC boiler system design will be used by KIUC. The design uses a stoker boiler manufactured by Standardkessel Baumgarte. The boiler will use a hydraulic pusher-type grate system that consists of two parallel paths that are arranged and speed controlled to ensure uniform biomass combustion across the entire width of the grate. A single condensing steam turbine will be used, coupled to an air-cooled condenser. Figure 2-3 illustrates the different components of the Standardkessel Baumgarte boiler system.

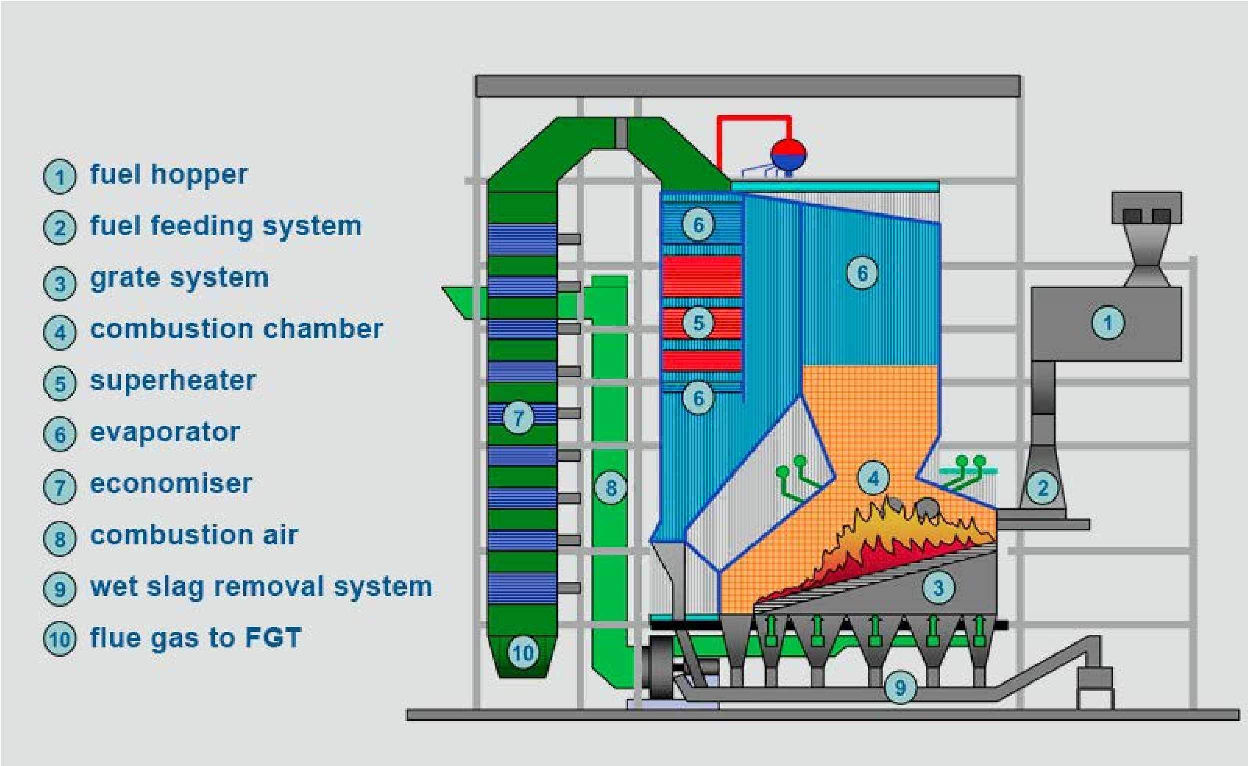

Figure 2-3. Standardkessel Baumgarte Biomass System

Source: Standardkessel Baumgarte[2]

A 6.7 MW biomass plant using Albezia and other tree chips is under development by Green Energy Team, LLC Hawai'i for the island of Kaua'i. The fuel will be supplied by more than

[2]Standardkessel Baumgarte. "Wood." http://www.standardkessel.de/index.php?id=36&L=1. Accessed October, 2011.

2,000 acres of short-rotation biomass. Biomass plants help ensure agricultural use of state and private lands to create jobs and reduce Kaua'i's dependence on foreign oil. The 6.7 MW plant will be located on Knudsen Lands near Koloa and construction is scheduled to start April 2012.

Landfill Recovery gas

Landfills produce emissions that can be captured, cleaned, and burned in engines to produce power. The gas produced from most landfills is primarily a mixture of CO_2 and methane.

A 1.6 MW landfill gas plant is being negotiated with the Navy at the Pacific Missile Range Facility (PMRF). The project will involve installation of a collection system, gas treatment and internal combustion (IC) engines. The location is on county land near PMRF.

New hydro

The island of Kaua'i currently has almost 7MW of hydroelectrical capacity on the island. A number of other hydroelectricity plants are being considered throughout the island. The potential projects are summarized below in Table 2-2.

Table 2-2: Potential and Proposed Hydro Projects on Kaua'i

FERC Permitted Potential Projects	
Hanalei River Hydroelectric Project	3.5 MW
Wailua Reservoir Water Power Project	2.0 MW
Wailua River Hydroelectric Project	6.6 MW
Makaweli River Hydroelectric Project	6.6 MW
Kitano Water Power Project	7.7 MW
Kekaha Waimea Water Power Project	1.5 MW

It is uncertain which of these projects will prove viable; however it is expected that 15 MW of additional hydroelectric capacity will be added in the near future, bringing the total installed capacity to approximately 22 MW.

2.4 Model development for Analysis

This section describes the general assumptions, cost data and resource data required to develop the HOMER model for Kaua'i.

Analysis Period

The analysis began in January 2010 when NREL staff from Deployment and Market Transformation and Electricity, Resources and Buildings Systems Integration areas met with Kauai Island Utility Coop (KIUC) as part of the Hawaii Clean Energy Initiative. NREL visited a year later to present their grid modeling and testing efforts to KIUC in March 2011.

Loads

The analysis was done using hourly electrical load profile data for 2007 provided by KIUC. The energy demand in 2007 was high but decreased substantially during the recession of 2008 and 2009. The decision to use 2007 as a typical year was requested since tourism is increasing and the demand for energy is expected to return to 2007 levels. Based on the 2007 set of data, NREL created the following typical day profile:

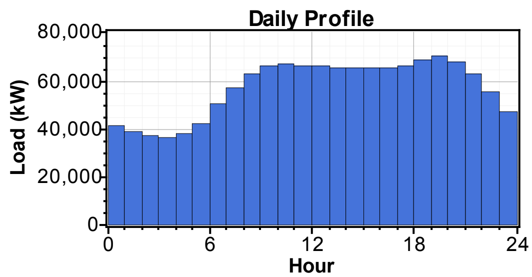

Figure 2-4. Daily Load Profile

Source: HOMER Energy LLC

The seasonal variation is minimal in Kauai and is shown in Table 2-7, with a peak power of approximately 77.5 MW and a minimum 30.0 MW.

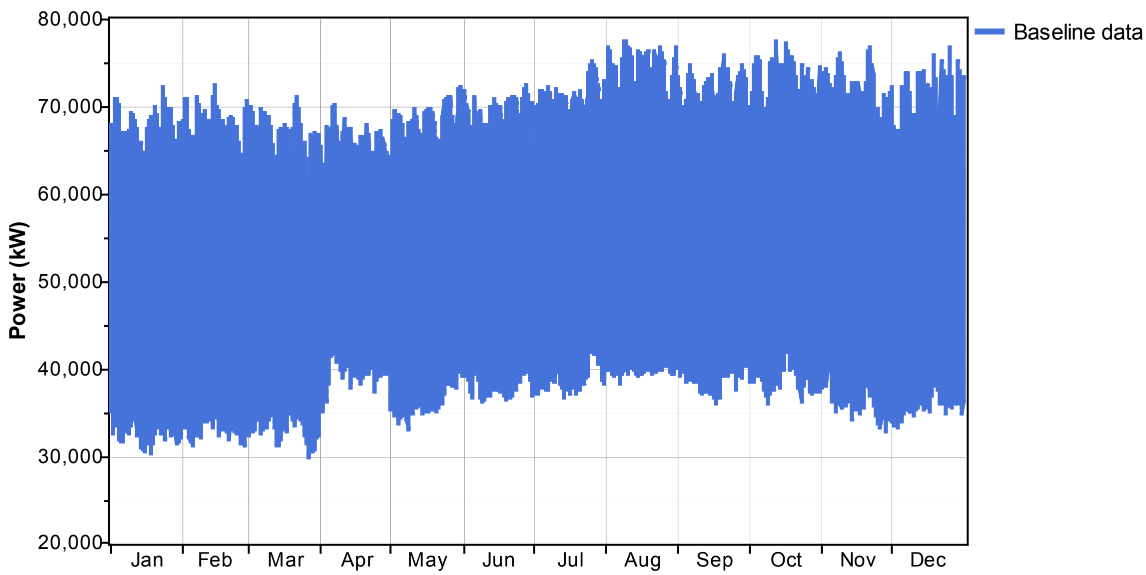

Figure 2-5. Kaua'i annual power production

Source: HOMER Energy LLC

Sensitivity analysis on loads

A sensitivity analysis was undertaken on the load to determine the impacts on system performance if the electrical load increased by 10%. This increased the daily average electricity consumption from 1,366,212 kWh/day to 1,502,831 kWh/day, and the annual peak from 77.5 MW to 85.3 MW.

Diesel Operation and Maintenance Cost

KIUC provided information on the heat rates, efficiencies and minimum load ratios for 13 fossil fuel generators that feed into the Kaua'i grid. Based on the net average power usage and average fuel flow, NREL created fuel curves for each generator on the system. In HOMER, the fuel curve of a generator is defined by at least two points where the X axis represents the kW output and the Y axis is the fuel consumption in liters/hr. All 13 generators represented in the UPlan data had a minimum of five data points.

KIUC also provided information relating to the O&M costs ($/MWh) for each generator and the annual hours of operation for each generator. KIUC informed NREL that although the generator S1 (steam plant) operated for a significant amount of time during 2009, KIUC intends to reduce reliance on this generator to a minimum. This allowed S1 to be excluded from the HOMER simulation of the KIUC system, as the simulation is meant to depict "normal" operations. Starting in the near future, operation of generator S1 will be considered extraordinary, rather than ordinary.

In addition, KIUC provided an hourly dispatch simulation. While this was a simulation rather than real, historic data, it allowed the O&M $/MWh variable, mentioned above, to be used and converted into the form required by HOMER ($/hr).

HOMER has the ability to model up to 10 fossil fuel generators. A conversation with KIUC clarified that the generators named GT1, GT2 and S1 could be excluded from modeling. This left 10 fossil fuel generators. To add biomass generators and landfill gas generators, diesel generators 1 and 2 were combined into a single generator, as were diesel generators 4 and 5.

Because the simulated run hours of the aggregated unit will be less than the sum of the individual units, the O&M cost in $/hr were assumed to be 1.5 times the O&M costs for the generators, individually.

The minimum load ratio for the combined generators was lowered by half, so there is effectively only a minimum load ratio on one of the two generators that have been combined.

Fuel Cost

The simulation assumed that KIUC purchased its fuel at a wholesale cost, as shown in Table 2-3:

Table 2-3. Fuel Cost

Fuel	Cost per liter	Cost per gallon
Diesel	$0.586	$ 2.22
Naphtha	$0.443	$1.68

Sensitivity analysis on fuel cost

A sensitivity analysis was undertaken on the fuel cost to determine the impacts on system performance if the cost of diesel increased to $0.80/L ($3.02/gal). The cost of naphtha was similarly increased by 36.5% to $0.605/L ($2.29/gal).

Interest Rate

The interest rate is another critical parameter that depends on factors that cannot yet be precisely specified. A 3% interest rate corresponds roughly to attractive government funding, while 8% is less attractive private funding. The HOMER models use a real interest rate, which is approximately equal to the nominal, or quoted, rate minus the expected inflation rate over the life of the project. For this analysis, a more conservative interest rate of 8% was assumed.

Operating Reserve

An operating reserve (or spinning reserve) constraint is included that requires the system to have sufficient idling capacity on-line to cover sudden changes in electrical production or electrical demand. The operating reserve requirement means that power capacity, but not necessarily production, must be available throughout the year.

Solar operating reserve

An operating reserve related to PV system output helps to reduce stability problems from sudden changes in PV electrical production. This value reflects how conservative KIUC will be with regard to the variability of the renewable resources. A 100% operating reserve constraint requires the system to have sufficient spinning reserve to cover the complete loss of solar output within each of HOMER's one hour simulation time steps and was used in this analysis. Although lower operating reserves may be used, 100% is the highest operating reserve recommended.

A more detailed analysis considering short term fluctuations in the resources, the stiffness of the KIUC grid and other technical factors is required before we can make precise recommendations regarding the appropriate level of operating reserve. For example, 100% operating reserve may be most appropriate if all of the PV is packed tightly in a single array. If multiple smaller arrays are sufficiently separated geographically then individual clouds will not have the same impact on the system output and a lower level of operating reserves could be possible. High operating reserve significantly reduces the cost-effectiveness of PV.

Load operating reserve
An operating reserve on load helps to reduce stability from sudden changes in system electrical loads. 0% load operating reserve is assumed for this model. A 10% load operating reserve is often used but without additional peaking plants in the model, there is not sufficient dispatchable generation to meet the 77.5 MW peak load with an additional 7.75 MW operating reserve requirement.

Resource Data
Resource maps are included in Appendix A for solar photovoltaics and hydro. To establish viability at a given site, each technology requires its own dataset. Local resources related to the technologies considered must be obtained from catalogued data or on-site measurements. If sufficient data is not available, then it is necessary to collect data for periods of up to one year to capture seasonal variations.

Further in-depth assessment of the technologies that appear viable is required to ensure that the specific proposed siting meets the requirements of the individual technology and complies with zoning and other considerations. For example, photovoltaic arrays must be installed in an un-shaded location on the ground or on building rooftops that have an expected life of at least 25 years.

Solar Resource Data
The solar resource data was obtained from NREL's GIS group using information from the Perez satellite data. The locations for solar data are numbered as a grid on the map in Figure A-3, Appendix A. Only one location for solar resource can be used at a time when modeling with HOMER. The solar data file used was: CPR_159452185_2007 kWh.csv corresponding to the grid location: 159452185 on the map near Poipu. This is the solar resource data obtained in 2007, so it correlates well with the load demand profile.

NREL also has hourly global solar resource data for the site near Kapaia, if exact data is needed for further analysis. The file used in this study is CPR_159352195_2007.csv.

Hydro generation
KIUC has multiple hydro-electric contributions to the electricity grid. All hydro systems were collated and modeled as a single hydro generator. According to the file "Kaua'i hourly dispatch simulation," all of these hydro generators run, effectively, 24/7 with little fluctuation. The hydro generator modeled in this file is a 7 MW combination of Waimea Mauka Hdyro, Waiwa Hydro, Lihue Lower, Lihue Upper, Wainiha Hydro, Kalahea Hydro and Waiahi Hydro as represented in the file "Kaua'i hourly dispatch simulation." They are labeled G&R Hydro, Hydro_UP, Hydro_LO, ADC and KCOFFEE.

Figure 2-6 illustrates the Hydro resource modeled with a seasonal profile based on the file "HYDRO UPLAN Kaua'i."

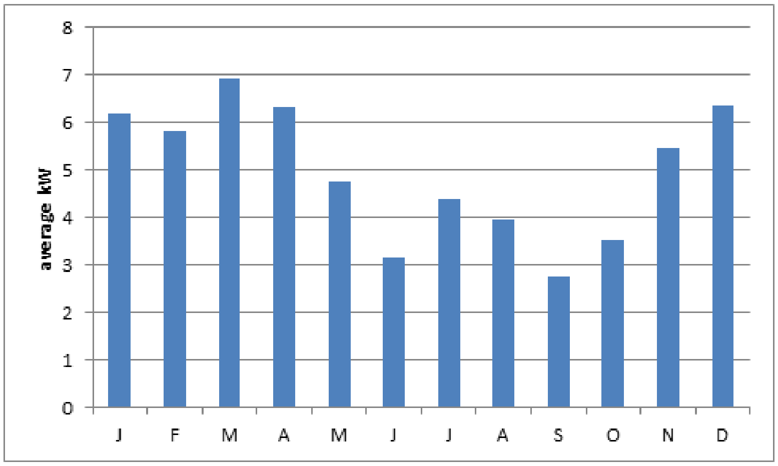

Figure 2-6. Hydro resource scaled such that there is an annual production of approximately 35MWh

Source: HOMER Energy LLC

The HOMER software only allows a single hydro resource, so the additional 15 MW of hydroelectric capacity was modeled with the same resource as the first 7MW.

2.5 Base Case HOMER Model

NREL modeled the Kaua'i electrical system base case with the existing fossil fuel and hydro resources. The system diagram in HOMER is shown in Figure 2-7.

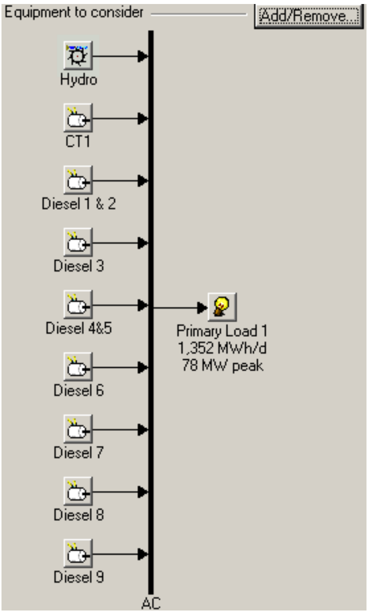

Figure 2-7. HOMER Base Case Model for Kaua'i

Source: HOMER Energy LLC

The base case in HOMER has the following production:

Table 2-4. List of Kaua'i Generators

Production	MWh/yr	%
Hydro turbine	35,578	7
CT1	240,811	48
Diesel 1 & 2	9,150	2
Diesel 3	8,531	2
Diesel 4 & 5	14,993	3
Diesel 6	51,687	10
Diesel 7	31,760	6
Diesel 8	44,184	9
Diesel 9	61,849	12
Total	498,542	100

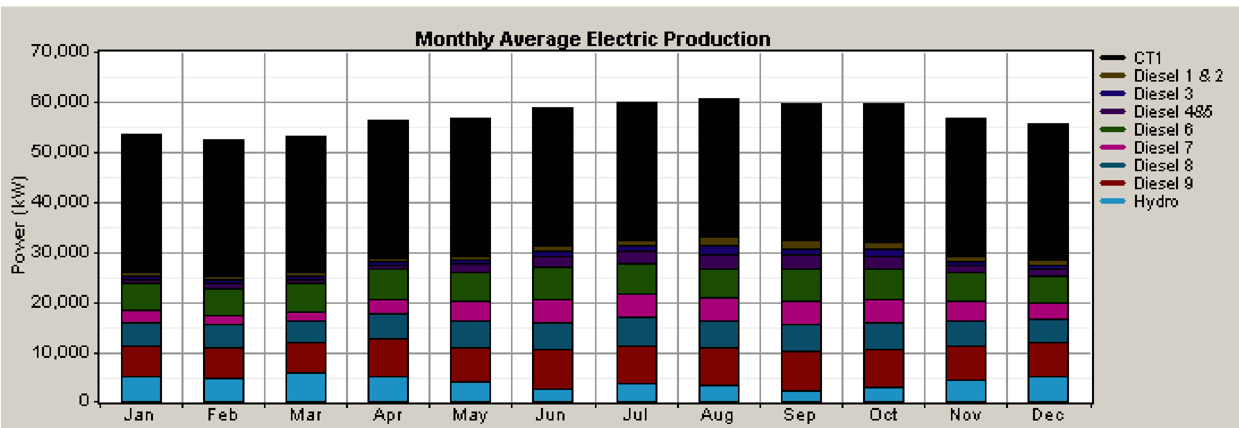

Figure 2-8. Monthly Average Electric Power Production (kW)

Source: HOMER Energy LLC

The annual fuel use is 55,146,744 liters of diesel and 68,188,080 liters of naphtha. This is a total fuel use (diesel + naphtha) of ~123.3 million liters/yr, which is ~32.6 million gallons/yr.

Under the Base Case, Kaua'i has a renewable energy fraction of approximately 7%, due entirely to hydroelectric generation.

The LCOE for the base case on Kaua'i is \$0.149/kWh. This cost includes only the cost of fuel and O&M of generation. It does not include the capital cost of the existing power plants or transmission and distribution costs to send the electricity to customers.

Sensitivity to fuel price increases

If the price of diesel increases 36.5% to \$0.80/L (\$3.02/gal), and the price naphtha increases by a similar amount to \$0.605/L (\$2.29/gal), the LCOE for the base case system increases 30.9% to \$0.195/kWh.

Sensitivity to load increases

If the load increases by 10% throughout the year, the base case system cannot meet the load growth. There are older fossil-fueled plants on Kaua'i that could be brought online to meet this demand growth, however they are not modeled in HOMER.

2.6 Renewable Energy Model Development

PV Size and Energy Storage Assumptions

The cost of PV varies widely across the United States; therefore a sensitivity analysis can be modeled in HOMER. Solar PV arrays have recently come down in cost so for this project, NREL used the estimated average PV capital cost $5.00/watt.

- PV
  - Sizes: 0 MW, 4.2 MW (representing 3 MW existing PV and the 1.2 MW farm at Kapa'a), 20 MW
  - Cost: $5/W (Capital and $4/W Replacement)
  - O&M $5000/ year for each MW of capacity
  - Tilt: 21.8 degrees
- Xtreme Batteries
  - Quantity: 0 batteries, 1 battery, 2 batteries
  - Sizes: 1 MW for 1.5 hours per battery
  - Cost: confidential
  - Obtained modeling data from the Xtreme website

Biomass and landfill gas assumptions

- Biomass
  - Sizes modeled: 6.7 MW only
  - Cost: $10,000,000/MW capacity (Capital & Replacement), based on KUIC conversation
  - O&M Cost: $27.75/operating hour for each MW of capacity
  - Fuel is woody biomass at $70/ton
  - Lifetime: 200,000 operating hours
- Landfill Gas
  - Sizes modeled: 1.6 MW
  - Capital Cost: $3,965/kW (replacement cost included in O&M cost), based on Black and Veatch landfill gas study[3]

[3] Kaua'i Island Utility Cooperative Renewable Energy Technology Assessments (March 2005). "10.0 Landfill Gas." http://www.kiuc.coop/pdf/KIUC%20RE%20Final%20Report%2010%20-%20Landfill%20Gas.pdf. Accessed October, 2011.

- O&M Cost: $41.33/operating hour for the entire 1.6 MW plant, including fuel changes, minor overhauls and major overhauls/replacements.
- Fuel is landfill gas at $7.135/m^3$

Hydro assumptions

- Existing hydro
  - Sizes modeled: 7 MW
  - Capital cost: $0 (already existing infrastructure)
  - O&M cost: $1,423,136/yr (based on expected output with $40/MWh)
- New hydro
  - Sizes modeled: 15 MW (22 MW total, including existing)
  - Capital cost: $76,846,000 (based on $3,500/kW new capacity)
  - O&M cost: $ 3,076,866 (based on expected output with $40/MWh)

2.7 Hybrid Analysis

NREL presents two scenarios for the HOMER analysis of Kaua'i. The base case includes the existing diesel generators and hydro plants, but the two scenarios consider the economics of adding different mixes of renewable energy. For each scenario, the fuel savings are presented along with the LCOE and/or simple payback and the renewable energy fraction. The HOMER model also includes sensitivity analysis on fuel price and primary load.

The scenarios for analysis were selected based on the expected installations on Kaua'i. These system designs were extracted from the HOMER model, and the results are presented below.

Base case: Existing fossil generators + Existing 7 MW Hydro

Scenario 1: Base case + 6.7 MW Biomass + 4.2 MW PV

Scenario 2: Base case + 6.7 MW Biomass + 20 MW PV + 1.6 MW Landfill Gas + 2 Xtreme batteries + additional 15 MW hydro

Scenario 1: Base case + 6.7 MW Biomass + 4.2 MW PV

Adding the 6.7 MW biomass plant and 4.2 MW of PV has an expected capital cost of $88,000,000 and yields a slight increase in cost at a diesel price of $0.536/L ($2.22/gal). Figure 2-9 shows the HOMER results from the *Electrical* tab of the *Simulation results* window. The LCOE has increased by 4.0% ($.155/kWh) from the base case LCOE.

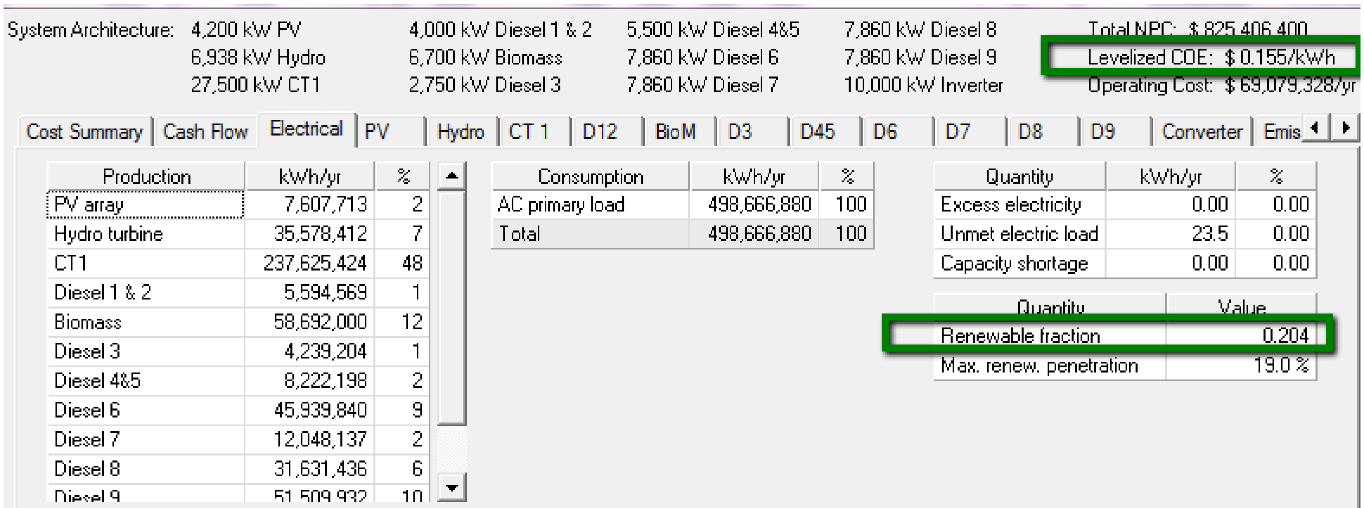

Figure 2-9. Scenario 1, electrical results tab from HOMER analysis

Source: HOMER Energy LLC

Table 2-5 shows the annual energy production by source. The total renewable energy fraction, including hydro turbines, biomass, and PV is ~20%, a nominal increase of ~13% over the Base Case.

Table 2-5: List of Kaua'i Generators in Scenario 1

Production	MWh/yr	%
PV arrays	7,608	2
Hydro turbine	35,578	7
Biomass	58,692	12
CT1	237,625	48
Diesel 1 & 2	5,595	1
Diesel 3	4,239	1
Diesel 4 & 5	8,222	2
Diesel 6	45,940	9
Diesel 7	12,048	2
Diesel 8	31,631	6
Diesel 9	51,510	10
Total	**498,689**	**100**

Figure 2-10 shows the monthly average electrical generation mix.

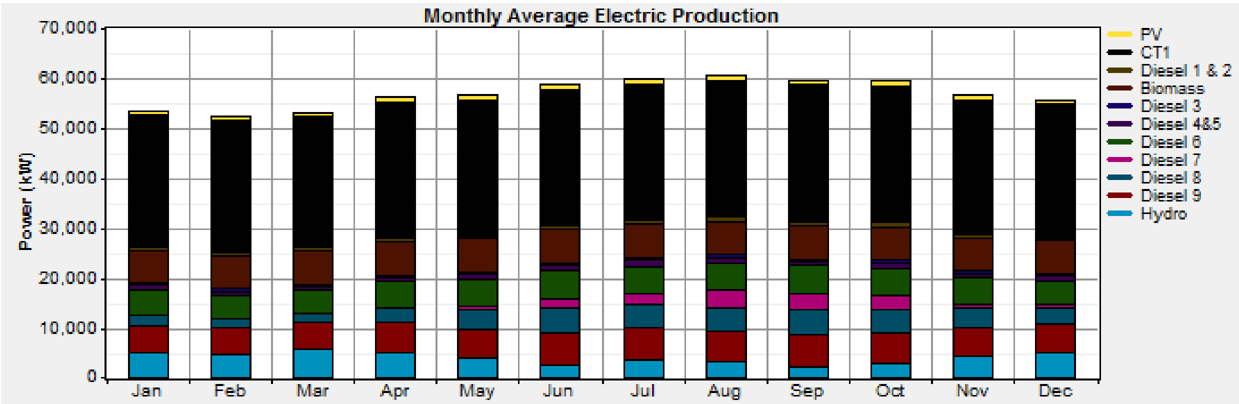

Figure 2-10. Scenario 1: monthly average electric generation mix

Source: HOMER Energy LLC

The total fuel consumption for Scenario 1 is ~106.8 million L/yr (~28.2 million gal/yr), which represents a ~13% reduction from the Base Case.

Sensitivity to fuel price increases

If the price of diesel increases 36.5% to $0.80/L ($3.02/gal), and the price naphtha increases by a similar amount to $0.605/L ($2.29/gal), the LCOE of Scenario 1 increases 25.0% to $0.194/kWh. Scenario 1 shows less sensitivity to fuel price increases than the base case, which experienced a 30.9% LCOE increase from the same fuel price increase.

Sensitivity to load increases

If the load increases by 10% throughout the year, LCOE increases 1% to $0.157/kWh, and the renewable fraction decreases slightly to 19%. The increased cost is due to the increased reliance on expensive fossil-fueled generation to meet load.

Scenario 2: Base case + 6.7 MW Biomass + 20MW PV + 1.6 MW Landfill Gas + 2 Xtreme batteries + additional 15 MW hydro

For Scenario 2 an additional 15.8 MW of PV was added to the generation mix, as well as a new 1.6 MW landfill gas plant, 15 MW of additional hydro, and a 1.5 MWh Xtreme DPR dry cell battery. This equipment has an expected capital cost of $254,190,000. Figure 2-11 shows the HOMER results from the *Electrical* tab of the *Simulation results* window. The LCOE has increased 7% ($0.159/kWh) from the Base Case LCOE. The fuel savings for this Scenario 2 is approximately 12.2 M gallons annually compared to the Base Case, which represents a 37.4% fuel savings. The total renewable fraction shown does not include the contribution from the landfill gas plant; the renewable fraction is manually calculated based on the production in kWh/yr shown on the left of Figure 2-11.

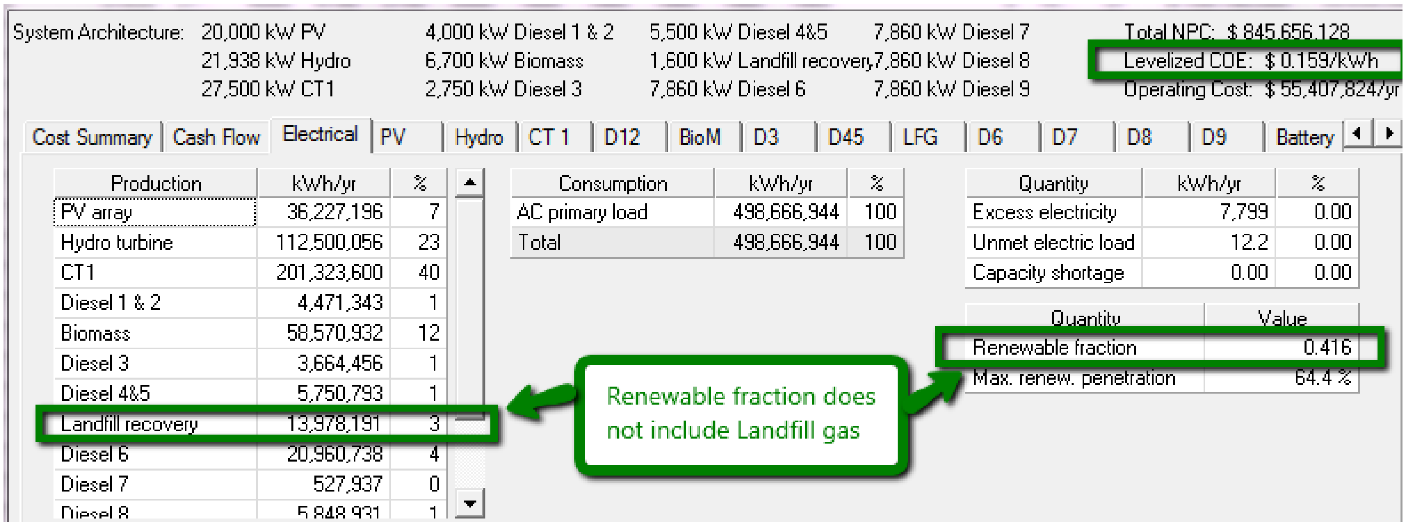

Figure 2-11. Scenario 2, *Electrical* results tab from HOMER analysis

Source: HOMER Energy LLC

Figure 2-12 shows the monthly average electrical generation mix.

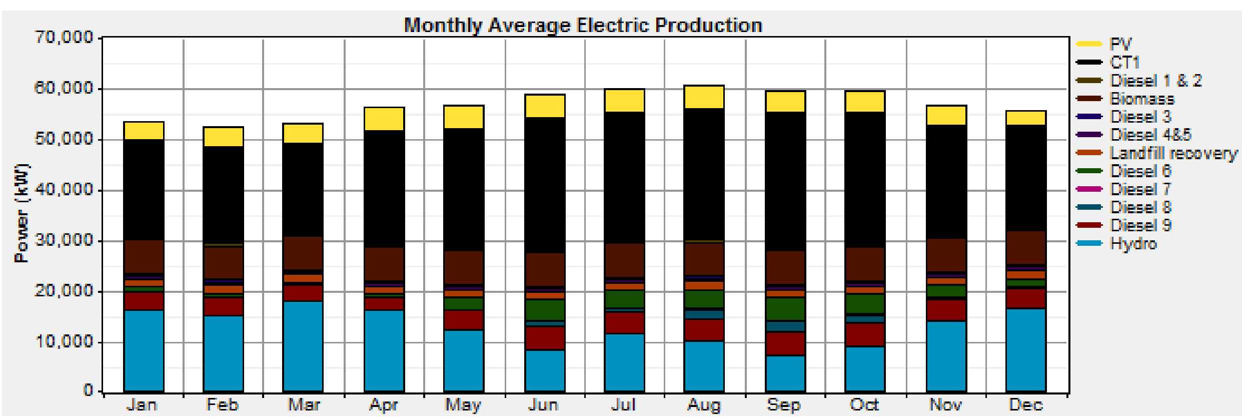

Figure 2-12: Scenario 2: monthly average electric generation mix

Source: HOMER Energy LLC

The renewable fraction can be calculated from the generation listed below in Table 2-6. The renewable fraction is 44.3%.

Table 2-6. List of Kaua'i Generators in Scenario 2

Production	MWh/yr	%
PV arrays	36,227	7
Hydro turbine	112,500	21
Biomass	58,625	11
Landfill gas recovery	14,008	3
CT1	217,450	40
Diesel 1 & 2	4,754	1
Diesel 3	3,983	1
Diesel 4 & 5	6,158	1
Diesel 6	31,695	6
Diesel 7	5,477	1
Diesel 8	16,044	3
Diesel 9	41,651	8
Total	**548,571**	**100**

Sensitivity to fuel price increases

If the price of diesel increases 36.5% to \$0.80/L (\$3.02/gal), and the price naphtha increases by a similar amount to \$0.605/L (\$2.29/gal), the LCOE of Scenario 2 increases 17% to \$0.186/kWh. Scenario 2 show less sensitivity to fuel price increases than both the base case and Scenario 1.

Sensitivity to load increases

If the load increases by 10% throughout the year, the LCOE does not change and the renewable decreases to40.3%.

Hybrid analysis summary

Table 2-7 summarizes the findings in the base case and the 2 scenarios at the default fuel price and default electrical load.

Table 2-7. Summary of Findings

Scenario	LCOE ($/kWh)	LCOE (% of Base case)	Simple Payback (years)	Total Renewable Energy Fraction	Variable Renewable Energy Fraction	Total Fuel Savings (Million gallons) % Savings
Base case	$0.149	n/a	n/a	7.1%	7.1%	n/a
1	$0.155	4.03 % increase	17.1	20.4%	8.7%	(4.3)/ 13.4%
2	$0.159	6.71% increase	13.5	44.3%	29.8%	(12.2)/37.4%

Scenario 1 showed less price sensitivity to increased fuel prices than the Base Case, and Scenario 2 showed yet less sensitivity to fuel price increases than Scenario 1. Both Scenario 1 and Scenario 2 were able to meet a 10% increase in load; the Base Casewas not able to meet the increased load.

One of the challenges in increasing the renewable energy penetration levels is using variable or non-dispatchable renewable energy resources. One of the advantages to Kaua'i's planned renewable energy plans is that many of the DERs are dispatchable (biomass, landfill gas, and hydro). Adding variable and non-dispatchable generation may increase the need for controls to avoid excessive ramp rates on the generation or overvoltage issues on the distribution lines. NREL has developed a rule of thumb for describing the impacts of variable generation on electric power systems as it relates to penetration level (see Table 2-8). In the study we did for Kaua'i the biomass plant and the landfill gas run as a base load power generation. The hydro turbines has some seasonal variability, and the PV has daily variability. For this analysis, NREL considered the hydro and PV in the variable renewable energy fraction. It is this variable renewable energy fraction that is considered when using Table 2-8 for determining the impacts of DER on the power generation or distribution system.

In Figure 1-10 HOMER calculates the maximum renewable penetration for scenario 2 to be 64.4%. This value is represented in Table 2-8 as 'Peak Instantaneous' value, and thus, Kaua'i would fall in the medium class of operating characteristics for Scenario 2. The medium operating class requires relatively simple control systems or additional storage to curtail the renewable generation.

Table 2-8. Penetration Class of Intermittent Generation of Renewable Energy

Class	Operating Characteristics	Contribution	
		Peak Instantaneous	Annual Average
Low	Diesel(s) or base load power run full-time	< 50%	< 20%
	Wind or PV power reduces net load on diesel		
	All wind or PV energy goes to primary load		
	No supervisory control system		
Medium	Diesel(s) of base load power run full-time	50% to 100%	20% to 50%
	At high wind or PV power levels, secondary loads dispatched to ensure sufficient diesel loading or renewable generation is curtailed		
	Requires relatively simple control system		
High	Diesel(s) or base load power may be shut down during high wind or PV power	100% to 400%	50% to 150%
	Auxiliary components required to regulate voltage and frequency		
	Requires sophisticated control system		

2.8 Summary

In summary, the analyses show that adding Biomass, Landfill gas and PV projects can make the levelized cost of energy less sensitive to increases in fossil fuel prices. As the island gets closer to reaching the generation mix in Scenario 2, there is expected to be about a 37% reduction in fuel use, and Kaua'i will reach its renewable energy penetration goal with a 44.3% renewable fraction. The maximum renewable penetration calculated in HOMER can be used as a rule of thumb to determine the impact on the operations of the power plants; the island of Kaua'i would fall in the medium class of operating characteristics for Scenario 2. The increasing price of petroleum and liquid fuels provide risk to Kaua'i that can be mitigated with an increased reliance on renewable generation sources. Increasing the renewable generation can also serve to meet future load growth. The projects will defer the need to build additional, fossil-fuel fired power generation.

3 Model development for Power System Studies

This section describes the need and development of power system models for technical studies such as an interconnection requirement study (IRS).

3.1 Background

Electrical power system studies are conducted by engineers to determine safe and reliable performance on electrical power systems. Normally, studies are conducted using commercially available software packages. The software packages allow the engineer to cost effectively evaluate existing and newly designed power systems. Load-flow, dynamic stability, transient, short-circuit, and protection are major types of power system studies that utility engineers perform.

The purpose of the electrical power system is to deliver high-quality, safe, and reliable electric power to homes, industrial plants, and commercial businesses. Large generation stations are connected through high-voltage transmission lines to substations. These substations contain transformers that reduce the voltage levels for the subtransmission and distribution systems. The electrical distribution system consists of substation transformers, three-phase and single-phase distribution circuits, protection and switching equipment, power factor improvement equipment, distribution transformers, and service drops.

3.2 Load Flow Studies

Load flow or power flow studies are used to help determine the state of the power system. Load flow studies determine system voltages, currents, the active and reactive powers, as well as the power factors. These parameters are used to determine system losses, conductor ampacity ratings, and voltage levels at particular connection points (busses) of the power system. Load flow studies are performed to ensure four basic steady-state operating requirements are met:

- Generation supplies the load plus losses on the system
- Maintain bus voltage near nominal or rated value
- Generation operates within specified real and reactive power constraints
- Confirm transmission and distribution lines are not overloaded.

3.3 Stability Studies (Electromechanical)

The majority of electric power generation comes from rotating synchronous machines. It is a fundamental requirement that all synchronous machines in the system operate in synchronism with each other, maintaining a common system frequency (60 Hz in the United States). “Synchronism” means that the frequency, voltage, phase rotation, and the phase (delta angle) of two or more generators match. However, power systems are exposed to various system disturbances. This may cause a sudden change in the real and reactive power balance of the system and lead to problems in certain machines. The ability of the system to recover from such disturbances and regain steady-state synchronism conditions becomes a major design and operating criterion for the electrical grid.

Stability focuses on one particular key electrical element, the magnitude and phase angle of the machine terminal voltage:

- Rotor angle stability – The angle between the machine rotor and the stator is called the power angle (real power). Power increases as the power angle increases (up to a certain extent, 90 degrees).
- Voltage Stability – The magnitude of the machine terminal voltage (reactive power).

There are basically three types of stability studies. Steady-state, dynamic, and transient. A brief conceptual description of each is given below.

3.3.1 Steady-State Stability

Under steady-state operation, the power generated by the source is equal to the power being consumed by the load. The load impedance is the principal determinant of the current magnitude (IEEE Std 242-2001). When an additional load (e.g. air conditioner) is turned on, the total load impedance is reduced, resulting in an increase in current flowing in the armature winding of the rotating machine. This increase in current will cause the machine's rotor to actually slow down due to the armature reactance. Due to this increased load demand, the frequency of the power system will deviate slightly lower. In order to maintain constant frequency (60 Hz in the United States), the generator turbine must respond with additional torque (prime mover) to match this new power demand.

How much power can we transmit along a given transmission line and still maintain a synchronism can be described by equation 1.1:

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{1.1}$$

Where V_1 and V_2 are the terminal voltages and δ is the angle between them. The impedance X is summation of the generators synchronous reactance and the electrical transmission line impedances between the two generating power sources. The maximum power transfer occurs when δ is 90 degrees.

3.3.2 Dynamic Stability

Dynamic studies usually analyze one or two machines undergoing gradual power system operating changes. Like steady-state stability studies, dynamic studies are concerned primarily with the steady-state operating points of the system. The difference between the two lies in the level of modeling detail used. Dynamic modeling includes modeling the exciter system, turbine governor, and synchronous machine. Steady-state models use simple constant voltage source generator models. Both dynamic and steady-state studies methods use linear equations to determine the machine stability condition due to small changes about equilibrium.

3.3.3 Transient Stability

Transient studies are the most commonly performed stability study. Transient studies are performed to determine if the system will remain in synchronism following major disturbances such as faults, sudden loss or gain of load, loss of generation, or line switching. Such large disturbances require non-linear algebraic and differential equations to be solved by the direct method or by using iterative computational methods. Transient stability studies generally focus on a one-second period after a disturbance. If the generator and the system remain in synchronism for one second or less it is said to be a stable system (Stevenson, 1982).

3.4 Transient Studies (Electromagnetic)

Power quality consists of voltage, frequency, and current waveforms. Good power quality can be taken to mean the voltage supplied by the utility at the customer's service entrance is steady and within the standard range of nominal operation. The desirable voltage versus time waveform should be absent of harmonic distortion or ripples along the sinusoidal voltage waveform. This ripple or harmonics produced can have adverse effects such as:

- Additional losses that result in overheating of various electric machines
- Interference with normal operation of communication circuits
- Harmonic resonance, which results in equipment failure in sensitive electronic equipment
- Performance modification of some interrupting devices and protective relays

The main source of harmonics in the electric power system stems from static converters used such as rectifiers for various industrial process, arc furnaces, and transformers (IEEE, Brown Book).

A harmonic load flow looks at the impact of non-linear loads on the EPS. Harmonics can have a significant adverse impact on the EPS, including improper protective device operation, circuit element overload, and failure of power factor correction capacitors.

3.5 Short-Circuit and Protection Coordination Studies

Short circuit or fault studies are conducted to determine the magnitude of currents flowing through the electrical system during faults. Short-circuit studies ensure that the wide range of electrical equipment used to generate, transmit, and distribute electrical power is sufficiently sized to interrupt or withstand short-circuit current. Electrical equipment and protective devices must be properly sized and set for such events. There are different types of faults to consider including three-phase, phase-to-phase, double-phase-to-ground, and phase-to-ground faults that can be located at different points throughout the system.

The magnitudes of the currents flowing through the power system after a fault vary with time until they reach a steady-state condition. During this time, the protective system is used to detect, interrupt, and isolate the faults. The duty imposed on this equipment is dependent on the magnitude of the current, which is dependent on the time from fault inception. This information is used to select fuses, breakers, and switchgear ratings and set protective relays.

A short circuit study is essential for determining parameters used in relay settings. Combining short circuit analysis with dynamics analysis can contribute greatly to the understanding of how DER will interact with a utility protection system. The time-dependant behavior of the protective devices is represented along with the dynamic characteristics of the machine and inverters. At present, no such tools are readily available without resorting to an electromagnetic transient computer program. This is one area for continuing research in the development of DER-related engineering tools (Dugan et al., 2002). Extending the conventional fault analysis to include inverter-based DER is challenging because it requires more detailed modeling than the models used to represent AC generators (Baran and El-Markaby, 2005). With the addition of DER, this may be very complicated to perform because of the difficulty of estimating the inverter impedance (IEEE 2008). If the internal impedance of an inverter could be determined then it would be possible to accurately model the inverters fault characteristics using power system modeling software.

Protective relays are required on a transmission and distribution system in order to cause the quick removal from service of any electrical equipment associated with the power system when a short-circuit fault occurs or when the power system begins operating in abnormal conditions. Protective relays are essentially the brains that determine when the appropriate circuit breaker tripping action should take place. The mechanical device capable of disconnecting the faulty element and physically isolating the electrical power system from short circuit disturbances is called a circuit breaker.

A protective relay receives information about the electrical system (voltage, current, and frequency) through current and voltage transformers. These transformers transform the measured voltage and current value to a more appropriate power level to be used by the protective relay. This information is processed by the protective relay and reacts to any abnormal conditions detected. Each protective relay needs to be set or programmed for the desired tripping time (i.e., time delay for relay coordination and system reliability purposes). The decision to trip open or to close the circuit breaker is made by the relay logic algorithms and must be programmed by a relay engineer.

3.6 PV Inverter and System Models

As high penetration levels of renewable energy sources come on-line in the near future, it will become necessary for power engineers to have tools to accurately model inverters. Understanding and accurately modeling an inverter and how it behaves during a variety of system disturbances is critical for planning and the overall well being of the electrical system.

As described in the last section, different distribution studies are available to investigate different kinds of power system challenges, and each of these uses a particular type of model to represent power system components and characteristics of interest. Once the type of distribution study has been selected and the system model has been identified, computer software suites are available to accurately calculate and specify the solution.

Four different types of PV inverter models have been identified for the modeling of PV inverter systems operating on the distribution grid. Each type of distribution system study outlined in Section 2 is discussed in terms of PV inverter models that appropriately model the PV inverter system for the study's intended time scale and findings.

3.6.1 Steady State Models

The primary analyses used by distribution engineers are steady-state power-flow and short circuit studies. Presently, the power-flow analyses for photovoltaic inverters are to use a synchronous machine model using steady-state constant real and reactive power model. It would be beneficial to the utility industry to have uniformity in distribution system analysis so comparisons can be made across platforms. The IEEE Distribution System Analysis Subcommittee has developed a number of "test feeders" for benchmarking distribution system analysis programs (Kersting 2006).

A distributed resource installation can be represented, as appropriate, by one of the following (IEEE 1547.7):

- A fixed source of real and reactive power
- A fixed source of real power, providing AC bus voltage control to a set level (subject to limits on reactive power output)
- A "swing" generator (only in a stand-alone power system), providing control of AC bus voltage, frequency, and phase angle (subject to limits on real and reactive power output).

On a bulk energy level, a PV inverter system operates similarly to any other traditional DER with the exception that most PV inverters operate at a unity power factor to maximize real power output. This results in most PV inverters being solely real power producers. A constant three-phase or single-phase power source, as is available in some unbalanced three-phase load flow modeling software packages, is thus sufficient to model PV inverter systems on the distribution grid. Reactive power, if generated by the PV inverter system, can also be included in the model as a constant reactive power source or sink.

3.6.2 Dynamic Stability Models

Stability studies have traditionally been focused on the transmission system, whereas stability issues are rarely considered on the distribution system. This is because most synchronous machines and induction motors connected at the distribution level are too small to cause power oscillation or stability problems to the grid. With the projected growth of DER coming on-line in the near future this could change and generic utility friendly inverter models will need to be developed to address these concerns. Stability studies are also helpful for identifying system parameters for the protective relaying during system contingency or disturbances.

The North American Electric Reliability Corporation (NERC) was formed in response to the blackouts in the northeastern United States in the 1960s to establish policies and standards for ensuring the reliability of the power system (Zavadil et al., 2005). NERC standards and guidelines for system reliability are implemented by the ten regional reliability organizations (RROs), see Figure 3-1. The interconnected nature of the bulk system demands close coordination and cooperation between these individual entities. There is immediate need for power system stability models to be developed for use by utility engineers for planning purposes.

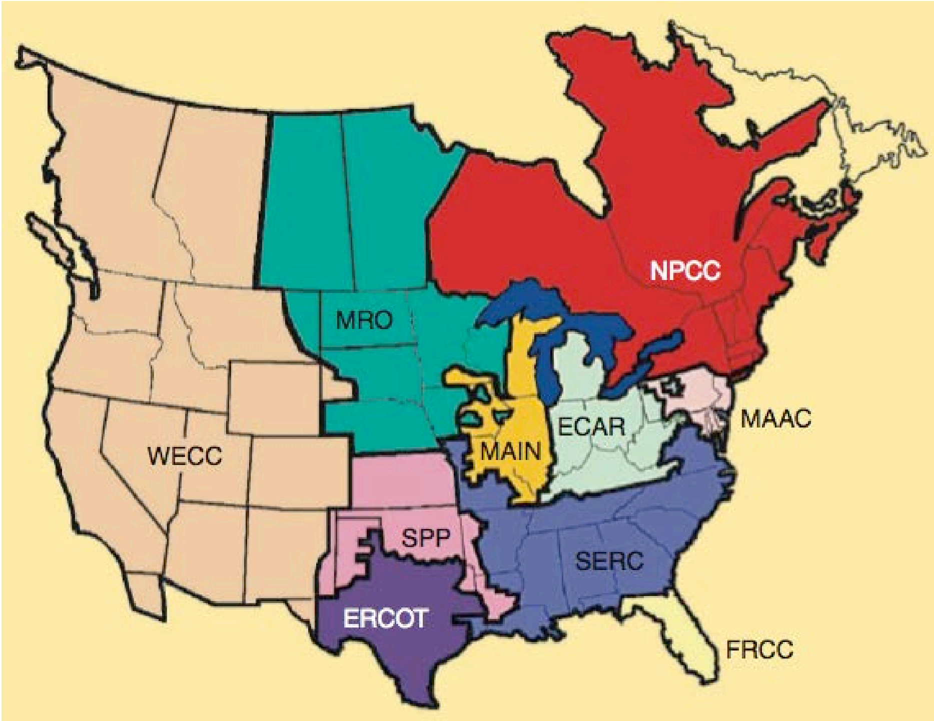

Figure 3-1. NERC (RROs) members

Source: IEEE Power and Energy Magazine 2005

NERC has identified the lack of validated, non-proprietary, positive sequence power flow and dynamic models for both transmission and distribution connected systems as a particular barrier for renewable energy development.

> "There is a need to develop and deploy valid, generic, non-confidential, and public standard power flow and stability (positive-sequence) models for variable generation technologies. Such models should be readily validated and publicly available to power utilities and all other industry stakeholders. Model parameters should be provided by variable generation manufacturers and a common model validation standard across all technologies should be adopted."
>
> (NERC Special Report, 2009).

Similar to PV inverters, the lack of suitable dynamic models for the wide variety of wind turbines available in the marketplace has been an obstacle in performing accurate analyses of this type, though efforts led by the Western Electricity Coordinating Council (WECC) to develop industry-standard wind turbine models are addressing this issue. The premise for coming up with a generic PV inverter model is to follow the lead of wind turbine Type-4 models. Type-4 wind models are fully rectified converters, very similar, if not identical to PV inverters. Therefore, it would be prudent to investigate what accomplishments have been made with Type-4 wind model efforts.

Generic models describing the dynamic characteristics of synchronous generators are readily available in software simulation packages as part of their standard library of models used for analysis. Accurate generic inverter-based dynamic models are non-existent. Today, inverter manufacturers view these models as proprietary and are not yet freely available are those for synchronous machine type dynamic models.

PV inverters can control output power, current, and voltage extremely quickly because they are not subject to conventional generation prime mover and exciter time constants that cause delayed response. Therefore, the inverter can control the AC output dramatically faster than synchronous generators. Due to this fast response (assumed to be instantaneous), the equipment associated with inverter-based DER can be modeled as an ideal current-limited, variable power source. The inverter input variability comes from the PV (DC side) array itself. This is due to the irradiance changes from clouds moving over the PV panel or array. The model should incorporate operational modes or parameters setting to ensure proper DER representation.

3.6.3 Transient Models

Models of PV inverter systems that emulate the general operational characteristics of individual PV inverter systems are required in order to understand the effects of connecting many small PV inverters to a common point on the distribution gird. These models would include general operational models of the PV inverter system such as: over-frequency trip, under-frequency trip, over-voltage trip, under-voltage trip, maximum power point tracking (MPPT) specific variables and anti-islanding methods. One study that develops a single-phase inverter model for a basic PV inverter including the effects of MPPT and anti-islanding ancillary functions using MATLAB/Simulink is presented by (Ropp and Gonzalez, 2008). In addition to the development of a single-phase inverter model, the study also simulates up to four single-phase inverters operating independently but attached to the same PCC. Specifically the performance of various anti-islanding detection functions is explored. Development of individual PV inverter models may lead to the ability to aggregate multiple PV inverter systems into a single operationally accurate PV inverter model greatly simplifying the effort required to model the operational stability of distribution systems with integrated PV inverters.

Detailed models are necessary to accurately study and simulate non-fundamental frequency disturbance. Some DER equipment may also be pre-certified from various authorities as a non-harmonic source. However, as discussed above, harmonic studies may still be necessary because of the harmonic sources that may be present. To help mitigate the effects of non-fundamental frequency present in the power system, it may be necessary to install inductive and capacitive power circuit filters. If the DER source is considered a potential harmonic source, the usual approach is to determine the steady-state frequency spectrum of the output current or voltage for rated operation, and to establish the frequency response of the power frequency-domain system analysis can identify the interaction between the source and the power system, including any potential resonance problems and the contribution to harmonic voltages at different buses in the power system (IEEE 1547.7).

Harmonic or transient models are used to determine harmonic voltages and currents. These highly detailed inverter models are typically developed using software tools such as, Matlab-Simulink and PSCAD.

4 Summary and Next Steps

In summary, this report describes the development of the economic HOMER simulation model and the cost assumptions made for the planned renewable energy projects by KIUC. The economic model indicates that KIUC can reach and exceed their goal of 50% renewable energy generation by 2023 in a cost-effective way. Depending on the renewable energy projects added into the generation mix, KIUC can reach their goals, reduce their overall LCOE and reduce the total fuel use by 51% to 53%.

Adding variable non-dispatchable generation such as PV can create potential high ramping rates on the diesel generators. The initial high level analysis indicates that the planned projects by KIUC have a balanced mix of renewable energy and should have low impact on the generation system. To further understand the impact of renewable energy on the electrical grid in Kaua'i, this report presents information on electrical power system models that are used in understanding the impacts of high penetrations of PV on the power system.

KIUC recently installed a 1.2 MW solar photovoltaic system on one of their electrical distribution feeders demonstrating high penetration levels of solar. According to KIUC during sunny days, the PV system can supply 90% of the demand required by the distribution circuit to which it is connected. The preliminary results in monitoring this circuit indicate that overall power quality has not been compromised. To accurately monitor the steady-state and transient response of KIUC PV systems, NREL plans to add data acquisition to capture electrical and environmental data from the installed PV system. The project will include nameplate data collection of electrical equipment at key points, enabling the development of high fidelity models of an electric power system with a high penetration of solar integration. The data collection will help to validate the models that are developed and NREL's work will continue to help Kaua'i meet its goal of 50% of its electricity coming from renewable energy by 2023.

Figure 4-1. 1.2 MW Photovoltaic array on Kaua'i, HI

(Credit: J. Keller, NREL)

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Appendix A: Resource Maps

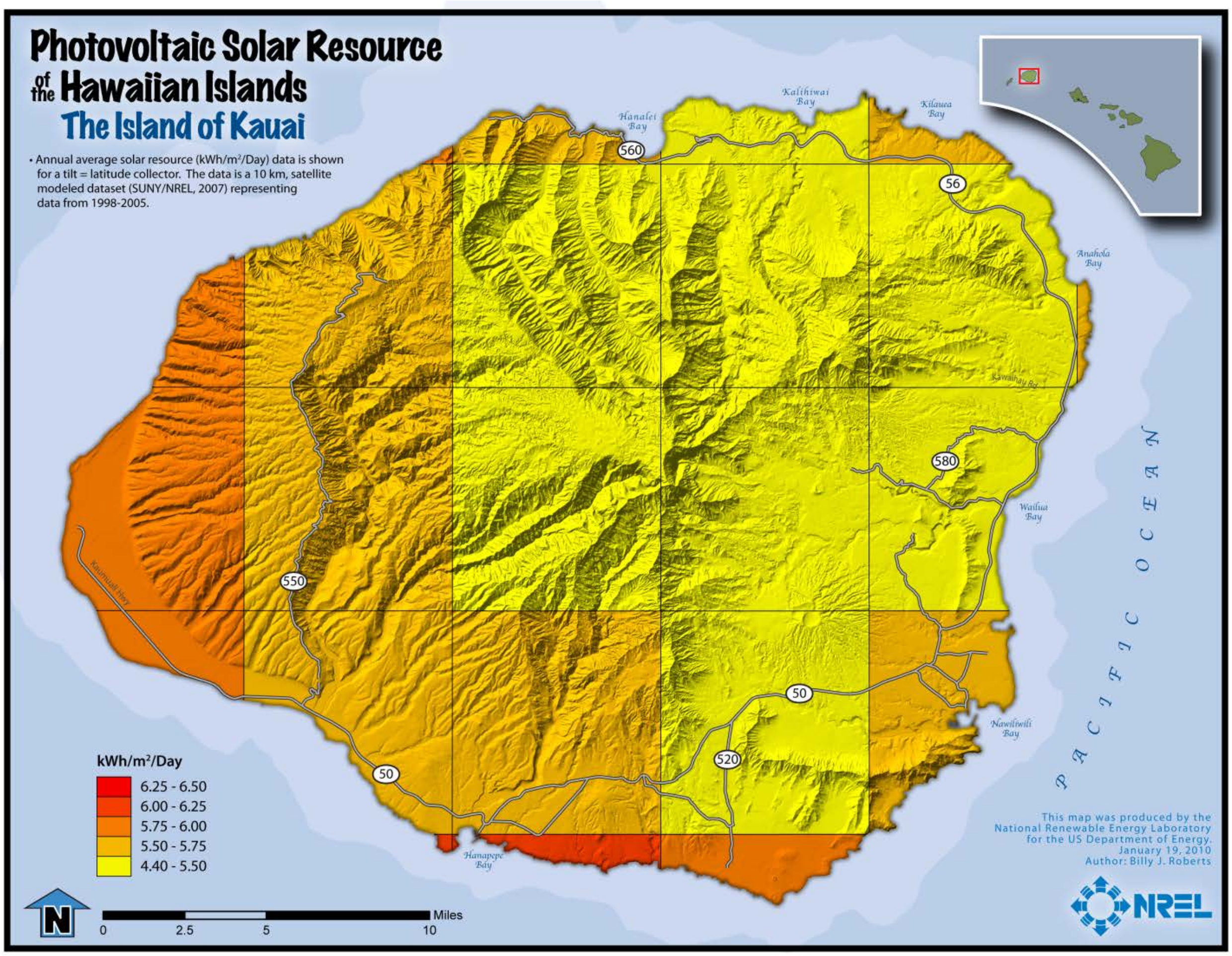

Figure A-1. Solar resource map for Kaua'i, HI

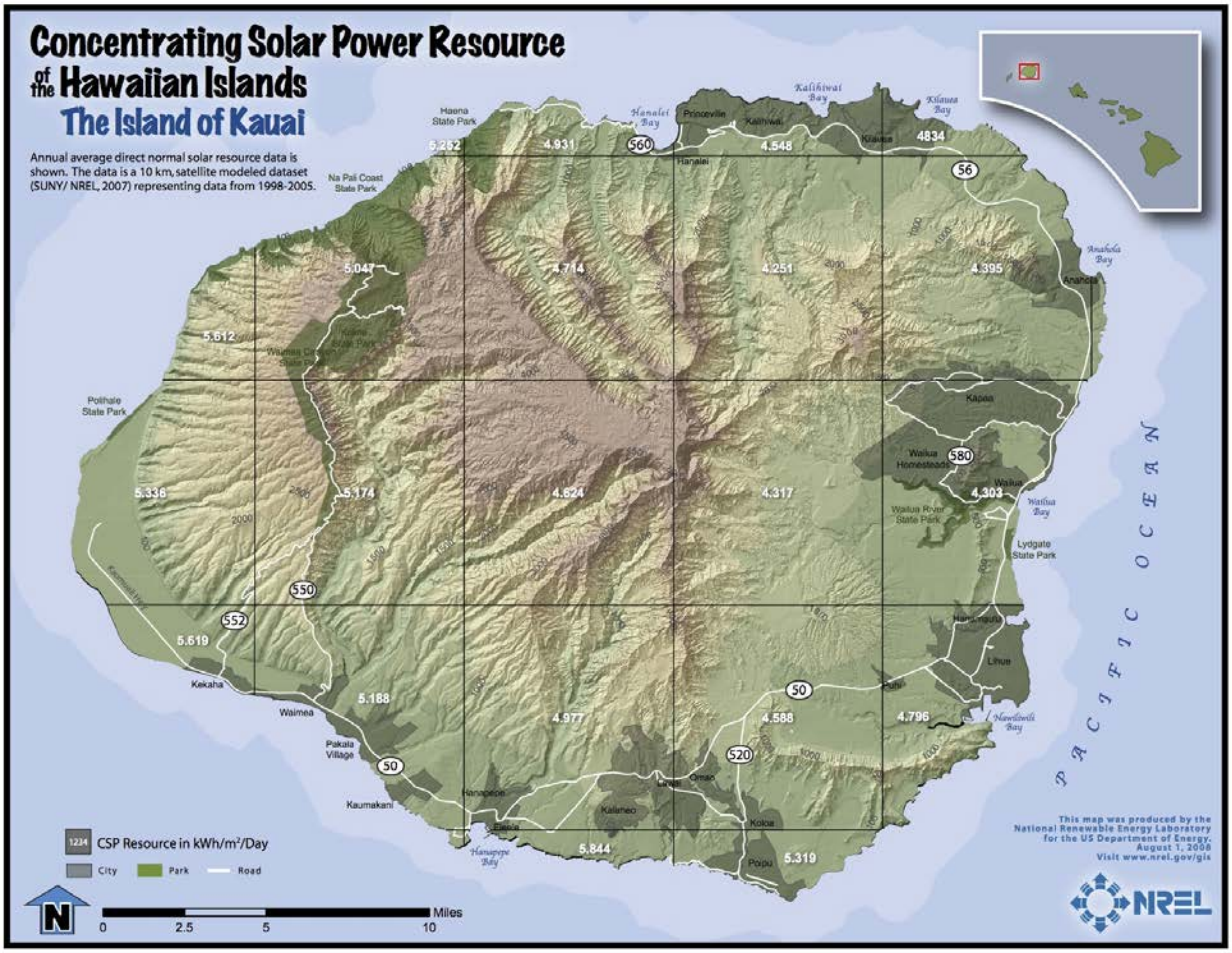

Figure A-2. Concentrating solar power resource map for Kaua'i, HI

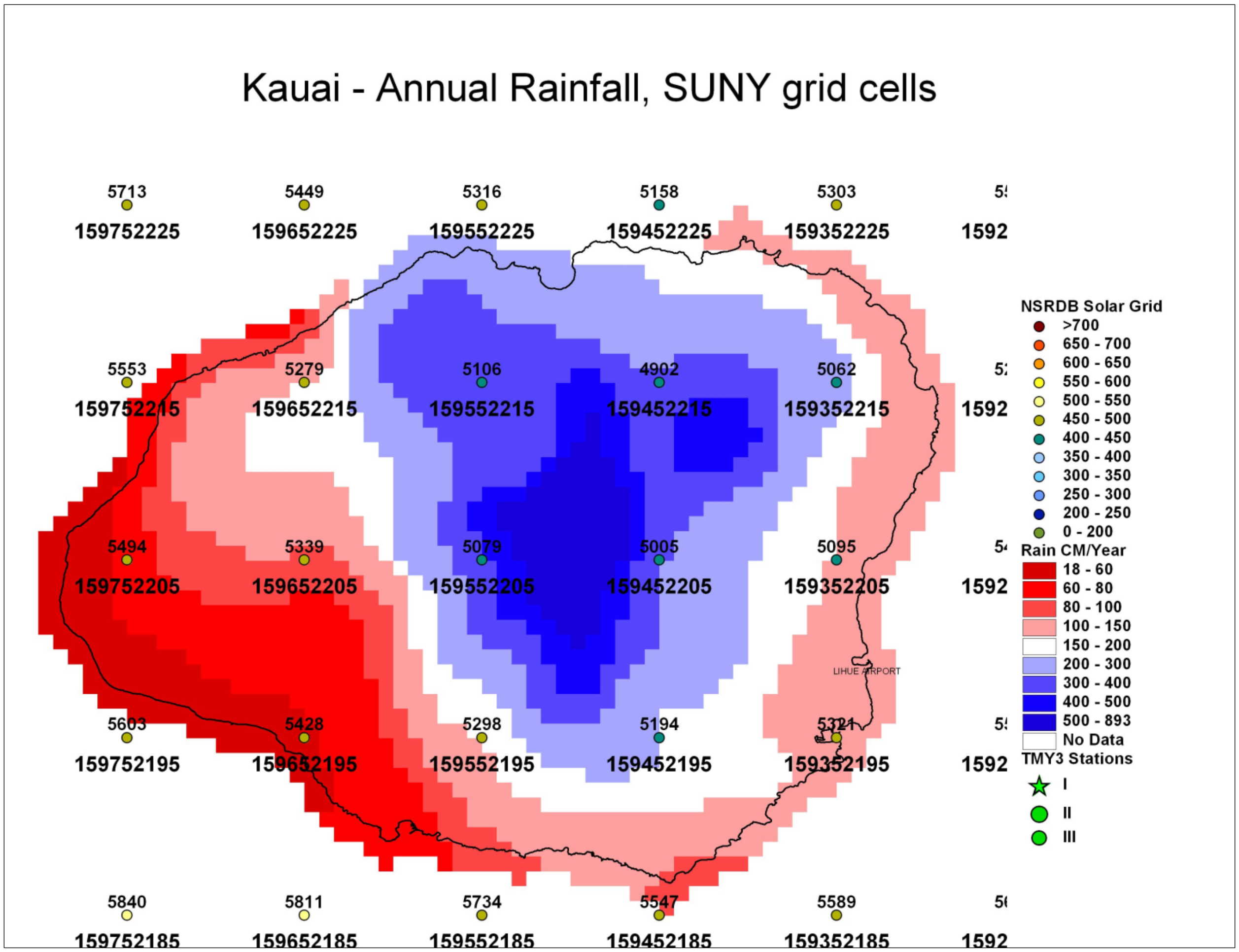

Figure A-3. Solar grid map of Kaua'i, HI

Source: NREL