Renewable Power Options for Electricity Generation: Molokai Case Study Leading to State-wide Analysis

Prepared for the

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by the

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1. Executive Summary and Background

Section 355 of the Energy Policy Act of 2005 requires the U.S. Department of Energy to "assess the economic implications of the dependence of the State of Hawaii on oil as the principal source of energy for the State," including "the technical and economic feasibility of increasing the contribution of renewable energy sources for generation of electricity, on an island-by-island basis …" The National Renewable Energy Laboratory (NREL) is assisting the Hawaii Natural Energy Institute (HNEI) in conducting the electric sector analysis. For the initial stage of the analysis, NREL employed a micropower optimization model known as HOMER (Optimization Model for Distributed Power) to conduct a preliminary analysis for the island of Molokai. Following completion of this analysis, it was agreed to use HOMER or a similar approach for analyzing the economics of renewable energy use in other parts of Hawaii.

NREL worked with Maui Electric to gather the data necessary for an initial test case for the island of Molokai. The resulting analysis shows that increasing levels of wind power in Molokai could be very cost-effective. Specifically, wind power could substantially reduce the consumption of diesel fuel for power generation on Molokai. The fuel use reduction could be from 38% to 70% with an overall lifecycle cost savings of 20% to 40%. These findings depend on a number of assumptions which are documented in this report. Electricity for photovoltaic systems was found not to be economic versus wind or diesel.

The Molokai analysis also highlighted some areas for further analysis that would be required before implementing high penetrations of renewable energy on Molokai or, for that matter, other parts of the state. Integration issues related to the variability of the wind resource are the most important issues. For example, the results depend strongly on how the utility handles these integration issues, such as the operating reserves they want (or need) to maintain and on operational issues associated with running diesels at lower load levels. However, even with very conservative estimates of these parameters, wind power still appears cost-effective at the lower level of the estimated savings. A more rigorous analysis will also require higher resolution wind data measured at promising locations on Molokai.

Additional analyses for other parts of the state were delayed due to funding issues. With this particular issue resolved, these types of analyses can be extrapolated to the other parts of the state using county-specific data, as available, along with similar approximations that were used in the analysis of the Molokai system. These analyses are currently in process.

2. HOMER as an Analysis Tool

This analysis was produced using NREL's HOMER computer model. HOMER simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand alone, and distributed generation (DG) applications. The model's optimization and sensitivity analysis algorithms allow evaluation of the economic and technical feasibility of a large number of technology options while accounting for variation in technology costs and energy resource availability. Information on technology characteristics is maintained at NREL. HOMER models both conventional and renewable energy technologies, including:

<u>Power Sources</u>

- solar photovoltaic (PV)
- wind turbine
- run-of-river hydro power
- generator: diesel, gasoline, biogas, alternative and custom fuels, co-fired
- electric utility grid
- micro-turbine
- fuel cell

<u>Storage</u>

- battery bank
- hydrogen

<u>Loads</u>

- daily profiles with seasonal variation
- deferrable (water pumping, refrigeration)
- thermal (space heating, crop drying)
- efficiency measures

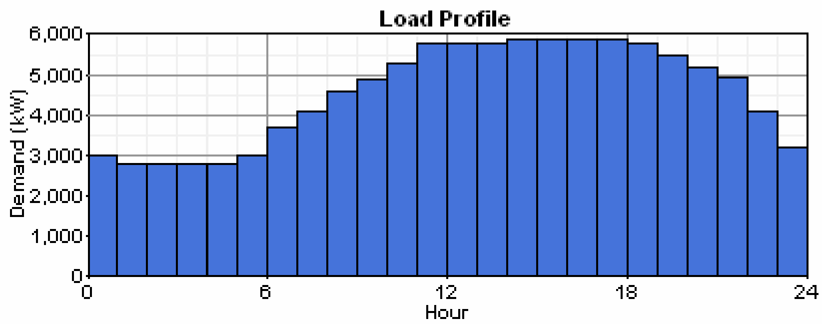
All of the inputs to the HOMER analysis are presented in the Appendix, which also presents charts for wind power density on all islands plus wind speeds for Maui County.

3. Molokai Power System

The Molokai power system consists of nine diesel-fueled reciprocating engines and one combustion turbine. The three newest and most efficient diesel units produce 96% of the total energy for the island. The other units are considerably older and less efficient, and are solely used for backup power. For this analysis, only the three main units were considered.

3.1. Loads

A load profile was created based on Molokai data that was received in a spreadsheet from Maui Electric Company (MECO), the utility that serves the island of Molokai. The spreadsheet listed the minimum loads and maximum morning and afternoon loads along with the time that they occurred. A separate spreadsheet showed the total kWh produced by each of the generation units in the Molokai system. Based on the first set of data, the following typical day profile was created:



Because there was very little seasonal variation in the data, the same profile was used for the entire year. "Noise" was added to the profile and the profile was scaled to match the annual peak load (6.4 MW) and total gross kWh (40,000 MWh). These values reflect a load factor of 71%, which is quite high for any utility system, but particularly for such a small system. However, based on discussions with Mike Ribao of MECO, it was concluded that it is a reasonable load factor for the Molokai system. The lack of significant seasonal variations and the relatively small penetration of building cooling loads on Molokai increase the load factor of the system. Furthermore, significant off-peak water pumping loads exist on Molokai.[1]

3.2. Diesel Operation and Maintenance Costs

MECO provided spreadsheets that listed their O&M costs by unit. In 2004 all three of the main units received 20,000 hour overhauls. The average cost of these three overhauls was $179,200. These costs are handled using HOMER's replacement cost and lifetime inputs. The remaining costs were averaged for 2004 and 2005 because the maintenance costs drop significantly after an overhaul. In this way, data from before and after the overhaul were averaged. The total cost of lube oil for 2005 was added and divided by the operating hours per year for each diesel (a value of 7,900 as provided by MECO) to derive a figure of $5.109 per operating hour.

3.3. Fuel Cost

It was assumed that MECO purchased its diesel fuel at a wholesale cost of $0.35 per liter or $1.32 per gallon.

3.4 Diesel Heat Rate

The three newest diesels are identical 2.2-MW Caterpillar 3608 gensets,[2] which produce more than 96% of the electric energy for Molokai. The older units are only used for backup power when the new units are not available because of maintenance. The new units have an average heat rate of 9,898 BTU/kWh, which corresponds to an average efficiency of 34%. Because data was not available on how the heat rate/efficiency varies with loading on the diesels, the following efficiency curve was estimated:

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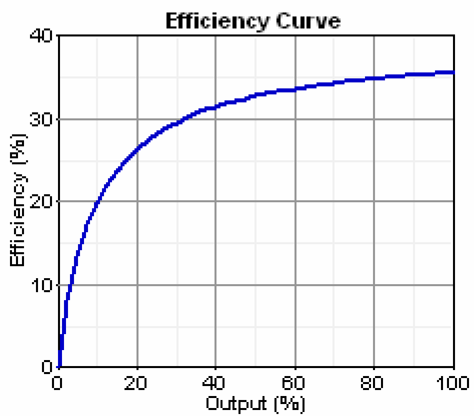
[1] These water pumping loads could be further managed to help integrate large quantities of variable wind power. HOMER has the ability to model water pumping as a deferrable load. This requires more data on the pumps and storage capacity than was available, and was beyond the scope of this initial analysis. It should be considered for more detailed analysis in the future.

[2] http://www.cat.com/cda/layout?m=56860&x=7



Under current operation, the diesels always run at 60% to 90% of their capacity. In a wind/diesel system, the units may run at lower load levels because the wind is carrying part of the load, but the diesel capacity needs to be on line to cover variations in the wind. Simpler analyses that only use the average diesel efficiency will overstate the diesel savings by overlooking this issue. Although we believe that the above curve is a good approximation for Molokai's diesel generators, this should be confirmed by further analysis.

3.5. Wind and Solar Potential

3.5.1. Wind

Wind resource data for the state of Hawaii are available through the State of Hawaii Web site.[3] The data for the island of Molokai is limited to seasonal average wind speeds for winter, spring, and summer for Ilio Point, which is insufficient for input to a HOMER analysis. However, the data shows that there is a qualitatively excellent wind resource on Molokai (see Table A-1).

Hourly wind data are preferable for a HOMER analysis. For this reason, wind data for Maui were used because they were viewed as the closest and most representative wind data available. Wind data is available for two sites on Maui: NifTal and Puunene. Of these two sites, NifTal has the better wind resource, but it is approximately the same as compared to the nine Hawaii sites for which annual wind data are available (see Table A-2). The other site, Puunene, has the lowest wind resource of the nine sites. For these reasons, the wind data for NifTal were used as the base case in the wind analysis for Molokai. Nevertheless, a sensitivity analysis was performed using the Puunene wind data to determine the effect of a weaker wind resource on this assessment. These results are discussed later.

For this analysis we modeled the use of the GE 1.5sl turbine, which has a peak output of 1.5 MW. We assumed its installed cost would be $2,550,000 or $1,700 per kW.[4]

3.5.2. Solar

The solar resource data for this analysis are from NASA's Surface Solar Energy Data Set, which provides monthly average solar radiation data for anywhere on earth.[5]

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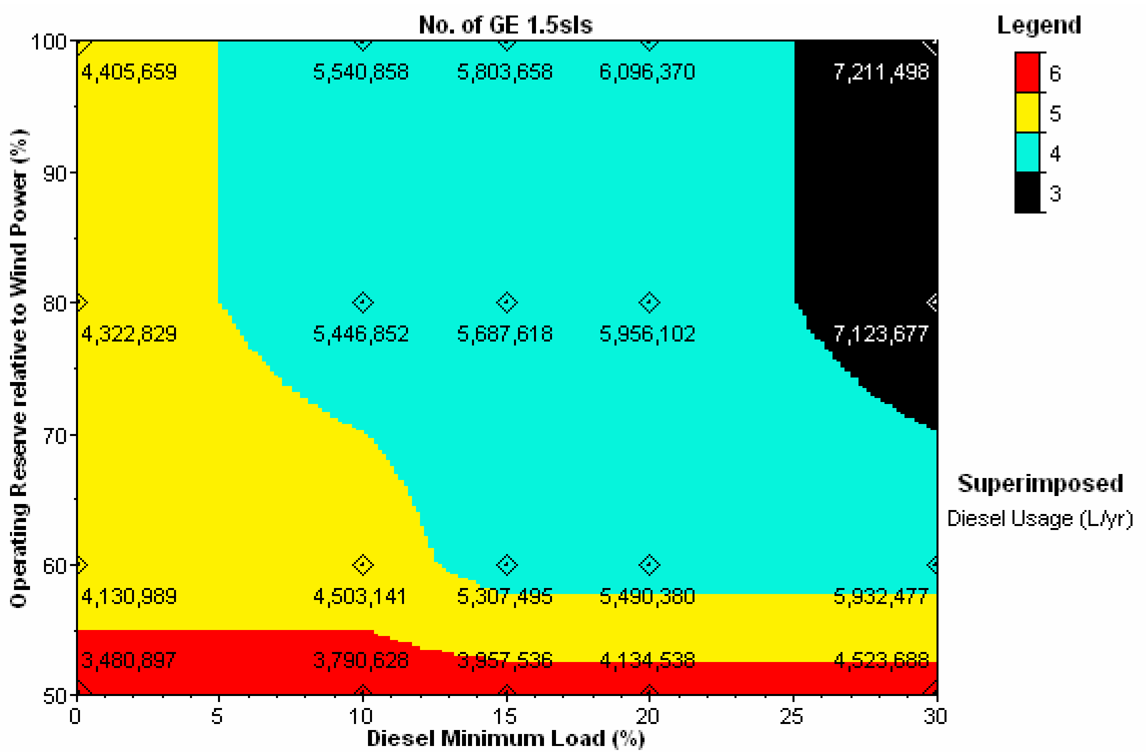
[3] http://www.hawaii.gov/dbedt/ert/winddata/winddata.html
[4] Use of the GE wind turbine is not meant as an endorsement of that particular turbine. Actual turbine choice will depend on availability and a variety of business development issues that are beyond the scope of this study.
[5] http://eosweb.larc.nasa.gov/sse/

4. Molokai Analysis

Several cases were run to test the sensitivity of the results to several variables. Some of these variables are uncertain while others can be determined by decisions that MECO can make over how to dispatch the diesel generators within their system. These decisions can have a substantial effect on the integration of wind power into the system. As shown in the following graphic, the optimal number of 1.5-MW turbines varies from three to six and the resulting fuel consumption varies from 3,480,000 liters to 7,211,000 liters. This represents a potential savings of 34% to 68% compared to the current diesel fuel consumption of approximately 11,000,000 liters.



4.1. Operating Reserve Relative to Wind Power

MECO must maintain operating reserves to cover both increases in the load and decreases in the power output of the wind turbines. This is modeled in HOMER by requiring the operating capacity to be greater than the load plus the operating reserves. The operating capacity is equal to the sum of the wind output in a particular hour plus the maximum capacity of the diesel generators that are operating in that hour even if the output of the generators in that hour is less than their maximum capacity. If the operating reserve relative to wind power is set to 100%, the system could lose all of its wind power within that hour and still be able to meet the load. In that scenario, the diesels are dispatched without regard to the wind turbines. Based on conversations with MECO, it was decided to also model cases with reduced operating reserves sufficient to cover the unexpected loss of 50% of the wind capacity within an hour. This allows some of the diesel capacity to be turned off during periods of high wind power output. Additional reserves to cover 10% of the load were modeled but without a sensitivity analysis.

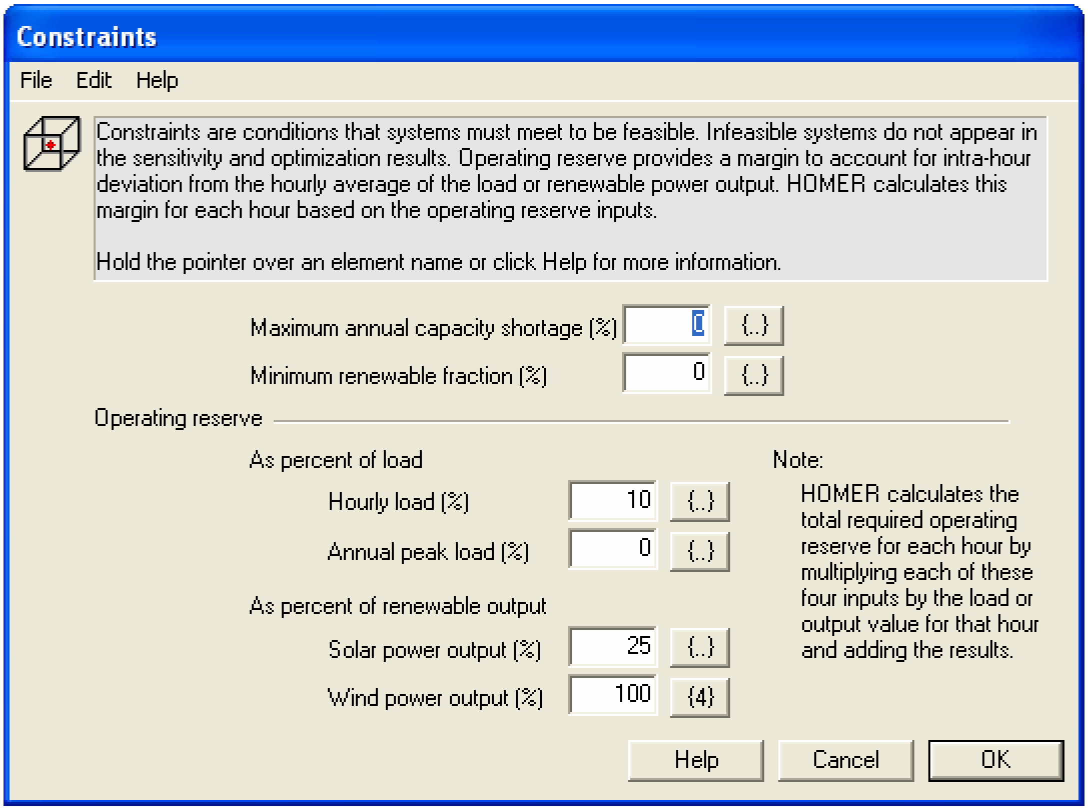
4.2. Diesel Minimum Load

A simultaneous sensitivity was performed on the diesel minimum load. This is a constraint in HOMER that prevents the diesels from ever operating below that level. To maintain this constraint it may be necessary to curtail wind power or send electricity to a dump load. Additional modeling would be required to consider scenarios where this excess energy would be used for water pumping or other deferrable loads.

There are two reasons why system operators may want to enforce a minimum load on the diesels. First, the efficiency of a generator falls quite steeply as its load decreases.[6] Second, extended operation of diesels at low loads can create maintenance problems for some diesels. HOMER calculates the operation and maintenance costs of diesels as a function of their operating hours. That cost neither increases nor decreases as a function of the load on the diesel. This is preferable to modeling the O&M cost as a function of the kWh output of the diesels which would cause an apparent reduction in O&M cost when the diesels ran at low load. The diesel minimum load constraint in HOMER is intended to accommodate the concerns of diesel operators for maintenance problems that may occur at low loads. Our experience is that these potential problems depend strongly on the specific diesel, the operator's maintenance regime, and the frequency and duration of the low load operations. For these reasons we chose not to explicitly model these maintenance issues but perform sensitivity analysis on the diesel minimum load as a constraint.

The results illustrate an interesting interaction between these two variables. A conservative approach to the operating reserve will require diesel generators to operate when they are only required as a reserve; the actual load on the generators will be very small. This raises the cost of enforcing a diesel minimum load. If both variables are set at the most conservative level, the optimal wind penetration is only 3 turbines or 4.5 MW. If a less conservative approach can be taken to either of these variables, more wind turbines become part of the optimal solution. In fact, at the least conservative values that were modeled for either of these variables, the other variable becomes quite insignificant.

[6] If this were the only consideration it would probably not be appropriate to enforce this constraint in HOMER because the model considers the economic trade-off of additional fuel costs in its system optimization. In other words, it may be preferable to occasionally run the diesels in an inefficient mode if that allows a configuration with a higher overall system efficiency.



In the example illustrated by the previous figure, HOMER requires that there is always sufficient diesel capacity on-line to handle a 10% increase in load or a 100% drop in wind power. The button, {4}, is used to access HOMER sensitivity analysis capability. It shows that separate optimizations were run for four different levels of operating reserve. The results are shown below:

Min Load = 10%,

OR Wind (%)	1.5sl	Total NPC	COE ($/kWh)	Diesel (L)	Diesel operating hours
100	4	$41,117,856	0.081	5,540,858	23,242
80	4	$40,475,260	0.079	5,446,852	22,204
60	5	$38,388,740	0.075	4,503,141	18,248
50	6	$37,404,328	0.073	3,790,628	14,823

Lower levels of required operating reserve reduce the net present cost (NPC) by allowing diesels to be turned off when they are running relatively inefficiently at low load levels. This makes it cost-effective to also use more turbines. More detailed analysis considering the wind turbulence, its intra-hour variability, the characteristics of specific wind turbines and their power electronics, and the geographic dispersion of the turbines and the characteristics of the grid is necessary to determine the level of operating reserve that is needed to achieve desired levels of reliability.

4.3. Wind Analysis Results

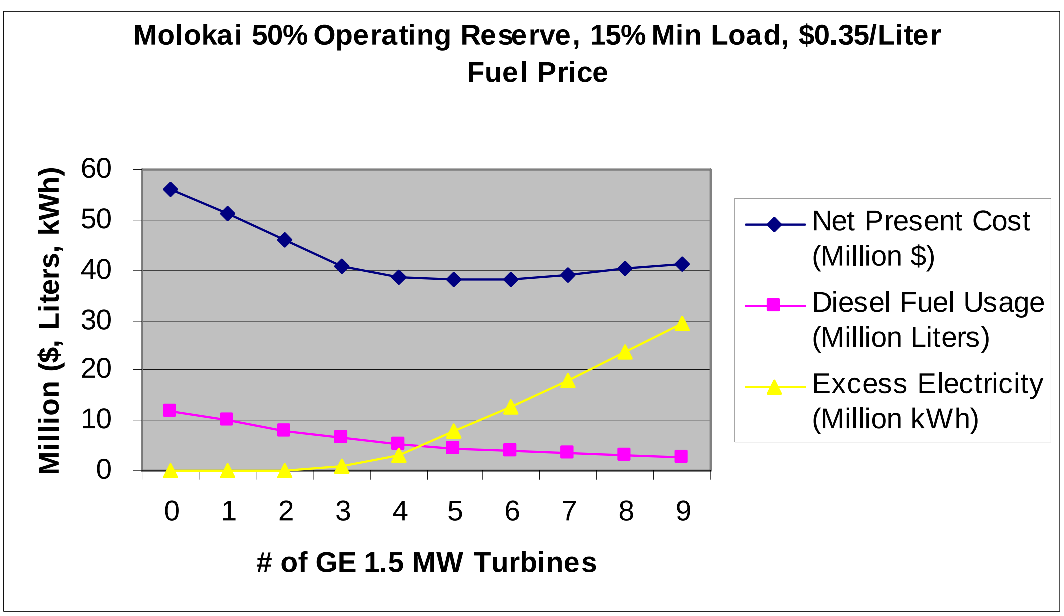
4.3.1. Base Case

For the base case, wind data was used from NifTal, an average wind site in Maui (referenced above in the 'Wind and Solar Potential' section), with an assumed 50% operating reserve and a minimum allowable load on the generator of 15% (as a percentage of its rated capacity). The "winning" scenario is highlighted below:

Base-Case Results:

# of Turbines	Total NPC	COE ($/kWh)	Diesel (L)	Total Diesel Hours
6	$38,095,976	0.075	3,957,536	14,823
5	$38,269,540	0.075	4,579,089	16,986
4	$38,423,756	0.075	5,231,787	18,248
7	$39,049,772	0.076	3,552,076	13,557
8	$40,426,000	0.079	3,233,271	12,482
3	$40,829,224	0.08	6,384,156	19,615
9	$41,281,768	0.081	2,833,339	10,557
2	$45,870,400	0.09	8,094,459	21,736
1	$51,072,448	0.1	9,886,042	22,742
0	$56,121,372	0.11	11,664,148	23,242

The chart below details the interplay between cost, diesel fuel usage and excess electricity. It can be seen that the least-cost scenario is comprised of six turbines. Intuitively, as the number of turbines increases, the diesel fuel usage decreases due to the production of wind to offset diesel fuel usage. However, it is important to pay attention to the excess electricity produced. The first three to four turbines displace fuel consumption at a constant rate because the system is able to use all of the wind output. Above four turbines, the rate of fuel savings drops off because the system is not able to use the wind energy that is produced when the wind is high and the load is low. This is clearly shown by the increasing amounts of excess wind energy.



4.3.2. Sensitivity Analysis with Lower Wind Resource

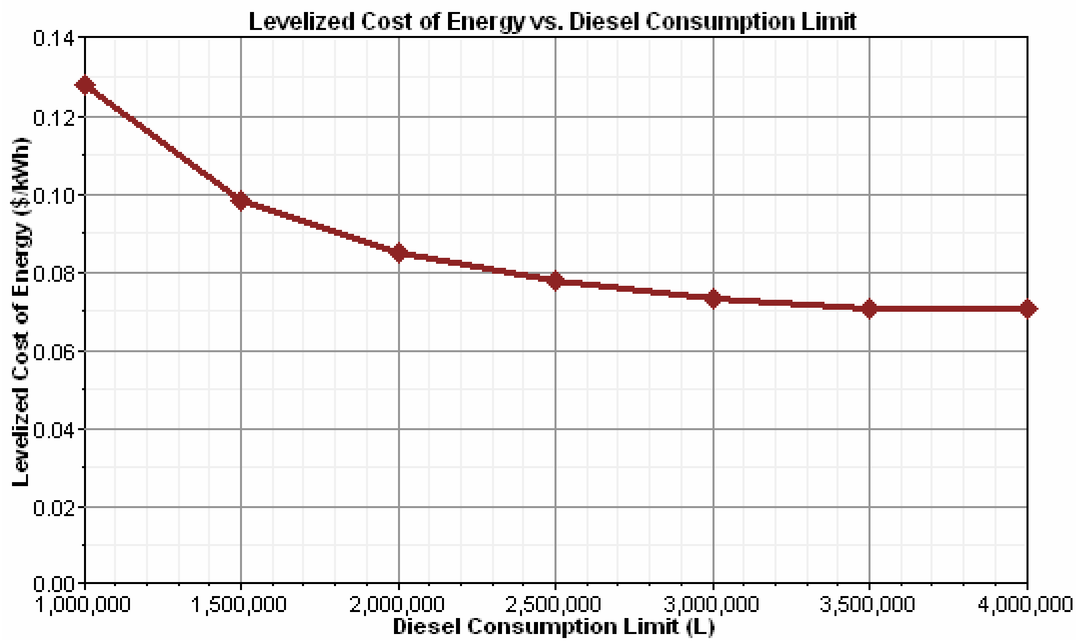
A sensitivity analysis was also performed using Puunene wind data, which is the lowest wind resource of the nine Hawaii sites. This analysis was done to examine the effect of a lower wind resource on the feasibility of wind turbines on Molokai. The results show that wind turbine deployment on Molokai is still cost effective. However, the least-cost system comprises four turbines and uses 7,477,717 liters of fuel (highlighted, below) when a weaker wind resource is available. So, even if Molokai has a weaker wind resource than assumed in the base-case scenario, wind is still cost effective but on a smaller scale.

Min Load=15% and OR = 50% Results:

# of Turbines	Total NPC	COE ($/kWh)	Diesel (L)	Total Diesel Hours
4	$48,830,104	0.096	7,477,717	20,226
3	$49,266,564	0.096	8,213,146	21,017
5	$49,649,876	0.097	7,025,236	19,389
6	$50,471,844	0.099	6,591,421	18,098
2	$51,406,616	0.101	9,308,762	22,300
7	$51,927,556	0.102	6,278,425	17,322
8	$53,608,540	0.105	6,012,349	16,635
1	$53,808,504	0.105	10,488,595	22,964
9	$54,947,780	0.108	5,692,886	15,386
0	$56,121,372	0.11	11,664,148	23,242

4.4. Potential for Greater Savings

In addition to identifying the least-cost system, HOMER can also perform a constrained optimization. This constrained optimization was used to identify the least-cost approach to achieving additional diesel fuel savings. In order to achieve greater fuel savings, the use of large-scale vanadium redox flow batteries was considered. (It should be noted that this is not meant to be an endorsement of vanadium-coupled systems, since the utilities in Hawaii are considering other systems, such as the sodium-sulfur batteries for energy storage.) The results in the following graph refer only to the busbar cost of electricity and do not include distribution or administrative costs. In the base-case analysis, the lowest cost system contained six turbines and no storage and consumed approximately 4,000,000 liters of fuel. The following graph shows that additional fuel savings can be achieved at an increasing cost of energy.



4.5. Photovoltaic Analysis Results

Preliminary analysis was performed on the cost-effectiveness of photovoltaics. A sensitivity analysis was performed in HOMER on the capital cost of photovoltaics. PV was not part of the optimal solution until its capital cost was less than $1.50 per watt, including inverter and installation costs; the exceptionally good wind resource comparatively reduces the cost-effectiveness of photovoltaics. When all technological and operational aspects of the cost-effective wind are considered, there are substantial periods of time when excess energy is available. During these periods, any power produced by PV would not be usable. These results could change with the use of more load management or storage and could be examined further in a more detailed analysis.

4.6. Potential for Load Management

There is considerable opportunity for load management in Molokai. In particular, there is a substantial water pumping load which is currently being managed by pumping at night. This is an appropriate load management practice for the current system and is partly responsible for the high load factor of the Molokai system. A more detailed analysis should be performed to identify ways to modify this strategy under a scenario with a high level of wind penetration.

5. Summary of Findings and Strategy for Analyzing the Other Islands

5.1. Molokai Findings

This initial analysis shows a high potential for wind power to reduce diesel consumption and overall utility costs on Molokai. Overall lifecycle costs could be reduced by 20% to 40% and diesel fuel consumption could be reduced by 38% to 70%. Additional analysis is warranted in the following areas:

- Molokai-specific wind data.
- Diesel-fuel cost sensitivity.

- Collaboration with MECO on operating reserves and minimum diesel load.
- Part-load performance of existing diesel generators.
- Potential for load management, particularly the water pumping load.
- Development costs for the wind farm.
- Alternative turbine types.
- The potential for energy storage.

The most important need is to verify the actual wind resource on Molokai. It is reasonable to expect that an excellent resource will be found there, but the current analysis used data from the other Hawaiian Islands. We also recommend that similar analyses be conducted for the other islands, where feasible.[7]

5.2. Assessment of Renewable Resource Use on Other Islands

This analysis has demonstrated that utilization of NREL models and data bases can be effectively utilized for other islands in Hawaii. Given that almost all of the islands to be analyzed are larger than Molokai (Oahu by more than two orders of magnitude), some approximations will need to be made with the information that is available to make the system work in a timely and effective manner.

NREL has now received funding to proceed with the additional state-wide analyses. Discussions are now underway with all of the utility system operators for all of the counties. It is anticipated that this overall effort will be completed consistent with the reporting requirement for the United States Department of Energy. This report must be evaluated in comparison to other scenarios outlined in Section 355. From this, the impacts of the implementation of these scenarios on refinery operation and, from that, the state economy must be evaluated and assessed. The resulting document will be sent from DOE to the Congress.

[7] Although better wind data exists for other islands, other model approximations will be needed because of HOMER's current limitation of modeling three diesel generators. NREL has overcome this limitation in the past by aggregating generators, which provides a reasonable approximation for a pre-feasibility analysis. NREL intends to enhance HOMER to handle a larger number of generators by early summer 2007.

APPENDIX – Hawaii Wind Resource Data

TABLE A-1

Data from 1980-1982 wind monitoring program of the U.S. Department of Energy.

Station Name	Lat	Long	Elev	Start	End	HT	Annual	Winter	Spring	Summer	Autumn
	dd.mm	ddd.mmm	m	yymmdd	Yymmdd	m	mph	mph	Mph	mph	mph
ILIO POINT, MOLOKAI	21.13	-157.15	61	810101	820531	45.7	24.4	20.8	23.5	30.9	
						30.0	18.1	11.6	17.7	23.5	
						9.1	16.3	11.9	17.4	18.3	
KAHUA RANCH, HAWAII	29.07	-155.47	1030	810201	820228	45.7	25.3		27.1	31.1	22.4
						30.0	20.6	19	23.7	23.7	17.4
						9.1	19.2	14.8	19.7	20.1	21.5
KAHUKU POINT, OAHU	21.42	-157.60	108	800901	820531	45.7	18.1	14.5	21.3		20.6
						30.0	17.9	14.3	20.8		19.9
						9.1	17	13.2	19.9		19.0

TABLE A-2

Data collected between 1992 and 1994 under the Hawaii Energy Strategy project.

Island	Location	Dates	Height	Average mph	text file
Hawaii	Kahua Ranch	1/28/92 - 6/1/94	90 feet	15.80	krab0192.txt
Hawaii	Kahua Ranch	1/28/92 - 6/1/94	140 feet	16.22	kraa0192.txt
Hawaii	Lalamilo Wells	11/14/91 - 6/1/94	90 feet	16.88	lalb1191.txt
Hawaii	Lalamilo Wells	8/23/91 – 3/24/94	140 feet	17.19	lala0891.txt
Hawaii	Lalamilo Wells	10/31/93 - 12/11/94	60 feet	20.51	lalb1093.txt
Hawaii	Lalamilo Wells	10/31/93 - 12/11/94	90 feet	21.77	lala1093.txt
Hawaii	North Kohala	10/30/93 - 12/11/94	60 feet	20.38	nkob1093.txt
Hawaii	North Kohala	10/30/93 - 12/11/94	90 feet	22.21	nkoa1093.txt
Oahu	Kahuku	12/05/93 - 12/12/94	60 feet	15.00	kahb1293.txt

Oahu	Kahuku	12/05/93 - 12/12/94	90 feet	16.35	kaha1293.txt
Oahu	Kaena Point	10/10/93 - 12/11/94	60 feet	13.87	kaeb1093.txt
Oahu	Kaena Point	10/10/93 - 12/11/94	90 feet	15.07	kaea1093.txt
Kauai	Anahola	11/07/93 - 11/23/94	60 feet	11.75	anab1193.txt
Kauai	Anahola	11/07/93 - 11/23/94	80 feet	12.98	anaa1193.txt
Kauai	N. of Hanapepe	11/06/93 - 12/31/94	60 feet	16.38	hanb1193.txt
Kauai	N. of Hanapepe	11/06/93 - 12/31/94	90 feet	16.96	hana1193.txt
Maui	NifTal	9/11/93 – 1/16/95	60 feet	12.88	halb0993.txt
Maui	NifTal	9/11/93 – 1/16/95	90 feet	14.82	hala0993.txt
Maui	Puunene	9/11/93 – 1/16/95	90 feet	12.46	puua0993.txt
Maui	Puunene	9/11/93 – 9/30/94	60 feet	11.03	puub0993.txt

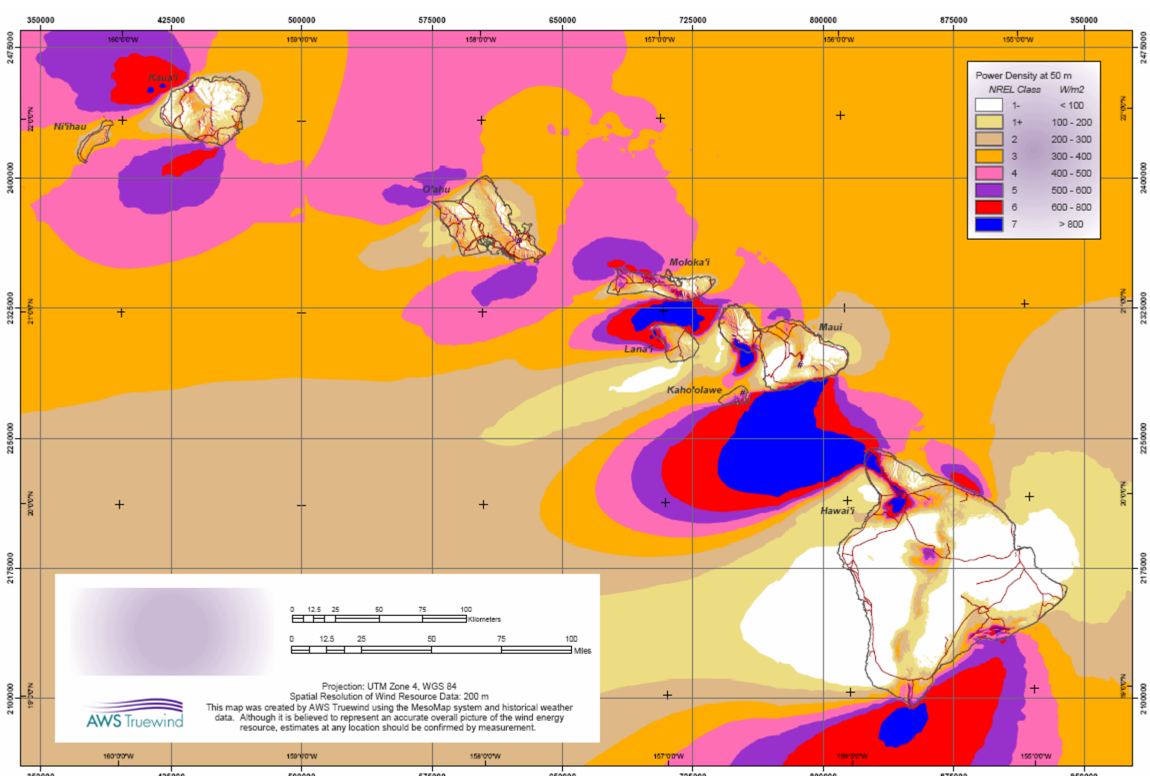


Figure A-1 Wind Power Density of Hawaii at 50 m

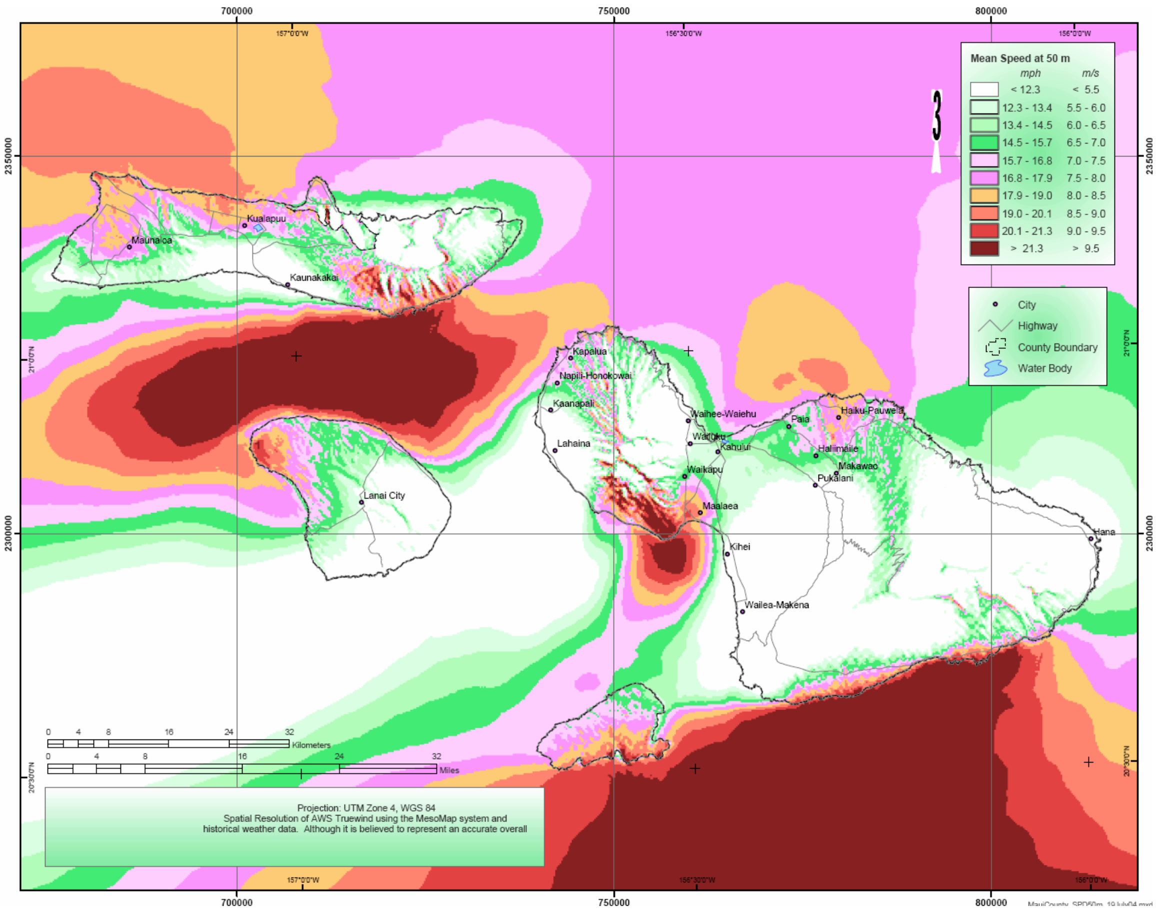


Figure A-2 Wind Speeds for Maui County at 50 m