

Optimizing Wind Energy for a Small Hybrid Wind/Diesel Grid in the Galapagos Islands

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ABSTRACT

In 2007 2.4 MW of wind turbines began operation on San Cristobal Island in the Galapagos but mismatch between wind resource and electric demand leaves significant demand still met by diesel generation. The University of California, Davis, working with EleGalapagos, investigated two approaches to reduce diesel consumption: Lowering demand through energy efficiency and using demand response incorporating temporary and permanent load shifting. Strategies were evaluated according to fuel savings, cost of saving fuel, and capital cost. Replacing lighting in addition to permanent load shifting offered the highest potential diesel savings and lowest cost while replacing refrigerators was not found cost-effective.



1. INTRODUCTION

Environmental disasters, such as spills from tankers and air pollution brought about by the consumption of diesel for electricity generation threaten the fragile ecosystem of the Galapagos Islands, Ecuador. San Cristobal, one of the four inhabited Galapagos Islands, has the second largest population of 5,970 [1] and prior to 2007, three 650 kW diesel generators were the only source of electricity. In October 2007, three wind turbines with a total capacity of 2.4 MW were installed and began commercial operation to minimize the use of diesel on the island. The wind resource is intermittent, and the output of the turbines can be greater or less than the peak electricity demand of approximately 900 kW. Industry Energy Associates (IEA), which played a leading role in the installation of these turbines, approached the University of California, Davis to model the grid configuration and make recommendations. This study focuses on determining the most economically and environmentally sound approach to utilize the excess the wind resource and minimize the diesel consumption on the island.

The San Cristobal Wind Project is a partnership between the E8 COMPANIES, which is composed of electricity companies that operate in the national territories of the G8 countries (Canada, France, Germany, Italy, Japan, United Kingdom, Russian Federation and the United States),” and Empresa Electrica Provincial Galapagos ElecGalapagos S.A, which is a local utility company on the island [2]. The operation of the program is also in coordination with UNDP umbrella program with the funding donated by the E8 members, the United Nations Foundation, the government of Ecuador, and 2004 Designated Income Tax Payments by Ecuadorian contributors through Municipality of San Cristobal [3]. The funding fully covered the cost of installation.

Industry Energy Associates originally considered installing three 660 kW fixed speed, or induction type, wind turbines with a battery energy storage system. A competitive bid process led to the installation of three 800 kW variable speed, or synchronous type, wind turbines without battery energy storage [2]. The reason for choosing this option was not disclosed, although it is estimated that a turbine capacity of 1,980 kW was deemed insufficient to continue to supply the rapidly growing

electric demand on the island even with the presence of the battery system.

Electrical demand on San Cristobal

Figure 1 shows the electric demand in San Cristobal by end use. According to user surveys by Solarquest [4], refrigerators account for 37 percent of the electricity consumption and account for the largest demand on the island. Air-conditioning systems and lighting are the second and third electric largest, with 21 and 17 percent of the electric demand respectively.

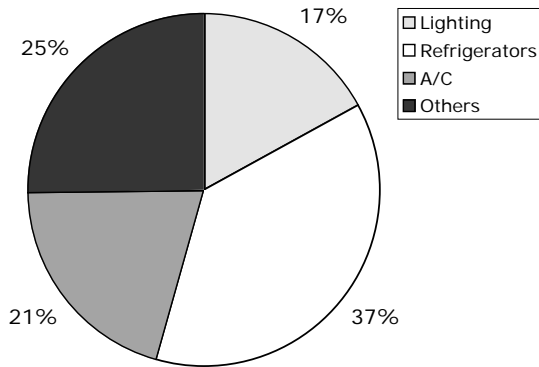


Figure 1: Electricity demand (2008) for San Cristobal by end use [4]

Based on historic wind data and turbine manufactures performance specifications, the annual production of wind energy is estimated to be 7,749,200 kWh/yr and is approximately equal to the annual electric demand on the island of 7,996,00 kWh/yr in 2008 [5]. Due to the absence of energy storage in the grid system, it is estimated that approximately 56 percent of the wind-based electricity is going to be un-utilized in 2008, with only 44 percent (3,409,600 kWh/yr) feeding the grid system. This accounts for only 43 percent of the annual electric demand on the island, thus 57 percent will still need to be met by the three existing 650 kW diesel generators (figure 2).

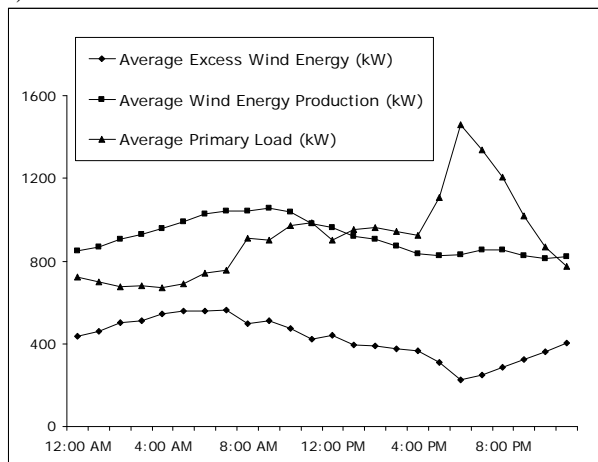


Figure 2: Mismatch between annual average primary load and average wind output

2. MAIN SECTION

Scope

This scope of this study was limited to the present wind/hybrid grid configuration and current consumer and commercial electrical demand on San Cristobal. Data for this study were obtained through interviews with stakeholders and utility officials, field research, literature review, and consumer use surveys for the island. This investigation focused on the potential of two diesel fuel reduction strategies: 1) lowering the primary demand for electricity through improvement of energy efficiency (EEI), and 2) using a demand response system (DR) to modulate a portion of the load to more effectively capture excess wind energy.

The first strategy investigates the potential of energy efficiency improvements, in particular replacing existing refrigerators and incandescent light bulbs with new high efficiency units. Three different case studies of energy efficiency improvements were examined in terms of their fuel saving potential and cost-effectiveness: 1) refrigerators, 2) lights, and 3) the combination of both. This study assumes that high efficiency refrigerators to be implemented would be 40 percent more efficient than the current models in use on the island. The high efficiency light bulbs were assumed to be 75 percent more efficient than the current models on the island. These energy efficiency criteria were modelled after the Energy Star program initiated by the U.S. Department of Energy and the U.S. Environmental Protection Agency.

The second strategy considers the effectiveness of demand response (DR). Demand response is defined as “a set of time-dependent activities that reduce or shift electricity use to improve electricity grid reliability, manage electricity costs, and encourage load shifting or shedding when the grid is near its capacity or electricity prices are high [6].” Under this scheme the utility company would shift a portion of the electric demand to more effectively utilize the wind resource on the island. Often this is done by having consumers agree to have particular loads made deferrable in exchange for a rate reduction. In this study DR is utilized through two approaches. The first DR strategy is temporary load-shifting (TLS). TLS requires deferrable loads to be turned off for sufficient time for a diesel generator to be brought on-line, reducing the need for spinning reserve, approximately 15 minutes. The TLS system presented here also replaces one of the three 650 kW generators with two 325 kW generators, so the smaller generators can be shut down sequentially, allowing for further spinning reserve reduction opportunities. The second DR strategy is permanent load shifting (PLS) which defers a portion of the electrical demand up to several hours per day. In this scenario, the grid system would service deferrable loads when the wind generation rate exceeds the electric demand. Conversely, when the electricity demand on the island exceeds the wind power production, these loads can be turned off for specified periods of time. Examples of permanent deferrable loads on the island

include water pumping and treatment, thermal storage refrigerators, air conditioners, and industrial and commercial activities that can be performed at alternate times.

Methodology

Six scenarios were modelled to compare the above diesel fuel saving strategies and are presented in Table 1. Scenario 1 represents the grid before the wind turbines were installed and Scenario 2 is the present configuration or “base case” as seen in figure 3. Scenario 3 includes energy efficiency improvements as outlined previously, scenario 4 and 5 are demand response strategies incorporating temporary and permanent load shifting, and Scenario 6 combines energy efficiency improvements and permanent load shifting. These scenarios were modelled using historic wind and current consumer demand data for San Cristobal. Each scenario was evaluated for its diesel saving potential (liters/yr), the capital cost (\$), and the cost of saving diesel (\$/liter).

Table 1: Scenarios considered in this study

Scenario	Diesel	Wind	EEI	Downsize Generator	TLS	PLS
1-Diesel	o					
2-Base Case	o	o				
3-EEI	o	o	o			
4-TLS	o	o		o	o	
5-PLS	o	o				o
6-Combination	o	o	o	o	o	o

The “cost of saving fuel” measures the financial burden to the ElecGalapagos and the Ecuadorian government to reduce diesel fuel consumption for each of the proposed scenarios. If the cost of saving diesel is below the diesel price that ElecGalapagos and the Ecuadorian government pay, it will make economic sense to implement the scenario. It should be noted that on the island of San Cristobal, the cost of diesel for electric production is subsidized at \$0.245/liter from \$0.670 per liter by the Ecuadorian government. Therefore, a proposed scenario will provide a financial incentive to the ElecGalapagos if they could reduce the consumption of diesel fuel at a cost below \$0.245/liter. The Ecuadorian government receives the incentive as long as the cost of saving diesel is below \$0.670/liter.

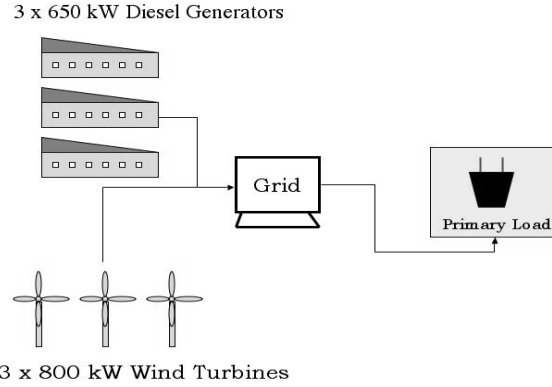


Figure 3: Current grid configuration for San Cristobal

Levelized cost of electricity

For this study the National Renewable Energy Lab (NREL) economic analysis software “HOMER” [7] was used to estimate the levelized cost of electricity (LCE) for each scenario. The analysis attempted to include the major costs for each system over its lifetime including initial investment, operations and maintenance, cost of fuel and cost of capitol. For the LCE determination, a net present value calculation was performed and solved in such a way that for the value of the LCE chosen, the project's net present value was zero. Thus the LCE is the minimum average price at which energy must be sold (over the lifetime of the project) to break even and is defined as:

$$LCE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

where

- LCE = Average lifetime levelized electricity generation cost
- I_t = Investment expenditures in the year t
- M_t = Operations and maintenance expenditures in the year t
- F_t = Fuel expenditures in the year t
- E_t = Electricity generation in the year t
- r = Discount rate
- n = Lifetime of the system

Analysis of each scenario was conducted under the following assumptions:

- Subsidized price of diesel = \$0.245/liter
- Unsubsidized cost of diesel = \$0.670/liter
- Economics of wind turbines, diesel generators, and deferrable loads are based on ElecGalapagos's expenditure

- Minimum load ratio of diesel generators (under idling) = 25%
- Annual primary load remains constant during the simulation period
- Real discount rate = 8.5 %
- Simulation period = 15 years
- Operating reserve = 12 %
- Operational life of generators = 30,000 hours

Primary Load Profile

The primary electric load profile refers to the estimated demand data in 2008 created by IEA, and the average daily load was 21,905 kWh/day [5]. The data consist of the annual average hourly load and the monthly load profile as shown in Figures 4 and 5 respectively. SolarQuest® provided average hourly load profiles for refrigerators and lights on the island, and they are shown in figure 4 along with the primary load [8]. As the figure represents, the refrigerator load is relatively constant while lighting load is concentrated in the evening.

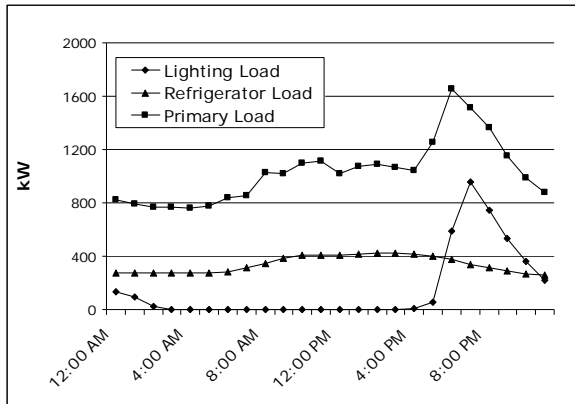


Figure 4: Overview of load profiles

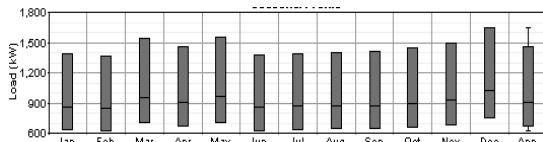


Figure 5: Seasonal primary load profile

Wind resource data

IEA provided hourly wind-speed data and the production capacity for wind turbines was obtained from the manufacturer (see Figure 6). Predicted monthly power output as seen in figure 7 was created based on the wind profile and the production profile of the turbines. Note that monthly average wind speed on the island is higher from July through December, closely overlapping with the wet season, which lasts from June to December in the Galapagos [9].

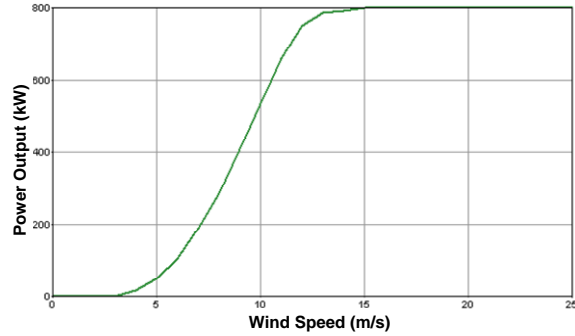


Figure 6: Power curve for MADE model AE59Turbine

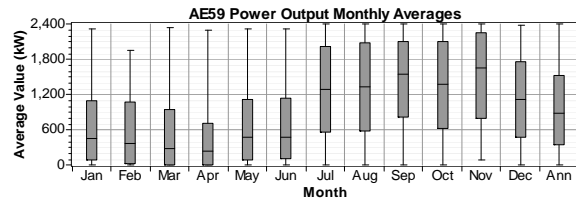


Figure 7: Monthly Average Power Outputs of the Turbines

Wind Turbine Economics

The economics of wind power in remote locations varies widely depending on the particular installation. For example, Hemri et al. investigated the feasibility of a wind-diesel hybrid grid system in a remote village in Algeria and used \$958/kW as the capital cost and \$667/kW as the replacement cost to install 600 kW capacity of a wind turbine in the village [10]. Greiner et al. examined the potential of a 2 to 3 MW wind turbine to supply 650 residents on a Norwegian island, located in 20 km off the coast of the main continent. They set the initial investment of installing the turbine at 900 Euro/kW (or \$1,431/kW) [11].

The actual installation cost of the wind turbines in San Cristobal was significantly higher than the initial estimate by the Galapagos Wind Project. The project initially estimated the capital cost of the 2.4 MW capacity of wind turbines to be \$5,000,000 (or \$2,083/kW) [3, 12-14]. The actual installation of the turbines resulted in \$9,840,000 (or \$4,100/kW) “due to the logistical and environmental challenges of building in the Galapagos, lack of island infrastructure, and the high diesel displacement objectives of the project” [3]. In this study estimates for the turbine lifetime, annual O&M cost, and replacement cost were based on the analyses conducted by Himri et al. and Greiner et al. Himri et al. using 25 years lifetime, 2.3 percent of the capital cost as annual O&M cost, and 70 percent of the capital cost as replacement cost [10, 11]. Greiner et al. assumed a turbine lifetime of 20 years, and annual O&M cost equalled to 2 percent of turbine’s capital cost, and did not specify replacement cost [11]. This study averaged the values from the two sources and set the turbine life time to be 22.5 years, O&M as 2.15 percent of the capital cost, and replacement cost to be 70 percent of the capital cost [10, 11].

Diesel generation economics

The figures used for estimating diesel generator capital and O&M are presented in table 2. This study used estimates based on Singal et al. and Arun et al.'s. Singal et al. for the capital cost of diesel generators in Neil Island in India (\$444/kW) and annual O&M costs equal to 2 percent of the capital cost [15]. Arun et al. estimated the present cost of diesel generators at \$556/kW and the annual O&M cost as 2.5 percent of the generator capital cost [16]. Our analysis uses the average of these two estimates and sets the generator cost at \$500/kW ($= (\$444/\text{kW} + \$556/\text{kW})/2$) and annual O&M cost as 2.25 percent of the generator cost (\$11.25/kW/yr). These studies neglect the cost of transporting generators to the island, which could make a significant difference in the Galapagos. To account for this, this study considered a "low generator cost" of \$500/kW and a "high generator cost" case. The high generator cost was determined based on a comparison between the initial estimate the Galapagos Wind Project made on the installation cost of the wind turbines (\$5,000,000 or \$2,083/kW), and the typical installation cost of wind turbines (\$958/kW - \$1,431/kW) [3, 11, 14, 17]. This study first calculated the average value of these general installation costs, \$1,195/kW ($= (\$958/\text{kW} + \$1,431/\text{kW})/2$), and found the ratio between the Galapagos Wind Project's initial estimate and the averaged regular installation cost, which was 1.74 ($= 2,083/1,195$). Referring to the ratio, this study made an assumption that the high generator cost was 1.74 times more costly than the low generator cost, and this led the cost to be \$870/kW ($= \500×1.74) with an assumed annual O&M cost of \$19.58/kW/yr ($= \11.25×1.74).

Table 2: Cost Table for Diesel Generators

	Generator cost (\$/kW)	O&M cost (\$/kW/yr)
Generator cost (high)	870	19.6
Generator cost (low)	500	11.3

Energy-efficient lighting and refrigerators

The high-efficiency refrigerators and lighting considered in this study were assumed to meet the standard for the Energy Star program, which is set by the U.S. Department of Energy and the U.S. Environmental Protection Agency [18]. Based on the energy consumption data provided by Solarquest, it was assumed that high-efficiency refrigerators consume 40 percent less electricity than the average refrigerators in San Cristobal, and high efficiency lighting would consume 75 percent less electricity than the incandescent light bulbs on the island. Based on a product search our grid modelling was conducted for a range of prices for high efficiency refrigerators and lighting [19]. A replacement cost of \$400/unit is assumed for the low refrigerator cost, and \$800/unit for the high refrigerator cost. Similarly, the average cost of fluorescent light bulbs is set at \$300/kW as the high lighting cost and \$100/kW as the low lighting cost.

Economic considerations for demand response (DR)

This study assumes that a remote controlled modulating system (RCMS) is incorporated into the grid system to implement demand response with the utilization of deferrable loads. A RCMS consists of a personal computer, an energy management system (EMS), a signalling device, and signal receivers. An EMS is commonly used by utility companies in recent years to optimize the performances of their grid systems[20]. A utility company needs to make a modification on its EMS to manage DR, and the modification can be easily completed by its vender [20]. With the modification, an EMS enables the utility company to monitor the signals sent to its deferrable loads and the signals replied by the deferrable loads to confirm that they received the signals and were modulated [20]. This study considered three different signalling devices: power carrier signals, cellular phones, and radio data systems (RDS). Refrigerators are planned to serve as primary electric appliances for deferrable loads, and the total number of refrigerators on the island is estimated to be 3,755 [8]. Because the first two options are unable to send signals to a large number of signal receptors, assume that a radio data system is incorporated into the remote control system as the signalling unit. A high end model, used by radio stations, is found at approximately \$10,000 [20]. DR needs a signal receiver on each deferrable load. A grid system signals to the receiver of each targeted load through a signalling device. This signal receiver modulates the load and returns a signal to the grid to confirm that load modulation is completed. A signal receiver can cost as low as \$20 per unit if it only needs to shut down and turn on the load [20].

This study conducted the analysis for deferrable load capacities of 10, 20, and 40 percent of the primary electric demand [8]. The annual electricity consumption in San Cristobal is 7,995,960 kWh/yr[5]. The average electric demand on the island can be calculated by dividing the annual energy consumption by the number of hours in a year (8,760 hours) and thus is 913 kW. It was assumed that the capacity of the deferrable loads is constant. This allows the capacities of 10 percent, 20 percent, and 40 percent deferrable loads to be estimated based on the average electric demand of 913 kW, at 91 kW, 182 kW, and 364 kW respectively.

The total capital costs and annual O&M costs for demand response strategies in this study are represented in Table 3. The minimum costs of RDSs and signal receivers are assumed to be \$10,000 per unit and \$20 per unit respectively [20]. To include the cost of installation, this study set the capital costs of these devices to be at \$20,000/unit and \$40/unit. Mr. Jim Torpey, at Madison Energy Consultants, examined the economics of DR and set the annual O&M costs at \$30/kW/yr for small controllable loads (20-50 kW), \$18/kW/yr for medium size controllable loads (51-300 kW), and \$10/kW/yr for large controllable loads (above 301 kW) [21]. The total capital cost is the sum of the RDS and signal receiver

installation cost for each deferrable capacity. The cost of RDS remains constant at \$20,000 because there is one unit needed to serve the role regardless of the deferrable capacities.

Table 9: Estimated costs of deferrable loads [20, 21]

	RDS price (\$/unit)	Total capital cost (\$)	O&M cost (\$/kW/yr)
10% Deferrable load (91 kW)	20,000	60,444	18
20% Deferrable load (182 kW)	20,000	100,900	18
40% Deferrable load (364 kW)	60,444	181,800	10

3. RESULTS

The simulation results are presented in table 4. The capital costs, cost of saving fuel, and fuel saving potential were calculated by comparing the values to the base case scenario, which represents the current grid system on the island (Wind + Diesel).

Table 4: Simulation Results

Scenario	Capital Cost (\$)	Cost of Saving Fuel (\$/liter)	Diesel Saving (liter/yr)
Scenario 1: Diesel Only	N/A	N/A	-588,000
Scenario 2: Diesel + Wind (Base Case)	N/A	N/A	0
Scenario 3:			
EEI of Refrigerators			
25 % replacement	375,800 - 751,600	1.34 - 2.74	32,700
50 % replacement	751,600 - 1,503,300	1.32 - 2.72	65,600
75 % replacement	1,127,400 - 2,254,900	0.82 - 1.85	140,900
100% replacement	1,503,300 - 3,006,500	0.71 - 1.63	213,800
EEI of Lighting			
25 % replacement	3,700 - 11,000	0 - 0.11	19,600
50 % replacement	7,300 - 22,000	0 - 0.08	45,500
75 % replacement	11,000 - 33,000	0 - 0.08	65,500
100% replacement	14,700 - 44,000	0 - 0.09	81,000
EEI of Refrigerators & Lighting			
75/75 % replacement	1,138,400 - 2,287,900	0.49 - 1.19	215,400
Scenario 4:			
Temporary Load Shifting (TLS)	501,800 - 742,300	0.66 - 0.92	79,200
Scenario 5:			
Permanent Load Shifting (PLS)			
10 % deferrable	55,400	0.03 - 0.06	54,900 - 55,100
20 % deferrable	95,900	0	156,700 - 165,400
40 % deferrable	176,800	0	282,400 - 300,900
Scenario 6:			
EEI of Lighting + PLS	106,900 - 128,900	0 - 0.04	233,800
EEI of Refrigerators & Lighting + PLS	1,234,300 - 2,387,800	0.23 - 0.70	353,300

Scenario 3: Energy Efficiency Improvements

The simulation revealed that replacement of refrigerators had a higher fuel saving potential (32,000-213,000 liters) than lighting. However, the cost of saving diesel was above \$0.670/liter therefore replacement of refrigerators provides no financial incentive to either ElecGalapagos or the Ecuadorian government for this intervention. The fuel saving potential from the replacement of incandescent lights proved to be only moderate (20,000- 80,000 liters) but cost-effective at \$0.09-\$0.10) per liter saved.

Scenario 4: Temporary Load Shifting

The fuel saving associated with the TLS scenario (79,200 liters) is realized solely from the reduced time the diesel generators spend idling. High, capital cost including a remote controlled modulating system and replacement of one of the 650 kW generators by two 325 kW generators lead to a high cost of saving fuel (\$0.66-\$0.92 per liter) for this scenario.

Scenario 5: Permanent Load Shifting

PLS was demonstrated to have substantial fuel savings potential (approximately 55,000-300,000 liters) and be cost-effective at \$0.03-\$0.06 per liter saved. The fuel saving potential increased significantly as the fraction of deferrable load increased and the cost of saving fuel became essentially zero.

Scenario 6: Combination of EEI, PLS

The fuel saving potential of 10% PLS was improved by including the replacement of selected lighting (up to 233,000 liters), while remaining a cost-effective option at \$0.04 per liter saved. Combining the replacement refrigerators and lights with 10% PLS achieves the cost of saving fuel at \$0.23-\$0.70/liter, perhaps providing financial incentives to the Ecuadorian government.

Discussion

The HOMER simulation revealed that purchasing energy-efficient refrigerators for the residents failed to be a cost-effective approach. However, the ElecGalapagos and the Ecuadorian government might still be able to provide large subsidies to encourage the residents to purchase them.

The maximum subsidies per energy-efficient refrigerator replaced while maintaining the cost of saving fuel at \$0.245/liter for the ElecGalapagos and \$0.670/liter for the Ecuadorian government is presented in table 5. The large jump in subsidy between 25 and 50 percent replacement occurred because 50 percent replacement would reduce the electric demand enough to shut down one of the two diesel generators, which had been operating or idling. Simultaneous replacement of lights and refrigerators increases the maximum subsidy per refrigerator because replacing lights cost effectively reduces fuel consumption, so it creates more budget to provide refrigerator subsidy. In addition, the Ecuadorian government can offer a larger subsidy than the utility, because fuel costs to them is \$0.67/liter instead of \$0.245/liter.

Table 5: Maximum subsidy, which can be provided for each energy-efficient refrigerator to maintain cost-effectiveness

Refrigerators only		
Percent Replacement of refrigerators	Max subsidy for Utility (\$/unit)	Max subsidy for Government (\$/unit)
25%	84	207
50%	90	213
75%	160	337
100%	179	380
With 75 % replacement of lighting		
75%	234	504

4. CONCLUSION

“The cheapest kWh of energy to produce is one you never use in the first place.”

This study outlines opportunities to overcome traditional issues associated with hybrid grids, i.e. energy storage and spinning reserve vs. reliability, without a costly dedicated energy storage system. Often the implementation of energy efficiency opportunities is the most cost-effective and should be investigated first. In small remote electrical grids with high fuel costs and an overabundance of off-peak renewable energy available, load shifting can also be cost-effective.

For the current San Cristobal grid configuration in this study replacement of lighting in addition to a demand response system with permanent load shifting offered the most diesel savings and lower overall operating cost for EleGalapagos and the Ecuadorian government. Although replacement of refrigerators was not found to be cost-effective if the full financial burden was placed on the government or ElecGalapagos to purchase the units, a large subsidy could still be provided for each energy-efficient refrigerator to encourage the residents to purchase them.

Although efforts were made to obtain the best data available, it should be noted that estimates presented in this study are based on simulations and many other factors may affect the actual diesel and cost savings. Furthermore some options (i.e. pumped hydro) may have environmental impacts not acceptable in the Galapagos. Pricing for demand response systems and controls are speculative since these are yet to be implemented in and environment similar to the Galapagos. Thermal storage refrigeration is a promising demand response option candidate, since refrigeration is the primary electricity end use on the island, but the technology is immature so performance and cost figure are also speculative. There are other issues which should be considered including consumer behavior, supply chains for energy-efficient devices, real diesel cost, as well as instability in governmental policy and subsidies

Future work by the UC Davis Energy Efficiency includes further investigation of thermal storage refrigeration to determine cost and performance parameters as well as a pilot demand response system in the Galapagos using the current water purification facility as a deferrable load.

6. AUTHOR(S)

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Kurt Kornbluth holds a PhD in MAE from UC Davis, is a Business Development Fellow, and the founder of the UC Davis Program for International Energy Technology (PIET). He received a 2008 World Bank Lighting Africa Development Marketplace grant to design and disseminate a low-cost lighting in Zambia and

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Presenter:

The paper is presented by Kurt Kornbluth.

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