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Kauai Island Utility Cooperative Energy Storage Study

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Abstract

Sandia National Laboratories performed an assessment of the benefits of energy storage for the Kauai Island Utility Cooperative. This report documents the methodology and results of this study from a generation and production-side benefits perspective only.

ACKNOWLEDGMENTS

Sandia National Laboratories (SNL) was the lead for this study and the authors want to acknowledge the support and cooperation of several Kauai Island Utility Cooperative (KIUC) staff.

The SNL authors also want to recognize the patient support and guidance of Mike Yamane (also a co-author of this report) and Dutch Achenbach, President and CEO, KIUC, for his unflagging support of this effort.

Brad Rockwell and Carey Koide made time in their busy schedules to provide an understanding of the KIUC system operations and provided the generation and the Commodities data. Jack Leavitt explained the T&D operations and system detail, and several other KIUC staff spent time acquainting the SNL study team with system details that are not always available from operations manuals and datasheets.

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EXECUTIVE SUMMARY

Sandia National Laboratories (SNL) was funded by Kauai Island Utility Cooperative (KIUC) to study the benefits of energy storage for the KIUC system. Energy storage has proven advantages for island locations such as Puerto Rico and Metlakatla and mainland Alaska, which technically is an “island” in terms of its electrically isolated grid.

The KIUC energy storage study focused on the economic impact of using energy storage to shave the system peak, which reduces generator run time and consequently reduces fuel and operation and maintenance (O&M) costs. It was determined that a 16-MWh energy storage system would suit KIUC’s needs, taking into account the size of the 13 individual generation units in the KIUC system and a system peak of 78 MW. The analysis shows that an energy storage system substantially reduces the run time of Units D1, D2, D3, and D5 – the four smallest and oldest diesel generators at the Port Allen generating plant. The availability of stored energy also evens the diurnal variability of the remaining generation units during the off- and on-peak periods. However, the net economic benefit is insufficient to justify a load-leveling type of energy storage system at this time. While the presence of storage helps reduce the run time of the smaller and older units, the economic dispatch changes and the largest most efficient unit in the KIUC system, the 27.5-MW steam-injected combustion turbine at Kapaia, is run for extra hours to provide the recharge energy for the storage system. The economic benefits of the storage is significantly reduced because the charging energy for the storage is derived from the same fuel source as the peak generation source it displaces.

This situation would be substantially different if there were a renewable energy source available to charge the storage. Especially, if there is a wind generation resource introduced in the KIUC system, there may be a potential of capturing the load-leveling benefits as well as using the storage to dampen the dynamic instability that the wind generation could introduce into the KIUC grid. General Electric is presently conducting such a study and results of this study will be available in the near future.

Another study conducted by Electric Power Systems, Inc. (EPS) in May 2006 took a broader approach to determine the causes of KIUC system outages. This study concluded that energy storage with batteries will provide stability benefits and possibly eliminate the load shedding while also providing positive voltage control.

Due to the lack of fuel diversity in the KIUC generation mix, SNL recommends that KIUC continue its efforts to quantify the dynamic benefits of storage. The value of the dynamic benefits, especially as an enabler of renewable generation such as wind energy, may be far greater than the production cost benefits alone. A combination of these benefits may provide KIUC sufficient positive economic and operational benefits to implement an energy storage project that will contribute to the overall enhancement of the KIUC system.

SECTION 1: Background and KIUC Perspective

Kauai Island Utility Cooperative (KIUC) is a not-for-profit electric cooperative that generates, transmits, and distributes electric power on the island of Kauai. The co-op's service territory covers 622 square miles, serves 29,000 members/owners, and employs 150 people. The system peak, December 30, 2004, was 76.09 MW. KIUC has two main generating facilities, located at Port Allen and Kapaia. Port Allen currently has 12 generating machines capable of producing 96.5 MW plus a heat recovery steam generator. The Kapaia Power Station facility is a 27.5-MW steam-injected gas turbine. Its output makes it the largest generating unit on the island. KIUC also owns two small hydroelectric plants and it purchases power from other hydro electric units located throughout the island. Hydro output is approximately 7.6% of total sales.

<i>Port Allen Power Plant</i>		Capacity	Name	Type	Brand	Year in service	Efficiency	#	Individual Capacities
		4.0	D1/2	diesel	EMD	1964	34%	2	2.0
		10.0	S1	steam turbine	GE	1968	22%	1	10.0
		8.2	D3/4/5	diesel	EMD	1968	34%	3	2.7
		19.2	GT1	combustion turbine	Hitachi/GE	1973	29%	1	19.2
		23.7	GT2	combustion turbine	John Brown/GE	1977	32%	1	23.7
		15.7	D6/7	diesel	Wartsila	1989	37%	2	7.9
		15.7	D8/9	diesel	Wartsila	1991	37%	2	7.9

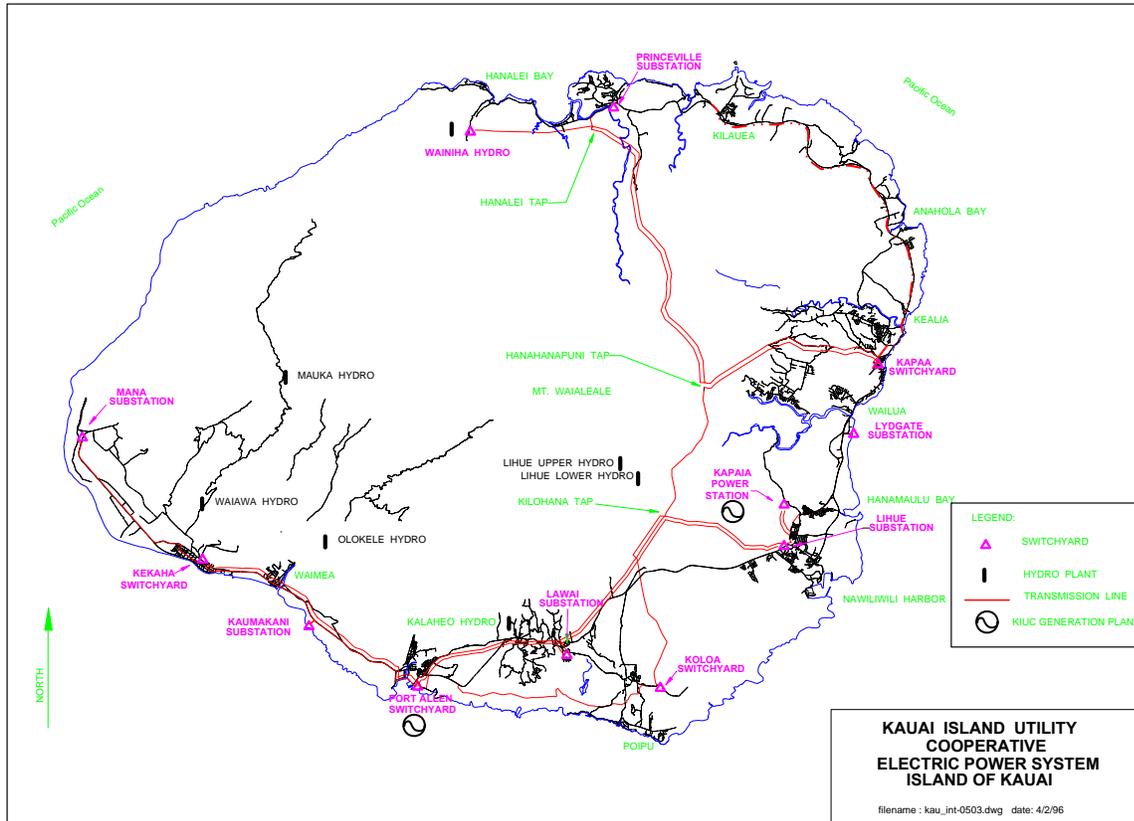
Port Allen currently has 12 generating machines capable of producing 96,500 kW's, plus a heat recovery steam generator.

The KIUC transmission system consists of 160 miles of 69 KV-rated line that delivers bulk power throughout Kauai, the majority of which is configured as a looped system. KIUC substations convert 60 KV to distribution voltages at 12.47 KV via a four-wire WYE system. KIUC has approximately 1,065 miles of distribution, configured as a radial system.

KIUC members are 90% residential, which account for approximately one-third of our sales. Less than 1% of our members are Large Power Commercial and Industrial, which account for another third of our sales. The remaining are small commercial entities.

The two main issues KIUC wants to address in the energy storage study are generation benefits and transmission and distribution (T&D) benefits.

KIUC wanted to explore the possibilities of fuel savings due to energy storage by providing on-peak energy from a storage system that is charged with off-peak energy.



SECTION 2: Electric Energy Storage

Electric utilities have successfully used large, pumped hydro storage facilities to capture the economic benefits of replacing expensive peaking energy with the less expensive stored energy. Despite its cost-effectiveness and technology maturity, however, pumped storage has not gained widespread popularity as a technology of choice due to its unacceptably high environmental impact. Public opposition has effectively blocked construction of new pumped storage facilities; the last pumped storage facility in the United States was commissioned in 1995.¹ Currently, the installed pumped storage capacity in the United States is approximately 21,000 MW, or 2.2% of the total U.S. generating capacity.²

Until the late 1980s, conceptual designs were being considered to build very large battery energy storage facilities that would offer benefits similar to pumped hydro storage. The primary purpose of such systems would be to replace higher-priced energy produced during peak energy consumption periods with lower-priced energy that had been stored in large battery banks during off-peak periods (i.e., load-leveling). However, the limitations of battery technology available at that time forced a reevaluation of load-leveling concepts. Since the early 1990s, battery technologies have advanced, with the emphasis shifting to smaller, more practical battery storage systems that offer other benefits, such as frequency regulation, spinning reserve, and other power quality applications, making the storage concept more attractive to utilities.

System specific studies conducted by the U.S. Department of Energy through Sandia National Laboratories (SNL)³ and the Electric Power Research Institute (EPRI) identified benefits from battery energy storage captured by smaller systems in the kW to 10s of MW size ranges. These smaller battery systems offered a practical energy storage alternative and some U.S. and overseas electric utilities built demonstration and commercial battery storage plants for various applications. The U.S. experience of battery energy storage at electric utilities and cooperatives is shown in Table 1, which highlights the various system-wide benefits offered by battery energy storage beyond the traditional, load-leveling application. Similarly, battery energy storage systems have been built, tested, and operated in Germany and Japan.⁴

¹ Rocky Mountain Pumped Storage Plant operated by Oglethorpe Power, located near Rome, GA, has an installed capacity of 848 MW with approximately 10 hours of storage.

² US DOE Energy Information Administration, 2004 database:
<http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html>.

³ [A.A. Akhil, L. Lachenmeyer, Sandia National Laboratories; S.J. Jabbar, Decision Focus, Inc.; H.K. Clark, Power Technologies, Inc., Decision Focus, Inc., Power Technologies, Inc.](#); *Specific Systems Studies of Battery Energy Storage for Electric Utilities* SAND93-1754. Sandia National Laboratories, Albuquerque, NM, 1993.
http://infoserve.sandia.gov/sand_doc/1993/931754.pdf.

⁴ Germany 1987: Berliner Kraft und Licht (BEWAG) 17-MW/8.5-MW lead-acid battery for spinning reserve and frequency control. This battery project served as a model for the battery system built by the Puerto Rico Electric Power Authority in 1994.

Japan 1986 onwards: Moonlight Project lead to test and deployment of lead-acid and sodium-sulfur battery systems at the Tatsumi facility, Kansai Electric Power Company ranging in sizes from 1-MW/4-MWh (lead-acid) to 1-MW/8-MWh (sodium-sulfur).

Table 1. Large Battery Energy Projects – U.S. Electric Utilities and Cooperatives.

Company Name	Application(s)	Size (MW/MWh)	Operational Date
Crescent Electric Coop.	Peak Shaving	0.5/0.5	1983
Southern California Edison	Load Leveling/ Transmission Line Stability	10/40	1986
San Diego Gas & Electric	Transit Peak Shaving	02./0.4	1992
Puerto Rico Electric Power Authority	Frequency Regulation/ Spinning Reserve	20/14/1	1994
GNB – Vernon Battery	Reliability/Peak Shaving	1.5/1.5	1995
Oglethorpe Power	Power Quality	2 MW 10 seconds	1996
Metlakatla Power & Light	Voltage Support	1.2 MW/1.2 MWh	1997
American Electric Power			2002
Golden Valley Electric Association	Var Support/Spinning Reserve/System Stability	46 MVA 27 MW/15 mts	2003
VRB			2005

Battery Energy Storage in Island Utilities

It is relevant to note that island electric systems have operating characteristics that are uniquely different from the regionally interconnected systems found in mainland electric systems. Island systems like the one at KIUC are inherently self-contained and must provide all the resources to meet their contingency requirements, without the benefit of support from a larger power pool beyond their system’s boundaries. Several studies conducted in Hawaii, Puerto Rico, and Alaska (considered an “electrically islanded” system) have shown the technical and economic feasibility of using battery energy storage to provide many system-wide benefits for island electric systems. These benefits include fossil fuel savings for spinning reserve, frequency regulation, voltage support and, in some cases, economic benefits for generation capacity deferral.

Hawaii

As early as 1992, Hawaii Electric Light Company (HELCO) and EPRI co-sponsored an economic feasibility study of a battery energy storage system at the Keahole Generating Station. The study showed that a 5-MW/15-MWh battery would be a cost-effective investment to offset the rapid load growth on the west side of the island.⁵ Subsequently, a turn-key specification was developed and a Request for Proposal was issued.⁶ A competitive solicitation led to the selection of a proposal by GE, in partnership with battery manufacturer GNB, that contained substantial battery performance guarantees of up to ten years. However, delays in project funding by

⁵ S. Chapel, C. Nagata, and H. Zaininger, Economic Evaluation of the Hawaii Electric Light Company Battery Energy Storage Plant, *Proceedings of the Fourth International Conference on Batteries for Energy Storage*, September 1993.

⁶ S. Eckroad, C. Nagata, and W. Stolte, Specification, Procurement and Status of a 10 MW Turn-key Lead-Acid Battery Storage Plant for Hawaii Electric Light Company, *Proceedings of the Fourth International Conference on Batteries for Energy Storage*, September 1993.

HELCO and other partners eventually led to the cancellation of the project. It is relevant to note that HELCO's need for energy storage still exists and the lack of storage on the island has only exacerbated the electric system issues on the island.

Puerto Rico

The Puerto Rico battery storage experience has been more successful and led to the commissioning in 1994 of the then-largest battery storage system. The first of five 20-MW/14.1-MWh battery systems was built and is currently operated by the Puerto Rico Electric Power Authority (PREPA) at the Sabana Llana Substation, San Juan. This system was the result of system studies performed in 1990 and 1991 that showed that the rapid response of battery storage systems could offset large combustion turbines that were planned for spinning reserve and frequency regulation duty and generate substantial savings in fossil fuel costs to offset the capital and O&M costs of the battery system.⁷ The power conversion system for this system was also built by GE and the batteries were supplied by C&D Batteries. The second 20-MW battery system is in the planning stages.

Alaska

(Note: Although Alaska is not a geographic island, it is treated here as an “electric island” because all its 170 rural communities are individual “electric islands” that are not interconnected. The exceptions are Anchorage and Fairbanks and Juneau and Ketchikan. Anchorage and Fairbanks are interconnected by the Railbelt transmission corridor that also serves a few of the smaller towns along its route. Hence the Alaskan communities are predominantly “electric islands.”)

The more recent battery systems experience in Alaska spans the full spectrum of battery system sizes that have been installed in electric utility grids, from the 46-MW Golden Valley Electric Association (GVEA) unit to the 1.2-MW battery owned by Metlakatla Power and Light (MP&L).

The larger GVEA battery system has seven distinct operating modes that include local Var support, spinning reserve, system stability, and local generation black start support. If a fault occurs on the transmission line heading north from Anchorage, the GVEA battery carries the native electricity loads in Fairbanks, until local generators are brought on line (up to 15 minutes). The GVEA system set a world record by discharging 26.7 MW during a forced outage of the transmission line soon after the battery system was commissioned.⁸

Commissioned in 1997, the smaller MP&L system was designed by a GE/GNB partnership to replace a 3.3-MW diesel gen-set, which had been installed to compensate for large load swings caused by the intermittent operation of 400 to 600 kW electric motors at a local lumber mill.

⁷ W. Torres, A. Rodriguez, and J. Sanchez, Battery Energy Storage for Rapid Reserve on the Island of Puerto Rico, PREPA, *Proceedings of the Third International Conference on Batteries for Utility Energy Storage*, March 1991.

⁸ URL <http://www.abb.com/global/abbzh/abbzh251.nsf!OpenDatabase&db=/global/gad/gad02077.nsf&v=2782&e=us&c=1709A281620B4845C1256DD000364389>.

The other generators of the MP&L system were multiple hydro units with an aggregate rating of 4.9 MW, which have a slower response time that could not follow the rapid load swings when the lumber mills large motors came on line.

SNL monitored the fuel savings due to the replacement of the diesel generator by the 1.2-MW battery system for almost three years after the battery was installed. The fuel consumption trend illustrated by the plot in Figure 1 shows the diesel consumption declining initially in August 1997, when the battery was commissioned, and declining to zero by October after the MP&L system operators had gained full familiarity with the operation of the battery system. Based on the diesel system's consumption rate of 475,000 gallons of fuel annually, the capital investment of the replacement battery system was paid back within three years.

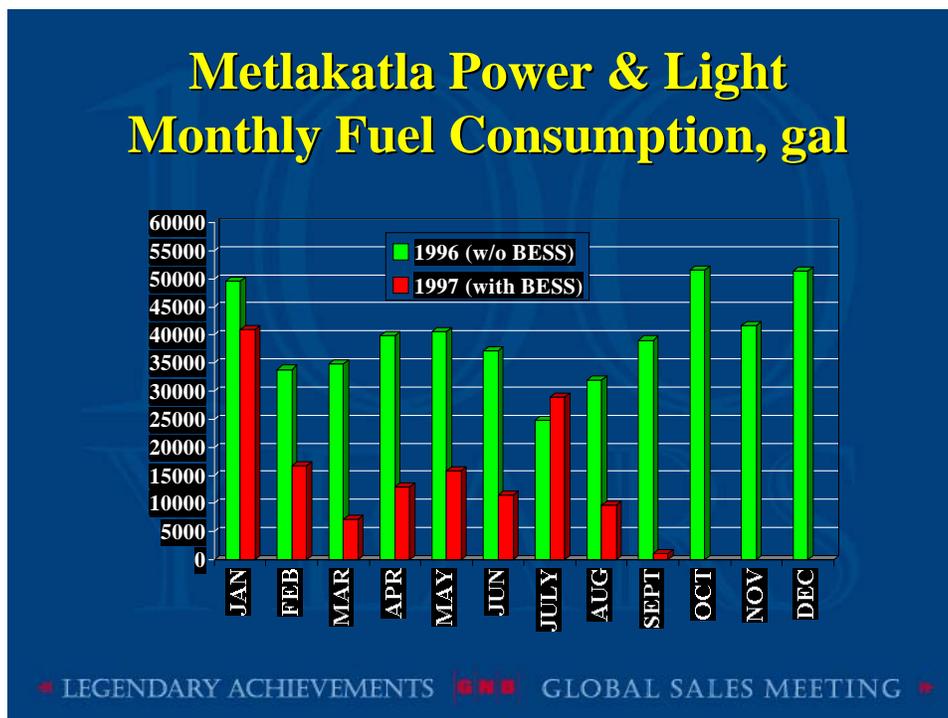


Figure 1. Diesel Consumption at MP&L Before and After Battery Installation.

Figures 2 and 3 show the battery bank and the MP&L Control Room with the PC control of the battery system on the system operator's desk.

Battery Room



◀ LEGENDARY ACHIEVEMENTS | GNB | GLOBAL SALES MEETING ▶

Figure 2. MP&L Battery System Showing GNB Battery Bank.

Operator Control Center AGC for Battery and Hydro Units



◀ LEGENDARY ACHIEVEMENTS | GNB | GLOBAL SALES MEETING ▶

Figure 3. MP&L System Control Room.

Battery Technologies for Electric Utility Storage Applications

Before 1997, lead-acid batteries dominated the electric storage field because of their technological maturity, commercial availability, and lower costs. Other advanced battery technologies, such as sodium-sulfur, Vanadium Redox Battery (VRB), and zinc-bromine were still under development and had not yet accumulated the proven experience in large systems. Without the field experience, advanced battery manufacturers could not warranty their battery systems to the satisfaction of utility requirements. The electric utility battery projects listed in Table 1 illustrate this preference quite clearly. The last three projects listed in that table from 2002 onwards have been sodium-sulfur, nickel-cadmium, and VRB, respectively, compared to the earlier projects that were exclusively lead-acid battery energy storage systems.

At present, the primary advantages of significantly longer cycle life and higher energy density of sodium-sulfur, nickel-cadmium, and VRB batteries, coupled with commercial availability of systems, has replaced the less-expensive lead-acid batteries as the technologies of choice. An additional advantage over lead-acid is that both sodium-sulfur and VRB batteries are impervious to life limitations in deep-discharge applications. This becomes a significant advantage in utility applications, in which a deep daily discharge might be required to support a load-leveling application.

Energy density plays an important role in the electric utility application of battery storage. The higher-density advanced batteries have a smaller footprint than lead-acid battery systems, which becomes an important issue when space is at a premium, for example, if a battery storage system is to be located inside the fence of an existing substation. Typically, the energy density of a lead-acid battery system, including all sub-systems, is between 1.2 and 1.7 kWh/sq.ft.,⁹ depending on the specific design of the battery energy storage facility. That is the measurement of the lead-acid energy storage systems shown in Table 1. In comparison, the sodium-sulfur battery energy density is in the 5 to 7 kWh/sq.ft. range and the VRB is 4 kWh/sq.ft., including subsystems. These are significantly higher than the lead-acid battery parameters and offer sizeable space advantages over lead-acid batteries.

The rare exception to this is when a lead-acid battery system is housed in a two-story structure that allows the building to house almost twice the battery storage capacity than its single-story counterpart with the same footprint, albeit at the expense of added facility cost. This approach was used in both the BEWAG battery system in Berlin and its derivative design in the Puerto Rico battery system. The buildings for BEWAG and Puerto Rico batteries are two-storied with an energy density of 5.25 and 2.43 kWh/sq.ft., respectively. These are the only two instances when a lead-acid electric utility storage project exceeded the energy density range cited above.

Both sodium-sulfur and VRB are recommended for KIUC applications, due to the specific advantages of life cycle, system size, cost, and technology maturity.

⁹ "Evaluating Battery Storage," an EPRI Workshop, October 1993.

It is relevant to note that other storage technologies such as flywheels have made significant advances in the past few years. However, the flywheel storage systems that are in development or in precommercial readiness target the high-power, low-energy applications such as power quality and uninterruptible power supplies. This study shows that KIUC energy storage requirements are high power with larger energy storage requirements in multiple MWh size range, for which flywheels are not deemed to be commercially ready at this time. A similar situation exists for super capacitors as well.

SECTION 3: KIUC Energy Storage Study

The underlying approach for the KIUC study was to examine the potential benefits of replacing the smaller diesel generation units at the Port Allen generating facility with electric storage systems. The smallest and oldest units at this facility are the five Electro Machine Diesel generators (EMDs) (units D1 and D2) at 2 MW each, and units D3 through D5, 2.7MW each, which were the primary units considered for full or partial replacement.

The KIUC data used to evaluate the results of the battery system replacements was taken from the Commodities model that KIUC uses to project unit-by-unit generation and dispatch for all the KIUC generators during 2006. KIUC generates the Commodities model by making an hourly load forecast for their system for one year, based on the prior year of historical data. The past year’s hourly data is modified with a projected load growth adjustment for the current year. This raw forecast data is fed into the Commodities model that, in turn, produces for the KIUC generators an economic dispatch taking into account the forced and scheduled outages of each generator.

The raw 2006 data is shown in the Excel file (BWR.xls) that is included in Appendix B. BWR.xls is organized into 12 monthly sheets, with accompanying Summary and MW Data sheets. The hourly forecast data for each month is estimated by KIUC planning staff and the sheet is populated for every hour of the year. For example, the January hourly forecast is shown by each day of the month on the “Jan” sheet in columns B through AF, rows 3 through 26. This hourly data generates the Commodities model for the year 2006. A sample set for January 2006 is presented in Figure 4. This hourly load forecast generates daily projected load profiles for each day of the year. The daily load profiles for January are shown in Figure 4.

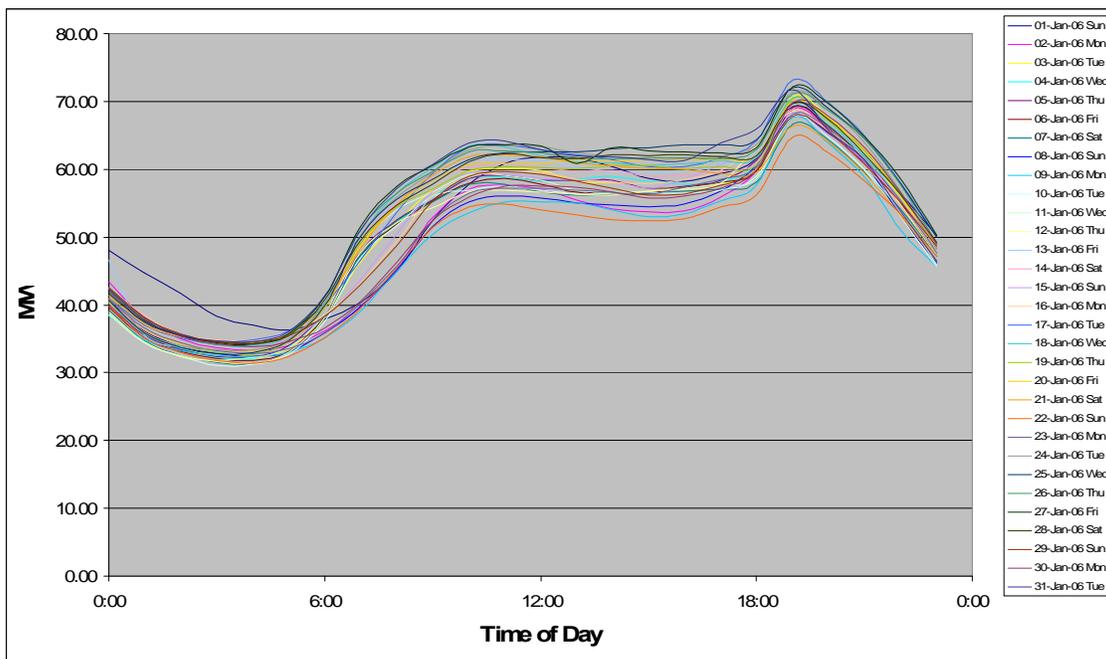


Figure 4. Daily Load Profile – January 2006.

Figure 4 illustrates two significant features in the load profiles. First, there is a prominent and sharp system peak that begins around 1800 hours and continues until about 2100 hours. Second, a pronounced dip is noted in the load during the off-peak period that lasts from about 0200 to 0600 hours. Both of these load shape characteristics are ideal for the classical application of battery storage for load leveling.

The corresponding January commodities summary shown in Figure 5 lists the MWh generation for that month for each KIUC generating unit, plus the fuel cost for that unit and related parameters, such as fuel consumption and heat rate.

In Figure 5, the five EMDs are listed as PT_ALLEN D1_5201 through PT_ALLEN D5_5205. The MWh generation for these units is generally low, ranging from 23 MWh for D2 to a high of 492 MWh for D4.

January, 2006		Commodities Summary							
Unit	Mwh	Mbtu	Mbtu/Mwh	\$Total	\$ Maint	\$/Mwh	\$ Fuel	Fuel Usage	
AGC_SUB K_COFFEE	2,133	0	0.00	\$346,704		\$0	\$162.54	\$346,704	0 MBTU P_KCOF
Total P_KCOF	2,133	0	0.00	\$346,704		\$0	\$162.54	\$346,704	0 MBTU P_KCOF
AGC_SUB KEKAHA	137	0	0.00	\$10,416		\$0	\$76.09	\$10,416	0 MBTU P_KEKA
Total P_KEKA	137	0	0.00	\$10,416		\$0	\$76.09	\$10,416	0 MBTU P_KEKA
AGC_SUB OLOKELE	235	0	0.00	\$22,320		\$0	\$94.94	\$22,320	0 MBTU P_OLOK
Total P_OLOK	235	0	0.00	\$22,320		\$0	\$94.94	\$22,320	0 MBTU P_OLOK
Total Purchase Power	2,505	0	0.00	\$379,440		\$0	\$151.47	\$379,440	
LESC WAIHI_HYD	558	0	0.00	\$20,088		\$20,088	\$36.00	\$0	0 GAL DIESEL
PT_ALLEN D1_5201	48	557	11.60	\$9,184		\$1,056	\$191.33	\$8,128	4,066 GAL DIESEL
PT_ALLEN D2_5202	23	261	11.60	\$4,305		\$495	\$191.33	\$3,810	1,906 GAL DIESEL
PT_ALLEN D3_5203	245	2,816	11.49	\$44,296		\$9,234	\$180.80	\$41,062	20,554 GAL DIESEL
PT_ALLEN D4_5204	492	5,523	11.23	\$88,806		\$8,118	\$180.50	\$80,688	40,314 GAL DIESEL
PT_ALLEN D5_5205	145	1,667	11.49	\$26,216		\$1,914	\$180.80	\$24,302	12,165 GAL DIESEL
PT_ALLEN GT2_CC	390	5,666	14.52	\$84,059		\$1,342	\$215.42	\$82,717	41,361 GAL DIESEL
PT_ALLEN S1_CC	8	147	18.43	\$2,244		\$92	\$280.50	\$2,152	1,076 GAL DIESEL
PT_ALLEN S1_SC	350	5,457	15.59	\$82,096		\$2,415	\$234.59	\$79,681	39,831 GAL DIESEL
SWD_PLNT D6_5208	3,680	33,483	9.10	\$537,214		\$48,420	\$146.00	\$488,794	244,403 GAL DIESEL
SWD_PLNT D7_5209	4,870	44,457	9.13	\$716,004		\$66,960	\$147.03	\$649,044	324,503 GAL DIESEL
SWD_PLNT D8_5210	3,033	27,581	9.10	\$442,662		\$39,870	\$145.95	\$402,792	201,396 GAL DIESEL
SWD_PLNT D9_5211	2,883	26,214	9.09	\$424,380		\$41,700	\$147.20	\$382,680	191,346 GAL DIESEL
Total DIESEL	16,724	153,840	9.20	\$2,481,554		\$235,704	\$148.38	\$2,245,850	1,122,921 GAL DIESEL
KAPAIA CT1	19,231	165,758	8.62	\$2,219,109		\$164,109	\$115.39	\$2,055,000	1,369,897 GAL KPPNAP
Total KPPNAP	19,231	165,758	8.62	\$2,219,109		\$164,109	\$115.39	\$2,055,000	1,369,897 GAL KPPNAP
Total KE Units	35,955	319,598	8.89	\$4,700,663		\$399,813	\$130.74	\$4,300,850	
Total for 2006	38,460	319,598	8.31	\$5,080,103		\$399,813	\$132.09	\$4,680,290	

Figure 5. Commodities Summary – January 2006.

The storage study focused on this data set to examine the effects of using a 16-MWh battery storage system. The objective was to fully or partially displace any of the five EMDs with a battery system and effectively flatten the daily afternoon peak shown in Figure 4.

This analysis was performed by modifying the hourly data for all of 2006 to incorporate the effect of discharging the 16-MWh battery in the afternoon and recharging it during the early morning off-peak time using the generation from the other KIUC generators. The battery system has round-trip efficiency for each charge/discharge cycle ranging from 70% to 85%, depending on the type of battery technology employed and other operational parameters. Generally, the larger lead-acid systems listed in Table 1 have all historically recorded net round-trip efficiencies ranging from 70% to 76%. The newer advanced battery systems have somewhat higher efficiencies, 75% to 80%. The KIUC storage study examined three round-trip efficiency scenarios of 70%, 80%, and 85%. The corresponding recharge energy used by the 16-MWh battery for the three efficiency cases is:

70%	22.8571 MWh
80%	20.0000 MWh
85%	18.8235 MWh

Three modified versions of the BWR.xls spreadsheet were generated to reflect the three net loss cases for the battery. Each day's hourly generation forecast was changed in the afternoon to a reduced value, in order to account for the discharged energy from the battery. The net energy available from the battery for this was fixed at 16 MWh. To simplify the calculations, it was assumed that all the 16 MWh were discharged every day, and no residual battery energy was carried into the following day.

The three spreadsheets with the 70%, 80%, and 85% round-trip efficiency are included in Appendix B ("70_Calc.xls," "80_Calc.xls," and "85_Calc.xls"). The effect on the daily load profile of the battery system is shown in Figure 6. Figure 6 shows that the battery discharge completely levels the afternoon peak and that the recharge eliminates the valley in the early morning load.

The additional operational advantage of load-leveling with the battery is that the KIUC generation units run at fixed set points during the afternoon discharge, with the battery essentially doing the load following. Similarly, the generation units run at a higher load set point during the early morning. At the Port Allen generation facility, this is a desirable operating strategy, because it minimizes the load swings seen by each generator during the diurnal cycle and has a beneficial impact on the long-term maintenance cost of the unit and the related manpower requirements during the day and night shifts.

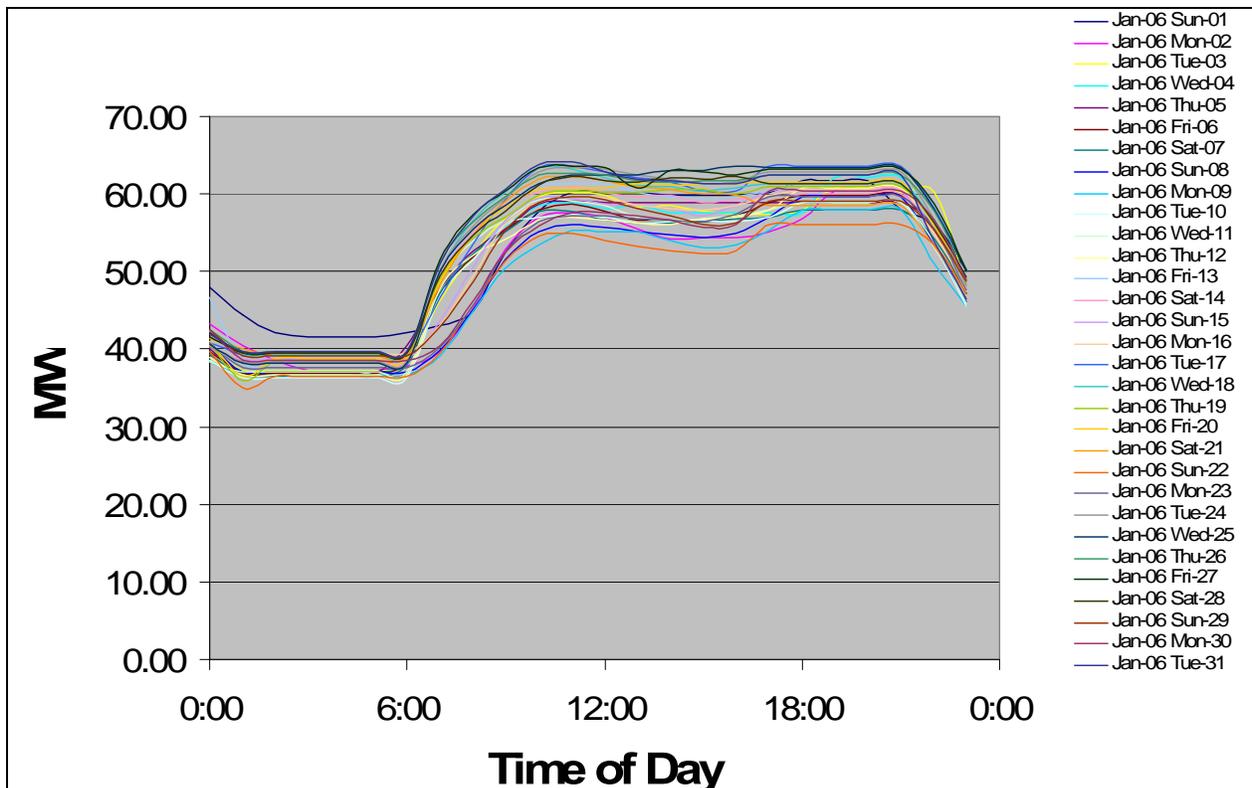


Figure 6. Daily Load Profile with Battery – January 2006.

The reduced MWh generation (and run time) and the fuel-saving effects of the battery are captured by the modified Commodities Summary included in Appendix B, “2006 Mod 15.pdf.” The January 2006 Commodities Summary shows significant reduction in MWh generation for all the EMDs except D4, as shown in Table 2. The effect of generation (hence, run time) reduction on Units 1, 2, and 5 for all of 2006 are shown in Figures 7, 8, and 9. The cumulative effect for the year shows a reduction of 40% for Unit 1, 36% for Unit 2, and 41% for Unit 5.

Table 2. Comparison of January 2006 Commodities Summary: With and Without Battery System.

EMD Unit	January MWh without Battery	January MWh with Battery
Unit 1	48	15
Unit 2	23	8
Unit 3	245	150
Unit 4	492	566
Unit 5	145	50

D1 Generation - 2006

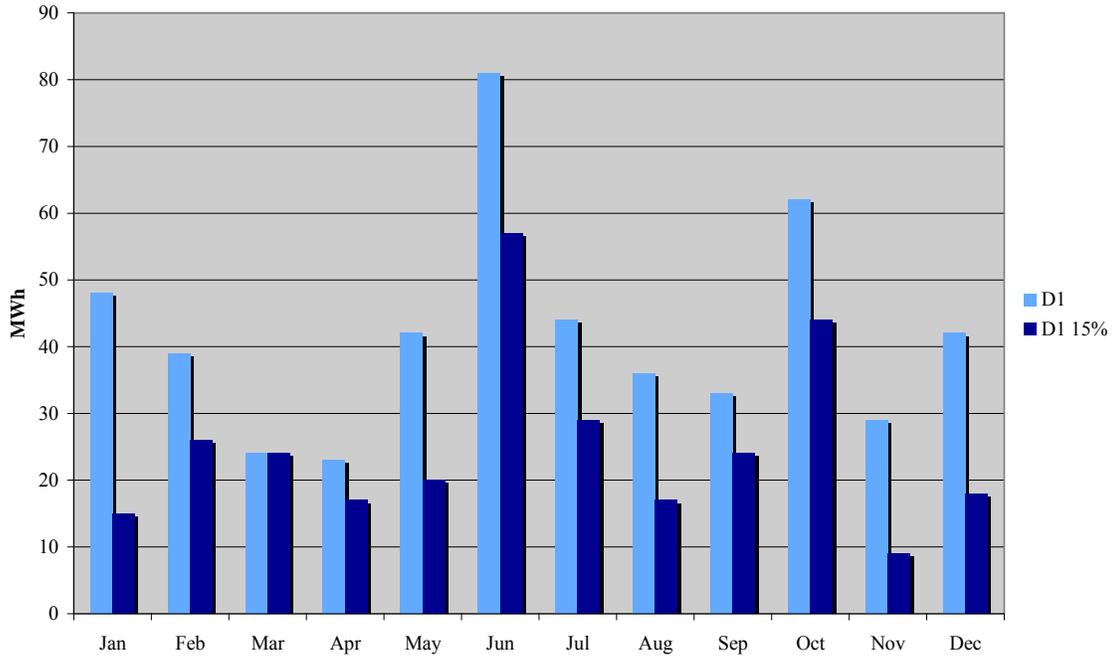


Figure 7. D1 MWh Generation With and Without Battery Energy Storage.

D2 Generation - 2006

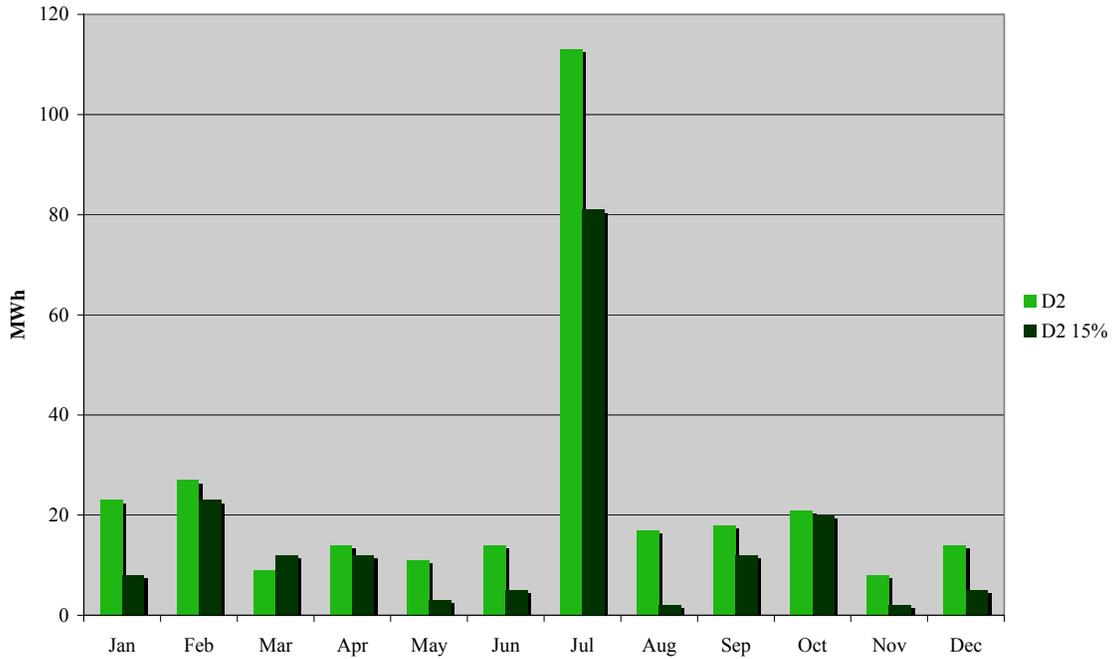


Figure 8. D2 MWh Generation With and Without Battery Energy Storage.

D5 Generation - 2006

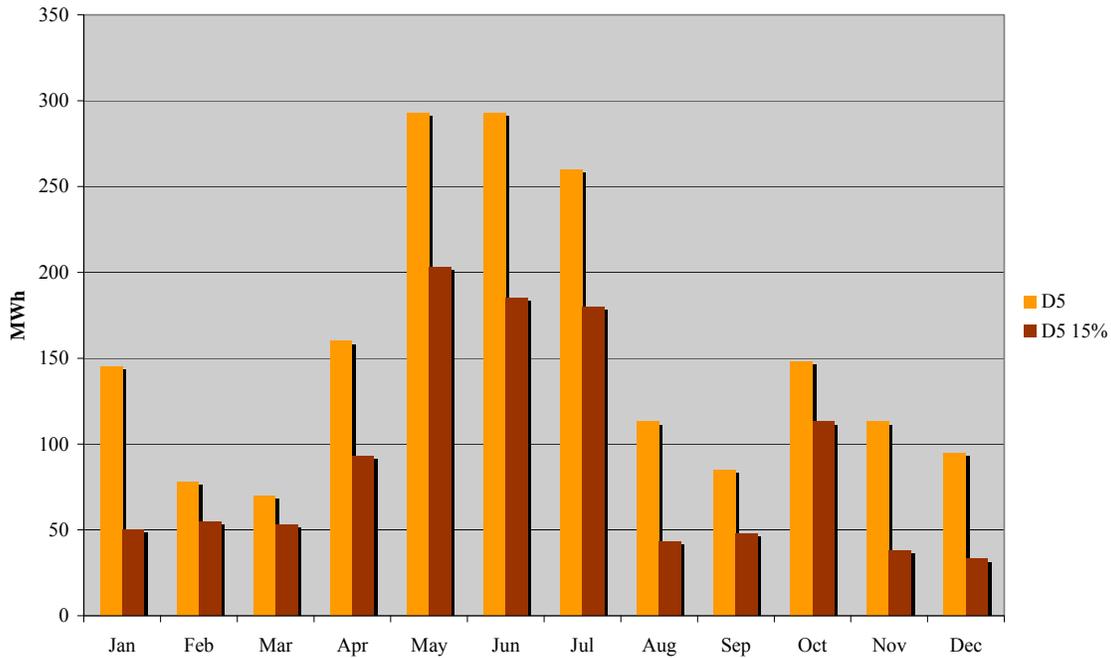


Figure 9. D5 MWh Generation With and Without Battery Energy Storage.

The reduction in the EMD generation is made up by the battery discharge. However, the recharge energy is made up from increased generation by the other units, primarily Kapaia Power Station (KPS). The modified Commodities summary, including the battery system, shows that KPS generation increases from 19,231 MWh without the battery system to 19,573 MWh with the battery. So, while there is a decrease in the EMD fuel costs, it is accompanied by a corresponding increase in fuel costs of the other units that are charging the battery system. A comparison of the two Commodities summaries shows a net savings in both maintenance and fuel costs, resulting in an annual savings of \$133,821, as shown in Table 3.

The present worth of this annual savings, extended for an operating period of ten years, is valued at \$1,499,906.

Table 3. 2006 Maintenance and Fuel Costs With and Without Battery Storage.

	Diesel Maint. Cost	Diesel Fuel Cost	KPS Maint. Cost	KPS Fuel Cost	Total
With 85% Eff. Storage	\$2,882,283	\$32,202,627	\$1,912,872	\$24,006,818	\$61,004,600
Without Storage	\$2,942,087	\$32,456,405	\$1,901,483	\$23,838,446	\$61,138,421
Savings	-\$59,804	-\$253,778	\$11,389	\$168,372	\$133,821

SECTION 4: Results and Conclusion

The analysis in the previous section clearly indicates that a 16-MWh energy storage system will eliminate the daily peaks and significantly reduce the run time for four of the five EMDs – Units 1, 2, 3, and 5. The storage system will also reduce the effects of unit ramp as they follow the load swings during the on- and off-peak periods, leading to reduced maintenance costs. An incidental benefit is the relief this operation scenario provides in manpower requirements between the daytime and night shifts. The production cost (fuel and O&M) savings derived from this application of the 16-MWh battery energy storage system amounts to \$133,821 per year or a Present Worth savings of \$1,499,906 over a ten-year study period.

While these are tangible savings, they are not sufficiently large to offset the cost of a 16-MWh battery energy storage system. The fact that there is no fuel diversity in the KIUC generation mix effectively eliminates a positive net economic benefit of the storage system from a production cost savings perspective.

The outcome of this analysis would be substantially different if there was a renewable resource such as hydro that could recharge the energy storage during the off-peak hours. It is important to note that there is a small amount of run-of-river hydro generation present in the KIUC generation mix rated at about 1.3 MW. There is some more hydro generation of similar capacity that KIUC purchases from outside operators. However, the Commodities Summary does not factor it into the production cost calculation and it appears as a straight credit to the system.

This hydro generation component was not used in this analysis because the KIUC staff perspective was that the value of the hydro generation is better captured by dispatching it into the system to offset the higher-cost diesel-based generation rather than using the hydro to recharge the storage. This strategy would evidently deplete the value of the hydro energy by 20% to 30% – which is the round-trip efficiency loss of the energy storage system. Hence, this scenario was not included in the scope of this analysis.

Wind energy also has the same potential of charging the storage if its output can be dedicated to the storage system. But in an island system, a penetration of wind energy in the 10% to 15% range of the total system generation capacity is likely to introduce system stability issues. The presence of energy storage could effectively dampen the instability as well as capture the production cost savings. An aggregation of these two separate benefits has a strong potential of completely changing the negative benefit/cost ratio into a positive economic benefit to KIUC from energy storage. This stability benefits analysis is part of a larger grid study being performed by General Electric for KIUC at the time of writing this report. GE plans to include this analysis assuming that a wind farm is developed on the island under the Renewable Portfolio Standard compliance requirements.

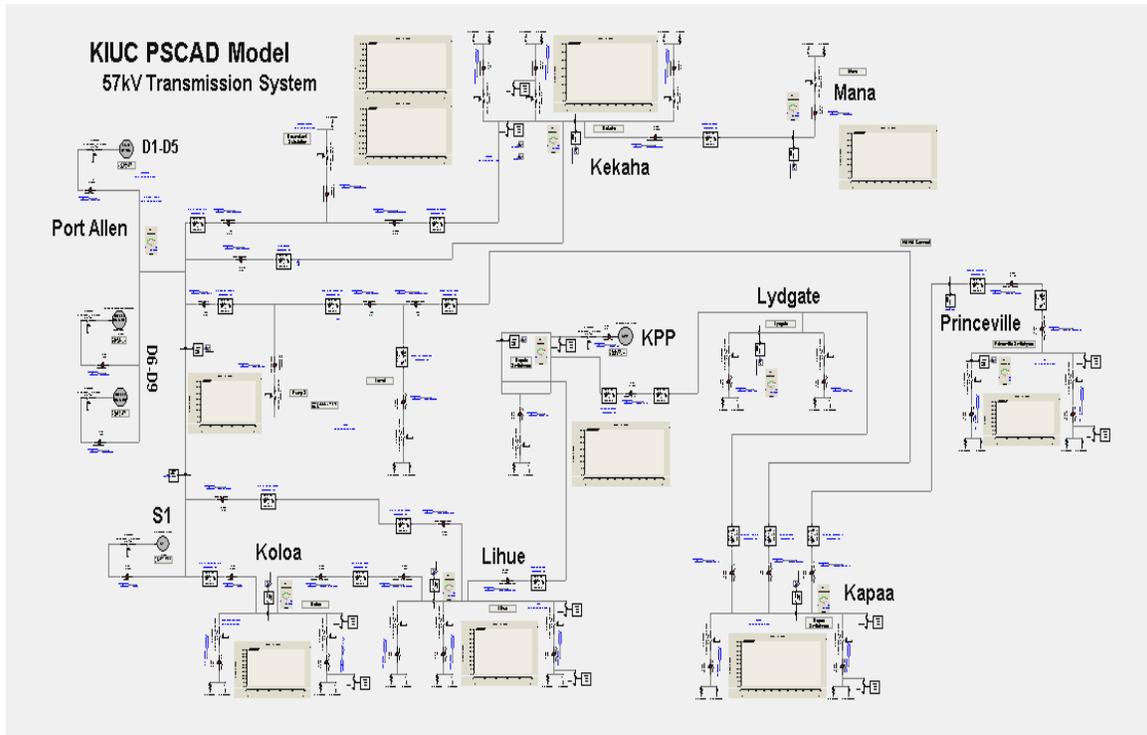
The SNL team attempted to quantify the stability benefits of energy storage using PSCAD as the analytical tool. This part of the study was stymied by the detailed data required for the governors and control systems used for each of the 13 generators of the KIUC system. Most of this data was not available due to the age of the EMD and Stork Wartsilla Diesel (SMD) units at Port Allen. The complete methodology and findings of this study are included in Appendix A.

While the SNL effort in the stability area was limited, KIUC contracted with EPS about the time that the SNL study was winding down. The EPS study in May 2006 took a broader approach to determine the root causes of KIUC system outages. The study focused on the role of the protection/relaying of the T&D system and any generator characteristics or controls that were contributing to these outages. The system analysis performed by EPS concluded among other factors that battery energy storage will provide many benefits to KIUC, which include possibly eliminating the instability and load shedding while providing positive voltage control.

In conclusion, SNL recommends that KIUC continue the efforts to quantify the dynamic benefits of energy storage. These stability benefits from energy storage may be far greater than the production cost benefits alone and may provide KIUC a positive economic and operational incentive to implement an energy storage system on the island.

APPENDIX A: PSCAD Stability Analysis — Methodology and Report

Dynamic Modeling of the Kauai Island Utility Cooperative (KIUC) Grid¹⁰



¹⁰ This project is part of an Energy Storage Assessment for KIUC performed by Sandia National Laboratories and was directly funded by KIUC. The information contained herein is proprietary to KIUC.

SUMMARY

Sandia National Laboratories (Sandia) performed an Energy Storage Assessment for the Kauai Island Utility Cooperative (KIUC). The project was two-pronged: (1) a study of the KIUC system relative to the potential benefits of implementing energy storage and (2) an effort to examine island-wide power outages that the KIUC system had been experiencing.

The Chief Executive Officer of KIUC, who had been exposed to the benefits of energy storage through an earlier Alaska project, was primarily interested in the economic feasibility of implementing energy storage into the Kauai grid. That analysis was duly performed and is reported in the main document. A secondary goal of the energy storage study was the development of a functional model of the KIUC power system's dynamic stability to assess the potential for energy storage. This report details that effort.

Based on PSCAD results, the Sandia team concluded that the KIUC transmission system was not dynamically unstable. Instead, the outages were more likely due to control instability. This conclusion was based on fault data related to the internal turbine governor of the Kapaia generation plant, the largest generating unit in the KIUC system at the time of the modeling. Kapaia, the primary base-load plant at the time, was responding to faults before the fault was cleared. This caused system frequency to quickly deviate from the normal operating window, which led to island-wide load shedding.

Near the completion of the modeling, Sandia's analysis was supported at a meeting between Sandia and Electric Power Systems (EPS) engineers, consultants who were working with KIUC on system protection coordination. EPS had initially made the same assessment as Sandia that the cause of the KIUC-wide outages was generator control instability.

SELECTION OF SOFTWARE FOR THE DYNAMIC MODEL

Generation plants have the greatest impact on the stability of a grid system because they operate with active control systems such as governors to maintain system frequency, exciters to maintain system voltage, and inherent mechanical inertia to help dampen the system from the effects of frequency swings. Protective relaying also plays an important role in system stability. The protective devices are constantly monitoring the system's frequency and voltage, ready to isolate a faulted device or line segment. Generator controls and protective relays must be coordinated appropriately for the entire system to maintain stability during disturbances.

With those factors in mind, Sandia's intent was to design a model of the KIUC grid that would dynamically simulate the current KIUC system's response to a disturbance by determining if the system voltage and frequency converge to a stable operating point. The team selected PSCAD,¹¹ a general purpose, time-domain simulation tool for studying transient behavior of electrical networks. PSCAD was the tool of choice because it is powerful and recognized world-wide by leading utilities such as Pacific Gas & Electric and Southern California Edison. PSCAD's solution engine, a graphical power system simulator had ready-to-use dynamic model libraries of various system components, includes generators, exciters, governors, turbines, FACTS devices, transmission lines, transformers, and a variety of system loads. PSCAD also offers waveform resolution on all three phases of a grid system, which allows users to perform power quality measurements while looking at voltage and current total harmonic distortion (THD).

¹¹ PSCAD® (Transients Simulation Software by Manitoba HVDC Research Centre, Canada).

VALIDATION OF THE PSCAD SOFTWARE

Before testing could begin, the model had to be validated as an accurate reproduction of the KIUC transmission network. To do this, Sandia compared a steady-state PSCAD output to an existing Aspen One-liner¹² power flow output of the entire KIUC system. As is normally the case, the key factor in preparing the PSCAD model was ensuring that the transmission lines and transformer models were representative of actual KIUC hardware.¹³ Modeling the generator characteristics was not necessary for the steady-state validation.

Because of the relatively short transmission lines in the KIUC system (26 miles is the longest), Sandia was able to utilize a Pi model, which helped to somewhat simplify the modeling. Validation required setting the sending and receiving end voltages constant and verifying that the power flows were in agreement with the Aspen One-liner. Similarly, for the transformers, primary and secondary voltages were held constant and power flow was verified. Figures A-1 and A-2 are representative of transmission and transformer parameters that Sandia included in the model.

The Aspen One-liner diagram provided by KIUC, with the voltages displayed at every bus and power flow documented on every branch, was used as a benchmark for the final PSCAD power flow validation. A voltage source was connected at every node, in order to keep the voltage and phase angle constant.¹⁴ Figures A-3 and A-4 represent the validation for one of KIUC's 60-kV transmission lines and one system transformer. As shown on the control meters in Figures A-3 and A-4, the PSCAD real and reactive power results match within 1% of the simulated Aspen results. Validations like these provided the KIUC team assurance that the Sandia model was an accurate representation of their transmission system.

The power flow validation ensured Sandia's goal to have a completely validated KIUC network in PSCAD, a critical phase in the complete modeling effort, before introducing any machine models.

¹² Aspen One Liner: A widely used, steady-state power flow program that KIUC was using at the time of Sandia's analysis.

¹³ Software is available that will convert an Aspen One Liner into a PSCAD program; however, due to economic considerations, Sandia was required to build the model component by component.

¹⁴ Appendix A lists all of the impedances and reactances for every transmission line and transformer.

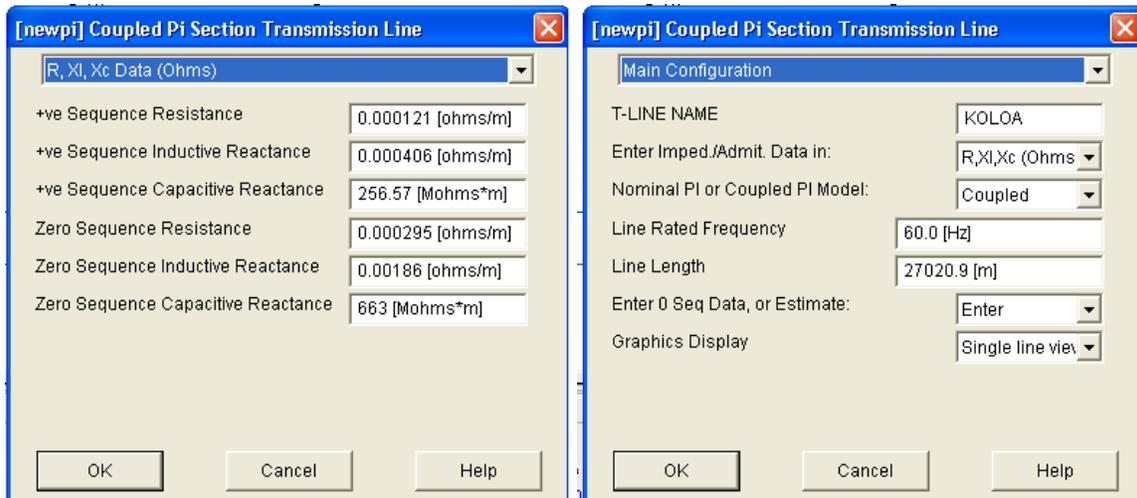


Figure A-1. Pi Model of a Typical KIUC Transmission Line.

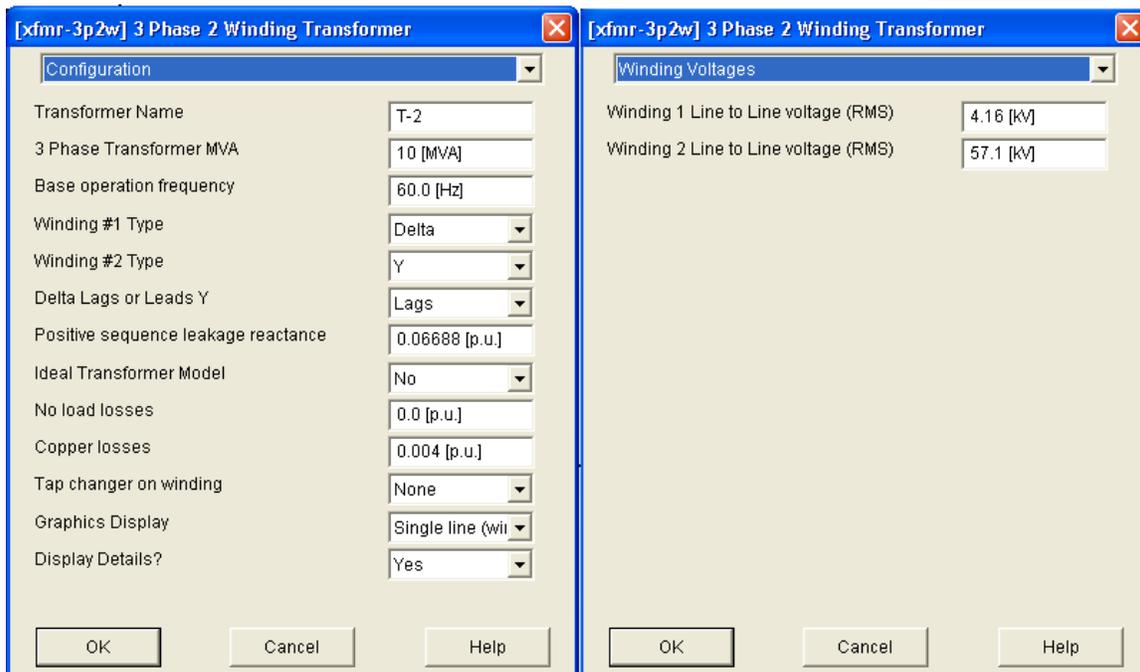


Figure A-2. Model of a Typical KIUC Three-phase Transformer.

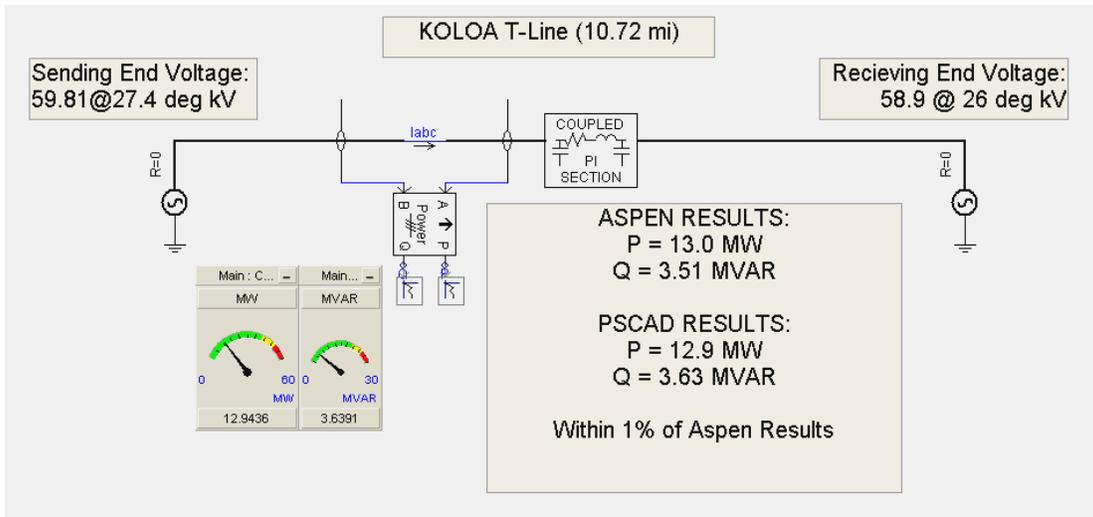


Figure A-3. Pi Model Transmission Line Validation.

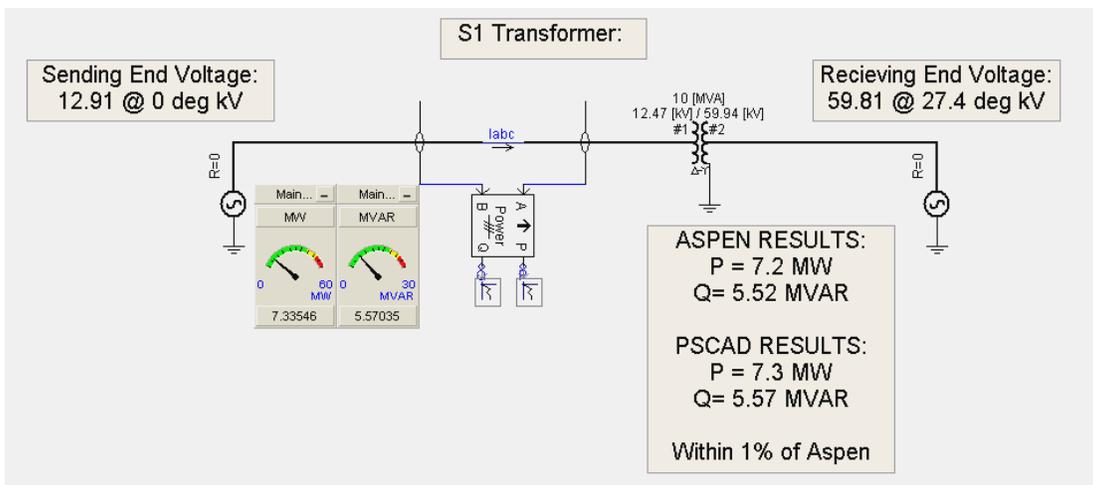


Figure A-4. Three-Phase Transformer Validation.

MODELING THE KIUC SYSTEM

Once the power flow of the PSCAD model had been validated, Sandia began developing detailed models of all the KIUC system generators. Dynamic machine models consist of several components, the primary ones being a generator with an exciter and an engine or “prime mover” (hydro turbine, steam turbine, etc.) that drives the generator. A full dynamic model includes a synchronous generator with an exciter, an engine or turbine (prime mover) and governor.

The synchronous generator, where various machine reactances, time constants, and machine inertia are required to be modeled effectively, contains an “exciter,” which controls the output terminal voltage of the generator by regulating the generator’s internal field voltage. PSCAD offered a list of IEEE-recognized exciter models.

The prime mover of the machine is the turbine (engine) that drives the generator. In order to model the engine effectively, the Sandia team built a transfer function control block diagram with corresponding gains and time constants. A governor controls the speed of the prime mover (the frequency of the synchronous generator). Sandia also built a complete transfer function control block diagram with corresponding gains and time constants for the governors.

The team was able to gather sufficient data for Kapaia (~ 27.5 MW) and the four Stork Wartsilla Diesel (SWD) generators (~ 7.8 MW each). However, the remaining five Electro Machine Diesel (EMD) generators lacked sufficient data. Therefore, Sandia compensated for that by including them in the model based on the SWD controls and characteristics, and then scaled them to appropriate sizes. Also due to a lack of data, the team modeled the 10-MW GE Steam Turbine (S1) with default hydro turbine and governor models from the PSCAD machine library. The remaining gas turbines (GT1 and GT2) lacked sufficient data and were not generating power in the Aspen One-liner, so they were not included in the PSCAD model.

Although the PSCAD library did not contain a complete set of components to match the KIUC system, the system data gathered by KIUC on the Kapaia and SWD units was sufficient for Sandia to develop a PSCAD dynamic model of KIUC’s grid.

Once the machine models were developed, they were introduced into the PSCAD transmission network. The system would represent the dynamic capability of the entire KIUC system if the frequency and voltage were left unconstrained. Basically, no load shed schemes nor any protective relaying were implemented into the PSCAD KIUC model. This would provide the Sandia team the ability to determine if load would have been shed during a disturbance, and determine whether the systems voltage and frequency would recover.

Modeling the Kapaia GE LM2500 STIG Gas Turbine

PSCAD did not contain a generic gas turbine model that would suffice for this 27.5 MW base load unit; therefore, Sandia implemented a GAST model, provided by GE, which is a simplified model of LM2500 gas turbine. The GE LM2500 GAST transfer function control block diagram is shown in Figure A-5.

The synchronous generator was modeled with appropriate reactances, time constants, and machine inertia, according to the KIUC data. Although the actual exciter is a cross between the IEEE AC7B and AC8B, Sandia was unable to duplicate that combination because the saturation function, SE, was not adequately defined in the KIUC data. Therefore, Sandia incorporated only the IEEE AC8B, because the AC8B's proportional, integral, and derivative (PID) control capability was adequate to overcome the limitation. The transfer function control block diagram of the AC8B is shown in Figure A-6. The PSCAD model of the entire Kapaia Unit including the GE LM2500 GAST model, synchronous generator, and exciter is shown in Figure A-7.

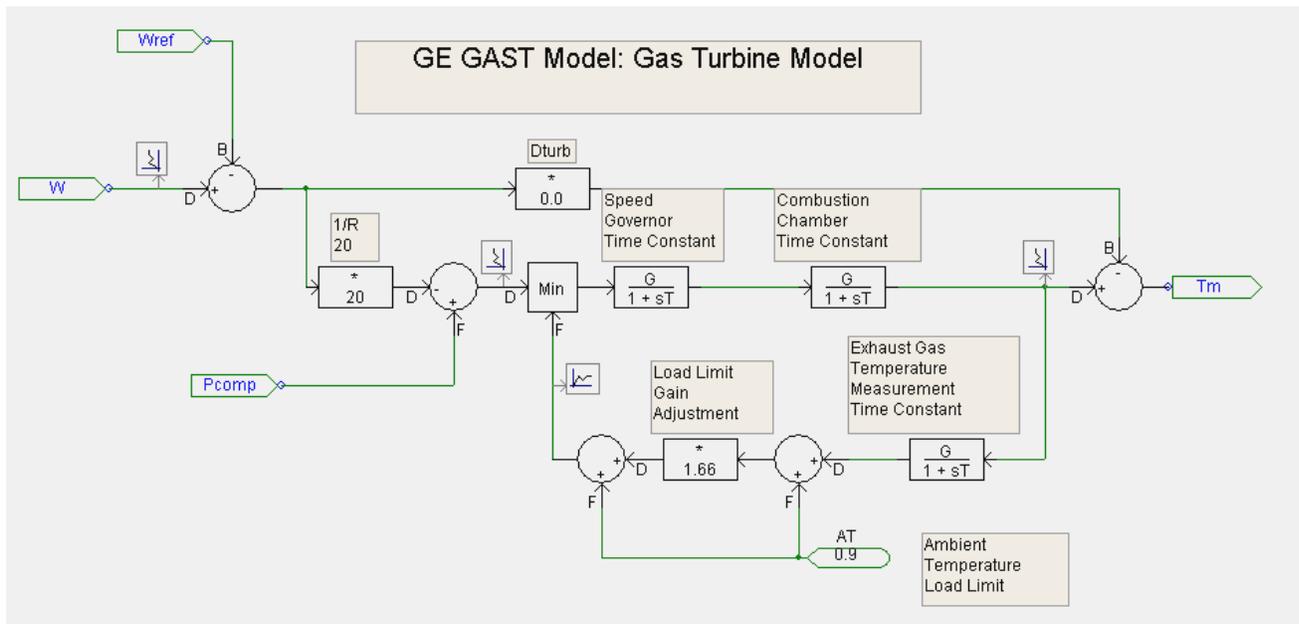


Figure A-5. GE GAST Model (Prime Mover and Governor).

IEEE Exciter Model AC8B

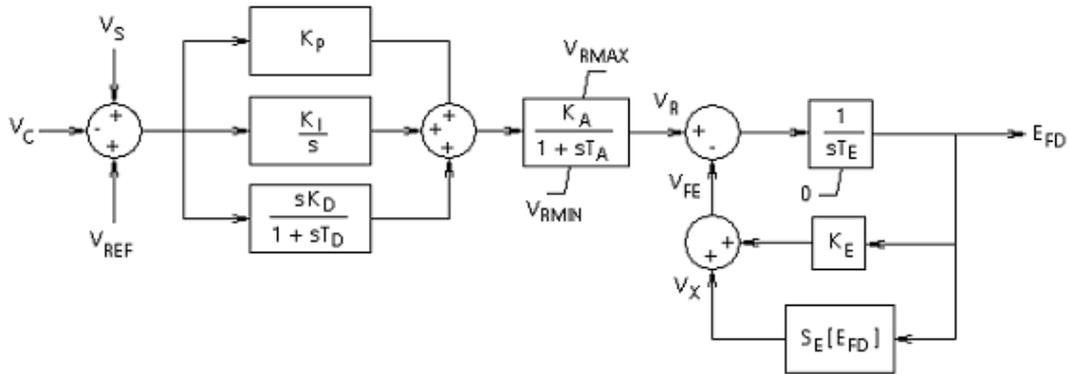


Figure A-6. IEEE AC8B Exciter Model.

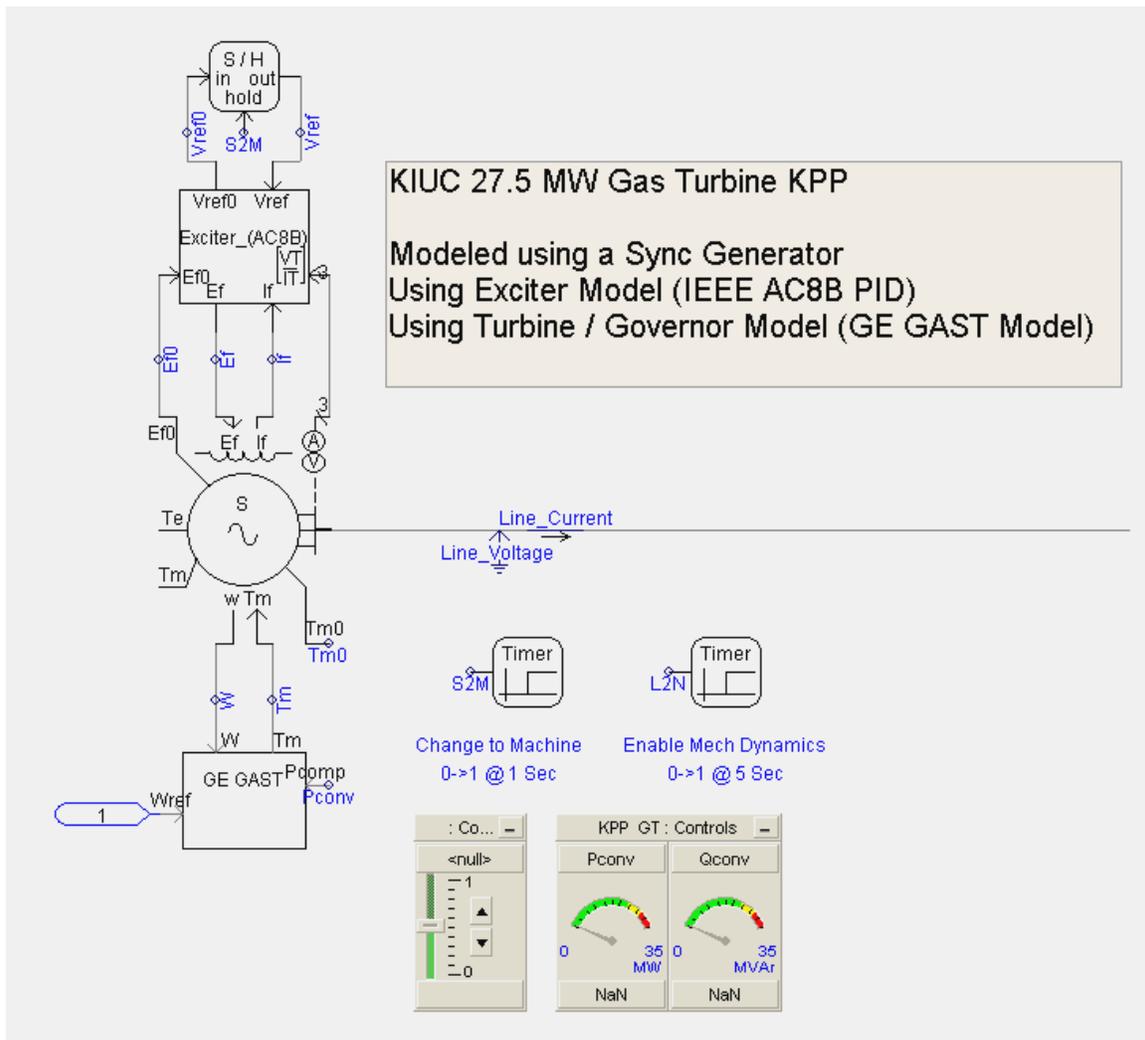


Figure A-7. Kapaia Generation Plant. 27.5-MW Gas Turbine.

Modeling the SWD 7.8-MW Diesel Generators

PSCAD does offer a generic internal combustion (IC) engine model, which was used to model the four SWD engines. Each IC was modeled as a 7.8-MW, six-cylinder engine. The engine is controlled by a Woodward 701A governor to regulate the speed of the engine. The transfer function control block diagram for the Woodward governor modeled in PSCAD is shown in Figure A-8.

The synchronous generator was also modeled with appropriate reactances, time constants, and machine inertia, again in accordance with the KIUC data. The SWD generators operate with an IEEE AC5A exciter. The transfer function control block diagram for the IEEE AC5A that was modeled in PSCAD is shown in Figure A-9. The PSCAD model of the entire SWD unit, including the IC, governor, synchronous generator and exciter, is shown in Figure A-10.

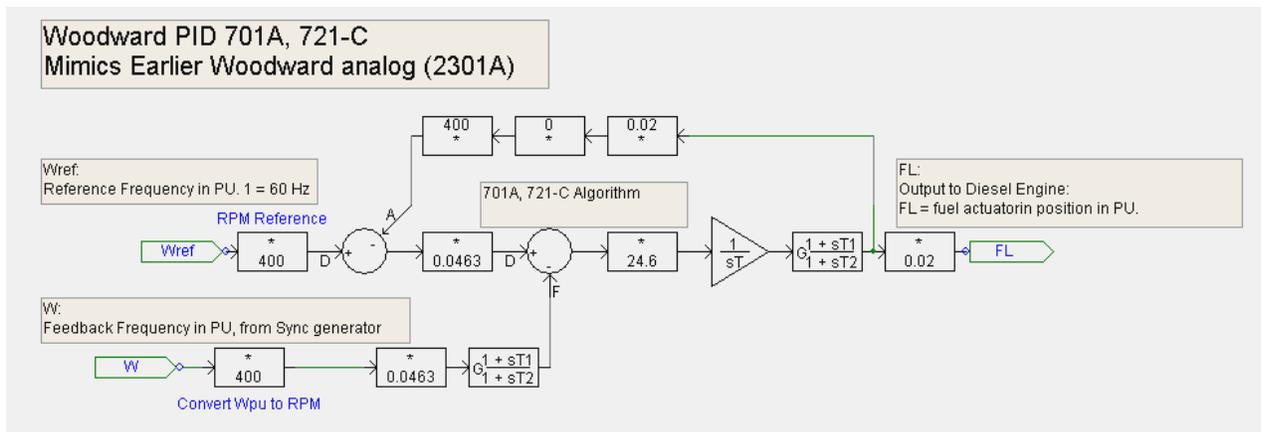


Figure A-8. Woodward 701A (SWD Governor).

IEEE Excitor Model AC5A

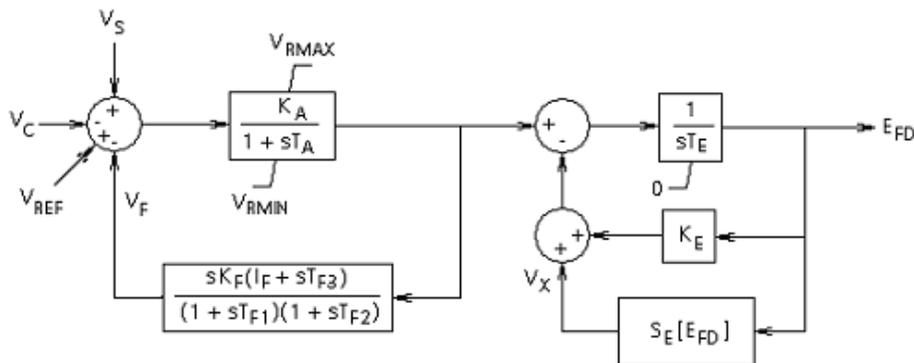


Figure A-9. SWD Exciter Model.

KIUC 8 MW Diesel SWD (D6-D9)

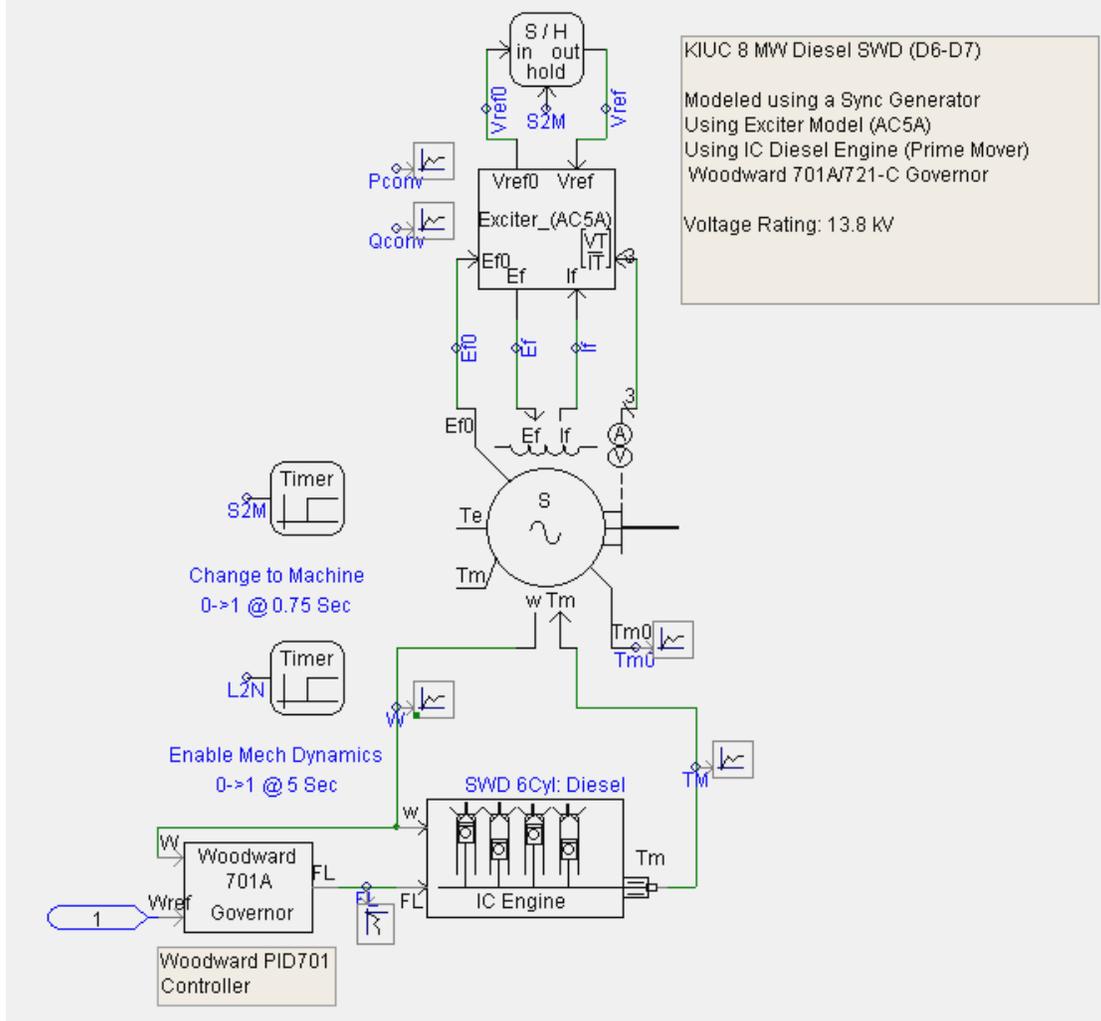


Figure A-10. PSCAD SWD Diesel Engine Model (D6-D9).

Modeling the S1 10-MW GE Steam Turbine Generator

The GE 10-MW steam turbine generator was modeled using default Hydro turbine and governor models due to insufficient data. The synchronous generator was also modeled with available reactances, time constants, and machine inertia, again in accordance with the KIUC data. The EMD generators were also modeled using the IEEE AC5A exciter. The PSCAD model of the entire S1 steam unit, including the turbine, governor, synchronous generator and exciter, is shown in Figure A-12.

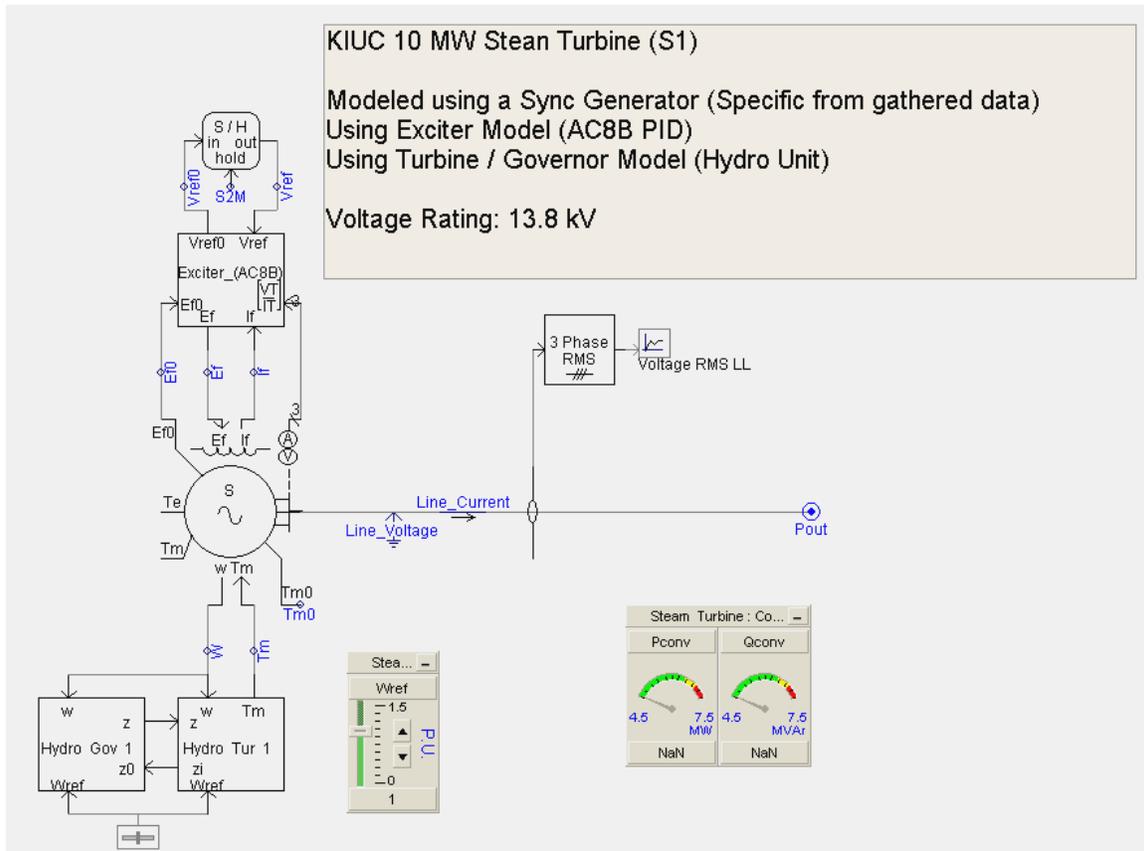


Figure A-12. PSCAD GE 10-MW Steam Turbine Model (S1).

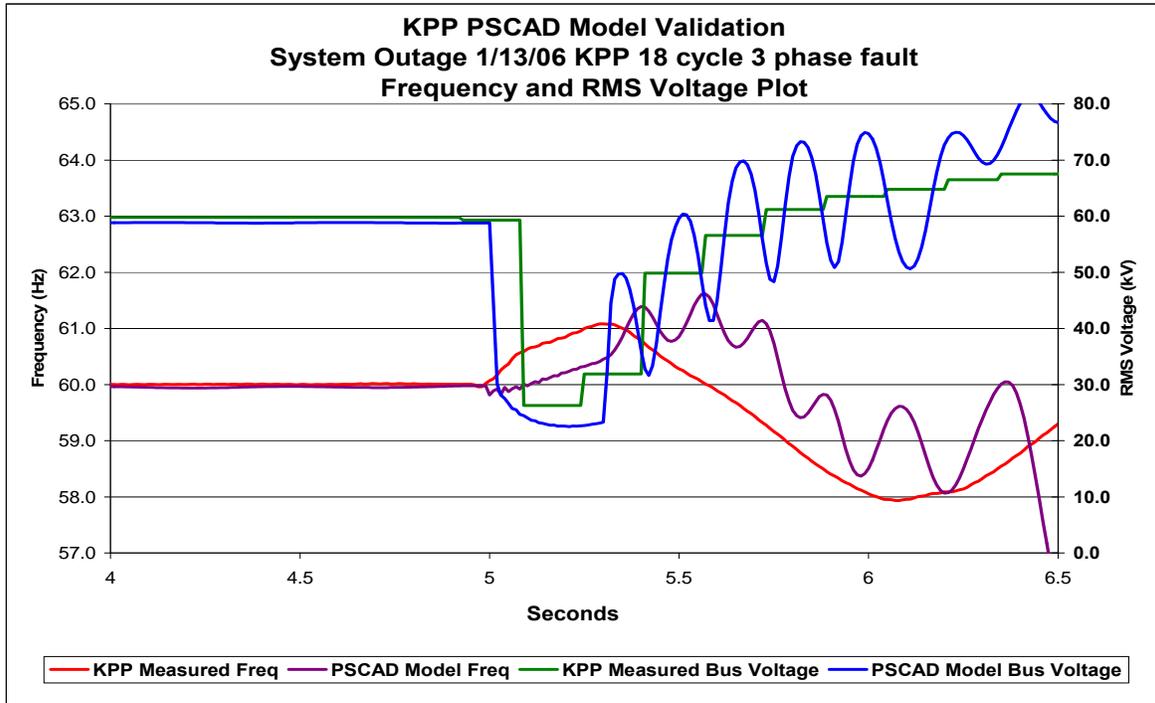
KIUC SYSTEM DYNAMIC RESPONSE PHASE

The PSCAD KIUC model was simulated with various system disturbances to determine if the system would go unstable or cease to converge to a stable operation point. The system was faulted with a series of three-phase and L-G faults at various substations. The fault duration was typically 6 to 18 cycles. The most critical fault simulated was a three-phase fault simulated near the Kapaia substation.

The KIUC system experienced a system disturbance on January 13, 2006, that brought the entire system down. The fault was considerably close to the Kapaia (KPP) substation. The KIUC plant engineers recorded the fault with a high-speed fault recorder that was made available to the Sandia team to compare the response of the PSCAD model to the actual recorded response.

The fault was believed to be a three-phase fault located just outside of the Kapaia substation on the 57-kV side. This fault was not a bolted fault; otherwise the system voltage would have suffered a much more severe voltage dip. In PSCAD the fault was modeled as an 18-cycle three-phase impedance fault. The response of the PSCAD model compared to the recorded data is shown in Plot 1. The green trace is the recorded root-mean-square (RMS) voltage at the Kapaia substation and the blue trace represents the RMS voltage of the KPP unit modeled in PSCAD. The red trace is the recorded system frequency at the Kapaia substation and the magenta trace represents the frequency of the KPP unit modeled in PSCAD. The traces follow a similar path for the first couple seconds; during the actual disturbance, the system frequency rose to 64 Hz, which caused the KPP unit to trip due to overfrequency. However, the PSCAD model shows the system would have suffered an even greater swing in frequency and voltage after the disturbance. The lack of modeled system protection and a corresponding load shed scheme explain the differences observed between the PSCAD model and the recorded data.

The results of the PSCAD simulation show the system would have recovered from the fault and converged to a stable operating point. This simulation draws the conclusion that the system did not become dynamically unstable during that particular disturbance, but rather the system would be susceptible to system outage in the event of a three-phase fault that close to the generation bus.



Plot 1. KPP Model Validation Plot.

Dynamic Response

The most common faults are L-G faults due to lightning or trees hitting transmission lines. It seemed only relevant to model a series of six-cycle L-G faults at various points of the 13.8-kV side of the transmission system. The three-phase faults appeared to have the largest overall impact to the systems response, so they were modeled on the 57-kV side of the transmission system. The table below quantitatively displays the response of the KIUC system under the various faults simulated.

Fault Location	Fault Type	Fault Duration	Minimum Frequency w/Duration	System Recover Time
Lihue	L-G	6 cycle	59.8 Hz	8 seconds
Lihue	3-phase	6 cycle	57.8 Hz	>25 seconds
Koloa	L-G	6 cycle	59.8 Hz	7 seconds
Koloa	3-phase	6 cycle	58.2 Hz	> 25 seconds

Based on the data gathered from the PSCAD model, three-phase faults had the greatest impact to the overall system, and had the greatest likelihood of system load shed. The closer the fault was to the main generation substations, Kapaia and Port Allen, the more severe the frequency would swing and result in greater amounts of system load shed.

CONCLUSIONS AND RECOMMENDATIONS

The KIUC system does not appear to be dynamically unstable. The possible problem with the system's reoccurring outages looks to be a machine controls issue. The KPP does not appear to have enough inertia to allow the fault to clear before compensating for its frequency. The KPP plant is the largest unit operated in the KIUC system, and has the largest impact on the overall system voltage and frequency. The sensitive controls currently implemented into the KPP plant cause the system's frequency to swing quickly into the load shed scheme windows.

Based on the results of the PSCAD system model, the KIUC system was always able to sustain the various faults, and eventually converge to a stable operating point. The actual system under the same conditions would have implemented protection schemes with over-current, over- and undervoltage, and over- and underfrequency relays to protect the various system components. These protection schemes were not modeled, so the actual system would have had to shed load in order to maintain operation.

The Sandia team recommends that the PSCAD model that has been built be refined with added machine controls and system protection by the KIUC system engineers. This will offer KIUC the capability to simulate their system on the dynamic level, a capability that is currently not available. The Sandia team also recommends installing a battery energy storage (BESS) system onto the KIUC system. The BESS would offer extremely fast and clean energy to their co-op members, which would help maintain the system's voltage and frequency during system disturbances, allowing for the fault to be cleared.

APPENDIX B: Storage Study Data

This is a list of the raw and processed data files used in this storage study:

1. **BWR.xls:**
Type: Excel file
Source: Brad Rockwell, KIUC
Purpose: Provides hourly load projections for 2006. This hourly demand data is used by KIUC used to set up the Commodities Model that generates the Monthly Commodities Summary Sheets for the entire year. A sample Commodities Summary for January 2006 is shown in Figure 5.
2. **85_Calcs.xls:**
Type: Excel file
Source: Sandia Laboratories
Purpose: A processed data file that provides the hourly load forecast after a 16-MWh battery energy storage system with a round-trip efficiency of 85% is included in the KIUC generation mix.
3. **Commodities2006NoBatt.pdf:**
Type: Acrobat file
Source: Carey Koide, KIUC
Purpose: Provides a full set of Commodities Summaries for 2006.
4. **2006 Mod 15.pdf:**
Type: Acrobat file
Source: Carey Koide, KIUC, using data provided by Sandia Laboratories in file 85_Calcs.xls
Purpose: Presents a modified set of 2006 Commodities Summaries to reflect the effect of including the 16-MWh battery system (85% round-trip efficiency) in the KIUC generation mix.

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