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Techno-Economic Assessment of a Biomass-Based Hybrid Energy System for Rural Electrification in Sierra Leone

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***Abstract* - This paper assesses the technical and economic feasibility of a biomass-based hybrid gasification power plant in meeting the power needs of an off-grid remote village in Northern Sierra Leone, where it was installed and has been operating since 2012. The configuration of the existing power plant is based on biomass gasifier, diesel generator, battery bank and converter. HOMER Software was used to shape an optimal system that eliminated the use of the diesel generator. The system simulations showed that with a daily load of 355 kWh/day and an annual peak load of 30 kW the optimal system is a combination of 20 kW biomass gasifier, 24 batteries, and 10 kW converter. This configuration has a capital cost of $64,250, operating cost of $12,716/year and net present cost of $187,747, which results in a cost of energy of $0.149/kWh compared to the existing configuration whose capital, operating, net present costs and cost of energy are $67,250, $13,664/year, $199.954 and $0.159/kWh, respectively. Operating the existing option can pose a serious challenge as diesel fuel costs may increase in the long term and there is no backup source if supply is disrupted. The optimal simulated system is not only sustainable and techno-economically feasible but has less greenhouse gas emission which complies with the Sierra Leone policy strategy of climate Resilient Green Economy.**

***Keywords*-- Biomass, Hybrid system, HOMER, Optimization.**

I. INTRODUCTION

Rural communities in Sierra Leone have one of the lowest rates of modern energy access in the world. Currently, less than 1% of the total rural population has access to electricity [1], and development of the national grid to reach this large underserved population has been besieged by financial and political challenges [2]. Traditional uses of biomass, mainly in the form of charcoal and firewood still dominate the energy mix with substantial impacts on economic activities, livelihood, health and the environment [3]. Moreover, lighting in rural areas is mainly based on kerosene lamps, candles and small generators. There is a high demand for access to electricity and modern energy services in these rural communities which is not being met through grid-extension, providing a unique opportunity for distributed off-grid generation based on renewable resources.

Biomass gasifier based electricity generation system is one of the feasible options to meet the rural energy needs of Sierra Leone utilizing locally available biomass. A biomass-based hybrid energy system, the first hybrid power plant in Sierra Leone that provides for rural electrification, has been successfully installed in Kychom, Northern Sierra Leone for electrification of the village. Hybrid systems are increasingly being favored as the best means of providing decentralized power with high reliability [4].

Accurate planning of power generation systems represents a major issue in Sierra Leone. Computational energy models are available that can support energy planners to decide the best configuration for energy supply systems, as they allow simulating different solutions and checking their technical and economic feasibility in the early stages of the planning process [5, 6]. This work analyses the Kychom biomass-based hybrid system by developing a model in HOMER (Hybrid Optimization Model for Electric Renewables), a software developed by the US National Renewable Energy Laboratory [7] to address the need for a hybrid system design tool accurate enough to predict energy system performance.

II. METHODOLOGY

HOMER optimization tool was used to determine the conditions that enable the Kychom biomass-based hybrid power plant to be most economically and technically feasible.

A. HOMER Software

The **H**ybrid **O**ptimization **M**odel for **E**lectric **R**enewables (HOMER) software is an energy modeling tool for designing and analyzing hybrid power systems comprising of conventional generators, biomass generators, solar photovoltaics, wind turbines, hydropower, batteries, and other technologies. This is done by creating a model of the system including electrical loads, energy resources, equipment and several economic inputs, then simulating the system based on each possible configuration, resource and load scenario. Sensitivity analysis can also be carried out in order to analyze the response of the model to varying input values. Important assumptions made in the simulation process include the following:

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- Simulation time step, the amount of time used to simulate the system is set to 60 minutes.
- The project lifetime is assumed to be 15 years. Project lifetime is used in the calculation of two very important outputs of the model, the Net Present Cost (NPC) and the Levelized Cost of Energy (COE).
- Annual real interest rate is assumed to be 6%. This is the average real interest rate in Sierra Leone.

After running the simulation, HOMER sorts the feasible cases in order of increasing net present (or lifecycle) cost. This cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs. HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type [7].

B. Kychom Village

Kychom village, comprising of 150 households, is situated in Kambia District, Northern Sierra Leone at a distance of 53 km from the capital city, Freetown, to the South and 33 km from Kambia town (location of the nearest utility grid). The Latitude and Longitude of Kychom are 8°55'56"N and 13°8'30"W, respectively. The population is mainly farmers, practicing off-season activities such as gardening and hunting. The major food crops grown are rice (the staple food), cassava, millet, sweet potatoes and sorghum, while groundnuts and maize constitute the major cash crops. In addition to farming, fishing along the many river estuaries and streams is practiced by a large proportion of the population. Outside agriculture, commerce is the most important source of income for the population. The products offered are mainly agricultural and food products, clothes and some imported consumer goods.

Electrical Load of Kychom: Electrical load assessment in the design of Hybrid Renewable Power Systems is the first step usually undertaken to determine the size of system components. Electrical load in Kychom include mainly residential, commercial and community. Table 1 shows the load type and daily energy requirement.

Table 1
Energy Demand For Kychom Village

No.	Appliance	Quantity	Power (W)	Hrs/Day	Wh/Day
ELECTRIC APPLIANCES FOR A SINGLE HOUSEHOLD					
1	Light bulb	5	11	6	330
2	Refrigerator	1	100	24	2400
3	Television	1	90	6	540
4	Table Fan	1	55	6	330
5	Radio	1	10	4	40
Total			266		3640
A.	Number of Houses: 150		39900		546000
STORE					
1	Light bulb	4	11	6	264
2	Deep Freezer	1	180	15	2700
3	Television	1	90	3	270
4	Ceiling Fan	1	30	15	450
5	Phone Charger	1	10	4	40
Total			321		3724
B.	Number of Stores: 5		1605		18620
HEALTH CENTRE					
1	Light bulb	4	11	12	528
2	Vaccine Freezer	1	68	24	1632
3	Ceiling Fan	1	30	10	300
Total			109		2460
C.	Number of Health Centres: 1		109		2460
SCHOOL					
1	Light bulb	4	11	5	220
2	Ceiling Fan	1	30	5	150
3	Desktop Computer	1	200	2	400
4	Printer	1	100	1	100
Total			341		870
D.	Number of Schools: 2		682		1740

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Microsoft Excel spreadsheet was used to estimate the entire Kychom hourly load with corresponding time of usage. The estimated values were used as one of the input parameters for HOMER software to determine a combination of economical hybrid energy system. Based on the set of data provided, the typical daily load profile depicted in Figure 1 was created.

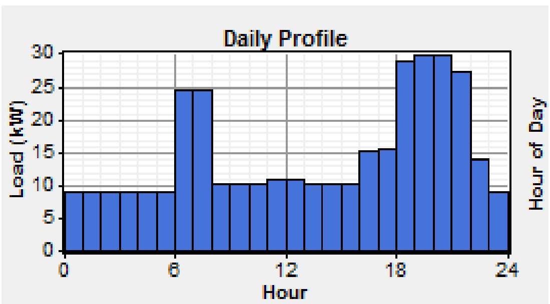

Figure 1. Daily load profile for Kychom

III. Description Of The KYCHOM Hybrid System Components And Price Inputs

The Kychom hybrid energy system consists of biomass gasifier, diesel generator, battery and converter. The system component size and price inputs to Homer Software are depicted in Table 2 and described below.

A. Biomass Gasifier

The 32 kW biomass gasifier is the core of the Kychom power plant. The gasification technology is a fixed bed downdraft system from ANKUR Scientific Energy Technologies Pvt. Ltd., India [8]. This particular model **Combo-50** can work both on woody biomass (Wood Based Gasifier) and rice husk (Fine Based Gasifier) with a simple one day changeover either from WBG to FBG mode or vice-a-versa. Rice husk is currently being used as feedstock. A photograph of the installed "Ankur" Biomass Gasifier Combo 50 is shown in Figure 2 wherein the critical components (reactor, gas cleaning and cooling system and gas engine-genset) are shown. The combustible gas generated from the gasifier can be used for power generation as well as thermal applications. For power generation, the gas, after the required cooling and cleaning processes, is fed to a producer gas engine. This engine is suitably modified to operate only on producer gas from the biomass gasifier. The unit retails for $50,000 with a replacement cost of $40,000 after 36,000 hours of operation [8]. Operation and maintenance costs are set at $0.65/hr and the sizes considered are 0 (no gasifier), 10, 20, 25, 30 and 60 kW.

TABLE 2
COMPONENT SIZE AND PRICE INPUTS TO HOMER SOFTWARE FOR THE SITE

	Gasifier Ankur COMBO-50	**Diesel Generator** Cummins	**Battery** Surrette 4KS25PS	**Converter** Sunny Island 4548
Size (kW)	32	7.5	1,900 Ah/7.6 kWh	5
Capital Cost ($)	50,000	3,000	1000	4,500
Replacement Cost ($)	40,000	2,000	1000	4,500
O & M Cost ($/hr)	0.65	0.05	0	0
Sizes to consider	[0, 10, 20, 25, 30, 60]	[0, 7.5, 15, 20, 25]	[0, 1, 2, 3]	[0, 5, 10, 15, 27]
Lifetime	36000 Hours	15000 Hours	10,965 kWh	15 Years

Figure 2. Photograph of the Kychom gasifier assembly.

Biomass Material: An economically viable gasification system depends on a feedstock supply that is reliable in quantity and quality throughout the year. There is sufficient biomass feedstock (rice husk) available in Kychom for operating the gasifier plant. The average rice husk available in Kychom is 0.27 tons per day [9]. The properties of the rice husk obtained from the rice variety (locally known as Pa Potho) cultivated in the Kychom area are given in Table 3 [10]. The rice husk is a relatively uniform material and does not require any treatment before use. It has a high volatile matter content (67.60%), high ash content (18.20%) and low fixed carbon (14.20%).

The high volatile matter content makes rice husk easily devolatilized, thus yielding low fixed carbon residue. The extremely high ash content of the rice husk (18.2%) compared to 1 – 5% for most other biomass materials warrants continuous ash removal during gasification as is the case with the gasifier used in this study. The major elemental constituents of the rice husk (carbon, oxygen and hydrogen) are important in assessing the heating value and the suitability of the material as fuel, and the low fractions of nitrogen, Sulphur and chlorine offer environmentally more desirable fuel properties.

TABLE 3
MAIN CHARACTERISTICS OF THE FEEDSTOCK

Characteristics	**Value**
Proximate Analysis (%)	
• Volatile matter	67.60
• Fixed carbon	14.20
• Ash	18.20
Ultimate Analysis (%)	
• Carbon	42.60
• Hydrogen	5.10
• Oxygen	33.44
• Nitrogen	0.51
• Sulphur	0.03
• Chlorine	0.13
• Ash	18.20
Lower Heating Value (MJ kg^{-1})	14.12

B. Diesel generator

A 7.5 kW AC diesel-powered generator is used in the Kychom power plant. Thermal power generation using diesel or other liquid fuels generally offers the lowest specific capital cost ($/kW) for small-scale power generation but has a very high operating cost due to high fuel prices. Capital cost for an industrial-grade diesel generator this size in Sierra Leone is $3,000 and the replacement cost is set at $2,000. Operation and maintenance cost is estimated to be around $0.05/hr and the sizes considered are 0, 7.5, 15, 20 and 25.

C. Batteries

The battery used in this system is the Surrette 4KS25P, 4 V, 1900 Ah gel-type valve-regulated lead–acid (VRLA) maintenance-free battery. The capital cost of the battery bank is assumed to be around $1,000 and this value is also used for the replacement cost in HOMER. The cells do not require maintenance so operation and maintenance cost is set to zero.

D. Converter

A 5 kW SMA Sunny Island manager is used in the hybrid system. It manages the stand-alone grid by coupling AC and DC components, as well as a bank of batteries. This is ideal for managing a system where primary generation and loads are AC but where the addition of a battery bank and DC-based inputs can be used to provide low-cost power at lower loads. The Sunny Island, modeled in HOMER as a converter, has a lifetime of 15 years, inverter efficiency of 95% and rectifier efficiency of 85% [11].

Figure 3 shows the schematic for the HOMER model which consists of a biomass gasifier, diesel generator, storage battery, converter and load. The annual primary peak load for Kychom is approximately 30 kW, with daily energy production of 355 kWh/day.

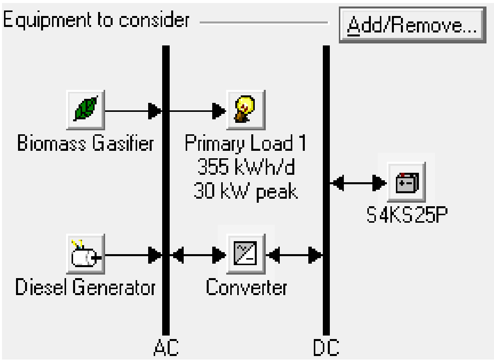

Figure 3. Schematic of the Kychom hybrid energy system generated in HOMER.

IV. Results And Discussion

At the end of the simulation, HOMER displayed 200 overall and 4 categorized lists of the optimization results in increasing order of the total Net Present Cost (NPC), which calculates the total cost of purchasing and operating the system over the project's lifetime, discounted back to provide this cost in present value terms. Key output variables for the 4 categorized optimization results are given in Figure 4.The categorized optimization results show that the optimal system, based on the NPC, is a 20 kW gasifier, 24 batteries, and a 10 kW converter. This configuration has a capital cost of $64,250, operating cost of $12,716/year, NPC of $187,747, which results in a cost of energy (COE) of $0.149/kWh. The second ranked configuration (Gasifier-Diesel generator-Battery) comprising of all the systems that make up the existing Kychom power plant gives the highest capital cost of $67,250. Operating this option can pose a serious challenge as diesel fuel costs may increase in the long term and there is no backup source if supply is disrupted. Important electrical, economic and environmental results of the top-ranked configuration (Gasifier-Battery) are discussed in the following sections.

BG (kW)	DG (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
20		24	10	$ 64,250	12,716	$ 187,747	0.149	1.00
20	7.5	24	10	$ 67,250	13,664	$ 199,954	0.159	0.97
25	7.5			$ 42,063	17,063	$ 207,784	0.165	0.96
	20.0	24	10	$ 41,000	55,845	$ 583,378	0.464	0.00

Figure 4. Categorized optimization results from HOMER model.

A. Electricity Production

Figure 5 shows the monthly average distribution of electricity produced in kW from the optimal system components. The total electrical production of the hybrid system, 143,937 kWh/yr, is contributed by the gasifier.

Figure 5 also indicates that the consumption is 129,569 kWh/yr and both the unmet electric load and capacity shortage values are zero. Hence, the optimal system can generate enough power to meet all the power demand of Kychom village, thus eliminating the use of the existing diesel generator.

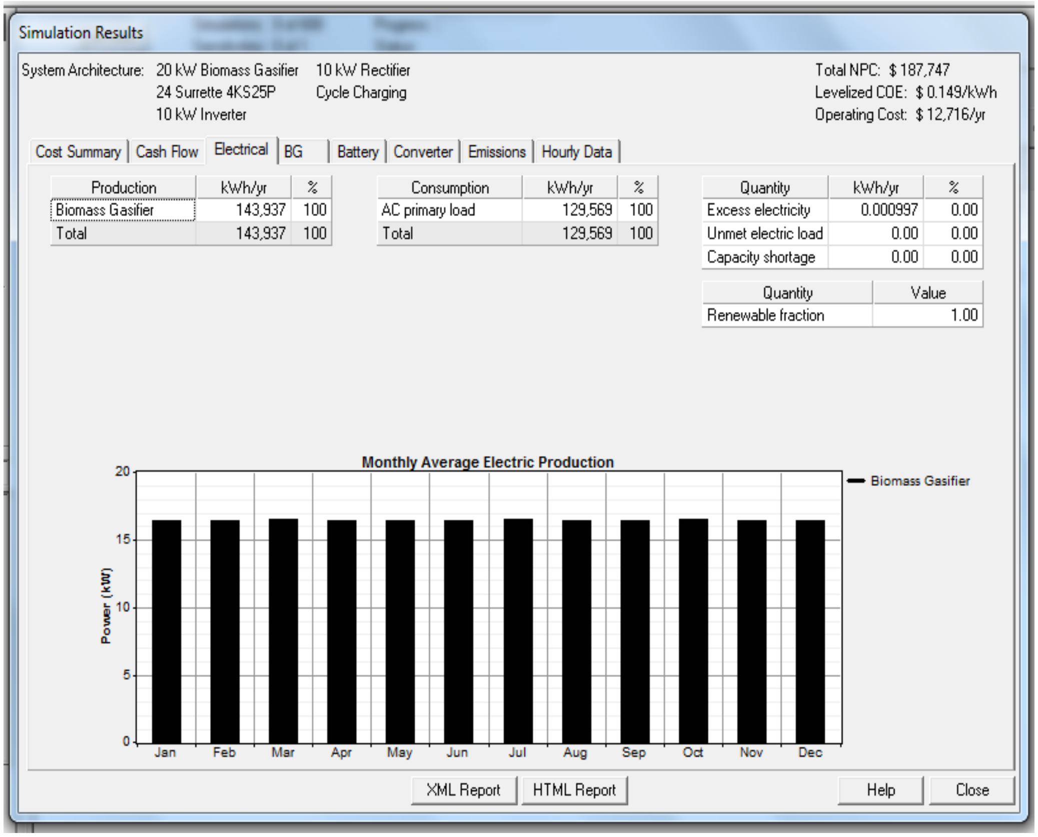

Figure 5. Monthly average electricity production of the optimal system configuration generated in HOMER.

B. Economic Aspects

The total NPC for each component of the Gasifier-Battery system is presented in Figure 6. The most costs are for the biomass gasifier and the least cost for the converter.

The largest portion of costs is accounted for by the capital and replacement costs. More than half this equipment cost is due to the biomass gasifier, which also contributes all of the O&M and fuel costs.

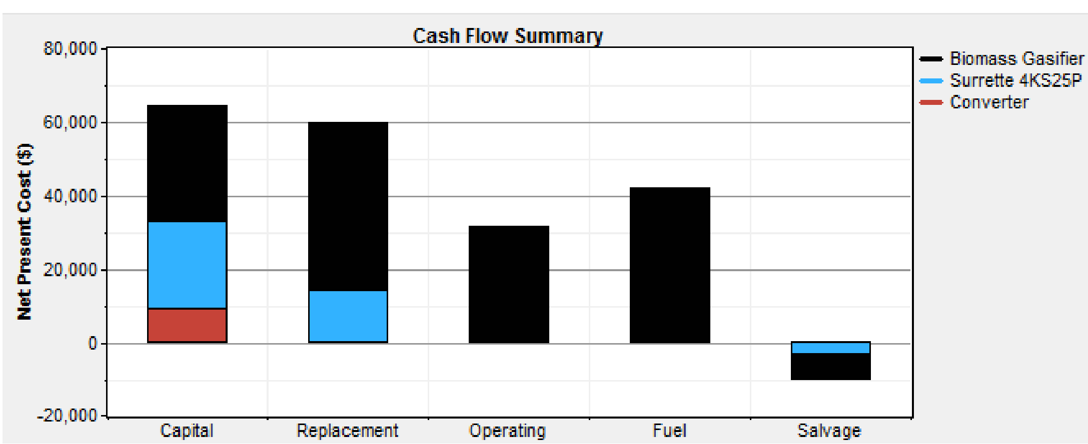

Figure 6. Cost summary of the Biomass-Battery system.

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Figure 7 presents the cash flow categorized by cost type for the 15 years of the project lifetime.

Replacement costs include the replacement of the batteries at year 5 and the repair or replacement of the gasifier at years 9 and 14.

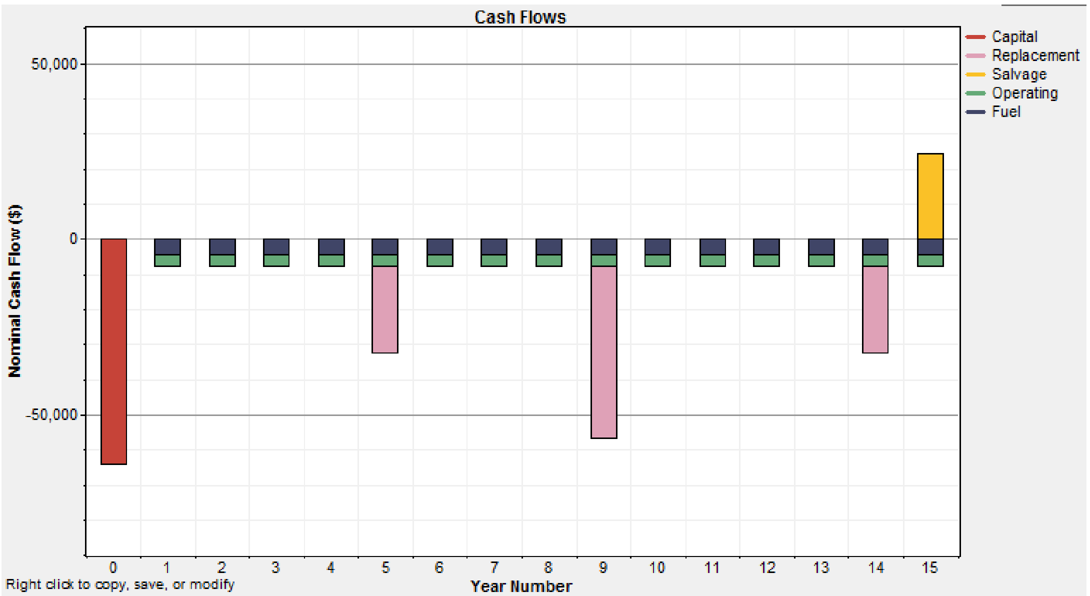

Figure 7. Cash flow by cost type over the project lifetime generated in HOMER.

C. Environmental Aspects

The evaluated quantities of greenhouse gas emissions from the optimal system simulated in this study and the existing system in Kychom village are depicted in Table 4. The emitted pollutions, measured as yearly emissions of the emitted gases, are carbon dioxide, carbon monoxide, unburned hydrocarbons, particular matter, sulfur dioxide and nitrogen oxides.

The results indicate that the optimal biomass-battery configuration generates the minimum values of pollution emissions. Therefore the optimal system is not only economically feasible in terms of life cycle cost but has less greenhouse gas emission which complies with the Sierra Leone's policy strategy of climate Resilient Green Economy [12].

TABLE 4
COMPARISON OF EMISSIONS FROM THE OPTIMAL AND EXISTING CONFIGURATIONS

Configuration	Carbon Dioxide (kg/yr)	Carbon Monoxide (kg/yr)	Unburned Hydrocarbons (kg/yr)	Particulate Matter (kg/yr)	Sulfur Dioxide (kg/yr)	Nitrogen Oxides (kg/yr)
Biomass Gasifier-Battery	5.48	0.565	0.0626	0.0426	0	5.04
Biomass Gasifier-Diesel Generator-Battery	3,701	9.67	1.07	0.729	7.42	86.3

V. Conclusion

The viability of a hybrid energy system comprising of a 32 kW biomass gasifier, a 7.5 kW diesel generator and a 5 kW battery/converter system installed in Kychom, a remote village located in Northern Sierra Leone, has been assessed using HOMER Software. As an alternative solution to this existing Kychom hybrid energy configuration, HOMER Software shaped an optimal system that eliminated the use of the diesel generator.

The model developed in HOMER simulated energy resources and electrical loads for Kychom, as well as various equipment configurations and financial data to create a cost-based ranking of different energy solutions. The HOMER optimization and simulation results presented in this paper show that the optimal system is the least-cost combination of 20 kW biomass gasifier, 24 batteries, and 10 kW converter.

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This configuration can satisfy the electrical needs of Kychom village in a reliable manner at a cost of $0.149/kWh and generates minimal greenhouse gas emissions. Given the abundant availability of biomass feedstock in this location, all of the electricity in the optimal option comes from the gasifier which provides a cheap source of power to the village. The batteries are used as a backup in the system and to maintain a constant voltage during peak loads or a shortfall in generation capacity.

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