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LEAST COST MICROGRID RESOURCE PLANNING FOR THE NATURAL ENERGY LABORATORY OF HAWAII AUTHORITY RESEARCH PARK

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ABSTRACT

The Natural Energy Laboratory of Hawaii Authority's (NELHA) campus on The Island of Hawai'i supplies resources for a number of renewable energy and aquaculture research projects. There is a growing interest at NELHA to convert the research campus to a 100% renewable, islanded microgrid to improve the resiliency of the campus for critical ocean water pumping loads and to limit the increase in the long-term cost of operations. Currently, the campus has solar array to cover some electricity needs but scaling up this system to fully meet the needs of the entire research campus will require significant changes and careful planning to minimize costs. This study will investigate least-cost solar and energy storage system sizes capable of meeting the needs of the campus.

The campus is split into two major load centers that are electrically isolated and have different amounts of available land for solar installations. The value of adding an electrical transmission line if NELHA converts to a self-contained microgrid is explored by estimating the cost of resources for each load center individually and combined. Energy storage using lithium-ion and hydrogen-based technologies is investigated. For the hydrogen-based storage system, a variable efficiency and fixed efficiency representation of the electrolysis and fuel cell systems are used. Results using these two models show the importance of considering the changing performance of hydrogen systems for sizing algorithms.

Keywords: Microgrid planning, optimization, hydrogen storage

1. INTRODUCTION

There are many cases in which it is of interest to operate a load center as an isolated microgrid using renewable power generation and electrical energy storage to support the load. This could be for many reasons including the insurance of steady electricity or backup supply, for disaster resiliency, power supply in remote areas, to name a few. Many studies have investigated the selection of microgrid resources for different cases, often using mixed integer programs with fixed efficiency assumptions to minimize cost over a time horizon for different scenarios [1-3], but each scenario provides unique considerations and challenges that affect what the most cost-effective system design.

Here we present an investigation of the Natural Energy Laboratory of Hawaii Authority's campus on The Island of Hawai'i, which supplies resources for several renewable energy and aquaculture research projects. One key resource that the campus provides is pumped sea water that is used widely for various applications. The energy to pump this water is a significant and critical component of the electrical demand of the campus. Also, given the prevailing rates, electricity costs to operate the campus are very high.

As such, there is a growing interest at NELHA to convert the research campus to a 100% renewable, islanded microgrid, not only as a demonstration and test-bed for renewable technologies, but also to improve the resiliency of the campus and reduce the long-term cost of operations. Currently, the campus uses a large solar array through a power purchase agreement but scaling up this system to fully meet the needs of the entire research campus will require significant changes to the current system and careful planning to minimize costs. This study will investigate least-cost solar and energy storage system sizes capable of meeting the needs of the campus.

2. SYSTEM CONFIGURATION

For this analysis, demand and solar generation data collected by researchers at NELHA was used and the specific needs of the campus were considered. The campus is split into two major load centers, the research park and 55in pump station,

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as shown in Figure 1, that are electrically isolated and have very different amounts of available land for renewable generation installations. Wind resources at the site are limited, so only solar generation were considered.

The major load at both locations are the seawater pumps that supply the various facilities on site. This water needs to be supplied with high reliability as outages of even thirty minutes can be fatal to some of the creatures being sustained. As such, though these areas are electrically isolated, they are hydraulically connected through a network of pipes that make it possible to shift pumping demand between the areas as needed to compensate for issues at various pump stations.

Figure 1: NELHA FACILITY MAP

In the scenario that NELHA converts to a self-sufficient microgrid, there is a question as to whether the two areas should also be connected electrically to maintain the flexibility of shifting loads and make full use of the available area at the 55in station for solar installations amongst other reasons. However, this is an expensive proposition as the transmission line to connect the areas would need to be run underground through a mile of volcanic rock.

Here we investigate least cost solutions to support NELHA's operations with local generation and energy storage. The following case study also looks at the value of connecting the research park and 55in station. Additionally, energy storage using lithium-ion and hydrogen-based technologies are investigated, including the effect of variable efficiencies of the essential components of a hydrogen system.

3. MODELING AND METHODS

NELHA collects electricity and water usage data from their system. Full years of energy usage data from 2015 to 2019 were used as the basis for this study. To determine the minimum amount of resources based on the historical data, an optimization algorithm was implemented to determine the sizes of the solar generation and energy storage components that would minimize the cost of islanding the network to give a basis for further investigation. Resources were sized assuming both lithium ion battery and hydrogen-based storage. The overall objective being to minimize the cost of the system to cover NELHA's demand by optimizing the dispatch of the energy storage system.

$$
\begin{aligned}
&\min_{P_C, P_D, P_{curt}} \quad C_{sol} I_{sol} + \sum_{i=Power,Energy} C_{i,ESS} I_{i,ESS} - \frac{\sum_t P_{curt,t}}{K} && (a)\\
&s.t. \qquad P_{L,t} + P_{C,t} + P_{curt,t} - P_{sol,t} - P_{D,t} = 0 && (b)\\
&\qquad\qquad P_{sol,t} = I_{sol} p_{sol,t} && (c)\\
&\qquad\qquad P_{curt,t} \le P_{sol,t} && (d)
\end{aligned}
$$

(1)

where C denotes a component cost, I denotes the installed capacity of the given component, P is power in kW, and p is the capacity factor (e.g. the output from a modeled 1kW system),. Subscripts L, C, $curt$, sol, and D represent the campus load, energy storage system (ESS) charge, curtailment, solar generation, and ESS discharge, respectively. The solar capacity factor was calculated from the measured output of a solar array located at the NELHA campus divided by the nameplate capacity of the array.

The cost function shown in Eqn (1)a is dominated by the installation cost for all the solar generation and energy storage system components. The cost of the energy storage system was separated into power costs (power electronics systems for Li-ion and additionally electrolyzer/fuel cell costs for H_2 storage) and energy costs (kWh battery costs or kg storage costs for hydrogen). The final term in Eqn (1)a gives a slight benefit to direct curtailment versus simultaneously charging and discharging the ESS to expend excess energy (K=100000). This removes simultaneous charge and discharge from the optimal ESS scheduling without significantly affecting the sizing results given the large K value or adding a significant computational expense. The objective is then to minimize the cost of the system components while supporting the demand of the campus by optimizing the charging and discharging operations of the energy storage system. Additional constraints were necessary to characterize changes in the state-of-charge of the energy storage systems and to size the power components of the system, as will be discussed in the following section.

3.1 Li-ion Battery State-of-Charge

The state-of-charge of the lithium ion battery system was modeled with an energy reservoir model, which tracks the kWh availability of the system [4]. For this analysis, this was taken to be a sufficient estimation of a lithium-ion battery system, which has a fairly constant efficiency across the power range of the system:

$$
\begin{aligned}
&S_{kWh,t} = S_{kWh,t-1} + \left(\eta_C P_{C,t} - \frac{P_{D,t}}{\eta_D} \right) \Delta t && (a)\\
&0 \le S_{kWh,t} \le I_{kWh,ESS} && (b)
\end{aligned} \qquad (2)
$$

where η_C and η_D are the charge and discharge efficiency of the battery system, respectively, S is the state-of-charge, and Δt is in hours. For this analysis, it was assumed that the charge and discharge efficiencies were both 90%. Further, to ensure that the proposed system could continue operations year-to-year, it was further required that the state-of-charge at the beginning and end of the analysis timeframe be 50% of the installed energy capacity ($I_{kWh,ESS}$).

Lastly, the power components of the system were sized using the following constraint:

$$P_{C,t} + P_{D,t} \le I_{kW,ESS} \qquad (3)$$

where I_{kW} is the installed power electronics system rating. As charge and discharge operations do not occur simultaneously, this essentially makes it such that the installed capacity is the peak charge or discharge power that is needed over the analysis period.

3.2 Fixed Efficiency Hydrogen Storage

To function as the energy storage system for an islanded microgrid, a hydrogen energy storage system would need to consist of an electrolyzer system to produce hydrogen from the electricity generated by the photovoltaic system, storage tanks to hold the produced hydrogen, and a fuel cell system to produce electricity from the hydrogen as needed. This is similar to the case with the lithium-ion battery system except that the power components for charging (electrolyzer) and discharging (fuel cell) should be sized and valued separately. When a fixed efficiency is assumed for the power components of the system, the hydrogen state-of-charge, in other words the kg of hydrogen stored at any given time, is calculated as follows:

$$\begin{aligned} S_{kg,t} &= S_{kg,t-1} + \left(h_C P_{C,t} - h_D P_{D,t}\right)\Delta t \quad (a) \\ 0 &\le S_{kg,t} \le I_{kg,H_2} \quad (b) \end{aligned} \qquad (4)$$

where h_C and h_D are the rate of hydrogen production from the electrolyzers and consumption from the fuel cells in kg/hr per kW of power, respectively.

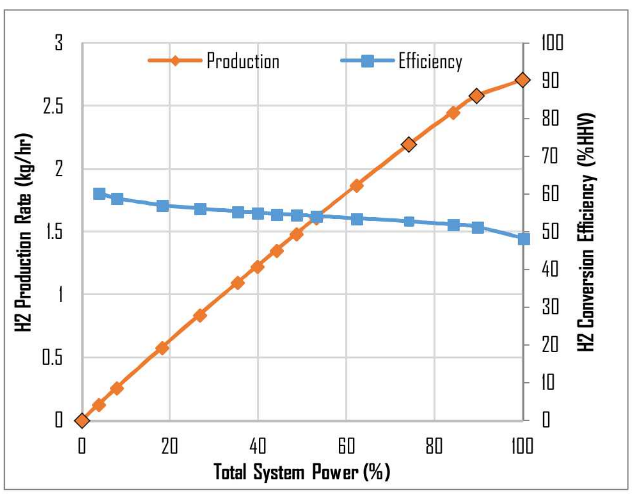

Figure 2: ELECTROLYZER EFFICIENCY AND PRODUCTION RATE VERSUS % FULL POWER

For this analysis, the hydrogen production and consumption rates were based on data from commercially available or deployed systems. The electrolyzer system modeled after a Proton C30 electrolyzer currently located at the NELHA research park. This is an approximately 250kW system, and a model of the overall system's power draw and corresponding hydrogen production rate including the balance-of-plant components has been developed [5]. The output of this model is shown in Figure 2.

Data regarding the system power draw versus hydrogen consumption rate is shown in Figure 3. Again, the values shown include the balance of plant power requirements for the system. The average ratio of the hydrogen consumption rate to the power output over the entire range is used for the fixed efficiency estimations (hD = 0.055825 kg,H2/hr/kW). Constraints on the power of the system were also imposed for the hydrogen storage system, but in this case, as the power components would be separate for the electrolyzer and fuel cell systems and pricing differs accordingly, separate constraints were necessary:

$$\begin{aligned} P_{C,t} &\le I_{kW,Elec} \quad (a) \\ P_{D,t} &\le I_{kW,FC} \quad (b) \end{aligned} \qquad (5)$$

where in this case, the storage system charge and discharge powers refer to the electrolyzer (Elec) and fuel cell (FC) system powers, respectively.

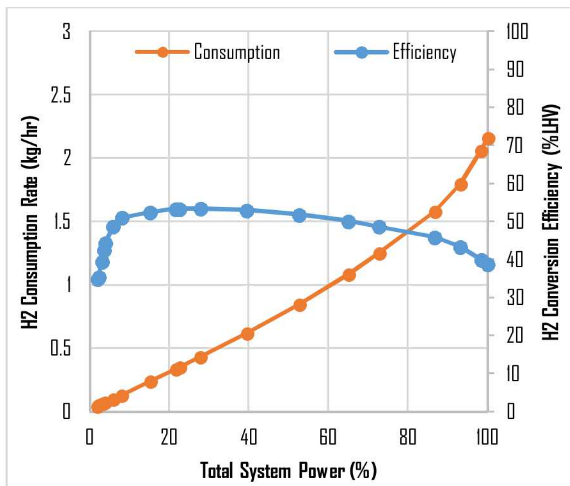

Figure 3: FUEL CELL EFFICIENCY AND PRODUCTION RATE VERSUS % FULL POWER

3.3 Variable Efficiency Hydrogen Storage

Though the use of fixed efficiency estimates is common for sizing operations such as this, the efficiency of electrolyzers and fuel cells can vary significantly over the operational power range. Particularly, it can be seen in Figure 2 and Figure ***3*** that the efficiency of both the electrolyzer and fuel cell systems taper off at high powers. This variation in hydrogen production and consumption with the power draw of the system could have a significant effect on how such systems should be properly sized.

To capture this effect within the sizing algorithm, piecewise linear representations of the hydrogen rates versus power for the electrolyzer / fuel cell systems (e.g. C/D in the following) were incorporated in the analysis using type 2 special ordered sets (SOS2).

$$\begin{aligned} p_{C/D,t} &= \sum_{k=1}^{B} b_{C/D,k} \cdot x_{C/D,k,t} && (a) \\ h_{C/D,t} &= \sum_{k=1}^{B} g_{C/D,k} \cdot x_{C/D,k,t} && (b) \\ 1 &= \sum_{k=1}^{B} x_{C/D,k,t} && (c) \\ x_{C/D,k,t} &\le \gamma_{C/D,k,t} && (d) \end{aligned} \tag{6}$$

where p is the power output scaled to 1kW of installed capacity, h is the hydrogen production/consumption rate scaled to 1kW of installed capacity, k denotes break points in the piecewise linear approximation, b_k is the power at breakpoint k, g_k is the associated hydrogen production/consumption rate at breakpoint k, x_k's are continuous variables introduced by the SOS2 representation for interpolation between break points, and γ_k's are binary variables for which only consecutive values can be non-zero. This imposes a piecewise linear relationship between the hydrogen production and facility scaled to 1kW of installed capacity. The following bilinear constraints were used to go from scaled hydrogen rates to absolute values:

$$\begin{aligned} P_{C,t} &= p_{C,t} I_{kW,Elec} && (a) \\ P_{D,t} &= p_{D,t} I_{kW,FC} && (b) \\ H_{C,t} &= h_{C,t} I_{kW,Elec} && (c) \\ H_{D,t} &= h_{D,t} I_{kW,FC} && (d) \end{aligned} \tag{7}$$

where H is the hydrogen rate in kg/hr and the fixed efficiency hydrogen storage constraint shown in Eqn. (4) becomes:

$$\begin{aligned} S_{kg,t} &= S_{kg,t-1} + \left(H_{C,t} - H_{D,t}\right)\Delta t && (a) \\ 0 \le S_{kg,t} &\le I_{kg,H_2} && (b) \end{aligned} \tag{8}$$

For this analysis, the piecewise linear representation of the electrolyzer and fuel cells used break points as shown in Table 1:

Table 1: BREAK POINTS FOR SOS2 REPRESENTATION OF ELECTROLYZER AND FUEL CELL SYSTEMS

Electrolyzer		Fuel Cell	
Power (kW)	**H2 Rate (kg/h)**	**Power (kW)**	**H2 Rate (kg/h)**
0.000	0.0000	0.000	0.0000
0.740	0.0099	0.394	0.0189
0.895	0.0117	0.867	0.0479
1.000	0.0124	1.000	0.0655

The inclusion of the variable efficiency representations adds significantly to the computational expense of the analysis but, as will be shown in the following section, also has a significant effect on the results. All of the formulations outlined here were implemented using Pyomo [6, 7] in Python and solved using Gurobi [8].

4. RESULTS AND DISCUSSION

The following results are based on metered solar generation and demand data from NELHA for the year of 2018. It should be noted that the optimization algorithm assumes perfect foresight of the demand and solar generation at the site to optimize the timing of charge and discharge operations for the energy storage system. As such, the following results should be considered minimum resource estimates to operate NELHA's facilities in an islanded mode and a starting point to assess systems for future variations in load and potential fluctuations in solar output. The costs assumed for the various system components are shown in Table 2:

Table 2: ENERGY STORAGE SYSTEM COMPONENT COST ASSUMPTIONS

Storage System	Component	Cost	Unit	Ref
Li-ion	Power	388	$/kW	[9]
	Energy	382	$/kWh	[9]
Hydrogen	Electrolyzer	1008	$/kW Elec	[10]
	Fuel Cell	500	$/kW FC	[11]
	Storage	600	$/kg H2	[12]

The cost for the power components of the Lithium-ion system are much lower than with the hydrogen storage system, but the cost of energy storage is significantly lower with hydrogen. As one kg of hydrogen can supply 15kWh of energy through a fuel cell (assuming 45% efficiency vs. LHV), the $/kWh cost of storage in hydrogen is approximately $40/kWh, nearly one-tenth of the cost of Li-ion storage. Depending on the amount of storage that is needed for a given scenario, it is possible that hydrogen storage could be a cheaper option despite the lower efficiency and increased cost of the power components.

Below, results are presented for the Research Park and 55" Pump Station separately and with the demands of each zone aggregated, referred to as "Connected Zones" below. The difference between the system cost in the "Connected Zones" case and the summation of the individual cases, referred to as "Independent Zones" below, should give a good indication of the value of adding electrical transmission between the areas. If the cost to create a single microgrid with the loads aggregated is significantly less than what it would cost to install two independent microgrids, it could be worth the cost of additional transmission between the zones.

4.1 Lithium Ion Sizing Results

First we will look at the sizing results using Li-ion storage with solar generation to cover NELHA's electric demand. The results of the sizing algorithm are shown below in Table 3. The optimal system cost to operate all of the NELHA facilities as an islanded microgrid in this scenario is approximately $36M, using

5MW of installed solar capacity and 2MW / 53MWh of energy storage whether the zones are electrically connected or not. Here it seems that there is very little advantage to connecting the research park and 55" pump station electrically as the cost of creating two independent systems is nearly identical to the cost of aggregating the loads. Connecting the zones would only reduce the cost of the installed system by around $5,000, which is far less than the cost of adding underground transmission.

Table 3: OPTIMAL LITHIUM ION SYSTEM SIZE FOR EACH ZONE

Zone	Solar (kW)	Energy (kWh)	Power (kW)	Total System Cost($M)
Research Park	1,889	17,578	709	12.6
55" Pump Station	3,377	35,101	1,263	23.9
Connected Zones	5,266	52,679	1,964	36.5
Independent Zones	5,266	52,679	1,972	36.5

While this would be a very large energy storage system, the relative scale of power to energy for the system does not imply the need to shift energy between seasons as is often cited as a possibility for 100% renewable grids. Here, the duration of the storage system would need about 27 hours in the optimal case.

To minimize the amount of storage required, the model recommends installing an excess of solar generation and curtailing a significant portion rather than maximizing the utilization of solar generation. In fact, the optimal system configuration leads to over 37% of the solar generation being curtailed to balance supply and demand. That said, it is likely that the suggested capacity of solar generation would be sufficient to cover most demand fluctuations for a more complete microgrid resiliency study given the excess of energy being produced. This will be explored further in future work.

4.2 Fixed Efficiency Hydrogen Storage Sizing Results

Results are somewhat different using hydrogen as the storage medium. The overall estimated system cost is approximately $41M, using nearly 12MW of installed solar capacity, 4.1 MW of electrolyzers, around 500kW of fuel cells, and 2600kg of hydrogen storage.

Table 4: OPTIMAL HYDROGEN STORAGE SYSTEM SIZE FOR EACH ZONE ASSUMING FIXED EFFICIENCY

Zone	Solar (kW)	Electrolyzer (kW)	Fuel Cell(kW)	Storage (kg)	Total System Cost($M)
Research Park	4,160	1,577	217	878	14.54
55" Pump Station	7,575	2,864	341	1,737	26.52
Connected Zones	11,734	4,440	518	2,607	41.03
Independent Zones	11,735	4,440	558	2,615	41.06

The recommended system uses nearly twice as much solar, but the cost of the system only increases by approximately 12.5%. This is largely due to the cost of electrolyzers, which requires a very high installed capacity to generate the necessary amount of hydrogen given the relatively low efficiency of conversion as compared to the Li-ion system. Also, less energy is curtailed with hydrogen storage because of the reduced efficiency of the storage system. About 26% of the energy produced by solar generation would be curtailed in this case, versus 37% with Li-ion storage. This could be a significant consideration if there were a value stream for the energy that would otherwise be curtailed.

4.3 Variable Efficiency Hydrogen Storage Sizing Results

The performance of electrolyzer and fuel cell systems can change significantly over the operating window. Particularly, both systems modeled here decrease in efficiency near the rated power. The optimal size could differ significantly if the variable efficiency is considered in the sizing methodology. Results of the optimal sizing algorithm are shown in Table 5:

Table 5: OPTIMAL HYDROGEN STORAGE SYSTEM SIZE FOR EACH ZONE ASSUMING VARIABLE EFFICIENCY

Zone	Solar (kW)	Electrolyzer (kW)	Fuel Cell(kW)	Storage (kg)	Total System Cost($M)
Research Park	3,679	1,051	362	747	12.58
55" Pump Station	6,623	2,000	725	1,439	22.85
Connected Zones	10,348	3,048	986	2,191	35.51
Independent Zones	10,302	3,051	1,087	2,186	35.44

Surprisingly, the optimal system cost determined by the algorithm using the variable efficiency representation of the hydrogen components is $35M, less than that of the system using a fixed efficiency representation of the system. This system would require around 10MW of installed solar capacity, 3 MW of electrolyzers, around 1MW of fuel cells, and 2200kg of hydrogen storage. Relative to the fixed efficiency case, the optimal system size here has less installed solar generation, electrolyzers, and hydrogen storage but more installed fuel cells. This is because the fuel cell system would be more efficient with partial loading, making it beneficial to oversize the fuel cell system such that it never has to operate at a its maximum capacity. In fact, the peak load reached in this configuration is 52% of the installed fuel cell capacity. This helps to operate the fuel cell system in a more efficient range more often, which ultimately reduces the amount of hydrogen that is needed. When considering the improved efficiency of the electrolyzer at partial load as well, less hydrogen is necessary to meet the demand, and the solar, electrolyzer, and storage components can be smaller.

Though the electrolyzer suffers from the same loss in efficiency at high power, it is not recommended to oversize the system in this case because peak power is needed during peak solar generation when some energy is also being curtailed. As such, there is no benefit to avoid lost energy to inefficiencies by oversizing the electrolysis system since the additional energy is being curtailed anyhow in this scenario. Ultimately, if plans were made to fully utilize the produced solar energy in the future, oversizing this system as well could be beneficial.

5. CONCLUSION

The goal of this study was to determine the size of solar generation and energy storage resources to fully support the demand of NELHA's facilities. Both lithium ion and hydrogen-based energy storage systems were investigated by modeling these systems in mixed integer programs for optimization. Also, as hydrogen-based systems' efficiency changes significantly over their operating range, type 2 special ordered sets and bilinear constraints were developed to incorporate the change in efficiency of the systems as a function of power into the sizing algorithm as a piecewise linear relationship.

Results show that it is important to consider the change in hydrogen efficiency within its operating range when sizing a system to support a significant load. When assuming that the electrolyzer and fuel cell systems would perform at the average efficiency at all power levels, the algorithm reported a system configuration that was significantly more expensive than a lithium ion based storage system to support the same load. When the increased efficiency at partial load is added to the sizing algorithm, it is found that it is beneficial to oversize the fuel cell system so it can operate in a more efficient range, leading to lower hydrogen needs and a significantly less expensive system. In fact, when the variable efficiency is considered, it was shown that the NELHA demand could be supported less expensively with a system based on hydrogen storage than lithium ion storage. This is because NELHA would require storage on the order of days, even if the solar system is oversized.

Future work will include a broader system sizing investigation around the configurations identified here to determine the sensitivity of sizing to various considerations such as prices and safety margins for NELHA given fluctuations in demand. Also, though this analysis suggests that hydrogen would be a good option for NELHA's hourly storage needs, it may be that other technologies may be necessary to handle the short time-scale fluctuations. Finer time-step data and other technology options will be analyzed to this end as well as methods to improve solution speed of the variable efficiency hydrogen model. Lastly, shifting of pumping loads between areas to minimize energy needs will also be investigated to determine the effect on demand and the resulting system requirement to operate NELHA as a self-contained microgrid.

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