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Ko'olauloa Community Resilience Hub Design Trade-off Study

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Abstract

The planned Koʻolauloa community resilience hub (KCRH) in Hauʻula Hawaii is intended to serve a dual function as a 3,660 m^2 community center, and a resilient storm shelter powered by a microgrid. This study analyzes the interaction of building energy efficiency and microgrid cost and performance of the KCRH. A building energy model of the KCRH is used to determine critical and noncritical loads for a business-as-usual system and a high-efficiency system. A techno-economic optimization was conducted using the Hybrid Optimization of Multiple Energy Resources software considering two microgrid configurations, one with diesel backup, and the other with renewables-only, including photo-voltaic (PV) and storage battery. High energy efficiency reduces estimated microgrid cost by 34% for the diesel-PV and by 36% for all-renewables in comparison to business as usual. A resilience analysis conducted with the Microgrid Design Toolkit reveals that the high-efficiency system option enables much higher resilience for the renewables-only microgrid that meets cost limitations. The results, showing tradeoffs between resilience, efficiency and cost may be used by the Hauʻula community to make informed decisions about the final design of the KCRH.

Introduction

Remote communities are often more vulnerable to disasters than urban communities because of high costs required to ensure infrastructure redundancy. The Hauʻula community, located on the North-east side of the island of Oahu in Hawaii and home to approximately 2,000 people, is connected to services by a two-lane coastal road (Highway 83) and by a single power distribution loop. Power outages are common and outages from a hurricane, earthquake, tsunami or similar event could last several weeks. Also, road access could be interrupted for similar spans of time. Community leaders are therefore planning infrastructure that could provide support to the local population until service is restored, in case of such events. The existing community center is not fully able to serve this purpose because of its size and location in a tsunami risk zone, hence the need for a new building that supports greater preparedness.

The Koʻolauloa community resilience hub (KCRH) is intended to serve as a community center during normal "blue sky" operations. For resilience "black sky" operations, it should function as a storm shelter providing electricity, communications, thermal refuge, water, and food for up to 30 days after a major disaster. During extreme events, community resilience hubs can reduce the burden on emergency response teams by supplying power before, during, and after grid outages through onsite energy systems (DOE 2022). For example, community center involvement in Japan has been shown to result in decreased recovery time from a major earthquake and tsunami (Lee et al. 2022). The "bottom-up" capacity of community resilience hubs enables strong social ties between providers and those in need after a disaster (Aida et al. 2023).

This work provides insight into the relationship between microgrid cost, microgrid resilience, and building energy efficiency (EE) for the KCRH, given the requirement that it should be able to operate under a series of resilience design basis threats (DBTs). To this end, we create an OpenStudio™ (DOE 2023) building energy model (BEM) of the KCRH and configure the model for high efficiency (HE) and business as usual (BAU) operations. Both configurations also include dropping of non-critical loads whenever DBTs events (e.g. a hurricane) occur. This reduces the amount of generation and storage needed by the microgrid. Any changes to thermal comfort due to dropping loads is tracked through the KCRH BEM . The load profiles from the KCRH BEM are fed into two microgrid analyses. The first is a scenario-based approach using the Hybrid Optimization of Multiple Energy Resources (HOMER) software (UL Solutions 2023). A single hurricane event that disrupts power for 30 days is used to design a microgrid that can maintain power to critical loads. The HOMER analysis includes two microgrid configurations 1) mixed PV and diesel generation and 2) PV generation with lithium ion battery storage, producing a techno-economic analysis that optimizes net present cost (NPC) over a 25-year expected lifetime. The second microgrid analysis uses a stochastic approach with the Microgrid Design Toolkit (MDT), a decision support software that can provide conceptual designs that optimize performance, reliability, and cost under black sky conditions (Eddy, Miner, and Stamp 2017). This second approach is used to obtain detailed statistical assessment of microgrid configurations suggested by HOMER.

This paper provides a short literature review of similar case studies. It then provides the simulation methodology used with clear delineations of the KCRH BEM configuration and complementary HOMER microgrid techno-economic analysis and resilience analyses. It then provides results showing tradeoffs between EE, energy costs and resilience. The paper concludes with a discussion of the implications for the Hau'ula community and the broader practice of resilience analysis.

Literature Review

Many communities are currently seeking to implement resilience hubs (Baja and Urban Sustainability Directors Network 2019; Jossi 2022). The need to extend the function of community centers to include resilience is increasing because of extreme events driven by climate change, pandemics such as that caused by COVID-19, and the need for increased equity and justice for disadvantaged populations (McShane and Coffey 2022; Burrage 2011). Ciriaco and Wong provide a review of concepts and examples of resilience hubs in North America (Ciriaco and Wong 2022). Their work highlights how transportation needs must be considered in resilience hub design. They cite many resilience hub initiatives and resources that give important background and case study information.

Only a few case studies exist in the literature similar to ours: 1) repurposing abandoned buildings for artistic community gatherings and food resilience (Quaranta et al. 2019), 2) Assessing passive survivability of a community hub in Ontario, Canada (Ozkan and Good 2022), 3) evaluating the relationship between EE and microgrid cost and resources (Dahowski et al. 2020), 4) evaluating the relationship between microgrid availability and cost for Puerto Rican coastal communities (Villa and Quiroz 2023), and 5) Investigation on how tiered circuits in buildings affect community microgrid costs in Puerto Rico (Villa et al. 2023a).

This study extends modeling of the KCRH from a previous study for energy and thermal resilience to heat waves (Villa et al. 2024). We extend the previous study to include different aspects of microgrid analysis whereas the previous study exclusively focused on the KCRH BEM, EE, and thermal resilience. We adopt both a scenario-based resilience approach (e.g., (Villa 2021)) using HOMER and a stochastic resilience approach (e.g., (Villa et al. 2023b)), using MDT.

The methods of this paper are unique because they introduce a new level of rigor in microgrid assessment for a community resilience hub with multiple modes of operation (blue sky - black sky) to supply economic and energy availability results. Though the techniques are standard practice, literature is lacking that gives sufficient examples of how to proceed with such analyses.

Simulation

The tools summarized in Table 1 were used to conduct a resilience analysis that aims to show how high-cost EE building systems with a renewable energy (RE) microgrid compare to low-cost BAU building systems with a fossil fuel dependent microgrid. Figure 1 shows the workflow between tools and inputs. First, preliminary design drawings were used to construct thermal zones, shading surfaces, and fenestration for the KCRH in the SketchUp™ OpenStudio™ Plug-in (OpenStudioCoalition 2023). This geometry was then brought into the OpenStudio application and heating, ventilation, and air-conditioning systems for the BAU and HE configurations were created resulting in two OpenStudio models. Both of these models were then sub-divided into a total of four OpenStudio models with the blue sky and black sky modes of operation. The same adjusted weather file as used in the previous study for the KCRH (Villa et al. 2024) was then altered to include a hurricane starting July 28th(Hawaii sees the most hurricanes July through September). For the 3-day hurricane event, temperature was decreased, relative humidity was raised, precipitation was increased and solar radiation was reduced. Four 8760-hour load profiles were created from this altered weather file, with all combinations of BAU and HE, and blue sky and black sky operations.

Using imputs from the BEM and modified typical meteorological year (TMY) files, HOMER and MDT are used in parallel, maximizing their complementary capabilities.The HOMER tool emphasizes lifetime economic performance, producing a set of solutions that meet stated energy needs, ranked by NPC. The MDT

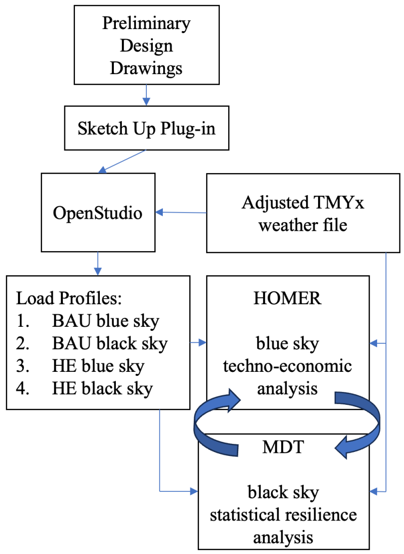


Figure 1: Simulation work flow

tool emphasizes resilience, producing a set of feasible solutions along a Pareto front, that must be evaluated by stakeholders by considering tradeoffs between optimization goals.

Building Energy Modeling

Complete details of the four KCRH BEM are available in our previous study (Villa et al. 2024).[1] Figure 2 shows the layout and space types of the KCRH BEM. The footprint of the building is 25 m x 64 m with a ground floor that allows covered parking and three levels above it totaling about 3,660 m^2 of floor space. The BEM contains 31 thermal zones and many shading surfaces include PV on the south facing side of the roof.

HOMER techno-economic analysis

HOMER determines the most cost-effective mix of energy resources that would serve the needs of the community during black sky conditions while reducing energy costs during blue sky conditions. HOMER was originally developed at the National Renewable Energy Laboratory (NREL) to enable researchers and designers to select technologies to power remote applications, but is now commercial software.

Figure 3 shows the configuration of the energy system

[1] The EnergyPlus models are publicly available in the Multi-scenario Extreme Weather Simulator repository example folder in examples/example_data/HuiOHauula (Villa, Schostek, and Macmillan 2023). The"ep_model" and"ep_models_business_as_usual" directories contain the HE and BAU cases respectively.

Table 1: Tool descriptions

Tool	Description
Sketch Up	Create geometry for BEMs shown in Figure 2
OpenStudio	Create four BEMs 1) BAU blue sky 2) HE blue sky 3) BAU black sky, and 4) HE black sky. The HE configuration uses combined thermal systems and a ground source heat pump. Whereas BAU uses normal efficiency isolated systems. Blue sky entails full operations whereas only critical loads are served for black sky operations. HE has extra insulation to make black sky operations EE. A complete description of the models is in (Villa et al. 2024).
MDT	Black sky resilience analysis: Finds pareto front of optimal microgrid designs for each BEM load profile through a Monte-Carlo study with thousands of evaluations of when DBTs cause outages to the grid.
HOMER	Microgrid blue sky resilience analysis that simulates a viable system (in the sense that it meets constraints set by the user, such as energy availability) for all possible combinations of the equipment that are being considered, and presents a portfolio of these viable alternatives ranked by NPC.

being considered in the HOMER optimization. The system is composed of loads and energy resources. The loads are approximated by an hourly time series encompassing an entire year, and can be split into critical and noncritical. These are shown in Figure 5, for the BAU (a) and for the HE (b) cases. HOMER attempts to serve critical loads at all times, according to the user's definition of an acceptable energy availability. Noncritical loads are dropped during grid outages, in this case for the 30 days following July 28. The resources that serve the loads mirror the typical real-life situation. The grid is the default resource, drawn upon when other resources are not available. Other resources are added as appropriate for the site. In Hawaii, solar is usually the renewable resource of choice, due to its year-round general availability. Wind was also considered for this case, since it could be a resource that operates along with solar which may be available during times that solar is not. To allow solar and wind resources to power the building when the sun is not shining and the wind is not blowing, an energy storage system, in the form of a Li-ion battery array, is included. Finally, a diesel backup generator acts as the resource of last resort, when the others, including the grid, are not available.

For optimization, each resource must be defined in terms

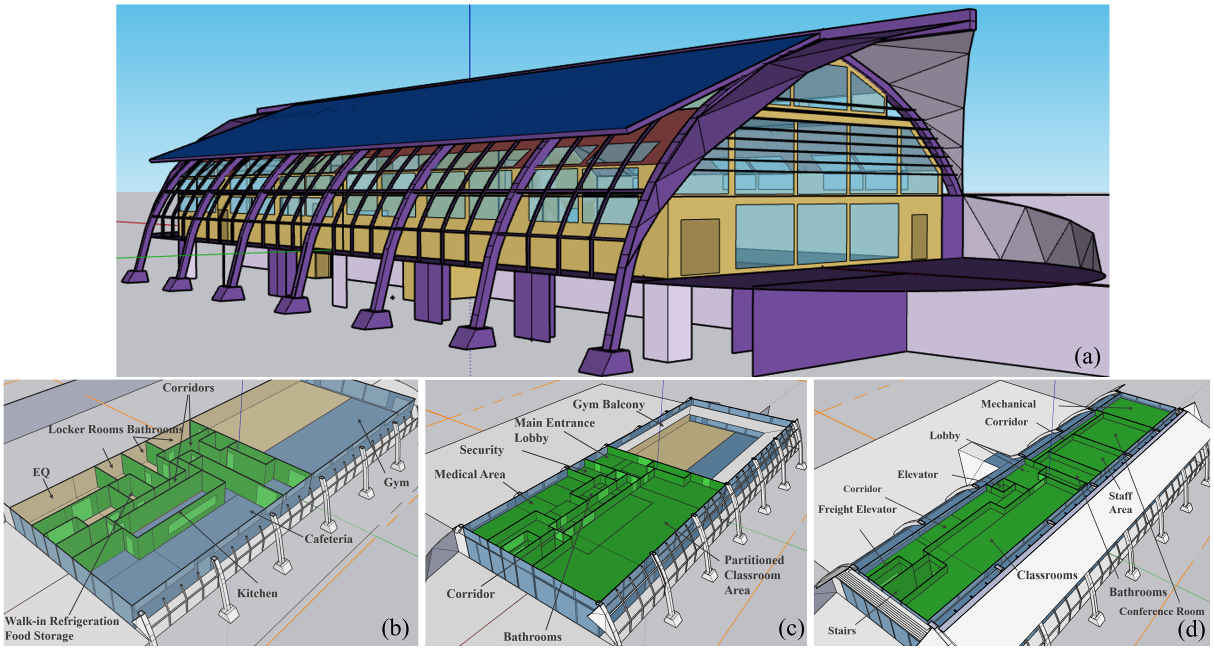


Figure 2: KCRH in Hau'ula, Hawaii OpenStudio model with three levels. (a) isometric view showing covered parking (b) lower floor, (c) main entrance floor, and (d) upper floor. The design is by +Lab Architect PLLC (Azaroff 2023). Used with permission from (Villa et al. 2024).

of energy and cost, as appropriate for the specific resource. For example, solar PV resources are defined by data files containing direct normal irradiance and global horizontal irradiance for a TMY, along with the orientation of fixed panels, and technical and cost specifications of the panels. For this study, TMY files for both solar and wind resources were used, obtained from the NREL repository for the closest meteorological station at Kaneohe Bay. The TMY files were adjusted as noted previously, and in addition global horizontal irradiance was reduced to 15% of its original value and direct normal irradiance was set to zero, for a period of three days beginning on July 28, to reflect cloudy conditions associated with the hurricane. Costs for the PV, wind, battery and diesel generator resources were obtained from NREL's Annual Technology Baseline, an online resource that is updated regularly and that reports current and forecasted costs of energy system components (Blair et al. 2015). Though RE is desirable for sustainability purposes, HOMER optimizes the system based on performance and cost. So, for example, if a diesel generator is cheaper than the battery, HOMER specifies a diesel generator rather than a combination of a more expensive larger battery and PV system. The user, however, can specify a minimum contribution of renewable energy or other constraints that shape the solution.

The grid must also be characterized in terms of cost, by entering details of the rate structure, including details of how net energy billing is handled, in terms of reliability, by entering statistics on possible outages, in terms of emissions, by entering the utility's emissions profile. For this case, Hawaii Electric rate schedule G was used (Hawaiian Electric 2022). A long outage of 30 days was used in the simulation, reflecting Hawaii Electric's assessment of possible outage duration resulting from a severe hurricane or tsunami. It should also be noted that Hawaii Electric offers rates designed for microgrids, however it was decided, for this case, to continue to use the rate that applies to the existing Hau'ula community center that the KCRH is replacing.

MDT resilience analysis

While HOMER provides a deterministic assessment of the performance of a microgrid during a grid outage, it does not provide sufficient details to fully evaluate how the system behaves in the face of the threats that actually produce the grid outage. In the context of this study, these DBTs could be a hurricane, an earthquake, a tsunami, a wildfire or even a manmade threat such as a cyberattack. MDT was developed at Sandia National

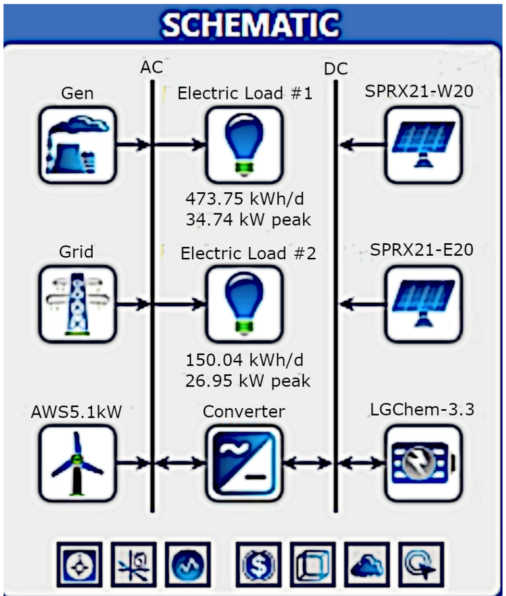


Figure 3: Layout of the HOMER model

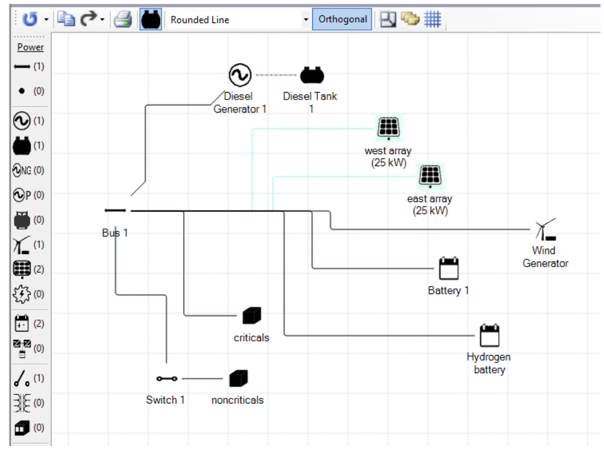


Figure 4: Layout of the MDT model. Note that the model allows for a hydrogen long-duration storage system.

Laboratories as a decision support software tool for microgrid designers in the early stages of the design process. The software employs search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user defined objectives. Common examples of such objectives are cost, performance, and reliability.

The process to set up an MDT model is similar to the process for the HOMER model. First, the layout of the microgrid is defined, to include loads and resources. A typical layout is shown in Figure 4. As in the case of HOMER, critical and noncritical loads are defined separately. Critical loads are connected directly to the main system bus, and are assigned a higher priority. Noncritical loads are connected to the main bus via an automated switch, and are assigned a lower priority. During a grid outage, if generation resources are insufficient to meet the noncritical loads, the switch opens and the load is disconnected.

MDT emphasizes the simulation of the operation of the microgrid during grid outages. Grid outage conditions result from the statistical definitions of DBTs. A specific system could be vulnerable to one or more DBTs. For each DBT, the frequency and expected duration of the associated outage is defined statistically, using appropriate distributions (e.g. a uniform distribution, or a log-normal distribution). Specific hazards associated with a DBT can also be defined statistically. For example, an earthquake could be defined by the time between occurrences, the duration of the grid outage caused by the earthquake, and by the magnitude of the earthquake, which represents a possible hazard connected with an earthquake.

As is the case with HOMER, resources that provide energy to the microgrid are defined by technical specification (e.g. PV module efficiency, sensitivity to temperature, nominal power rating) and if appropriate, the renewable resource that powers the device, in the case of a PV panel, the irradiance in the plane of array. In addition to performance characteristics, each component of the system (including electrical conductors, switches, wind turbines etc.) are also characterized by reliability (the likelihood of failure not correlated with a particular hazard) and by fragility to hazards (i.e. the likelihood of failure resulting from a threat of a certain magnitude). Reliability and fragility are also defined using appropriate statistical distributions.

For each resource, the user specifies a discrete series of possible options. For example, the rating of a PV array could take on the value 25 kW, 50 kW or 75 kW. MDT simulates each possibility and determines which works best. To make this determination, MDT must evaluate system performance in terms of user-defined metrics. Metrics that are almost always used are cost and energy availability, but these are not the only ones possible. For example, a third metric associated with environmental performance could be defined. Finally, the total simulation time must be defined, to allow for a sufficient number of threats to occur for the purposes of evaluating performance statistics. For example, if the mean time

Table 2: Results for all four BEMs

BEM (3,660 m^2) $kWh/m^2/yr$	BAU	HE	Energy savings (%)
blue sky	99.39	62.22	37.39
black sky	63.94	47.26	26.07

between occurrences of an earthquake is 10 years, then a simulation time of 1000 years will result in approximately 100 earthquake-related grid outages of varying duration.

The optimization produced by MDT is in terms of a Pareto front that spans all of the performance metrics defined by the user. For example, if the metrics are cost and energy availability, then the pareto front is composed of all solutions that maximize energy availability over the entire range of costs. It should be noted that not all solutions reported on the pareto front are feasible. For example, some solutions may be excessively costly, or may not produce sufficient energy availability.

Results

Building Energy Modeling

In our previous KCRH study, the BEM was compared to publicly available energy use intensity (EUI) data to show that the resulting load profiles are reasonable (Villa et al. 2024). The four resulting load profiles are shown in Figure 5. The BEM results for the adjusted weather file for HE and BAU configurations of the model are shown in Table 2. Much more detailed results concerning the BEM are available in the previous KCRH study (Villa et al. 2024).

HOMER techno-economic optimization

The HOMER analysis produced results for the HE and BAU cases. For each case, two sub-cases were considered, one where a diesel backup generator is allowed, and one where the expectation is to rely on RE resources alone. The principal results are summarized in Table 3.

Table 3: HOMER optimization results

	PV (kW)	Battery (kWh)	Genset (kW)	NPC ($US K)
BAU diesel	99.8	0	84	862
BAU RE	635	386	0	3,350
HE diesel	61.4	0	68	564
HE RE	443	257	0	2,140

HOMER provides a wealth of information on the operation of the system, including a breakdown of the costs, in terms of total lifetime or annualized quantities, cash flow, as well as details on the contribution of various resources to satisfy the system electrical load. The cost breakdown for the HE case, for both diesel backup and RE-only subcases, is shown in Figure 6. For the system with backup diesel, the highest cost is the purchase of grid power, at $243K. The cost of the PV array (including the inverter) is second, at $165K. Purchase and operation of the genset is third, in large part resulting from the cost of fuel for one month, with cost of the inverter a distant fourth. It should be noted here that the fuel cost is likely high, since month-long outages are not expected every year. With the RE system, the PV array supplies most of the power, so that grid purchase cost is reduced to $60K over the lifetime of the system. For this case, the cost of the oversized PV array required to produce power during prolonged cloudy conditions as the hurricane passes dominates the lifetime system cost at $1.29M. The cost of the battery is also high, $785K.

HOMER also provides insight into the operations of various components of the system, as illustrated in Figure 7, where the interaction of the battery system and grid purchases is shown for the RE system in the HE case. The battery charges during the day (from excess PV generation) and discharges in the evening and early morning, with the grid supporting the load when PV or battery are not available. Operation of the battery and grid is of particular interest during the hurricane event on July 28-30, and the off-grid operation for the 30 days after the hurricane. During the hurricane event, the PV array partially charges the batteries, which in turn provide a limited amount of energy during the early morning and night. During black sky operations in the month of August, when regular sunlight conditions return, the PV and battery system are able to fully support critical loads.

The contribution of individual energy resources to the electrical load for each month is shown in Figure 8. The two solar arrays provide most of the power, with an overall renewable penetration of 76%. Grid purchases are seasonal, with winter purchases larger than during the summer. During the grid outage, primarily in August (chosen because of the higher likelihood of hurricanes), the solar arrays and battery system supply the entire critical load. It should also be noted that the PV array produces considerably more energy overall than is consumed by the load, however it is not possible to take advantage of this production due to the limited size of the batteries. While it would be possible to export power

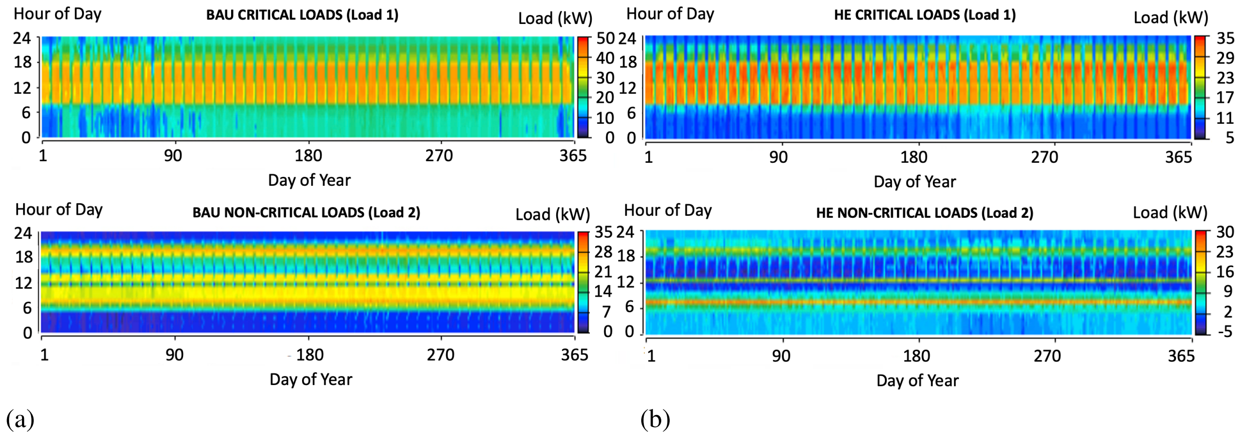


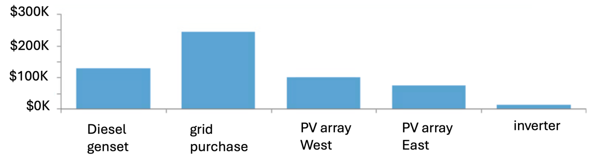
Figure 5: Detail of the critical and noncritical loads for BAU (a) and for HE (b), resulting from the OpenStudio BEM. Yearly variation in load is along the horizontal axis, daily variation is along the vertical axis. Note that the scales are different.

to the grid, in this study it was assumed that net energy metering would not be available to the KCRH. Operation of the battery is of particular interest during the hurricane event on July 28-30, and the off-grid operation for the 30 days after the hurricane. During the hurricane event, the PV array partially charges the batteries, which in turn provide a limited amount of energy during the early morning and night. During black sky operations in the month of August, when regular sunlight conditions return, the PV and battery system are able to fully support critical loads.

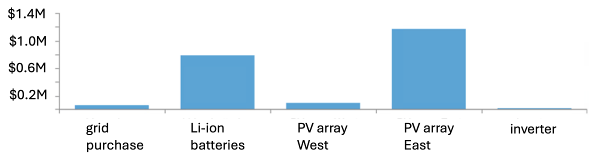
While HOMER provides a detailed simulation of system performance over its lifetime, the resilience analysis is not the primary focus. Specifically, resilience is treated by HOMER in a deterministic way, as in this case, where a single long duration event was considered, while in reality, it should be treated stochasitcally. In remote areas such as Hau‘ula, short grid outages, on the order of several hours to a few days, are common, long ones less so, however the requirement is to design the system for the worst expected case of a 30-day outage. Moreover, the time of year during which the outage occurs may make a difference on the energy system chosen - an outage in December may require a larger PV array due to the shorter days. In principle, it is possible to run several simulations with outages of different durations occurring at different times, this is not practical as it would be an intensive manual process that is prone to transcription error.

MDT resilience-based optimization

To overcome the limitations of the deterministic nature of the HOMER optimization, an MDT analysis was also conducted. MDT was designed with the goal of providing a comprehensive statistical assessment of the resilience of an energy system. In a typical MDT simulation, the optimizer considers thousands of years of system operation, with threats (e.g. a hurricane) and associated hazards (e.g. flooding, wind, cloudy sky) occurring at various times of year and various levels of severity, as defined by appropriate statistical distributions. The simulated system is therefore likely to experience a vast array of possible ‘resilience’ conditions, that likely covers all of the conditions that the real system would experience in its lifetime. The outputs of two simulations of the system depicted in Figure 4, roughly corresponding to the BAU case simulated in HOMER, are shown in Figure 9. The two MDT simulations are identical, except that in one simulation the maximum cost is \$2M, in the other, the cost limit is \$1.5M. The output of the optimization is displayed as a Pareto front for the two metrics chosen to evaluate the solution, cost and energy availability. Each point on the Pareto front represents a combination of energy assets that maximizes one metric with the other(s) held fixed. For example, for a particular value of the cost metric, the Pareto front is the maximum energy availability that is possible at that cost. In both cases, the red dots represent solutions that do not satisfy all constraints, while the dark blue dots represent feasible solutions that satisfy the constraints. For the solution with a \$2.0M cap, the solution highlighted by the cyan



(a)



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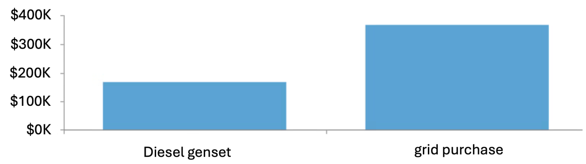
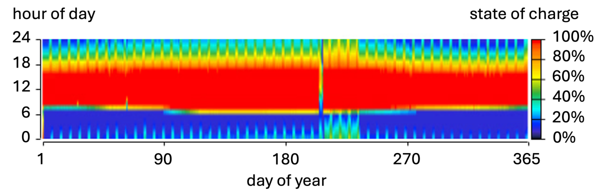
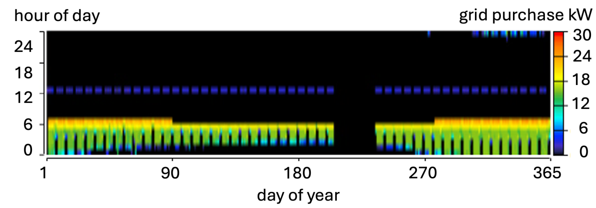


(c)

Figure 6: Comparison of system costs for the HE case, with diesel backup (a), RE (b) and grid-only with diesel backup (c).



(a)



(b)

Figure 7: RE system operations for the HE case: battery State of Charge (a) and grid purchases (b). Yearly variation in load is along the horizontal axis, daily variation is along the vertical axis.

marker has a cost of \$1.6445M, and an overall energy availability to critical loads during outages of 99.98%. For the solution with a \$1.5M cap, the solution highlighted by the cyan marker has a cost of \$1.414M, and an overall energy availability to critical loads during outages of 99.82%. The solution portfolio is a set of discrete points because MDT can only choose among energy resources defined discretely, rather than on a continuum, similarly to what would happen in reality, where, for example, only a limited set of diesel generator models are available. While for this study only two Pareto dimensions were considered ("cost" group of metrics and "performance" group of metrics), there is not a strict limit - for example including a third independent Pareto dimension (for example, one associated with emissions), would have produced a three-dimensional Pareto front surface.

To gain insight into the characteristics of the solutions portfolio, it is useful to consider how often individual technologies are selected by the optimizer, and the location on the Pareto front of individual solutions associated with a specific technology selection. This type of analysis is shown in Figure 10. The bar charts at the bottom of the output panels indicate how many of the total 79 solutions for the \$1.5M maximum budget case contain a particular technology option. For the case of the technology option that contains no diesel generator (highlighted in dark blue), the corresponding solutions are at the high end of the cost fitness metric (i.e. cheaper) but also with lower performance, as the red dots indicate in Figure 9 b. This indicates that a diesel generator is necessary to achieve a high level of energy availability, at least for the case limited by a maximum energy system budget of \$1.5M.

In the process of selecting an optimal solution, it is also instructive to investigate the performance of individual solutions in depth. MDT offers an intuitive way to perform this analysis. To illustrate this, the difference in performance of a system with diesel backup generation and a system with no diesel backup, using either Li-ion or hydrogen storage in its place. MDT allows a user to filter solutions by technology. For example, it is possible to view all solutions that feature no diesel backup, and select the solution with the highest performance. This solution, shown schematically in Figure 11, costs \$845K and has a 94.6% energy availability to critical loads and 75.7% energy availability to noncritical loads, on average, over grid outages realized over 2000 years of simulation time. MDT provides extensive statistics on the performance of individual components. For example, over all realization of outages, load is not served for a minimum of 0.16 kWh, a maximum of 5,060 kWh (not necessarily continuous) and an average of 653 kWh (approximately equal to the average critical daily load for

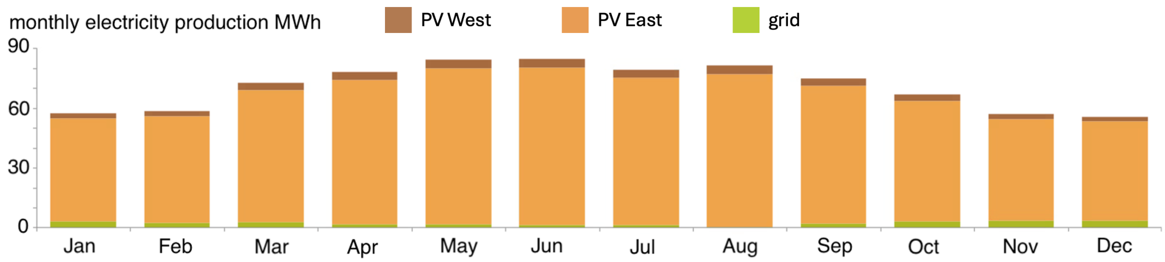


Figure 8: Contribution of various resources to the load in the RE BAU system.

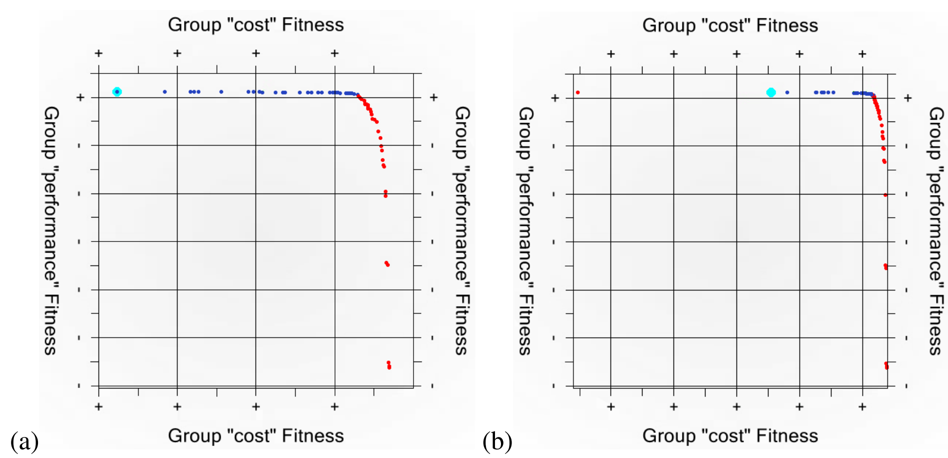


Figure 9: Pareto fronts for two MDT solution portfolios for the BAU case, one with a cost cap of $2M (a), the other with a cap of $1.5M (b). The "cost fitness" dimension combines capital cost and fuel use, while the "performance fitness" dimension combines emissions and energy availability. Each dot represents a solution portfolio consisting of a combination of the generation technologies available. Blue dots meet constraints, red dots do not.

BAU of 641 kWh).

A system realization of similar cost ($863K) with a 50 kW diesel backup generator combined with a 100-gallon tank, and a 160 kW / 672 kWh Li-ion battery has an energy availability of 96.5% to critical loads and energy availability to non-critical loads of 94.6%. Higher performing realizations with the same size diesel backup involve larger PV arrays and a cost of $1.48M, producing energy availability of 99.2%. Still higher energy availability requires a larger diesel tank.

To conclude the analysis, an optimization was performed considering loads associated with the BAU system. Among all solutions in the portfolio, the highest performing solution that does not contain a backup diesel generator was selected. This solution, costing $2.12M, is shown in Figure 12. During resilience scenarios, the system is powered by a 125 kW array on the western section of the roof, supplying 30% of the energy, a 250 kW array on the eastern section of the roof, supplying 68% of the energy, a 25 kW wind turbine on the ridgeline of the roof, supplying 2% of the energy. An 80 kW/336kWh Li-ion battery and a 30 kW / 2000 kWh hydrogen storage system provide energy storage capacity. For this case, critical loads are served with a 99.8% energy availability, and noncritical loads with an availability of 95.9%.

Discussion

The systems that result from the HOMER optimization and from the MDT optimization are qualitatively similar, but there are important differences in the simulation results that must be considered by a designer. For example, HOMER considers technology replacement cost when evaluating costs over the lifetime of the system, while MDT considers only upfront costs. On the other hand, the HOMER solution, especially one evaluated over a single realization of a grid outage, does not consider all

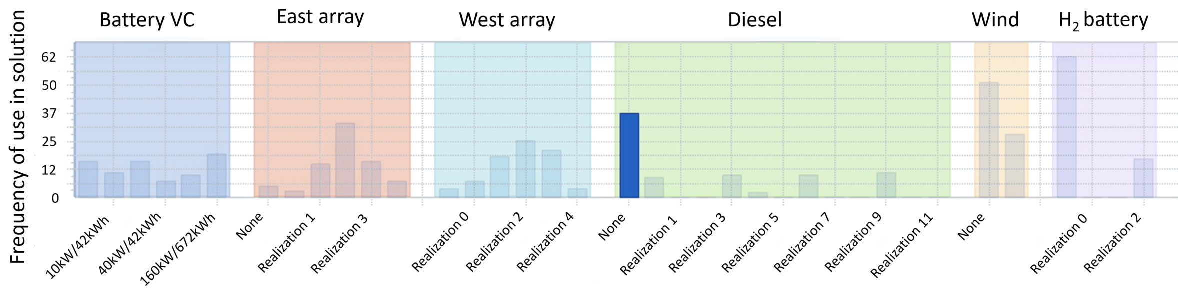


Figure 10: Display of frequency for individual technology options, showing the "Diesel empty realizations" as a dark blue bar.

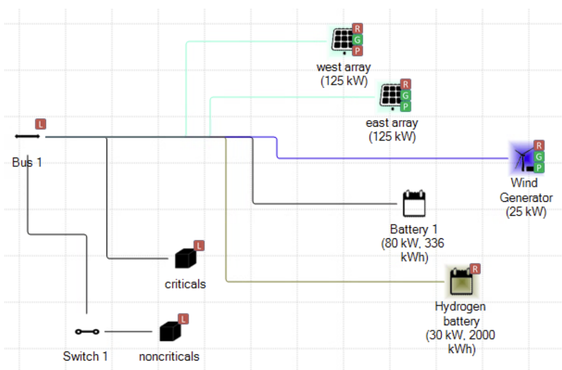


Figure 11: Schematic of the best performing solution with no diesel generator, composed of two 125 kW PV arrays, a 25 kW wind generator, an 80 kW/336 kWh Li-ion battery, and a 30 kW/2 MWh hydrogen storage system.

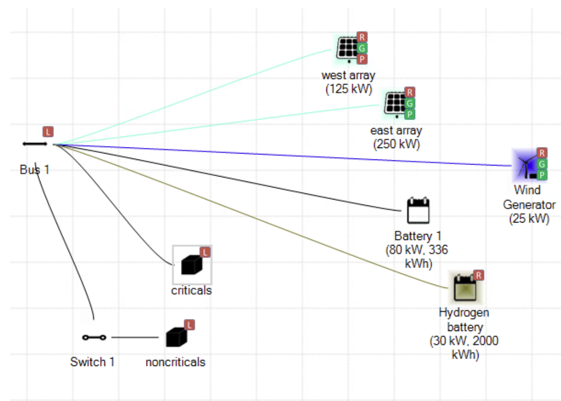


Figure 12: Solution with no diesel generator, for the DBT case, showing that critical loads are served 99.8% of the time. Note that this solution contains a long-duration hydrogen storage system.

possibilities of threats and associated hazards that a system could experience. Like HOMER, MDT also recommends larger PV, diesel backup and larger batteries if a system is to meet the certain resilience metrics, such as energy availability close to 100% at limited cost and with moderate emissions. Ultimately, an iterative process is likely the best option for a system designer: the technologies and system size can be determined with an initial HOMER analysis, then MDT can be used for a more detailed statistical analysis in resilience scenarios, and finally a second pass of HOMER can be used for a full techno-economic analysis that yields accurate lifetime costs.

An interesting outcome of the MDT simulation is that, under the constraints used in this study of a maximum system cost of $2M, a solution providing in excess of 99% energy availability to critical loads for the BAU system always required a diesel backup generator. In contrast, critical loads in the HE KCRH BEM can be powered by a renewable-energy-only system at reasonable cost, taking advantage of a long-duration hydrogen energy storage system.

An issue identified in this work is that it is difficult to simultaneously optimize for both "blue sky" performance (primarily measured by economics) and "black sky" performance (measured by energy availability". One way to address both objectives simultaneously could be an iterative approach, where HOMER is used to identify technologies that best suit the prevailing climate conditions and load characteristics. An MDT simulation could then be informed by these preliminary HOMER recommendations, resulting in a set of technology portfolios chosen by stakeholders. HOMER could then be used to provide better estimates of the economic performance of the portfolios evaluated.

Conclusions

This analysis shows that it is possible to design an energy system that provides a high level of energy availability to the KCRH at reasonable cost. It is difficult to do so using renewable energy alone without fossil backup unless the HE KCRH dsign is used. The use of Open Studio to determine critical and noncritical building loads and microgrid optimization tools like HOMER and MDT, is an effective way to arrive at a solution that is well-tailored to the climatic environment in which the building is sited, the requirements of the community using the resilience hub, and the threats that are characteristic to the site. As is often the case in optimization of engineering systems, it is not always possible to satisfy all requirements simultaneously. For example, minimizing capital costs entails reliance on fossil backup and as a consequence increased emissions. Selecting the technology portfolio that best balances multiple and often competing objectives is up to the stakeholders of the project. This analysis however serves to quantify the tradeoffs so they can be appropriately considered.

In terms of actionable technology recommendations for the KCRH, a building with an HE envelope and mechanical systems integrated for efficiency allows substantial reductions in energy use. Reducing energy use makes it possible to achieve sufficient resilience with all-renewable resources, removing the need for on-site storage of diesel fuel. Of course, the added costs that the HE design entails must be considered, because these may be higher than the reduction in energy costs. A reduction in fossil energy use may be desired by the community utilizing the resilience hub to reduce emissions or to avoid contamination of the aquifer used by the community to source drinking water. As a result, minimizing energy use may be instrumental for reasons other than economics alone.

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Acroymns

BAU	business as usual.
BEM	building energy model.
DBT	design basis threat.
EE	energy efficiency.
EUI	energy use intensity.
HE	high efficiency.
HOMER	Hybrid Optimization of Multiple Energy Resources.
KCRH	Koʻolauloa community resilience hub.
MDT	Microgrid Design Toolkit.
NPC	net present cost.
NREL	National Renewable Energy Laboratory.
PV	photo-voltaic.
RE	renewable energy.
TMY	typical meteorological year.

Disclaimer

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