INL/RPT-22-67704
Revision 0

Net-Zero Microgrid Program Project Report:

Small Reactors in Microgrids

August 2022

Technoeconomic Analysis

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The Net-Zero Microgrid Program provides cross-cutting research to accelerate the use of renewable and zero-carbon generation in microgrids.

Idaho National Laboratory

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EXECUTIVE SUMMARY

This report presents the results of technoeconomic analysis that advances understanding of the potential of small modular reactors and microreactors, collectively referred to as small reactors (SRs) in this report, in microgrids. This analysis was conducted using a proxy model for SR in microgrids based on the datapoints that were identified and explored in a predecessor report "Small Reactors in Microgrids: Technical Studies Guidance."[1]

These datapoints—specific to SRs—are representative of what is understood as of today about the expected characteristics of SRs (costs and operational). They are the starting point for the technoeconomic analysis in this report.

This report recognizes that the development of technoeconomic analysis for SRs in microgrids must consider that:

- Microgrids built with SRs have different configurations depending on their boundaries, the loads and resources within those boundaries, energy storage, and the connection and interaction with the distribution network. Primary technical design principles include power and energy adequacy, system economics, system reliability, and operational resilience.
- Technical studies required to evaluate the feasibility of SR in microgrids include siting, generation optimization, operational framework and feasibility, economic optimization, and risk analysis. Technoeconomic models specific to SRs are necessary to conduct these feasibility studies.

Utilizing the detailed financial and operational parameters and datasets specific to SRs, a proxy representation of SR, referred to as the proxy model in this report, is created in the XENDEE platform based on a gas generator model already modeled for microgrids. The proxy model captures the major characteristics of SRs and effectively represents them in microgrid planning studies. This report discusses the development and implementation of this proxy model and presents feasibility studies that showcase its use in a technoeconomic analysis of a practical microgrid use case.

In this report, considerable attention is given to estimating the SR's installation costs. The factors that influence the SR's installation cost include simpler design, lower plant footprint, smaller exclusion zones, accelerated learning with factory production, lower construction time, and co-location of multiple modules. The specific capital cost per MW ($/MW) of conventional nuclear power plants (NPPs) is lower as the size of the plant increases. The economies of scale in sizing apply to SRs as well, typically valid within the fleet of small and/or modular reactors with similar deployment models (i.e., produced in factory settings and assembled onsite). For example, the 1-MW SR plant will have more capital cost per MW than a 10-MW SR plant (single- or multi-module).

This report is organized into six sections and three appendixes:

- Section 1 provides the background on SR in microgrids and its role in the overarching aim of achieving the net-zero objective. The incorporation of SRs as a cornerstone of power and grid services in a microgrid will be of large benefit in providing resilience and greenhouse-gas reduction.
- Section 2 discusses the development of the proxy model for SR in the XENDEE platform using the existing gas-generator model to represent SR in technoeconomic analysis.
- Section 3 details a case study developed in the XENDEE platform using the proxy model in an existing military base in California. The objective is to identify the optimum generation portfolio for the microgrid system. Several scenarios were developed around the objectives of cost-minimization, CO_2 emission reduction, and microgrid resilience.
- Section 4 provides a comparative analysis of different scenarios and concludes the report. The results and the subsequent comparative analysis show that SRs could be a cost-competitive generation option when capital costs are modeled considering potential economies of scale in sizing. If the CO_2 tax is

imposed on carbon fuels, SRs would be even more attractive than gas generators. Then, SRs in microgrids would play a pivotal role in reducing the carbon footprint at the local distribution level. However, it is particularly important to identify the most suitable use cases for early adoption and the right balance of generation mix with other clean technologies as SRs achieve a level of technological and financial maturity.

- Section 5 describes ongoing work to develop the comprehensive SR model in the XENDEE platform and adapt it for integrated energy system studies. As the next step, a model is being built that is specifically designed for SR in microgrids in the XENDEE microgrid design and planning platform. The SR model will consider all datapoints described in the predecessor report.
- Section 6 provides the list of references.
- Appendix A provides an overview of the XENDEE optimization platform for technoeconomic assessment and portfolio optimization for future microgrids. The sample reports showing the comprehensive financial and operational results for two different scenarios are provided as Appendices B and C.

This report is a product of the Net-Zero Microgrid (NZM) Program at Idaho National Laboratory supported by the Department of Energy, Office of Electricity Microgrid Program.[2] The NZM Program recognizes SRs as carbon-free energy sources for generation necessary for microgrids to transition away from carbon fuel-based generation that is prevalent in today's microgrids (see Figure ES-1).

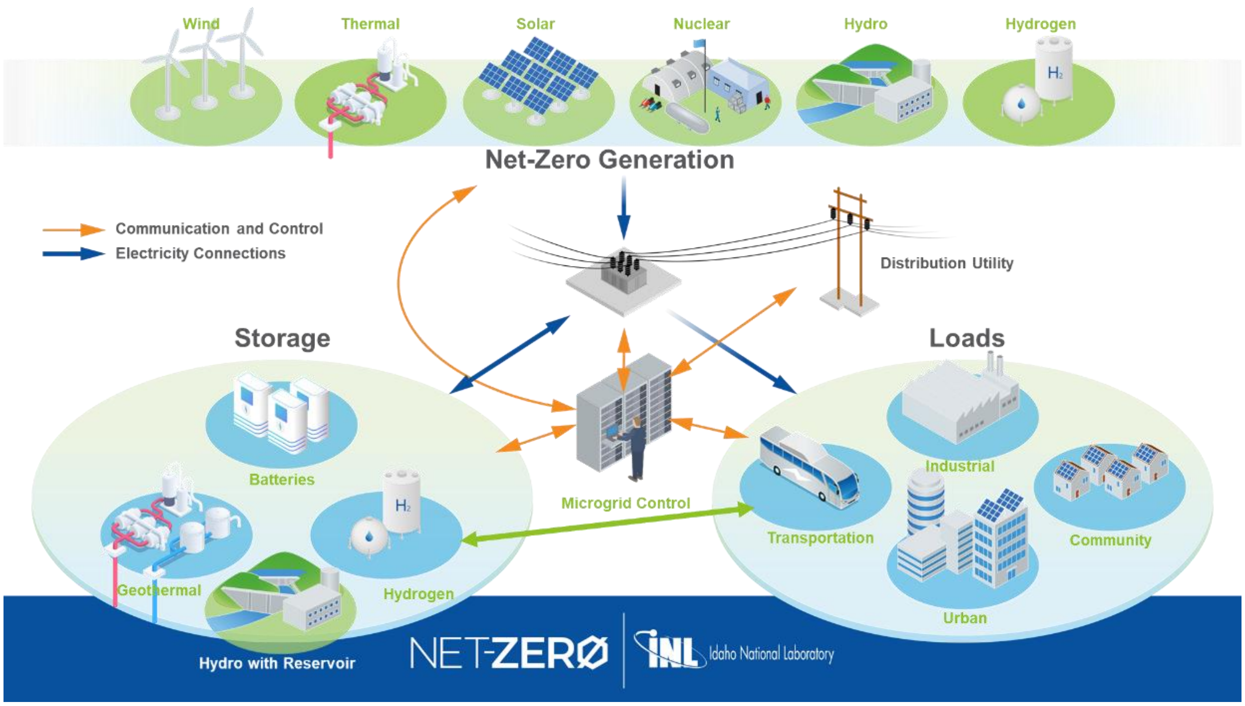

Figure ES-1. Net-zero generation.

ACKNOWLEDGMENTS

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ACRONYMS

BES	battery energy storage
CAISO	California Independent System Operator
CHP	combined heat and power
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EOS	economies of scale
HALEU	high-assay low enriched uranium
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
LCOE	levelized cost of electricity
MARVEL	Microreactor Applications Research Validation and EvaLuation
MMR	Micro Modular Reactor
NGG	natural gas generator
NPP	nuclear power plant
NREL	National Renewable Energy Laboratory
NZM	Net-Zero Microgrid
O&M	operations and maintenance
OPG	Ontario Power Generation
PV	photovoltaic
SCE	Southern California Edison
SCO	Strategic Capabilities Office
SMR	small modular reactors
SOC	state-of-charge
SR	small reactors
TOU	time of utilization
TREAT	Transient Reactor Test
TRISO	tristructural isotropic
USNC	Ultra Safe Nuclear Corporation

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Net-Zero Microgrid Program Project Report: Small Reactors in Microgrids

1. MICROGRIDS AND SMALL REACTORS

A microgrid is defined by IEEE 2030.7™-2017, "IEEE Standard for Specification of Microgrid Controllers," as:

> *A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that act as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected and island modes.*[3]

Microgrids are considered foremost for their value for resiliency in times of extreme weather events or other natural or human-caused calamities. Scientific evidence shows that these events arising from global warming are becoming more common and adversely impacting the resiliency and integrity of electrical grids.[4] The rapid shift towards clean but variable generation technologies, such as wind and solar photovoltaics (PVs), will affect the resilience of the electrical grid due to the increased generation uncertainty and intermittency and reduction of spinning inertia from retired fossil-based synchronous generation.

In addition to their use in communities and industries in remote areas that are isolated from or weakly connected to the central grid structure, microgrids are increasingly considered an integral component within the electrical grid structure. The grid connection allows the two-way exchange of power providing the flexibility of generation sizing within microgrids. Microgrids can decentralize larger grids into smaller entities, each capable of sustaining themselves without supply from the grid by aggregating local distributed resources and with support from energy-storage technologies. Depending upon the availability of reliable generation sources, microgrids can be made immune to grid loss arising from the loss of weak transmission infrastructure or due to extreme weather events. While microgrids are increasingly adopted by commercial and industrial facilities and military bases irrespective of grid-connection availability, their eventual adoption in future applications, such as charging plazas and extraterrestrial stations, is widely accepted. The scale of microgrids can vary widely by application depending on the critical functions to be supported when islanding is required and the investment in generation assets made by microgrid owners/operators to support those critical functions and/or to supply power and energy or other services to the connected utility. Applications targeted in this project range from hundreds of kilowatts to tens of megawatts; however, no hard lower and upper limits are set by the definition of a microgrid. Currently, distributed wind and solar PV generators are central to microgrid architecture due to their cost-effectiveness and scalability, but their operation as non-dispatchable generation and their intrinsic variability mean that there is a need for a scalable and reliable clean generation to complement their shortcomings for sustainable microgrids.

The use of small modular reactors (SMRs) and microreactors, collectively referred to as small reactors (SRs) in this report, in microgrids has received significant research interest due to their smaller size, compact and long-lasting fuel, ease of transportation and assembly, flexible siting, improved safety features, and improved flexible-operation capabilities.[5] The SR generations that would be of interest to the scale microgrids referenced in this report range from 100 kW to 20 MW that would be encompassed by reactors referred to as microreactors and SMRs. For microgrid applications, SRs designs that are manufactured in a factory setting and can be transported in a commission-ready form to the microgrid by truck, rail, or air transportation are of most interest. SRs are typically designed with long-lasting fuels. Once loaded, the reactor fuel can last from 5 to 30 years.[6] This is a major advantage of SRs over diesel generators, which, apart from their large carbon emissions, face difficulties in fuel transportation during extreme weather events. SRs are designed to be inherently safe and accident-tolerant due to features, such as simpler integral designs, passive coolant circulation, containment, shutdown systems, and underwater/underground configurations.[7] Further, the potential of SRs to provide heat along with electricity enhances their economic potential and adds value to flexible-operation capability, adding more impetus towards achieving carbon-reduction goals.

SRs are being developed in all major technological lines of reactors, including water-cooled reactors, high-temperature gas-cooled reactors, fast-neutron reactors, and molten-salt reactors.[5] The Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor project, supported by the U.S. Department of Energy, will be one of the first SRs in the U.S. and will be developed at Idaho National Laboratory (INL) and installed at the Transient Reactor Test Facility (TREAT) by late 2023. MARVEL is a 100-kWt fission reactor that will enable the testing of several new non-traditional nuclear microgrid applications.[8] Under Project Pele, the Department of Defense's Strategic Capabilities Office (SCO) is building a mobile microreactor technology with a prototype set to be demonstrated at INL by 2024.[9] The tristructural isotropic (TRISO) fuel makes Pele reactors inherently safe and resilient against external attacks without needing large evacuation zones. Pele reactors will be sized between 1 to 5 MW, use high-assay low enriched uranium (HALEU), and can be transported by trucks, rails, and ships. The Micro Modular Reactor (MMR) is another SR project in Canada, which will be hosted at the Chalk River Laboratory site. It is a joint venture between the Ultra Safe Nuclear Corporation (USNC) and Ontario Power Generation (OPG) that aims to host an SR plant by 2026. Several other SR technologies are under development and are expected to start operation by the late 2020s for demonstration purposes.[8,10-12] For practical use in microgrids in the first few years of production, SRs will need financial incentives to compete with other clean-energy generation.[10] As the technology matures and moves into factory production, SRs are expected to become economically competitive with other sources of clean generation. SRs can work with other forms of clean generation to develop sustainable energy microgrids.

2. THE PROXY MODEL

SR introduce a significant shift in the energy market and the deployment model traditionally adopted by the nuclear industry. The initial deployments of SRs are expected to be more towards the markets valuing resilience, energy equity, and environmental justice and less constrained by the differential cost for technology learning. Some of these initial potential use cases identified in the literature include military bases, isolated communities, urban applications, and disaster relief. SRs have the potential to expand to the emerging energy market in Eastern Europe and Asia in the mid-term and support urban markets and megacities and electrical grids in the longer term.[13] Although losing the economy with drastically reduced size from older NPP designs, SRs can recover their costs by offsetting gains from simplified designs, standardized modules, increased learning rates, reduced construction schedule, and factory production. Efforts have been made to represent the cost characteristics of SRs with specific designs modifying the traditional top-down and bottom-up cost estimation techniques used for older NPPs.[10,14] This report utilizes the generic set of parameters identified in the predecessor report[1] to characterize SRs for technoeconomic studies.

Before developing the SR model, a proxy model was created in the XENDEE platform by changing the parameters of the existing gas-generator model in a way that reflects the behavior of SRs. The objective is to examine XENDEE's adaptability to include SRs in technoeconomic feasibility analysis and obtain initial optimization results for SR in microgrids. Appendix A provides an overview of the XENDEE platform and its functional capabilities for technoeconomic analysis and portfolio optimization of microgrids. The technoeconomic characteristics that are common to the XENDEE's gas-generator model are translated into the proxy model. The parameters that are applicable only to SRs are yet to be added. Figure 1 shows the technoeconomic datapoints explored in the earlier report[1] and highlights the ones used in the proxy model.

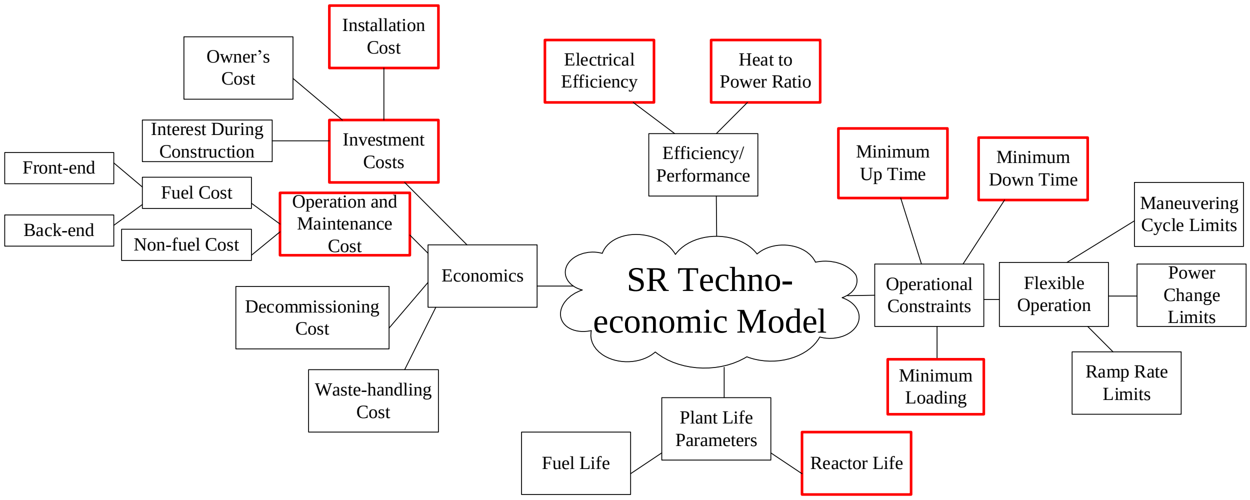


Figure 1. Small reactor parameters for technoeconomic studies identified in the earlier report.[1]

The purchase cost is an area where SRs differ significantly from gas generators. A significant portion of SR's investment cost goes for the plant installation including land rights and site utilities, building and structures, engineering and design, and construction services.[1] The installation cost calculated for SR in the earlier report[1] is used as the purchase cost of the plant. The economies of scale in the sizing of SR are driven by cost reduction due to factory-produced units and/or co-location of multiple modules at the same site. It will result in a reduced relative installation cost ($/MW) as the plant size increases.

The fuel cost for the gas generator is calculated based on the utilization (i.e., cumulated output in kWh) with the choice fuel and the corresponding price rate. The fuel in the gas-generator model could either be biogas or natural gas. In SRs, the fuel lasts for several years before it needs refueling. To simplify, the front- and back-end fuel costs are calculated and annualized over the refueling period to represent them as a part of annual operations and maintenance (O&M) costs. Alternatively, the uranium fuel supply and cost can be manually calculated and translated into the biogas or natural-gas fuel cost for the proxy representation. For the proxy model, the variable O&M cost calculated in the earlier report[1] will be used to represent both fuel and non-fuel costs. Since the gas-generator model needs the specification for the choice of fuel, biogas was selected with a supply price of 0 $/kg because the fuel cost is already considered in the O&M cost.

SRs can be operated in combined heat and power (CHP) mode to supply both heat and electricity. This could be done in two different ways: either by extracting process steam or by using the unused heat from the turbine exhaust. The process steam is extracted when high-quality heat is needed (e.g., high-temperature electrolysis). For low-temperature heat applications, such as district heating, the heat available at turbine exhaust can be used. XENDEE considers the latter form of the CHP operation utilizing the heat at the turbine exhaust[a]. For the proxy model, it is assumed that the SR can provide maximum CHP capability with all remaining heat at turbine exhaust available for low-temperature heating applications. For 33.33% thermal efficiency, the maximum possible heat to power ratio would be 2:1. The rest of the datapoints are minimum up and down times, minimum loading, and the plant life taken as 12 hours, 20%, and 50 years respectively, as shown in Figure 2.

[a] A new feature would be required in XENDEE to account for SR's high-grade heat applications for industrial processes or high temperature electrolysis.

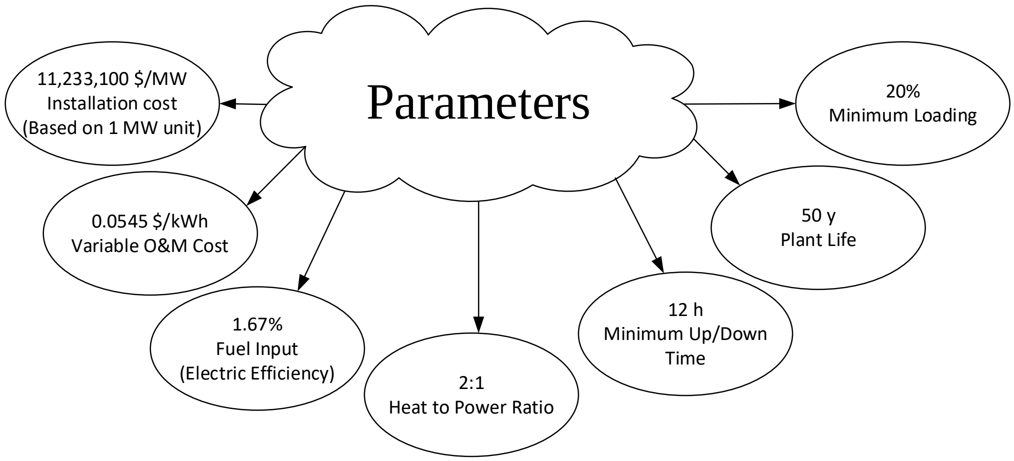


Figure 2. Parameters estimates used for the proxy model.

3. CASE STUDY

3.1 System Overview

3.1.1 Generation Options

The SR, represented by the proxy model for this case study, is considered a generation option for a microgrid developed on a 15-MW electric peak military site in southern California, which has a peak hot water/heating load of 1800 kWh. Other generator options include solar PV, electric storage, boilers, and natural gas generator (NGG)[b]. The XENDEE optimization tool uses mixed-integer linear programming to evaluate the optimum types, numbers, and sizes of generators to meet the microgrid demand with various objectives (e.g., cost minimization, CO_2 minimization). Figure 3 shows a single-node XENDEE microgrid setup showing different generation options for the proposed microgrid. The technoeconomic parameters for all potential generation assets in the microgrid are listed in Table 1.

Figure 3. XENDEE single-node GIS microgrid model with potential generator options.

[b] This case study can be implemented effectively with the proxy model because it uses only low-grade heat that is part of the existing XENDEE platform.

Table 1. Technoeconomic modeling parameters for other generation technologies considered in microgrid.

Generation Technology	Technoeconomic Parameters
PV	PV panel cost = 1700 \$/kW$_{DC}$, Lifetime = 30 y; Inverter cost = 200 \$/kW$_{DC}$, Lifetime = 15 y, Power factor = 100%; System losses = 14%, Inverter eff = 96%, Panel eff = 10%, PV tilt = 34º S; Panel technology = Thin-film, Array type = Fixed ground-mounted; Maximum install space = 274278 ft^2
Electric Storage	Energy module cost = 550 \$/kWh, Inverter cost = 196/ kW, O&M cost = 0.333 \$/kWh/mo Module size = 600 kWh, System Life = 18 y Charging Eff = Discharging Eff = 87%, Power factor = 100%, Max SOC = 100%, Min SOC = 5%.
Natural-Gas Generator	Unit size = 1 MW, Nameplate efficiency = 26%, Heat to power ratio = 1.56, CHP mode = ON Purchase price = \$2.9 M/unit, Lifetime = 15 years, O&M (variable) = 0.0024 \$/kWh/y, O&M (fixed) = 0.0185 \$/kW/y, Fuel price = 0.5716 \$/Therm, CO_2 emission factor = 0.1808 kgCO_2/kWh

The PV performance data is calculated based on the location of the microgrid to generate an hourly time-series profile shown in Figure 4. The performance data represents the fraction of the installed electrical power capacity that a PV plant can generate each hour. In addition to the time-series irradiance profile, the panel technology type (standard, premium, or thin-film), array type (fixed or tracking), mounting type (ground-mounted or roof-mounted), system losses, inverter efficiency, and array tilt-angle and pointing direction are other inputs required to compute the PV performance data. The available space for the PV installation is specified by the user as a numeric value or drawing a polygon in the map.

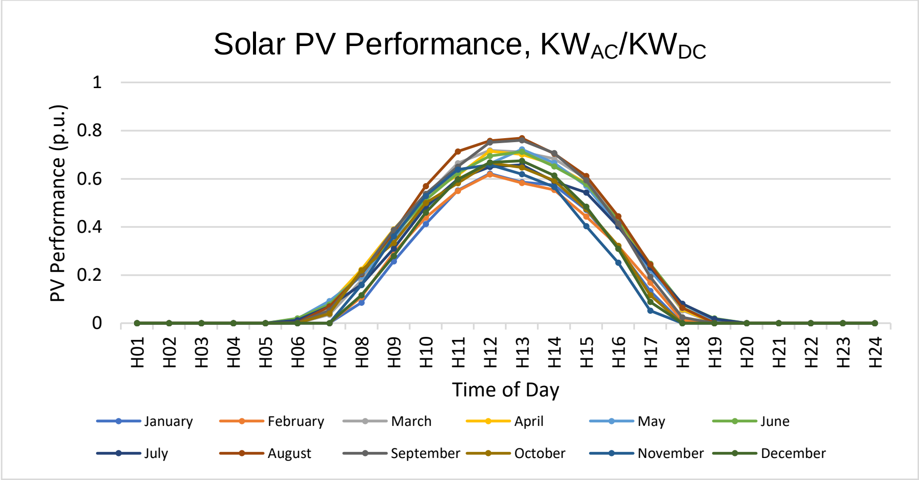


Figure 4. Time-series profile for solar PV performance data.

3.1.2 Electricity and Heating Demand

The hourly load demand time-series profile is obtained using the NREL load-shape importer built-in in XENDEE. The load profile importer uses the climate zone corresponding to the location of the microgrid as input, in addition to the average age of the buildings, annual energy consumption, and load types (electrical-only, heating, cooling, etc.). In this case study, the desired microgrid is located in a hot-dry climate zone of the U.S.[15]; and electricity and water-heating loads are considered in the analysis (Figure 5 and Figure 6). For electricity profile, a higher load occurs between the hours of 8:00 through 17:00, which are in general working hours, and it is consistent throughout the year with small magnitude variations due to the seasons. In contrast, the water-heating load has two distinct peaks early in the morning and late in the afternoon. A wide variation is in the seasonal loads throughout the year.

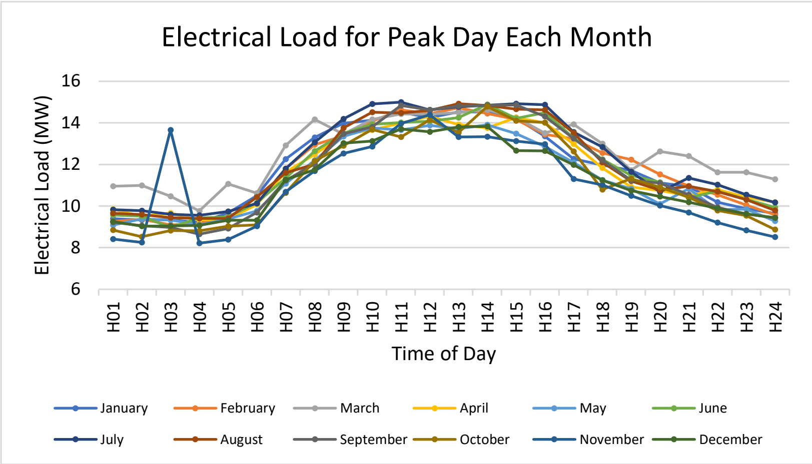


Figure 5. Time-series profile for electrical load (shows peak day each month).

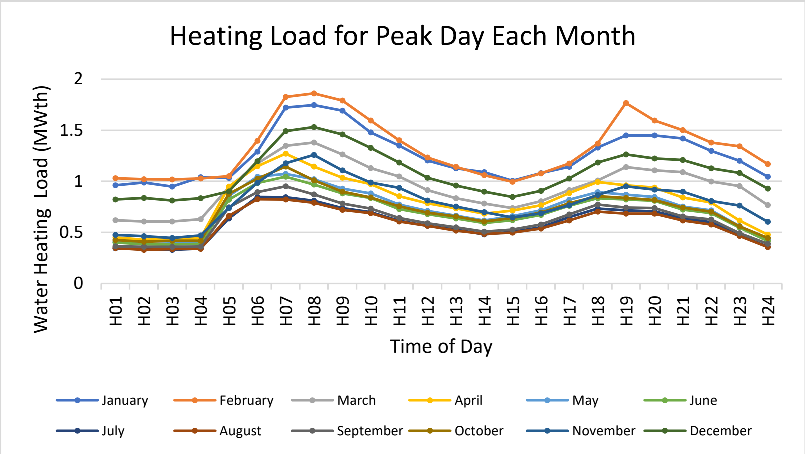


Figure 6. Time-series profile for water-heating load (shows peak day each month)

3.1.3 Utility Tariff and Fuel Price

Using the microgrid's location, XENDEE identifies and lists all applicable utility tariffs. The tariff selected for the microgrid is based on Southern California Edison with multi-season rates with three different time of use (TOU) rates provided for each day (SCE TOU-8-E-2-50kV-NEM2).[c] The demand charge and access fees are specified along with the electricity export sales price, which is lower than the purchase price at any specific time. The CO_2 emission for electricity purchase from the grid is estimated based on average hourly marginal CO_2 emission data of the California utility grid for 2018 reported by the California Independent System Operator (CAISO) shown in Figure 7. The emission rate was consistent

[c] For further information on the selected tariff, please refer to XENDEE's tariff catalog SCE TOU-8-E-2-50kV-NEM2.[17]

throughout the year with an average of 0.3780 metric tons CO_2/MWh and, minimum and maximum of 0.3774 to 0.3784 metric tons CO_2/MWh.

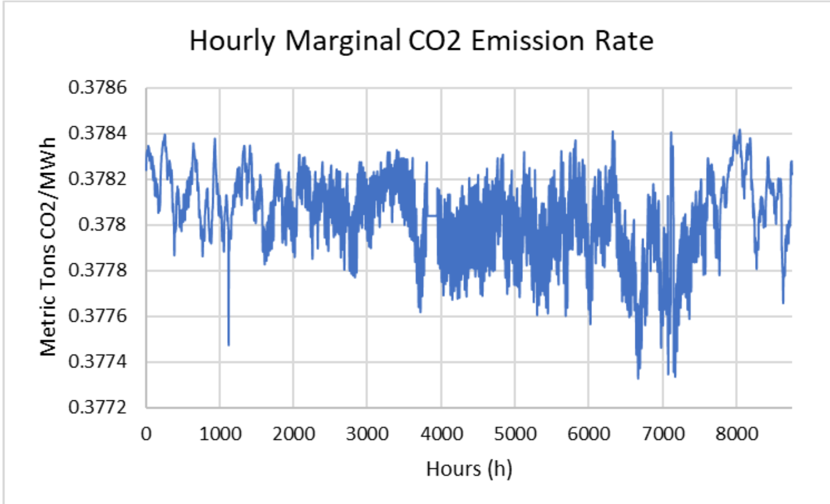


Figure 7. Hourly marginal CO_2 emission of CAISO in 2018.

The microgrid can purchase fuel from the utility. The fuel options available in XENDEE include natural gas for heating and onsite generation, biogas, diesel fuel, bio-diesel fuel, biomass fuel, and hydrogen. The biogas fuel is reserved for the proxy model, as discussed earlier. The fuel prices, monthly access fees, and corresponding carbon emission rates for the rest of the fuel types are provided based on XENDEE's default catalog. However, only NGGs and SRs are considered in this report. The natural-gas fuel is priced at 0.4451 $/Therm for heating application and 0.5716 $/Therm for onsite generation. The emission factor of 0.1808 kgCO_2/kWh is used for natural gas.

3.1.4 Grid Exchange and Outage Models

Microgrid generators and battery energy storage (BES) can be sized to allow electricity export to the grid. In this case study, SR, PV, and NGG are optimized only to meet the microgrid energy demand without the option of electricity export. BES, on the other hand, is allowed to export electricity and charge from the grid as required. In XENDEE, the resilience event is simulated with an extended outage of the utility grid. The 3-day outage is considered in August (August 24, 12:00 AM through August 26, 11:59 PM), which is the month of highest average hourly demand. To allow responding to outages lasting more than 24 h, the BES is modeled in multi-day discharge mode in which it does not have to return to the state-of-charge (SOC) level at the start of the day. The complete ride-through strategy is adopted for load management during the resilience event, in which the microgrid assets are sized to meet the total load demand during the grid outage. Although not considered in this study, the load-curtailment strategy can also be used by specifying the cost incurred for curtailing a certain percentage of the load.

3.2 The Scenarios

Microgrid optimization can have different objectives depending upon the intended application. This exercise will showcase the use of the proxy model developed in XENDEE to conduct technoeconomic feasibility studies for SRs in microgrids. The two major objectives considered here are to reduce the cost of electricity and the net carbon emission from the microgrid. Apart from that, the microgrid assets should also meet the resilience criteria, which is to ride through a three-day grid outage without any load disruptions.

Two different scenarios are considered to identify the optimum microgrid configurations–the first scenario (S1) without CO_2 tax, and the second one (S2) with CO_2 tax. In S2, The CO_2 tax is fixed at 50

$/metric ton based on the current lower estimate of the social cost of carbon.[16] Each scenario has three different cases. The reference case (C0) is built assuming all required energy is purchased directly from the utility without hosting onsite generation assets. The resilience criteria are not met in C0. Case 1 (C1) considers onsite generation but the SR is modeled with the purchase price scaled linearly based on 1-MW unit price, referred to as the flat cost model. In Case 2 (C2), SR's purchase price considers economies of scale, referred to as the economies of scale (EOS) model, which reflects the reduction in specific cost ($/kW) as the size of the plant increases, as shown in Figure 8. The EOS model is based on the estimated installation costs from the earlier report[1].

Figure 8. Small reactor's economies of scale in purchase price (EOS model) [1].

The scenarios discussed in the next sections of this case study are summarized as follows[d]:

1. Scenario 1: No CO_2 tax is considered, and the microgrid is optimized to reduce cost and meet the resilience criteria. The optimization is run for three different cases—S1C0: utility purchase, S1C1: with flat cost model of SR, and S1C2: with EOS model of SR.
2. Scenario 2: The CO_2 tax of 50 $/metric ton is considered and the microgrid is optimized to reduce cost and meet the resilience criteria. The optimization is run for three different cases—S2C0: utility purchase, S2C1: with flat cost model of SR, and S2C2: with EOS model of SR.

3.3 Scenario 1: Without Carbon Tax

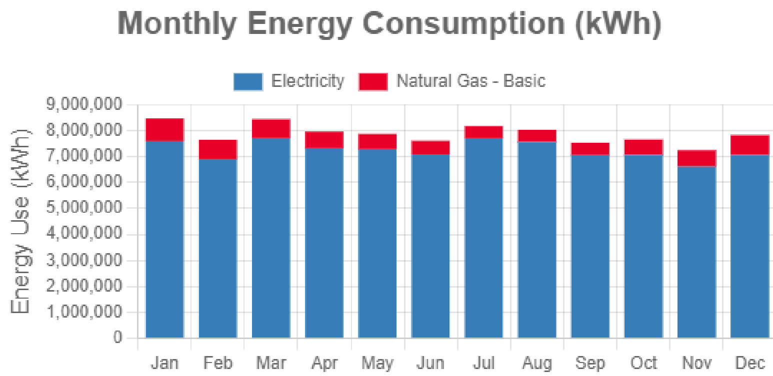
3.3.1 S1C0: Utility Purchase

In the reference case, no new generation is considered in the system. The required electricity is imported directly from the utility grid. The water-heating load is met by the existing 1.86-MWth natural-gas boiler. Without onsite generation, the reference case cannot meet the resilience criteria; therefore, it does not include a resilience event in the optimization.

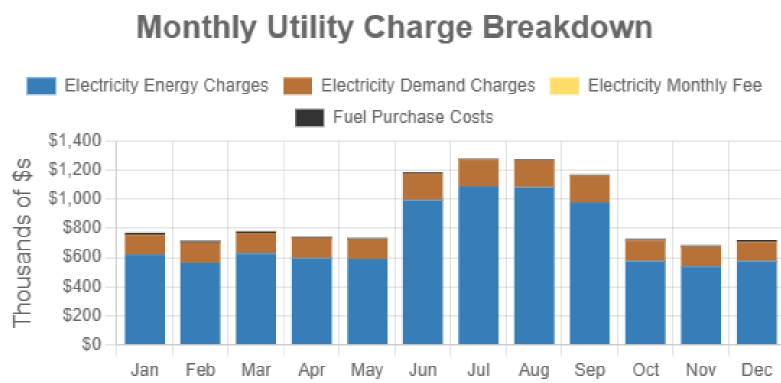
The total annual electricity and natural gas imports are 86,923,620 and 6,046,034 kWh, respectively. The total annual energy cost is calculated as 10,774,100 $/y, which includes both electricity and natural gas fuel purchase charges. The load-served levelized cost of electricity (LCOE) is obtained as 0.1159 $/kWh. Figure 9(a) and (b) show the breakdown of energy consumption and corresponding monthly charges for each month of the year. Figure 9 (c) and (d) show the breakdown of microgrid demands and

[d] Other scenarios could be developed by considering investment support and tax incentives for SR development and operation, multiple energy products (economies of scope), and the hydrogen ecosystem (production, consumption, and storage models) in the microgrid. However, these are not within the scope of this report.

corresponding CO_2 emissions for heat and electricity. The total annual carbon emission is 34,226 metric tons, 96 % of which comes from electricity.



(a)



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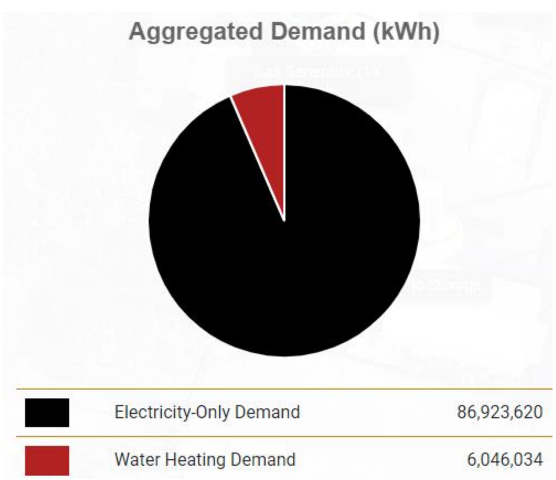
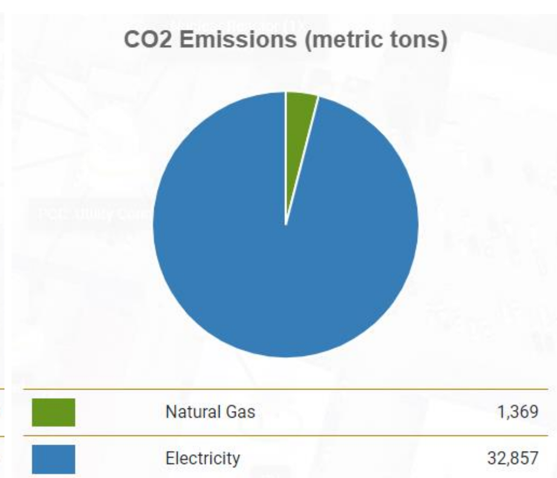




(c) (d)

Figure 9. Technoeconomic analysis result summary for S1C0: (a) Month-by-month total electricity and natural gas consumption, (b) Utility charges breakdown, (c) Total electricity and heating demand over the year, and (d) CO_2 emission from different sources.

3.3.2 S1C1: With SR Flat Cost Model

In this case, new on-site generators are considered but without taking the advantage of SR's economies of scale. The flat cost model is used for SR scaled based on 1 MW unit price, i.e., $11,233,100.

NGGs are less expensive to run without CO_2 tax. Therefore, the optimizer results in an onsite generation mix that includes 2.5 MW of PV, 6.6 MWh of BES, and 11 MW of NGGs (eleven units of 1-MW NGGs) without an SR. There is a 3.3% saving compared to the reference case (S1C0) with a total annualized electricity cost of 10,418,000 $/y. With a 6% interest rate, the project investment will be paid back in 10 years period. The load served LCOE is calculated as 0.1128 $/kWh. Due to onsite generation in the microgrid, the electricity import is significantly reduced. The microgrid sells approximately 21% of its generated electricity back to the grid to boost revenue (Figure 10[a]). The net electricity import from the grid is reduced by 94.3% compared to the reference case (S1C0). The annual CO_2 emission is increased by 63.6% to 55,996 metric tons, which mostly comes from the onsite NGG (Figure 10[b]).

The optimum generation portfolio meets the required resilience criteria (ride through a 3-day outage) without increased cost. Figure 10(c) shows that most of the energy consumption is in the form of natural gas used to produce electricity onsite. Since the NGGs are operated in CHP mode, the exhaust heat from the turbine can be recovered to meet the heating demand. Figure 10(d) shows the breakdown of monthly utility costs which is mainly due to the fuel purchase. Figure 11 shows the monthly breakdown of the microgrid costs and compares it with the reference case (S1C0). The monthly costs for the reference case are lower except for June, July, August, and September when the electricity price is higher than in other months.

Figure 12(a) and (b) show the hourly electricity and heat dispatch for January 1. The electricity mostly comes from onsite NGG. Since the NGGs are still expensive to run, the system continues purchasing electricity from the grid during the hours when the electricity price is low. The maximum import from the utility grid for January is 1.5963 MW, which is optimized to reduce the utility demand charge part of the total cost. BES charges during the daytime when PV generation is available and discharges in the evening time when the utility electricity price is high. The microgrid receives revenue by selling the electricity to the grid by discharging the BES at peak electricity export price. Since the heating demand is much less compared to the heat available from NGG, most of the heat remains unused.

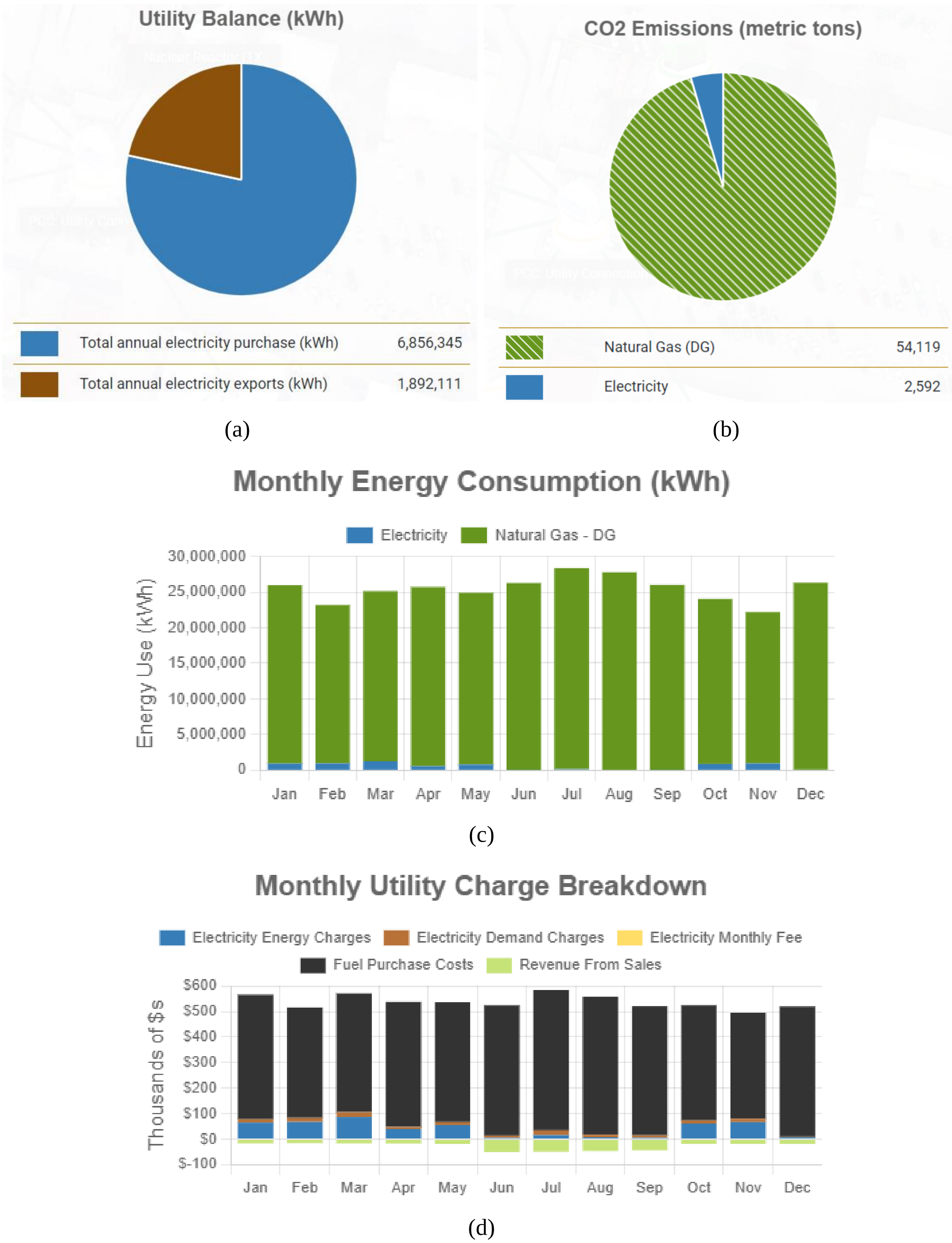


Figure 10. Technoeconomic analysis result summary for S1C1: (a) total electricity imports and exports over 1 year, (b) CO2 emission from different sources, (c) month-by-month total electricity and natural gas consumption, (d) utility charges and revenue from sales.

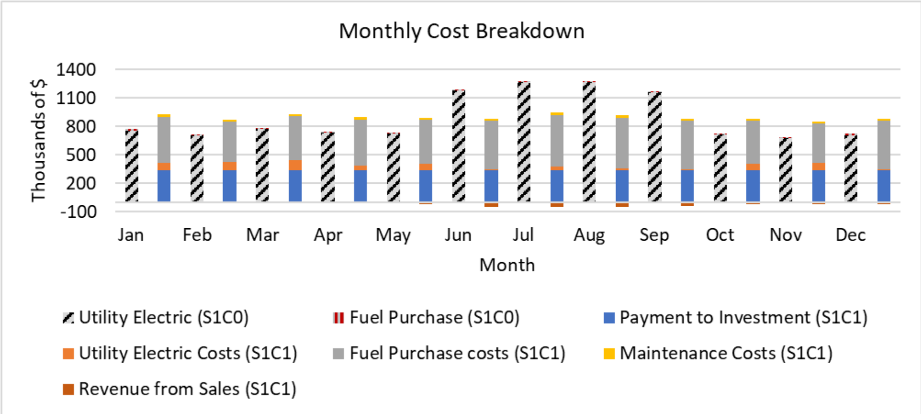
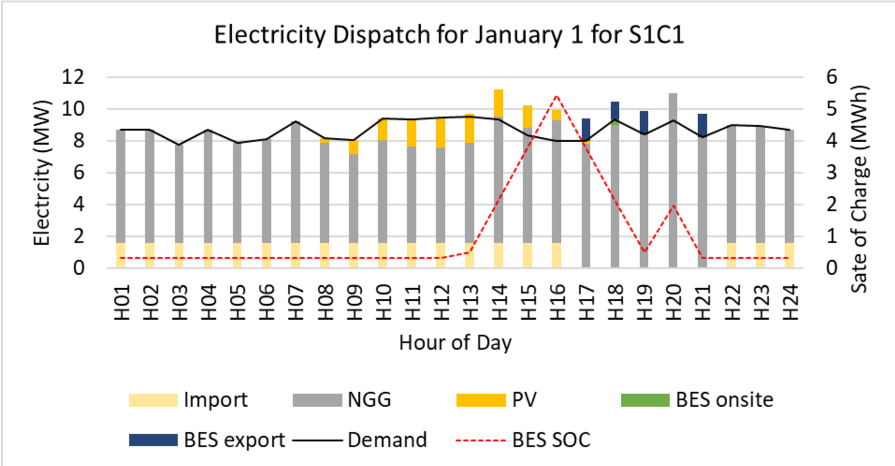
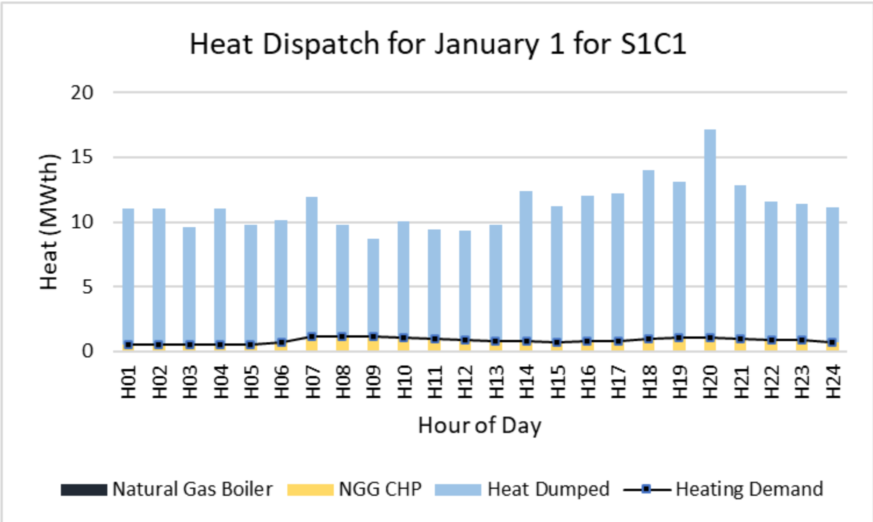


Figure 11. Monthly breakdown of microgrid cost for S1C1 and comparison to S1C0.



(a)



(b)

Figure 12. Time-series dispatch for the microgrid assets for January 1 for S1C1: (a) electricity dispatch and (b) heating dispatch.

3.3.3 S1C2: With Economies of Scale

In this case, the EOS model is used for SR. The specific purchase price per MW decreases with the increase in SR size. Therefore, SR becomes an attractive option to NGGs even without considering the benefits of reducing CO_2 emissions. With the EOS model, the generation portfolio optimized using XENDEE includes 2.52 MW of PV, 9.6 MWh of BES, and 11 MW of SR. The optimization does not select any NGGs. The savings compared to the reference scenario (S1C0) is 7% with a total annualized cost of 10,015,600 $/y. The project is paid back in 14 years with a 6% annual interest rate. The load-served LCOE is reduced to 0.1085 $/kWh. The biggest advantage however is the reduction in CO_2 emissions by 102.2% to -740 metric tons/y. The negative value of CO_2 emission is due to exporting clean electricity back to the grid. The microgrid's total electricity imports and exports are 762,731 kWh and 2,720,655 kWh, respectively. A total of 4,402,360 kWh of electricity is obtained from PV. The calculated generation profile also meets the required resilience criteria without increased cost. Figure 13 shows the breakdown of the microgrid costs for the optimized case and its comparison with the reference case (S1C0).

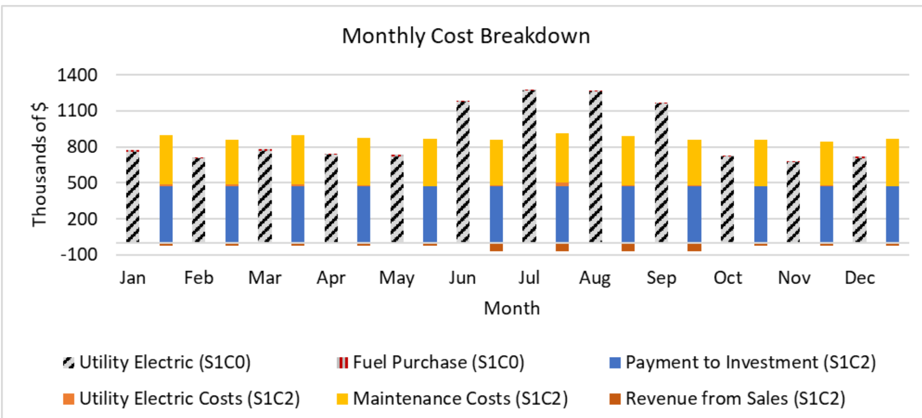


Figure 13. Monthly breakdown of microgrid cost for S1C2 and comparison to S1C0.

Figure 14 shows the hourly electricity dispatch time series for January 1. The electricity mostly comes from onsite SR. SRs have high capital costs but are cheaper to run. Therefore, in contrast to S1C1, the microgrid does not purchase electricity from the grid when SR can meet the local demand. BES charges during the daytime when generation is excess and discharges mostly to sell back to the grid when the electricity price is high.

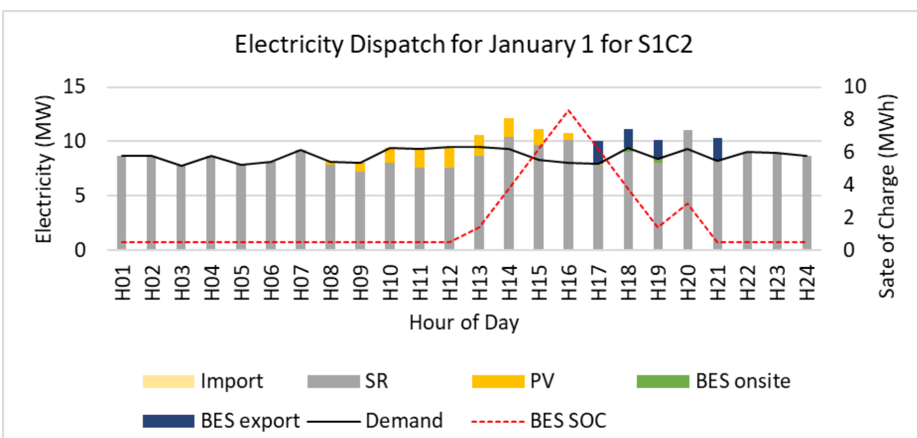


Figure 14. Time-series electricity dispatch in microgrid on January 1 for S1C2.

3.4 Scenario 2: With Carbon Tax

3.4.1 S2C0: Utility Purchase

The energy required for the system is directly purchased from a single utility; therefore, the electricity and natural gas imports, the operational dispatch results, and net CO_2 emission remain the same as the scenario without CO_2 tax (S1C0). The only difference would be the total annual cost, which will have a CO_2 tax added based on the energy consumption. Figure 15 shows the monthly breakdown of the microgrid cost with the CO_2 tax added. With CO_2 tax, the total annual energy cost increases to 12,485,400 $/y (an 11.1% increase) based on the hourly marginal utility CO_2 emission of CAISO (Figure 7). With this increased cost, LCOE also increases to 0.1343 $/kWh.

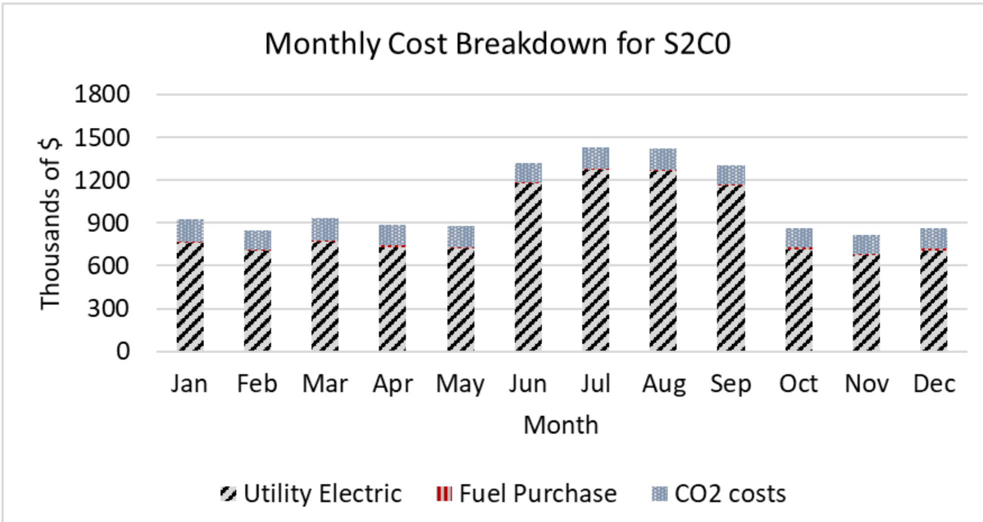


Figure 15. Monthly breakdown of microgrid costs for S2C0.

3.4.2 S2C1: With SR Flat Cost Model

Because NGGs produce a large amount of CO_2, they are not as attractive as in the first scenario when the CO_2 tax was omitted. But, with the flat cost model, SR is still an expensive investment and cannot replace all NGGs.

The optimization results include onsite generation consisting of 2.55 MW of PVs, 6.6 MWh of BES, 9 MW of SR, and 2 MW of NGG. The annualized energy cost is calculated as 12,627,500 $/y which is 1.1% more expensive compared to the utility purchase case (S2C0). This increase in annual cost is due to the requirement to meet the resilience criteria, incurring the total increased cost of 1.1% or 142,089 $/y from the reference case (S2C0). This is equivalent to 0.19 $/kWh or 1973.46 $/h on average. The load-served LCOE is obtained as 0.1347 $/kWh, and the investment is paid back in 16 years with a 6% interest rate. The total annual CO_2 emission is reduced to 3,103 metric tons/y, which is a 90.9% reduction from the utility purchase case. The net CO_2 emission is due to the electricity imported from the grid and the fuel consumed by the NGGs. As shown in Figure 16, the natural gas and electricity imports from the utility are significantly reduced—electricity import reduces by 53.6% and natural-gas import reduces by 99.7% on average compared to the similar case in the first scenario (S1C1). This further reduces the dependency on the utility. The total annual electricity export is also reduced by 60.55% compared to S1C1.

Figure 17 shows the breakdown and month-wise comparison of microgrid cost with the reference case (S2C0). The CO_2 tax added to the optimized case is less compared to the reference case. A major portion of the monthly cost is due to the annualized payments to recover the initial investment. There is also a new incurred cost for maintenance due to a large share of the electricity generated onsite with SR.

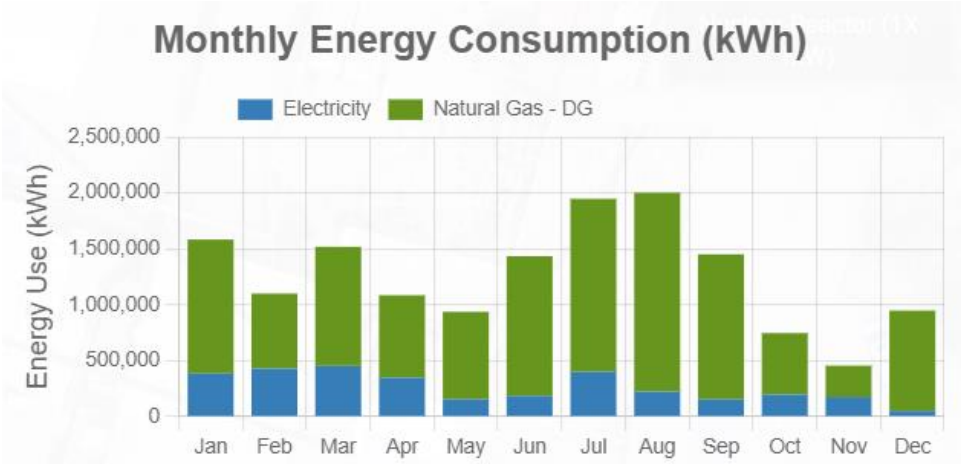


Figure 16. Monthly breakdown of electricity and fuel imports for S2C1.

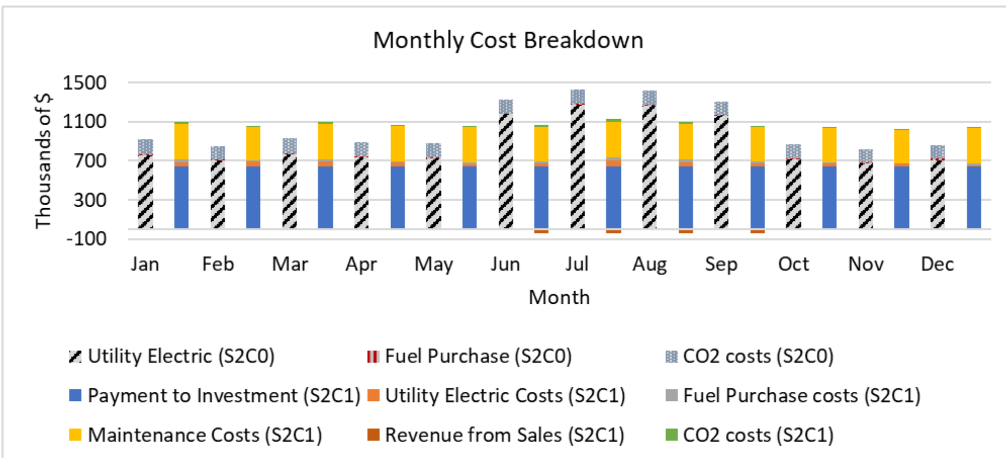


Figure 17. Monthly breakdown of microgrid cost for S2C1 and comparison to S2C0.

NGGs have lower investment costs but are expensive to run with CO_2 tax. Therefore, whenever the demand can be met with other onsite generators, NGGs will not be used. On January 1, the electricity demand remains below 10 MW, as shown in Figure 18. The demand can be met by using SR, PV, and BES while keeping NGGs as a backup.

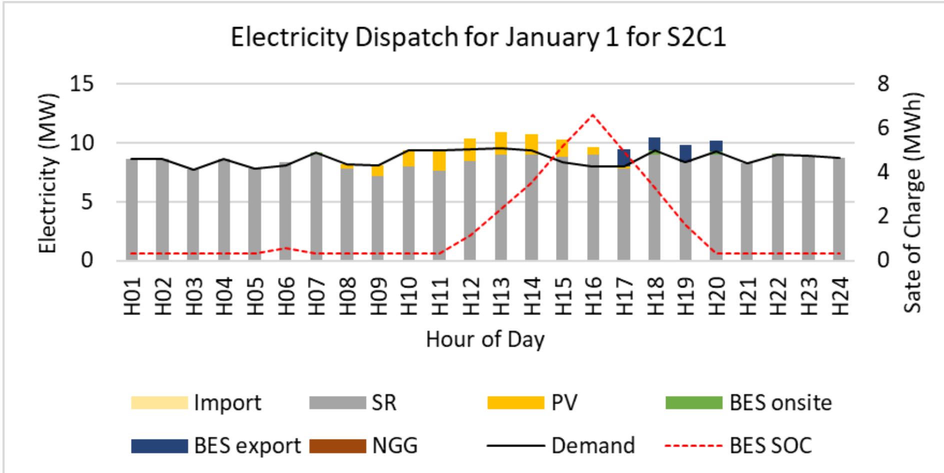


Figure 18. Time-series electricity dispatch in microgrid on January 1 for S2C1.

On January 4, the electricity demand peaks above 13 MW, as shown in Figure 19. The power available from PV is significantly low. SR operates at its rated output of 9 MW throughout the day. During the daytime, when the load peaks, NGGs are operated along with a small import from the utility grid. BES is optimized to reduce electricity import during the hours when electricity price is high.

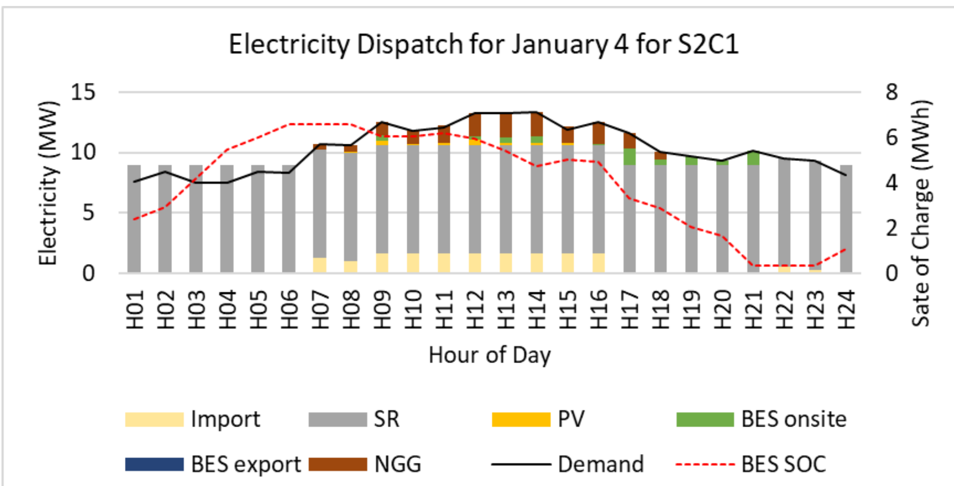


Figure 19. Time-series electricity dispatch in microgrid on January 4 for S2C1.

3.4.3 S2C2: With Economies of Scale

The optimization already results in negative CO_2 emission even without considering CO_2 tax if the EOS model is used for SR as seen in S1C2. Adding the CO_2 tax makes the financial case of SR even more attractive. The load-served LCOE is obtained as 0.1092 $/kWh. The microgrid onsite generation includes 2.47 MW of PV, 11.4 MWh of BES, and 11 MW of SR.

The generation profile is similar to the case without CO_2 tax (S1C2), but with a 1.8 MWh increase in BES. LCOE is slightly increased because CO_2 tax is added to the electricity imported from the utility grid. The CO_2 emission, in this case, is -934 metric tons/y, which is slightly lower than the case without CO_2 tax (S2C1). The microgrid savings are 19.3% and the project pays back faster in 11 years with a 6% interest rate. Figure 20 shows the breakdown and comparison of the microgrid monthly cost with the reference case (S2C0). The rest of the financial and operational results are provided in Appendix B.

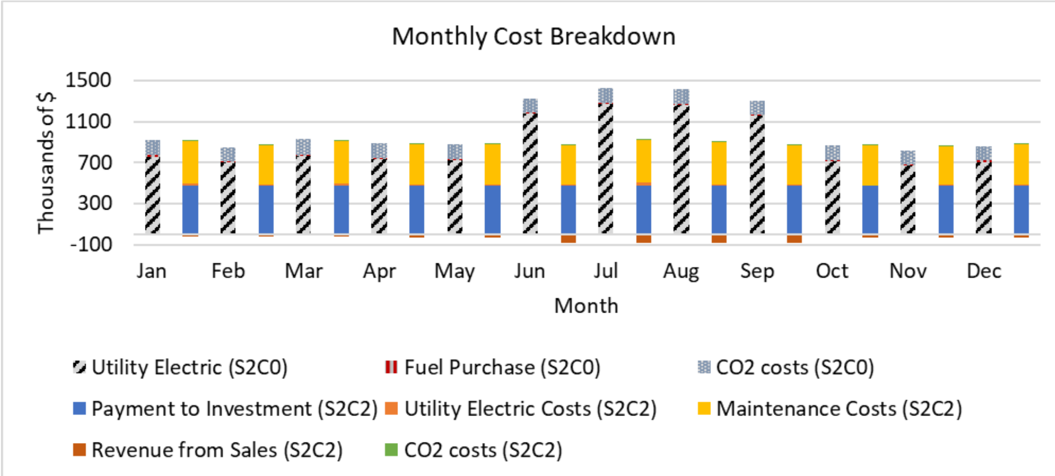


Figure 20. Monthly breakdown of microgrid cost for S2C2 and comparison with S2C0.

Figure 21 shows the hourly electricity dispatch time series for January 1 which looks similar to the electricity dispatch for S1C2. The microgrid does not purchase electricity from the grid when SR can meet the local demand. BES charges during the daytime when generation is excess and discharges to sell back to the grid when the electricity price is high.

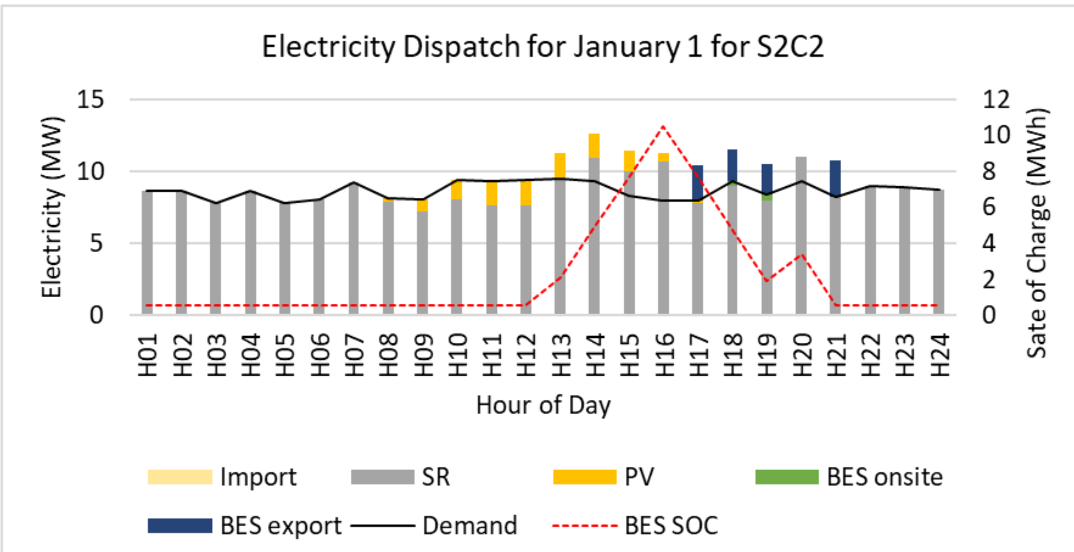


Figure 21. Time-series electricity dispatch of microgrid for January 1 for S2C2.

4. DISCUSSION AND CONCLUSION

SRs needs a bigger investment compared to conventional NGGs. But when their economy in sizing is considered in their installation costs, they can be as cost competitive as NGGs and potentially more beneficial when CO_2 tax is included. In the case study presented in this report, different scenarios were explored to understand the operational performance and cost-competitiveness of SRs against other forms of generation in a practical microgrid use case. Solar PV, NGG, and SR were seen as potential generation options. Considering the system was in an urban area, one additional limitation was imposed for PVs in terms of available land space for PV panel installation. SRs were assumed to be sufficiently safe to be hosted in an urban area without exclusion boundaries. The installation cost from the previous report[1] was used for SR's purchase cost in the proxy model.[e] Table 2 summarizes the optimization results for different scenarios for comparison.

In Scenario 1, the CO_2 tax was not considered. In reference case (S1C0), the system continued purchasing electricity and natural gas. One of the major disadvantages, in this case, was the lack of local backup generation to ride through the grid outages the system may face during extreme events. Another disadvantage was the large amount of CO_2 produced by the utility grid to meet the electricity demand.

When the flat cost model of SR was used (S1C1), SR did not appear as a favorable generation option compared to NGGs without CO_2 tax. The optimizer selected PV, NGG, and BES but without SR. While the investment required was less compared to other cases, the disadvantage was the rise in onsite CO_2 emissions. The electricity import decreased, whereas the natural gas import increased to produce electricity onsite using NGGs. When the EOS model was used instead of the flat cost model (S1C2), all NGGs were replaced with an equivalent 11 MW of SR. Compared to the case with the flat cost model, the investment necessary was more than twice and took 4 more years to get paid back. However, the net LCOE decreased by 3.8%. The microgrid exported more electricity than what it was importing resulting in net negative CO_2 emission. This result showed that the microgrid developed with an SR can be made net-zero while at the same time making it cost competitive.

Another advantage of SR was the independence from the external supplies during extreme events that cause electrical power and potentially natural gas pipeline outages. The microgrid developed with NGGs, although able ride-through extended electrical grid outages, still require a continuous supply of natural gas. In extended extreme weather or cyber-related outages, the natural-gas pipeline/supply chain can get disrupted. On the other hand, SRs can sustain such extreme outages due to long-lasting fuel. The fuel once loaded can last for multiple years (at least 2 years) without needing refueling.[5] In some reactor technologies, such as the 4S, the fuel once loaded can last until the end of the plant life (30 years for 4s).[6] This significantly boosts the case for SRs in microgrids when resilience is a primary consideration.

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[e] The optimization scenarios were run using the full investment cost in SR's proxy model instead of installation costs. The optimization results with investment cost-based proxy model varied depending upon the case:

- If economies of scale of SR and CO_2 tax are not considered, the optimizer selects gas generators and results are similar to the case S1C1 of this report.
- If economies of scale of SR is not considered but CO_2 tax is considered, the optimizer selects gas generators and no SR. Due to high CO_2 tax, the project does not pay back—the optimized solution is not found.
- If economies of scale are considered but CO_2 tax is not, the optimizer again selects gas generators and no SR.
- If economies of scale of SR and CO_2 tax considered, the optimizer selects 10-MW SR and 1-MW gas generator. Appendix C provides the XENDEE-generated financial and operational results for this case.

Table 2. Comparison of optimization results with different microgrid scenarios and cases.

Scenarios		Scenario 1: Without CO_2 Tax			Scenario 2: With CO_2 tax		
		Utility Purchase (S1C0)	*SR Flat Cost Model (S1C1)*	*SR EOS Model (S1C2)*	*Utility Purchase (S2C0)*	*SR Flat Cost Model (S2C1)*	*SR EOS Model (S2C2)*
Generation Profile		-	NG: 11 MW PV: 2.5 MW BES: 6.6 MWh	SR: 11 MW PV: 2.52 MW BES: 9.6 MWh	-	SR: 9 MW NG: 2 MW PV: 2.55 MW BES: 6.6 MWh	SR: 11 MW PV: 2.47 MW BES: 11.4 MWh
Total CAPEX (thousands of $)		-	41,104	85,461	-	116,202	86,437
Total OPEX (Thousands of $/y)		10,774	6387.1	4379.1	12,485	4862.4	4352.4
Annual Energy Cost (Thousands of $/y)		10,774	10,418	10,015	12,485	12,627	10,081
Total Savings (%)		-	3.3	7.0	-	-1.1	19.3
Load-served LCOE ($/kWh)		0.1159	0.1128	0.1085	0.1343	0.1367	0.1092
Annual CO_2 Emission (Metric tons/y)		34,226	55,996	-740	34,226	3103	-934
Payback Period (y)		-	10	14	-	17	11
Renewable Generation (kWh/y)		-	4,370,943	4,402,360	-	4,454,933	4,317,356
Annual Utility Electricity Exchange (kWh)	*Import*	86,923,620	6,856,345	762,731	86,923,620	3,181,932	600,118
	Export	-	1,892,111	2,720,655	-	746,270	3,070,326
Annual Utility Natural-gas Fuel Exchange (kWh)		6,046,034	298,867,429	-	6,046,034	12,048,301	-

In Scenario 2, with the addition of the CO_2 tax, the energy price for the reference utility purchase case increased to account for the CO_2 emissions incurred by the utility while meeting the microgrid demand. For CO2 tax of 50 $/metric ton, the reference case was 16% more expensive with an LCOE of 0.1343 $/kWh. With the flat cost model of SR (S2C1), the optimization resulted in a generation mix of both SRs and NGGs with 9 MW of SR and 2 MW of NGGs. SRs provided the majority of demand and NGGs were operated only when SR was not able to meet the demand. The CO_2 emission was reduced by 91% compared to the reference case. Adding the resilience requirement imposed an increased total cost which was reflected in the increased LCOE calculated as 0.1367 $/kWh. Furthermore, nearly three times more investment was required, and it took 7 more years to get paid back compared to the case when CO_2 tax was excluded (S1C1).

Finally, when the EOS model was used with CO_2 tax included (S2C2), SRs became an even more financially attractive option. With the reduced purchase price of SR, all NGGs were replaced with SR and the dispatch result was similar to S1C2. The total CAPEX was 1.1% more than S1C2, but the investment was paid back sooner in 11 years because the reference case itself became expensive due to the inclusion of CO_2 tax. The only difference was the BES rating which was 1.8 MWh more compared to S1C2. The LCOE was slightly more (0.65%) due to the CO_2 cost premium added to the electricity imported from the grid.

In conclusion, the above case study showed that SRs can deliver resilient net-zero microgrids while being economically competitive with other generation technologies. However, it is particularly important to identify use cases and optimal generation mixes with other technologies so that SRs can provide an economic energy solution while gaining technological maturity. For example, in each of the optimization cases, a significant amount of heat remained unused due to the lower heating demand of the microgrid. If thoughtfully planned, the unused heat could be utilized to expand the industrial or commercial opportunities within the microgrid, which supports the business case for microgrids even more. The first SRs would be more cost-effective in national critical infrastructures situated in off-grid locations where power supply reliability and resilience are of vital importance.

5. PATH FORWARD TO THE SR MODEL

The case study results using the proxy model and the discussion presented in this report highlighted the potential for SRs in microgrids. The above analysis also demonstrated the suitability of the XENDEE platform to perform technoeconomic feasibility studies of microgrids developed with SRs. The proxy model was effective in capturing the most important financial and operational characteristics and sufficiently represent SRs in technoeconomic optimization. It is clear from the case study that the model can analyze multiple scenarios to establish metrics for a path toward a cost-competitive and zero carbon microgrid completely isolated or connected to the grid. The proxy model is fully integrated within the NZM platform for modeling and analysis of clean energy microgrids with storage and other generation technologies. The next step is to develop a detailed SR model that will replace the current proxy model in XENDEE. The SR model will capture the capabilities, constraints, and nuances of SR by incorporating all the parameters shown in Figure 1. The additional characteristics that will be considered in the SR model are summarized as:

- Economies of scale in O&M costs with fixed and variable parts
- Fuel life cycle cost with separate front-end and back-end fuel costs, waste-handling and disposition costs, and refueling intervals,
- Plant decommissioning cost at the end of plant life,
- Standard operational framework with limits specified in terms of power change, ramp rate, and power cycle parameters for baseload or semi-baseload operations.

Apart from producing electricity, SRs can be used for diverse heat applications, such as hydrogen production with high-grade heat and district heating using low-grade heat. XENDEE currently has hydrogen, low-grade heat, and electricity ecosystems with integrated optimization capability. One major modeling recommendation for the SR and gas generator model is to reconfigure the CHP process to allow process heat extraction from SR for high-grade heat application. This high-grade heat feature could be paired with a new high-temperature electrolyzers module within XENDEE to use high-grade process heat extracted from SRs or cleaner diverse fuel gas generators.

The SR model will be upgraded with advances in SR technology and the acquisition of data as SR technology and its installation and operational costs are improved and obtained through ongoing research and development. A catalog will be created for leading SR technologies sized 100 kW–20 MW from major advanced reactor technology lines considering manufacturer's specifications, whenever available.

The SR catalog will provide an option to select the most suitable reactor technology for the microgrid from among the multiple available reactor options. A XENDEE plugin can be developed to take raw input for a reactor technology and convert it into generic SR catalogs. The technoeconomic plugin will consider all possible characteristics of advanced nuclear reactors, including reactor type, fuel technology, fuel-enrichment process, cost of maintenance of coolant/moderator, and waste-handling and storage options. Potential radiation hazards and safety characteristics could also be included in later versions.

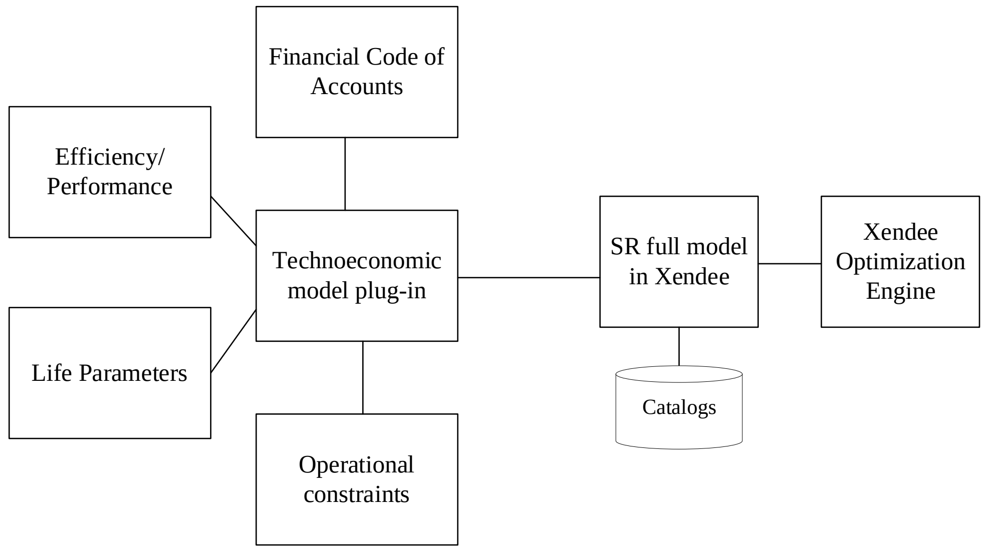

Figure 22. Plugin for producing and importing SR catalog in XENDEE.

The SR model will enable technoeconomic analysis for the deployment of SR in microgrids for multiple applications and scenarios using datasets and data specific to SR as they are known and as the technology matures.

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Appendix A

Overview of XENDEE Platform

A-1. Introduction to XENDEE

XENDEE is an informed techno-economic decision-making platform built on well-established scientific models of microgrid power and energy behavior modeling. It captures all steps needed to design and implement microgrids, community energy projects, and Distributed Energy Resource (DER) projects for optimal planning and operation dispatch strategies in the multi-energy system context. XENDEE provides the optimal planning and operation dispatch of microgrids by guaranteeing the reliability, resilience, and practical boundary conditions of such projects.

XENDEE provides screening, conceptual design, basic technical design, detailed technical design, and implementation all in one web-based platform. XENDEE has two modeling interfaces: Geographic Information System (GIS) Configurator and Expert Mode Configurator. The GIS Configurator is an easy-to-use interface that is ideal for new users and quick feasibility studies using interactive icons and network connections in the GIS view. The Expert Mode is the advanced interface for developing microgrid projects. It combines a tree view and multiple uploads, database, and catalog functions with spreadsheet displays to provide full-model customization for experienced users. Projects created in the GIS Mode can be exported into the Expert Mode where one can continue to build on the same project for more detailed analysis.

XENDEE automates as much of the design as possible through features such as automated one-line diagram design, automatic calculation of cable length and costs, and calculation of local data, such as utility tariffs and solar/wind resources. XENDEE employs an extensive catalog of vendor-specific technologies, real-world utility tariffs, and representative demand profiles, empowering rapid model development. XENDEE also employs several calculators for detailed inputs such as determination of outage costs, solar PV and wind performance, and automatic conversion of units.

XENDEE design algorithms are grounded in extensive research on energy and power system optimization and analysis. In addition to government-funded research and development of the core software tools, the XENDEE team regularly conducts research on new features and improvements to its algorithms. A list of XENDEE publications[f] is available on its website, which includes research papers on optimization techniques, and additional sources on the scientific background of the XENDEE optimization engine.

A-2. XENDEE Portfolio Optimization

The energy flows and the DER technologies that can be modeled in the XENDEE optimization engine are shown in Figure A-1. The choice of energy purchase and sales, onsite energy sources comprising various DER technologies and fuels, local storage options, and the end-use equipment comprising essential demand types show the complex structure of the XENDEE portfolio optimization.

[f] Recent Publications by the XENDEE Team: https://xendee.com/publications/.

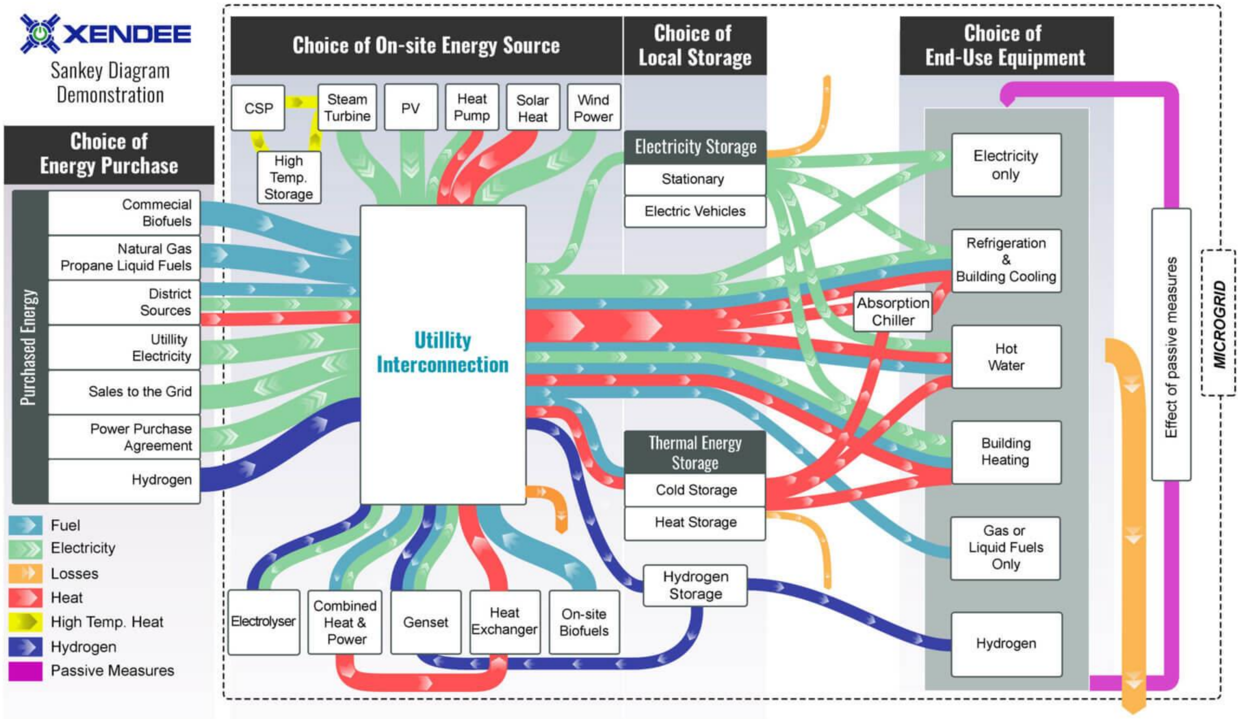


Figure A-1. Energy flows in the XENDEE optimization engine.

The most common DER technologies include solar PV and battery in electrical energy systems, solar thermal, natural gas-based boilers and thermal storage in thermal energy systems, and electric chillers and cold storage in cooling energy systems. With sector coupling, the applications of different DER technologies are increased such as the electricity that is generated via solar PV can be utilized to provide to the end-user demand of electrical by using batteries or directly providing it, or it can be utilized to provide to end-user demand of heating by using Combined Heat and Power (CHP) technology, or it can also be utilized to generate hydrogen fuel to provide to the end-user demand of hydrogen mobility network.

XENDEE models such complex sector coupled networks using best optimization practices, practical constraints, and boundary conditions of these multi-energy systems. The optimization algorithm of XENDEE uses techno-economic input data and determines the DER technology combinations in terms of optimal capacities of the DER technologies, determines how to operate them in terms of optimal schedules of the DER technologies, and also determines the optimal placement of DER in the system by minimizing the total energy system costs, and total energy system carbon dioxide emissions together with guaranteeing the reliability and resilience of energy system subject to certain practical constraints. The workflow of the XENDEE optimization engine from inputs to outputs together with objectives is shown in Figure A-2.

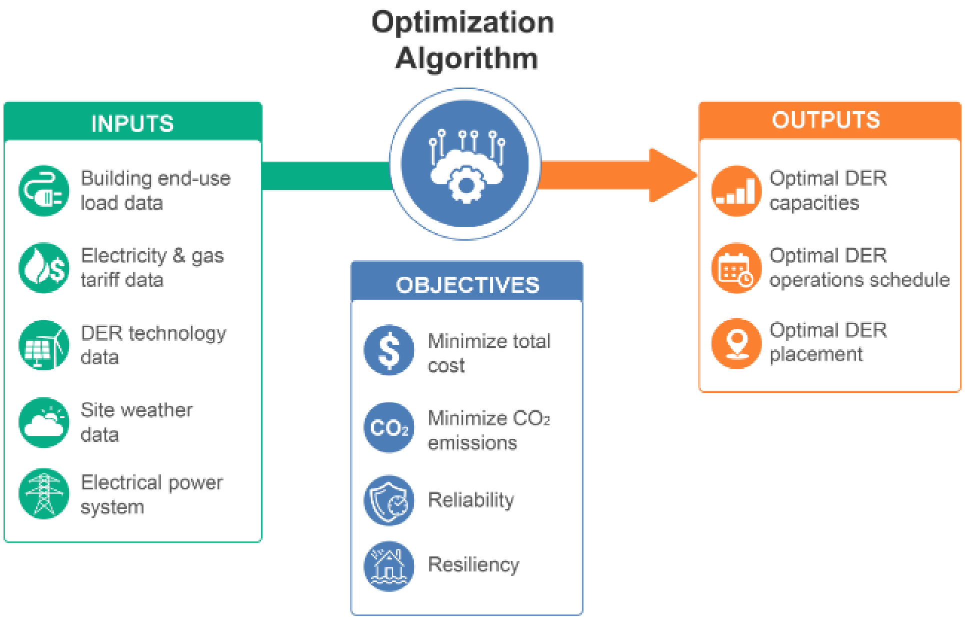


Figure A-2. The workflow of XENDEE optimization engine.

A-3. The Mathematical Modeling of XENDEE Optimization Engine

The XENDEE optimization engine uses the Mixed-Integer Linear Programming (MILP) modeling framework for its portfolio optimization. The MILP can minimize the total annual energy costs, total annual carbon dioxide emissions, or both in a multi-objective setting. The XENDEE optimization engine can optimize microgrids for a single year as well as multiple years over the project horizon. The MILP framework developed by XENDEE minimizes the objective function using two different time resolutions in a typical year. The first model uses three representative day types (e.g., weekdays, peak days, and weekend days in each month with 24 hours in a single representative day type), resulting in time indices of hour h € $\{1, 2, \dots, 24\}$, day type d € $\{1, 2, 3\}$, and month m € $\{1, 2, \dots, 12\}$. This model is a simplified version of the second model that uses full-scale time-series (i.e., 8760 hours in a typical year) by replacing the time indices h, d, and m with just timestep t € $\{1, 2, \dots, 8760\}$. Both models are equally capable of handling the full complexity of multi-energy systems in microgrids shown by the energy flows in Figure A-1.

The simplified objective function related to the total annual energy costs (C) is given in Eq. 1.

$$\min C = C_{utility} + C_{invest} + C_{O\&M} + C_{fuel} + C_{carbon} - R_{sales} - R_{incentives} \quad (1)$$

where $C_{utility}$ are the costs associated with utility purchase, C_{invest} are the costs associated with the investment of DER technologies and infrastructure, $C_{O\&M}$ are the operation and maintenance costs of the DER technologies, C_{fuel} are the costs associated with the fuels for onsite generators, C_{carbon} are the costs associated with the carbon taxes, R_{sales} are the revenues from sales to the utility, and $R_{incentives}$ are the revenues due to incentives and tax credits.

The simplified objective function related to the total annual carbon dioxide emissions (CO_2) is given by Eq. 2.

$$\min CO_2 = CO_{2\,utility} + CO_{2\,fuels} + CO_{2\,embedded} + CO_{2\,PPA} \quad (2)$$

where $CO_{2_{utility}}$ are the marginal emissions associated with the purchase of the electricity from the utility, $CO_{2_{fuels}}$ are the emissions associated with the burning of fuels to generate onsite power, and also the fuel purchase, $CO_{2_{embedded}}$ are the emissions associated with the manufacturing of the DER technologies, and $CO_{2_{PPA}}$ are the emissions associated with the purchase made from an external Power Purchase Agreement (PPA) into the microgrid.

The XENDEE optimization engine can calculate the reference costs and reference carbon dioxide emissions of microgrid use cases using just utility input. Alternatively, users can also optimize microgrids relative to their reference costs and reference carbon dioxide emissions as user-defined inputs. These reference costs are often used to run the multi-objective optimization scenarios where the total annual carbon dioxide emissions are minimized by keeping a limit on the total annual energy costs of the system using a Premium Cost Factor (PCF) as a multiplication factor of costs of the reference case ($C_{reference}$). This is essential due to the fact that the minimization of carbon dioxide emissions can cause infeasible solutions since the costs of the system might go up relative to costs of the reference case and the PCF ensures that the infeasibility does not occur. This multi-objective setting is given by Eq. 3.

$$\mathrm{C} \leq PCF * C_{reference} \tag{3}$$

The MILP framework developed by XENDEE minimizes the objective function subject to several constraints associated with power quality, climate, reliability, energy storage operation, regulatory functions, financial functions, operation limits, energy balance, etc., as shown in Figure A-3.

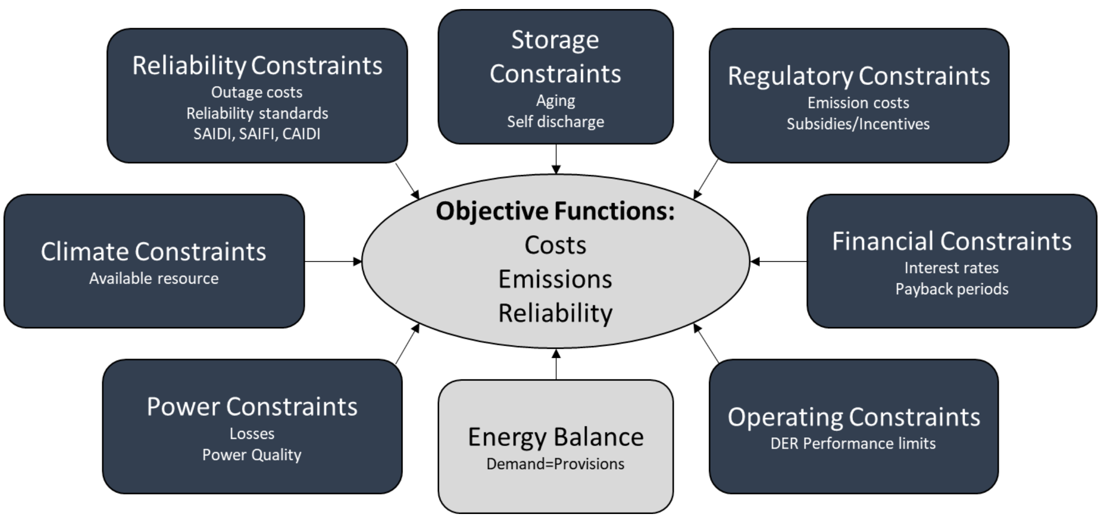


Figure A-3. Several constraints modeled in the XENDEE optimization engine.

All these constraints are equally important to ensure that the practical boundary conditions of microgrid models are respected. Out of these constraints, the most important constraint to mention here is the energy balance constraint that ensures that the end-user energy demand meets energy provisions from diverse sources present in a microgrid. The simplified form of this energy constraint is given by Eq. 4.

$$L_t + S_t = u_t + \sum_j g_{j_t} \tag{4}$$

where t is the timestep of the optimization (i.e., it includes hour $h \in \{1, 2, \dots, 24\}$, day type $d \in \{1, 2, 3\}$, and month $m \in \{1, 2, \dots, 12\}$ for the three representative day types model and just time $t \in \{1, 2, \dots, 8760\}$ for the full-scale time-series model, L is the end-user energy demand, S is the energy exported, u is the energy purchased and g is the energy generated by DER technology j). This equality constraint ensures that the demand plus the exports is equal to the energy purchased plus the energy generated by DER technologies in each timestep of the MILP optimization.

Appendix B

Operational and Financial Results for S2C2

Table of Contents

65.1%
OPEX Savings (%)

XENDEE

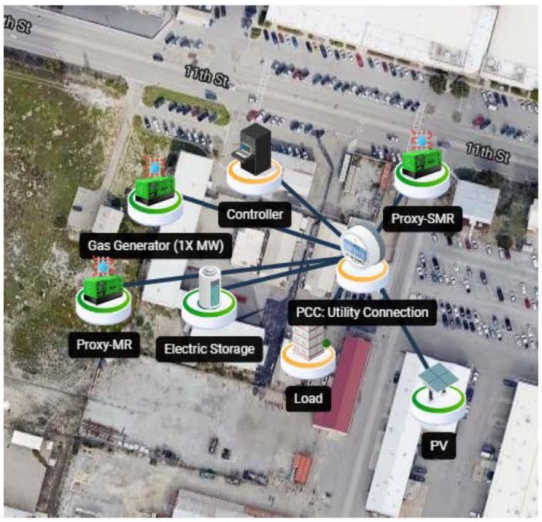
Operational and Financial Results for S2C2

Considering installation cost for SR's technoeconomic model. Economy of scale is considered. CO2 tax 50 $/metric tons.

Model Input

The Naval Base

311 Main Rd, NAS Point Mugu, CA 93042, USA



Objectives

Minimize cost; Outage ride-through from Aug 24 12:00 AM through Aug 26 11:59 PM.

Financing

Interest Rate	**6.00 %**
Investment Tax Credit	**No**
MACRS	**Yes**

Energy Costs

Energy Price	**$0.42 / kWh**
Avg. Natural Gas Cost	**$0.5716 / therm**
Avg. Diesel Fuel Cost	**N/A**
Reference LCOE	**$0.14 / kWh**

Demand Charges

Peak TOU Rate	**$4.72 / kW**
Non-Coincident	**$8.11 / kW**

Demand Characteristics

Peak Demand	**15 MW**
Annual Consumption	**86.3 GWh**
Schedulable EV	**N/A**

Financial Indicators for Investment

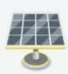
$-5,102,537	**$69.4M**	**11 Years**
Cumulative NCF (at year 10)	Cumulative NCF (at year 20)	Payback Period

Impact

$86.4M	**19.3%**	**102.7%**
Upfront Capital Cost	Annual Cost Reductions	Emission Savings

	Total Annual Energy Costs (dollars in thousands)	Total Annual CO_2 Emissions (metric tons)
Reference	$12,485.4	34,226
Investment scenario (incl. annualized capital costs and electricity sales)	$10,081	-934
Total Savings (%) (incl. annualized capital costs and electricity sales)	19.3 %	102.7 %

Result	Value
Interest Rate	6.00 %
OPEX Savings (%)	65.1%
Generation-Based Levelized Cost of Energy ($ / kWh)	$0.1043
Load-Served Levelized Cost of Energy ($ / kWh)	$0.1092
Simple Project Break-Even Year	11 years
Detailed Project Break-Even Year	11 years
Simple Project Payback Period	11 years
Detailed Project Payback Period	11 years
XENDEE Project Savings to Investment Ratio	1.74

Type	Total New Capacity	Technology (New Capacity)
	2.47 MW	PV (2.47 MW)
	11.4 MWh	Electric Storage (11.4 MWh)
	11 MW	Proxy-SMR (11 MW)

This optimization meets the following resiliency criteria:

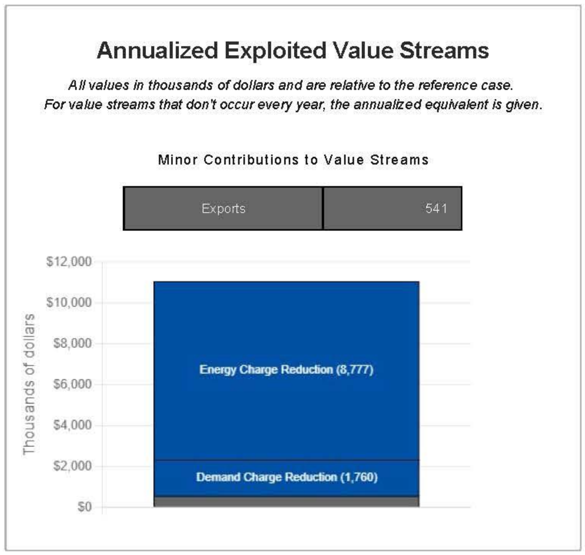
Supplied load will ride-through an electric utility outage from **August 24 12:00 AM** through **August 26 11:59 PM**.

There are no increased costs needed to ride through an outage of this duration.

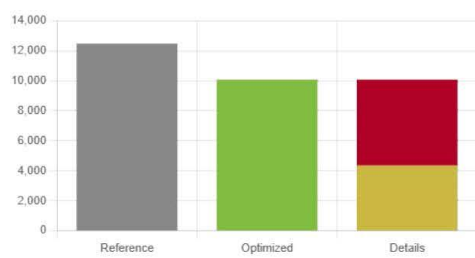
Summary

Provided in this section is an overview of projected annual costs and savings over a twenty-year period. Annualized Energy Costs summarizes the annualized operational and investment costs of the optimized microgrid, and the Costs and Savings Projection (Non-Discounted) presents costs as upfront investment capital, yearly operational expenses, and accumulated savings based on results from the year optimized.

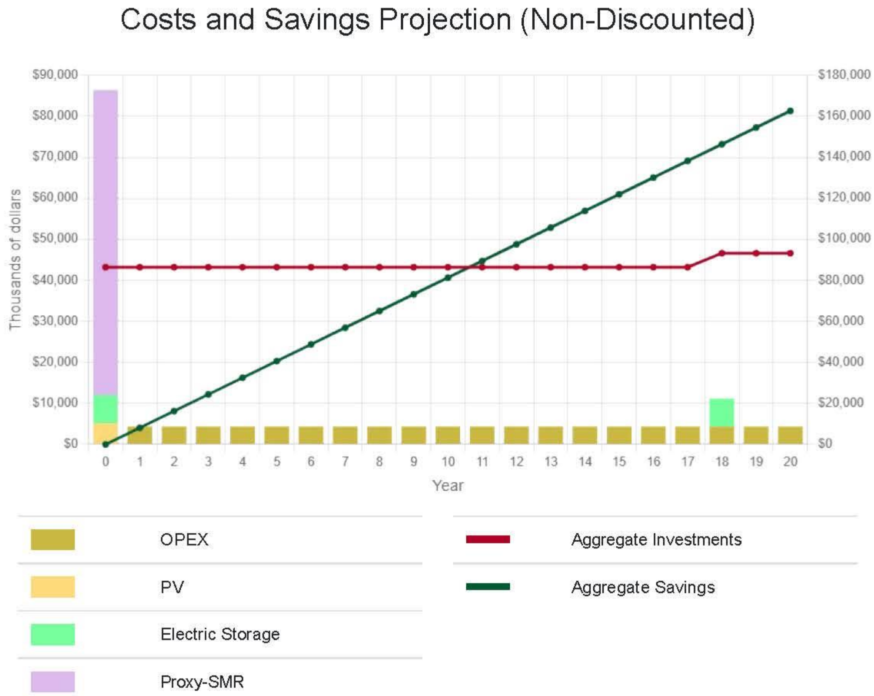
Value Streams



Annualized Energy Costs



Reference	$12,485
Optimized - Total	$10,081
OPEX	$4,352
Annualized Investment Costs	$5,729

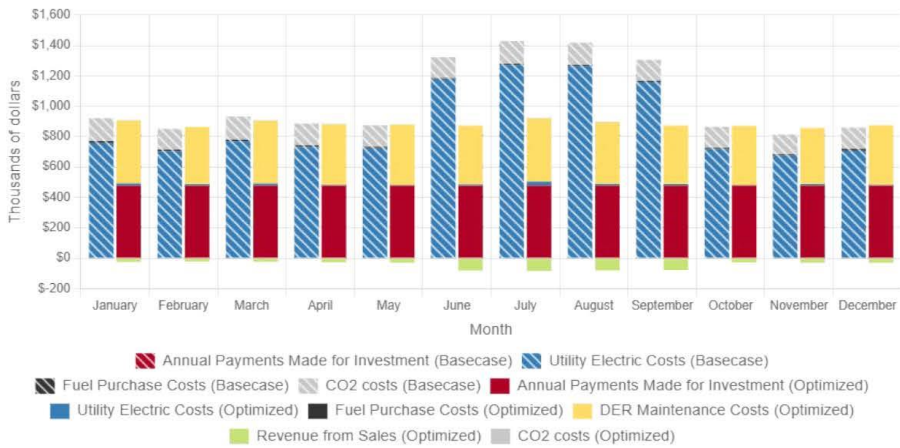


This is a non-discounted projection of the project costs and savings that assumes no changes in operation over time. Use the multi-year optimization feature to examine changes in investment and savings over time.

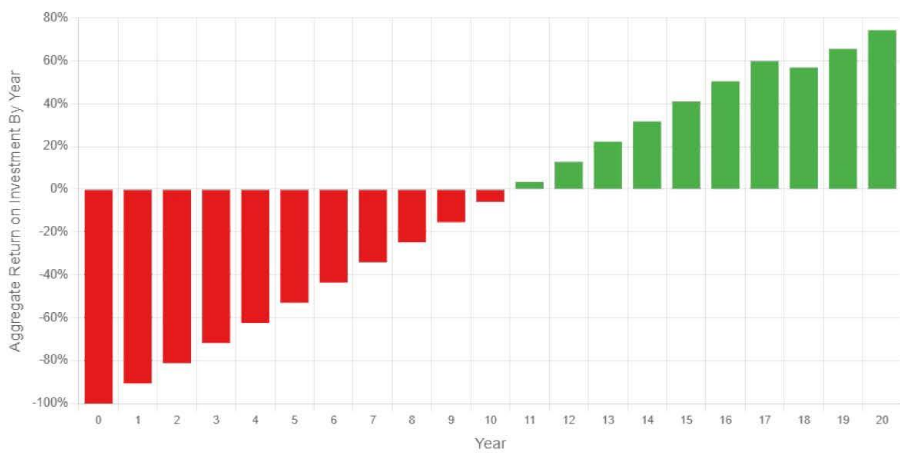
Financial Data

Primary financial indicators are provided in this section to facilitate assessing project returns. Return on investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR) are calculated and graphed for each year leading out to twenty years from project implementation, providing insight on returns at different timelines. Also included is a detailed cash flow table.

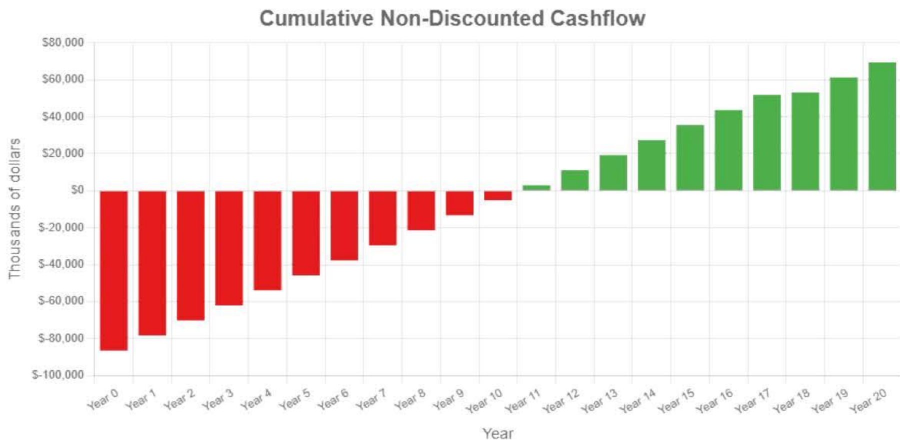
Microgrid Cost Breakdown



XENDEE ROI



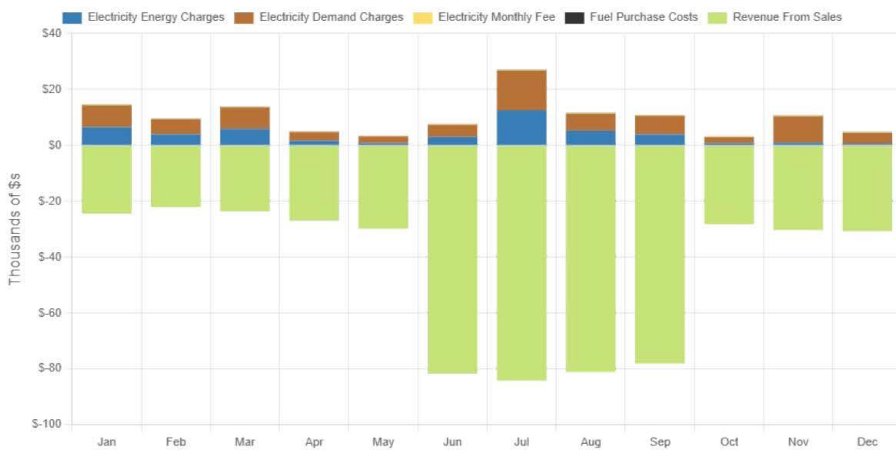
Cumulative Non-Discounted Cash Flow



Utility Data

This section provides a summary of electricity and fuel utility purchases. Monthly breakdowns of energy consumption [kWh], demand by time-of-use period [kW], and total charges [k$] are included.

Monthly Utility Charge Breakdown



Utility Billing Period

Billing for Annual

Annual Summary of Charges

Electricity Energy Charges [$]	-495,209.69
Electricity Demand Charges [$]	73,615.87
Electricity Monthly Fee [$]	2,558.16
Fuel Purchase Costs [$]	857.10
CO2 Tax [$]	11,346.86
Total [$]	-406,831.70
Reference [$]	12,485,374.17

Annual Fuel Charges

Fuel Category	Consumption [kWh]	Rate [$/kWh]	Fuel Charge [$]
BioGas - Contracted	285,700,912.46	-	857.10
Fuel Subtotal [$]			857.10
Reference [$]			114,806.63

Annual Electricity Charges

Energy Category	Consumption [kWh]	Rate [$/kWh]	Energy Charge [$]
Period 1	6,804.05	-	887.25
Period 2	40,659.00	-	2,992.50
Period 3	552,654.86	-	42,271.98
Exports	3,070,325.62	-	-541,361.42
Energy Subtotal [$]			-495,209.69
Reference [$]			8,823,189.88

Demand Category	Demand [kW]	Rate [$/kW]	Demand Charge [$]
Non-coincident	1,761.27	-	71,553.45
Period 1	771.00	-	2,062.41
Demand Subtotal [$]			73,615.86
Reference [$]			1,833,537.08

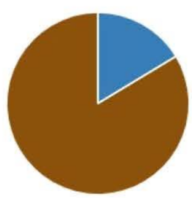
Energy Balance and Technology Investments

This section provides data on system energy demand and portfolio technologies. Included are details on total annual demand for each end-use modeled, share of demand met by utility purchases and on-site DER assets, total capacities of existing and new DER assets, and upfront investment costs.

Annual Electricity Balance (kWh)

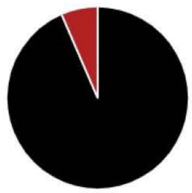
Total annual electricity purchase (kWh)	600,118
Total annual on-site generation from conventional DG (kWh)	85,710,274
Total annual on-site generation from renewables (kWh)	4,317,356

Utility Balance (kWh)



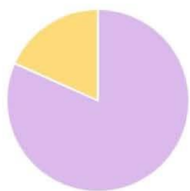
Total annual electricity purchase (kWh)	600,118
Total annual electricity exports (kWh)	3,070,326

Aggregated Demand (kWh)



■	Electricity-Only Demand	86,348,582
■	Water Heating Demand	6,000,000

Generation Technologies (kWh)

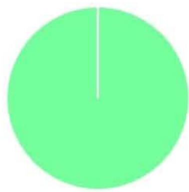


■	New Proxy-SMR (kW) (x11)	11,000
■	New PV (kWdc)	2,469

Tech	Used / Available Space (ft²)	%
PV	265,807 / 274,277	96.91%

Tech	Capacity Factor
PV	19.96%

Storage Technologies

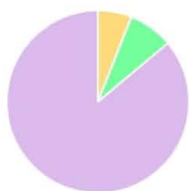


	New Electric Storage Capacity (kWh)	11,400

Tech	Annual / Allowed Cycles	%
Electric Storage	378 / N/A	N/A

Tech	Inverter Size (kW): Calc. / Specified	Ratio
Electric Storage	2,850 / 2,850	1.00

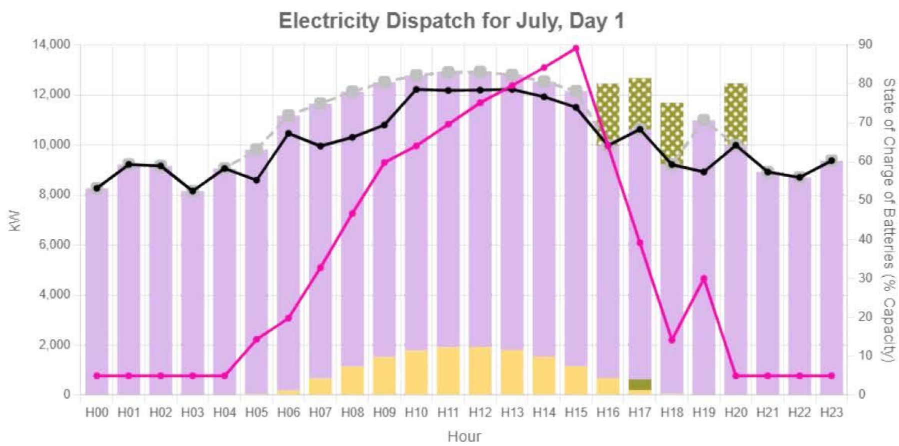
Investments



	New PV	$5,185,761
	New Electric Storage	$6,828,600
	New Proxy-SMR	$74,422,782

The following dispatch curves show the optimal system operation to meet all electricity loads on a selection of modeled days. Electricity dispatch shows both the electricity-only loads and any electricity used to operate cooling and/or refrigeration technologies. System operation includes on-site generation and storage dispatch, utility purchases, and load management strategies.

Electricity Dispatch for July, Day 1



Demand lines are stacked to show the cumulative impact.

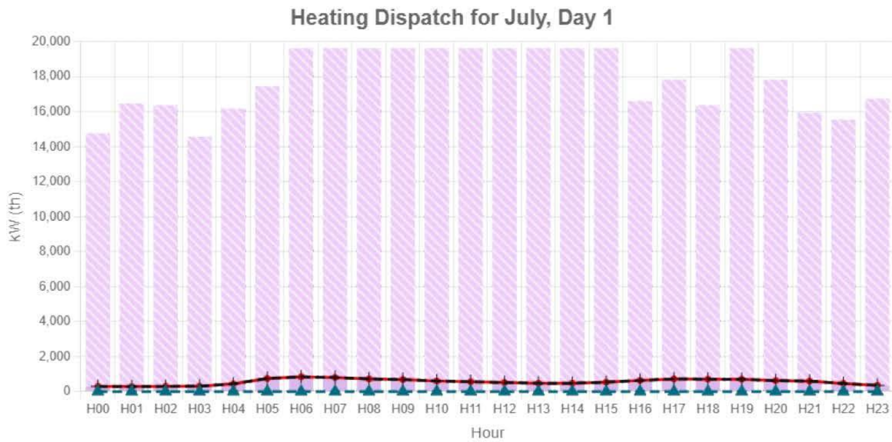
- Electricity-Only Load
- Electricity Supplied to Storage
- Utility Purchase
- PV for Self Consumption
- Electric Storage for Self Consumption
- Proxy-SMR for Self Consumption
- Electric Storage for Export
- State of Charge of Electric Storage

* Axes NOT Scaled on Dispatch Graph By Data Across All Months / Day Types

Heating Dispatch

The following dispatch curves show the optimal system operation to meet all heating loads on a selection of modeled days. Heating loads include both space heating and water heating. System operation includes heating provided by central HVAC systems, on-site thermal generation and storage technologies, and heat generated by CHP generators (electricity provided by CHP units is shown in Electricity Dispatch).

Heating Dispatch for July, Day 1



Demand lines are stacked to show the cumulative impact.

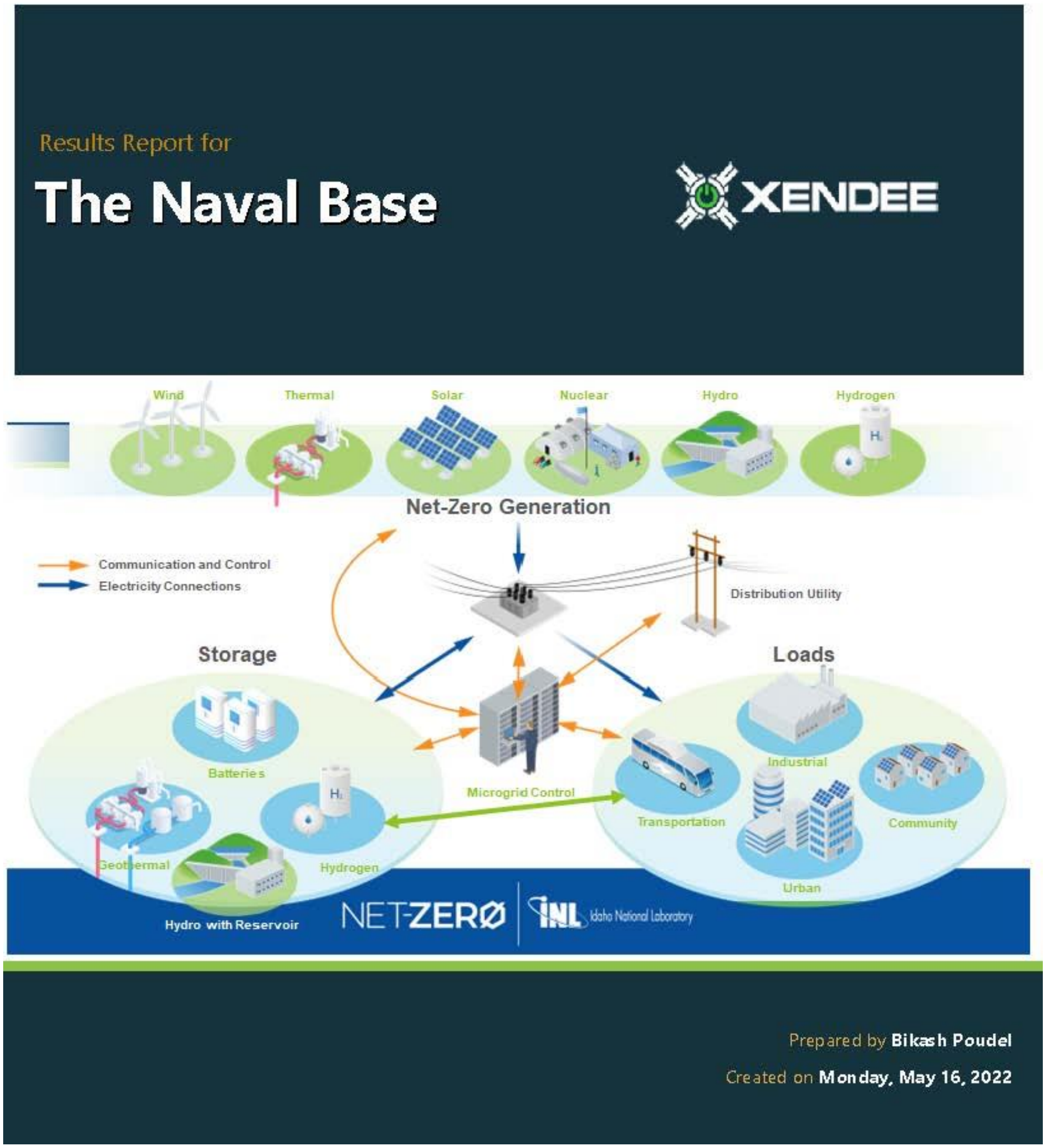
▪▪▪▪	Space Heating Load
▪▪▪▪	Water Heating Load
▬	Heat for Chilling
▇	Proxy-SMR
▨	Heat dumped by Proxy-SMR

* Axes NOT Scaled on Dispatch Graph By Data Across All Months / Day Types

Appendix C

Operational and Financial Results with Investment Cost Model

NET-ZERØ INL Idaho National Laboratory



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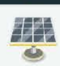
XENDEE				
	Project:	The Naval Base 2	Date:	5/5/2022
	Address:	311 Main Rd, NAS Point Mugu, CA 93042, USA	Equations:	3,479,437
	Analysis:	With CO2 Cost Investment Cost Model	Variables:	3,824,734

	Total Annual Energy Costs (dollars in thousands)	Total Annual CO_2 Emissions (metric tons)
Reference	$12,485.4	34,226
Investment scenario (incl. annualized capital costs and electricity sales)	$12,700.5	385
Total Savings (%) (incl. annualized capital costs and electricity sales)	-1.7 %	98.9 %

Result	Value
Interest Rate	6.00 %
OPEX Savings (%)	63.8%
Generation-Based Levelized Cost of Energy ($ / kWh)	$0.1335
Load-Served Levelized Cost of Energy ($ / kWh)	$0.1375
Simple Project Break-Even Year	16 years
Detailed Project Break-Even Year	16 years
Simple Project Payback Period	16 years
Detailed Project Payback Period	16 years
XENDEE Project Savings to Investment Ratio	1.2

Type	Total New Capacity	Technology (New Capacity)
	2.55 MW	PV (2.55 MW)
	9.6 MWh	Electric Storage (9.6 MWh)
	11 MW	Gas Generator (1X MW) (1 MW) Proxy-SMR (10 MW)

This optimization meets the following resiliency criteria:

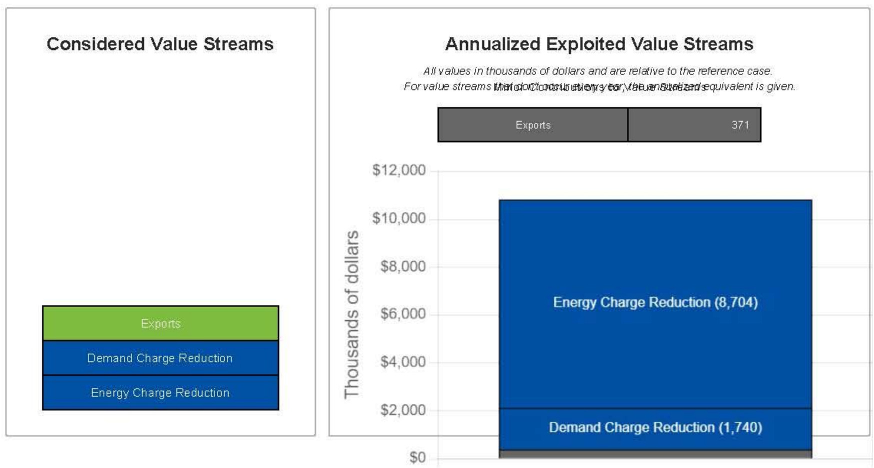
Supplied load will ride-through an electric utility outage from **August 24 12:00 AM** through **August 26 11:59 PM**.

This incurs a premium cost of **$215,172**, which is **$0.29/kWh** met or **$2,988.50 per hour**.

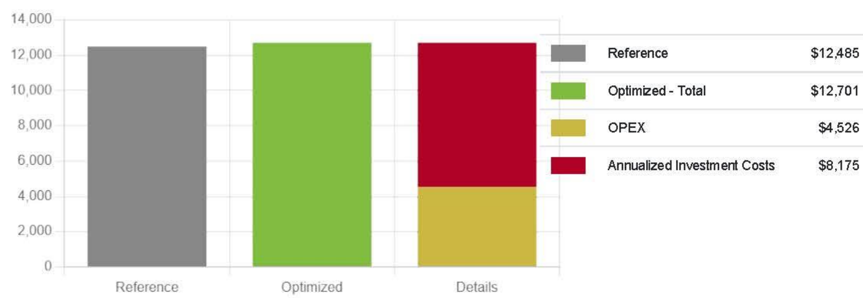
Summary

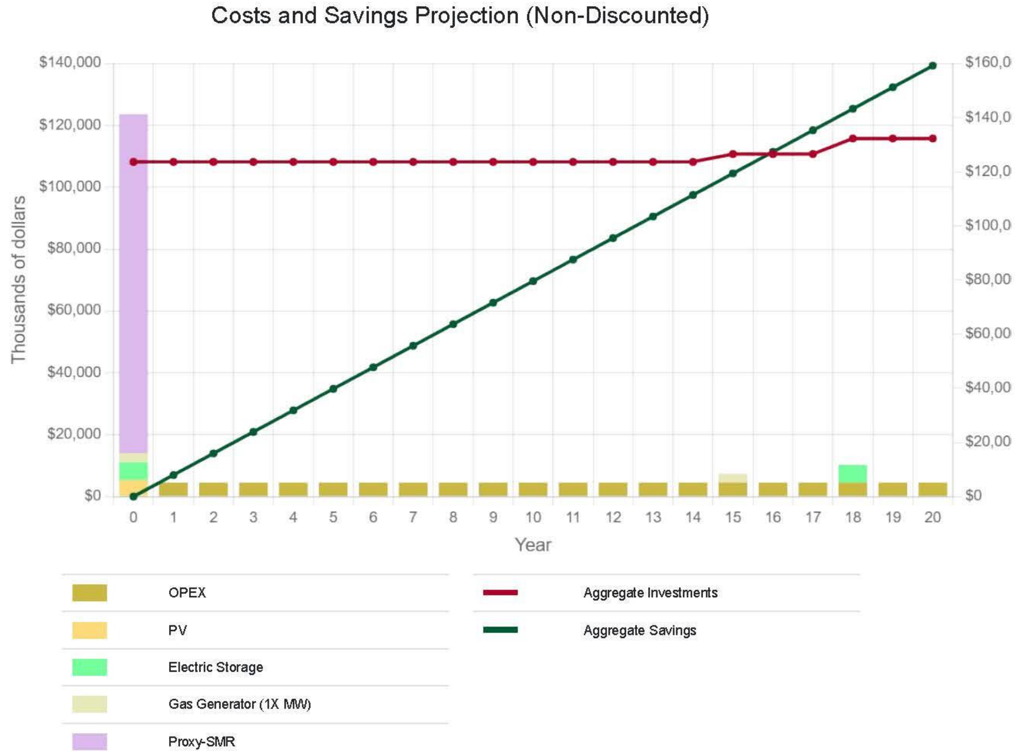
Provided in this section is an overview of projected annual costs and savings over a twenty-year period. Annualized Energy Costs summarizes the annualized operational and investment costs of the optimized microgrid, and the Costs and Savings Projection (Non-Discounted) presents costs as upfront investment capital, yearly operational expenses, and accumulated savings based on results from the year optimized.

Value Streams



Annualized Energy Costs

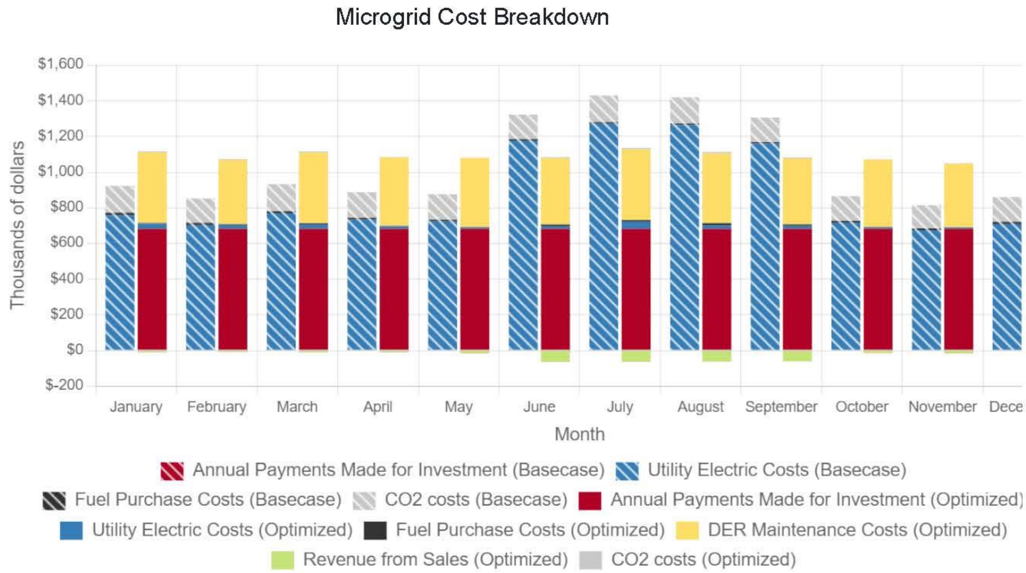


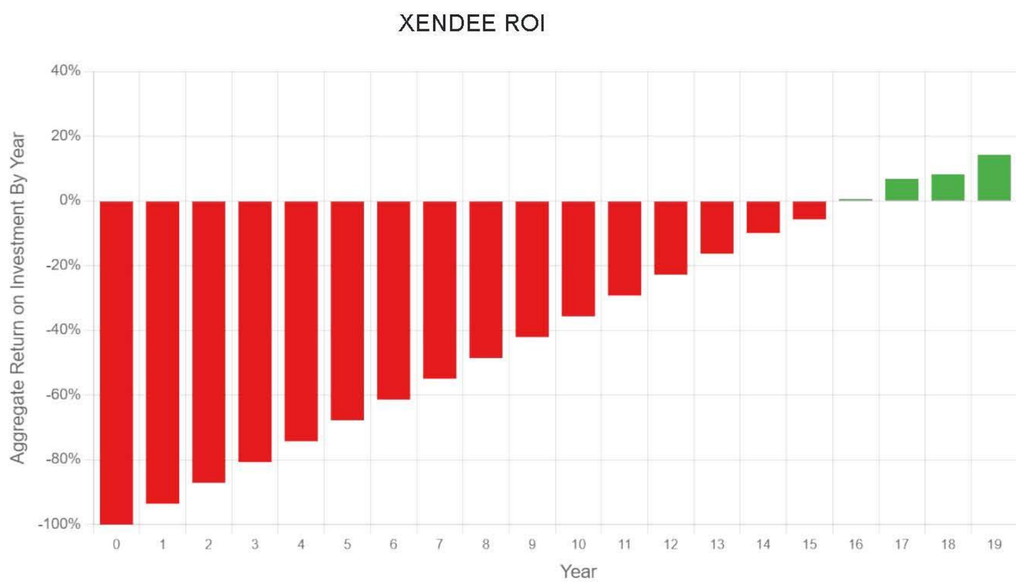


This is a non-discounted projection of the project costs and savings that assumes no changes in operation over time. Use the multi-year optimization feature to examine changes in investment and savings over time.

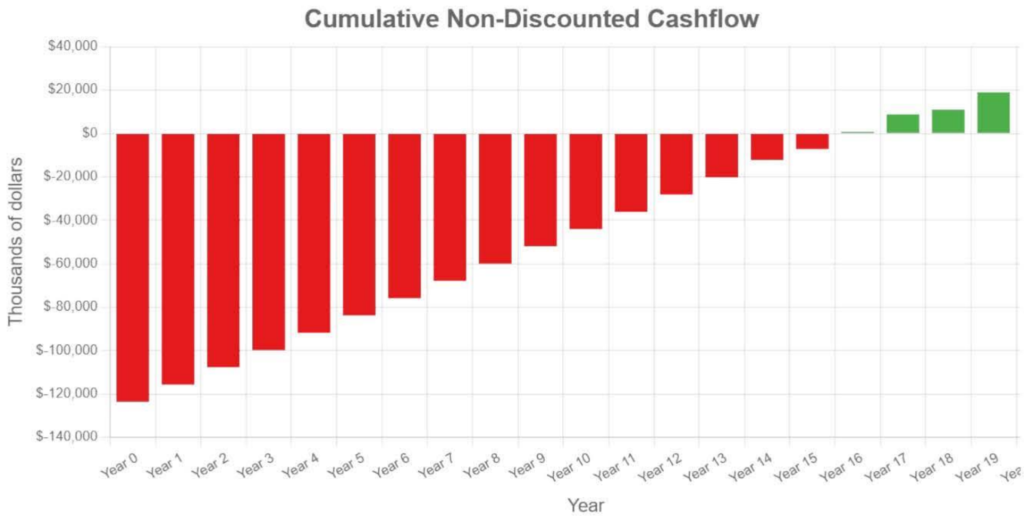
Financial Data

Primary financial indicators are provided in this section to facilitate assessing project returns. Return on investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR) are calculated and graphed for each year leading out to twenty years from project implementation, providing insight on returns at different timelines. Also included is a detailed cash flow table.





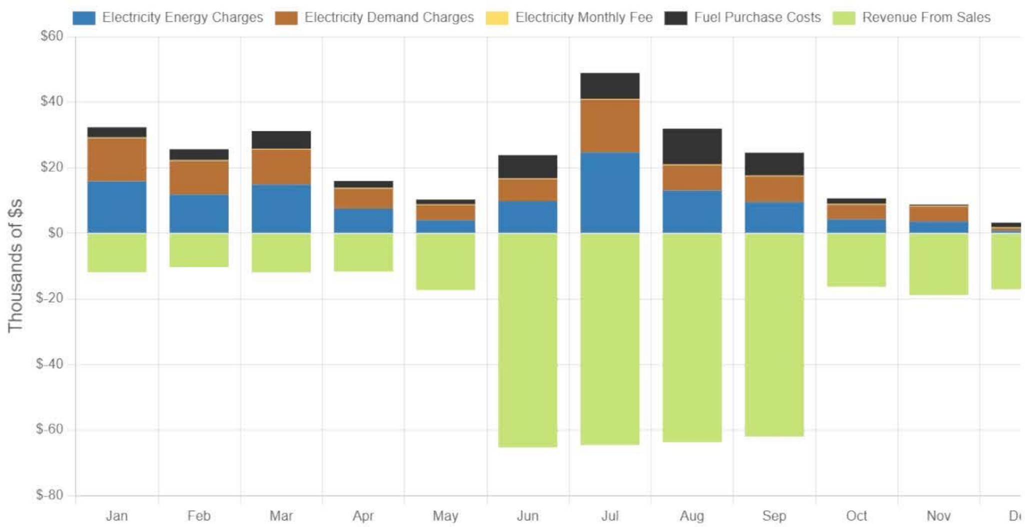
Cumulative Non-Discounted Cash Flow



Utility Data

This section provides a summary of electricity and fuel utility purchases. Monthly breakdowns of energy consumption [kWh], demand by time-of-use period [kW], and total charges [k$] are included.

Monthly Utility Charge Breakdown



Utility Billing Period

Billing for Annual

Annual Summary of Charges	
Electricity Energy Charges [$]	-251,034.56
Electricity Demand Charges [$]	93,217.91
Electricity Monthly Fee [$]	2,558.16
Fuel Purchase Costs [$]	52,063.14
CO2 Tax [$]	53,861.92
Total [$]	-49,333.43
Reference [$]	12,485,374.17

Annual Fuel Charges

Fuel Category	Consumption [kWh]	Rate [$/kWh]	Fuel Charge [$]
Natural Gas - DG - Contracted	2,626,562.03	-	51,238.97
BioGas - Contracted	274,722,450.39	-	824.17
Fuel Subtotal [$]			52,063.14
Reference [$]			114,806.63

Annual Electricity Charges

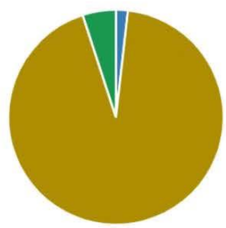
Energy Category	Consumption [kWh]	Rate [$/kWh]	Energy Charge [$]
Period 1	3,201.78	-	417.51
Period 2	186,400.15	-	13,856.98
Period 3	1,401,403.49	-	105,342.21
Exports	1,831,970.27	-	-370,651.26
Energy Subtotal [$]			-251,034.56
Reference [$]			8,823,189.88

Demand Category	Demand [kW]	Rate [$/kW]	Demand Charge [$]
Non-coincident	1,982.66	-	91,855.18
Period 1	405.67	-	1,362.73
Demand Subtotal [$]			93,217.91
Reference [$]			1,833,537.08

Energy Balance and Technology Investments

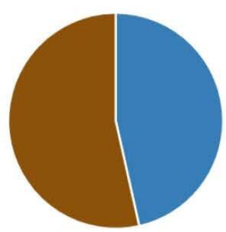
This section provides data on system energy demand and portfolio technologies. Included are details on total annual demand for each end-use modeled, share of demand met by utility purchases and on-site DER assets, total capacities of existing and new DER assets, and upfront investment costs.

Annual Electricity Balance (kWh)



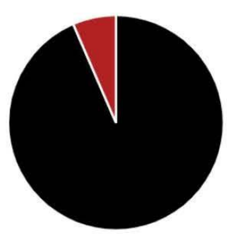
Total annual electricity purchase (kWh)	1,591,005
Total annual on-site generation from conventional DG (kWh)	83,099,641
Total annual on-site generation from renewables (kWh)	4,454,933

Utility Balance (kWh)



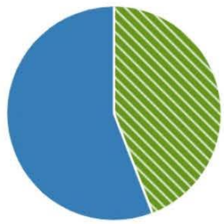
Total annual electricity purchase (kWh)	1,591,005
Total annual electricity exports (kWh)	1,831,970

Aggregated Demand (kWh)



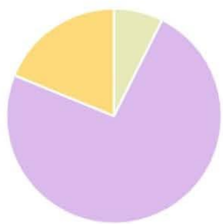
Electricity-Only Demand	86,348,582
Water Heating Demand	6,000,000

CO_2 Emissions (metric tons)



	Natural Gas (DG)	476
	Electricity	602

Generation Technologies (kWh)

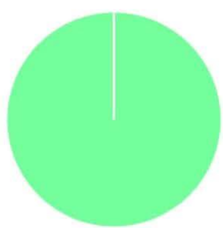


	New Gas Generator (1X MW) (kW) (x1)	1,000
	New Proxy-SMR (kW) (x10)	10,000
	New PV (kWdc)	2,548

Tech	Used / Available Space (ft²)	%
PV	274,277 / 274,277	100.00%

Tech	Capacity Factor
PV	19.96%

Storage Technologies

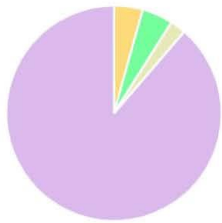


	New Electric Storage Capacity (kWh)	9,600

Tech	Annual / Allowed Cycles	%
Electric Storage	358 / N/A	N/A

Tech	Inverter Size (kW): Calc. / Specified	Ratio
Electric Storage	2,400 / 2,400	1.00

Investments

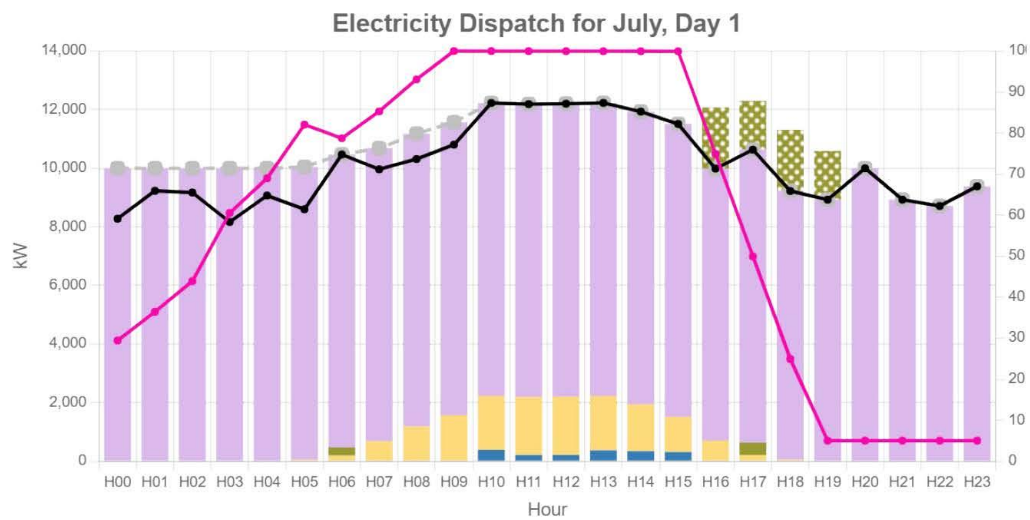


	New PV	$5,351,010
	New Electric Storage	$5,750,400
	New Gas Generator (1X MW)	$2,900,001
	New Proxy-SMR	$109,645,890

Electricity Dispatch

The following dispatch curves show the optimal system operation to meet all electricity loads on a selection of modeled days. Electricity dispatch shows both the electricity-only loads and any electricity used to operate cooling and/or refrigeration technologies. System operation includes on-site generation and storage dispatch, utility purchases, and load management strategies.

Electricity Dispatch for July, Day 1



Demand lines are stacked to show the cumulative impact.

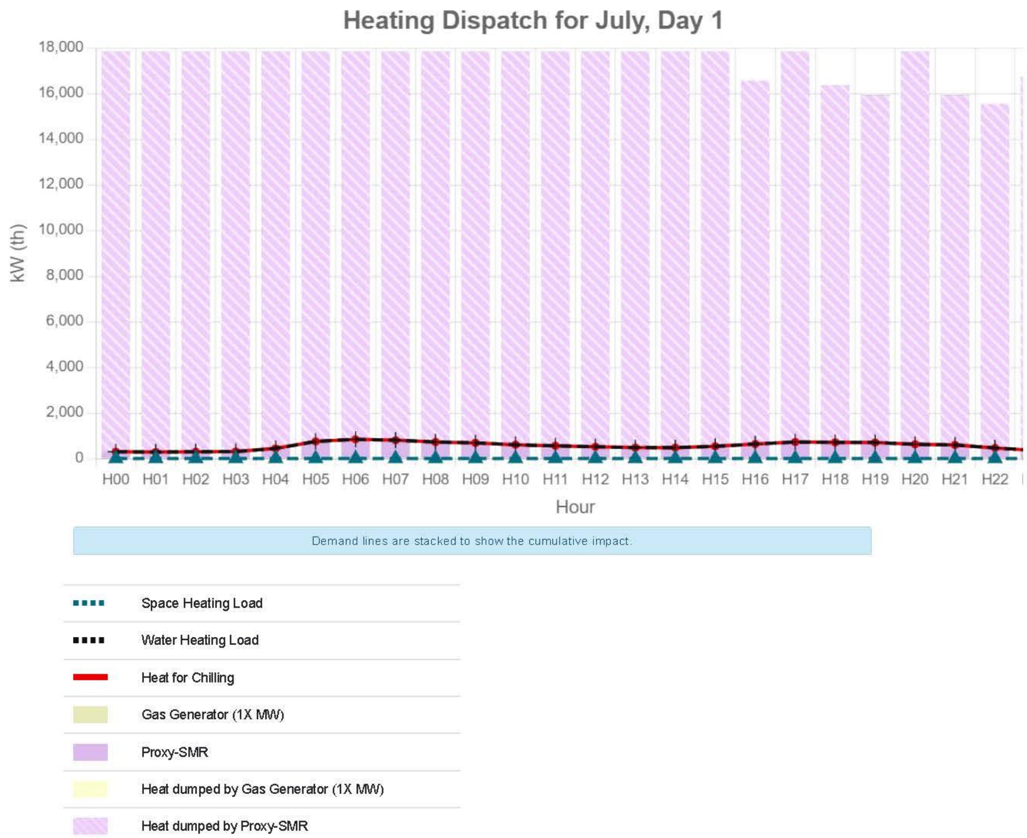
- Electricity-Only Load
- Electricity Supplied to Storage
- Utility Purchase
- PV for Self Consumption
- Electric Storage for Self Consumption
- Gas Generator (1X MW) for Self Consumption
- Proxy-SMR for Self Consumption
- Electric Storage for Export
- State of Charge of Electric Storage

* Axes NOT Scaled on Dispatch Graph By Data Across All Months / Day Types

Heating Dispatch

The following dispatch curves show the optimal system operation to meet all heating loads on a selection of modeled days. Heating loads include both space heating and water heating. System operation includes heating provided by central HVAC systems, on-site thermal generation and storage technologies, and heat generated by CHP generators (electricity provided by CHP units is shown in Electricity Dispatch).

Heating Dispatch for July, Day 1



* Axes NOT Scaled on Dispatch Graph By Data Across All Months / Day Types