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Igiugig Comprehensive Energy Plan Implementation Assistance

Becki Meadows, Kumaraguru Prabakar, and
Yaswanth Nag Valega

National Laboratory of the Rockies

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

Technical Report
NLR/TP-5700-92527
February 2026

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Acknowledgments

This report was funded by the U.S. Department of Energy’s Energy Technology Innovation Partnership Project (ETIPP). ETIPP is a community-led technical support program for coastal, remote, and island communities to access unique solutions and increase energy resilience. By uniting federal agencies, national laboratories, regional organizations, and community stakeholders, ETIPP provides tailored technical support to help communities achieve affordable reliable solutions to their energy system challenges. This collaborative model leverages the combined expertise and resources of its partners to deliver comprehensive, practical solutions that align with local needs.

List of Acronyms

BESS	battery energy storage system
CEP	Community Energy Plan
DOE	U.S. Department of Energy
EMT	electromagnetic transients
ETIPP	Energy Technology Innovation Partnership Project
HRS	heat recovery system
NLR	National Laboratory of the Rockies
PV	photovoltaics

Executive Summary

The U.S. Department of Energy’s Energy Technology Innovation Partnership Project (ETIPP) provides strategic energy planning for remote and island communities to address local energy and infrastructure challenges and enhance the long-term resilience of their energy systems. In 2023, the National Laboratory of the Rockies partnered with the Renewable Energy Alaska Project and Gray Stassel Engineering to provide technical assistance to Igiugig Village Council.

The overall objective of this ETIPP project was to provide technical support to the community to help them implement high-priority strategies detailed in their 2022 Community Energy Plan (CEP). Some of these strategies included identifying and planning for additional renewable energy solutions like renewable heating options and heat-recovery systems, supporting leaders in communicating progress and challenges, and developing a high-fidelity grid model to help diagnose issues and plan new projects. In addition to the technical assistance, the ETIPP team engaged in community outreach through two site visits and input to the community newsletter on the status of the CEP.

Given that Igiugig uses more diesel fuel for heating than for electricity generation, a high-priority project in their 2022 CEP was to evaluate the feasibility of installing additional renewable energy to meet both electricity and heating demands. A techno-economic assessment was completed to evaluate renewable heating scenarios, Igiugig’s existing (2024) electric and thermal energy infrastructure (Table ES-1), and a larger wind turbine and solar photovoltaics (PV) array.

Table ES-1. Summary of Igiugig’s Electric and Thermal Energy Infrastructure in 2024

Asset	Description
Diesel Generators	Three 65-kW John Deere 4045 diesel generators installed in 2013
Solar PV	1.2-kW residential solar PV
Wind Turbines – Horizontal Axis	Six 2.5-kW turbines by Skystream; only two are currently operational
Wind Turbines – Vertical Axis	Two 2-kW turbines by Wing Power Energy; neither are functional
RivGen Unit ^a	40-kW RivGen power system installed in 2019; lessons learned were applied to RivGen 2.1, installed in the summer of 2021
Battery Energy Storage System/Controller	253-kWh/125-kW system installed in the summer of 2021 with microgrid controller
Heat Recovery System	Buildings served: water treatment plant, post office, store, and offices
Space Heating	Most homes use heating oil for Toyo stoves or baseboard heat, and many homes have wood stoves for backup heat and to reduce diesel costs. Most businesses use diesel boilers.
Domestic Hot Water Heating	Diesel hot water heaters are used for residential and businesses

^a The RivGen hydrokinetic power system generates power from river currents in the Kvichak River.

In this project, the baseline scenario and four additional scenarios were modeled:

- High RivGen performance: two RivGen units operating at 85% availability
- Medium RivGen performance and solar: one RivGen unit operating at 85% availability
- Solar
- Solar and wind.

All of the considered renewable energy scenarios result in the reduction of diesel-generated electricity and heat; therefore, the power plant and heat recovery system (HRS) will need to be augmented to meet the resulting heat supply deficit. The community selected Scenarios 3 and 4 for developing HRS redesign options that could utilize the excess renewable energy generated in each case.

In Scenario 3, the addition of 200 kW of solar energy generation to the electric grid would result in approximately 60,000 kWh of unused solar electricity. Of this surplus, approximately 11,400 kWh could be used to power an electric boiler and unit heater in the power plant to augment the HRS during times of reduced thermal output from the diesel generators. However, when there is excess solar generation, there is often enough thermal output from the generators to meet the HRS load, which creates a surplus of excess solar generation that is available to serve other heating or future electrification loads. The remaining excess is estimated at 48,500 kWh. It is most abundant March through September (Figure ES-1) and can offset ~1,600 gallons of seasonal heating fuel oil.

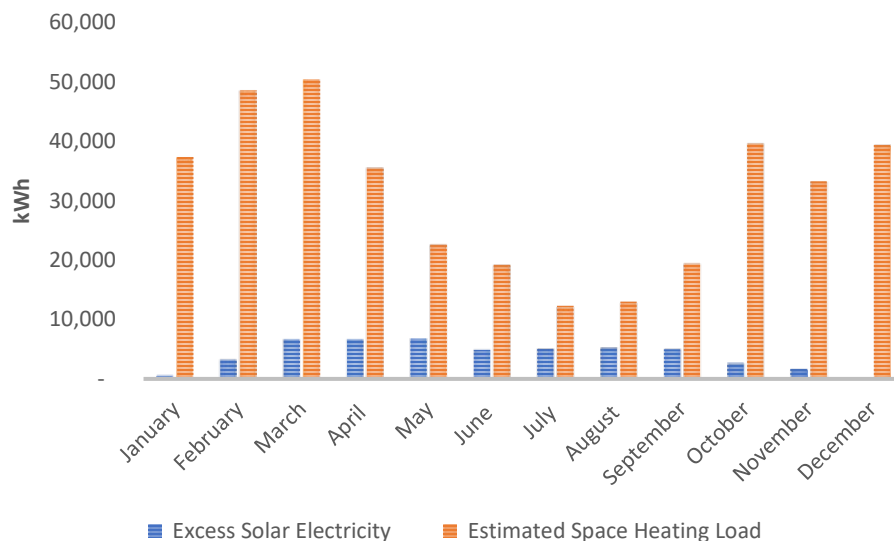


Figure ES-1. Excess electricity from solar and wind resources after serving heat recovery system and power plant heating loads

In Scenario 4, the addition of 200 kW of solar energy generation and 100 kW of wind energy generation to the electric grid would result in approximately 150,700 kWh of unused renewable electricity. Of this surplus, approximately 29,900 kWh could be used to power an electric boiler and unit heater in the power plant to augment the HRS during times of reduced thermal output from the diesel generators. The remaining excess renewable electricity of 120,800 kWh is most

abundant February through September (Figure ES-2) and can offset ~4,000 gallons of seasonal heating fuel oil.

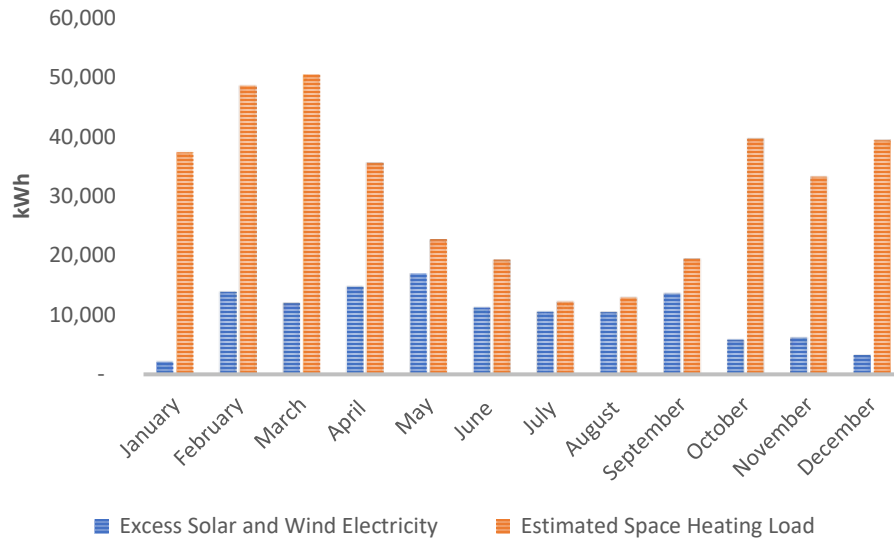


Figure ES-2. Excess electricity from solar and wind resources after serving heat recovery system and power plant heating loads

In both scenarios, the offline power plant and existing heat recovery end users would benefit from the installation of a renewable energy electric boiler in the power plant to keep the plant warm during times of reduced diesel operations. Neither of the renewable scenarios provides sufficient, consistently available excess renewable energy to be useful for residential space heating, but both scenarios could be used to assist in powering an electric boiler in the power plant and in the airport hangar.

In addition to the techno-economic assessment, a high-fidelity model of Igiugig’s power system was developed in the electromagnetic transients domain to assess power quality issues and the source of system losses. Field data collection and modeling efforts indicated there are no-load current losses in the large transformer located at the end of the power system. Actions taken to remove the no-load transformer can reduce total losses by 30%. The open-source models developed for the Igiugig power system will help the community with future investments, including the assessment of optimal locations, controller evaluation, and interoperability studies for future renewable energy investments.

Leveraging the techno-economic assessment completed through this ETIPP project, Igiugig received grant funding to install a 200-kW solar PV array. Once installed, and in conjunction with the existing battery energy storage system, the 200-kW solar array is expected to reduce the diesel fuel used for electricity generation by approximately 36% and reduce the levelized cost of electricity by \$0.15/kWh. The HRS design schematics developed through this project were also leveraged in this award and will fund the installation of an electric boiler to keep the power plant warm during diesel off periods.

Another result of this project is that Igiugig will receive follow-on hardware and continued technical assistance support to optimize renewable energy and storage in their microgrid through advanced microgrid controller development and field testing.

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1 Background

1.1 About the Community

Igiugig is a remote southwestern Alaskan community (Figure 1) of approximately 70 people primarily of Yup'ik Eskimos, Aleuts, and Athabascan Indian descent. They belong to the place where Lake Iliamna is swallowed by the Kvichak River. The Kvichak River is vital to the Igyararmiut (people of Igiugig) for drinking water and for salmon, which the community has relied on as a primary staple to their subsistence lifestyle for generations.

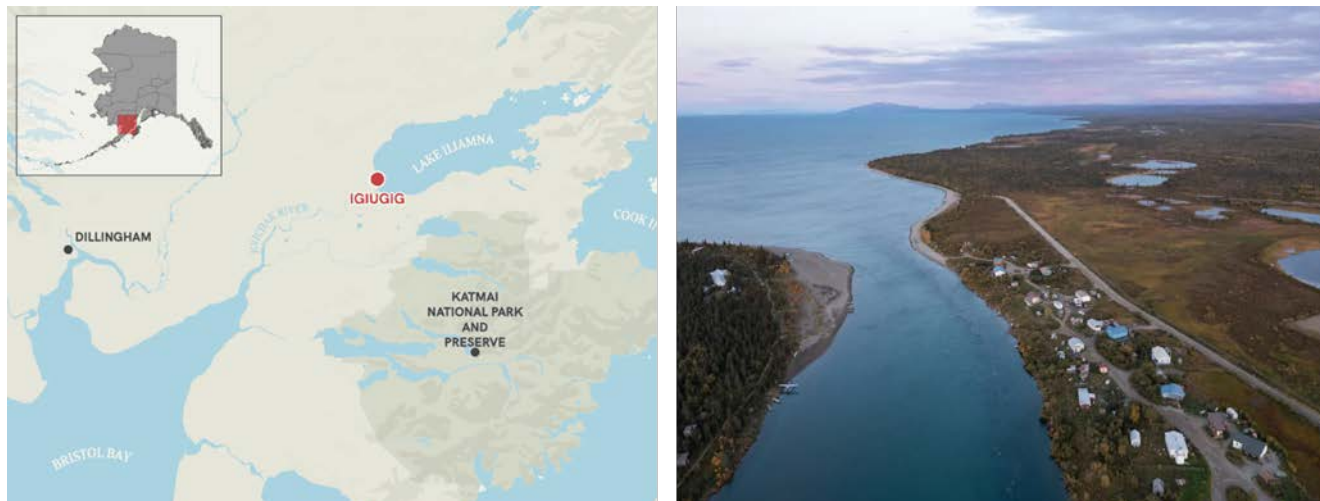


Figure 1. Igiugig Village is located in southwestern Alaska.

Photo from Igiugig Village Council

For more than 8,000 years, the Igyararmiut have lived sustainably on their land. They are a traditional community, gathering to talk about challenges and to put forth solutions rooted in Indigenous knowledge and value-based governance. Igiugig's traditional food preservation techniques required no electricity. However, some preservation methods now use machinery and require electricity, which is expensive and depends on diesel fuel—a resource the community has been trying to shift away from for the past 20 years (Salmon et al. 2022).

1.2 Igiugig's Energy Landscape

Remote villages like Igiugig, which are disconnected from the state's larger electric and road systems, must bring in oil by plane or barge. That extra transportation makes deliveries expensive and risky. An oil spill could cripple Igiugig's Kvichak River, their main source of drinking water and home to the largest salmon run in the United States.

Today, diesel fuel remains a basic necessity to maintain life in Igiugig. It is flown in 2,000 gallons at a time on old DC4 airplanes, which is expensive. The village is only accessible by air and primarily relies on diesel fuel for electricity, which is provided by the Igiugig Village Council. The annual electricity generation is approximately 350,000 kWh (Figure 2), which equates to roughly 25,000 gallons of diesel fuel used to meet electricity demands in the community (Alaska Energy Authority n.d.). Approximately 27,000 gallons of diesel fuel are used annually for space heating. In 2023, diesel fuel prices rose to \$9.61 per gallon for electricity and

\$10 per gallon for heating fuel (Figure 2). While the cost of electricity is subsidized for residential and community use through Alaska’s Power Cost Equalization program, the cost of heating can present a significant financial burden for residents.

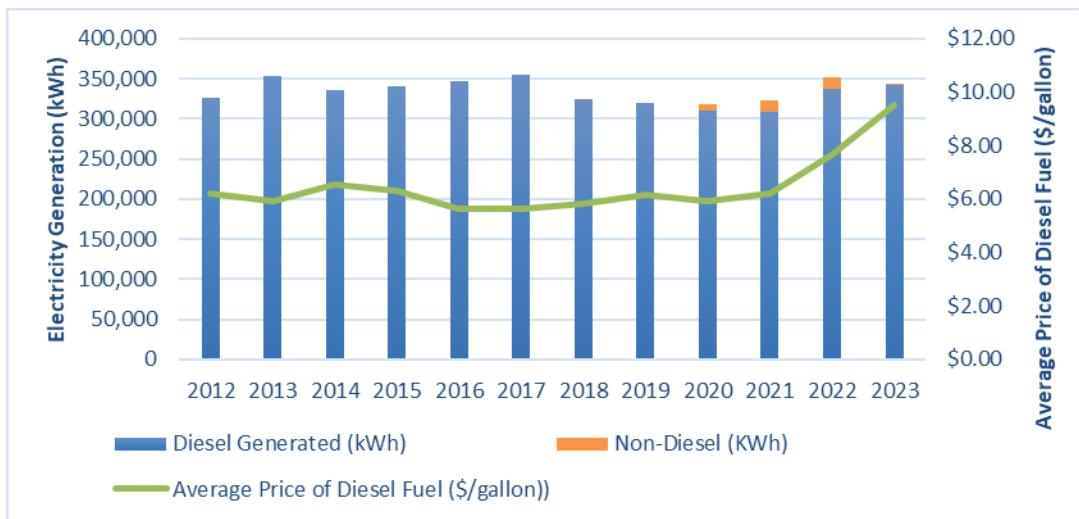


Figure 2. Igiugig’s electricity generation by year, source, and price.

Data compiled from reports listed at Alaska Energy Authority (n.d.)

The community are critically aware of their energy sources, needs, and regional and global impacts, having witnessed substantial changes to access of subsistence foods, which threaten their survival and traditional way of life. The Yupik value of Ellanguq—or awareness—has been the ultimate driver of Igiugig’s sustainability initiatives. Once there is awareness of an issue, they must do something about it if they are able.

1.3 Igiugig’s Energy Journey

Igiugig’s journey toward sustainability started in 2008 when the entire village completed its first comprehensive community vision and plan. The planning process was guided by Indigenous knowledge and gave everyone in the community a voice, resulting in input from all age groups, including pictures drawn by preschoolers that envisioned the future of the community. Alternative energy was identified as a top priority (Salmon et al. 2022).

In 2014, after completing renewable energy feasibility studies with the help of the Alaska Energy Authority and the National Laboratory of the Rockies (NLR), the community decided to move forward with permitting a test bed for hydrokinetic devices. Two devices were tested, and the community chose to enter into a sole partnership with Ocean Renewable Power Company to pursue a hydrokinetic project that could deliver baseload renewable energy without harming the salmon, the central component of Igiugig’s subsistence lifestyle.

In 2019, with funding from the U.S. Department of Energy’s (DOE’s) Water Power Technologies Office, Igiugig installed a hydrokinetic energy device in the river. The RivGen, built by Ocean Renewable Power Company, was estimated to generate enough energy to provide close to half the village’s electricity needs (Salmon et al. 2022). But they were concerned whether the device, which is fully submerged in the Kvichak River and uses underwater turbines

to harness river currents, might harm the fish that the villagers depend on. Over two seasons, no negative impacts were observed.

Since 2014, there have been two deployments of the RivGen device and power system, with lessons learned incorporated in each deployment. In 2022, a second RivGen (2.1) and battery energy storage system (BESS) (Figure 3) were installed, with an additional 200 kW of solar photovoltaics (PV) planned for the summer of 2025. The major existing components of Igiugig’s electric power plant and thermal infrastructure are summarized in Table 1.

Table 1. Summary of Igiugig’s Electric and Thermal Energy Infrastructure in 2024

Asset	Description
Diesel Generators	Three 65-kW John Deere 4045 diesel generators installed in 2013
Solar PV	1.2-kW residential solar PV
Wind Turbines – Horizontal Axis	Six 2.5-kW turbines by Skystream; only two are currently operational
Wind Turbines – Vertical Axis	Two 2-kW turbines by Wing Power Energy; neither are functional
RivGen Unit	40-kW RivGen power system installed in 2019; lessons learned were applied to RivGen 2.1, installed in the summer of 2021
Battery Energy Storage System/Controller	253-kWh/125-kW system installed in the summer of 2021 with microgrid controller
Heat Recovery System	Buildings served: water treatment plant, post office, store, and offices
Space Heating	Most homes use heating oil for Toyo stoves or baseboard heat, and many homes have wood stoves for backup heat and to reduce diesel costs. Most businesses use diesel boilers.
Domestic Hot Water Heating	Diesel hot water heaters are used for residential and businesses

In 2020, the Igiugig Village Climate Change Adaptation Assessment was completed through a series of eight community planning meetings. The main hazard identified was wildfire threat to subsistence resources, infrastructure, and community health. Other primary hazards included the shifting seasonal harvest calendar, water quality issues due to increased water temperatures, melting permafrost, and erosion, which impacts fuel deliveries (Igiugig Village Council 2020).



Figure 3. (left) Diesel power plant and (right) battery energy storage system in Igiugig.

Photos from Kumaraguru Prabakar, National Laboratory of the Rockies

1.4 2022 Comprehensive Energy Plan

DOE's Water Power Technologies Office funded NLR to support Igiugig in updating their Comprehensive Energy Plan (CEP). The CEP was developed through a series of community meetings followed by data collection and analysis throughout 2021. The plan was adopted by the community in January 2022. The energy planning team, which was led by Igiugig and included NLR and Deerstone Consulting, gathered baseline data and reviewed existing plans and studies to identify and evaluate strategies (Salmon et al. 2022).

As part of the planning process, a baseline assessment of energy usage and an inventory of past planning efforts were conducted. Due to anomalies in diesel fuel usage during the COVID-19 pandemic, the baseline assessment year was chosen as 2019. In 2019, approximately 318 MWh of electricity was generated, including 272 MWh of consumption over 51 premises. Peak electricity demand ranged from 66 kW to 97 kW. Slightly more diesel fuel was used for heating than for electricity use. Figure 4 summarizes electricity and heating fuel use by premise type in 2019.

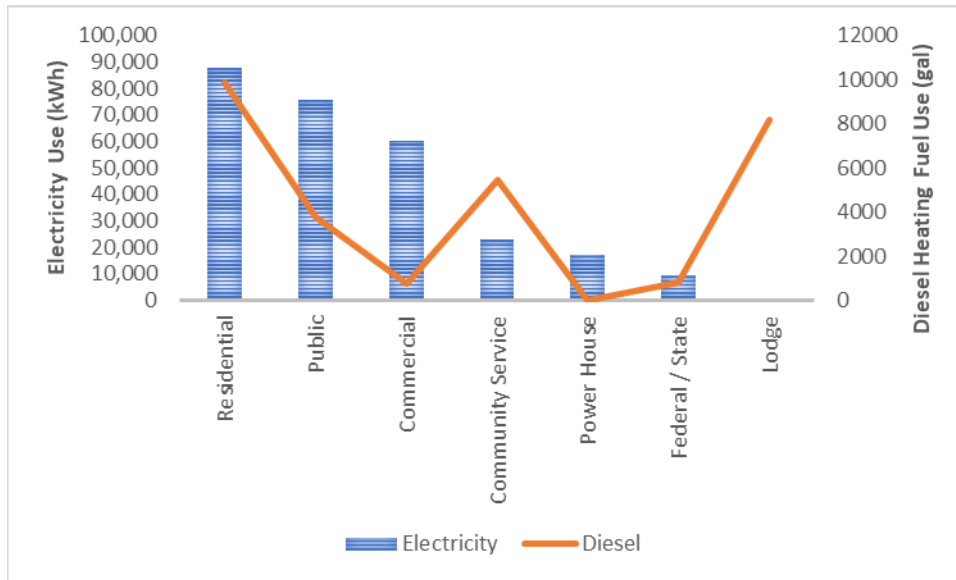


Figure 4. 2019 electricity and diesel use by premise type

Key findings by focus area from the baseline assessment are summarized in Figure 5.






Focus Area	Key Findings
 1. Energy Infrastructure	<ul style="list-style-type: none"> • More diesel fuel is used for space heating than electricity • Power system line losses are high and present a savings opportunity • Ongoing power quality issues with frequency dips
 2. Energy Efficiency and Conservation	<ul style="list-style-type: none"> • Energy efficiency on residential housing stock is good • Opportunities for efficiency are in the commercial/community loads and improving the efficiency of space heating • There is a disincentive for IVC to work with largest consumers who are customers to save diesel fuel usage due to revenue loss
 3. Renewable Energy	<ul style="list-style-type: none"> • Ownership scenarios and future maintenance costs for the RivGen units are not clear • Additional PV and Wind could be cost effective, depending on the performance of the RivGen • While Igiugig has a good wind resource, it is difficult to find a reliable wind turbine option in the 25-100kW range with adequate maintenance support for their remote location.
 4. Capacity Development	<ul style="list-style-type: none"> • As the technology and microgrid have become more complicated, there has been a loss of independence and predictable budgeting. • Training on renewable energy O&M is key to future renewable energy deployment success
 5. Climate Adaptation	<ul style="list-style-type: none"> • Initial assessment was developed in 2020 with University of Alaska Fairbanks through a series of 8 community planning meetings • Main hazard identified was "wildfire threat to subsistence resources, community and health"

Figure 5. Key findings from the 2019 baseline assessment by focus area.

Source: Salmon et al. (2022)

As part of developing the CEP, the community established a goal to achieve 50% diesel fuel reduction by 2030 from the 2019 electricity usage baseline (50% of ~25,000 gallons). While the ownership structures and performance of the RivGen devices and the BESS are under evaluation, the community is focusing on additional initiatives. One priority is the energy efficiency of community buildings. A second priority involves solving power quality and line loss issues before they consider adding more renewables to the system and incorporate renewable heating

strategies. Figure 6 summarizes high- and medium-priority strategies from the CEP by focus area.






Focus Area	Immediate: 2021-2023	Midterm: 2024-2025
 1. Energy Infrastructure	<ul style="list-style-type: none"> Implement upgrades to power plant and resolve line loss issues Optimize heat recovery system Explore RivGen ownership opportunities 	<ul style="list-style-type: none"> Implement strategic renewable heating
 2. Energy Efficiency and Conservation	<ul style="list-style-type: none"> Complete high-priority energy conservation measures Complete high-priority energy efficiency measures 	<ul style="list-style-type: none"> Complete medium-priority energy conservation measures Complete medium-priority energy efficiency measures
 3. Renewable Energy	<ul style="list-style-type: none"> Evaluate the need for additional renewables and right-sizing diesel Evaluate renewable heating options 	<ul style="list-style-type: none"> Install additional renewables and right-sized diesel as needed
 4. Capacity Development	<ul style="list-style-type: none"> Explore Bristol Bay regional partnerships 	
 5. Climate Adaptation	<ul style="list-style-type: none"> Complete climate adaptation Plan 	<ul style="list-style-type: none"> Implement climate adaptation plan and fire mitigation work

Figure 6. Igiugig’s Comprehensive Energy Plan strategies by technical priority.

Source: Salmon et al. (2022)

1.5 2023 Community Energy Plan Implementation and Engagement Support Through ETIPP

The overall objective of this Energy Technology Innovation Partnership Project (ETIPP) project was to provide technical support to the community to help them implement high-priority CEP strategies (summarized in Figure 6), including identifying and planning for additional renewable energy solutions like renewable heating options and heat-recovery systems (HRS), supporting leaders in communicating progress and challenges, and developing a high-fidelity grid model to help diagnose issues and plan new projects.

This support was accomplished through the following four technical tasks, which are described in detail in the sections that follow.

1. Evaluate renewables and renewable heating scenario
2. Identify HRS design options for high-penetration renewables
3. Investigate power quality and line loss issues
4. Evaluate battery storage and solar integration support.

In addition to the technical assistance, the ETIPP team engaged in community outreach through two site visits and input to the community newsletter on the status of the CEP. The first site visit occurred Oct. 24–26, 2023. The goals were to obtain data to help with modeling the power system and determining sources of power quality issues and line losses and to conduct community outreach. The NLR team presented at a community meeting with the Igiugig Village Council to communicate the status of the CEP and current energy projects.

During that visit, a high-level energy efficiency assessment was completed for the clinic, one of the top energy use intensity premises in the community. The assessment revealed that heat tape used on an old collapsed well was still live. Heat tape keeps pipes from freezing in the winter but is often left on in summer months and adds unnecessary additional load to the village's electric demand. In this case, the well had collapsed 7 years prior, but the heat tape remained live, resulting in a constant daily electricity load for the clinic for those 7 years. After identifying this, electricity supply to the heat tape was turned off.

The project team made a second site visit June 11–14, 2024, to engage with the field deployment team on microgrid operation with the BESS acting as the grid-forming asset. During this visit, the project team confirmed that the BESS was charged with the diesel generator operation and was able to form the grid without the diesel generator.

2 Review of Technical Tasks

2.1 Task 1: Evaluate Renewable Heating Scenarios

The primary objective of this task was to evaluate the economic feasibility of installing additional renewable energy to meet both electricity and heating demand in both commercial and residential buildings.

2.1.1 Methodology

A techno-economic assessment was completed based on guidance from the Igiugig Village Council and data gathered throughout the ETIPP project. UL Solutions' HOMER model for evaluation of hybrid systems was used. Table 2 includes a summary of key modeling inputs and assumptions. Incentives in the 2022 Inflation Reduction Act are available to the community for direct pay of funds in an amount equal to the investment tax credit (ITC) for community-purchased renewable energy and storage projects. These incentives are significant and are included in the analysis.

Table 2. Key Techno-Economic Modeling Assumptions Across All Scenarios

Input	Assumption
Discount rate	5.5
Nominal inflation rate	2.5
Analysis period	20 years
Electric load	2022–2023 hourly SCADA ^a data increased by 10% to account for future load growth
Cost of diesel fuel	\$9.61 per gallon for electricity; \$10 per gallon for heating fuel
Diesel costs (capital; replacement; O&M ^a ; minimum load ratio, heat recovery ratio)	\$0; \$2,400/kW; \$0.03/operating-hour/kW; 25%; 45%.
Heat recovery system demand	2011–2017 measured data; 91,140 kWh for HRS load
RivGen costs	Power purchase agreement rate modeled at \$0.47/kWh; the marginal generation rate of the diesels for 20 years (fuel cost divided by the kilowatt-hours generated, including diesel efficiency)
RivGen performance	Estimates for RivGen production used monthly average water velocities and developer-provided power curve. Assumed non-operational one month in the winter due to icing and one month in the summer for maintenance (83% availability).
Solar costs (capital; replacement; O&M)	\$3,500/kW (includes 30% reduction in capital expenditures from ITC); \$5,000/kW; 32/kW/year
Solar resource data	National Solar Radiation Database
Solar derating factor	82%
Solar lifetime	25 years
100 kW wind (capital; replacement; O&M)	\$591,000 (includes 30% reduction in capital expenditures from ITC); \$5,000/kW; \$10,000 annually

Input	Assumption
Wind resource data	NLR wind study at Igiugig, typical meteorological year hourly wind profile
Wind turbine availability	85%
Lithium-ion costs (replacement; O&M; life expectancy, state-of-charge range)	\$350,000; \$2,500 annually; 15 years; 30%–90%
Controller strategy	Load-following; battery charging comes only from renewables
Incentives/other	30% federal ITC ^b

^a SCADA = supervisory control and data acquisition; O&M = operations and maintenance

^b Alaska Native Corporations and rural electric co-ops to receive ITC-equivalent payments from the U.S. Department of the Treasury for qualified renewable energy and BESS projects.

In addition to the assumptions above, diesel fuel logs were compiled from 2019 to summarize heating fuel usage by premise type. In 2019, the community used a total of 27,688 gallons across all premises for space heating, water heating and electricity to seasonal lodges. (Table 3).

Table 3. 2019 Heating Fuel Usage by Premise Type

Premise Type	Heating Fuel Usage (Gallons)	Buildings Served
Residential	9,496	22 homes
Public	3,615	Hangar, clinic, pump house, rec hall, post office
Commercial	896	Man camp, boarding house, pump house dryer, church
School	5,482	school
Lodge	8,179	4 seasonal lodges
Total	27,688	

To estimate the space heating load, seasonal lodge usage was removed because diesel fuel is used for electricity generation, and the team estimated that ~75% of the remainder would roughly account for the space heating demand of 15,000 gallons annually. The HEQAT Heat Load Model along with ambient temperatures from the nearest Automated Surface Observing System weather station were used to convert from gallons of heating fuel oil to kilowatts to create an hourly space heating load profile for the community. Assumptions included a thermostat setting of 68°F; the wall, ceiling, and window insulation R-values average out across the community; a boiler efficiency of 80%; and 38.675 kWh per gallon of heating fuel.

Figure 7 shows the estimated space heating load for Igiugig by month.

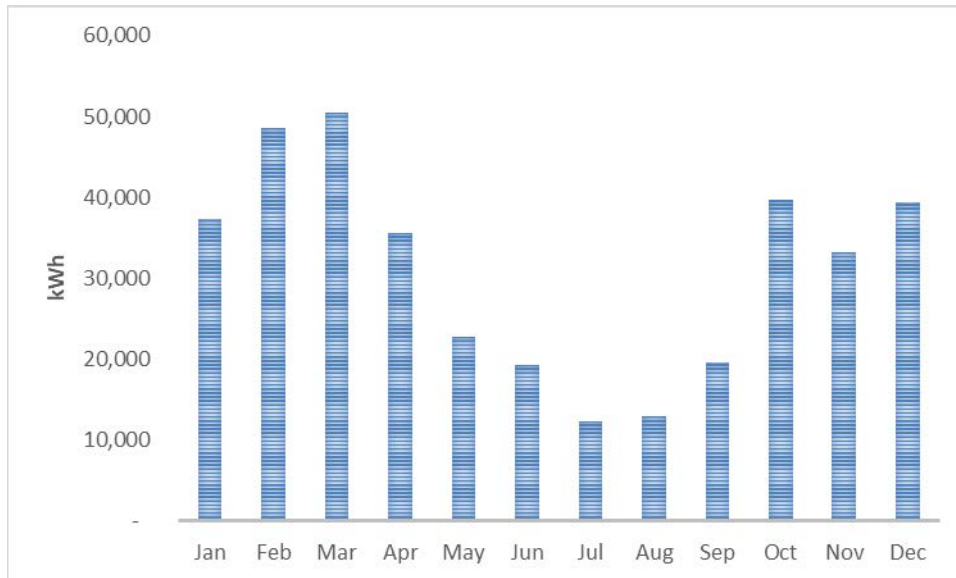


Figure 7. Estimate of Igiugig's space heating load by month (kWh)

2.1.2 Key Findings

In addition to the existing RivGen and BESS, this task evaluated additional renewable heating scenarios, including the use of a larger wind turbine and solar PV. In addition to the baseline, four scenarios were modeled:

1. High RivGen performance: two RivGen units operating at 85% availability
2. Medium RivGen performance and solar: one RivGen unit operating at 85% availability
3. Solar
4. Solar and wind.

Table 4 summarizes the results of techno-economic modeling for each renewable energy scenario. Key findings include:

- A reduction of approximately 12,500 gallons of diesel was achieved in all scenarios except the scenario with solar only, which achieved an approximate 36% reduction. Thus, in all scenarios (See Table 4) except the solar-only scenario, Igiugig's goal of reducing diesel fuel for electricity by 50% can be achieved.
- At the assumed power purchase agreement price of \$0.47/kWh, the lowest-cost systems for offsetting diesel used for electricity do not include RivGen.
- Using excess generation from renewable energy for heating can be economical if the price for the excess electricity was below \$0.26/kWh (assuming a heating oil price of \$10/gal in 2024 and 38.675 kWh (thermal)/gal).
- Scenarios in which electricity is generated with only renewable energy (i.e., operation without diesel) must consider augmenting the power plant and the HRS, which are dependent on diesel operation for heat. The community selected Scenarios 3 and 4 for the follow-on task of identifying HRS design options for high-penetration renewables.

Table 4. Summary of Results of Techno-Economic Renewable Energy Scenario Analysis

Category	Parameter	Baseline Scenario	Scenario 1 High RivGen Perf.	Scenario 2 Med. RivGen Perf. and Solar	Scenario 3 Solar	Scenario 4 Solar and Wind
Load	Electric load (kWh/year)	369,453	369,453	369,453	369,453	369,453
	HRS load (kWh/year)	91,140	91,140	91,140	91,140	91,140
Components	# Diesel generators/total power per unit (kW)	2 units/65	2 units/65	2 units/65	2 units/65	2 units/65
	# RivGen 2.1 units/total power per unit (kW)	-	2 units/40	1 unit/40	-	-
	Battery storage (kWh)	-	253	253	253	253
	Solar PV power (kW)	-	-	125	200	200
	Wind turbine power (kW)	-	-	-	-	100
System Performance	Levelized cost of energy (\$/kWh)	0.86	0.76	0.64	0.71	0.60
	Net Present Cost (\$M)	5.20	4.67	4.00	4.37	3.75
	Total operating costs ^a		305,100	231,300	234,300	160,400
	CO ₂ emissions (kg/yr)	283,500	121,600	114,700	181,800	104,100
	Total fuel consumption (gal)	28,600	12,300	11,600	18,400	10,500
	Total diesel fuel reduction (%)	-	57%	59%	36%	63%
Generator	Gen 1 production (kWh/year)	366,500	136,300	125,200	219,000	108,000
	Gen 2 production (kWh/year)	3,000	100	700	2,800	600
	HRS thermal load deficit (kWh)	-	42,000	42,200	30,400	55,400
Renewables	RivGen production (kWh/year)	-	304,400	152,200	-	-
	PV production (kWh/year)	-	-	132,500	212,000	212,000
	Wind production (kWh/year)	-	-	-	-	204,600
	Excess renewable electricity (kWh/year)	-	70,100	37,300	59,900	150,700

^a Includes O&M, administration, fuel, and power purchase agreement costs

2.2 Task 2: Identify Heat Recover System Design Options for High-Penetration Renewables

2.2.1 Methodology

The objective of this work was to develop HRS design options that align with diesel reduction goals and the additional renewable energy options selected by the community as a result of the techno-economic analysis (Scenarios 3 and 4). The following activities were undertaken in this task:

1. Review prior designs, reports, historical power plant generation records, and the condition of existing generation equipment.
2. Perform an on-site assessment to evaluate the diesel generation equipment and status of the existing HRS.
3. Model available recovered heat from the existing HRS to determine baseline conditions along with preliminary recommendations for improvements and options for using excess renewable energy to meet heating demands.

2.2.2 Key Findings

Heat Recovery System Description

The power plant heat recovery equipment includes piping, a plate heat exchanger, a BTU meter, a circulating pump (which circulates hot engine coolant through the heat exchanger), and an expansion tank. Recovered heat is provided to the water plant, located about 150 feet east of the power plant, and the adjacent building that houses the Iliamna Lake Contractors office, post office, and Igiugig Village Council store, referred to here as the ILC/PO/store. The location of the power plant, water plant/washeteria, ILC/PO/store, and approximate arctic piping routes are shown in Figure 8.



Figure 8. Igiugig heat recovery system diagram.

Photo from Gray Stassel Engineering

A site visit was conducted to assess the current status of the HRS. The assessment revealed leaks in the arctic piping and that the water plant heating and HRS design is atypical and inefficient. Typically, a building heating system is designed as the primary heat source, and an HRS is designed to reduce the building heating system fuel consumption. Proposed renovations to the HRS will correct the HRS design from a primary heat source to a secondary heating source designed to reduce the fuel consumption of the water plant heating system. Recommendations include:

- Correct operation of Water Plant Magna3 heat recovery pump (increase gpm)
- Pressure test and repair arctic piping leak(s)
- Revise the water plant heat recovery piping to improve system functionality
 - Add unit heaters in the water plant and washeteria
 - Extend heat recovery to teen center.

2.2.3 Renewable Energy Heat Recovery Integration

A heat recovery analysis was run to estimate the currently available recovered heat from the existing power plant, based on current generation equipment (diesels only). The results show as much as 6,300 gallons of recoverable heat is rejected to the power plant radiators, which is 2 to 3 times the expected heat load of the water plant/washeteria and ILC/PO/store.

Scenarios 3 and 4 from the renewable energy techno-economic analysis (Table 4) were chosen by the community to evaluate redesign options for the HRS and for using renewable energy for space heating.

In Scenario 3, the addition of 200 kW of solar energy generation to the electric grid would result in approximately 59,984 kWh of unused solar electricity. Of this surplus, approximately 11,420 kWh could be used to power an electric boiler and unit heater in the power plant to augment the HRS during times of reduced thermal output from the diesel generators. However, when there is excess solar generation, there is often enough thermal output from the generators to meet the HRS load, which creates a surplus of excess solar generation that is available to serve other heating or future electrification loads. The remaining excess is estimated at 48,500 kWh. It is most abundant March through September (Figure 9) and can offset ~1,600 gallons of seasonal heating fuel oil.

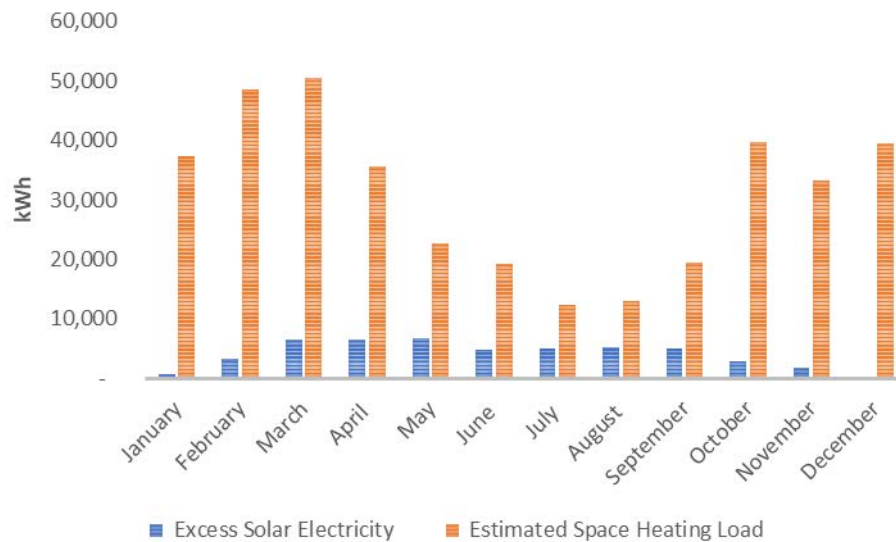


Figure 9. Excess solar electricity after serving HRS and power plant heating loads

In Scenario 4, the addition of 200 kW of solar generation and 100 kW of wind generation to the electric grid would result in approximately 150,700 kWh of unused renewable electricity. Of this surplus, approximately 29,900 kWh could be used to power an electric boiler and unit heater in the power plant to augment the HRS during times of reduced thermal output from the diesel generators. The remaining excess renewable electricity of 120,800 kWh is most abundant February through September (Figure 9) and can offset ~4,000 gallons of seasonal heating fuel oil.

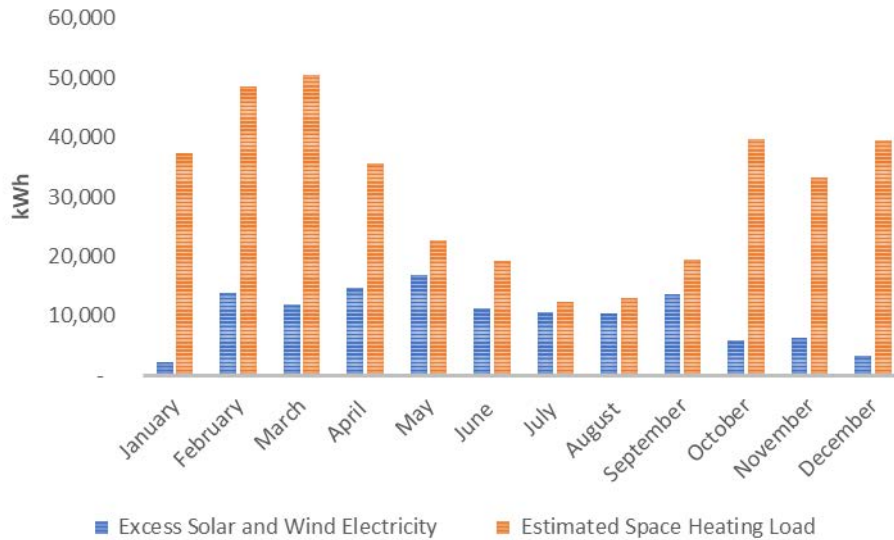


Figure 10. Excess solar and wind electricity after serving HRS and power plant heating loads

In either scenario, both the offline power plant and existing heat recovery end users will benefit by installing a renewable energy electric boiler in the power plant, which would eliminate the need for an electric boiler in the water plant. The use of excess PV electricity to heat domestic hot water is not advised, as domestic hot water loads are sporadic, of short duration, and very high demand and not well suited to being served by interruptible renewable energy. Neither of the renewable scenarios provide sufficient, consistently available excess renewable energy to be useful for residential space heating. Should sufficient excess renewable energy be available, installing an electric boiler in the airport hangar for space heat is recommended. Another option is to use excess renewable energy to help meet seasonal lodging electricity demands if future power distribution extensions are planned.

2.3 Task 3: Investigate Power Quality and Line Loss Issues

The Igiugig power system has one power plant. The power plant has a control room, generation room, and parts room. The generation room houses three diesel generators with auto-start/stop controls, paralleling switchgear, autofill day tank, fire suppression system, and external radiators with variable frequency drives. Power is generated at 480 V, three-phase. A 200-kVA three-phase pad mount transformer steps up the voltage to 12.47/7.2-kV distribution voltage. Three single-phase 15-kVAR shunt reactors located adjacent to the step-up transformer provide power factor correction for the long, lightly loaded underground distribution system. The power system contains distribution transformers near the loads to step down the voltage from 12.47/7.2 kV to 208 V or 120 V.

The smart meters installed at generation assets and loads at the Igiugig power system indicate losses of approximately 15%. This number has been increasing due to load growth and possibly due to other power quality challenges. This section presents information on the modeling, simulation efforts, field data collection, and results from the field and software analyses to understand power quality and line loss issues in the Igiugig power system.

2.3.1 Methodology

In a standard distribution system, line losses on conductors and transformer core and leakage losses can contribute to system losses. In some cases, load imbalances and lack of reactive power coordination can cause additional losses.

Core loss (no-load loss) and copper loss (load loss) contribute to power losses in distribution system transformers. The no-load loss is primarily due to core loss, and a negligible dielectric loss. The full-load loss is the I^2R loss in the windings of the transformer and the eddy-current loss due to circulating eddy currents in the transformer core. These losses are dependent on model type and can be obtained from manufacturer nameplate. In the Igiugig power system, all the distribution transformers are primarily one model type.

In literature, some studies (e.g., Usman et al. 2018) have discussed the use of distributed generation to support losses. The general consensus is that a distributed generation like PV will improve voltage profile, reduce losses, and support some of the power lost in the system. In the system under study, the generation assets are located at one bus, which includes the diesel generator and BESS (currently in the process of commissioning).

Modeling Igiugig Power System in Electromagnetic Transients Domain

In our work, we modeled the system in the electromagnetic transients (EMT) domain to create a baseline for loss characterization. EMT platforms are used to model inverter-based resources, which have high deployment, and study their impact on distribution systems. EMT simulation tools can be classified into offline and real-time tools. Offline simulation tools are used to conduct simulations on a computer, whereas digital real-time simulation tools are capable of running simulations in real time and can be interfaced with physical devices to generate results synchronous with the current time. In this work, offline EMT models were created. In the future, this offline EMT model can be converted to run in real time to evaluate controllers and power system equipment prior to field deployment. In this project, we used PSCAD to model the system in the EMT domain and run offline EMT simulations. The results from these simulations will allow power system operators to strategically invest in distributed energy resources to compensate for losses in the system.

The model consists of three generator assets and represents one grid at rated voltage, shown in Figure 11. Table 5 shows the cable data for 12-kV and 480-, 208-, 120-V cables. These parameters are used to model lines in the network using the PI model. Impedance parameters are converted from ohms per kilometer to ohms per meter. High-voltage cables (12 kV) connecting the switchgears and step-down transformers are assumed to be 1 km in length, except for the cable connecting SC2 and SC3, which was assumed to be 1.5 km in length. Low-voltage cables from step-down transformers to loads are assumed to be 0.1 km in length. In addition, data collection equipment was used at the site to collect current and voltage measurements at different buses.

The network under study has several transformers for stepping up and down from generation to the load. Three-phase, two-winding and single-phase, single-winding transformers are modeled per the rating in the one-line diagram (as shown in Figure 11). Reactance and losses (eddy current, copper) are assumed to be 0.035 per unit (p.u.), 0.05 p.u., and 0.1 p.u.

Loads are represented using the constant impedance model. Active and reactive power ratings of each load are assumed values. Detailed values are presented to support repeatability and reproducibility of the simulation.

Table 5. Underground Cable Data

Specification	12 kV	480 208 120 V
Conductor size	2 AWG	2 AWG
Conductor resistance	0.8715 Ω /km	0.5518 Ω /km
Capacitance	0.157 μ /km	0.12 μ /km
Positive sequence impedance	1.19 Ω /km	0.56 Ω /km
Zero sequence impedance	2.5 Ω /km	1.176 Ω /km

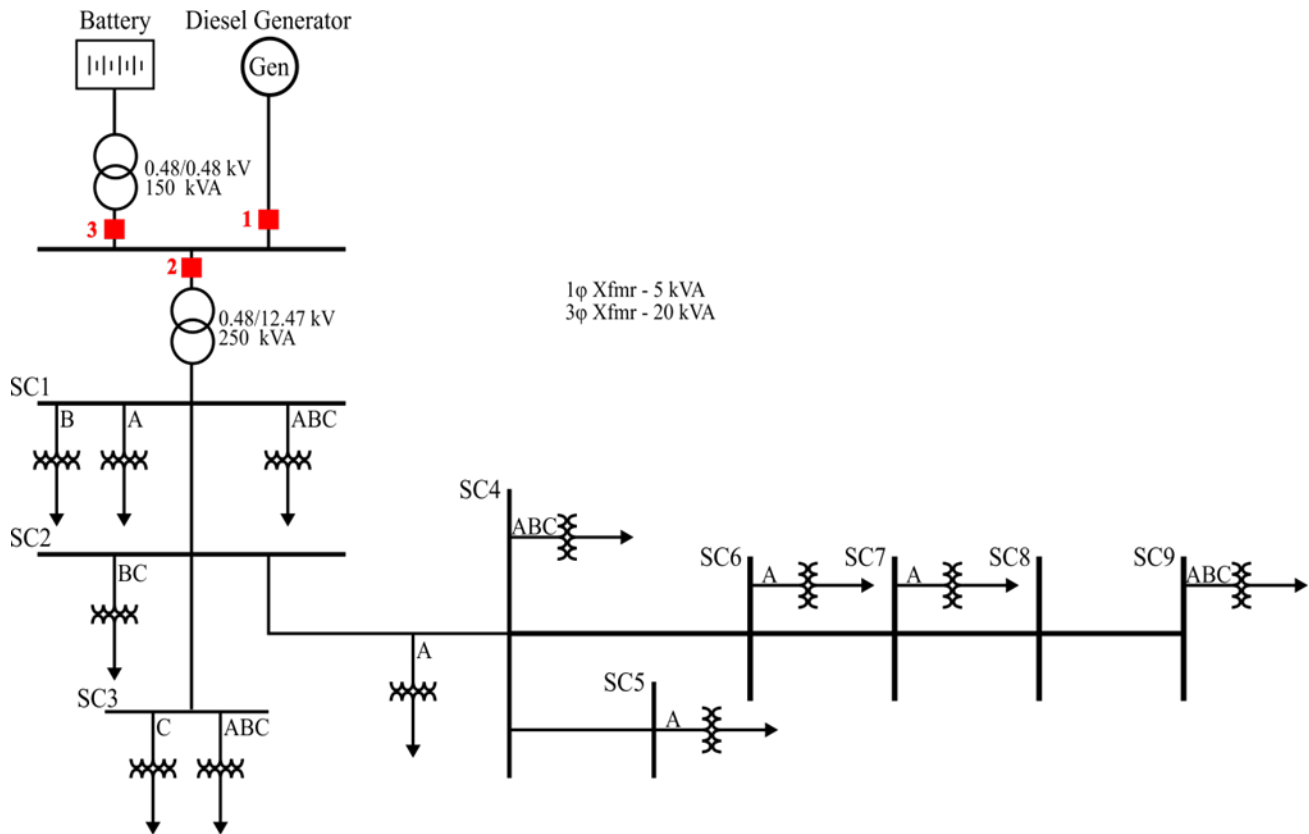


Figure 11. One-line diagram of Igiugig power system

Network Model

The network topology for the Igiugig system is primarily radial. The diesel generators and the BESS are at the top of the feeder system. The river generator is located approximately at the middle of the feeder. The additional planned solar PV system will be at the end of the system (SC9). The distribution system is primarily underground cable and is a good test distribution feeder for the systems in the contiguous United States that are being converted from overhead

lines to underground cables to reduce wildfire-related risks. For the purposes of the loss calculation, we only dispatch the diesel generators. The BESS and the river generators are not dispatched.

Energy Resources

Currently, there are three diesel generators, two river generators, and one BESS included in the model. The ratings and capabilities of the generation systems in the field are presented in Table 6. The diesel generators are the primary source of generation. In the EMT model, one aggregated generator model of 90 kW is modeled because diesel generators are not expected to supply more than 90 kW during peak load conditions.

Table 6. Existing Resources in the Igiugig System

Type	Rating	Grid-Forming or Grid-Following
Diesel generators (three in number)	65 kW	Grid-forming and grid parallel
Battery energy storage system	125 kW/250 kWh	Grid-forming and grid-following
River generator (two in number)	40 kW	Grid-following

Cable Model

The underground cable model is developed based on the assumed data in Table 5. All the cables between switchgears and from switchgear to transformer are modeled using PI lines. All the impedance parameters in the PI model are modeled based on Table 5.

Load Models

Most of the loads in the Igiugig system are building loads. There are a few machine loads that are utilized for the water distribution system. These are considered small motor loads compared to the asset sizing, so they do not create major transient challenges during startup. Most of the loads are refrigeration, space heating, and lighting. Figure 12 shows the hourly load for one year, from May to April. Figure 13 and Figure 14 show the weekly load obtained from the yearly load during high and medium peaks. These figures show that peak load is greater at night compared to daytime. During the summer months, the average load of the network is around 30 kW. The load gradually increases to a peak of 60 kW during winter, except for a few peaks of 100 kW. These peaks are caused during BESS testing, which demanded current to charge. Since the power values of the loads are not available, load numbers are assumed based on the transformer ratings.

Table 7 shows the load distribution at each transformer. The total assumed three-phase load is 61 kW and 6.1 kVAR. Load models in the EMT domain are represented as constant impedance loads.

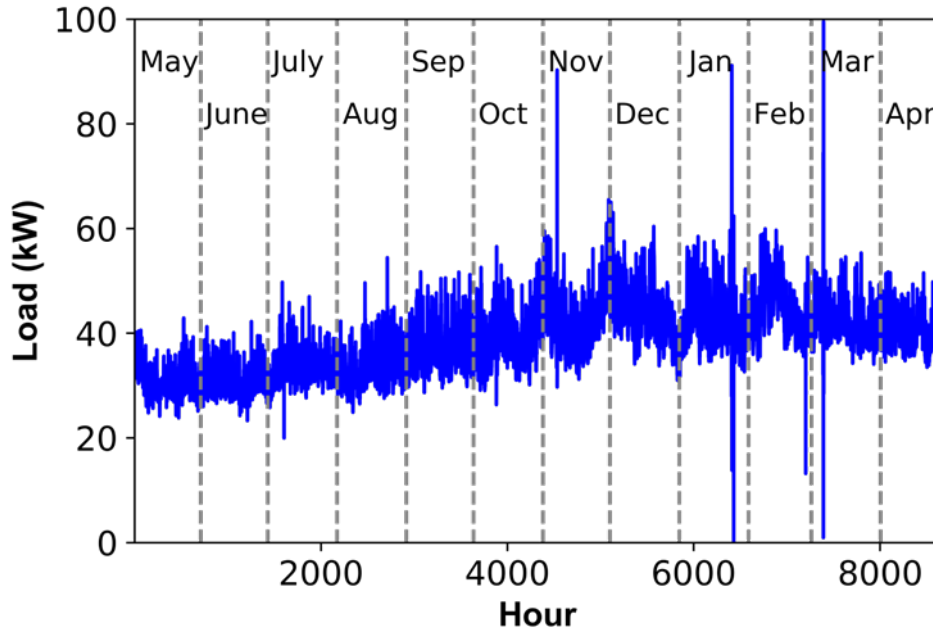


Figure 12. Total Igiugig hourly load for one year

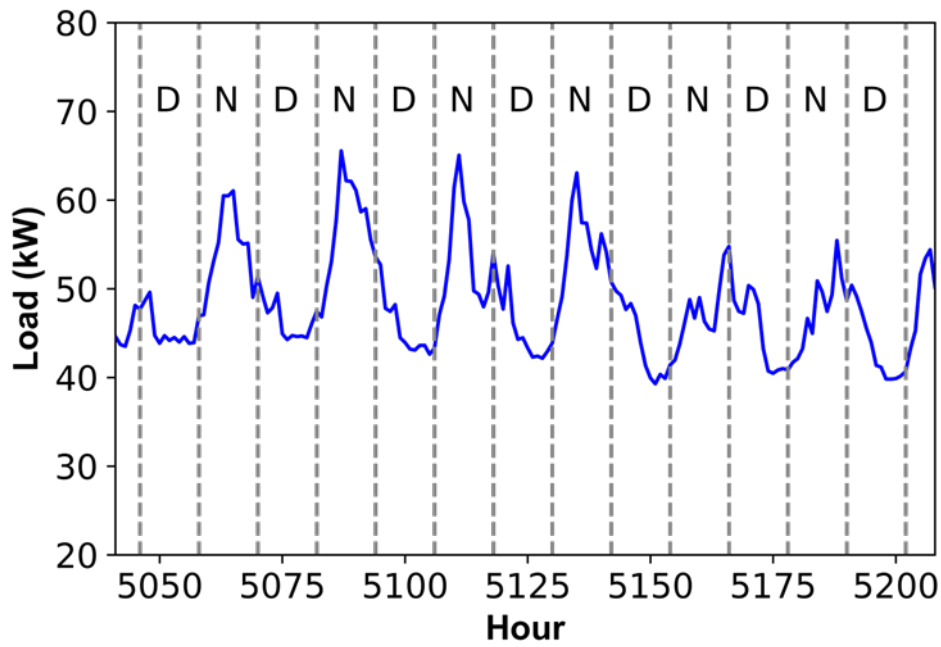


Figure 13. Hourly load during a week with high nighttime peaks (D = day, N = night)

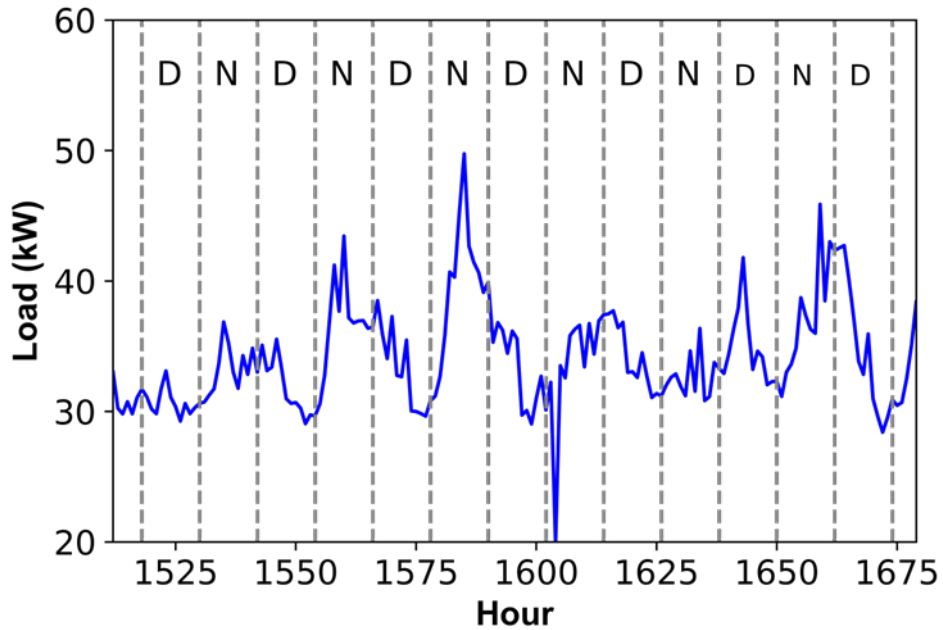


Figure 14. Hourly load during a week with medium peak occurring at night (D = day, N = night)

Table 7. System Load Distribution at the Different Switchgears

Switchgear	Load Real Power (kW)			Load Reactive Power (kVAR)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
SC1	0.5	0.5	0.5	0.05	0.05	0.05
	5	0	0	0.5	0	0
	0	5	0	0	0.5	0
SC2	0	0.5	0.5	0	0.05	0.05
	0.5	0	0	0.05	0	0
SC3	5	5	5	0.5	0.5	0.5
	0	0	1.5	0	0	0.15
SC4	5	5	5	0.5	0.5	0.5
SC5	0.5	0	0	0.05	0	0
SC6	0.5	0	0	0.05	0	0
SC7	0	0.5	0	0	0.05	0
SC9	5	5	5	0.5	0.5	0.5
Total load	22	21.5	17.5	2.2	2.15	1.75

2.3.2 Simulation Scenarios and Results for Power Quality

The Igiugig network modeled in the EMT domain was simulated under three loading scenarios (high, medium, and low) to determine the losses in the network experienced by the system. This

effort is critical for the system operator to understand the steps needed to add renewable energy into the system.

Scenario 1: High Load

In this scenario, the network is simulated at full load to estimate the extent of losses in the system. Figure 15 shows the voltages, currents at different switchgear locations, and the diesel generator active and reactive power. The full network is connected in three steps: (1) diesel generator breaker 1 in Figure 11 is closed at 1 s, (2) load network breaker 2 is closed at 11 s, and (3) BESS breaker 3 is closed at 13 s. Voltages in Figure 15 (a) show that all the switchgear locations are approximately 1 p.u. For a full load of 61 kW and 6 kVAR, the diesel generator supplies 68.5 kW and absorbs the excess reactive power generated from underground cables. Total active power loss at full load is 11% (see Table 8).

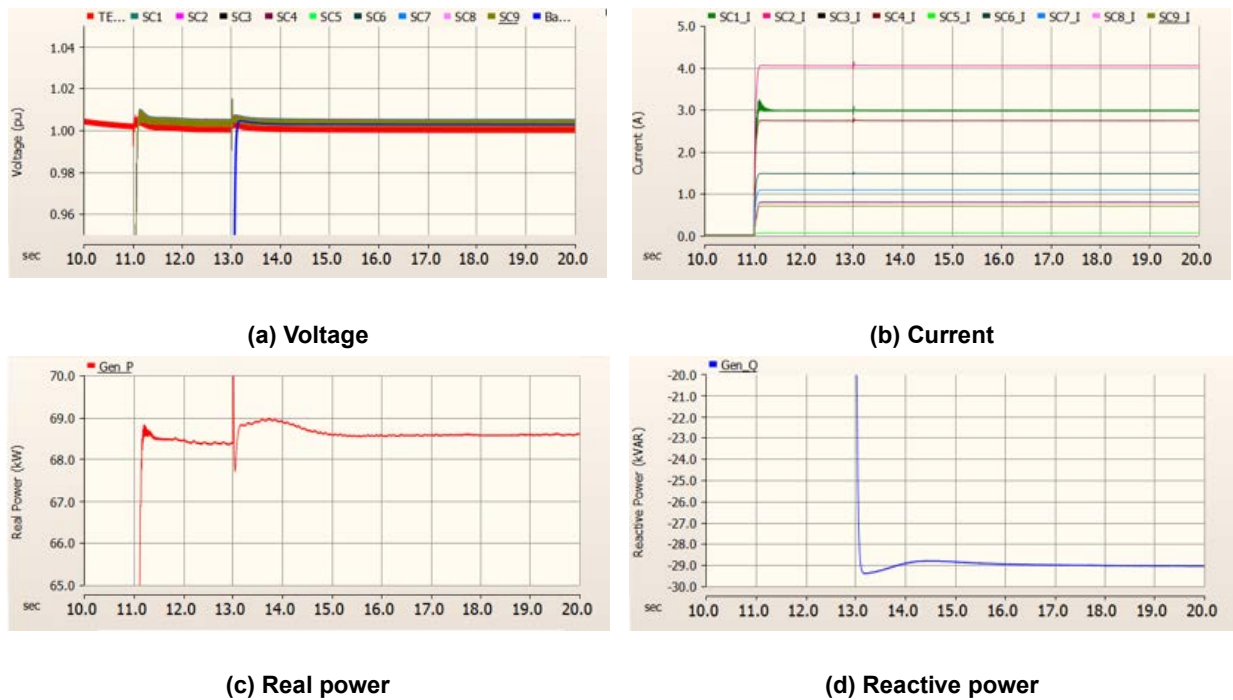


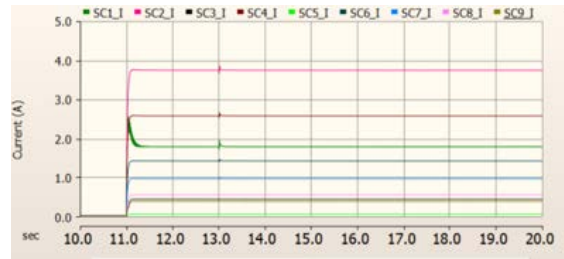
Figure 15. Scenario 1, High Load: network voltage and currents, and diesel generator real (active) and reactive power

Scenario 2: Medium Load

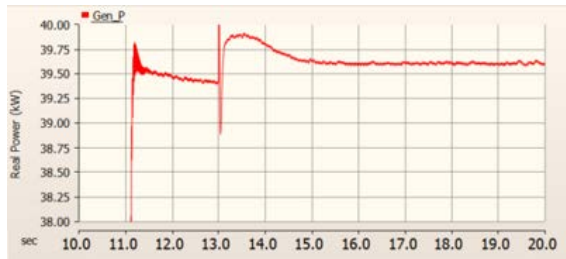
In this scenario, the network is simulated at 50% of the load to estimate the extent of line losses and is compared to the high and low scenarios. Figure 16 shows the voltages and currents at different switchgear locations and the diesel generator active and reactive power. Figure 16(a) shows the voltages at the end of the network SC9 are greater than 1 p.u. This is due to the Ferranti effect of underground cables. Even though diesel absorbs excess reactive power, there are shunt reactors to absorb additional reactive power from underground cables. For 50% load, diesel generation supplies 39.5 kW, and reactive power is absorbed due to the excess reactive power generated from underground cables. In fact, reactive power absorption increased compared to Scenario 1 due to less load. Total active power loss at full load is 23% (see Table 8).



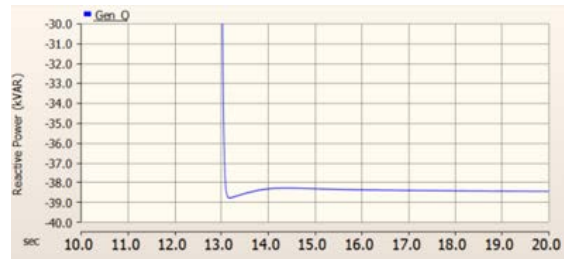
(a) Voltage



(b) Current



(c) Real power



(d) Reactive power

Figure 16. Scenario 2, Medium Load: network voltage and currents, and diesel generator real (active) and reactive power

Scenario 3: Low Load

In this scenario, the network is simulated at 10% of the load to determine the extent of static losses. Figure 17 shows the voltages, currents at different switchgear locations, and the diesel generator active and reactive power. Figure 17 (a) shows the voltages at the end of the network SC9 are approximately 1.4 p.u. This is due to the Ferranti effect of underground cables. For 10% load, diesel generation supplies 14.3 kW, and reactive power is absorbed due to the excess reactive power generated from underground cables. In fact, reactive power absorption further increased due to light load compared to Scenario 2. Total active power loss at full load is 57% (see Table 8). From Scenario 1 to Scenario 2 to Scenario 3, total loss increases only slightly, which means most of the losses are static. Static losses are present irrespective of the load value, as transformer losses seem to be more pronounced.

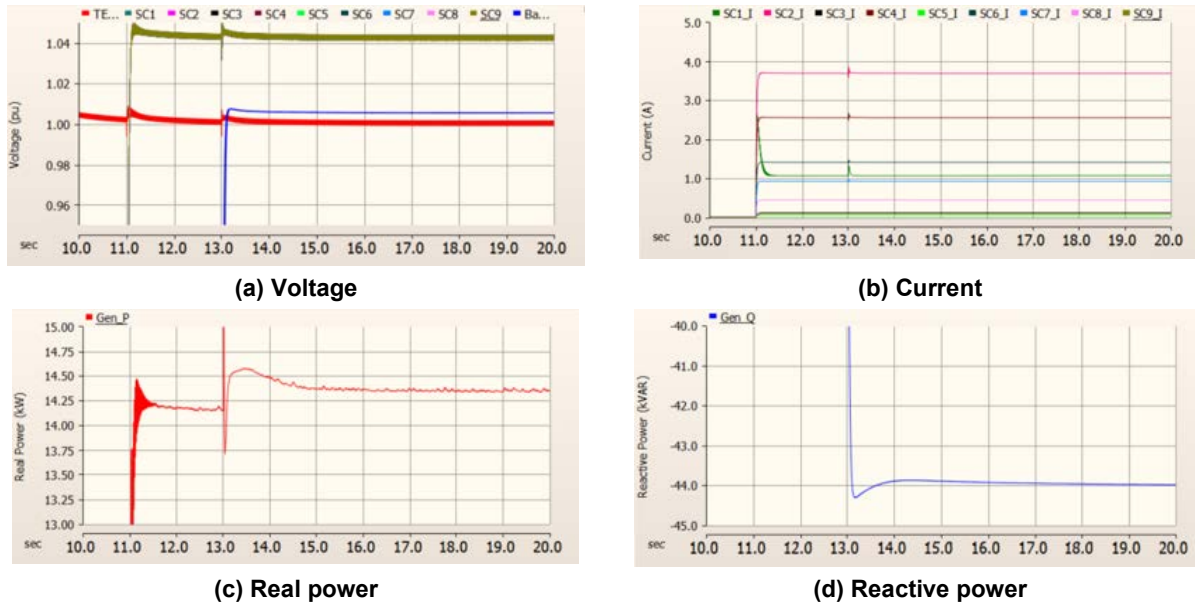


Figure 17. Scenario 3, Low Load: network voltage and currents, and diesel generator real (active) and reactive power

Table 8. Network Loss Summary

Scenario	Load		Generation		Losses (kW)
	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)	
1: Full Load	61	6	68.5	-29	7.5
2: Medium (50%) Load	30.5	3.05	39.5	-38.5	9
3: Low (10%) Load	6.0	0.6	14.3	-44	8.1

2.3.3 Key Findings

The following are the key findings:

- The field data collection indicated there are no-load current losses in the large transformer located at the end of the power system. There are plans to add distributed energy resources at this transformer. The project team recommend removing this transformer until new distributed energy resources are added. We also recommended adding controller breakers for transformers that are installed but not used. The no-load transformer identified in the system is a 100-kVA rated transformer with a no-load loss of 2% to 5% (2 kVA to 5 kVA). 5-kVA no-load losses can be significant for a 50-kVA to 100-kVA system.
- Strategically adding distributed PV (at residential or small pole mount) can help in yearly losses. For example, large-scale commercial loads have consistent load profiles and associated real estate where solar PV can be installed. Co-locating the solar PV will help avoid losses in the lines (as power will be consumed at the bus itself) and will reduce diesel use for a significant time period in the year.

- Replacing the existing legacy meters with higher-fidelity smart meters (higher measurement bandwidth, communication capabilities, etc.) will also help identify the power quality issues within the system.
- To support the phase imbalance requirements of the BESS, it is recommended to create a distribution operation plan to capture the phasing of the loads and to capture any changes made in the phasing of the loads. Adding controllable switches to change the load phasing of the distribution transformers can also help in remote operation of the phasing of the loads.

2.4 Task 4: Evaluate Battery Energy Storage and Solar Integration Support

2.4.1 Methodology

To study the impact of solar on the network losses, a grid-following inverter of rating 200 kW was added to the switchgear SC91 (see Figure 18). The inverter is interfaced through a 12.47/0.480-kV transformer.

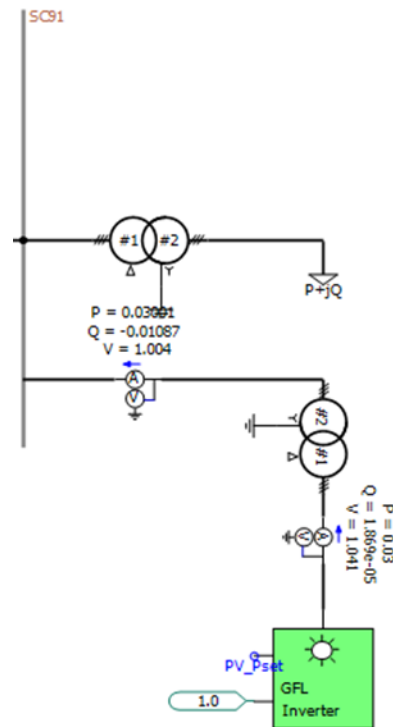
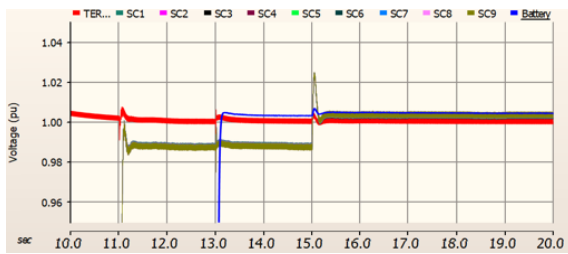
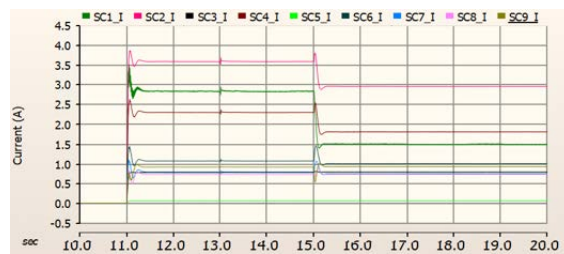


Figure 18. Grid-following solar inverter integration with network

Solar was dispatched at 15% (30 kW) of the capacity under the full load scenario. Figure 19 shows the switchgear voltages, currents, and generation. Solar was dispatched at 15 s, which reduced the diesel generation. Because part of the load is supplied by solar, generator contribution is adjusted, which in turn reduces the upstream switchgear currents. Reduction in currents directly contributes to fewer ohmic losses. Figure 19 shows a reduction in losses by more than 25% with and without solar in the full load scenario. Table 9 presents the network losses for scenario 1 with load and solar generation.



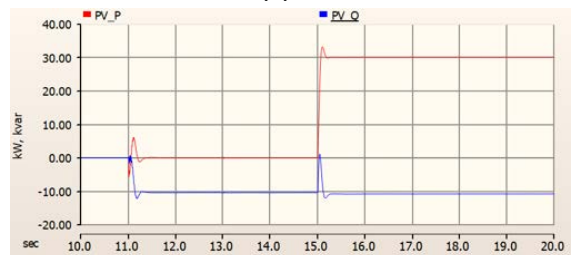
(a) Voltage



(b) Current



(c) Diesel generator output



(d) Solar output

Figure 19. Network voltage and current, and diesel and solar generation

Table 9. Network Loss Summary in Scenario 1, Full Load, With PV

Scenario	Load		Diesel Generation		PV Generation		Losses (kW)
	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)	
Without Solar PV	61	6	68.5	-29	0	0	7.5
With Solar PV	61	6	36.5	-23.8	30	0	5.5

2.4.2 Key Findings

The following are the key findings:

- Battery systems with grid-forming inverters can help run the power system without additional assets (optimal decision is made by a management system like a microgrid controller).
- Even though most battery architectures can survive in extreme temperatures, installation of these assets in a controlled environment will help with operation and maintenance of these assets.
- Interoperability (communications) and interconnection (response to changes in power system parameters like voltage and frequency) are critical to understand. Compliance to standards will reduce the cost of installation.
- Interoperability and interconnection compliance prior to field deployment (primarily inverters and management systems) will save money and effort for debugging in the field.
- Install inverters with advanced capabilities like grid-forming, handling motor start, and phase imbalances.
- Purchase spare inverters to support long-term operation of battery and PV systems.

3 Project Impacts and Future Work

Since Igiugig's CEP was adopted in 2022, the community has made significant progress toward achieving their goal of reducing diesel fuel used for electricity by 50% by 2030.

Leveraging the HOMER modeling work created through this ETIPP project, Igiugig was awarded a 2023 Renewable Energy Fund grant to install a 200-kW solar PV array. Once installed and operating in conjunction with the existing BESS, the 200-kW solar array is expected to reduce diesel fuel used for electricity generation by approximately 36% and reduce the levelized cost of electricity by \$0.15/kWh. The HRS design schematics developed through this project were also leveraged in the Renewable Energy Fund grant, which will fund the installation of an electric boiler to keep the power plant warm during diesel off periods.

A subset of the ETIPP team will continue to work together as a result of the 2023 Office of Electricity Call on Remote Microgrids, awarded in October 2024. As part of this project, Igiugig will receive hardware and continued technical assistance to optimize renewable energy and storage in their microgrid through advanced microgrid controller development and field testing.

Finally, the open-source power system models that act as representative models of Igiugig's power system can be used for future interoperability studies as more renewables are added to their grid.

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