Shungnak Energy Configuration Options

Energy Infrastructure Optimization to Reduce Fuel Cost and Dependence in Shungnak Alaska

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Abstract

Power systems in rural Alaska villages face a unique combination of challenges that can increase the cost of energy and lowers energy supply reliability. In the case of the remote village of Shungnak, diesel and heating fuel is either shipped in by barge or flown in by aircraft. This report presents a technical analysis of several energy infrastructure upgrade and modification options to reduce the amount of fuel consumed by the community of Shungnak. Reducing fuel usage saves money and makes the village more resilient to disruptions in fuel supply. The analysis considers demand side options, such as energy efficiency, alongside the installation of wind and solar power generation options. Some novel approaches are also considered including battery energy storage and the use of electrical home heating stoves powered by renewable generation that would otherwise be spilled and wasted. This report concludes with specific recommendations for Shungnak based on economic factors, and fuel price sensitivity. General conclusions are also included to support future work analyzing similar energy challenges in remote arctic regions.

Summary

This report analyzes the energy infrastructure and natural resources available in the village of Shungnak, Alaska, and evaluates options to improve the community's energy resilience. A large quantity of diesel fuel is used by Shungnak's four generators that supply electric power to the village. Many community buildings and homes rely on heating fuel to keep them warm through the long Alaska winters. Both fuels are imported, resulting in a substantial dependence on the supply line. An extended disruption of supply or storage failure during the long winters could develop into an emergency situation, involving fuel rationing, dislocation, or very high costs if fuel needs to be imported by air, as was the case in the spring of 2017. Further, unstable fuel prices create significant uncertainty in the operating cost of the electric power system and the cost to heat residential homes. An analysis was performed to assess how the village might reduce fuel consumption to become more resilient to supply disruption and hedge against high fuel prices. A benchmark goal was to achieve 50% reduction in fuel usage while providing a positive return on investment. A summary of the current Shungnak microgrid and energy used in the community is provided in Table EX-1.

The GMLC Alaska Microgrid Partnership leveraged DOE national laboratories' expertise and advanced analyses tools address this technical challenge. The analysis presented in this report used the Microgrid Design Toolkit (MDT) developed at the Sandia National Laboratories. The MDT has the capability to optimize microgrid design optimization by choosing the most cost effective configuration among generation mix, network upgrades and operational strategies. The MDT is also able to quantify the role of equipment reliability in the performance of microgrids. A summary of the MDT analysis decision variables is provided in Table EX-2.

Table EX-1 Shungnak Energy Overview

Diesel Plant	202 kW generator 350 kW generator 365 kW generator 400 kW generator
Annual electricity generation (kWh)	1,747,196 (Avg. load: 181 kW)
Annual thermal consumption (kWh)	2,813,163 (Avg. load: 291 kW)
Annual diesel fuel consumption [FY 2016] (gallons)	129,385
Annual heating oil consumption [FY 2016] (gallons)	56,690
Average Diesel fuel cost [FY 2016] ($/gallon)	$7.99
Average Heating oil cost [FY 2016] ($/gallon)	$7.16

Table EX-2 Analysis Decision Variables.

Decision Variables	Choices
Wind turbines (# of 100kW turbines)	1, 2, 3, 4, or 5
PV capacity (# of 100kW installations)	1, 2, 3, 4, or 5
Hydro power plant installation (235 kW)	Yes, No
Battery storage rating (kW/kWh)	50/50, 100/100
Number of Thermal Stoves (6kW each)	Positive Integer Values
Install New 100kW Generator	Yes, No

Figure EX-1 displays the net percentage reduction in total fuel imported as a function of the estimated capital cost of the implementing the configuration. There are many configuration options to achieve 50% reduction in imported fuel. In this aggregated figure, the candidate configurations are plotted against their respective capital cost. The specific decision variables states for each configuration are described in the report. The highest fuel saving options come from a combination of energy efficiency and significant renewable power installation. The configurations with the highest total NPV balance the cost of investments with the cost savings achieved primarily through reduced fuel consumption. Hence the optimal configuration is driven by the cost of fuel and the cost of capital. Sensitivities of the configurations to each of these are studies in this report. Cases where fuel cost remains the same or increases, and capital costs are low, promote stronger investment in renewable power as these configurations achieve higher NPV. If fuel costs decline, or if borrowing is expensive, lower investment would be warranted both in renewable power and energy efferently.

The base case configuration consumes approximately 180,000 gal/year of fuel each year total, including both heating and diesel fuel. Energy efficiency (EE) measures would reduce this by roughly 12% (low EE case), 19% (medium EE case), or 26% (high EE case). In each configuration, options that include the use of heating stoves save more fuel compared to options that do not include heating stoves. Consequently, while 50% fuel use reduction (to less than 90,000 gal/year) is achievable without heating stoves, doing so is less expensive when they are included in the resource mix. These results demonstrate that it is indeed technically feasible to achieve substantial reductions in fuel consumption.

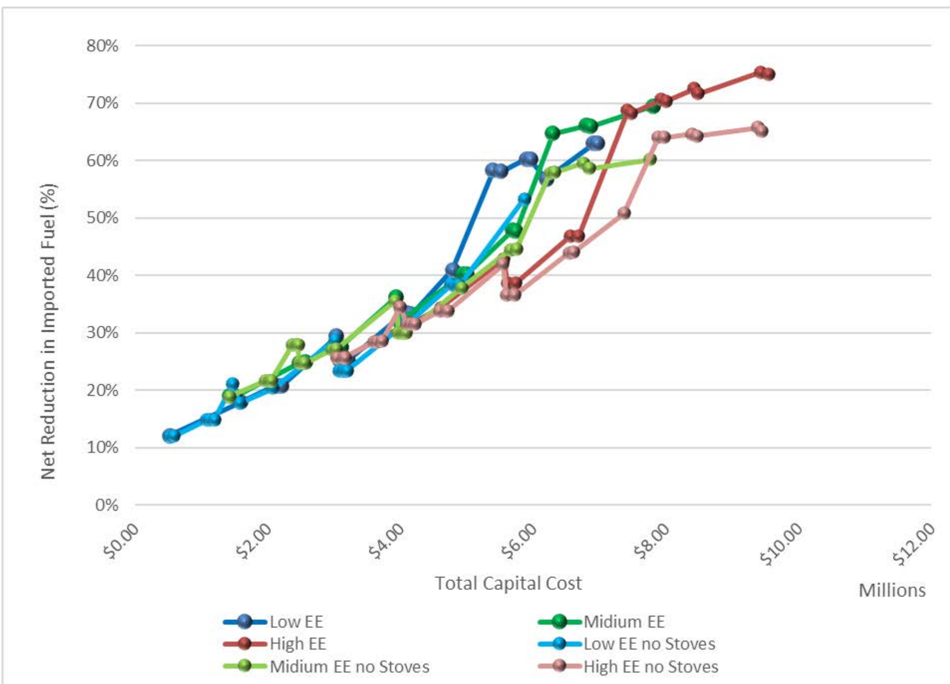

Figure EX-1: Net Reduction in Imported Fuel as a Function of Capital Investment

The results of each configuration are compared based on their Net Present Value (NPV), which is calculated by assessing the costs and benefits over a 20-year horizon and discounting both to their equivalent value in the present. Figure EX-2 shows the range of NPV at each capital cost expenditure level. The same configurations are presented in Figures EX-1 and EX-2, meaning that the highest reduction in fuel consumption is not the case with highest NPV. Rather the highest NPV case balances the cost savings from reduced fuel consumption with the cost of implementing the configuration. While financing structures are out of the scope of this report, each optimal case is presented to inform future financial assessment.

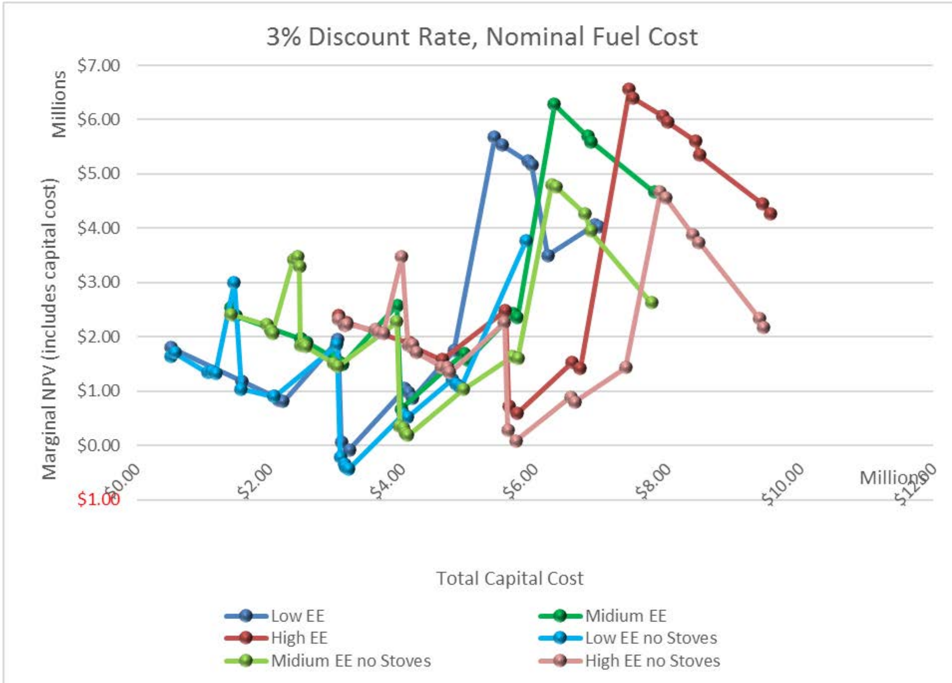

Figure EX-2: Economic Analysis at 3% Nominal Discount Rate

Conclusions (Shungnak Specific)

This analysis assesses options to retrofit Shungnak's energy infrastructure in order to save money and reduce reliance on imported fuel. Optimal cases depended on the cost of fuel, who the system was being optimized for (the utility, the heating customers, or both together), the financial discount rate (3% or 7%), and whether residential heating stoves could be installed to absorb excess renewable power. The base case and each configuration in this analysis assumes that the generator waste heat is fully utilized, which may involve expansion of the existing waste heat recovery system. In the circumstance where stoves could be installed, and future costs were discounted at 3% per year, the optimal cases reduced fuel consumption (including diesel and heating fuel), by 65% - 69% while resulting in a net cost savings from $2.7M – $3.7M in 2018 dollars (NPV over a 20-year horizon). A higher discount rate results in a lower NPV for fuel savings as future fuel costs are weighted less.

Based on this analysis, it is recommended that the use and integration of stoves be studied in greater technical and financial detail as they enable highly efficient use of spilled renewable power. If the use of heating stoves is feasible from a business case perspective, and if financing can be secured at a discount rate of 3% per year, this analysis recommends the following configuration: energy efficiency retrofitting to reduce Shungnak's electrical load by 15% and thermal load by 45%, followed by installation of up to 500kW of wind generation coupled with the installation of a smaller 100kW generator to run during periods of low net load, followed by installation of up to 100kW of solar generation. This configuration would, if implemented, reduce Shungnak's annual fuel consumption by approximately 69%. Broken out by fuel type, this means that average diesel fuel consumption would be reduced to 33,551 gal/year (from 129,385gal/year), and the average heating fuel consumption would be reduced to 24,719 gal/year (from 56,690 gal/year). With the existing maximum fuel storage volume, this would extend the average on-site supply duration for diesel from 53 days to 204 days and for heating fuel from 193 days to 443 days, making the village more resilient to fuel supply disruptions. The improved resilience that this configuration provides would also save the community roughly $6.5M in NPV over the next 20 years, assuming fuel price remains at current levels. The potential for increasing or decreasing fuel price was captured in a fuel cost sensitivity analysis.

The benefit of this configuration is somewhat robust as its NPV is positive even with a 30% reduction in current fuel prices, though this would provide a significantly lower return on investment. In this and other configurations, the highest value comes from the initial investments in energy efficiency, followed by wind power and a smaller diesel generator, followed by solar power. Hence, it is our recommendation that investments be prioritized in that order as well. If it is determined to be viable, a heating stove program should be rolled out with Shungnak heating fuel customers as the planned wind power would reach levels where it may be spilled regularly. The purchase of an efficiently size generator should be similarly planned to prevent wet-stacking in the other generators during low net-load conditions due to high penetration of renewable power.

Conclusions (General)

Most of this analysis applies only to the specific circumstances of this village under its current conditions. However, several general conclusions can be drawn around the framework of this analysis.

Despite poor access to local renewable energy resources such as wind or solar, relative to prime locations, the economic case can be driven by high energy costs. The right combination of enough wind and solar, effective energy efficiency measures, and high fuel prices enables positive returns on investment while achieving a greater than 50% reduction in imported fuel.

At high renewable utilization rates, the application of heating stoves can make the difference between an installation having a positive or negative NPV. This can be challenging under existing cost recovery structures as the utility, who has access to capital, is not the entity that directly benefits. A similar situation exists for other energy efficiency retrofitting measures. The community benefits directly whereas the utility may lose some revenue from reduced energy consumption. There are potential solutions to this problem that spread out the benefits and costs appropriately, though they are beyond the scope of this analysis.

Heating stoves essentially act as thermal batteries whose energy is stored as heat in people’s homes. This can be a very low cost way of accommodating excess renewable generation on mini-grid systems. The use of heating stoves enables a higher reduction in imported fuel through higher penetration of renewable power. High penetration of renewable power, with or without stoves, greatly reduces fuel consumption and can save considerable cost. However, this comes with low diesel generator utilization factors, which increases the risk of wet-stacking. This can be addressed by installing an appropriately sized (smaller) diesel generator to support the load when other generators would be lightly loaded. These key general observations derived from the Shungnak analysis will likely be important to consider in future analyses of other arctic communities with high heating loads and fuel costs.

Acknowledgments

The authors would like to acknowledge the significant contributions and support of the organizations involved in the GMLC Alaska Microgrid Partnership, including the Alaska Center for Electric Power, the Alaska Energy Authority, the National Renewable Energy Laboratory (NREL), and the Pacific Northwest National Laboratory (PNNL). Tony Jemez of NREL, and his concurrent analysis on the village of Chefornak Alaska, was an invaluable source of information, data, and feedback. Trevor Hardy and Mark Weimar from PNNL provided helpful and extensive technical feedback and critique throughout the analysis. Ian Baring-Gould provided a helpful review of this report.

Acronyms and Abbreviations

AEA	Alaska Energy Authority
F	degrees Fahrenheit
gal	Gallons
GHFE	Gallons Heating Fuel Equivalent
gpm	Gallons per minute
HP	Horse Power
kBTU	1000 BTU
kW	Kilowatt
kWh	Kilowatt-hour
LED	Light emitting diode
MDT	Microgrid Design Toolkit
NPV	Net Present Value
O&M	Operation and Maintenance
w	Watt

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1.0 Introduction

Arctic regions around the world, including Alaska, face a unique combination of energy infrastructure challenges. Rural communities in Alaska rely on imported fuel (diesel fuel and heating oil) to power their grid, to run their vehicles, and, to a large extent, heat their homes. Extreme cold in the winter elevates resilient access to energy from a luxury, as it is in many other regions, to a critical health and safety issue. The remote locations of these communities make fuel expensive to deliver, leading to some of the highest costs per gallon in the U.S. For the roughly 200 isolated minigrid-powered communities across Alaska, initiatives to reduce fuel consumption have the potential to significantly reduce energy costs and to make the village more resilient to fuel supply disruption.

Imported fuel consumption can be reduced by either reducing the electrical/heating load, or by installing generation that gets its fuel locally (e.g. wind, solar, biomass, etc.). Electrical and thermal load can be reduced through a variety of energy efficiency measures such as insulation retrofitting, updated appliances, or LED lighting. Once certain energy efficiency measures have been taken, the fuel use can be further reduced by installing renewable energy generation that use local wind, solar, and/or water resources. Each of these technology options has costs and technical limitations that must be considered in a techno-economic analysis. Other technologies such as battery storage and heating stoves (which can absorb excess renewable generation to offset heating load) can further improve the efficiency of energy usage in the power system and so should also be considered.

To address this challenge, the Alaska Microgrid Partnership (AMP), funded through the U.S. Department of Energy, has leveraged the expertise of America's national laboratory system to bring some of the most advanced analyses tools to bare on this problem. The Microgrid Design Toolkit (MDT) was developed at the Sandia National Laboratories to perform microgrid design by choosing the most cost effective generation mix. The MDT is also able to assess the role of stochastic equipment failures in the reliability of microgrids. AMP aims to demonstrate a combination of investments that achieves a 50% reduction in imported fuel volume with a positive return on investment for rural Alaska villages. This report analyzes the energy infrastructure and natural resources available in the village of Shungnak Alaska in order to find ways of improving the community's energy independence with positive NPV.

Shugnak has been the subject of analysis before. The Strategic Technical Assistance Response Team (START) performed an energy opportunity assessment of Shungnak[1] which offered several recommendations for achieving low cost imported fuel use reductions. The high-level conclusions of the report were that cordwood heating, and expansion of the powerhouse heat recovery loop, are very cost effective solutions while wind power and solar power are cost effective at certain price levels. Building on the work of the START, our report focuses on the goal of 50% reduction in imported fuels (rather than lowest cost solutions), and further reorganizes the optimization objective to achieve this target at the highest value.

A similar report was prepared by the National Renewable Energy Laboratory (NREL) for the village of Chefornak, Alaska. The results of both of these reports will be used by researchers at the Pacific Northwest National Laboratory (PNNL) to explore viable financing models for investment in fuel use reduction.

This report is organized as follows:

- Chapter 2 gives an overview of the village of Shungnak Alaska

[1] Dan Olis, Travis Simpkins, and Jared Temanson, "Energy Opportunity Assessment for Shungnak, AK" National Renewable Energy Laboratory, June, 2016

- Chapter 3 briefly describes the electrical and thermal infrastructure of Shungnak.
- Chapter 4 describes the electrical and thermal usage at the community
- Chapter 5 describes various energy efficiency (EE) options available to the community.
- Chapter 6 details past, current, and anticipated fuel consumption and cost.
- Chapter 7 gives an overview of diesel generator performance and cost
- Chapter 8 discusses the existing heat production infrastructure within the community
- Chapter 9 discusses the wind resource at the community and the anticipated wind turbine cost and performance.
- Chapter 10 covers solar cost, performance, and the solar resource
- Chapter 11 covers cost and performance of the converter, storage, and integration equipment.
- Chapter 12 discusses system modeling issues.
- Chapter 13 goes over the analysis results, focusing on net present cost (NPC), fuel consumption, and diesel run time.
- Chapter 14 summarizes the high level analysis conclusions.

The results in this report apply specifically to Shungnak. However, the process of the analysis developed significant knowledge that can be generally applied to Alaska and to arctic regions, and rural areas, around the world. 770 million people living in these areas worldwide do not have access to electricity that could be provided through the deployment of the low-cost minigird technologies discussed in this paper[1].

[1] See International Energy Agency, World Energy Outlook 2012, pages 533 and 539. Accessed on September 25, 2015 http://www.iea.org/publications/freepublications/publication/world-energy-outlook-2012.html

2.0 Community Overview

Shungnak is a village in rural Alaska located on the upper Kobuk River in the Northwest Arctic Borough. It is located approximately 300 miles northwest of Fairbanks, 150 miles east of Kotzebue, and 10 miles west of Kobuk (location shown in Figure 1). Photos of the community are provided in Figures 2 and 3. Table 1 lists basic information about Shungnak and its population.

Table 1 Overview of the Village of Shungnak

Current Population[1]	299: 2016 Dept. of Labor Estimate 262: 2010 Census 256: 2000 Census 223: 1990 Census 202: 1980 Census 221: 1970 Census
Incorporation Type	2nd class
Borough Located In	Northwest Arctic Borough
Economic Region	Northern
Regional Native Corporation	NANA Regional Corporation
Latitude	66.887902
Longitude	-157.139870
Elevation	144 feet
Electrical Utility	Alaska Village Electric Co-Op
# Housing Units	77 [2]

Economic activity is comprised mainly of subsistence hunting/gathering. Shungnak has around 77 housing structures. Other buildings include the following: Safety Building, VPSO Building, City Offices, Water Plant, Clinic, School, National Guard Armory, Native Store, and New Cook House.

[1] "Alaska Population Estimates by Borough, Census Area, City, and Census Designated Place (CDP), 2010 to 2016" US Department of Labor, Available: http://live.laborstats.alaska.gov/pop/

[2] "Northwest Arctic Borough 2014 Alaska Housing Assessments" Alaska Housing Finance Corporation, 2014

Figure 1 Shungnak Location in Alaska (top left), in Northwest Arctic Borough (top right), on the Kobuk River (bottom left) and an aerial map of Shungnak Village (bottom right).

Figure 2 Aerial photograph of Shungnak, looking west with the Kobuk River in the foreground.

Figure 3: Shungnak looking north from end of the airport runway. The center of the community is on the right and extending back into the trees, with predominately housing to the left. The Kobuk River is off to the right and the runway directly to the left.

3.0 Overview of Community Electricity and Heating Infrastructure

This chapter describes the electricity and thermal energy infrastructure already installed in Shungnak. The village powerhouse includes the four generators shown in Table 2. These generators supply the 480-V electrical distribution system in the village.

Table 2 Shungnak Generator Data[1]

	G-1	G-2	G-3	G-4
Engine Make	John Deere	Caterpillar	Detroit	Cummins
Engine Model	6619AF-00	3406B	Series 60	KTA19 G2
Generator Make	Kato	Kato	Kato	unknown
Generator Model	155-482361111	268-483361111	268-483361111	unknown
Capacity	202 kW	350 kW	365 kW	400 kW
Fuel Rate Intercept	1.04 gal/hr	1.80 gal/hr	1.88 gal/hr*	2.06 gal/hr
Fuel Rate Slope	0.0310 gal/hr/kW	0.0538 gal/hr/kW	0.0561 gal/hr/kW*	0.0615 gal/hr/kW

* Note: the fuel rate data for G-3 is taken from the reference below, while the fuel rate data for the other generators is approximated by scaling these data to their rated power.

The efficiency and fuel rate of G-3 is shown in Figure 4. It is important to note that the generator efficiency increases with increasing load.

[1] Shungnak_AEA Village Powerhouse Data.pdf

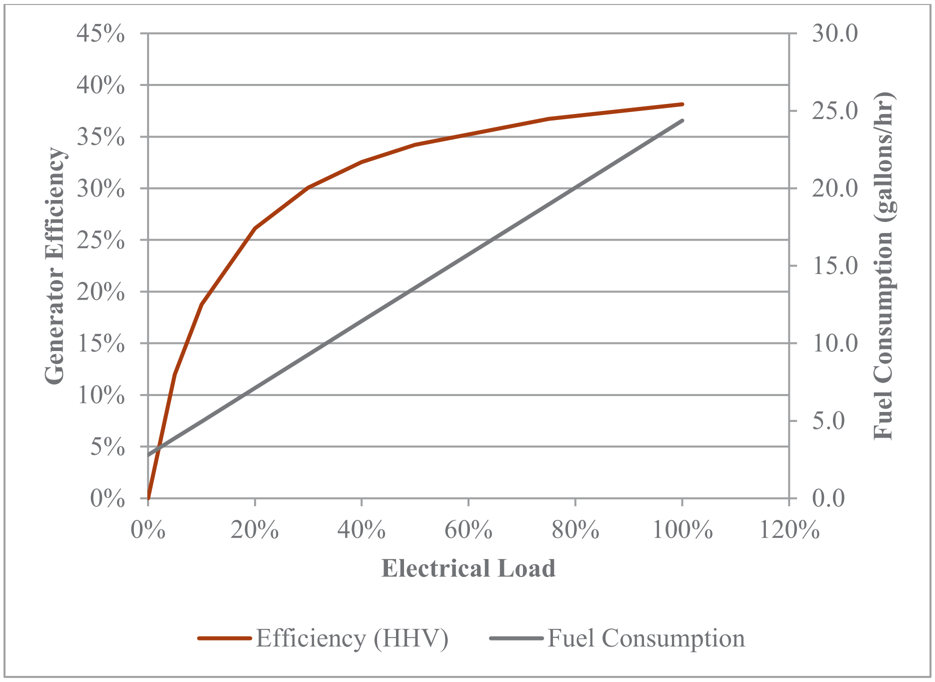


Figure 4 Fuel Rate and Efficiency of Detroit Diesel 365 kW Generator[1]

The generators must be maintained and replaced after reaching their end of life. Both maintenance and replacement occurs on a schedule dependent on generator runtime. Useful diesel generator lifetimes range from 60,000 to 100,000 hours[2] so we have chosen the middle of this range (80,000 hours) to use for this analysis. Replacement costs are estimated according to an informal survey of local projects. A linear fit of these generator costs was estimated to be $411/kW + $105. A similar survey of local operation and maintenance costs was conducted and a linear interpolation was performed between generators of similar sizes in order to estimate O&M costs.

The model included a 10-minute startup time for each generator any time it transitioned from off to on.

Table 3 Generator Replacement and O&M Costs

Generator	Replacement Costs ($/hour)	O&M Costs ($/hour)
JD 6619	1.038	15.78
CAT 3406	1.613	16.45
SD 60	1.874	16.76
CMS K19G2	1.946	17.14

The community has 40,000 gal of heating fuel storage and 25,000 gal of diesel storage in the village. However, roughly 25% of this storage is reserved to supply nearby villages. Hence resilience assessments will be based on storage volumes of 30,000 gal heating fuel and 18,750 gal diesel storage respectively.

[1] Marshall-Wind-Diesel-Feasibility-Study-V3-Energy-Sept.-2012.pdf
[2] AVECK "Diesel Generator Technology Report" ACEP, 2015

At present the power plant provides recovered heat to water treatment plant (WTP) and City office[1].

The heating load in Shungnak is served by oil-burning furnaces in homes and community buildings. The heating fuel that these furnaces burn has the following energy conversion factors that help use data on the heating load in kWh to calculate the volume of fuel burned.

- HHV (heating fuel) 134000 BTU/gallon
- Conversion factor 0.000293071 kWh/BTU

The costs of heating and diesel fuel assumed for this analysis are listed below. This assumption was made based on the average unsubsidized fuel costs of 2013, 2014, and 2015 according the Alaska Energy Authority[2]. Fuel is typically purchased at the community store on an as needed basis and placed in fuel tanks at individual buildings.

- Heating Fuel Cost $7.99/gal
- Diesel Fuel Cost $7.16/gal

According to conversations with Shungnak residents in June of 2017, fuel price had increased to $8.25/gal (retail price) for heating fuel delivered by river barge and roughly $16.00/gal (retail price) for diesel fuel delivered by airlift. A typical home will use approximately 700 gal/year of heating fuel. This increase in price is reportedly associated with reduced flow in the Kobak River that has prevented large barges from reaching the village. While options exist for dredging the riverbed to open this route and reduce fuel costs, the reduction in river flow could be associated with long term changes in the regional climate making this a reoccurring issue. While these options are out of the scope of our analysis, to factor these realities into our analysis we explore the following asymmetric sensitivity in fuel price: -30%, -15%, +50%, +100%.

A 12.47kV line connects Shungnak to Kobuk allowing the two communities to exchange some electrical power[3]. The roughly seven-mile route that the line takes is shown in Figure 5. The line is supported with treated wood poles supported by H-piles. Power flow over the line is a result of generation in Kobuk being either lower or higher than their electrical load. The power flow over this tideline is modeled as and incorporated into the load data from the power house as discussed in Section 4.2.1.

[1] "Heat Recovery Feasibility Study: Shungnak, Alaska" Alaska Native Tribal Health Consortium Division of Environmental Health and Engineering, September, 2016

[2] Data here from Power Cost Equalization (PCE) reports at http://www.akenergyauthority.org/Programs/PCE

[3] Joel Neimeyer, "Electric Intertie Options for Several Rural Alaskan Villages," Alaska Village Electric Cooperative and Denali Commission Technical Report, October 2014

Figure 5 Shungnak – Kobuk electrical intertie

4.0 Electrical and Thermal Loads

4.1 Loads Overview

The electrical load in Shungnak was available from measurements collected from the powerhouse in 2014 and 2015. This aggregates the real electrical load, consumed by customers, the net power flow over the tie line to Kobuk and any losses in the distribution system. While detailed data were not available, the tie line power flow is reportedly a small fraction of the electrical load and so can be effectively represented as an element of load. Generation minus load in Kobuk is modeled here as load over the tie line. Reactive load is not considered in this study but it can increase losses. The thermal load was estimated based on the number and type of building in the community. A thermal simulation, described in Section 4.3.1, was performed taking into account the number and occupancy of buildings. Figure 6 shows the relative size of thermal and electrical heating loads for Shungnak in kWh per year. Figure 7 converts the raw energy demands into the volume of each fuel required to supply those demands. Because of the relatively low efficiency of diesel power generation, when compared to burning fuel for heat, most of the fuel use in the village can be attributed to electrical power generation rather than home heating.

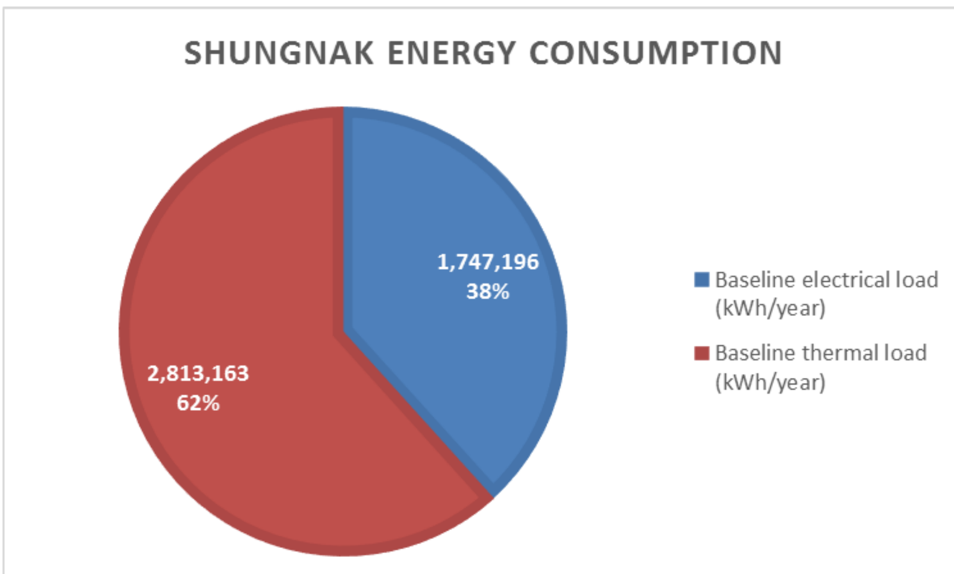


Figure 6 Combined Electrical and Thermal Energy Consumption in kWh/year

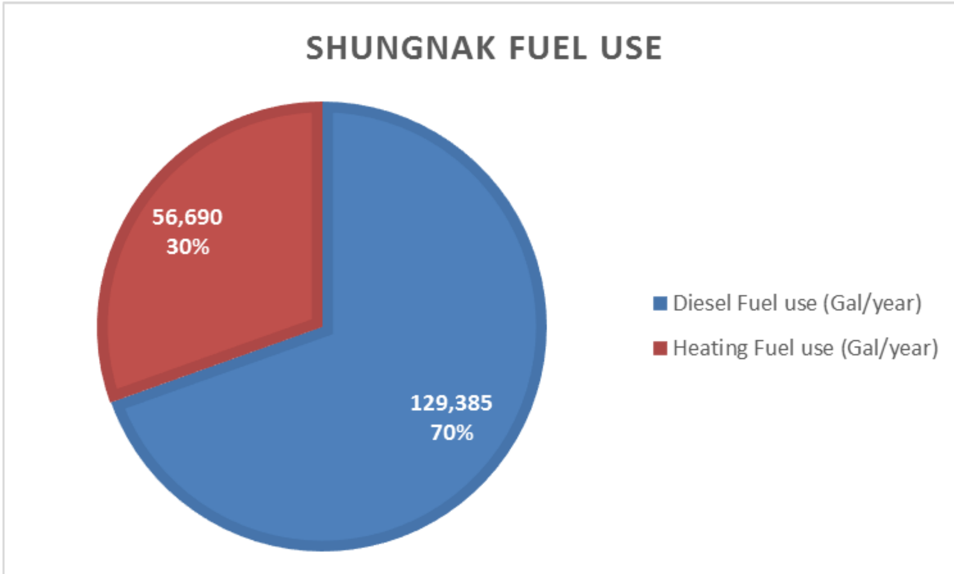


Figure 7 Combined Heating and Diesel Fuel Use in gal/year

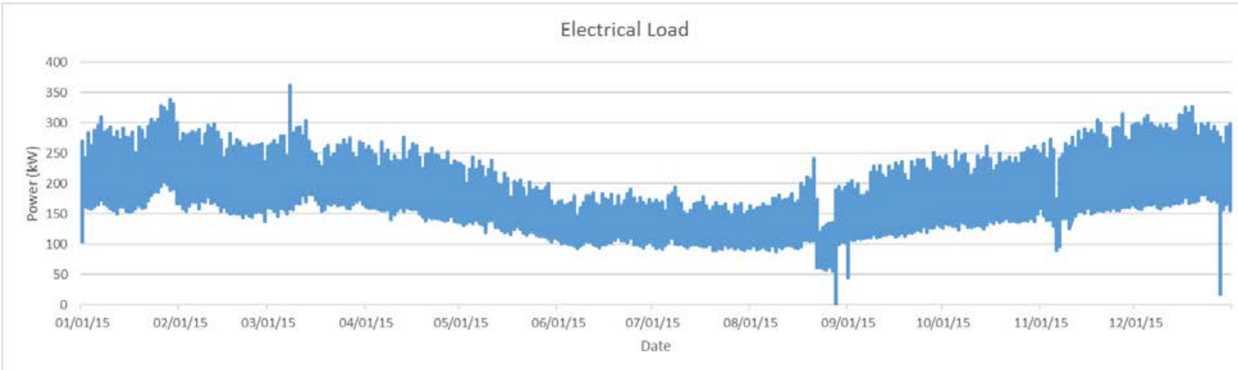
At the average diesel consumption rate of 129,385gal/year the on-site diesel storage of 18,750 gallons would last approximately 53 days. At the average heating fuel consumption rate of 56,690 gal/year the on-site heating fuel storage of 30,000 gallons would last approximately 193 days. This is a simplistic look at the fuel supply line for the village but it provides a useful benchmark for the effect on fuel use reduction on the community's resilience.

4.2 Electrical Loads

4.2.1 Current Electrical Loads

In the combine 2014 – 2015 dataset used, Shungnak's electrical load averaged 180.9 kW with maximum 15-minute interval load of 362.5 kW. Figure 8 shows the average electrical load sampled every 15 minutes. The following procedure was performed in order to fill in gaps in the time series electrical load data:

- Time series (10 min) data was collected from 2015. (~70% data recovery).
- Small gaps (up to 3 hours) filled by averaging from loads just prior and just after the gap
- Large gaps filled by 1) Using data from 2016; 2) Copying data from prior to or after the gap.
- Signal was resampled to convert to 15 min time steps



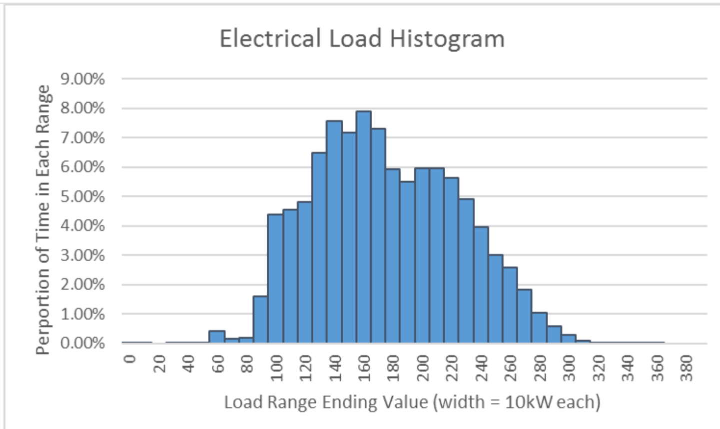


Figure 8 Shungnak Electrical Load (15 minute intervals, Avg. 181 kW, Peak 362 kW)

4.2.2 Future Electrical Load (Modeling Assumptions)

Historical average electrical load was surveyed to determine annual load growth. Load has been mostly flat with an estimated future increase of 0.75% per year. The modeling methodology was to determine the average load profile over the next 20 years given this growth rate. This was determined to occur 13 years after the assumed start year given the exponential growth curve. This single year's average profile was then used uniformly across the simulation time horizon. With stoves added electrical load would increase. However, the increase would only occur during periods where renewable power would otherwise be curtailed. Hence the electrical load attributed to the stoves is modeled simply as the "spilled" renewable power tracked by the MDT simulation algorithm.

4.3 Heating Loads

4.3.1 Current Heating Load

A thermal analysis was performed in EnergyPlus[1] an open source software package developed by NREL to help building designers improve energy efficiency. This analysis estimated the total community thermal energy requirements based on detailed building square footage and insolation data, along with meteorological data from in 2016[2]. The result was the estimate of the thermal load shown in Figure 9.

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[1] EnergyPlus™ whole building energy simulation program,

[2] Jim Fowler, "Targeted Level 1 Energy Audits in the Native Village of Shungnak, AK" US DOE Office of Indian Energy Policy & Programs, 2015/2016 START Program

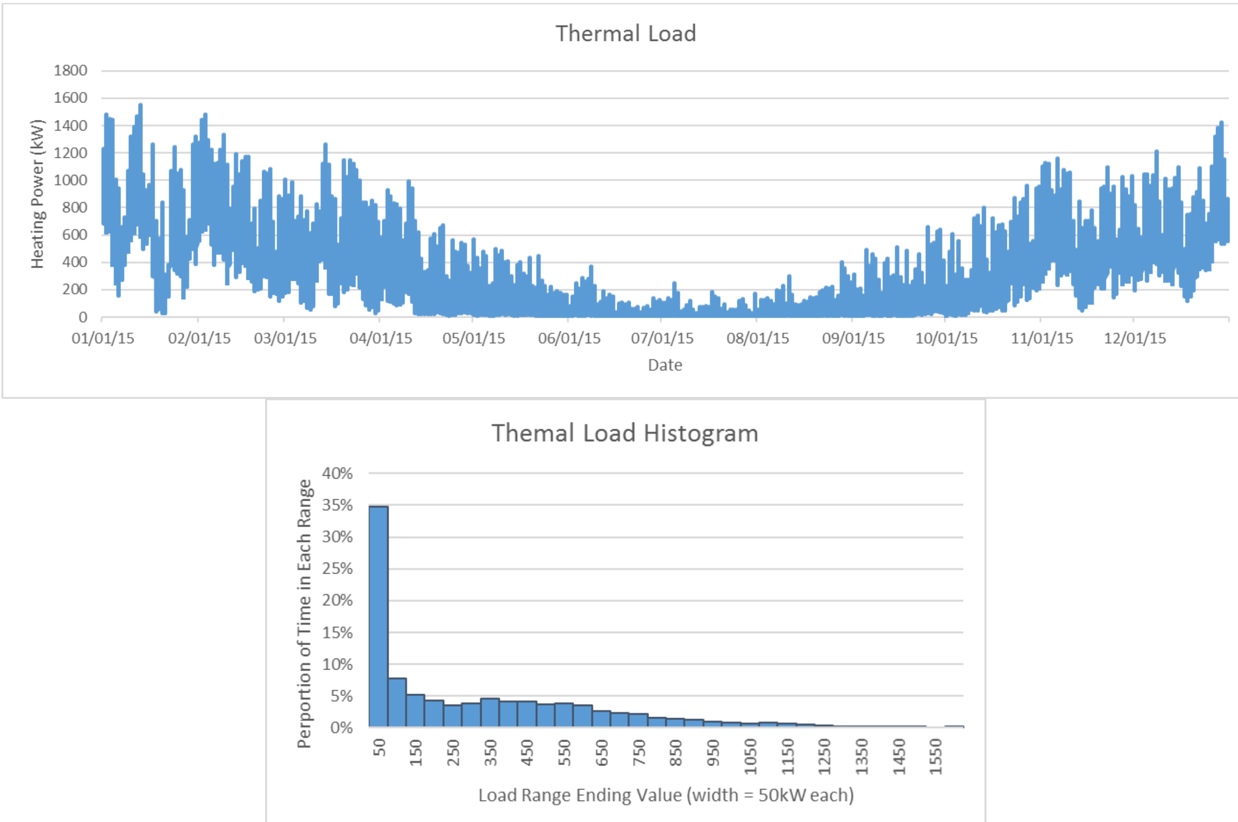


Figure 9 Shungnak Thermal Load (15 minute intervals, Avg. 291 kW, Peak 1551 kW)

The thermal load, normally represented in BTU/hour, can be converted into kW to make it comparable to the electrical load. Figure 9 shows the village's estimated thermal load as calculated through a detailed simulation of building size and type in Shungnak. Note that the thermal load is concentrated in the winter. The average thermal load (291 kW) is much higher than the average electrical load (181 kW). However, due to the different efficacies when converting fuel to electrical power rather than to heat, most of the volume of fuel required by the village is diesel fuel for generators.

4.3.2 Future Thermal Load (Modeling Assumptions)

Historical average thermal load was surveyed to determine annual load growth. Thermal load has been mostly flat with an estimated future increase of 0.75% per year. The modeling methodology was to determine the average load profile over the next 20 years given this growth rate. This was determined to occur 13 years after the assumed start year given the exponential growth curve. This single year's average profile was then used uniformly across the simulation time horizon.

5.0 Energy Efficiency

Often the most cost effective method for reducing fuel consumption is to reduce the thermal and electrical loads through energy efficiency retrofitting. The following energy efficiency strategies were explored in this study.

5.1 End Use Electrical and Thermal Energy Efficiency

Heating and electrical load reduction can be the most cost effective method for reducing imported fuel. The cost and effectiveness of this type of retrofit depends greatly on the unique qualities of local buildings. A survey of similar projects in the region (shown in Figure 10) was performed to estimate the potential savings per cost. A least squares polynomial fit was performed on these data and the resulting function was used to approximate three energy efficiency scenarios for further analysis.

- Scenario 1 Low energy efficiency: Electrical Load reduced by 5% and thermal load reduced by 25% at a onetime cost of $518,433 (interpolated from quadratic best fit line from regional data below)
- Scenario 2 Medium energy efficiency: Electrical Load reduced by 10% and thermal load reduced by 35% at a onetime cost of $1,414,120 (interpolated from quadratic best fit line from regional data below)
- Scenario 3 High energy efficiency: Electrical Load reduced by 15% and thermal load reduced by 45% at a onetime cost of $3,040,717 (interpolated from quadratic best fit line from regional data below)

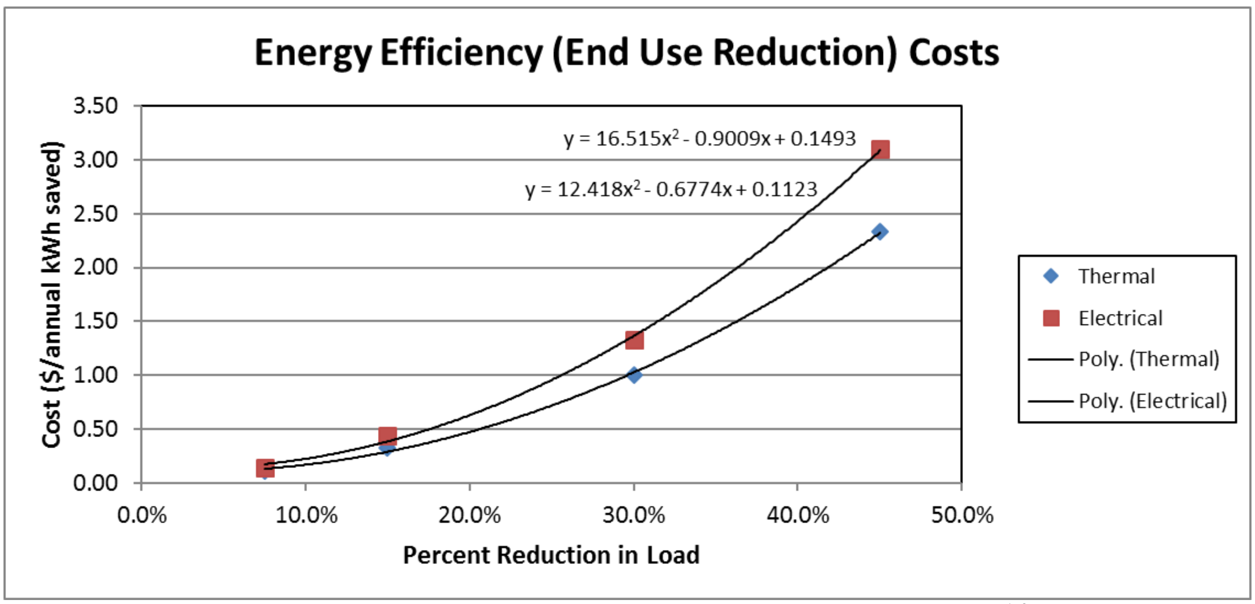


Figure 10 Energy Efficiency Cost Curves Based on Regional Data[1,2]

[1] Residential weatherization cost and performance data from ARIS

[2] AEA, "Remote Alaska Communities Energy Efficiency Competition: Phase II Summary and Strategic Energy Efficiency Plan-Chefornak", August, 2016

5.2 Heating stoves for thermal energy conversion

A thermal load controller can be installed to use excess renewable power, that would otherwise be curtailed, to heat homes in the community.

- Fixed cost of $10,000 for integration
- Marginal cost of $3,000 per 6kW stove

Other means to provide heat to buildings have also been considered, including electric heat pumps. Heat pumps were not modeled explicitly but could be considered as an option in future assessments. Both of these devices would require the continued use of traditional heating oil or biomass based heating sources when excess electrical energy was not available or the temperatures would not allow the use of heat pumps. These different technologies would likely be used as part of system control in different ways. For example, the use of heat pumps would generally shift energy consumption from heating oil to electrical power generated by the diesel plant, but would likely not be controlled by the plant control system. Thermal stoves would be used to consume excess renewable based power, and could be controlled.

5.3 Waste Heat Recovery

A feasibility study was performed to assess the expansion of the waste heat recovery system in Shungnak[1]. As referenced in Section 3.0, the power plant provides recovered heat to water treatment plant (WTP) and City office (though this line has leaks that must be repaired to be used). The Clinic, Village Public Safety Officer (VPSO) Housing, New Cookhouse, Community Store, and School were evaluated for excess heat recovery potential. Two options were discussed in the report: (1) extend heat recovery system to the Clinic, Cookhouse, VPSO housing, Community store, and repair the line to the city office, or (2) extend heat recovery system to only the school and repair the line to the city office. Option 1 was estimated to cost $1,292,000, saving 14,000 gallons of heating fuel per year. Option 2 was estimated to cost $917,000, saving 20,000 gallons of heating fuel per year. The school pays a lower amount for its heating fuel, which was not available for this analysis, so it is difficult to compare these options on an even basis.

Rather than select an option for our analysis, our analysis assumes that either is selected and implemented, resulting in a full utilization of generator waste heat. The MDT simulations presented here supply the thermal load with heat proportional to each generator's loading. By doing this, we can capture the effect that reducing the electrical load through efficiency and introduction of renewable energy will reduce the waste heat available.

5.4 Efficient Generator Sizing

At high levels of renewable power integration generators can be underutilized causing increased O&M costs and shortening their useful life. In these circumstances a smaller generator is installed to support the load when the other generators would otherwise be wetstacked below 30% utilization. A survey of local projects was conducted and a linear fit estimated a 100kW generator would cost $411/kW + $105.

- Estimated Cost for 100kW Generator $41,205, rounded to $41,000

---

[1] "Heat Recovery Feasibility Study: Shungnak, Alaska" Alaska Native Tribal Health Consortium Division of Environmental Health and Engineering, September, 2016

5.5 Battery Energy Storage

Under low generator utilization conditions, an appropriately sized battery can be used to support load while a generator is turned off. This strategy allows the generators to operate more efficiently by burning no fuel when off and burning fuel more efficiently, at higher utilization from charging the battery, when on. In this analysis, cases that included batteries were enabled to turn off all generators for as long as the batteries and renewable power sources were able to support the load.

- Batteries
  - Fixed cost: $50,000
  - Marginal cost: (> 160 kW): $600/kW
  - Marginal cost: (> 200 kWh): $480/kWh
  - Replacement cost: 75% of initial cost
  - O&M: $20/kWh/year
- Converter
  - Fixed cost: $50,000
  - Marginal cost (Up to 160 kW) $875/kW
  - Marginal cost: (> 160 kW): $600/kW
  - Replacement cost: 75% of initial cost
  - O&M: $10/kW/year

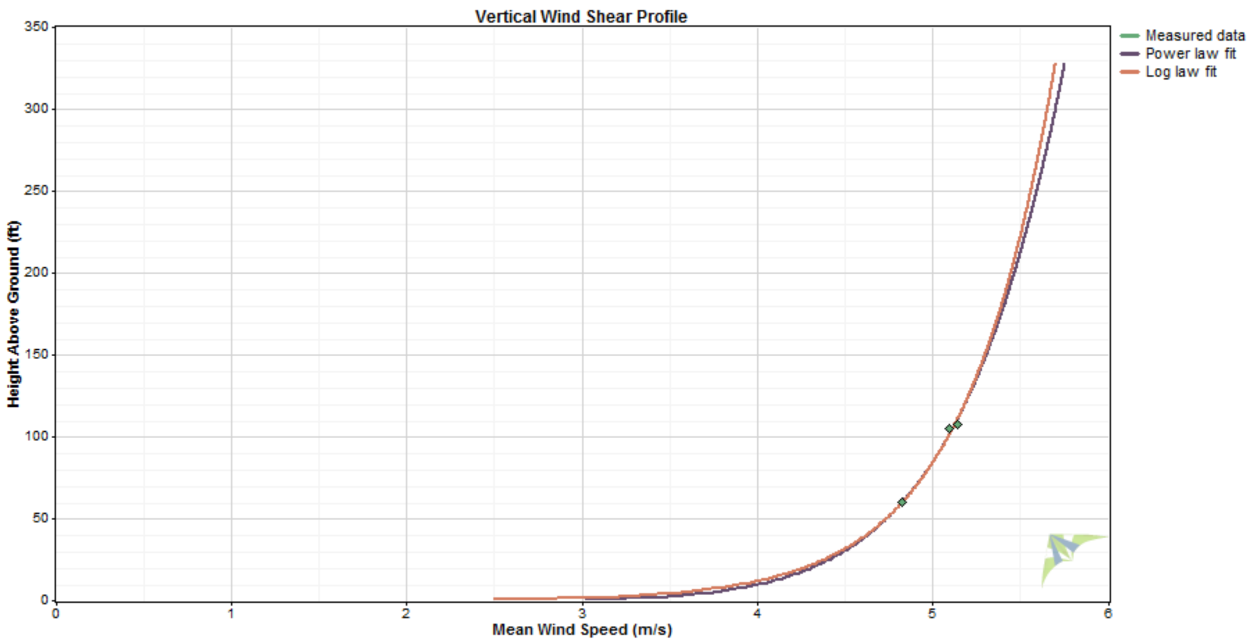
Several generic batteries and power converter sizes were analyzed including: 100kW/100kWh, and 200kW/200kWh.

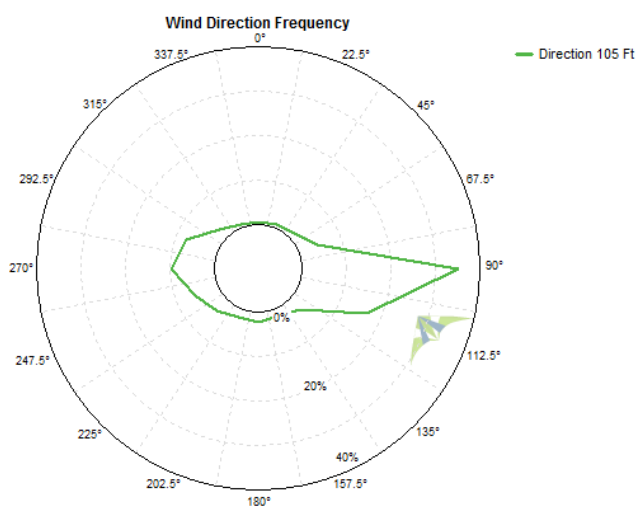
6.0 Wind Power Technology

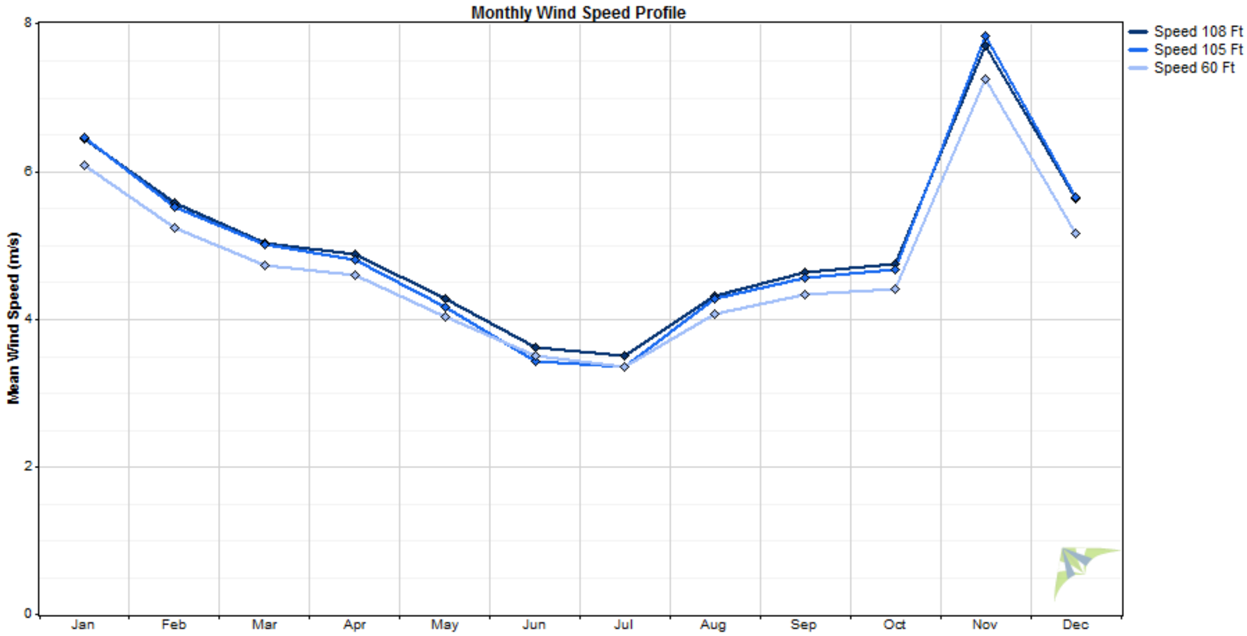
Currently Shungnak does not have a significant renewable power supply. This section provides a baseline assessment of the feasibility of turbine installation.

6.1 Wind Resource

Shungnak has a relatively light class 2 (marginal), though close to class 3 (fair), wind resource. Figure 11 Shows the results of 22 months of data collection from a 33m meteorological tower. Table 4 then shows the critical statistical information about the wind resource.







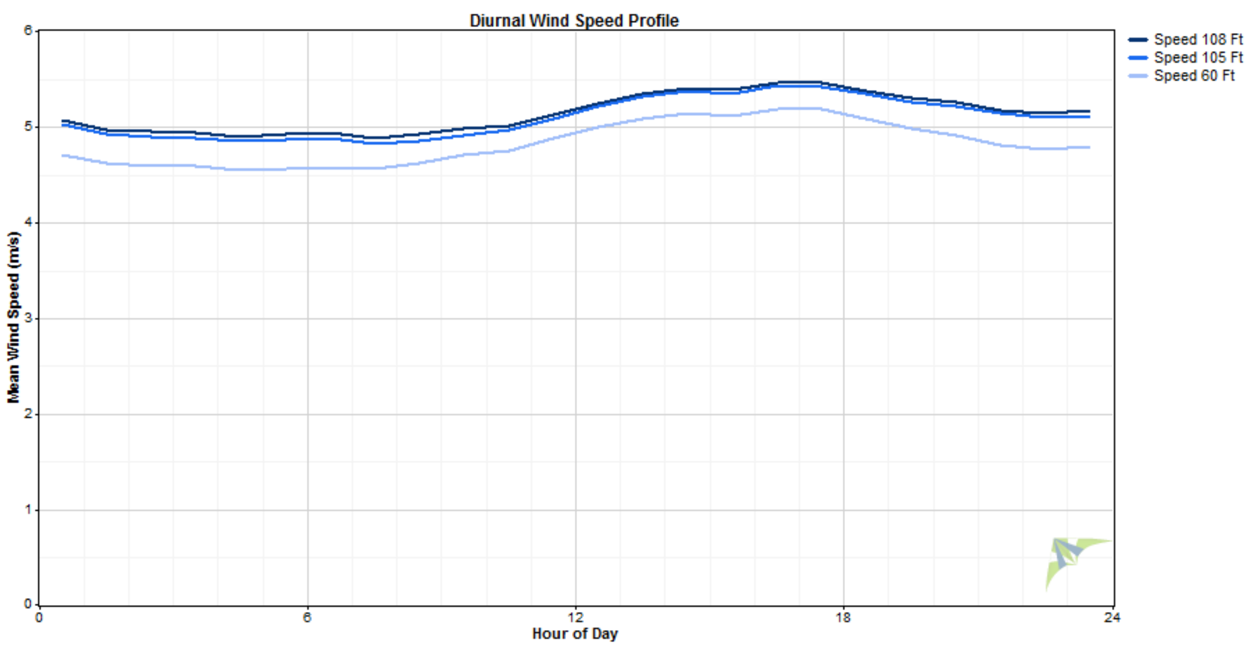


Figure 11 Shungnak Wind Resource Data (a) maximum wind speed at different heights (b) wind direction frequency (c) monthly wind speed profile (d) diurnal wind speed profile [1]

Table 4 Shungnak Wind Resource Statistics[14]

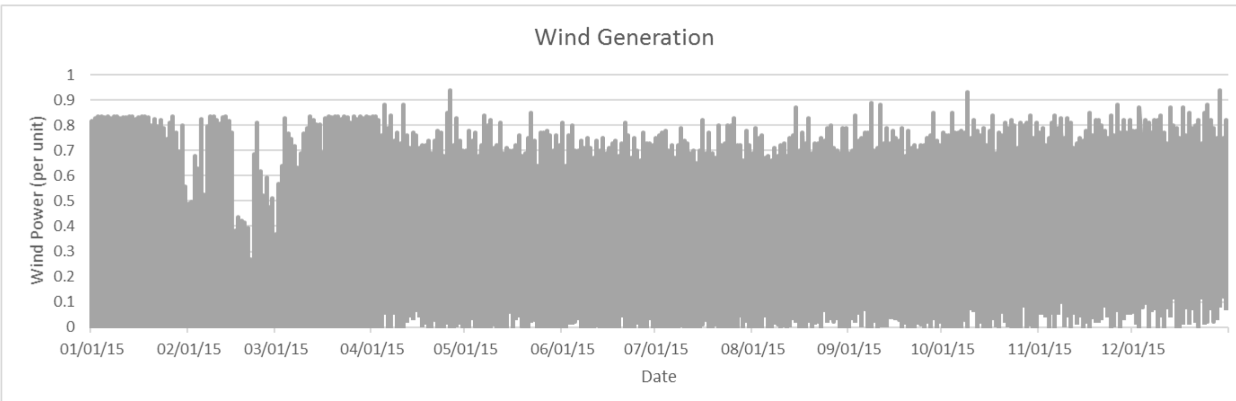
Measurement height (m)	33	32	18
Mean wind speed (m/s)	5.139	5.095	4.824
MoMM* wind speed (m/s)	5.018	4.969	4.719

[1] "Shungnak Wind Resource Report" WHPacific, Inc. 2015

Median wind speed (m/s)	4.3	4.2	3.9
Min wind speed (m/s)	0.4	0.399	0.373
Max wind speed (m/s)	23.1	23.2	22

**The mean of monthly means (MoMM) is an average of the twelve monthly averages. Because it avoids seasonal bias, the MoMM often provides a better estimate of the long-term mean than would a simple mean*

These data were fed into a model of a "Frontier F24" 100 kW wind turbine to obtain the normalized power time series in Figure 12. This model is a rebuilt and upgraded Windmatic turbine with 24m diameter rotor[1]. The turbines will be installed on 50m towers.



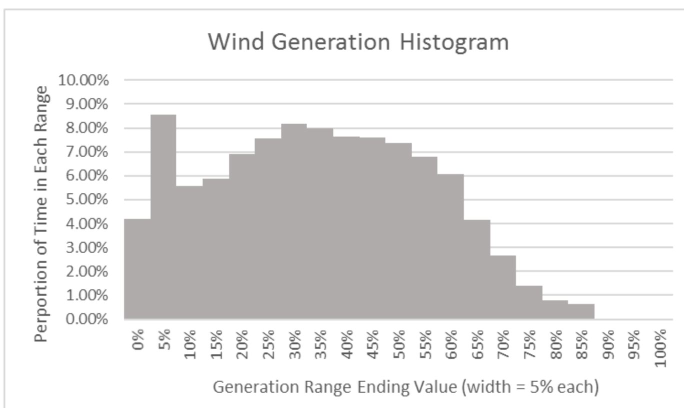


Figure 12 Shungnak Estimated Wind Resource (15 minute intervals, from simulations based on reginal wind data)

6.2 Wind Turbine Cost

The Frontier F24 100 kW unit was used as a model turbine. In this region, this has an in approximate capital cost of $700,000[2]. Installing multiple turbines reduces the per unit cost of each succeeding turbine by 5% each (assumed value). Per ACEP report, we assumed an O&M cost of $17,500 per year.

[1] Tony Jimenez, "Chefornak Minigrid Configuration Options" GMLC Report, October, 2017

[2] From discussions with Dennis Meiners

An additional fixed cost of $200,000 is assigned to the integration costs of the first turbine. So, the first turbine would cost $900,000, the second turbine would cost an additional $665,000, etc.

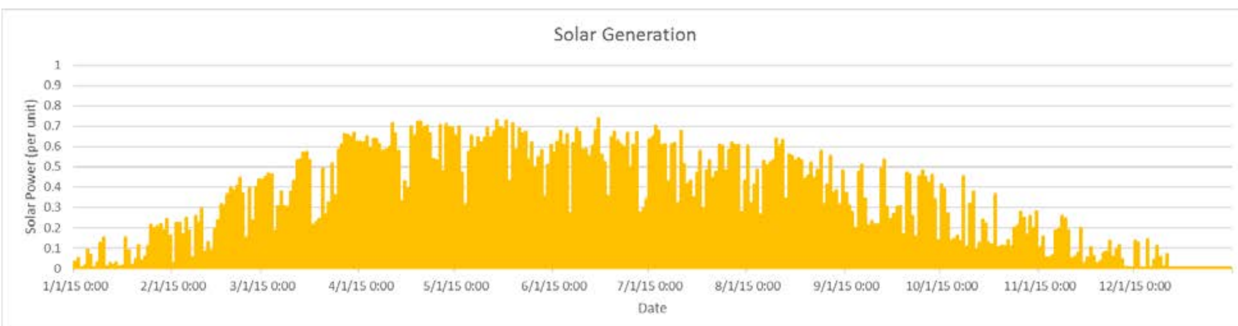
7.0 Solar Photovoltaic (PV) Technology

There is a single 7.5 kW solar PV system installed on the Shungnak Water Treatment Plant building. This installation is small enough to be ignored in this analysis.

7.1 Solar Resource

Solar irradiance data was collected from the weather station in the nearby village of Bettles Alaska (Latitude 66.92, Longitude 151.52). As Bettles is at an identical Latitude, 150 miles east, and has a similar regional climate we can expect that the solar resource for the two communities will be nearly identical. Using the online tool PVWatts[1], a unit PV installation was simulated to generate hourly PV power production likely to be available in Shungnak. Assuming the inverter is sized according to a 1:1 DC to AC ratio and that the PV array is installed at 20° tilt, the capacity factor for a PV plant would be 10.3%. Note that a higher DC to AC ratio, more solar panels,

The hourly power curve shown in Figure 13 demonstrates that an installation produces a maximum of 76 % of DC rated power. Note that available solar power is concentrated in the summer meaning that it would be less effective for serving net load which is concentrated in winter.



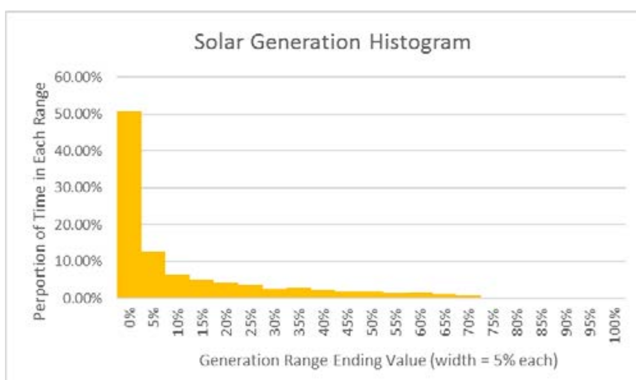


Figure 13 Shungnak Estimated Solar Resource (1 hour intervals, Bettles, AK used as a proxy for Shungnak)

[1] PVWatts Online PV Power Estimation Tool, [online], Available: http://pvwatts.nrel.gov/

7.2 Solar PV Costs

The solar PV installation cost is assumed to be \$5000/kW installed, based on rated DC output. This is intended to be a conservative estimate for a centralized plant, based on local trends. Residential cost would much higher. Installations larger than 50kW are purchased and installed in the region at a cost of roughly \$4000/kW rated[1].

[1] AKAES "Solar Photovoltaic Technology Report, ACEP, 042216 document

8.0 Hydro-power Technology

The nearby Dahl creek can be used to generate hydropower using a micro-turbine run-of the river design. The capacity factor for similar installations was estimated to be 24%. A detailed study performed on the local hydropower resource estimated that a 235kW unit would cost roughly $10,319,000 including the spillway, powerhouse, transmission line, and integration[1]. Figure 14 shows the proposed installation site including intake, penstock, and power house.

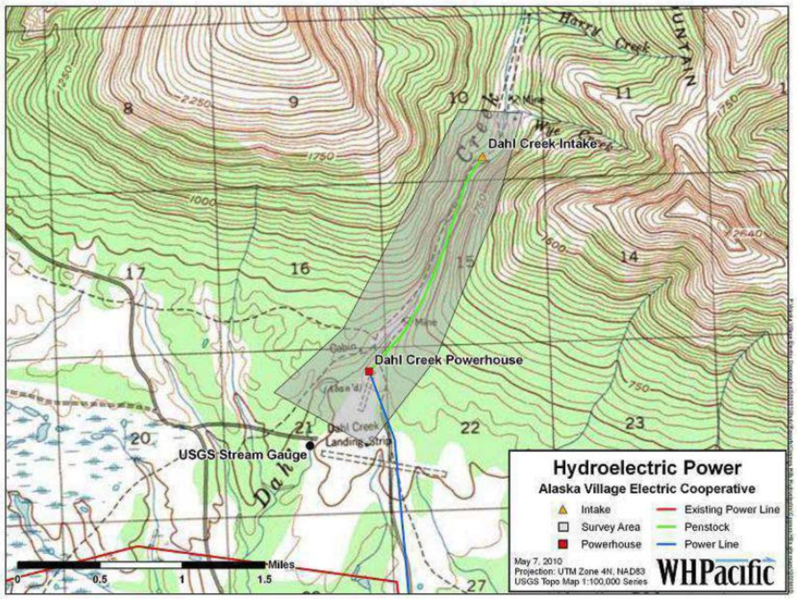


Figure 14

Table 5 Proposed Run-of the River Hydro-power Details

Watershed drainage area (sq. mi.)	9
Installed capacity (kW)	430
Est. annual energy (MWh)	1,800
Est. net head (ft.)	220
Est. hydraulic capacity (cfs)	35
Number of turbine-generator units	1
Turbine type	Crossflow
Est. penstock pipe I.D. (inches)	32
Est. penstock length (ft.)	7,800
Est. power line distance (miles)	2

As no additional information was available on the hydro output profile, a constant 24% (56.4kW) output was assumed during simulations. It was discovered early in the configuration analysis that the capital cost of a hydropower system was greatly above other configurations that were under consideration its fuel use reduction potential did not make up for the increased cost. A caveat to this is that this analysis only considered a 20-year horizon, which is much shorter than the expected serviceable life of a hydro-power system.

[1] Brian Yanity "Dahl Creek Community Hydroelectric Proposal" 2016

9.0 System Modeling

Modeling the Shungnak electrical and thermal system was primarily performed in the Microgrid Design Toolkit[1] (MDT) software package. The MDT simulates the microgrid under a number of proposed contingency scenarios. The algorithm moves along the Pareto optimal frontier[2] to reduce the number of simulated cases to the unique maximum cost/benefit tradeoffs cases. Cost is the capital cost and benefit is a combination of generator utilization, energy availability, renewable energy applied to thermal (spilled from electrical use), diesel fuel use, and heating fuel deferred. In the cases where heating stoves are allowed, an additional benefit is assigned to spilled renewable power in order to incentivize the optimization to make use of the spilled energy to offset thermal load. Table 5 lists the optimization decision variables along with the values they are able to take. Within this framework each energy efficiency cased (low, medium and high) along with the stoves and no stoves cases are implemented though different optimizations that produce different Pareto frontiers.

Each component within the system is assigned a probabilistic failure rate and failures are allowed to occur throughout the simulation horizon. For this reason, a very long time horizon is needed for simulation (25 years is chosen here) in order to reach numerically consistent steady state results. This is not the same as the economic analysis time horizon.

After the simulations have been performed, the data is exported into a series of spreadsheets where the economic analysis can be conducted. For the base case and each scenario in each Pareto frontier a yearly payment schedule for fuel costs (from each fuel cost case), generator replacement costs, and O&M costs, is calculated and projected back to the present using each nominal discount rate. The full set of sensitivity scenarios is listed in Table 6. The full list of case combinations, each of which has its own Pareto frontier, is shown in Table 7.

In the economic analysis costs and benefits are assigned to one of two groups: the utility, or the heating customers. The utility is assigned any costs associated with capital investment in energy assets (generators, turbines, PV panels, batteries, etc.) and the purchase of diesel fuel to run the generators. The heating customers are assigned the costs of any energy efficiency retrofitting, including heating stoves, and the purchase of heating fuel. While these two groups are not so cleanly divided, this split helps identify where the decisions of one can positively or negatively affect the other. In the cases without heating stoves for example, the installation of large quantities of renewable power would reduce the low-cost waste heat available to heating customers and could increase their costs.

Table 6 Analysis Decision Variables.

Decision Variables	Choices
Wind turbines (# of 100kW turbines)	1, 2, 3, 4, or 5
PV capacity (# of 100kW installations)	1, 2, 3, 4, or 5
Hydro power plant inhalation (235 kW)	Yes, No
Battery storage rating (kW/kWh)	50/50, 100/100
Number of Thermal Stoves (6kW each)	Positive Integer Values
Install New 100kW Generator	Yes, No

[1] Microgrid Design Toolkit, Sandia National Laboratories

[2] The Pareto optimal frontier refers to the range of choices that are considered ‘optimal’ in a multi-objective optimization problem. In this context, this means the configuration options that reduce fuel usage the most, at the least cost. When the benefits are plotted against the costs these choices form an arc (called a frontier) from the highest benefit highest cost options, to the lowest benefit lowest cost options.

Table 7 Analysis Sensitivity Cases

Sensitivity Case	Values
Nominal discount rate	3%, 7%
Low Energy Efficiency	Reduce thermal load by 25% Reduce electrical load by 5% Add $518,433 system capital cost to account for EE implementation cost
Medium Energy Efficiency	Reduce thermal load by 35% Reduce electrical load by 10% Add $1,414,120 system capital cost to account for EE implementation cost
High Energy Efficiency	Reduce thermal load by 45% Reduce electrical load by 15% Add $3,040,717 system capital cost to account for EE implementation cost
Heating Stoves Considered	Heating Stoves Allowed or Disallowed
Heating and Fuel Cost Sensitivity	Start at $7.99/gal heating and $7.16/gal diesel fuel costs respectively. Modify by the following factors: -30%, -15%, +0%, +50%, +100%

Table 8 Analysis Sensitivity Case Combinations

Low Discount Rate All Energy Efficiency Cases -30% fuel cost Heating Stoves Allowed	High Discount Rate All Energy Efficiency Cases -30% fuel cost Heating Stoves Allowed	Low Discount Rate All Energy Efficiency Cases -30% fuel cost Heating Stoves Disallowed	High Discount Rate All Energy Efficiency Cases -30% fuel cost Heating Stoves Disallowed
Low Discount Rate All Energy Efficiency Cases -15% fuel cost Heating Stoves Allowed	High Discount Rate All Energy Efficiency Cases -15% fuel cost Heating Stoves Allowed	Low Discount Rate All Energy Efficiency Cases -15% fuel cost Heating Stoves Disallowed	High Discount Rate All Energy Efficiency Cases -15% fuel cost Heating Stoves Disallowed
Low Discount Rate All Energy Efficiency Cases +0% fuel cost Heating Stoves Allowed	High Discount Rate All Energy Efficiency Cases +0% fuel cost Heating Stoves Allowed	Low Discount Rate All Energy Efficiency Cases +0% fuel cost Heating Stoves Disallowed	High Discount Rate All Energy Efficiency Cases +0% fuel cost Heating Stoves Disallowed
Low Discount Rate All Energy Efficiency Cases +50% fuel cost Heating Stoves Allowed	High Discount Rate All Energy Efficiency Cases +50% fuel cost Heating Stoves Allowed	Low Discount Rate All Energy Efficiency Cases +50% fuel cost Heating Stoves Disallowed	High Discount Rate All Energy Efficiency Cases +50% fuel cost Heating Stoves Disallowed
Low Discount Rate All Energy Efficiency Cases +100% fuel cost Heating Stoves Allowed	High Discount Rate All Energy Efficiency Cases +100% fuel cost Heating Stoves Allowed	Low Discount Rate All Energy Efficiency Cases +100% fuel cost Heating Stoves Disallowed	High Discount Rate All Energy Efficiency Cases +100% fuel cost Heating Stoves Disallowed

10.0 Modeling Results

This section provides a summary of the modeling results. The results are presented by plotting a certain metric, such as total fuel use, as a function of the total capital cost required.

10.1 Technical modeling results

Figure 14 displays the net percentage reduction in total fuel imported as a function of the estimated capital cost of the implementing the configuration. There are many configuration options to achieve 50% reduction in imported fuel. In this aggregated figure, the specific states of the decision variables are not visible. However, they are plotted against the capital cost associated with each configuration. The base case configuration consumes approximately 180,000 gal/year of fuel each year total, including both heating and diesel fuel. Energy efficiency measures would reduce this by roughly 12% (low EE case), 19% (medium EE case), or 26% (high EE case). In each configuration, options that include the use of heating stoves save more fuel than those that do not. Consequently, while 50% fuel use reduction (to less than 90,000 gal/year) is achievable without heating stoves, doing so is less expensive when they are included in the resource mix. These results demonstrate that it is indeed technically feasible to achieve substantial reductions in fuel consumption.

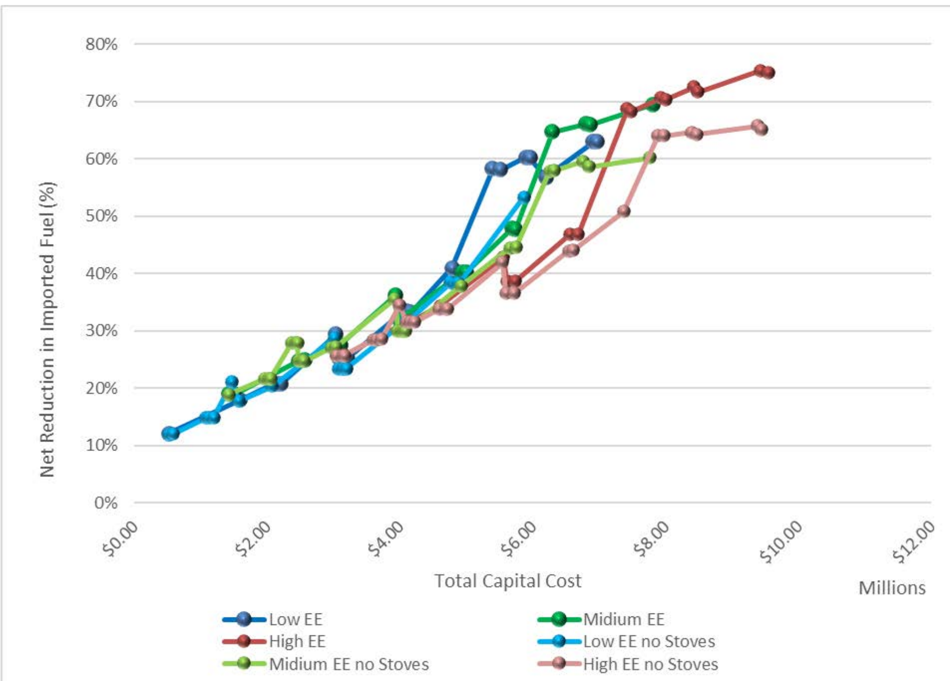


Figure 15 Net Reduction in Imported Fuel as a Function of Capital Investment

The impact of heating stoves on fuel usage can also be derived from these results. The number of heating stoves chosen for each configuration is effected by both the reduction in load due to energy efficiency and the increase in renewable power. This is because the number of stoves is driven by the maximum spilled renewable energy. These stoves both stabilize the grid and increase the efficacy of renewable power systems to reduce fuel consumption. Figure 15 shows the linear relationship between then number of stoves installed and the heating fuel saved in the configurations that utilize them. This would not hold for more stoves in any specific case as the number of stoves was chosen based on the amount of available spilled renewable power in each configuration. However, where the stoves are fully utilized, the fuel savings were calculated to be approximately 1,300 gallons/year of heating fuel saved per 6 kW stove installed.

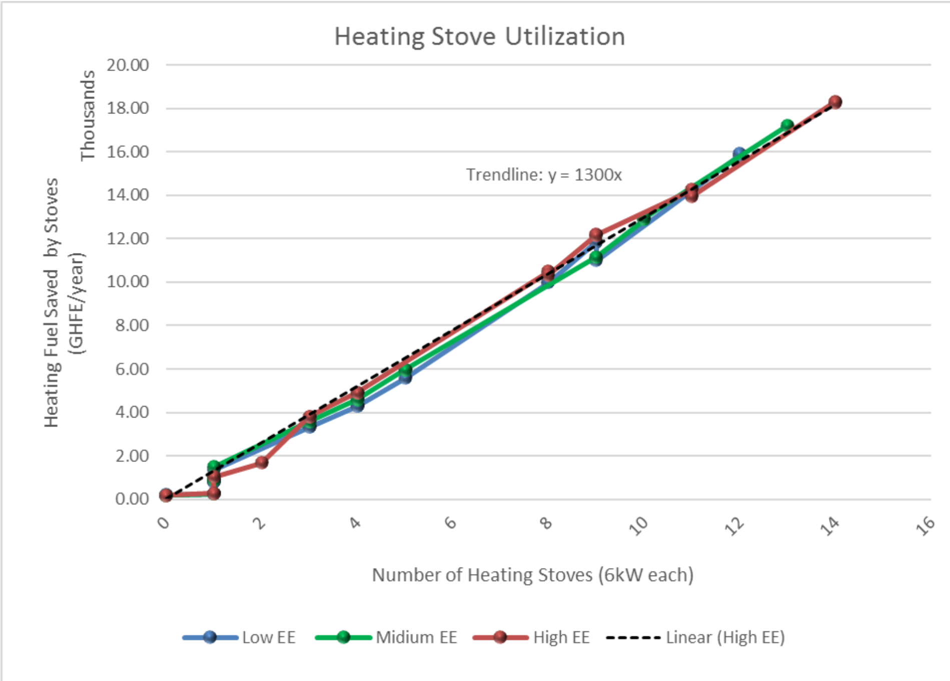


Figure 16 Heating Fuel Saved as a Function of the Number of Stoves Installed

Another trend that can be observed is in the runtime of the generators in each configuration. The base case total runtime is lower than each of the energy efficiency cases which is a counter intuitive outcome. This is a result of the various generators sizes employed in the village, as load is reduced it spends more time in the transition period (10 minutes per startup) from a large generator to a small generator and back again. During these times two or more generators must run simultaneously thereby increasing the total runtime and resulting replacement / O&M costs. Despite these small trends the total runtime between all generators remained roughly constant over all configurations.

10.2 Economic modeling results

The results of each configuration are compared based on their Net Present Value (NPV) which is calculated by assessing the costs and benefits over time (20-year horizon) and discounting both to their equivalent value in the present. Figure 16 shows the highest NPV configuration at each capital cost expenditure level. The same configurations are presented in Figure 16 and Figure 14 above, meaning that the highest reduction in fuel consumption roughly correlates with the highest return on investment. While financing structures are out of the scope of this report, each optimal case is presented to inform future financial assessment. The conclusion of this report discusses the configuration associated with the maximum value (highest NPV) on this curve.

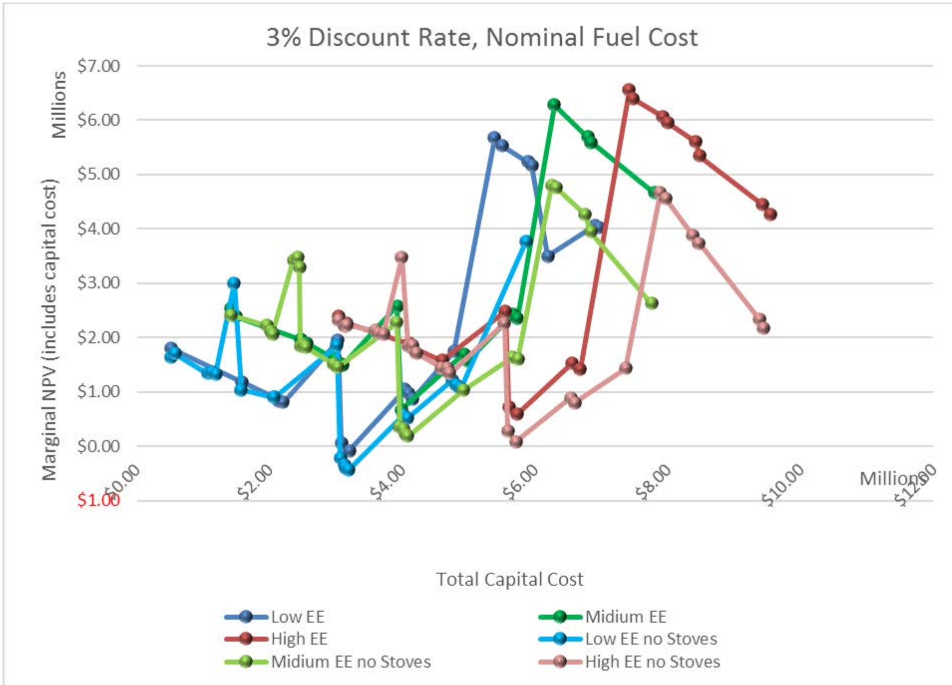


Figure 17 NPV of Configurations (presented in order of increasing fuel consumption reduction percentage matching Figure 14).

Given the strong dependence of these results on the price of fuel a sensitivity analysis was performed. Under cases where barges are able to freely travel up river the fuel price may fall to between $6 and $7 per gallon. However, under cases where no barges are able to traverse the river, due to ice or low water levels, prices can jump to over $16 per gallon. To capture this whole range a fuel cost adjustment factor, from -30% to +100%, was applied. The results of this analysis are shown in Figure 17 and Figure 18. At 3% nominal discount rate configurations with positive NPV exist at all fuel prices studied. Higher fuel prices predictably increase the NPV of fuel saving interventions. These results demonstrate that the highest NPV configuration is robust across a wide range of potential fuel prices. Further, at this discount rate, all configurations maintain positive NPV even if fuel prices fall 30% below expected levels.

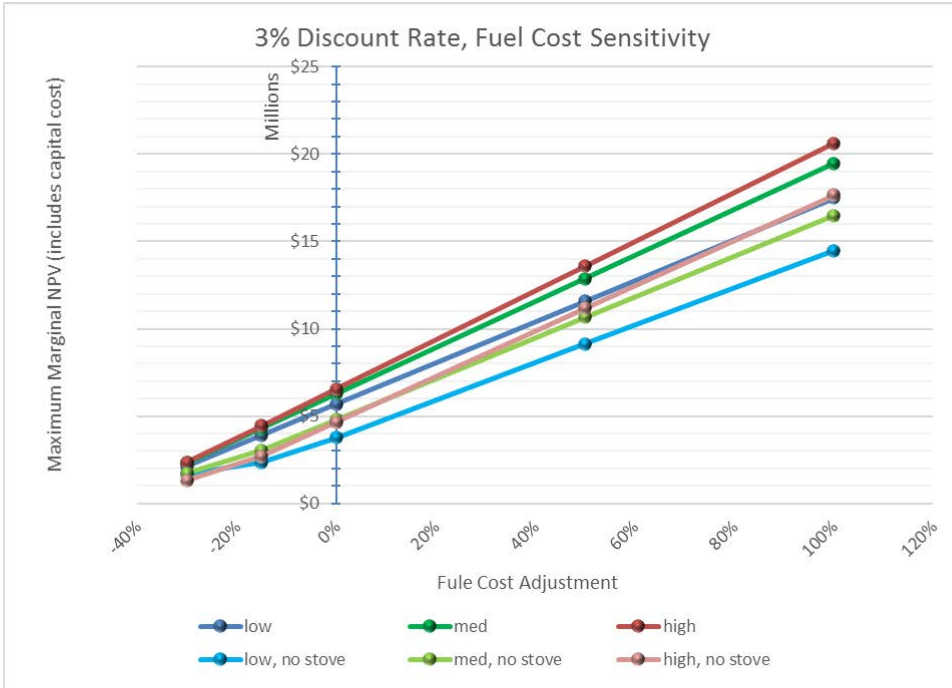


Figure 18 Maximum Marginal NPV as a Function of Fuel Cost at 3% Nominal Discount Rate

At a 7% discount rate, as shown in Figure 18, future fuel savings are assigned a lower weight. Under these conditions, not all cases achieve positive NPV. Specifically, the high-energy-efficiency configuration has negative NPV under the case where fuel prices are 30% lower than expected. However, the highest NPV configuration at nominal fuel rates, using medium energy efficiency, is robust across this range.

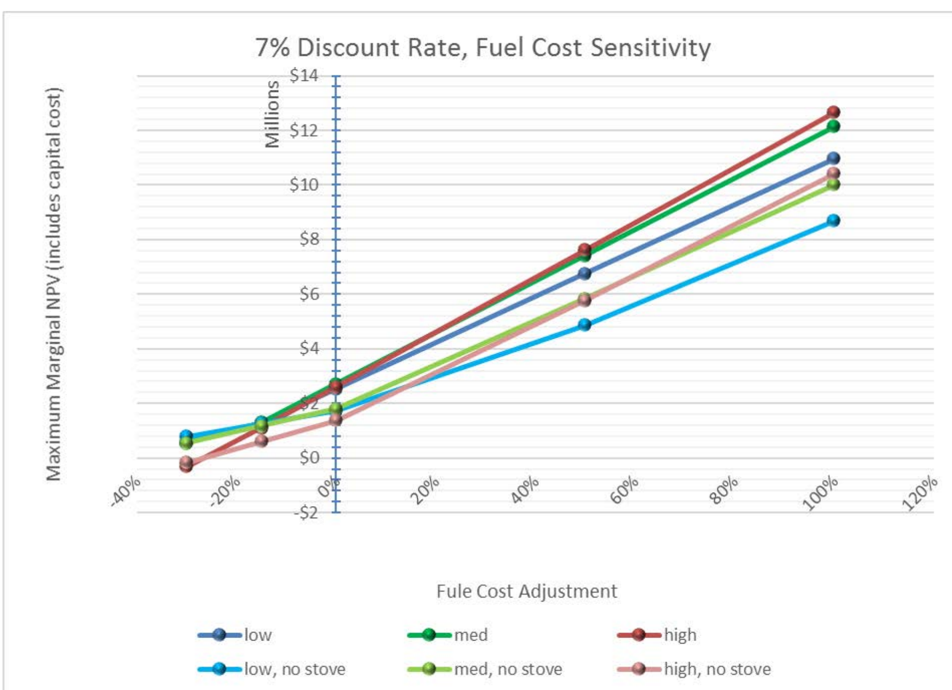


Figure 19 Maximum Marginal NPV as a Function of Fuel Cost at 7% Nominal Discount Rate

From these results we can determine an optimal configuration for each discount rate and for circumstances with and without the utilization of heating stoves. In the tables below, columns are each descriptive of a component of an optimal configuration. The first 5 rows describe what additional power assets are installed in each case. The next four rows describe the different purchase costs and who the analysis allocates the cost to (either the utility or the heating customers). Additional costs that are not shown in the table include diesel fuel cost (Utility), heating fuel cost (Customers), and generator operation and maintenance cost (Utility). The reason for breaking out these different entities is to illustrate how each will be effected by the optimal configurations. The net reduction in imported fuel presents a self-descriptive metric for how much the supply independence and thereby energy resilience of the community has been improved. Together with the purchase costs, the savings in the fuel and O&M costs discounted to the present are shown in the next three rows as the NPV allocated to the utility, the heating customers, and the total, which is the sum of the two. The last row is the return on investment (ROI) which is the ratio of the total savings to the capital cost.

When a 3% discount rate is used and heating stoves are included in the analysis, the results are shown in Table 8. Each of the optimal cases include both five, 100 kW wind turbines (500 kW total) and an efficiently sized diesel generator (100 kW) to improve fuel efficiency and prevent wet-stacking the larger generators. None of the optimal cases include the hydro facility due to the high cost relative to the other potential resources.

Table 9 Optimal Cases with Heating Stoves and 3% Discount Rate

With Heating Stoves 3% Discount rate	**Highest NPV Case for Utility**	**Highest NPV Case for Heat Customer**	**Highest Total NPV Case**
New Solar	SG 100	SG 500	SG 100
New Hydro	No Generator	No Generator	No Generator
New Wind	WG 500	WG 500	WG 500
New Storage	No Battery	No Battery	No Battery
New Generator	100kW Diesel	100kW Diesel	100kW Diesel
Energy Efficiency Cost (Customers)	$3,041,000	$1,414,000	$3,041,000
Renewable Energy Purchase Cost (Utility)	$4,300,000	$6,300,000	$4,300,000
Stove Purchase Cost (Customers)	$33,000	$48,000	$33,000
New Generator Purchase Cost (Utility)	$41,000	$41,000	$41,000
Net Reduction in Imported Fuel	69%	69%	69%
Marginal NPV (Utility Only)	$5,719,000	$2,355,000	$5,719,000
Marginal NPV (Heating Customers Only)	$835,000	$2,305,000	$835,000
Total Marginal NPV	$6,554,000	$4,660,000	$6,554,000
Total % ROI	189%	160%	189%

Without heating stoves, no value is derived from spilled renewable power. This changes results as the optimal case for heating customers under these conditions involves the lowest level of energy efficiency and no extra renewable power. Part of this result comes from the benefit of waste heat to heating customers. As renewable power reduces the utilization factor of the diesel generators, there would be less waste heat available which would make the customers more dependent on heating fuel. The highest total NPV is still derived from a strong investment in wind power (500 kW), purchasing a smaller diesel generator (100 kW), and moderate investments in energy efficiency (10% electrical and 35% thermal load reduction) and solar power (200 kW).

Table 10 Optimal Cases without Heating Stoves and with a 3% Discount Rate

Without Heating Stoves 3% Discount rate	**Highest NPV Case for Utility**	**Highest NPV Case for Heat Customer**	**Highest Total NPV Case**
New Solar	SG 200	No Generator	SG 200
Hydro	No Generator	No Generator	No Generator
New Wind	WG 500	No Generator	WG 500
New Storage	No Battery	No Battery	No Battery
New Generator	100kW Diesel	No Generator	100kW Diesel
Energy Efficiency Cost (Customers)	$1,414,000	$518,000	$1,414,000
Renewable Energy Purchase Cost (Utility)	$4,800,000	$0	$4,800,000
Stove Purchase Cost (Customers)	$0	$0	$0
New Generator Purchase Cost (Utility)	$41,000	$0	$41,000
Net Reduction in Imported Fuel	58%	12%	58%
Marginal NPV (Utility Only)	$4,429,000	$191,000	$4,429,000
Marginal NPV (Heating Customers Only)	$371,000	$1,454,000	$371,000
Total Marginal NPV	$4,800,000	$1,645,000	$4,800,000
Total % ROI	177%	417%	177%

When a 7% discount rate is used, corresponding to expected ROI in financial markets, future fuel costs and generator O&M costs are weighted less than they are for the 3% discount rate condition. This, in effect, makes purchases in the present more difficult to justify, corresponding to lower calculated NPVs across the decision space. However, the optimal cases were nearly the same as with the 3% discount rate. The optimal case for the utility still includes a strong investment in energy efficiency (15% electrical and 45% thermal load reduction), wind (500 kW), solar (100 kW), and a new smaller generator (100 kW). This configuration would not have positive NPV for heating customers and so would be difficult to justify without a utility program to incentivize energy efficiency or take on some of the cost in another way. The optimal case for the heating customers differs in that it includes more solar power, a small battery, and much less energy efficiency. This case is essentially driven by maximizing spilled wind power and, as it would not have positive NPV for the utility, is not a viable configuration. The highest total NPV case has a similar renewable power and diesel generator makeup as for the 3% rate while it is based on a moderate investment in energy efficiency (10% electrical and 35% thermal load reduction).

Table 11 Optimal Cases with Heating Stoves and a 7% Discount Rate

With Heating Stoves 7% Discount rate	**Highest NPV Case for Utility**	**Highest NPV Case for Heat Customer**	**Highest Total NPV Case**
New Solar	SG 100	SG 500	SG 200
Hydro	No Generator	No Generator	No Generator
New Wind	WG 500	WG 500	WG 500
New Storage	No Battery	No Battery	No Battery
New Generator	100kW Diesel	100kW Diesel	100kW Diesel
Energy Efficiency Cost (Customers)	$3,041,000	$518,000	$1,414,000
Renewable Energy Purchase Cost (Utility)	$4,300,000.00	$6,300,000.00	$4,800,000.00
Stove Purchase Cost (Customers)	$33,000	$45,000	$34,000
New Generator Purchase Cost (Utility)	$41,000	$41,000	$41,000
Net Reduction in Imported Fuel	69%	63%	65%
Marginal NPV (Utility Only)	$2,856,000	$472,000	$1,944,000
Marginal NPV (Heating Customers Only)	$250,000	$1,432,000	$773,000
Total Marginal NPV	$2,606,000	$961,000	$2,716,000
Total % ROI	135%	114%	143%

As with the 3% discount rate, the optimal configurations at the 7% rate without the use of heating stoves use significantly less renewable power and achieves less reduction in imported fuel than the cases that use stoves. This difference is increased by the higher discount rate devaluing future fuel and O&M costs. The optimal case for the heating customers in this case is to simply invest in a moderate improvement in energy efficiency and not install any renewable power. The optimal case for the utility takes the opposite approach, installing significant renewable power opting for strong investment in energy efficiency. However, this could impact heating customers significantly. Again, the highest total NPV case is a balanced approach utilizing moderate energy efficiency, some wind power, and a small battery. Note that this configuration does not achieve the 50% fuel consumption reduction target though it is still the best option under the circumstances. The profitability of this configuration is also more robust then the high-energy efficiency cases to lower fuel price as shown in Figure 18.

Table 12 Optimal Cases without Heating Stoves and with a 7% Discount Rate

Without Heating Stoves 7% Discount rate	Highest NPV Case for Utility	Highest NPV Case for Heat Customer	Highest Total NPV Case
New Solar	SG 200	No Generator	No Generator
Hydro	No Generator	No Generator	No Generator
New Wind	WG 500	No Generator	WG 100
New Storage	No Battery	No Battery	No Battery
New Generator	100kW Diesel	No Generator	No Generator
Energy Efficiency Cost (Customers)	$3,041,000	$1,414,000	$1,414,000
Renewable Energy Purchase Cost (Utility)	$4,800,000	$0	$950,000
Stove Purchase Cost (Customers)	$0	$0	$0
New Generator Purchase Cost (Utility)	$41,000	$0	$0
Net Reduction in Imported Fuel	64%	19%	28%
Marginal NPV (Utility Only)	$2,254,000	$771,000	$1,354,000
Marginal NPV (Heating Customers Only)	$1,131,000	$561,000	$434,000
Total Marginal NPV	$1,124,000	$1,331,000	$1,788,000
Total % ROI	114%	194%	176%

11.0 Caveats, Limitations, Conclusions, and Future Work

11.1 Conclusions (Shungnak Specific)

This analysis assesses options to retrofit Shungnak's energy infrastructure in order to reduce energy cost and reduce reliance on imported fuel. Optimal cases depended on the cost of fuel, who the system was being optimized for (the utility, the heating customers, or both together), the financial discount rate (3% or 7%), and whether or not residential heating stoves could be installed to absorb excess renewable power. The base case and each configuration in this analysis assumes that the generator waste heat is fully utilized, which may involve expansion of the existing waste heat recovery system. Thermal and electrical demand was not scaled over the NPV analysis. The NPV analysis did not explicitly consider inflation for fuel cost or electricity price; however, the analysis did explore sensitivity to the cost of fuel. The neighboring village of Kobuk was treated as an electrical load for the purposes of this analysis. In the circumstance where stoves could be installed, and future costs were discounted at 3% per year, the optimal cases reduced fuel consumption (including diesel and heating fuel), from 65% - 69% while resulting in a net cost savings from $2.7M – $3.7M in 2018 dollars. A higher discount rate results in a lower NPV for fuel savings as future fuel costs are weighted less.

Based on this analysis it is recommended that the use and integration of stoves be studied in greater technical and financial detail as they enable highly efficient use of spilled renewable power. If the use of heating stoves is feasible from a business case perspective, and if financing can be secured at a discount rate of 3% per year, this analysis recommends the following configuration: energy efficiency retrofitting to reduce Shungnak's electrical load by 15% and thermal load by 45% followed by installation of up to 500kW of wind turbines, coupled with a smaller 100kW generator to run during periods of low load, followed by installation of up to 100kW of solar power. This configuration would, if implemented, reduce Shungnak's annual fuel consumption by approximately 69%. Broken out by fuel type, this means that average diesel fuel consumption would be reduced to 33,551 gal/year (from 129,385gal/year), and the average heating fuel consumption would be reduced to 24,719 gal/year (from 56,690 gal/year). With the existing maximum fuel storage volume, this would extend the average on-site supply duration for diesel from 53 days to 204 days and for heating fuel from 193 days to 443 days making the village more resilient to fuel supply disruptions. The improved resilience that this configuration provides would also save the community roughly $6.5M in net over the next 20 years, assuming fuel price remains at current levels.

The profitability of this configuration is somewhat robust as its NPV is positive even with a 30% reduction in current fuel prices, though this would provide a significantly lower return on investment. In this and other configurations the highest value comes from the initial investments in energy efficiency, followed by wind power, followed by solar power. Hence it is our recommendation that investments be prioritized in that order as well. If it is determined to be viable, a heating stove program should be rolled out with Shungnak heating fuel customers as the planned wind power would reach levels where it may be spilled regularly. The purchase of an efficiently size generator should be similarly planned to prevent wet stacking in the other generators due to high penetration of renewable power.

If circumstances warrant a higher discount rate of 7%, and/or do not permit the use of heating stoves, the cost optimal configurations can be found in Table 10, Table 11, and Table 12. The recommended configuration for these cases correspond with the highest total NPV as these solutions weight value to the heating customers and the utility equally. For 3% discount rate and no-stoves the fooling configuration is recommended: energy efficiency retrofitting to reduce Shungnak's electrical load by 10% and thermal load by 35% followed by installation of up to 500kW of wind turbines, coupled with a smaller 100kW generator to run during periods of low load, followed by installation of up to 200kW of solar power. This configuration would reduce fuel consumption by 57.83% with similar outcomes as described above. At a 7% discount rate with stoves the optimal configuration would reduce fuel consumption by 64.71% (Table 11) and without stoves the optimal configuration would reduce fuel consumption by 27.90% (Table 12). The 7% discount rate without stoves condition's optimal configuration did not reduce fuel consumption by greater than 50% as it

11.2 Conclusions (General)

Most of this analysis applies only to the specific circumstances of this village under the conditions that it is currently under. However, several general conclusions can be drawn around the framework of this analysis.

Despite poor access to local renewable energy resources such as wind or solar, relative to prime locations, the economic case can be driven by high energy costs. The right combination of enough wind and solar, effective energy efficiency measures, and high fuel prices enables positive returns on investment while achieving a greater than 50% reduction in imported fuel.

At high renewable utilization rates, the application of heating stoves can make the difference between an installation having positive NPV and not. This can be challenging as the utility, who has access to capital, is not the entity that directly benefits. A similar situation exists for other energy efficiency retrofitting measures. The community benefits directly whereas the utility may lose some profit from reduced energy consumption. There are potential solutions to this problem that spread out the benefits and costs appropriately though they are beyond the scope of this analysis.

Heating stoves essentially act as thermal batteries whose energy is stored in the heat of people's homes. This can be a very low cost way of accommodating excess renewable generation on mini-grid systems. The use of heating stoves enables a higher reduction in imported fuel through higher penetration of renewable power. High penetration of renewable power, with or without stoves greatly reduces fuel consumption and can save considerable money. However, this comes with low generator utilization factors which could result in wet-stacking. This can be addressed by installing an appropriately sized (smaller) diesel generator to support the load when other generators would be lightly loaded. These novel interventions were key aspects in this analysis and the achievement of high fuel use reduction and hence will likely be important to consider in future analyses of arctic communities with high heating loads and fuel cost

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