Hydro and Wave Generation Integration Planning for an Isolated Diesel System in Hot Springs Cove, Canada

by

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B.Eng., University of Victoria, 2009

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Supervisory Committee

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Abstract

Most remote communities in Canada and around the world rely on diesel power for their electricity. Remote diesel power is emissions intensive, expensive to service, noisy, unreliable, costly and risky to transport. Governments, communities, utilities and industry want to displace diesel generation with renewable energy. Renewable electric generation is intermittent and cannot meet electrical demand without energy storage or combination with another generation source. This work examines the cost optimization of renewable energy integration with existing diesel infrastructure in remote communities.

Given the variety of geographical locations of remote communities and their proximity to different renewable resources, there is value in developing and understanding a variety of alternative electric supply systems. This work focuses on integrating micro-hydro and wave energy because the case study community is near excellent wave energy and hydro energy resources.

Most remote communities in Canada receive electrical services from regional utilities. These utilities have moved towards net-metering programs and power purchase agreements (PPAs) with the goal of integrating renewable energy into isolated diesel systems. This approach has the benefit of outsourcing a difficult technical challenge and controlling costs. Such PPA programs are designed to be cost neutral, without raising community electric rates. Rates offered under PPAs are based on avoided diesel fuel cost. Thus far, these rates have encouraged little renewable energy investment.

This work provides an alternative method for calculating allowable costs for renewable energy integration that could facilitate crafting new utility policy, including setting optimal incentives for PPA contracts with Independent Power Producers. A detailed computer-based model of a case study community electric system was used to calculate allowable Levelized Cost of Electricity (LCOE) using the following inputs: electric demand, local renewable resources, generator models and existing costs. Hydro-diesel, wave-diesel and wave-hydro-diesel energy inputs with different capacities were modeled to provide greater insight into the value of renewable energy resources to mitigate diesel use.

The hydro-diesel systems performance had little variability in operations and costs for selected hydro capacities of 225kW, 275kW and 325kW. The 225kW hydro-diesel system had the best utilization, meeting 65.2% of annual demand and reducing fuel by 65.8%. The variability in the hydro resource will cause year-to-year variability in fuel use reductions ranging from 64-92%. The emissions rate for this system is 293gCO_2/kWh. The allowable costs for 225kW hydro generation are \$0.68/kWh and 17,000\$/$kW_{installed}$.

For the wave-diesel system, wave capacity ranges from 200kW to 90kW with respective fuel use reductions of 68.4% to 39.6%. The emissions rate is 271 gCO_2/kWh to 518gCO_2/kWh. The range of allowable LCOE values of the wave systems are 0.51-0.60\$/kWh and the range of allowable installed costs are 19,800\$/$kW_{installed}$ to 25,400\$/$kW_{installed}$.

For the 200kW wave plus 225kW hydro scenario, the allowable LCOE is 0.67$/kWh where 80% of the wave supply is utilized and 24% of the hydro supply is utilized. For the 90kW wave plus 225kW hydro scenario, the allowable LCOE is 0.66$/kWh where 93% of the wave supply is utilized and 58% of the hydro supply is utilized.

The greatest advantage of the combined hydro and wave systems is to maximize diesel offsets with hydro generation supplementing wave generation. Hydro system utilization is rolled back to maximize zero-cost wave generation. Hydro and wave generation contribute similar generation amounts except during the summer season, when hydro generation decreases.

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Nomenclature

Acronyms

AVEC	Alaska Village Electric Cooperative
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CIPP	Commercial and Institutional Power Producers
DSA	Dynamic Systems Analysis
GAMS	General Algebraic Modeling System
GHG	Greenhous Gas Emissions
GNWT	Government of the Northwest Territories
GW	Giga-watt
HOMER	Hybrid Optimization Model for Electric Renewables
H2	HYBRID2
IESO	Independent Electricity System Operator
INAC	Indigenous and Northern Affairs Development Canada
IEA	International Energy Agency
IRP	Integrated Resource Plan
kW	Kilo-watt
kWh	Kilo-watt-hour
LCOE	Levelized Cost of Electricity

MILP	Linear Mixed Integer Problem
MW	Mega-watt
NO2	Nitrogen Dioxide, NOx
NIA	Non-Integrated Areas
NMHC	Non-Methane Hydro Carbons
NCPC	Northern Canada Power Commission
NTPC	Northwest Territories Power Corporation
NWTPUB	Northwest Territories Public Utilities Board
PM	Particulate Matter
PPA	Power Purchase Agreement
PV	Present Value
QEC	Qulliq Energy Corporation
RCOM	Remote Community Optimization Model
RPS	Renewable Portfolio Standard
RRA	Revenue Requirement Application, BC Hydro
WAPA	Western Area Power Authority
WCWI	West Coast Wave Initiative
WEC	Wave Energy Conversion

Subscripts

$V_{tank}(t)$	Volume of diesel fuel storage capacity (L)
$V_{Fuel}(t)$	Volume of diesel fuel in time period (t)
V_{Fuel}	Volume of diesel fuel (L)
$V_{Delivery}$	Volume of diesel fuel per delivery by barge (L)
$X_{Barge}(t)$	Value 1 is barge delivery occurrence in time period (t), value 0 is no barge delivery in time period (t)
$P_{D}Max$	Maximum capacity or power output of the diesel generator
$P_{D}(t)$	Power output of diesel generator at the community bus (net losses) in time period (t)
P_{D}	Power output of diesel generator at the community bus (net losses)
$X_{D}(t)$	Diesel generator ON state (X is 1), OFF state (X is 0) in time period (t)
$X_{DswitchOn}$ (t)	Value 1 is an occurrence of the diesel generator switches from an OFF state to an ON state in time period (t)
A	Minimum hours for diesel generator to be ON before shutting down
η_{Deff}	Diesel conversion efficiency kWm to kWe
$X_{H}(t)$	Value 1 is hydro generator state is ON, value of 0 is hydro generator state is OFF in time period (t)
$X_{SwitchON}(t)$	Value 1 is hydro generator switched from on OFF state to an ON State in time period (t)
$Q_{Turbine}(t)$	Flow rate into the hydro generator in time period (t),
$Q_{Turbine}$	Flow rate into the hydro generator
Q_{D}	The ‘Q Design’ value is the maximum flow rate selected for the hydro generation system
$P_{H}(t)$	Power output of the hydro generator at the community bus (net losses) in time period (t)

P_H	Power output of the hydro generator at the community bus (net losses)
P_H, Max	Maximum hydro generator power output. It is not a parameter of the model. Constraints are placed on the $Q_{turbine}$ (t) variable.

P_H, Min Shutdown

Minimum hydro generator power output before switching from an ON state to an OFF state. It is not a parameter of the model. Constraints are placed on the $Q_{turbine}$ (t) variable.

P_H, Min Start-up

Minimum hydro generator power output before switching from an OFF state to an ON state. It is not a parameter of the model. Constraints are placed on the $Q_{turbine}$ (t) variable.

Q_{IFR}	Inflow stream requirement, hydro flow rate.
H_{Net}	The effective head value for hydro power calculation. The energy losses due to water flowing through the penstock is accounted for and deducted from gross head.
H_{Gross}	The gross head is the physical height of the penstock pipe.
η_{Total}	Total efficiency is defined by the electrical equipment specifications.
$\eta_{Turbine}$	Hydro turbine system, containing a generator and motor, efficiency is defined by the equipment specifications.
$\eta_{Powerhouse}$	Hydro Powerhouse efficiency is defined by the electrical equipment consumption.
$\eta_{Transformer}$	Hydro Powerhouse step-up voltage transformer efficiency defined by the electrical equipment specifications.
$\eta_{Transmission}$	Transmission line and step down transformer at community bus efficiency is based on Hydro One's published losses for distribution level utility equipment.

$V_{Reservoir}$ (t) The volume of the reservoir at the head of the penstock, m^3

$Q_{Measured}$(t) The measured flow rate

$Q_{Netmeasured}$ (t) The net measured flow rate is the deduction of the Q_{IFR} from the measured flow rate in each time period (t).

Q_{Spill} (t) The spilled flow rate over the reservoir containment. The overflow of the net measured flow rate in time period (t). The hydro flow amount in excess of the containment capacity and utilization of the hydro turbine system.

1.0 Introduction

1.1 Motivation

A community is considered "remote" if it is not connected to central energy infrastructure, such as a regional electrical grid or a natural gas pipeline. Being disconnected forces the community to rely on locally stored fossil fuels that are delivered by land, sea, or air for electric generation [1]. Remote communities can be found in a variety of climates and typically have small populations.

In 2011, Natural Resources Canada reported Canada had 292 remote communities with a total population of 194,281 [2]. Of the 292 communities, 170 remote communities were identified as indigenous with a collective population of 126,861, while the remaining 122 sites were non-indigenous communities or commercial outposts with a total population of 67,420. The vast majority of these remote communities, 251 in total, have fossil fuel power plants, consisting mainly of diesel fuelled generation [2], with a combined capacity of 453.3 MW.

In comparison to the national average of 0.129 $/kWh for a Canadian household, electricity in remote communities is expensive and carbon intensive [3]. Consider Nunavut, population 37,000, spread across 2.1 million square kilometers [4]. The Qulliq Energy Corporation (QEC) is the only power generating utility in Nunavut, with 25 standalone diesel power stations. In 2016, Nunavut's GHG electric generation intensity was 750 gCO2/kWh, nearly 5.4 times greater than the national average of 140 gCO2/kWh [5]. Electric rates for residential customers range from 0.5856 to 1.487 $/kWh [6].

The Northwest Territories Power Corporation (NTPC) provides electric services to most of the remote communities within the Northwest Territories and operates 28 isolated diesel plants [7]. As of September 2020, for 20 communities that are diesel or natural gas powered, electricity is provided at a subsidised rate of 0.306 $/kWh up to 1000 kWh. Electrical use past 1000 kWh is no longer subsidized and costs 0.6837 $/kWh[1], approximately five times the national average.

There are many challenges and implication of diesel fuel dependency in remote locations. Diesel electric supply infrastructure is expensive, creates noise and chemical emissions and presents environmental risk. There is inherent risk of fuel spills and soil contamination in the transportation and storage diesel fuel. Fuel prices are based on the global market, creating uncertainty for future operations costs. Fuel combustion emits Carbon Dioxide (CO2) and contributes to regional greenhouse gas concentrations. These challenges combined with the high cost of electricity have spurred isolated diesel fuelled electric systems stakeholders to investigate electric supply alternatives.

Electric utilities have financial levers to mitigate existing high electric costs in remote communities including: managing subsidies, bulk fuel purchases, and equalization of electric rates [4]. Central grid extension projects through new transmission lines have historically been the principle tool for regional utilities to reduce diesel electric supply [8]. Other diesel mitigation options include: installing alternative sources of electric supply, increasing systems efficiencies, and reducing electric demand.

The location of many isolated communities with respect to renewable resources limits electric supply options. As an example, any community may consider system efficiency improvements though not all communities may have a significant wind resource to harness as an alternative electric supply. Given these geographical limitations to renewable resources, there is value in developing a variety of alternative electric supply systems. Diversity of electric supply options increases the basket of diesel mitigation options for any isolated community.

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[1] https://www.ntpc.com/customer-service/residential-service/what-is-my-power-rate [last accessed: 2021-03-25].

This work will focus on hydro-based electric supply options to mitigate diesel fuel use for a coastal remote community in Canada's Pacific region with an isolated diesel electric supply system. Specifically, a mix of wave energy converter (WEC) technologies that harness ocean wave power and small scale hydro run-of-the-river systems[2] are considered. Wave energy supply systems are not widely deployed in Canada [9]. For the 14 remote or non-integrated areas that BC Hydro provides electric service to, approximately 50% of electricity is generated from diesel and 50% is generated from renewable sources, mostly hydro [10].

Many West Coast communities in Canada are in proximity to one or both of the renewable resources illustrated in Figure 1-1[3]. Diesel powered communities are represented by orange dots, the magnitude of river current energy potential is represented by blue lines and the mean annual wave power density is indicated with shades of blue in the ocean. Many coastal communities are adjacent wave density potential ranging from 5 kW/m to 40 kW/m and river current energy potential ranging from 5 kW to 1 MW. Despite the magnitude of the wave energy resource, wave energy technology is pre-commercial and there have been no WEC deployments to date on the BC coast. However, the state of the technology does not reflect the potential of this renewable resource to contribute to Canada's coastal electric supply options.

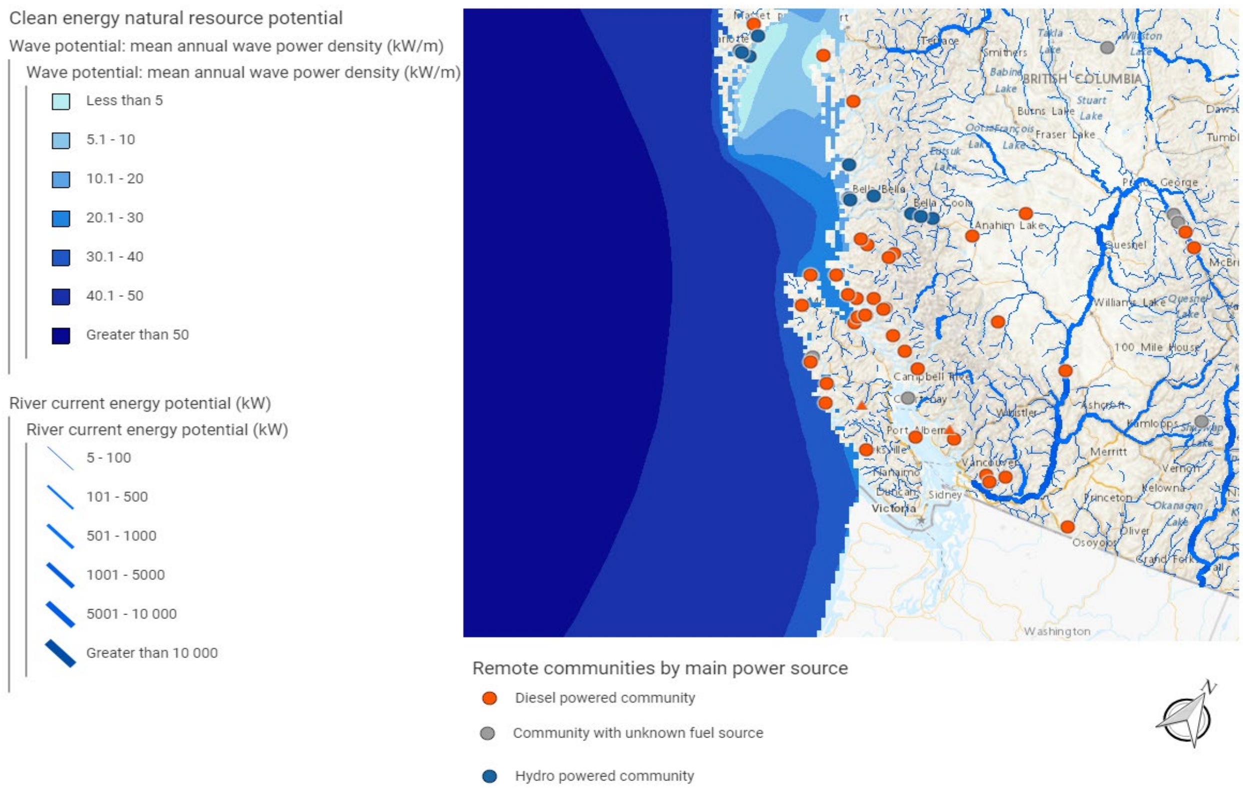
For the remote coastal community under investigation, the focus is to understand the value of both hydro and WEC systems to diesel mitigation. This work does not diminish the value of other non-hydro-based electric supply options or other diesel mitigation options. Rather it is intended to contribute to the commercialization and deployment of these technologies for other remote coastal communities to consider as viable diesel mitigation options.

The pathway to propose an alternative electric supply is not only an engineering exercise. The intersection of technology and community electric supply systems must address the current challenges and needs of the community.

[2] A run-of-the-river hydro system is a system without a reservoir.

[3] http://atlas.gc.ca/rced-bdece/en/index.html [last accessed: 2021-03-25].

Figure 1-1: Remote Communities and Hydro Resources of British Columbia Coast



1.2 Renewable Energy Integration Planning

Remote communities have many services that are reliant on continuous and affordable electric supply systems. Food storage, education and health services are just a few examples of community operations that are critical to the community. Remote community residents face high electricity costs, diesel emissions and power supply interruptions. In order to maintain these community services, diesel electric supply systems owned and operated by regional electric utilities are the norm.

Adding alternative electric supply to existing diesel systems must address local needs and current business operations. There have been numerous studies and programs aimed at reducing reliance on diesel use in remote communities [11] [12]. Remote electric supply system stakeholders should guide renewable energy integration planning.

The electric service business case is focused on sales volume, minimizing operational costs, orchestrating capital sustaining investments and avoiding adverse impacts on customer electric rates and charges [13]. Utility institutional knowledge is built on decades of experience working with existing generation and transmission assets. For remote communities, this means working with diesel power assets and the cost structure of diesel power. Proposals for increasing renewable energy supply must fit within utilities' existing decision making framework so that utilities can continue to fulfil their mandates, especially cost control and reliability.

Nunavut's Qulliq Energy Corporation (QEC), Northwest Territories Power Corporation (NTPC), British Columbia's BC Hydro and Ontario's Hydro One have moved towards implementing net-metering programs and Power Purchase Agreements (PPA) [14] [15] [16] [17]. Current utility driven renewable energy programs are low risk for utilities and require little utility-sourced capital investment.

In May 2020, in an application to the Minister responsible for QEC, QEC proposed a cost-neutral pricing structure for Commercial and Institutional Power Producers (CIPP) [14]. The proposed program offers Independent Power Producers (IPPs) the opportunity to invest in QEC isolated systems by interconnecting renewable energy supply systems. The proposed rate for QEC power purchase agreements with CIPP are based on the 3-year average avoidance of diesel fuel costs, proposed at 0.2520 $/kWh. The term of the power purchase agreements is 25 years. By comparison, this is significantly lower than existing electric rates for residential customers ranging from 0.5856 – 1.487 $/kWh [6].

Hydro One Remote Communities has one of the most progressive net-metering and PPA programs available to remote community customers. Maximum installed renewable capacity (kW) cannot exceed the size of the existing generation (kW) [17]. The PPA maximum rate is equal to the community's average three year fuel cost ($/kWh). Most of these community fuel costs in 2019 were in the 0.40 $/kWh range.

As regional utilities develop renewable energy integration programs and offer PPAs based on the avoidance of diesel fuel costs, the allowable cost formulation has become a fundamental metric to integration analysis for any renewable energy technology under evaluation. Utilities are fiscally constrained and integration of new renewable supplies cannot increase costs.

An IPP usually includes a team of technology specific designers, contractors and investors who invest in and deploy commercial scale renewable energy systems. IPPs will use their expertise to provide renewable energy generation at an agreed upon electric rate under a PPA, without the utility assuming the risks associated with introducing new generation technologies, such as unforeseen costs.

As more territorial governments target GHG reductions from energy use, utilities face an increasing challenge to help meet this goal. An integrated resource plan (IRP) is a tool used to create a measurable action plan, proactively planning for a utility's power resource needs. This work is not an IRP for a case study, but serves to inform IRP planning of the case study results and will inform how hydro, wave resources compare and have synergistic value for decreasing diesel use. The engineering methodology upholds diesel cost avoidance as the economic value in PPA arrangements to interconnect and service the community electric supply with wave and hydro resources.

Another key metric of this study is how wave and hydro resources impact emissions intensity (gCO2/kWh). In IRP planning for electric supply options costs cannot be increased. For the same set of electric supply options under consideration, the emissions metric can be dialed to meet GHG reduction targets.

To determine these cost and performance metrics for wave and hydro integration, an energy system computer model is required; a model that emulates a remote community electric supply system and can predict how integration of renewable electric supply impacts diesel fuel use. Technical and economic analyses and modeling is a critical step in system planning prior to decision making for major infrastructure investments [18] [19]. There are many complexities to design and development of an electric supply system computer-based model [20].

Capital and operating costs remain an information gap for WEC technology in Canada's coastal region. In 2015, BC Hydro reported costs between 337 $/MWh and 533 $/MWh USD [21]. The International Energy Agency (IEA) reports costs from 200 $/MWh to 700 $/MWh

USD for small pre-commercial arrays. In the future, costs could decrease to 100 $/MWh to 150 $/MWh USD as worldwide cumulative deployments reach 10GW [22].

In this study, allowable cost is the modeled avoided diesel costs attributed to the integration of wave generation to the diesel system. Allowable cost will be a valuable measure to the WEC industry for determining capital and operational costs. The allowable cost benchmark is for remote community life cycle costs of WEC deployments in Canada's Pacific Coast region.

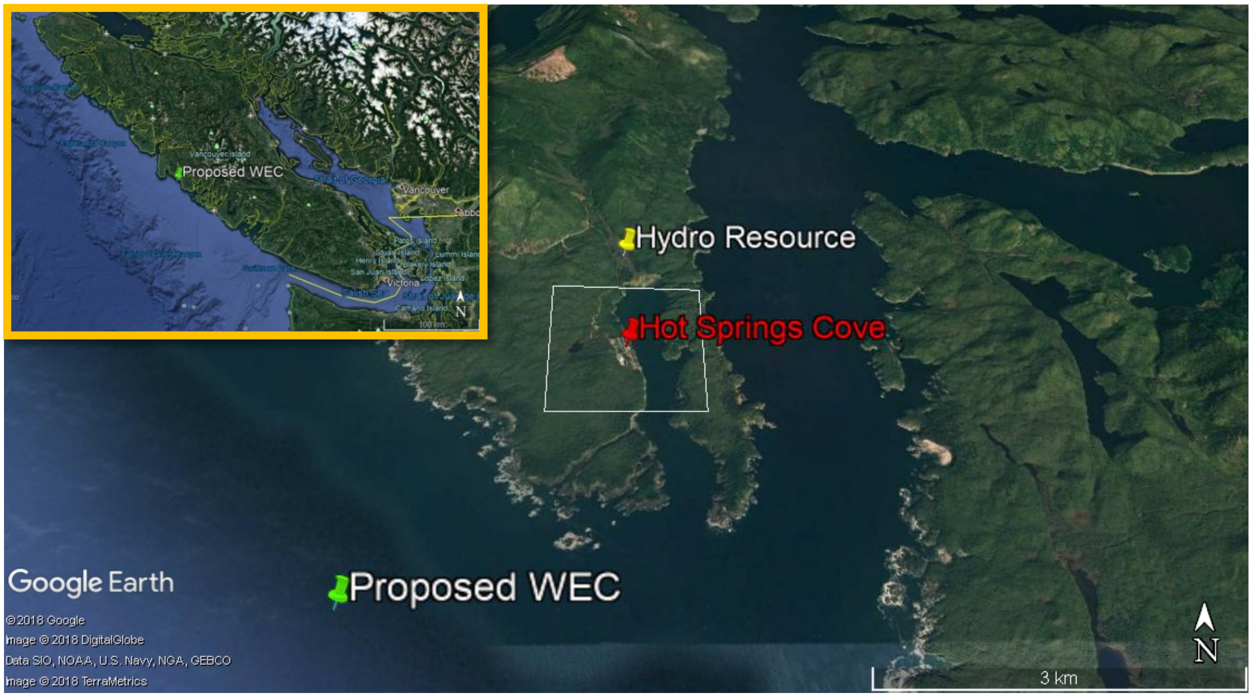
The final step of a technical and economic analysis of wave and hydro integration is to assemble the performance metrics for allowable costs, GHG intensity and other diesel mitigation values into a development plan. A development plan includes first steps to project development, the identification of potential challenges and subsequent steps that meet short-term opportunities and long-term goals. Technical and economic analyses often focus on lowest cost technology options but it is important to consider the needs of the various stakeholders of remote community electric systems.

1.3 Case Study Remote Community

The community of study is Hot Springs Cove – a remote community on Vancouver Island, British Columbia, of the Hesquiaht First Nation. Hot Springs Cove is entirely reliant upon diesel fueled energy generation. The community owns and operates a diesel supply system with constrained funding from the Canadian Federal Government. Hesquiaht administration has communicated there have been years where funding is divested from other community programs to meet the expense of the diesel supply system.

Figure 1-2 shows the location of Hot Springs Cove with respect to the local hydro energy resource, Ahtaapq Creek. The distance from the community to the Ahtaapq Creek area is approximately 2km. Hot Springs Cove is also near the abundant wave resource of the open Pacific Ocean. The proposed location of the Wave Energy Converter (WEC) is approximately 4km from the community.

Figure 1-2: Google Earth Map of Hot Springs Cove, British Columbia



BC Hydro is the regional electric utility in British Columbia. One of BC Hydro's programs is the Remote Community Electrification (RCE) Program that has the purpose of offering low cost electric utility services and if feasible, connection to the central BC Hydro grid. In 2013, the RCE program sponsored a community electric plan for Hot Springs Cove [23]. The plan investigated community energy use and evaluated community power supply options. Unfortunately, the utility did not offer Hot Springs Cove electric service and admission into the RCE program.

After the completion of the 2013 BC Hydro study, the community investigated micro-hydro development to offset diesel generation. A University of Victoria research team supported the hydro contractor's early design work. The team contributed to the design of a computer-based hydro generation model to quantify the total project costs and the diesel costs savings of micro-hydro generation. The performance metrics of the model and analysis justified further detailed engineering design work.

In addition to modeling community electric supply with micro-hydro generation, wave generation is modeled in this research. Data defining the characteristics of the strong wave energy resource adjacent Hot Springs and how technology can harness it, is available through the West Coast Wave Initiative (WCWI) at the University of Victoria. Research at the WCWI supports the BC wave energy industry through extensive resource assessment and technology performance assessment outputs[4]. WEC numerical simulation tools to quantify wave electric supply are available for Hot Springs Cove at a resolution equivalent to micro-hydro supply.

1.4 Thesis Objectives

This analysis consists of a case study of wave and hydro integration into a remote community's existing diesel electric supply located on Canada's West Coast. Diesel mitigation potential of competing system designs is evaluated based on technical, economic and environmental factors. Each system design is a different mix of electric generation from diesel, micro-hydro and wave energy.

Proposed wave and hydro generation systems will interconnect with the existing diesel system. The case study defines wave and hydro scenarios and completes comparative analyses of integrating each system and defining a range of capacities. Capacity range evaluation will be based on equipment selection under consideration by the existing hydro contractor and research team. It is outside the scope of this work to consider and compare different technology suppliers than those already selected. Results are presented utilizing metrics that ensure cost-neutral investments and quantify diesel mitigation.

Underpinning this integration analyses is an electric supply system computer-based model. The model requires community specific input data. This refers to the: local hydro and wave resource, electric use and details of the current diesel electric system. The electric supply model is defined by: cost formulations, mathematical representation of engineering design and

[4] https://www.uvic.ca/research/projects/wcwi [last accessed: 2021-02-28]

operations, and synthesis of community data. The integration study integrates community data, wave and hydro technology and a community electric supply system defined by synthesized community diesel data. The electric supply computer model formulates the results.

In summary, the objectives of this work include:

1. Develop an electric supply computer-based model as a tool for calculating economic, technical and environmental metrics associated with candidate hybrid diesel systems;
2. Employ a scenario-based comparative analysis of both wave and hydro electric supply options; and
3. Discuss the key findings of the comparative analysis to inform decision making.
    a. Quantify the potential for wave and hydro generation to mitigate diesel electric supply for the case study BC coastal community.
    b. Quantify the allowable costs for wave and hydro generation for the case study BC coastal community.

1.5 Thesis Content Overview

The remaining chapters discuss the methodology underpinning the comparative analyses of different combinations of renewable energy sources with existing diesel generation. Chapter 2.0 characterizes the community electrical load data, the current diesel system, the historical hydro resource located at Ahtaapq Creek including catchment area and the local wave energy resource that is utilized for the WEC system. In Chapter 3.0, the electric supply computer-based Remote Community Optimization Model (RCOM) is presented including the mathematical formulation of the system cost objective function and the technical operational constraints. Chapter 4.0 and 5.0 illustrate the optimization results in the context of the technical and environmental metrics and present a proposed wave and hydro integration plan. Chapter 6.0 provides conclusions of the study and recommendations for ongoing research.

2.0 Coastal Community Profile

The community of Hot Springs Cove, a village of the Hesquiaht Nation on the shore of Hesquiaht Sound on Vancouver Island, British Columbia, Canada was illustrated in Figure 1-2. This community is in a remote area and only accessible by seaplane or boat. In 2011, the community on-reserve population was 80. Infrastructure includes a school building, 3 administration and community buildings and 30 residential homes [24]. As introduced in Subchapter 1.2, what follows is a discussion of the following: the community's existing supply, electric system management, past studies, and hydro and wave renewable resources.

2.1 Community Electric Utility Management

Hot Springs Cove's electric supply system is owned and operated by the community to service community homes and community facilities. Due to the challenges faced by an isolated community with limited capital funding for electric supply service, the community applied to BC Hydro's Remote Community Electrification (RCE)[5] Program but was not approved.

As part of the RCE application process, BC Hydro developed a power supply assessment that considered a number of electric supply options, all of which would be owned by BC Hydro [23]. Table 2-1 provides a summary of the power supply options with cost estimates (+50% to -30%) based on 25 and 50-year project lifetimes, a 7% discount rate and a 2% inflation rate.

[5] https://www.bchydro.com/energy-in-bc/operations/remote_community_electrification.html [last accessed: 03-28-2021]

Table 2-1: BC Hydro Hot Springs Cove Power Supply Assessment (2013)

Option	Description	Total Cost ($ 2013)
1. Grid extension	19 km of single or three phase submarine cable.	Capital cost: $11.2-$16.9 million Net present value: $11.3 million
2. Diesel generation	Upgrade facilities for 225kW, 135kW and 72kW diesel generators	Capital cost: $3.7 million Net present value: $13 million
3. Mini-hydro and diesel generation	200kW mini hydro system and diesel generation system (as noted in option 2.0)	Hydro capital cost: $3.5 million Diesel capital cost: $3.7 million Net present value: $11.5 million
4. Wind and diesel generation	275kW wind turbine system and diesel generation system (as noted in option 2.0)	Wind capital cost: $0.6 million Diesel capital cost: $3.7 million Net present value: $8.5 million
5. Solar and diesel generation	200kW solar system and diesel generation system (as noted in option 2.0)	Solar capital cost: $2 million Diesel capital cost: $3.7 million Net present value: $12.1 million
6. Mini-hydro, solar and diesel generation	200kW mini hydro system, 200kW solar system and diesel generation system (as noted in option 2.0)	Capital Cost: $9.1 million Net present value: $10.5 million
7. Wind, solar and diesel generation	275kW wind turbine system, 200kW solar system and diesel generation system (as noted in option 2.0)	Capital Cost: $6.2 million Net present value: $9.4 million

BC Hydro's final recommendation resulted from a comparative analysis of each electric supply option considering financial, environmental and social measures. Operations and maintenance costs for all on-site electric supply scenarios were more costly than the grid extension option. For total life-cycle costs, only options with wind generation were less expensive than the grid extension. This finding was uncertain due to the intermittency of wind generation. For environmental measures (GHG, noise, fuel spill potential, land area impacts and the fraction of electricity provided by renewables), all options were equal to or worse than the grid extension option. For social measures, there was no clear best option. BC Hydro's comparative analysis found the best overall option was the grid extension option and recommended further assessment of extending a central grid connection from Ahousaht to Hot Springs Cove via submarine cable. If grid extension was not feasible, the diesel system at Hot

Springs Cove was to be upgraded to BC Hydro standards, demand side management implemented and renewable generation incrementally added to mitigate diesel fuel consumption.

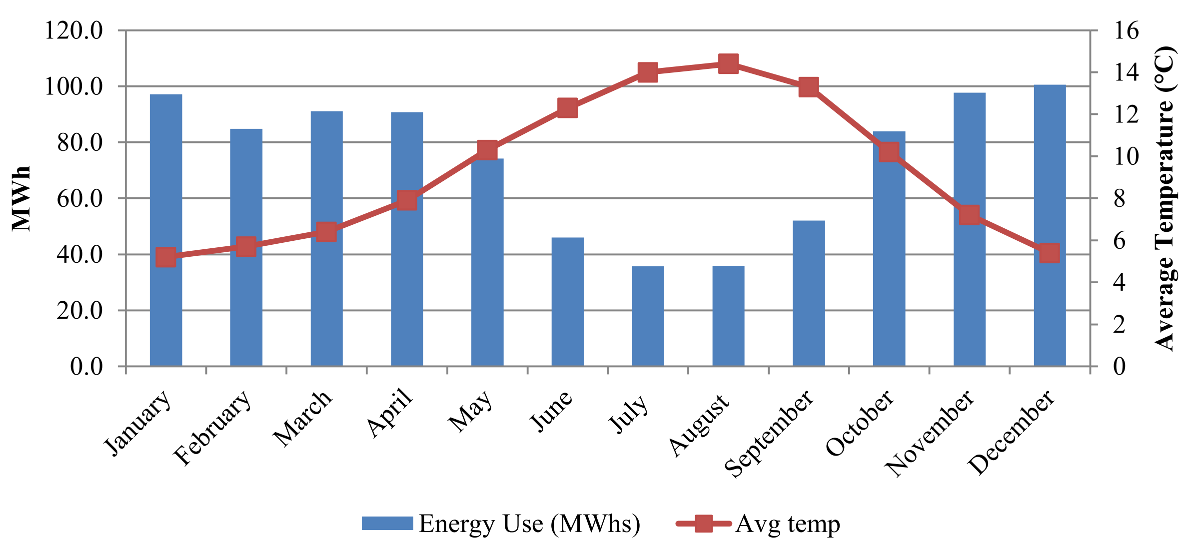
The BC Hydro study demonstrated electric utility reliance on traditional solutions, such as transmission lines. Similar projects, connecting remote communities to the central grid, have come with challenges. Operations and maintenance of transmission and substation assets occur in remote areas with limited access. There are on-going capital investments to minimize power outages and to upgrade equipment to meet electric demand [25].

2.2 Community Climate and Electrical Profile

As a community on Canada's West Coast within a mountainous watershed that feeds nearby Ahtaapq Creek, Hot Springs Cove is surrounded by hydro and ocean-based resources.

The coastal community has mild winter temperatures compared to Canada's North. Figure 2-1 illustrates the average high and low monthly temperatures for this moderate, coastal climate. Average temperatures range from 5°C during winter months and approach 15°C during summer months [26].

Figure 2-1: Average Monthly Temperature for Hot Springs Cove



In April 2014, the community installed electrical meters to record demand data. By fall 2015, a full and continuous year of demand data had been recorded, establishing the community's annual demand and providing a basis to evaluate and compare electric supply options. The community electrical demand is measured in 15-minute intervals. For each time period, the average demand for a one-hour period is the average of four fifteen-minute data intervals. Figure 2-2 displays the community electrical demand between September 2014 and August 2015. The time series demonstrates the largest demand occurs in the winter months at 193.5 kW. Demand drops down in the summer season; increasing again in the fall season. Total annual electric use is 909,500 kWh.

Figure 2-3 shows the cumulative demand in each quarter. Quarter 1 consists of the months of January, February and March. Quarter 2 consists of the months of April, May and June. Quarter 3 consists of the months of July, August and September. Quarter 4 consists of the months of October, November and December. Based on temperature data, the largest demand occurs during the colder, winter months. Peak demand of 193.5 kW occurs in Quarter 4. During the moderate summer, electric demand is at its lowest. The minimum demand of 33.1 kW occurs in Quarter 3. The range of mean values indicates the seasonal range of demand. Quarters 1 and 4 have similar maximum mean values of 127.9kW and 126.4 kW. The Quarter 3 mean is 64.9 kW. Summer usage is roughly half of winter electric use.

Figure 2-2: 2014-2015 Annual Demand Time Series

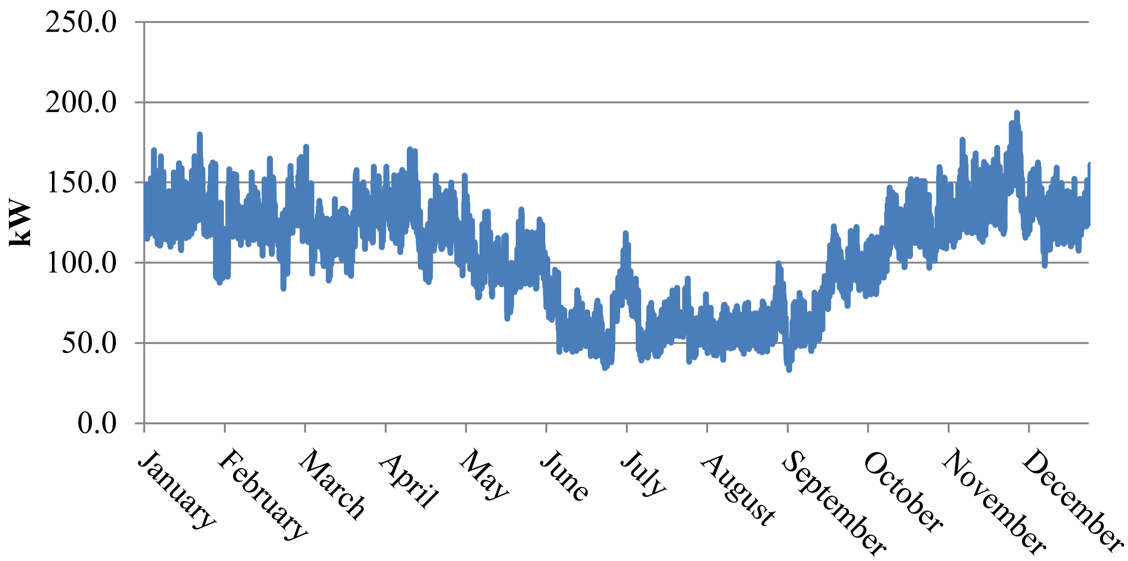
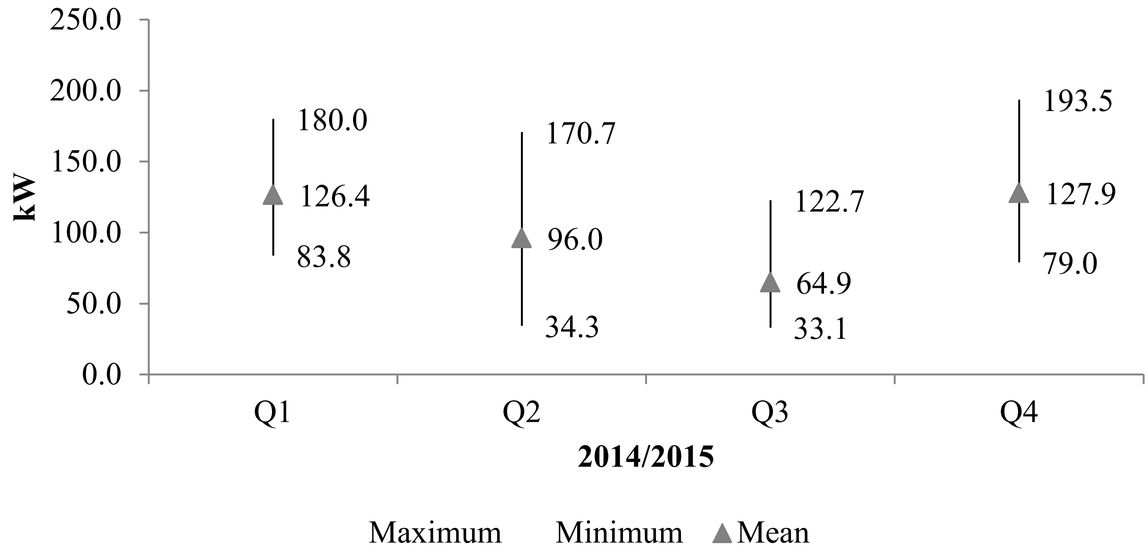


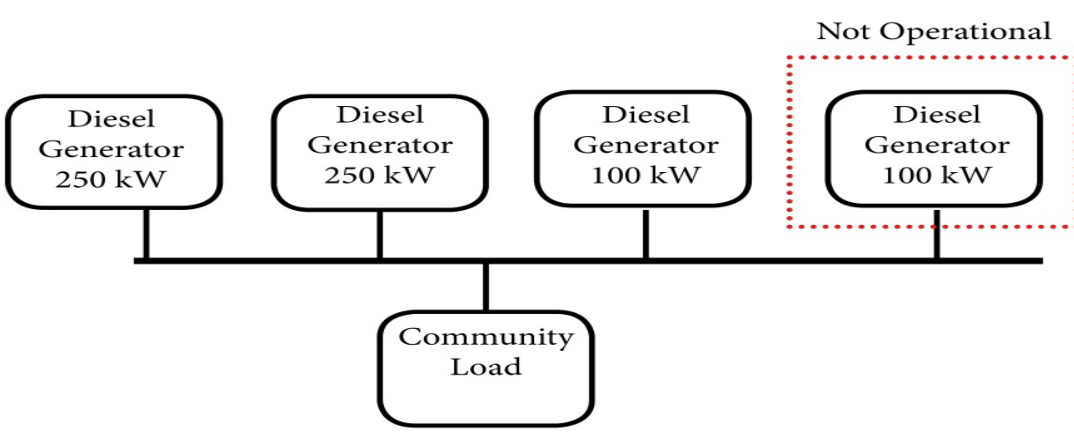
Figure 2-3: 2014-2015 Annual Demand per Quarter



2.3 Community Diesel Generation

Electric needs and some heating needs are currently met by diesel generators in Hot Springs Cove. At the start of this study, community diesel information was collected and established as the existing diesel system. As depicted in Figure 2-4, the diesel generator system consists of two pairs of generators; each pair consists of a primary and a backup generator. The 250kW generators are used primarily during the winter and the 100 kW generators are used primarily in the summer. Hot Springs Cove is down to one 100 kW generator as the back-up generator is not currently operational.

Figure 2-4: Community Diesel Generators Plant



Diesel fuel is barged to the community by G&N Towing, located in Ucluelet, BC. Each barge delivery includes 3 diesel fuel trucks from Ucluelet Co-op, approximately 85km distance. Total fuel delivery is approximately 50,000 litres of diesel fuel. If the seas are rough, there is another delivery location, separated from the community by a logging road, up the channel between Hesquiaht shores and Flores Island.

There are no fuel meters that record fuel use for diesel generation. An accounting of the community's diesel fuel costs and delivery schedule in 2015 is listed in Appendix A. This accounting illustrates the variability in unit fuel costs and a vulnerability to retail price fluctuations.

Fuel volume, cost and fuel unit cost are listed for each delivery. The fuel unit cost is dynamic, reflecting market changes – it is not supplied under a fixed-price contract. The fuel unit cost listed in the table includes the provincial fuel tax deduction as fuel delivered to the community is tax exempt[6]. The 2015 average fuel unit cost was 1.46 $/L. The average fuel unit cost in 2018 increased to 1.60 $/L

In addition to the primary use of fueling centralized generators, delivered diesel is also used for stand-alone generators at the band office and lodge as well as use for band-owned vehicle use. Appendix A provides a breakdown of diesel use based on the months of May to November. During these months, 98.8% of fuel delivered is utilized by the centralized diesel generators.

The remaining operations and maintenance costs and diesel generator overhaul and replacement costs are detailed in Appendix A. The information was provided by a local diesel operations contractor and is not based on performance specific to the Hot Springs Cove diesel system. Overhauls and replacement refer to the anticipated need for either an overhaul in major

[6] http://atlas.gc.ca/rced-bdece/en/index.html [last accessed: 2021-02-28].

equipment components or replacement after a certain number of generator operating hours. Fixed operations and maintenance costs are the salary costs of community facility personnel.

2.4 Hydro Resource

Hot Springs Cove has an opportunity with the local hydro resource at Ahtaapq Creek, only 2 km from the community. The Ahtaapq Creek watershed has wet winters with heavy precipitation from Pacific storms and mild summers with low river flows during late summer months [27].

In the absence of long-term measured Ahtaapq creek flow data, a local hydrologist contractor developed synthetic hindcast Ahtapq Creek flow rates using Carnation Creek measured data [27]. Carnation Creek is 110 km southeast of Ahtaapq Creek and is approximately the same inland distance and elevation. The hindcast produced forty years of annual flow rate data for the integration analysis. Figure 2-5 is based on the hindcast hourly data sets for 1973-2014 and displays the mean annual discharge (MAD) for each year and the percentage of recorded hours. Given the large data set of annual hydro flows, there is the opportunity to reconcile each annual data set and select years that define the range of MAD values that has occurred and the average MAD. This collection and reconciliation of Ahtaapq Creek hydro flows establishes both the average resource data for a hydro system and the range of hydro variability that may be experienced over the lifetime of the hydro system.

The MAD is the sum of the annual hourly flow rates divided by the number of recorded time periods in each year. The long-term MAD over 1973-2014, is 0.386m3/s. The yellow colored bars in Figure 2-5 mark the maximum MAD year, an average MAD year, and the minimum MAD year with details in Table 2-2. Within the hindcast time frame, there are three years of hydro data identified as the maximum MAD year (1997), the minimum MAD year (1985), and the average MAD year (2006) - closest in value to the long-term MAD value. All three years have 100% of recorded hours.

Figure 2-5: Ahtaapq Catchment Hindcast Hydro Resource

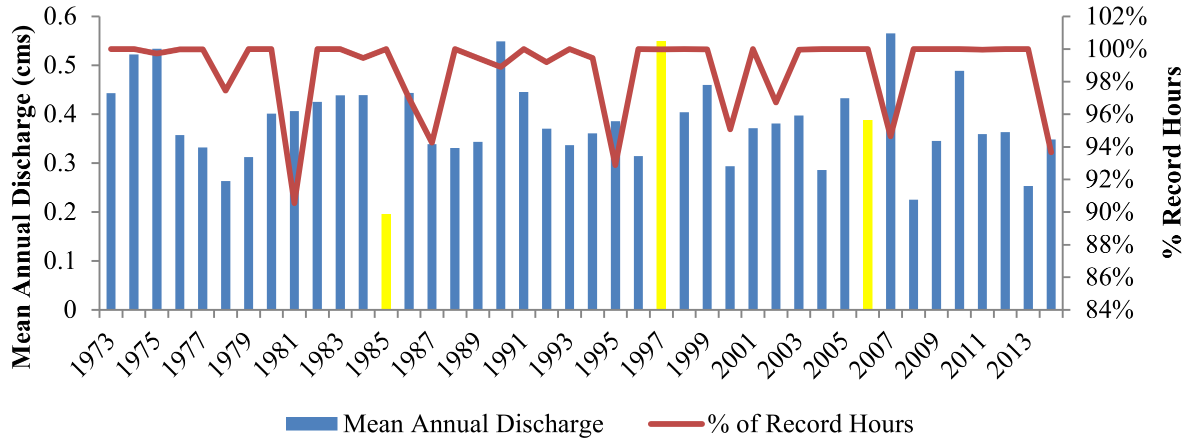
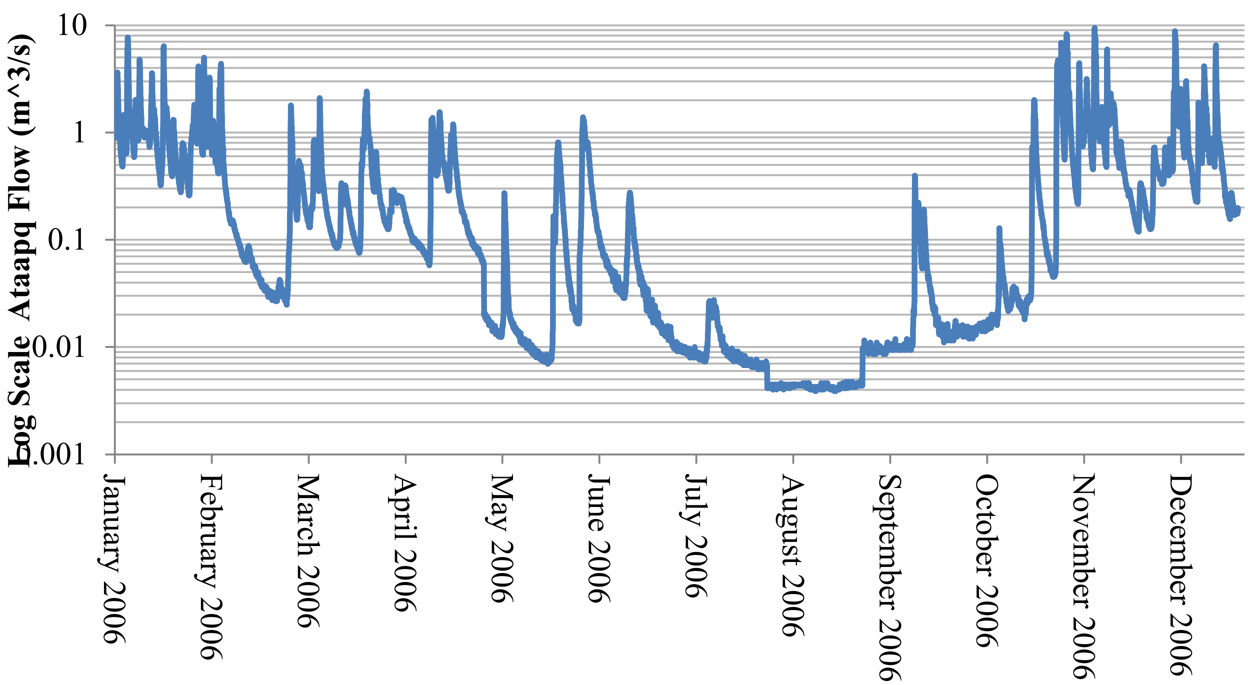


Table 2-2: Hydro Flow Rate Data Series and Hydro Rates

High MAD Year	1997 flow data series, MAD = 0.550m3/s
Low MAD Year	1985 flow data series, MAD = 0.196 m3/s
Avg MAD Year	2006 flow data series, MAD = 0.388 m3/s

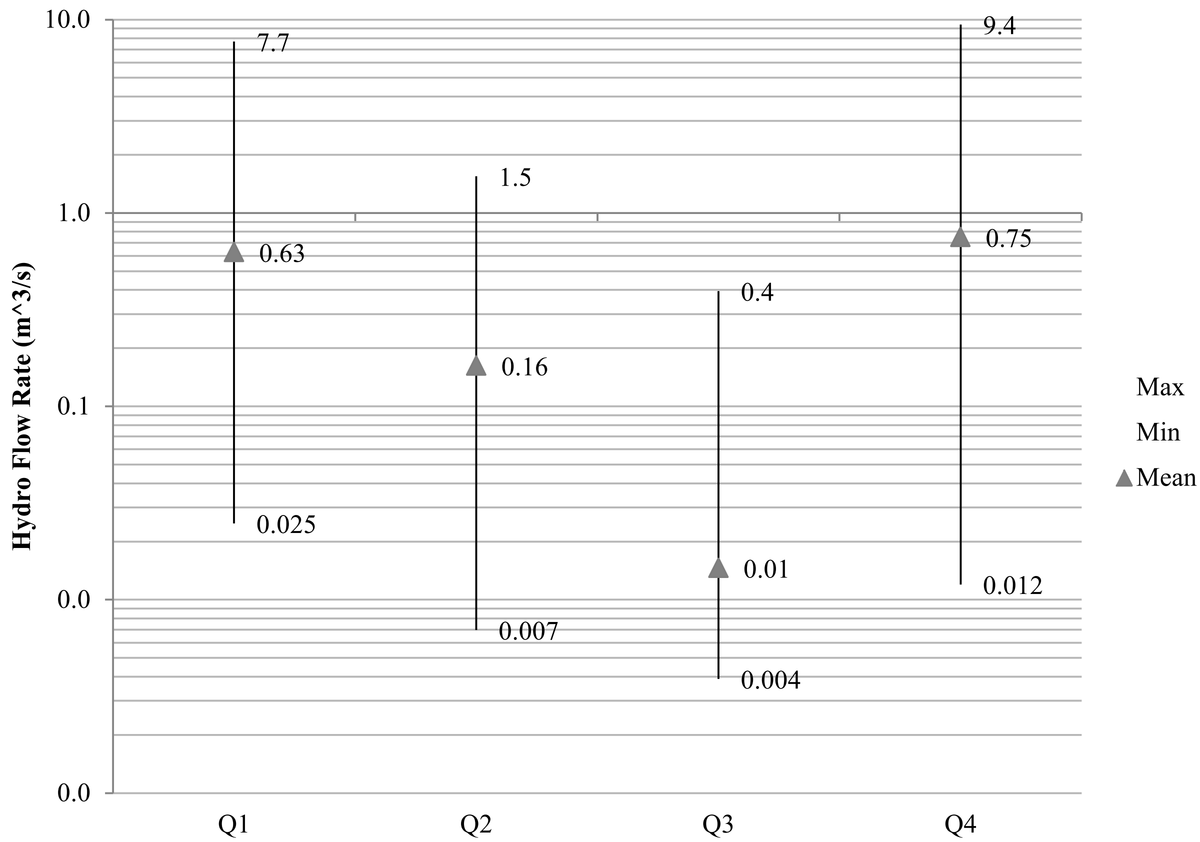
Figure 2-6 shows a logarithmic time series of 2006 hydro flow data synthesized for Ahtaapq creek. The hydro flow seasonal profile shows a similar trend to the seasonal electrical demand profile: the maximum hydro flows occur in the wet winter months and the lowest hydro flows in the dry summer months.

Figure 2-6: Ahtaapq Creek Hourly Flow Rates Time Series for 2006



Quarter 4 as shown in Figure 2-7 records the annual peak measured hydro flow value of 9.4m^3/s and the highest mean value of 0.75m^3/s. The minimum recorded value in Quarter 4 of 0.012m^3/s, is approximately 0.32% of the annual peak value, indicating a variability range of nearly 100%. This variability of measured values in the winter months indicate high flow values for storm periods but also periods of very low flow, similar to the summer months.

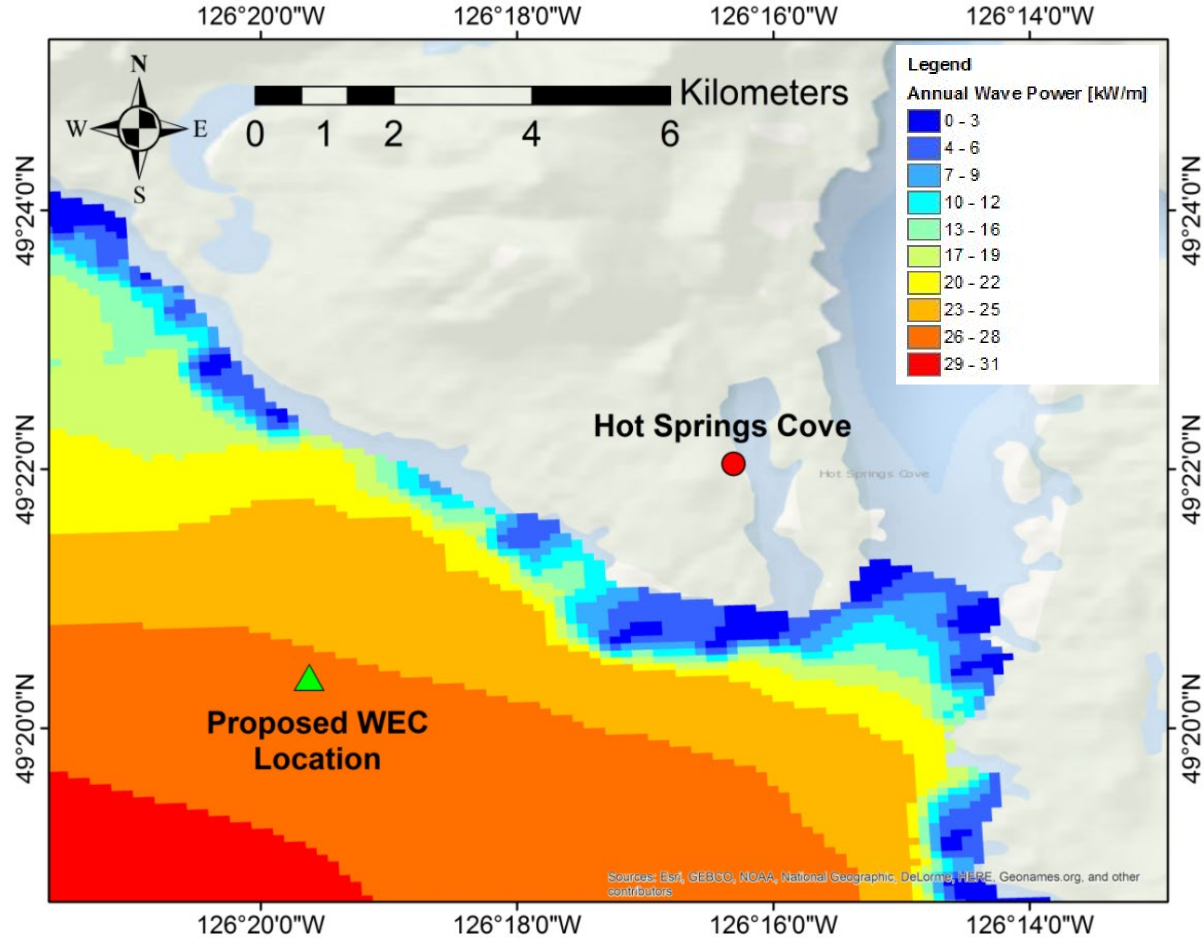
Figure 2-7: Ahtaapq Creek Seasonal Characteristics in 2006



2.5 Wave Resource

Figure 2-8 illustrates the wave energy flux for the remote coastal regions surrounding Hot Springs Cove. A power transport (or flux) range defines wave energy per meter of ocean area. The proposed wave energy conversion system transforms a portion of wave energy to electrical energy. This map shows an annual wave power density 26 - 28 kW/m near the vicinity of the proposed WEC location [28].

Figure 2-8: Wave Resource Map near Hot Springs Cove



The region considered for a wave energy converter deployment is located to the west of Hot Springs Cove and south of Hesquiaht Peninsula. To minimize the underwater cable distance and the associated transmission costs, the proposed WEC deployment site is 49°20'20.08"N and 126°18'25.80"W. This location is approximately 2 km from shore at 40m depth; the preferred operating depth of the WEC.

A critical step is to develop site specific wave resource data to assess the potential for wave energy generation. The wave resource data was selected to match the recorded electric demand data. The availability of this data is dependent on buoy measurements, numerical models and data duration. The near shore wave energy resource data at this location is a result of a regional assessment that utilized: local buoy data, National Ocean and Atmospheric

Administration's (NOAA) WaveWatchIII model boundary conditions, bathymetric data from Canadian Hydrographic Service, and SWAN wave modeling software [29].

Figure 2-9 displays the hourly significant wave height measurements [30] over the same community electric demand period in 2014 to 2015. The time series displays a seasonal profile with peak measurements occurring in the winter months and minimum measured values in the summer months.

Figure 2-9: 2014-2015 Significant Wave Heights at the Proposed WEC Location

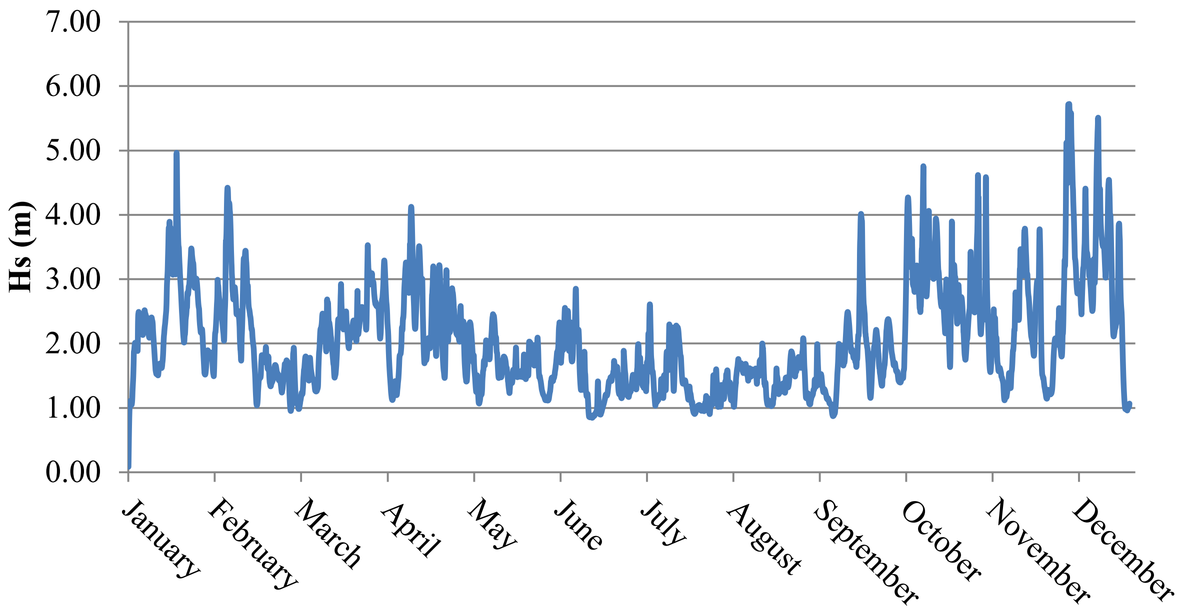
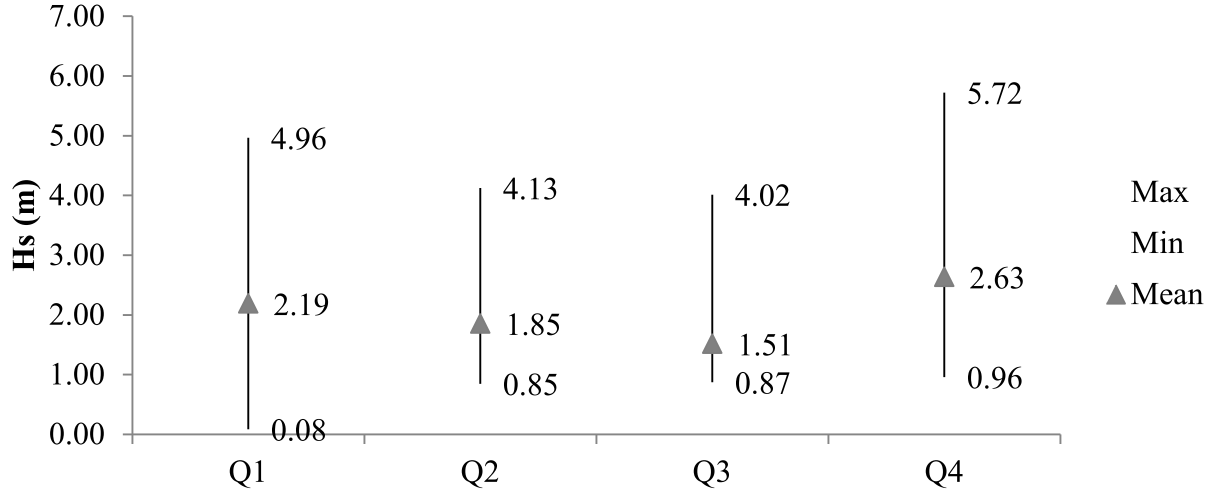


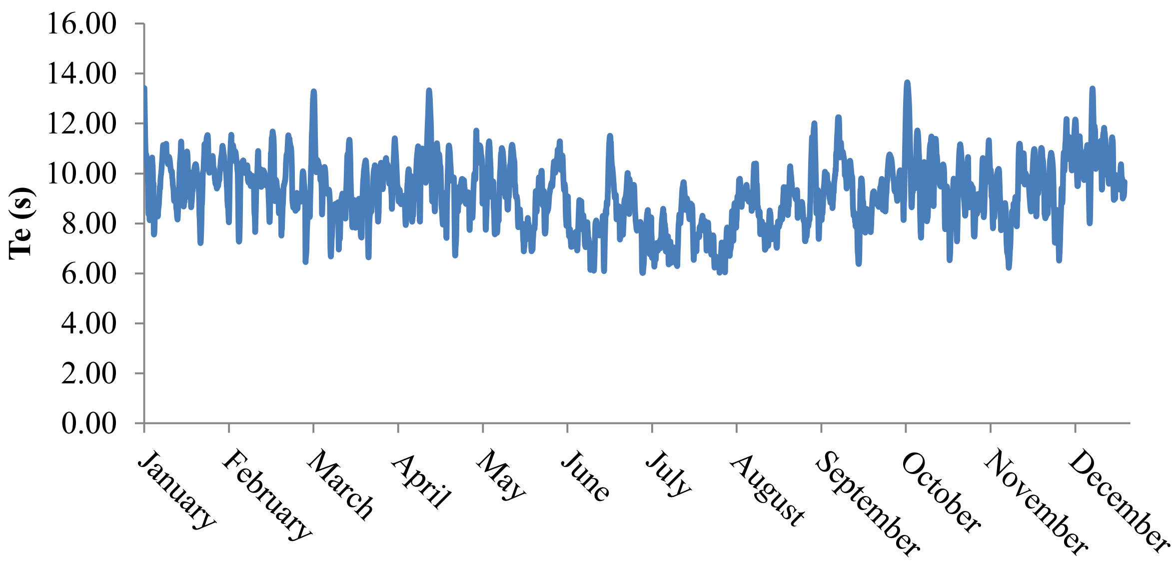
Figure 2-10 displays the significant wave height measurement data in quarterly time periods (Quarter 1 – Quarter 4). The Quarter 1 extreme minimum value is due to the wave resource model spin-up and isn't representative. The minimum value during Quarter 1 should be comparable to Quarter 2 or Quarter 3 minimum value. The summer season within Quarter 3 has the lowest mean value of 1.51 m. Quarter 4 records the annual peak measured significant wave height value of 5.72 m and the highest mean value of 2.63 m. The minimum recorded value in Quarter 4 of 0.96 m is approximately 17% of the annual peak value, indicating a variability range of 83%. The variability of measured values in the winter months indicate high values for storm periods but also periods of calm with measured values like those of the summer months.

Figure 2-10: 2014-2015 Significant Wave Height per Quarter



The wave period measurements are shown in Figure 2-11. Wave period is the time difference between sequential waves and indicates both wave speed and kinetic energy. In comparison to the significant wave height data, there is less variability and more uniformity in wave period data. Wave height and wave energy period data are critical WEC generation model inputs. The wave generation model estimates power generation based on wave energy period and significant wave height.

Figure 2-11: 2014-2015 Wave Energy Period Measurements at WEC location



3.0 Electric Supply Community Model

This Chapter presents the electric supply computer-based model developed for this study. The basis for this task is defined by engineering design; mathematically formulations, and synthesis of community data presented in Chapter 2.0. The purpose of this model is to formulate the impacts of wave and hydro systems to existing diesel electric supply.

Subchapter 3.1 presents the electric supply computer-based model platform and the associated methodology to define the model. The methodology is a techno-economic model, where costs are reliant upon electric supply operations. Subchapter 3.2 presents the translation of the existing and proposed electric supply technology (generation models) to the computer based generator formulas. Subchapter 3.3 delivers the cost spreadsheets for the hydro technology and existing diesel operations.

3.1 Techno-Economic Modeling and Optimization

The Remote Community Optimization Model (RCOM) in Figure 3-1 illustrates the key concepts of RCOM. The results are measures of technical and economic outcomes to characterize the performance of the electric supply system.

RCOM encompasses both the representation of the electric supply system and a solver for the optimization problem that is formed when considering how the different energy sources in the system are used to meet demand over the study time period. RCOM is developed within the General Algebraic Modeling System (GAMS) software platform, which contains several built-in solvers for mathematical optimization problems.

RCOM is formulated as a linear, mixed integer mathematical problem that minimizes the objective function defined by the electric supply costs of Hot Springs Cove. The cost function is the summation of all costs related to the energy system operation. The operational constraints provide the rules for system operation, such as generation and load balance.

To determine the economic distribution of electric demand between multiple electric supply systems, the variable operating costs must be in terms of the system's electric output [31]. The most significant variable operating cost for fossil fuel based systems is fuel. To establish fuel costs, a mathematical relationship can be developed defining incremental fuel use over a range of diesel electric outputs. There are additional diesel operation costs as noted in Figure 3-1. The variable unit costs must be applied to the respective state of diesel operations. The most important functions are the incremental diesel fuel use relationship and the incremental change in hydro system output based on a range of hydro flow rates. Each relationship can be approximated by a linear function.

Economic dispatch balances electric supply systems to meet demand, accounts for operational costs and defines incremental linear relationships between system inputs and outputs [20]. A mathematical model that optimizes for lowest cost dispatching is essential. For this reason, the computer-based model is defined as a mixed-integer linear program that: minimizes system cost; subject to defined constraints with no non-linear terms; and using integer (discrete) or binary variables[7]. Binary ($X \in 0, 1$) integer variables can define: ON and OFF states; cycling limits; and conditions for start or shut down states. The constraints of the optimization model serve as limiting unrealistic operation, such has diesel cycling.

As previously discussed, wave generation models are dependent on both significant wave height and period. This is defined as a non-linear relationship. To maintain linear relations, the wave system generation time series is pre-run using a separate model. The resultant time series is used as a data input to RCOM.

There are other electric system models that utilize GAMS for economic optimization. The Electric Power Research Institute's United States Regional Economy, Greenhouse Gas and Energy (US REGEN) model [32] and NREL's Regional Energy Deployment System (REEDS)

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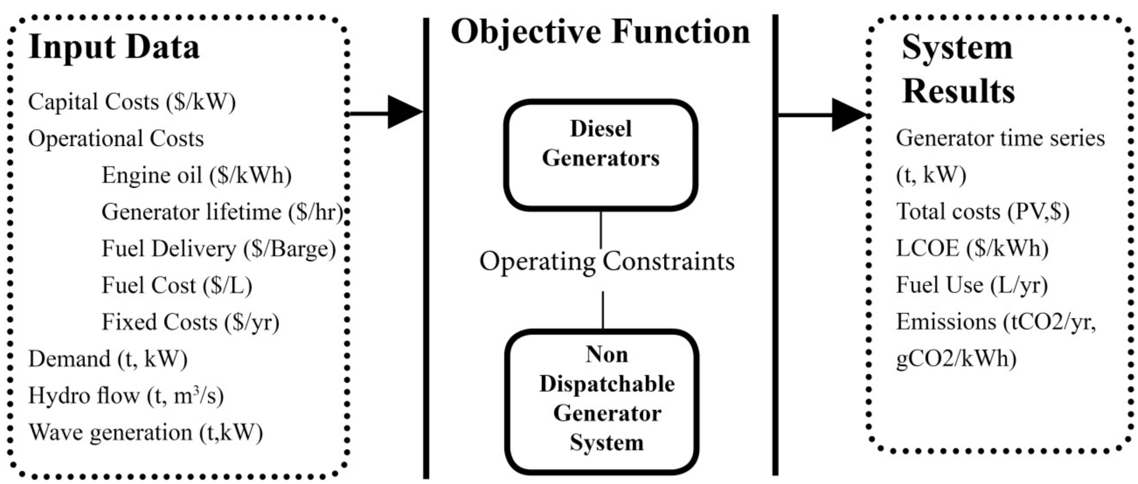
[7] https://www.gams.com/33/docs/UG_ModelSolve.html [Last accessed 03-28-2021]

are utilized to analyze the critical energy issues in the United States electric sector [33]. The US REGEN model determines the optimal cost mix of technologies that will meet electric power demand requirements across multiple load balancing areas. The model is formulated as a linear cost minimization problem in the GAMS environment. Widespread use by these agencies demonstrates the effectiveness of GAMS as a framework for solving Mixed Integer Linear Programming.

Figure 3-1: Remote Community Optimization Model (RCOM)



The objective cost function is by definition the present value of all capital and operational costs over the project lifetime. The system results generate power time series for all generation sources and the economic data computation is dependent on projection of project lifetime costs.

Operating constraints represent production processes for the ascribed technologies; i.e. diesel generation, hydro generation and wave generation (non-dispatchable). The operating constraint definitions are presented in Subchapter 3.2. The following list of electric supply systems are under investigation:

- Diesel-only system
- Hydro-diesel system
- Wave-diesel system
- Wave-hydro-diesel system

Each system scenario represents a fixed capacity of wave or hydro for the above systems. The intention is not for RCOM to optimize the wave or hydro rated capacity, it is only to optimize for lowest cost operations of each system scenario. The size or rated capacities of wave and hydro have been pre-determined by the hydro contractors and the research team. This is greatly influenced by the selected equipment specifications and construction constraints.

The Levelized Cost of Electricity (LCOE) is a function of the present value of the technology's total life cycle costs, the capital recovery factor (CRF) as shown in Table 3-1 [34]. These LCOE formulations are normalized by annual electric supply generation. The Total Cost is a term in present value dollars (reference year: 2018), the summation of costs incurred in each project year. The application of a discount rate to future costs is the concept of the time-value of money. A dollar today is worth more than a dollar in the future. RCOM establishes the system costs of year one and these costs are projected using cash flows for each project year thereafter (i.e. RCOM does not re-run the optimization for each project year).

For operational costs incurred each year, one dollar of diesel costs in year one has more value than a dollar of diesel costs in year 30. In cash flow accounting, operational costs translated to 2018 dollars experiences exponential decay over the project lifetime. The higher the discount value, the greater the decay of costs incurred in later project years.

For the economic formulation of total avoided diesel costs, aggregate diesel savings of each project year without considering capital costs is a very conservative valuation. This conservative valuation is justified because of the risks due to uncertainty of an alternative electric supply to mitigate diesel use. Recall in BC Hydro's options analysis for Hot Springs Cove, wind electric supply was presented with this uncertainty of diesel mitigation. Therefore the allowable cost formulation accounts for uncertainty in diesel mitigation.

The LCOE values are the unit cost of electric supply, a function of the present value of the Total Cost, Capital Recovery Factor and Generation [34]. Since RCOM only optimizes for a single year of operation, annual generation for electric supply does not change. For this reason, only the annual generation as determined by RCOM for the electric supply is needed. For allowable LCOE, this is the purchase price for the all renewable electric supply at the community distribution system. From the perspective of the developer, the costs to install and operate the renewable system, the cost of debt and needed rate of return must be less than or equal to the allowable LCOE. For the renewable systems, the allowable cost accounts for only utilized renewable generation over the year. Utilized generation is the amount used through the community distribution system. Excess generation cannot displace diesel use and therefore has no value.

Allowable LCOE refers to allocating zero cost to renewable electric supply (or generator) in RCOM. Allowable LCOE for renewable supply is calculated using the avoided diesel costs over the project lifetime compared to diesel-only system costs. The diesel-only system cost is the basis for all system scenario calculations of allowable cost of electricity values. Avoided diesel costs accounts for: diesel fuel, diesel operations and maintenance costs (O&M) including fixed and variable costs per kWh output, an overhaul cost based on each hour of operations, and barge costs to ship fuel to the community.

Overhaul costs are related to major equipment replacements due to run time hours. Unit cost is a normalization of the total replacement cost on a per hour basis (Total replacement cost is $10,000 every 10,000 hours of operation, overhaul cost is 1$/hr). These costs were provided by a diesel contractor familiar with typical operations costs and by the community historical prices for diesel fuel and delivery charges. Refer to Appendix A Diesel System Costs, for actual values.

Table 3-1: Cost of Electricity Formulations

Diesel Costs	$\boldsymbol{Total\ Diesel\ Cost}\ (\boldsymbol{C_{Fuel}}, \boldsymbol{C_{Diesel\ O\&M}}, \boldsymbol{C_{Overhaul}}, \boldsymbol{C_{Barge}})$ $C_{Fuel}\ (\$/L)$ $C_{Varible\ O\&M}\ (\$/kWh)$ $C_{Fixed\ O\&M}\ (\$/yr)$ $C_{Overhaul}\ (\$/h)$ $C_{Barge}(\$/delivery)$ Refer to Appendix A for present value formulations of Total Diesel Cost
Hydro Costs	$\boldsymbol{Total\ Hydro\ Cost}\ (\boldsymbol{C_{Hydro\ O\&M}}, \boldsymbol{C_{Hydro\ Capital}})$ $\boldsymbol{C_{Hydro\ O\&M}}\ (\boldsymbol{C_{rental\ variable}}, \boldsymbol{C_{rental\ cap}}, \boldsymbol{C_{fixed\ Hydro}})$ $C_{Hydro\ Capital}\ (\$/kW)$, Hydro Capital cost $C_{rental\ variable}\ (\$/kWh)$, Water license rental cost: Output $C_{rental\ cap}\ (\frac{\$}{kW}/yr)$, Water license rental cost: Capacity $C_{Fixed\ hydro\ O\&M}\ (\$/yr)$, Total Fixed hydro O&M Refer to Appendix B for present value formulations of Total Hydro Cost
Wave Costs	$\boldsymbol{Total\ Wave\ Cost} = \$0$
LCOE	$= \frac{Total\ Project\ Cost\ \cdot CRF}{Annual\ Generation}$
Allowable LCOE	$= \frac{Avoided\ Diesel\ Costs\ \cdot CRF}{Annual\ Utilized\ Generation}$
Capital Recovery Factor	CRF$= d \cdot \frac{(1+d)^N}{(1+d)^N - 1}$ $d = discount\ rate$ $N = project\ lifetime, years$

Hydro costs are the costs for the proposed system for Hot Springs Cove and Ahtaapq Creek, including capital and operations costs. Actual values provided by the contractor are in Appendix B. Costs are only for the hydro electric supply system and powerline from the hydro system to the community distribution network. For hydro-diesel scenarios, total project cost is formulated by combining total hydro and diesel costs. Variable operations costs impact RCOM optimization to determine lowest cost solutions. Factors such as capital costs or fixed annual or operations and maintenance costs do not impact RCOM optimization.

Wave costs are not included in this evaluation and RCOM does not assign costs to wave generation. For the system scenarios with wave electric supply, there is only allowable cost formulations. Allowable costs are only reliant on accounting of avoided diesel costs.

The capital recovery factor is dependent on the selected discount rate and the project lifetime. This analysis does not account for energy system revenues nor apply the cost of financing large capital projects.

The installed cost formulations are specific to the respective generation source. The formulations are provided in Table 3-2. Installed cost is based on total cost of the electric supply generator, normalized by the generator's capacity. For allowable wave or hydro costs, the formulation is the diesel avoided costs due to of either the wave or hydro generator, normalized by the generator's capacity.

Table 3-2: Installed Cost Formulations

Installed Cost ($\$/kW_{installed}$)	$= \frac{Total\ Project\ Cost}{Installed\ Capacity\ (kW)}$
Allowable Installed Cost ($\$/kW_{installed}$)	$= \frac{Avoided\ Diesel\ Costs}{Installed\ Capacity\ (kW)}$

A typical diesel generation system with inputs and outputs is illustrated in Figure 3-2. Electric energy demand from residential, commercial and industrial use is met by electric energy generation. There is a constant balance between demand and generation in every time step of the time period considered, as shown in Table 3-3.

Figure 3-2: Electric Supply System Technical and Economic Factors

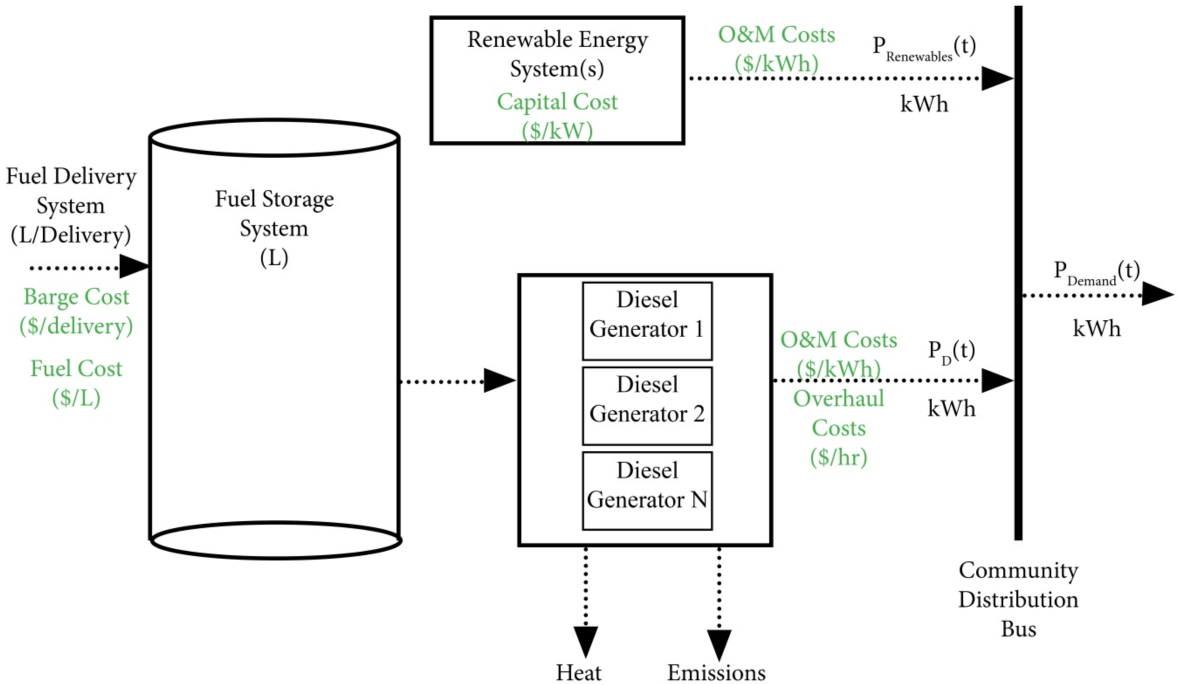


Table 3-3: RCOM Power Balance Equation

Power Balance Constraint	Assignments
$P_{Renewables}(t) + P_D(t) = P_{Demand}(t)$ $P_H, P_W \in P_{Renewables}$	t, hour P, kW D, Diesel Generation System H, Hydro Generation System W, Wave Energy Conversion System

In order to provide continuous power, supply must always meet demand. A fuel storage tank allows the diesel generators to run continuously. To refill the storage tank, a fuel delivery system transports diesel by air, sea or land. A diesel generation plant may contain any number of diesel generators, typically sized to meet peak power demand, and may contain backup generators for redundancy.

Waste heat from electric generation provides another valuable by-product that can offset heating loads in existing boiler systems. Utilizing waste heat can increase overall fuel efficiency (for both electric generation and heat recovery systems) to 80% [35]. While recovery systems can be economically viable, the scope of the research presented in this thesis does not include waste heat recovery in the integration analysis, only electric generation. Demand side management and energy efficient technological improvements can change a community's demand profile. These demand changes can positively or negatively impact diesel generation and efficiency. This subject has value in energy modeling, though is not included in this study.

The storage models incorporated into this study are the diesel fuel storage system and the hydro reservoir system. Storage systems provide: generator dispatch elasticity, increased system reliability, diesel fuel efficiency management and utilization of excess renewable generation. Electric storage technology and related costs are outside the scope of this study.

3.2 Generation Models

3.2.1 Diesel Generation

The diesel numerical model is defined by power capacity constraints. These are the maximum and minimum values for each generator. An addition constraint defines the fuel use (L/hr) to generate power (kW). Diesel cycling constraints apply limits to switching from an ON state to an OFF state. The fuel use for each generator are aggregated to total fuel demand from the fuel storage tank.

In Hot Springs Cove, there are two diesel generator systems – two 250 kW Volvo units and two 100 kW Deutz units. Specific fuel consumption data per unit from the manufacturer is used from the 250 kW Volvo[8] and the 100 kW Deutz[9]. The manufacturer's fuel data defines a

[8] https://www.volvopenta.com/industrialpowergeneration/en-en/home.html [last accessed: 2021-02-28].

[9] https://www.deutz.com/en/products/engines/#scope=4 [last accessed 2021-02-28].

curve (a nonlinear function), that relates diesel fuel use (g/kWh) to diesel power output. The fuel use data (g/kWh) is converted to (L/hr).

The estimated linear fuel use equations for each generator are shown in Figure 3-3. The respective time (t) dependent linear equations for diesel fuel are listed in Table 3-4.

Figure 3-3: Diesel Generator Linear Fuel Use

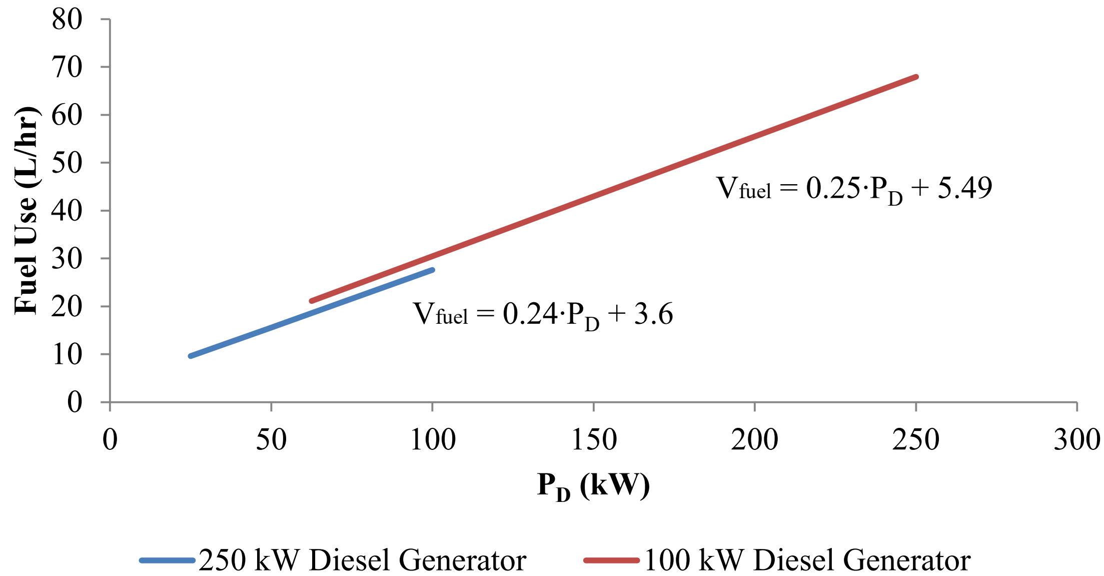


Table 3-4: Fuel Consumption Parameters per Diesel Generator Model

Rated Power (kW)	P_D Max (kW)	P_D Min (kW)	Linear Fuel Use Constraints (L/hr)
Universal Constraint			$P_D Max \cdot X_D(t) \geq P_D(t) \geq 0.2 \cdot P_D Max \cdot X_D(t)$
250	250	50	$V_{fuel}(t) = 0.25 \cdot P_D(t) + 5.49 \cdot X_D(t)$
100	100	20	$V_{fuel}(t) = 0.24 \cdot P_D(t) + 3.6 \cdot X_D(t)$

The P_D Max and P_D Min provide the upper and lower limit respectively for diesel power output, $P_D(t)$. Minimum power output of the diesel generators is set at 20% of maximum power output. The binary variable $X_D(t)$ has a value of one or zero, indicating that the diesel generator is on or off. The corresponding values for each diesel generator are listed in Table 3-4.

The diesel fuel storage system equation accounts for fuel in the storage tank, dependent on fuel deliveries and generator use. The fuel storage tank technical constraint and parameters are provided in Table 3-5. The fuel use variable $V_{Fuel}(t)$, is the summation of all diesel generator fuel use. A conversion efficiency (η_{Deff}), is applied to the fuel use variable ($V_{Fuel}(t)$), which converts diesel mechanical power to diesel electrical power[10 11].

Diesel cycling refers to the shutdown and start-up operations of diesel generators. If the cycling frequency is high over short periods of time, the generator is not running optimally. The diesel cycling constraints are shown in Table 3-5. The first constraint determines a switch-on occurrence, defined as $X_{DswitchOn}(t)$. The second formulation of the cycling constraint defines the number of hours for a single diesel generator to remain in operation once there is a switch-on occurrence (defined as 4 hours). There is no minimum downtime before the next switch-on occurrence.

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[10] https://www.volvopenta.com/industrialpowergeneration/en-en/home.html [last accessed: 2021-02-28].

[11] 13.9https://www.deutz.com/en/products/engines/#scope=4 [last accessed 2021-02-28].

Table 3-5: Fuel Delivery and Storage System and Cycling Constraints

Fuel Storage System Constraints and Parameters	$V_{Tank}(t+1) = V_{Tank}(t) - \eta_{Deff} \cdot V_{Fuel}(t) + V_{Delivery} \cdot X_{Barge}(t)$ $V_{Delivery} = 49{,}400\ L$ $\eta_{Deff} = 90\%$
Diesel Cycling Constraints per diesel generator	$X_D(t) - X_D(t-1) = X_{DswitchOn}(t)$ $\sum_{j=1}^{A} X_D(t+j) = C \cdot X_{DSwitchON}(t)$ **C** = 4 hours

The 250 kW Volvo and the 100 kW Deutz generator systems are classified as Tier 2 emissions systems. The federal standards for Tier 2 emissions systems are classified as off-road diesel engines and are specified for a range of generator capacities. Listed in Table: 3-6[12], the standards define the maximum emissions rate for CO, particulate matter, NOx and non-methane hydrocarbons. The prescribed CO_2 emissions rate is based on the BC Greenhouse Gas report for diesel fuel use in off road applications [36]. For simplification within the model, the CO_2 rate is assumed to be identical for both generators.

Table 3-6: Diesel Generation Emission Rates, 100kW/250kW

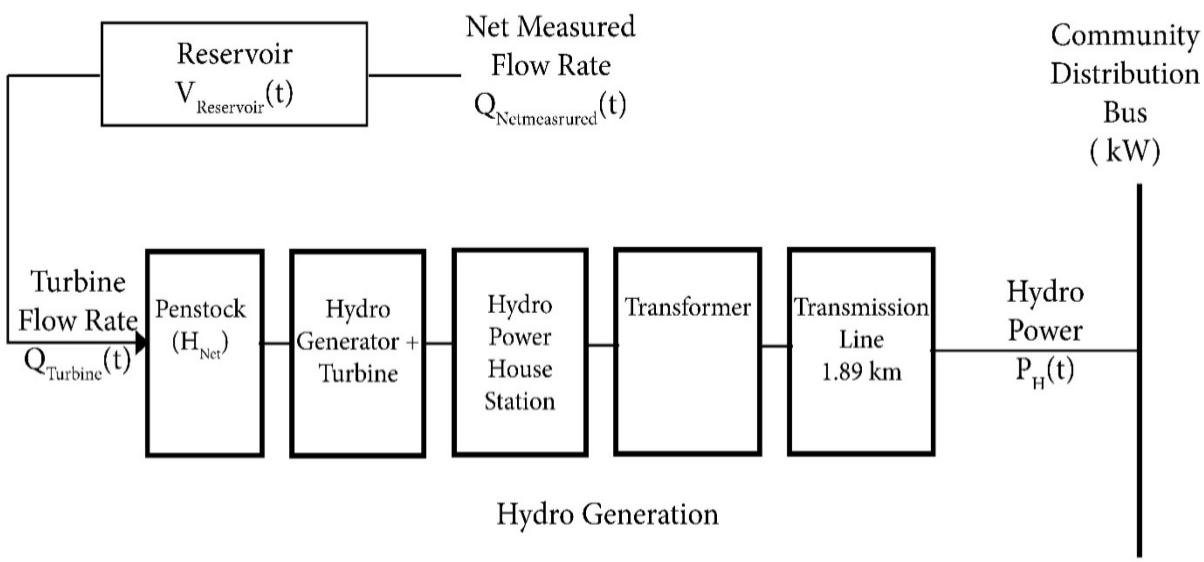
CO_2	CO	Particulate Matter	NOx + Non-methane Hydrocarbons
2663 (g/L)	5.0/3.5 (g/kWh)	0.3/0.2 (g/kWh)	6.6/6.4 (g/kWh)

[12] https://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=0CBF3BCC-1&offset=6 [last accessed: 03-28-2021]

3.2.2 Hydro Generation

The generation and losses of hydroelectric power in RCOM are defined by six components that define the effective hydro power at the community distribution. Figure 3-4 illustrates the components and the following discussion provides the parameters and governing equations. For the purpose of terminology, hydro generation encompasses efficiency losses.

Figure 3-4: Power System Components of Hydro Generation



The rated capacity of the hydro system is a function of design parameters including design hydro flow rate, efficiency and net head of the penstock pipe. The proposed hydro generation design has a fixed penstock length of 2,238 meters composed of both plastic and steel materials as illustrated in Figure 3-5. The gross head is 228 meters, the physical height of the penstock. The resulting head losses from hydro flows and pipe materials determine the net head available to the turbine system. Losses are from friction of flow in the pipeline[13].

[13] https://www.canyonhydro.com/guide/HydroGuide7.html [last accessed: 03-28-2021]

Figure 3-5: Penstock Pipe Material and Dimensions for Head Losses

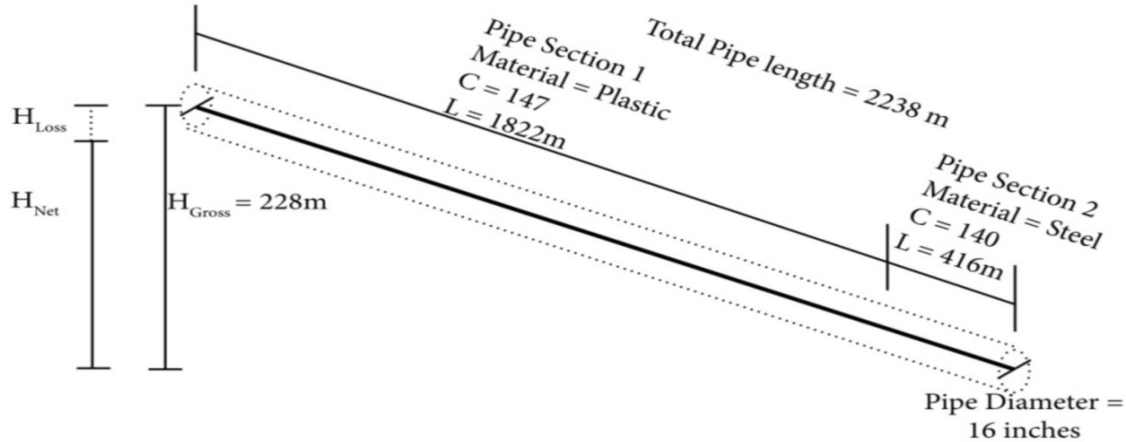


Table 3-7 provides the design parameters for the three hydro generation scenarios based on the rated hydro systems and the specifications of the turbine and generator system selected for Hot Springs Cove. The head loss values and net head for each Q_D are provided by Canyon Hydro.

Table 3-7: Hot Springs Cove Hydro Generation Scenarios

Rated Hydro Capacity (kW)	H_{Net} (m)	Q_D (m^3/s)
225	219.5	0.125
275	214.9	0.157
325	209.5	0.19

Appendix B provides the equations and definitions to calculate hydro power generation $P_H(t)$ available at the community bus. Penstock losses impact the flow rate $Q_{Turbine}(t)$ available to the turbine system. The hydro power equation calculates $P_H(t)$ and is dependent on Net Head (H_{Net}), flow rate ($Q_{Turbine}(t)$) and total electrical efficiency (η_{Total}). Total efficiency is defined by the electrical equipment specifications. A post-hydro-power calculation includes the pre-assigned hours of availability. Unavailability refers to planned and unplanned events throughout the year. There are pre-assigned hours that apply a 0 value for $P_H(t)$ regardless if there is sufficient flow rate to generate power.

The powerhouse station load losses are the internal electric load. The electric load includes the fan that cools the generating system during the summer months and the electric heater to heat the generating system in the winter months. Lights and power electronic control systems also consume electricity at the hydro powerhouse station. In total, these losses are estimated to be 1% and conversely the efficiency is 99%.

The transformer losses for a Schneider Electric 300kVA are approximately 1.2% [37]. The transformer losses are a combination of core losses and coil losses. The transformer losses are provided over a range of part load to full load conditions. The efficiency is estimated as 98.8%, based on the average provided loss values.

The combined transmission losses and interconnection losses into the community bus are estimated to be 2.3%. This value is based on power transmission from the hydro power plant to the community at a distance of about 2km. It is assumed at the point of interconnection there would be voltage step down equipment to interconnect at the main community electric bus. Electric utilities have similar configurations and similar equipment. The efficiency for transmission and connection to the community bus is 97.6%. The value is based on Hydro One's published losses for distribution level utility equipment[14].

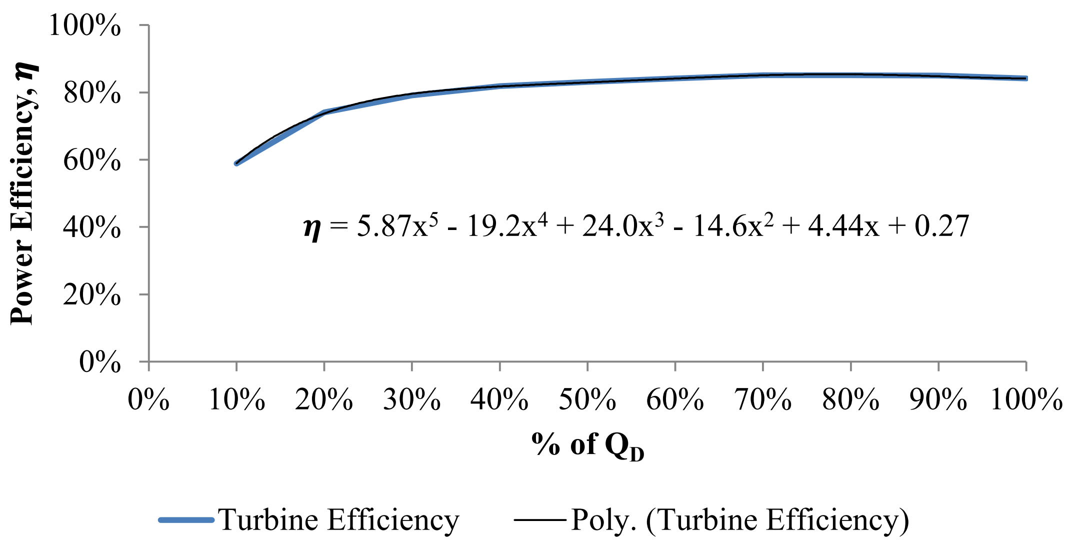
Hydro unavailability includes periods with planned and unplanned outages. For this model, it is assumed there is 5% unavailability, equivalent to 110 hours of no hydro power per quarter, or 440 hours per year.

The hydro power function is defined, and dependent on hydro flow rate. Total efficiency is dependent on the hydro flow rate, $Q_{Turbine}(t)$. The goal is to develop a linear hydro function dependent on hydro flow rate for each rated hydro capacity: 225kW, 275kW, and 325kW. Hydro power has zero emissions in the model.

[14] https://www.hydroone.com/abouthydroone/RegulatoryInformation/dxrates/2008dxrates [last accessed: 2021-02-28].

Canyon Hydro is the proposed hydro turbine supplier for installation at Ahtaapq Creek. Canyon Hydro provided the specifications for a Pelton turbine system, containing a generator and motor. Specific to Canyon Hydro's performance data, the hydro turbine and generator efficiency curve is provided in Figure 3-6. This non-linear curve is estimated by the fifth order polynomial in terms of an 'x' abscissa value. The 'Q Design' value is the maximum flow rate selected for the hydro generation system. The horizontal axis in the figure is the percentage of Q Design. Canyon Hydro provided the required Q_D values for 225kW, 275kW, and 325kW rated hydro turbine systems ($0.125 m^3/s$, $0.157 m^3/s$, $0.19 m^3/s$ respectively).

Figure 3-6: Pelton Turbine Power Efficiency Curve



As previously discussed, hydro power is dependent on both total system efficiency and hydro flow rate. A tabular method is used to develop a linear hydro power function dependent only on hydro flow rate, Q. For each hydro generation system, a unique linear function is generated from a table that relates the hydro power and total efficiency of the hydro system to each potential Q value. As an example, Figure 3-7 shows the total efficiency function and the resultant non-linear power function for the 225 kW hydro generation system. The nonlinear 225kW Hydro function is generated from the table of values for Q and the calculated hydro power for each Q. As illustrated, this non-linear power function can be estimated by a linear function, as shown.

Figure 3-7: 225 kW Hydro Power Function and Efficiency

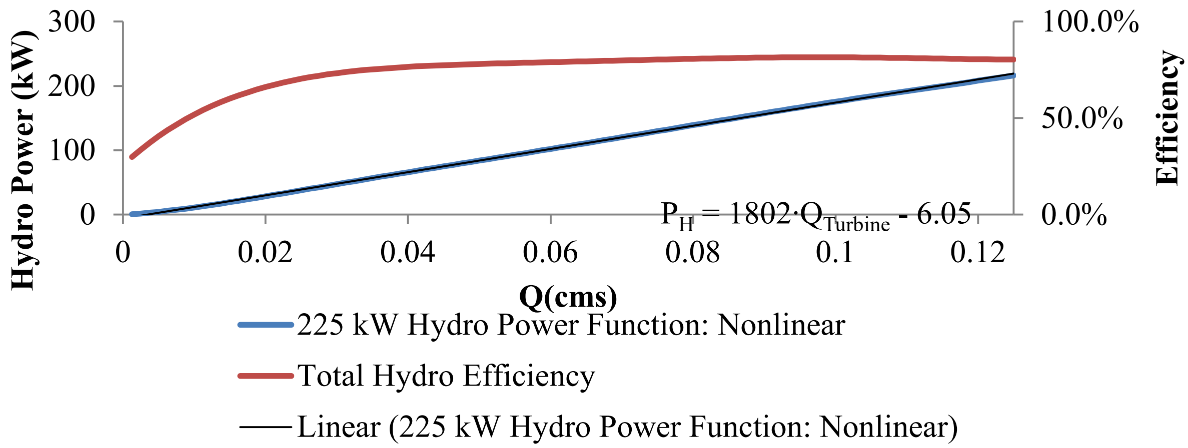


Table 3-8 provides the linearized power curves for each rated hydro capacity and the maximum and minimum power output values available at the community bus. The table lists the hydro power outputs as well the minimum shutdown limits. Minimum power before shutdown is 5% of maximum power and start-up minimum power is 10% of Maximum power. For all other periods of time, hydro power is optimally determined.

Table 3-8: Hydro Power Constraints

Hydro Rate Power (kW)	$P_{H,\,Max}$ (kW)	$P_{H,\,Min}$ Shutdown (kW)	$P_{H,\,Min}$ Start-up (kW)	Hydro power constraints
Universal Constraint				$X_H(t) - X_H(t-1) \le X_{SwitchON}(t)$ $Q_{Turbine}(t) \le Q_D$ $Q_{Turbine}(t) \ge .05 \cdot Q_D \cdot X_{SwitchON}(t) + .05 \cdot Q_D \cdot X_H(t)$
225	219	11	22	$P_H(t) = 1802 \cdot Q_{Turbine}(t) - 6.05 \cdot X_H(t)$ $Q_D = 0.125\ m^3/s$
275	270	13.5	27	$P_H(t) = 1764 \cdot Q_{Turbine}(t) - 7.44 \cdot X_H(t)$ $Q_D = 0.157\ m^3/s$
325	318	16	32	$P_H(t) = 1720 \cdot Q_{Turbine}(t) - 8.78 \cdot X_H(t)$ $Q_D = 0.19\ m^3/s$

The proposed hydro generation system for Hot Springs Cove depends on water flow rates (Q m^3/s) from a reservoir to generate electrical power. The reservoir is fed from Ahtaapq Creek. The hydro reservoir has a capacity of $6000 m^3$ and stores the measured hydro flows from Ahtaapq Creek. The reservoir feeds the hydro turbine system with the required $Q_{Turbine}$ flow rate for hydro-electric power.

Table 3-9: Reservoir Constraints and Hydro Flow Rate Data

Reservoir Hydro Volume	$V_{Rervoir}(t) = 3600\big(Q_{Netmeasured}(t) - Q_{spill}(t) - Q_{Turbine}(t)\big) + V_{Reservoir}(t-1)$
Reservoir Capacity	$V_{Reservoir(Max)} = 6000\ m^3$
Instream Flow Requirement	$Q_{IFR} = 0.011\ \frac{m^3}{s}$, 3.4% of long term Mean Annual Discharge $Q_{Netmeasured}(t) = Q_{Measured}(t) - Q_{IFR}$
Variable Hydro Resource Data	
Measured Flow Input Data	$Q_{measured}(t) = \begin{cases} 1985\ time\ series, MAD = 0.196\, m^3/s \\ 1997\ time\ series, MAD = 0.550\, m^3/s \\ 2006\ time\ series, MAD = 0.388\, m^3/s \end{cases}$

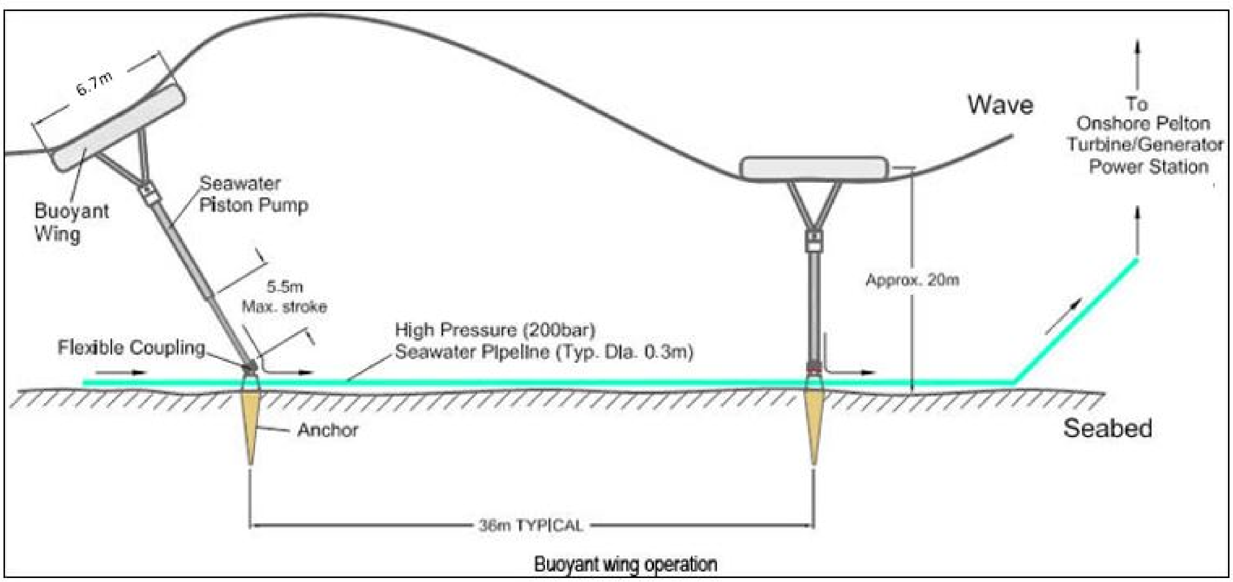
Table 3-9 provides the reservoir containment constraints and Ahtaapq Creek hydro flow data. There is a connection from the reservoir to the lower region of the Creek to provide consistent flow rates to maintain fish habitat. Environmental studies have determined there are no fish in the diversion reach. The conditional water license requires a minimum in-stream flow release of $0.011 m^3/s$ to pass the intake structure. In the model, this is called the Instream Flow Requirement (IFR). IFR is deducted from the measured flow rate in all time periods unless there is no flow available (value of 0) and no deduction occurs. Excess hydro flows from Ahtaapq Creek that cannot be stored in the reservoir are spilled over the edge of the containment (Q_{spill}).

3.2.3 Wave Generation

This chapter provides the description of the wave energy electric generation potential for the community, based on the local wave resource (Subchapter 2.5) and the rated capacity of the selected wave energy converter (WEC).

To transform wave energy flux to electrical energy, the WEC utilized in this study is based on the Seawood Designs "SurfPower" WEC. The high-fidelity numerical WEC model used has been developed by the West Coast Wave Initiative (WCWI), Seawood Designs Inc. and Dynamic Systems Analysis Ltd (DSA). The collaborative work to develop performance simulation for Seawood Design's SurfPower WEC has been published (Bailey et. al., 2014) [38]."

Figure 3-8: Seawood SurfPower WEC Design and System Configuration



The SurfPower WEC, shown in Figure 3-8, illustrates the design of the SurfPower system. The buoyant wing dimensions are 6.7m by 24m and the piston pumps seawater through a high-pressure hydraulic pipeline system to an onshore Pelton turbine. The rectangular pontoon floats on the surface of the ocean. The hydraulic cylinder is anchored at its base to the ocean floor and it can rotate around this point. This configuration has a rating of 200kW in 9sec 4-meter waves [38].

As part of the WCWI, Seawood Designs and DSA collaboration, a SurfPower power matrix as a function of wave period and wave height was developed. The power matrix provided in Appendix C is a 2D lookup table that indexes power output against the Hs and Te value experienced at the deployment site. This matrix accounts for the efficiencies of the generator and Pelton turbine and translates the localized wave resource time series data into wave power. time series.

Table 3-10: WEC Mean Power

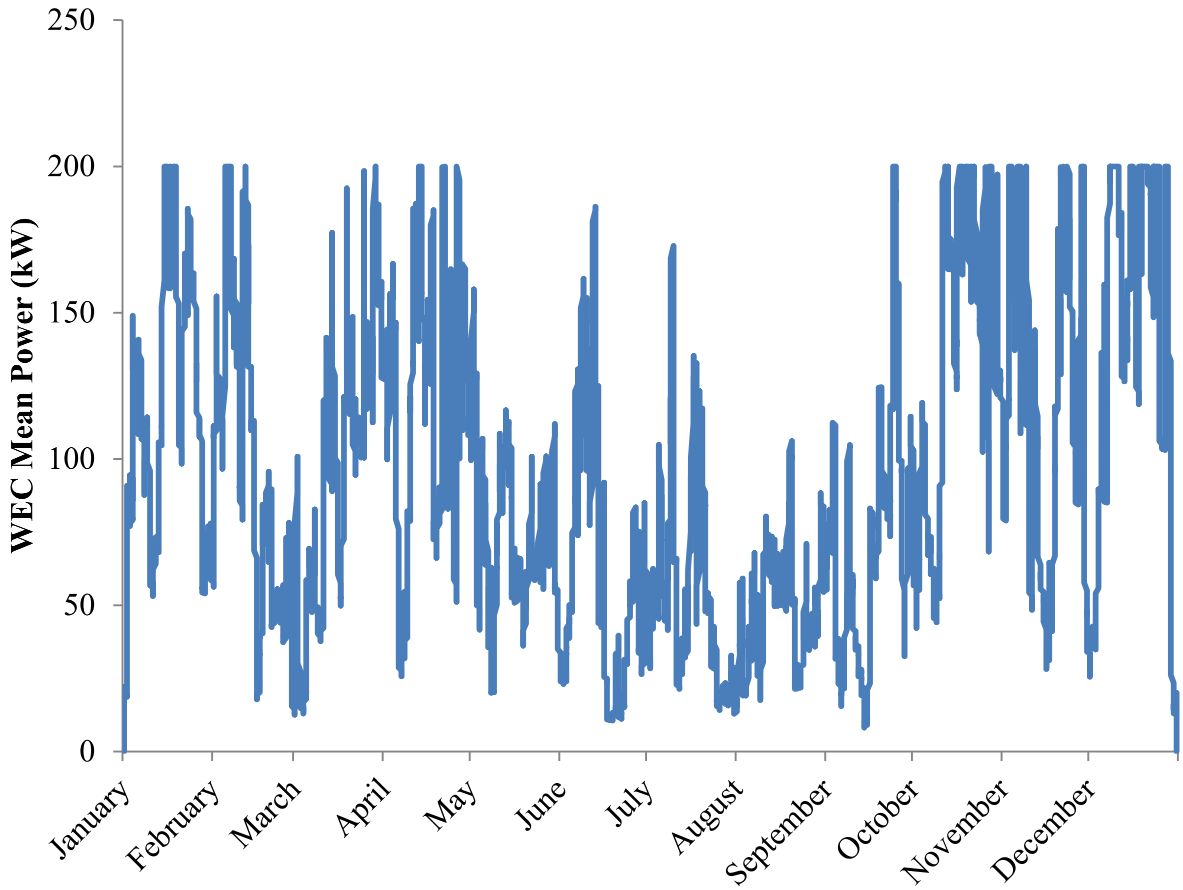
WEC Pontoon length	L = 24m
Available wave power	$P_{Waves} = \frac{\rho g^2}{64\pi} \cdot Hs^2 \cdot Te$
WEC mean power	$P_{WEC} = \eta_{WEC} \cdot P_{Waves} \cdot L$

Table 3-10 provides the simplified wave energy flux and WEC performance functions used to determine the mean power of each sea state for the Surfpower WEC. η_{WEC} is detailed in the efficiency matrix shown in Appendix C based on the numerical modelling [38]. With a pontoon length of 24m and the local wave resource (detailed in Subchapter 2.5), the 200kW WEC power time series is shown in Figure 3-9.

Since WEC mean power calculation is dependent on both Hs and Te, it becomes a non-linear power function. The RCOM model is a linear model, limited to linear functions and constraints. The wave power time series is pre-processed to develop the WEC mean power time series. The power time series is an input into the RCOM model. The same availability of the hydro generation model is applied to the WEC time series. The WEC is unavailable (P_{WEC} is zero) for 5% of hours in a year. Unavailable hours are pre-selected in the model as the first 5% of hours in each quarter, resulting in an even distribution of unavailability and negate the errors in the model spin-up data.

Ramping constraints that limit hour-to-hour changes in power output have not been defined for the diesel generation system. It is assumed that diesel generation can meet any hour-to-hour fluctuations in demand. Diesel cycling constraints limit unwanted high variability in diesel power output.

Figure 3-9: Surfpower 200kW WEC at the Proposed Location 2014-2015



The peak power demand of Hot Springs Cove is approximately 193kW and the rated full-scale WEC capacity is approximately 200kW. The wave power system can only accommodate a single SurfPower WEC.

The rated power of the WEC can be approximated through reduction in the physical dimensions of the WEC. For example, to reduce the rated power output by 50%, the pontoon length is reduced by 50%, reducing energy output by 50%. The WEC capacity scenarios with differing pontoon length are provided in Table 3-11. To reduce WEC effective 'capacity' beyond 50%, peak power output is limited by implementing a 'peak shaving' control scheme. This could be achieved with either mechanical dampening devices, limiting the maximum flow rate into the Pelton turbine, or electrical resistive devices. Pontoon length is not impacted.

Table 3-11: WEC Rated Capacities

Rated capacity	WEC Pontoon Dimension	% Capacity Reduction (of Maximum Capacity)	Control Methods	Annual Energy Output
200 kW	24m X 6.7m	-	None	828 MWh
180 kW	21.6m X 6.7m	10%	None	745 MWh
140 kW	16.8m X 6.7m	30%	None	579MWh
100 kW	12m X 6.7m	50%	None	414 MWh
90 kW	12m X 6.7m	45%	Peak Shaving	407 MWh

For WEC power data, five data time series have been generated. Each RCOM model scenario utilizes a single generated wave power time series. For the 100kW WEC and diesel generation scenario, the associated time series has a peak WEC power of 100kW and annual energy output of 414 MWh.

3.3 Cost Data and Formulations

This subchapter provides the overview of cost inputs and formulations for the RCOM model. The RCOM optimization objective function is composed of system operational costs, incurred annually over the project lifetime, in 2018 dollars. Post model processing incorporates the capital costs to determine total cost, or total allowable cost values.

In Table 3-12, the cost parameters provided as input for RCOM economic formulations are shown. The average historical annual inflation rate in Canada from 2007 to 2017 is 1.6% [39]. Economic analyses for marine technologies internationally use discount factors in the range of 8%-15% [40], [41]. Higher discount rates are applied to less commercially developed technologies. The discount rate for the following economic analysis assumes a 10% rate.

Table 3-12: Project Cost Parameters

Inflation (i)	1.6%
Discount (d)	10%
Project lifetime	30 years
Year 0	2018 Present Value, $2018
Variable Cost Data	
Diesel Fuel Cost	$Average\ C_{Fuel} = 1.6\ \$/L$ $High\ C_{Fuel} = 2\ \$/L$ $Low\ C_{Fuel} = 1.2\ \$/L$

The discount rate accounts for all potential system costs and risks. Higher discount rates increase the de-valuing of future costs. The LCOE calculation for large upfront costs due to construction and low annual operational costs results in higher LCOE values. For allowable LCOE, zero capital costs and higher de-valuing for future costs will have lower LCOE values.

The diesel-only system represents the business-as-usual (BAU) case. The BAU system performance is the basis for operational, environmental and economic system evaluation of alternative systems and associated scenarios.

All diesel-related costs are listed in Appendix A. The Barkley Group reported that the operations and maintenance costs consist of a fixed annual cost and a variable fuel cost. The Hot Springs Cove community accounting department provided the cost to barge fuel from Ucluelet

Co-op and the average diesel fuel unit cost, which is not subject to the provincial fuel tax. The diesel system cost formulations incurred each year of operations are defined in Appendix A.

There are three diesel fuel costs values considered for the evaluation. Application of an average diesel fuel cost over the project lifetime subject to the project annual inflation rate is only to develop a baseline for the economic evaluations. Diesel price variability can be volatile and justifies the evaluation of electric systems that minimize diesel fuel use.

The proposed hydro-diesel system consists of hydro system components introduced to the existing diesel system. For the hydro-diesel system, the total project cost includes the cost to install the hydro generation system and the cost to operate the combined hydro and diesel generation systems. Appendix B lists the capital costs related to the design and construction of the hydro generation system.

The hydro design cost includes the feasibility study as well as electrical and civil engineering design. The hydro turbine and generator capital cost comes from a quotation by Canyon Hydro, the proposed equipment supplier. The Barkley Group has provided a cost estimate for hydro construction consisting of a powerhouse, penstock, roads, civil works, electrical equipment and construction management.

The annual hydro operational costs are provided by the Barkley Group and listed in Appendix B. The water rental costs are determined by the BC Government [42]. The hydro operations and maintenance cost are a function of hydro energy output, hydro capacity and the annual fixed costs.

In the absence of equipment suppliers and reference costs for other regional installations of WEC technology, the costs to design, install and operate the proposed WEC systems are unknown. For the wave-diesel generation system, the diesel cost is an objective function. The allowable cost for the wave system is the difference between the total cost of the diesel-only system and the total cost of the wave-diesel system.

3.4 Mixed Integer Linear Programming

RCOM formulates the energy system cost minimization problem inside a Mixed Integer Linear Programming (MILP) framework. For each candidate energy system considered, the objective function is the total cost of the system operation and the constraints are a set of linear functions that enforce the supply-demand balance as well as all operational constraint on the various generators. The design variables include a mix of integer values, including binary variables defining whether generators are 'on' or 'off' as well as continuous variables defining the specific generator outputs.

All technology and system constraints are presented throughout Chapter 3.0. This section presents the MILP formulation for the diesel only system as an example case. The linear optimization problem is characterized by solving a set of linear functions with an optimal solution defined within a feasible range of solutions [43]. The mathematical problem for the diesel system is illustrated in Table 3-13.

Table 3-13: Diesel MILP Mathematical Problem

Objective Function	$\underset{P_D, X_D, V_{fuel}, X_{Barge}}{Minimize} \quad Total\ Diesel\ Costs\ *$ *Refer to Appendix A for Total Cost Formulation
Variable parameters	$P_{D,250kW}, P_{D,100kW} \in P_D$ $X_{D,250kW}, X_{D,100kW} \in X_D$ $t = \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_n \end{bmatrix} \quad n = 8760$
Constraint 1: Power and Supply Balance	$\begin{bmatrix} \Sigma P_{D1} \\ \Sigma P_{D2} \\ \vdots \\ \Sigma P_{Dn} \end{bmatrix} = \begin{bmatrix} P_{Demand1} \\ P_{Demand2} \\ \vdots \\ P_{Demandn} \end{bmatrix}$
Technology Constraint 2: Diesel Capacity	$P_D Max \cdot \begin{bmatrix} X_{D1} \\ X_{D2} \\ \vdots \\ X_{Dn} \end{bmatrix} \geq \begin{bmatrix} P_{D1} \\ P_{D2} \\ \vdots \\ P_{Dn} \end{bmatrix} \geq (0.2 \cdot P_D Max) \cdot \begin{bmatrix} X_{D1} \\ X_{D2} \\ \vdots \\ X_{Dn} \end{bmatrix}$

Technology Constraint 3: Diesel Fuel Use	$$\begin{bmatrix} V_{Fuel1} \\ V_{Fuel2} \\ \vdots \\ V_{Fueln} \end{bmatrix} = A \cdot \begin{bmatrix} P_{D1} \\ P_{D2} \\ \vdots \\ P_{Dn} \end{bmatrix} + B \cdot \begin{bmatrix} X_{D1} \\ X_{D2} \\ \vdots \\ X_{Dn} \end{bmatrix}$$ $A_{250kW}, A_{100kW} \in$ A $B_{250kW}, B_{100kW} \in$ B
Technology Constraint 4: Diesel Fuel Storage	$$\begin{bmatrix} V_{Tank(1+1)} \\ V_{Tank(2+1)} \\ \vdots \\ V_{Tankn} \end{bmatrix} = \begin{bmatrix} V_{Tank1} \\ V_{Tank2} \\ \vdots \\ V_{Tankn} \end{bmatrix} - \eta_{Deff} \cdot \begin{bmatrix} V_{Fuel1} \\ V_{Fuel2} \\ \vdots \\ V_{Fueln} \end{bmatrix} + V_{Delivery} \cdot \begin{bmatrix} X_{Barge1} \\ X_{Barge2} \\ \vdots \\ X_{Bargen} \end{bmatrix}$$
Technology Constraint 5: Diesel Cycling	$$\begin{bmatrix} \Sigma_{j=1}^{c} X_{D(1+j)} \\ \Sigma_{j=1}^{c} X_{D(2+j)} \\ \vdots \\ \Sigma_{j=1}^{c} X_{D(n+j)} \end{bmatrix} = \mathrm{C} \cdot \left\{ \begin{bmatrix} X_{D1} \\ X_{D2} \\ \vdots \\ X_{Dn} \end{bmatrix} - \begin{bmatrix} X_{D(1-1)} \\ X_{D(2-1)} \\ \vdots \\ X_{Dn} \end{bmatrix} \right\}$$

The optimization function is a cost function that is completely specified by the diesel system design variables of: $P_D, X_D, V_{fuel}, and\ X_{Barge}$. The total diesel cost function listed in Appendix A expressed all costs in terms of these same design variables. Each design variable, for example X_D, is an array of 8760 values, one value for each hour of the year of system operation considered. There are four diesel system technology constraints. The cycling constraint limits the vector values of X_D. The solution of the power and supply balance constraint determines which of the diesels' (100kW or 250kW) vector value equates to the demand vector value. The diesel capacity constraint defines the range of allowable diesel power vector values. The diesel fuel use vector is dependent on: the diesel power vector, the X_D vector and the scalars A and B. The fuel storage vector is the limiting function of the diesel fuel use vector value and the barge delivery occurrences vector value.

The system of linear equations consisting of four sets of 8760 variables is a complex mathematical problem. As additional technologies (battery, heat capture, etc.) are incorporated into RCOM, the software platform may need to be re-evaluated to facilitate the increasing model complexity.

4.0 Wave and Hydro Integration Model Results

The following chapter presents the RCOM results generated for each electric supply system scenario, providing an assessment for each electric supply scenario to reduce diesel generation and its environmental impacts in Hot Springs Cove.

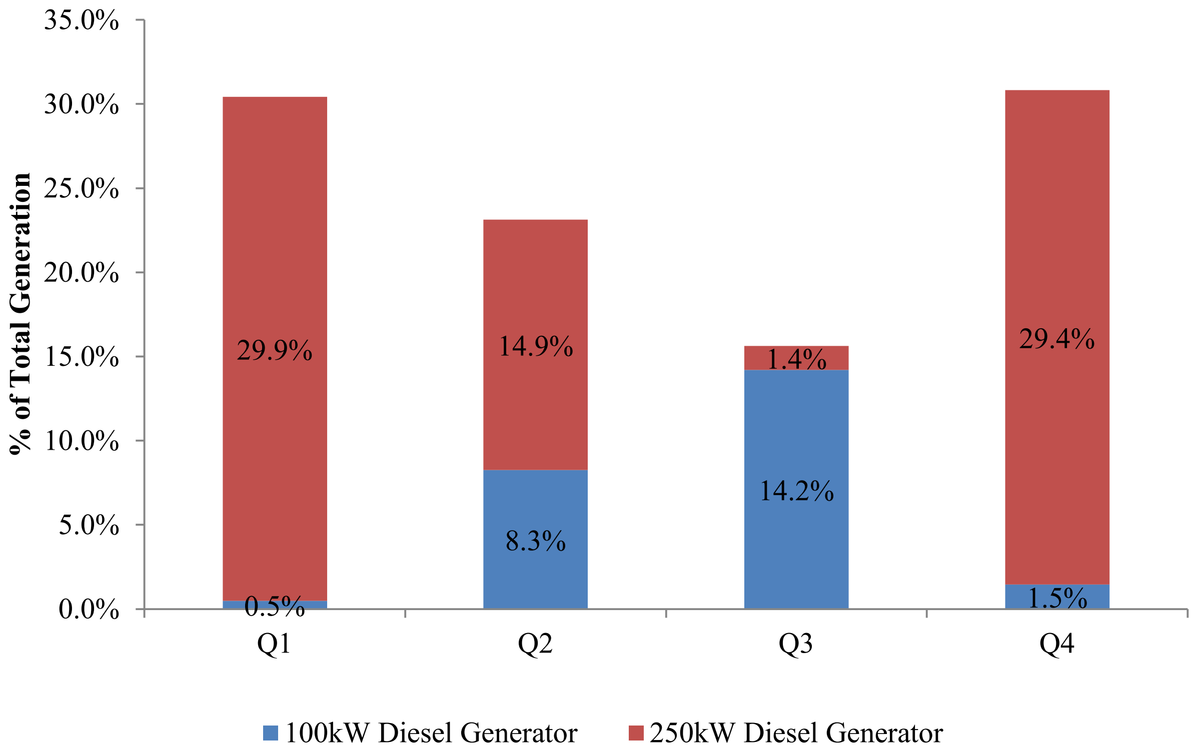
Subchapter 4.1 presents the results of the BAU case (the diesel-only system). These BAU values are the comparative basis for cost and environmental impact reductions for all hybrid-diesel systems described in 3.2. Subchapters 4.2, 4.3, and 4.4 discuss the economic and environmental impacts for the hydro-diesel, wave-diesel and wave-hydro-diesel energy systems respectively. The diesel only system is subject to diesel fuel price variability and the hydro-diesel system is subject to variability in hydro resources. Subchapter 4.5 provides a results summary of each system scenario and provides a comparative analysis of all systems scenarios. Chapter 5.0 evaluates the project development of integrating wave and hydro into an existing diesel electric system using decision criteria from the RCOM results.

4.1 Business as Usual System Performance

The diesel generator operational constraints and emissions rates were discussed in Subchapter 3.2 and the operational costs in Appendix A. The BAU results set the baseline for diesel generation, fuel utilization and diesel costs. The comparative analysis quantifies changes to system performance due to wave and hydro utilization relative to the BAU results.

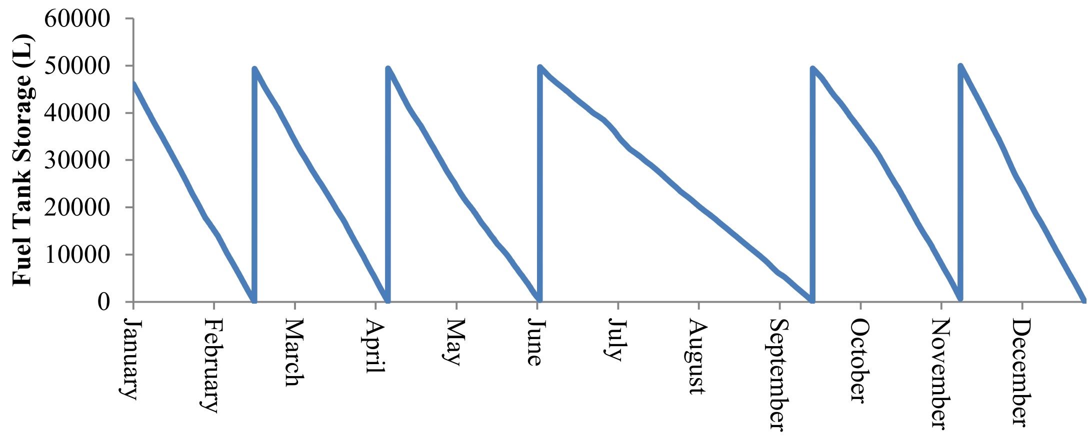
Figure 4-1 presents diesel energy output from the two diesel generator systems as a percentage of total diesel generation. The total annual diesel generation is 909,500 kWh. During Quarter 1, 2 and 4r, the 250-kW diesel generator has the largest utilization. In Quarter 3, the 100-kW diesel generator has the largest utilization for summer demand. The average capacity factor for the 250kW diesel generator is 31% and the 100kW diesel generator is 25%.

Figure 4-1: Percentage of Annual Diesel Generation per Diesel Generator



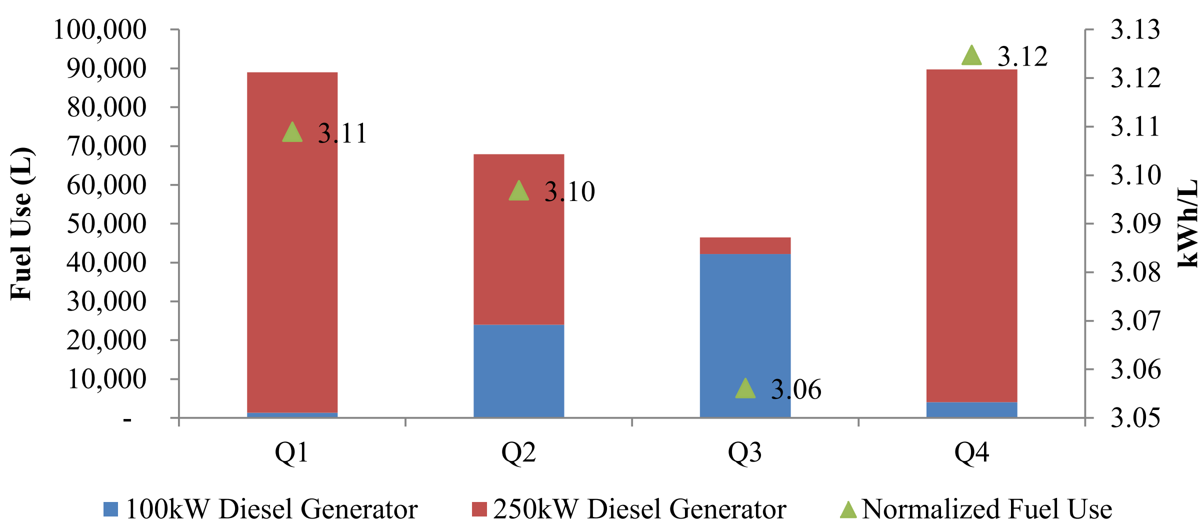
The annual fuel use is 293,000L and the fuel use profile is illustrated in Figure 4-2. There are six annual fuel deliveries indicated with the fuel storage tank fuel level instantaneously increasing from close to zero to 50,000L. All RCOM solutions for each scenario result in the last hour of the year with 0L of fuel in storage. The assigned volume of fuel in storage for the first hour of the year is 46,135L and for the last hour (hour 8,760), is 0L. There is no fuel delivery occurrence corresponding to the initial fuel storage value for the first hour. To account for total diesel fuel delivery costs, a fixed value of one is included in the summation of annual fuel delivery occurrences. In this example, the summation of RCOM annual fuel delivery costs is one plus five diesel fuel delivery occurrences.

Figure 4-2: Annual Fuel Use and Fuel Delivery Schedule



The portion of the fuel use per generator is shown in Figure 4-3. The fuel use is greatest in the winter months, mostly by the 250kW diesel generator. The summer months have the lowest fuel use, mostly by the 100kW diesel generator. Over the year, the 250kW and 100kW diesel generator consumes 222,000L and 72,000L respectively. The normalized fuel use (kWh/L) is the sum of the fuel consumed by both generators, divided by the sum of the demand in each quarter. Higher fuel efficiency is gained from the 250kW generator, as shown in Quarter 1 and Quarter 4. Quarter 3 results confirm the smaller diesel generator exhibits lower fuel efficiency. The normalized fuel efficiency for all generators for all quarters is 3.10 kWh/L.

Figure 4-3: Fuel Use per Diesel Generator



The annual emissions rates are provided in Table 4-1. The CO_2 rate is the result of the annual CO_2 emissions normalized by the annual diesel generation. Over the project lifetime of 30 years, the CO_2 emissions equate to 23,400 tonnes of CO_2. The CO_2 emissions rate of 858 gCO_2/kWh is a value that can be compared to any electric supply system of any size. The annual CO2 (kg/yr) emission value of 780,500 is mostly influenced by the size of the electric system. For small electric supply systems such as remote communities, it is difficult to compare this value to larger regional electric supply systems.

Table 4-1: Diesel-Only System Annual Emissions

CO_2 Emissions Rate	CO_2	PM	NO2+NMHC	CO
858 gCO_2/kWh	780,500 kg/yr	204 kg/yr	5,870 kg/yr	3,500 kg/yr

The annual breakdown of diesel system costs is provided in Table 4-2. It is important to highlight that diesel fuel costs are the largest component; hence significant savings can be achieved through the reduction of diesel fuel use. By comparison to utility offered PPA rates, the allowable LCOE costs will be greater due to the inclusion of additional costs. For Hot Springs Cove, this value is up to 20% of additional diesel costs above fuel costs.

Table 4-2: Percentage Breakdown of Diesel System Costs

Fixed O&M Cost	Oil Cost	Barge Delivery Cost	DSL fuel Costs	Overhaul Cost
9.7%	0.8%	3.6%	79.9%	6.0%

The total cost and LCOE of the diesel-only system is presented in Table 4-3 for three fuel cost values. All other unit diesel costs for oil, replacement and barge delivery remain the same in these results. These high fuel and low fuel cost values are arbitrary values. Recall that large regional utilities have diesel fuel storage and purchase strategies to reduce variability in fuel prices. This community-owned utility system does not have the ability to store more than

50,000L of fuel to take advantage of fuel price reduction and is subject fuel price at the required time of delivery.

For a +/- 0.04$ range in diesel fuel prices, the total cost over a 30 year period changes by +/- $1.29M or +/- 0.15 $/kWh, indicating changes in fuel price and system costs are uniform. The proceeding evaluation of hydro-diesel and wave-diesel systems assumes an average fuel cost of 1.6$/L and that any changes to fuel costs would have uniform changes to system costs or system savings. Price variability will continue to exist under any scenario. Minimizing diesel fuel use will also reduce the impact of fuel price volatility.

Table 4-3: Base Case Economic Values

Variability in fuel price:	**High Fuel Cost (2$/L)**	**Avg Fuel Cost (1.6$/L)**	**Low Fuel Cost (1.2$/L)**
Total Cost	$ 7.73 million	$ 6.44 million	$5.15 million
LCOE	0.90 $/kWh	0.75 $/kWh	0.60 $/kWh

4.2 Hydro-Diesel System

The hydro-diesel system performance is based on the hydro and diesel operational constraints and capacity scenarios discussed in Subchapter 3.2. The hydro-diesel system technical model was introduced in Subchapter 3.2.2 and the hydro costs are available in Appendix B. The hydro system has system costs associated with the proposed hydro-diesel system scenarios. Total system costs for the hydro-diesel scenarios are included. The allowable system cost for hydro electric supply is also included in the economic analysis. The average diesel fuel cost of 1.6$/L is only considered and hydro resource variability discussed in Subchapters 3.2.2 and 3.3 are applied in the following evaluation.

Table 4-4 lists the operational results of each hydro-diesel system scenario for an average flow-rate year (MAD = 0.388 m^3/s) and average diesel fuel cost (1.6$/L). The 225kW hydro system achieves the largest integration of hydro generation with a value of 65% of annual demand. By comparison, the 275kW and 325kW hydro systems result in marginally larger diesel fuel use and marginally lower hydro generation. As discussed in Subchapter 3.2.2, each hydro scenario has specified minimums for start-up and shut-down in terms of a percentage of rated capacity. The results demonstrate best-fit hydro rated capacity should consider these minimum constraints for a system reliant on hydro resources with dry periods. For Ahtaapq creek, the dry periods occur in the summer season (June – August).

Since hydro generation is dispatchable (within the energy limits of the storage reservoir), hydro generation is determined by demand. The 275kW and 325kW hydro systems have more generation capacity than the 225kW hydro system but are not fully utilized.

Table 4-4: Hydro-Diesel System Operational Results Summary

Rated Hydro Capacity (kW)	Fuel Use (L/yr)	Annual Fuel Reduction (%)	100 kW Diesel Capacity Factor	250kW Diesel Capacity Factor	Diesel Fuel Efficiency (kWh/L)	Annual Hydro Generation (% of Demand)
225	100,100	65.8%	31.0%	2.0%	3.16	65.2%
275	102,200	65.1%	28.1%	3.3%	3.13	64.9%
325	102,800	64.9%	30.7%	2.5%	3.15	64.4%

The hydro-diesel system reduced the diesel capacity factor of the 250kW diesel generator from 31% (diesel-only system) to 2-3%. The 100kW generator capacity factor rose slightly from 25% (diesel-only system) to 28-31%. The annual fuel use is greatest for the 325kW hydro-diesel system, while having the lowest value of annual hydro generation. The range of annual fuel use is 100,100L to 102,800L, a difference of 2,700L.

Applying a fuel cost rate of 1.6$/L (to 2,700L), the differential cost is approximately $4,320. The trade-off of this differential cost is 100kW of additional hydro capacity. With increasing hydro capacity, the minimum capacity also increases. In combination with periods of low volumetric flows in Ahtaapq creek and a draining reservoir, the larger hydro capacity systems are shutting down for longer periods of time to meet their shutdown and start-up requirements. Overall the 100kW diesel generator is well matched to supplement the hydro system.

Figure 4-4 shows the breakdown of generation by quarter. The hydro generation profile is like the 250kW generation profile of the diesel-only system. For all the hydro-diesel systems, the 100kW diesel generator supplements hydro generation the most in each quarter, ranging from 2%-14%, while the 250kW diesel generators supplement in the range of 1%-3%. Overall, the diesel fuel efficiency increases to 3.16 kWh/L from the average value of 3.10 kWh/L of the BAU system. This 225kW hydro-diesel system utilizes the 100kW diesel generator the greatest amount of all hydro-diesel scenarios. Recall an availability factor of 95% is applied to the hydro electric supply. Diesel generation is required for a minimum of 5% of hours per quarter.

Figure 4-4: Hydro-Diesel System Generation

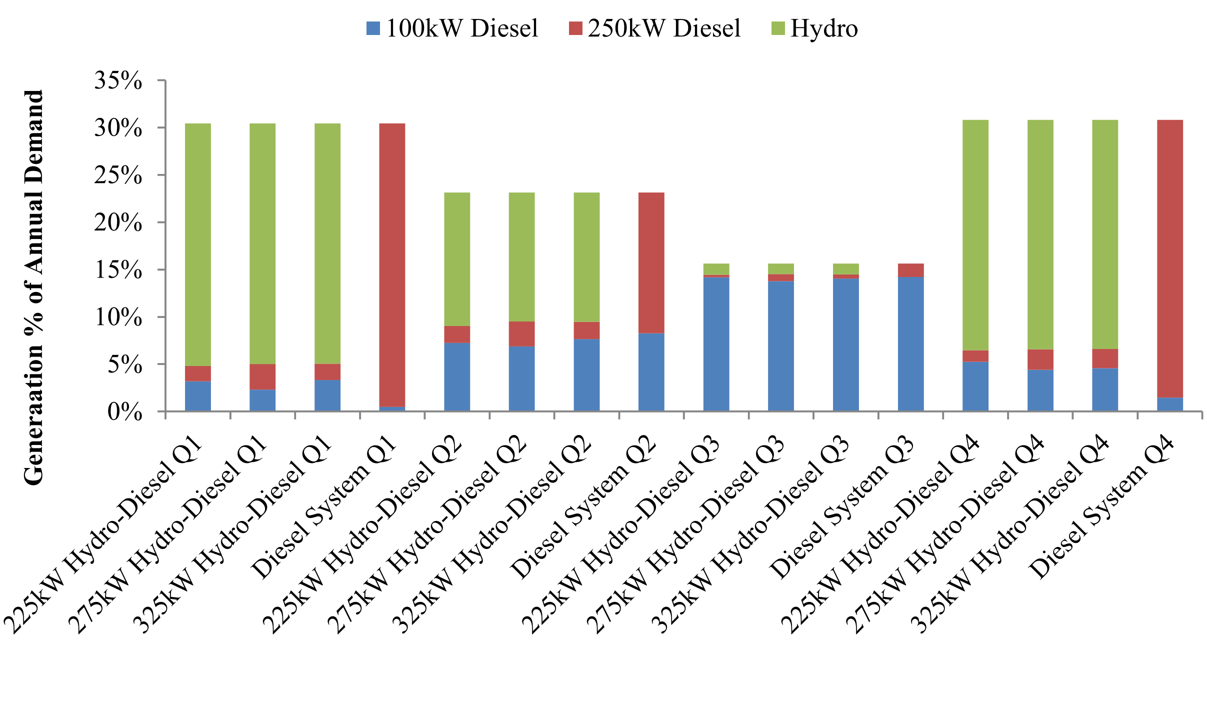


Table 4-5 lists the environmental impacts for all hydro-diesel systems due to hydro flow rate variability. Annual fuel use reductions for the 225kW hydro-diesel system range from approximately 64% in a low flow year, to 92% in a high flow year. The annual fuel use reduction for the average flow year is 65.9%. Fuel use is directly correlated to fuel cost, resulting in savings ranging from 64%-92%. Both the 275kW and 325kW hydro-diesel systems achieve slightly lower fuel use reductions. Reductions in fuel delivery range from 50% during low flow years to 83% during high flow years.

Reductions in Diesel ON hours and resultant noise range from 54% to 12%. It is evident the emissions rate and total annual emissions will vary year-to-year with the magnitude of the hydro resource. The average flow year best predicts the fuel savings and emissions rate over the course of the project. Based on the average flow, the emissions rate for the 225kW, 275kW and 325kW hydro-diesel systems are 293gCO_2/kWh, 299gCO_2/kWh, and 304gCO_2/kWh respectively.

Table 4-5: Hydro-Diesel Environmental Impacts

	225kW Hydro		**275kW Hydro**		**325kW Hydro**		
	Low Flow	**High Flow**	**Low Flow**	**High Flow**	**Low Flow**	**High Flow**	***Base Case***
Fuel Reduction	64.0%	92.0%	63.3%	87.6%	56.0%	87.3%	*293,135*
Fuel Deliveries	3	1	3	1	3	1	*6*
% Diesel ON hours	46.2%	12.2%	47.0%	14.8%	54.0%	15.3%	*100%*
Emissions Rate (gCO_2/kWh)	309	70	315	106	377	109	*858*
Emissions (tCO_2/yr)	281	63	287	97	343	99	*781*

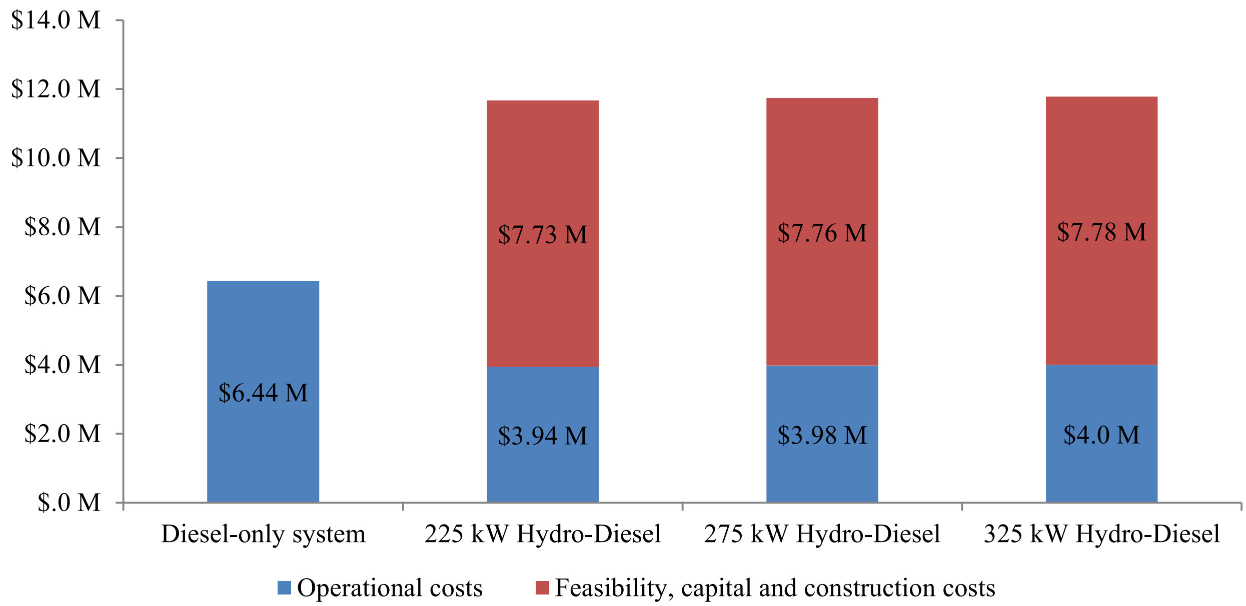
The LCOE values shown in Table 4-6 below are based on the LCOE formulations presented in Subchapter 3.1 and Appendix B. The primary observation is all hydro-diesel systems have larger LCOE values than the respective diesel-only systems. The approximate increased cost of the hydro-diesel systems by comparison to the diesel-only systems with high, average and low diesel fuel cost scenarios is 59%, 83%, and 120% respectively. This indicates that with increasing fuel cost, the cost increase associated with any hydro-diesel system is minimized.

Table 4-6: Hydro-Diesel System LCOE Values

	LCOE: Low Fuel Cost ($/kWh)	LCOE: Avg Fuel Cost ($/kWh)	LCOE: High Fuel Cost ($/kWh)
Diesel-Only	0.60	0.75	0.90
225 kW Hydro-Diesel	1.31	1.36	1.41
275 kW Hydro-Diesel	1.32	1.37	1.43
325 kW Hydro-Diesel	1.32	1.37	1.43

Excluding the high and low diesel fuel cost scenarios, the total costs associated with each proposed hydro-diesel system utilizing the average flow year are shown in Table 4-6. As presented in Appendix B, there is minimal difference in capital costs between the 225kW to 325kW hydro generation systems for feasibility, capital and constructions costs. Combined with the very small range of the differential diesel mitigation of each hydro-diesel system, the total cost is very similar, ranging from $11.7M to $11.8M. The operational costs include both hydro and diesel operational costs. The hydro feasibility, capital and construction costs are greater than the total diesel cost of the diesel-only system.

Figure 4-5: Hydro-Diesel System Costs



Without including the hydro costs, the diesel cost savings can be calculated. For each system, diesel cost savings are $3.82M, $3.78M and $3.77M. These values are the basis to calculate the allowable hydro system costs listed in Table 4-7 and Table 4-8.

Table 4-7: Allowable Hydro System Costs

	225kW hydro	275kW Hydro	325kW Hydro
Allowable Cost (LCOE)	$0.68/kWh	$0.68/kWh	$0.68/kWh

Total hydro costs include hydro feasibility, capital, construction and hydro operational costs (excluding diesel costs). Costs are normalized by the installed hydro capacity shown in Table 4-8. The 225kW hydro-diesel system results in the highest installed hydro cost. The 325kW hydro-diesel system has marginally higher hydro costs, with a hydro capacity 1.4 times larger. The 325kW hydro system has the lowest installed hydro cost of 28,000 $/kW installed. These allowable costs are much lower, indicating the current contractor cost estimates are high with respect to related diesel savings.

Table 4-8: Hydro System Cost per kW Installed

	Hydro Capacity	Total hydro installed cost ($/kWinstalled)	Allowable hydro installed cost ($/kWinstalled)
225 kW Hydro-Diesel	225kW	40,200	$17,000
275 kW Hydro-Diesel	275kW	33,000	$13,800
325 kW Hydro-Diesel	325kW	28,000	$11,600

4.3 Wave-Diesel System

The wave-diesel system performance is based on the constraints and scenarios discussed in 3.2. The results quantify the operational and environmental impacts. The basis for the economic results is the diesel generation cost savings.

Table 4-9 lists the operational results of each wave-diesel system. Wave-diesel systems achieve a range of annual fuel use reductions from 68% to 40%. The wave energy converter capacity factor ranges from 47% to 52%. Capacity factor is formulated using the total annual WEC generation from the wave resource and the wave energy conversion technology. The 100kW-200kW wave electric supply scenarios have the same capacity factor because variation of wave capacity and energy generation scales uniformly. Modeled annual generation is dependent on one year of wave resource data matched with metered community electric demand. The wave resource data is unlike the hydro resource data that is based on an average year selected from a database of historical data. Hydro resource data created for Ahtaapq creek is synthesized from nearby Carnation creek, with similar geologic and meteorologic characteristics. The wave resource is measured data near the proposed location of the WEC.

Utilized wave generation is the amount of wave generation integrated into the community electric supply system to offset diesel electric supply. Similar to the hydro electric supply system, this is considered wave electric supply at the point of interconnection to the community distribution. The availability factor is 95%, where 5% of the time wave generation is not available and diesel electric supply meets the demand. There are hours where there is an abundance of wave resource and wave generation in excess of community electric demand, or over-generation. Over-generation would be considered a loss for an IPP unless it could be sold to an electric utility. Wave energy utilization, which is the amount of utilized annual wave generation to offset demand, ranges from 78%-94%. Excess wave generation is accounted for as over-generation (not utilized) while excess hydro flow is stored in the reservoir or spilled over the containment.

With the wave-diesel system, the 250kW diesel generator capacity factor drops from 31% (diesel-only system) to a range of 3% to 6%. The 100kW diesel generator capacity factor increases from 21% to 44% as wave capacity decreases. The average diesel fuel efficiency marginally drops from 3.1kWh/L (Diesel-only system) to a range of 2.8-3.0kWh/L. Wave generation ranges from 71.3% to 42% of annual demand. These values account for 95% availability, but do not include any additional losses to transmit and interconnect the power from the wave system to the community distribution network.

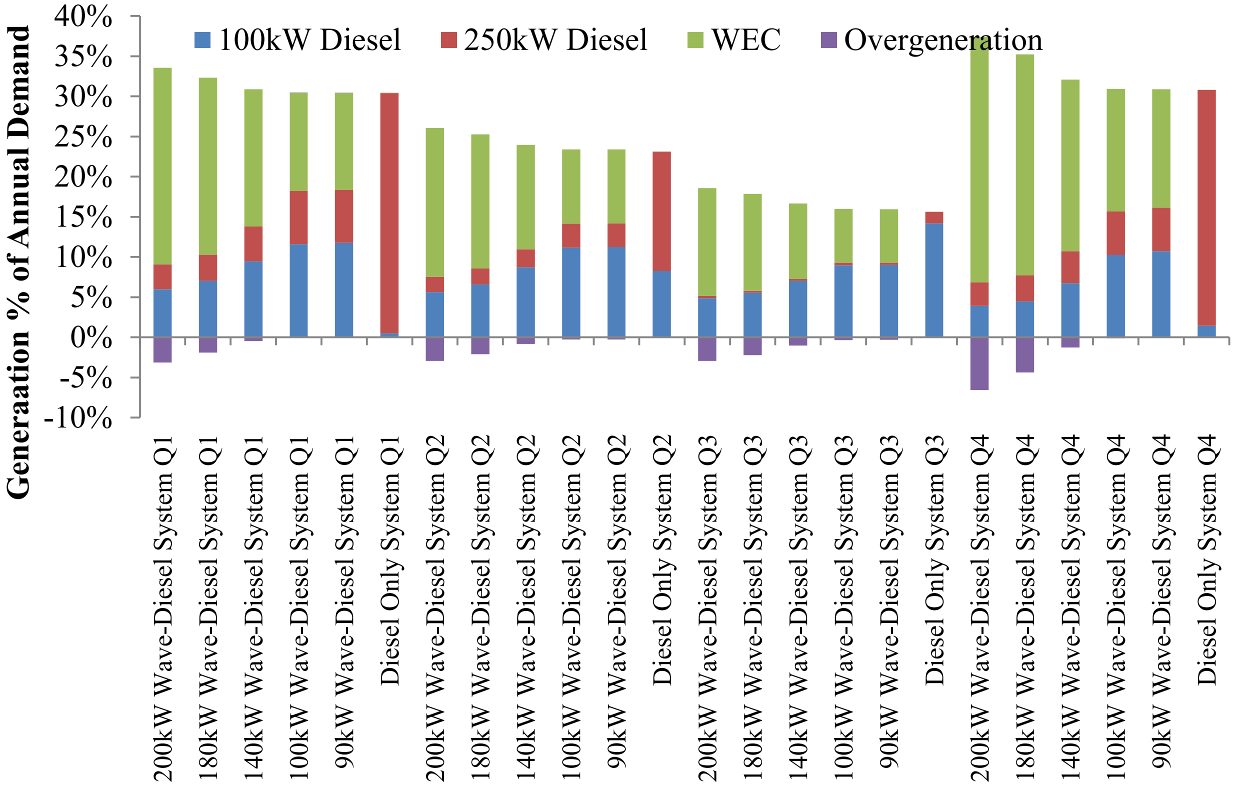
For the 200kW and 180kW wave-diesel systems, 71.3% and 67.6% of demand is met by wave generation, respectively. This is comparable to the 225kW hydro-diesel system, where 65% of demand is met from hydro generation.

Table 4-9: Wave-Diesel Operational Results

Rated Wave Capacity (kW)	Fuel Use (L/yr)	Annual Fuel Reduction (%)	WEC Capacity Factor	Utilized Wave Energy	100 kW Diesel Capacity Factor	250kW Diesel Capacity Factor	Diesel Fuel Efficiency (kWh/L)	Wave Generation (% of Demand)
200	92,500	68.4%	47.2%	78.4%	21.2%	3.4%	2.82	71.3%
180	104,300	64.4%	47.2%	82.5%	24.5%	3.7%	2.83	67.6%
140	135,500	53.8%	47.2%	89.9%	33.1%	4.5%	2.87	57.2%
100	175,300	40.2%	47.2%	93.9%	43.6%	6.4%	2.97	42.7%
90	177,000	39.6%	51.6%	94.0%	44.3%	6.3%	2.98	42.0%

Figure 4-6 illustrates the generation in each quarter for all scenarios. Detailed bar values from Figure 4-6 can be found in Appendix C. The profile of wave generation reduces the use of the 250kW diesel generator in all seasons. This indicates the 250kW diesel generator is not beneficial in most cases, such as wave-diesel systems with a WEC capacity of 140kW or larger. The 100kW diesel generator is utilized in all systems throughout the year. In the summer season, only the 100kW diesel generator supplements wave generation. As WEC capacity increases, excess wave energy increases, accounted for as over-generation. Excess energy is highest for the 200kW wave-diesel system in Quarter 4, reaching 7% of annual demand.

Figure 4-6: Wave-Diesel System Annual Generation



Environmental impact results are listed in Table 4-10. Fuel use reduction corresponds to a proportional reduction in CO2 emissions. As discussed earlier, the smaller WEC capacity wave-diesel systems have the highest utilization and very little excess energy. However, the reduction of diesel operations of small wave-diesel systems is minimal by comparison to large wave-diesel systems. For example, the 100kW wave-diesel system requires the diesel generators to remain on 98.4% of the year, while the 200kW wave-diesel system requires the diesel to operate only 63% of the year, reducing emissions and noise. The fuel delivery requirement for the 200kW wave-diesel system is 2 per year, while both the 100kW and 90kW wave-diesel systems require 4 fuel deliveries per year. The emissions rate of the 200kW and 90kW wave-diesel system is 271 gCO_2/kWh and 518gCO_2/kWh respectively. The 90kW wave-diesel system has approximately double the diesel generation requirements and impacts of the 200kW wave-diesel system.

Table 4-10: Wave-Diesel System Environmental Impact Results

	Wave-Diesel System					
	200kW	**180kW**	**140kW**	**100kW**	**90kW**	*Base Case*
Fuel / Emissions Reduction	68.4%	64.4%	53.8%	40.2%	39.6%	*293,135*
Fuel Deliveries	2	3	3	4	4	*6*
% of Diesel ON hours	62.8%	70.2%	87.3%	98.4%	98.6%	*100%*
Emissions Rate (gCO_2/kWh)	271	305	397	513	518	*858*
Emissions (tCO_2/yr)	246	278	361	467	471	*781*

The allowable LCOE values are presented in Table 4-11. LCOE formulation provides levelized allowable cost. The allowable LCOE values for average diesel fuel cost of 1.6$/L range from 0.51-0.60$/kWh for 200kW to 90kW wave-diesel systems respectively. The 90kW wave-diesel system has the highest allowable cost of 0.73$/kWh in a high diesel fuel cost scenario and the 200kW wave-diesel system has the lowest allowable cost of 0.39$/kWh in a low diesel fuel cost scenario. As previously discussed, the wave-diesel systems with the smallest WEC capacity have much higher utilization and the lowest excess wave generation.

Table 4-12 lists the allowable LCOE for utilized wave generation. Table 4-11 uses the total annual wave generation in the calculation and Table 4-12 uses the total utilized wave generation in the calculation. Total utilized wave generation deducts the over-generation value. The percent utilized values are listed for reference. These values include the impacts of reduced wave generation based on 95% availability.

Table 4-11: Allowable LCOE for Wave Generation.

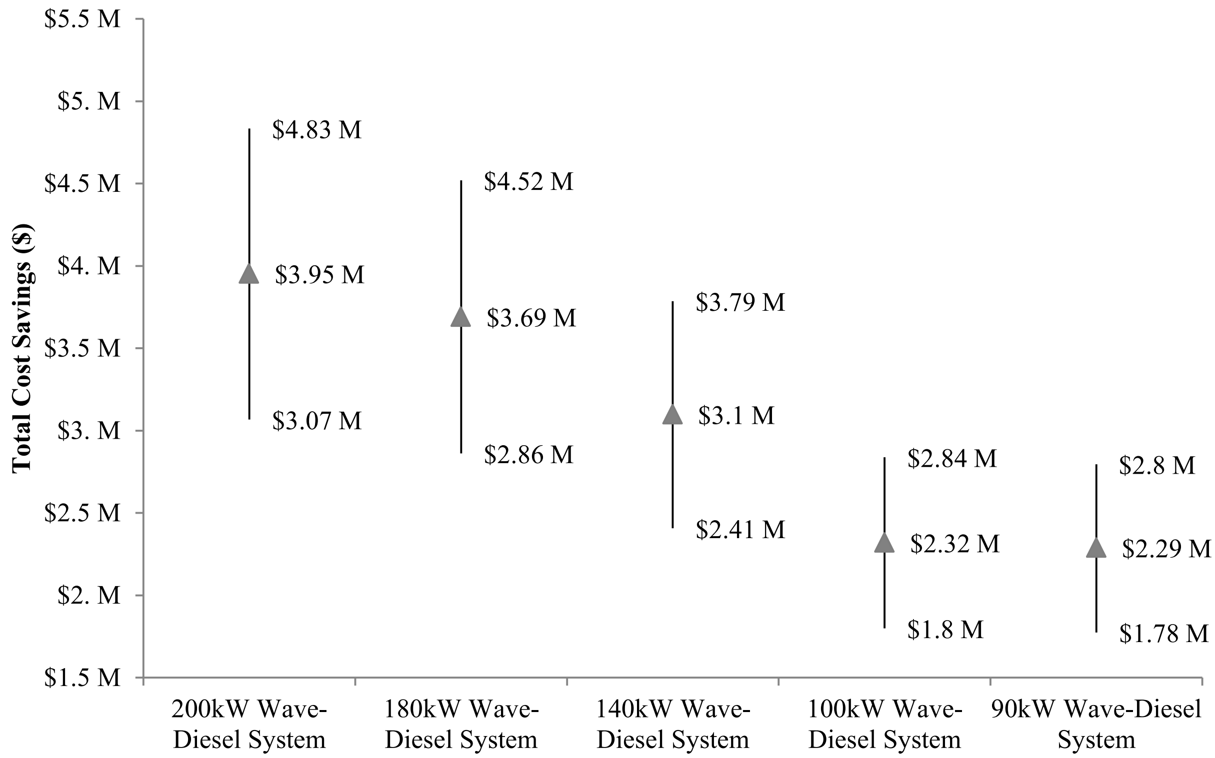
	Low Fuel Cost ($/kWh)	High Fuel Cost ($/kWh)	Avg Fuel Cost ($/kWh)
200kW Wave-Diesel System	0.39	0.62	0.51
180kW Wave-Diesel System	0.41	0.64	0.53
140kW Wave-Diesel System	0.44	0.69	0.57
100kW Wave-Diesel System	0.46	0.73	0.59
90kW Wave-Diesel System	0.46	0.73	0.60

Table 4-12: Allowable LCOE for Utilized Wave Generation

	Low Fuel Cost ($/kWh)	High Fuel Cost ($/kWh)	Avg Fuel Cost ($/kWh)	% Utilized Wave Generation
200kW Wave-Diesel System	0.50	0.79	0.65	78%
180kW Wave-Diesel System	0.49	0.78	0.64	83%
140kW Wave-Diesel System	0.49	0.77	0.63	90%
100kW Wave-Diesel System	0.49	0.77	0.63	94%
90kW Wave-Diesel System	0.49	0.78	0.64	94%

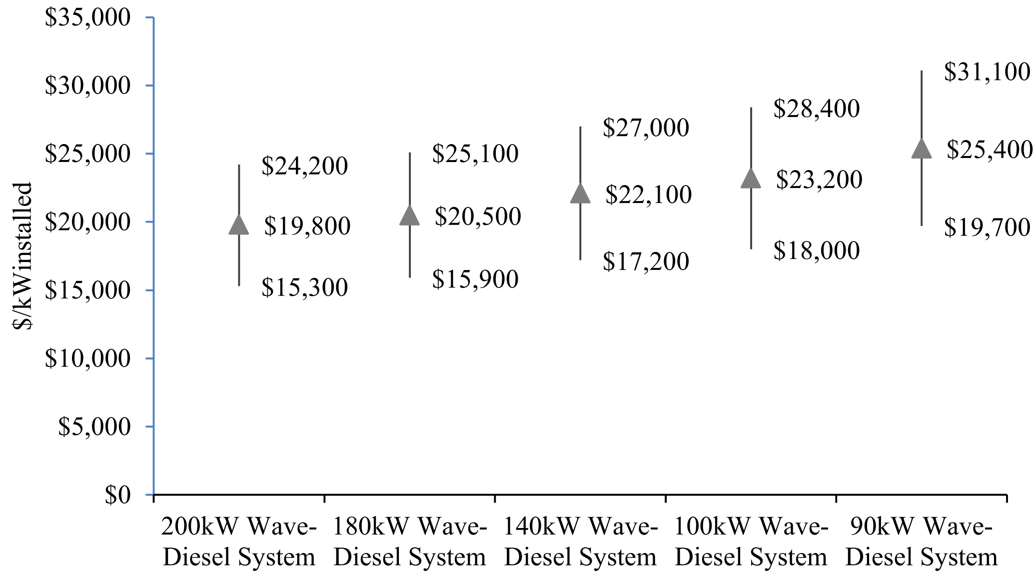
Figure 4-7 illustrates cost savings of each wave-diesel system for high, low and average diesel fuel cost scenarios. Cumulative savings over the 30 year project lifetime for the 90kW wave-diesel system range from $1.78M to $2.8M. Savings for the 200kW wave-diesel system range from $3M to $4.8M.

Figure 4-7: Wave-Diesel System Operational Cost Savings



The allowable installed cost for each of the wave-diesel system is shown in Figure 4-8. The range of values for each system are due to high, average and low fuel costs and the relative diesel cost savings. The trend shows increasing allowable costs for smaller WEC rated capacities. As discussed previously, the smaller WEC capacities have higher utilization that further reduces diesel use and costs. These additional cost savings influence this upward trend for decreasing WEC capacity. With an average fuel cost of 1.6$/L, the allowable installed cost for the 200kW wave-diesel system is 19,800$/kWinstalled and the 90kW wave-diesel system is 25,400$/kWinstalled. Comparing known hydro system costs of Subchapter 4.2, smaller hydro systems had higher costs relative to rated hydro capacity. A large proportion of capital hydro costs are fixed, regardless of capacity. The capital cost structure for wave systems is likely to be similar.

Figure 4-8: Wave Allowable Installed Cost.



4.4 Wave-Hydro-Diesel System

Wave-hydro-diesel system performance is based on the WEC capacity scenarios discussed in 3.2.3 and the 225kW hydro system of 3.2.2. Selection of the 225kW hydro system is based on the low range of operations near minimum capacity. The strategy is to have the most flexible hydro generation to compliment wave generation, a non-dispatchable source. The hydro resource utilized in all wave-hydro-diesel scenarios is the annual flow data with average MAD of 0.388 m^3/s. The performance results quantify the operational and environmental impact changes due to wave and hydro generation compared to the diesel-only system.

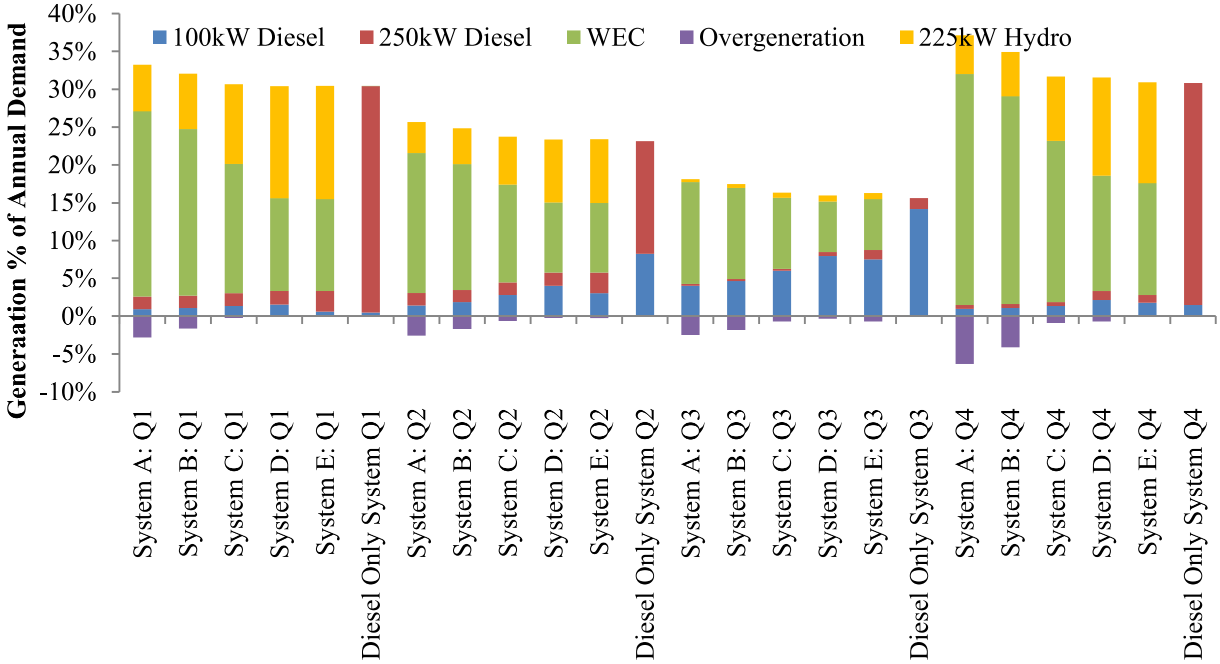
Table 4-13 lists the operational results for each wave-hydro-diesel system configuration, Systems A-E. These systems achieve fuel use reductions from 78% to 88%. The 250kW diesel capacity factor drops from 31% (diesel-only system) to less than 1-3% for all wave-hydro-diesel systems. The 100kW diesel generator capacity factor drops from 25% to 8-13% for all wave-hydro-diesel systems. Additionally, the average diesel fuel efficiency drops marginally from 3.1kWh/L (diesel-only system) to 2.9-3.0 kWh/L.

Table 4-13: Wave-Hydro-Diesel System Operation Results

System	Wave-Hydro-Diesel System Configuration	Fuel Use (L/yr)	Annual Fuel Reduction (%)	100 kW Diesel Capacity Factor	250kW Diesel Capacity Factor	Diesel Fuel Efficiency (kWh/L)	Annual Wave and Hydro Generation (% of Demand)
A	200kW Wave-225kW Hydro	36,100	88%	7.6%	1.70%	2.88	88.6%
B	180kW Wave-225kW Hydro	40,100	86%	9.0%	1.67%	2.88	87.3%
C	140kW Wave-225kW Hydro	48,900	83%	12.0%	1.69%	2.90	84.4%
D	100kW Wave-225kW Hydro	60,800	79%	16.4%	1.67%	2.96	80.2%
E	90kW Wave-225kW Hydro	65,900	78%	13.4%	3.25%	2.86	79.3%

Figure 4-9 illustrates the generation mix for all systems. Appendix D illustrates the figure with the data values in the bars for reference. The generation merit order prioritizes the lowest cost generation. Wave generation has zero generation cost, therefore has the highest priority. Hydro generation has second priority due to low operational costs. Diesel generation has last priority due to high operational costs. The 100kW diesel generators are required to supplement wave and hydro generation throughout the year and the 250kW diesel generator will meet deman during periods of wave and hydro unavailability. Excess wave generation is accounted for as over-generation, while under-utilized hydro flow is stored in the reservoir or spilled over the containment.

Figure 4-9: Wave-Hydro-Diesel System Annual Generation



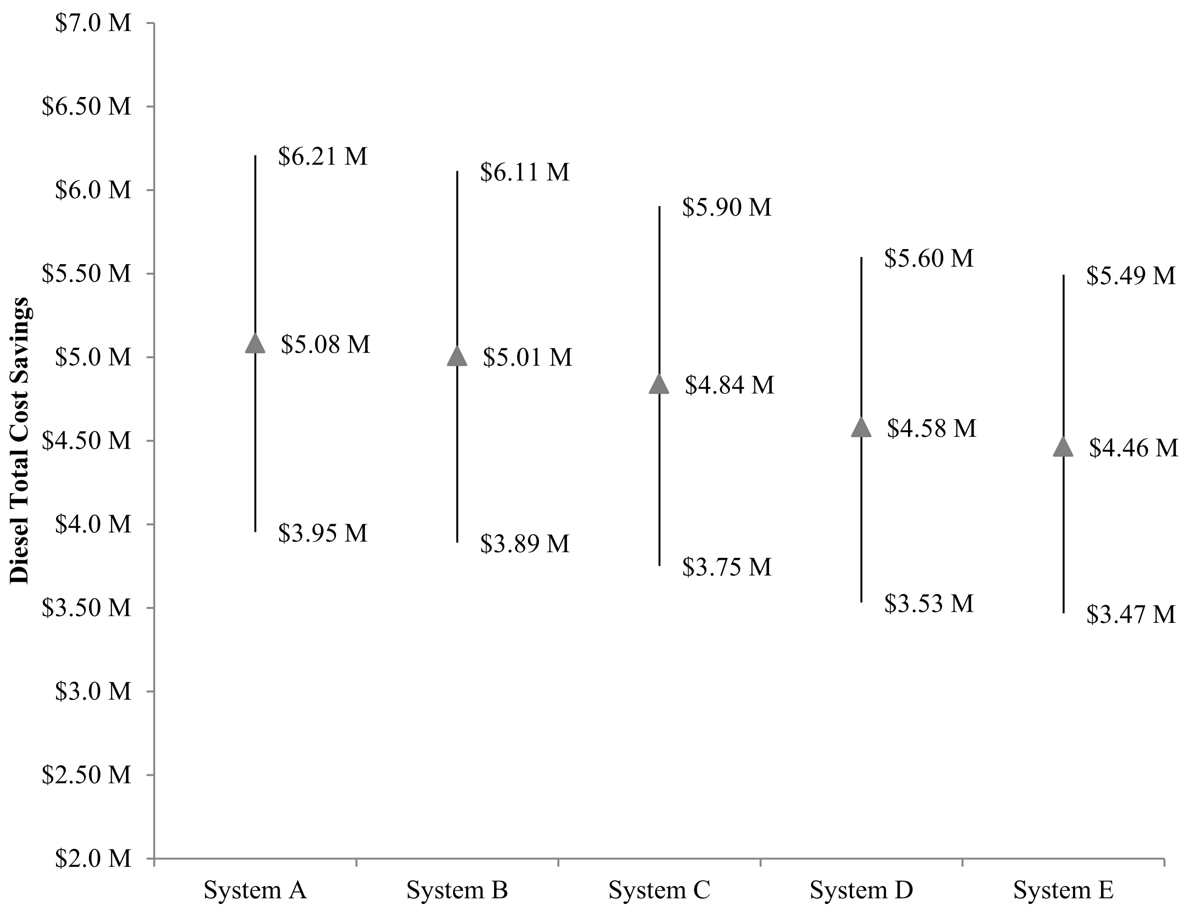
The environmental impacts are listed in Table 4-14. Systems A and B have nearly 50% fewer fuel deliveries and diesel ON hours than the 225kW hydro-diesel system. Fuel use reduction ranges from 78%-88%, with equivalent reductions to the emissions rate. Systems A to C require 1 annual fuel delivery and Systems D and E require 2 fuel deliveries, down from 6 deliveries with the diesel-only system. The diesel ON hours range from 22% to 40% for all systems scenarios. Systems A and B have nearly 50% less fuel deliveries and diesel ON hours than the 225kW hydro-diesel system.

Table 4-14: Wave-Hydro-Diesel System Environmental Impact

	System A	**System B**	**System C**	**System D**	**Syste m E**	**225kW Hydro Diesel System**	**Diesel Only**
Annual Fuel Use Reduction	87.7%	86.3%	83.3%	79.3%	77.5%	65.8%	293,140
Annual Fuel Deliveries	1	1	1	2	2	3	6
% of Diesel ON hours	22.1%	25.1%	30.4%	35.7%	39.5%	45.1%	100%
Emissions Rate (gCO_2/kWh)	106	117	143	178	193	293	858
Emissions (tCO2/yr)	96	107	130	162	175	267	781

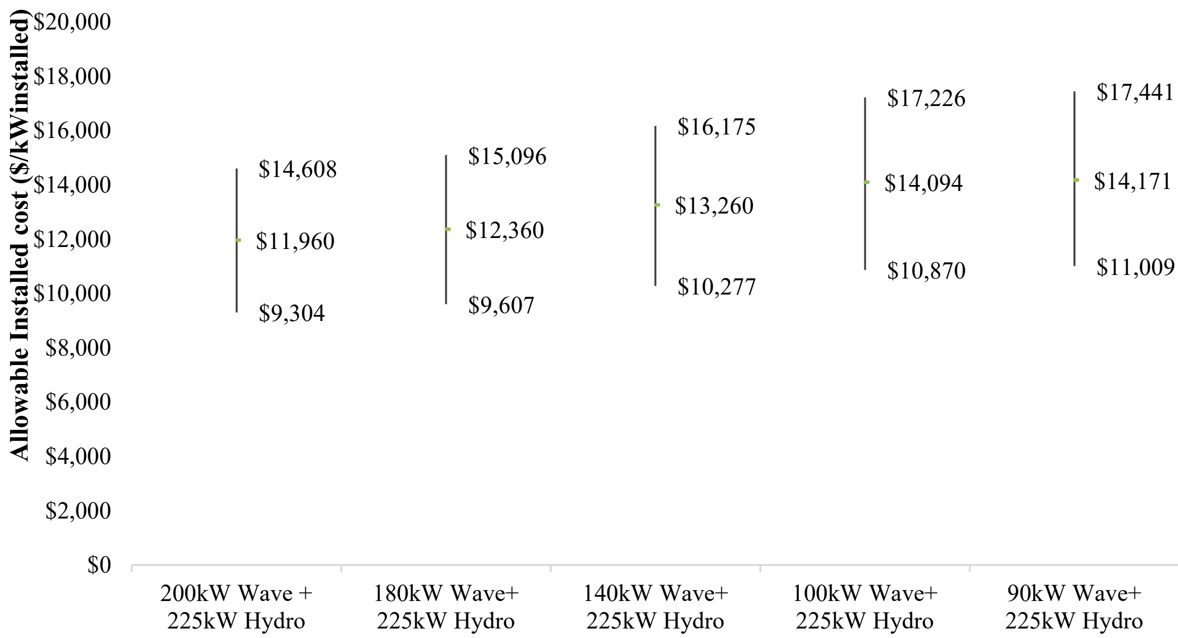
The diesel cost savings from the wave and hydro generation are illustrated in Figure 4-10 from high, average and low fuel costs. Systems A-E reduce diesel costs compared to the diesel-only system from 80%-71% for high diesel cost, 79%-69% for average fuel cost and 77%-67% for low fuel cost.

Figure 4-10: Diesel Cost Savings due to Wave and Hydro Generation



Hydro capital and operations costs are already incorporated in Subchapter 4.2. In this wave-hydro-diesel system, the focus is on diesel cost savings to calculate allowable costs for the combined wave and hydro systems. In these results, hydro costs are not included. The allowable installed costs for the wave and hydro systems are illustrated in Figure 4-11. Total capacity is the addition of the WEC capacity and the 225kW of the hydro system.

Figure 4-11: Wave and Hydro System Allowable Installed Cost



The allowable LCOE values for utilized wave and hydro system are presented in Table 4-15. Allowable LCOE calculates the value based on system diesel cost saving shown in Figure 4-10 using the average fuel cost scenario and the utilized total wave of each WEC and the 225kW hydro system of Subchapter 4.2. The utilization calculation for the WEC system compares the WEC generation used by the community distribution system to the total generation produced by the WEC. The utilized hydro compares dispatched hydro to total hydro generation in the 225kW hydro diesel scenario that produced 593,317kWh. The LCOE values are for the combined annual utilized hydro and wave generation.

Wave generation has the greatest utilization with the hydro system and diesel system supplementing the remaining electric supply. The hydro system can store hydro flow in the reservoir and the diesel system can store diesel fuel for dry and low sea-energy periods of time. The challenge in this scenario is to split the wave and hydro generation and treat them as separate systems for costing the LCOE and installed values. The greatest advantage of the combined system is the maximized diesel offsets. The hydro system becomes a supplementary system to wave generation. The hydro system utilization is rolled back to maximize zero cost wave generation. This roll back of hydro utilization is with respect to 225kW hydro generation of the hydro-diesel system, producing 593,371 kWh. Hydro and wave generation contribute similar generation in all quarters except for Quarter 3. In this summer quarter, wave generation is mostly used to mitigate diesel use.

Table 4-15: Wave and Hydro LCOE Values

	% Utilized Wave	%Utilized Hydro	Allowable LCOE for utilized Wave and Hydro
System A	80%	24%	$0.67
System B	84%	28%	$0.67
System C	92%	40%	$0.67
System D	93%	57%	$0.68
System E	93%	58%	$0.66

4.5 Results Summary

The following subchapter summarizes the key findings presented in Subchapters 4.1, 4.2, 4.3 and 4.4. The comparative analysis summarizes all system scenario outcomes for the remote community of Hot Springs Cove, population 80. Community infrastructure includes four community buildings and 30 residential homes, equating to an annual load of approximately 910MWh. Community peak load occurs in the winter, measured at 193.5 kW. In the summer, the average load is 65kW.

Numerous scenarios were modeled and many of the findings are discussed to assess the value of each technology for supplying community electricity. A planning exercise is included at the end of this subchapter as a resource to present findings to utility management and other stakeholders. It is important for engineering professionals to provide decision criteria for utility management stakeholders as part of a detailed technical and economic analysis.

The existing diesel-only system contains 2 summer load diesel generators rated at 100kW and two winter load diesel generators rated at 250kW. The highest fuel efficiency is achieved in the winter at 3.12kWh/L. In the winter, the 250kW diesel generator meets most of the demand. On an annual basis, the 250kW and 100kW diesel generators have a capacity factor of 31% and 25% respectively and an average fuel efficiency of 3.10kWh/L.

Annual diesel fuel use is 293,000L, requiring six fuel deliveries. The emissions rate is 858gCO_2/kWh. Diesel generators are operational every hour of the year, creating CO_2, CO, particulate matter, NO_x non-methane hydrocarbons and noise pollution.

Diesel fuel costs constitute 80% of total system cost. The diesel LCOE value for high fuel cost (2$/L) is 0.90 $/kWh, for average fuel cost (1.6$/L), 0.75 $/kWh and for low fuel cost (1.2$/L), 0.60$/kWh.

The hydro-diesel systems performance had little variability in operations or costs for the selected hydro capacities of 225kW, 275kW and 325kW. The 225kW hydro-diesel system has a lower cut-off value (% of maximum capacity), resulting in slightly greater utilization. In terms of hydro generation meeting annual demand, the 225kW, 275kW and 325kW hydro-diesel systems meet 65.2%, 64.9% and 64.4% of annual demand, respectively. The hydro-diesel system reduces the diesel capacity factor of the 250kW diesel generator from 31% (diesel-only system) to 2-3%. The 100kW generator capacity factor rose slightly from 25% (diesel-only system) to 28-31%. The diesel fuel efficiency is slightly higher than the diesel-only system ranging from 3.13-3.16kWh/L.

On an annual basis, the 225kW, 275kW and 325kW hydro-diesel systems achieve fuel use reductions of 65.8%, 65.1% and 64.9%, respectively. Each system requires 3 fuel deliveries, down from the baseline of 6. Year-to-year, hydro resource variability will cause fuel use variability. For example, whether a given year is low-flow or high-flow, the 225kW hydro-diesel system could experience fuel use reductions ranging from 64-92%, fuel deliveries ranging from 1-3, diesel operational hours ranging from 12-46% and emissions rates ranging from 70-309 gCO_2/kWh.

The hydro-diesel systems LCOE range for low fuel cost is 1.31-1.32$/kWh, for average fuel cost, 1.36-1.37$/kWh and for high fuel cost, 1.41-1.43$/kWh. All hydro-diesel systems have larger LCOE values than the respective diesel-only systems, achieving no cost savings from the addition of hydro generation. The approximate total cost increase of the hydro-diesel systems from high, average and low diesel fuel cost scenarios is 59%, 83%, and 120%, respectively. The 225kW hydro-diesel system results in the highest installed hydro cost of 40,200$/$kW_{installed}$. The 325kW hydro-diesel system has marginally higher hydro costs, with a hydro capacity 1.4 times larger. The 325kW hydro system has the lowest installed hydro cost of 28,000$/$kW_{installed}$.

The allowable hydro installed costs are based only on diesel costs savings and do not include hydro costs. For each system, diesel cost savings are \$3.82M, \$3.78M and \$3.77M and the allowable LCOE values for all systems is 0.68$/kWh. The differences in LCOE values to the allowable LCOE values indicate the current contractor costs estimates are high with respect to related diesel savings.

For the wave-diesel system, wave generation capacity ranges from 200kW to 90kW, meeting 71.3% to 42% of annual power demand. The 250kW diesel generator capacity factor drops from 31% (diesel-only system) to a range of 3% to 6%. The 100kW diesel generator capacity factor increases from 21% to 44% as wave capacity decreases. The average diesel fuel efficiency marginally drops from 3.1kWh/L (diesel-only system) to a range of 2.8-3.0kWh/L.

The reduction of diesel operations of small wave-diesel systems is minimal by comparison to large wave-diesel systems. The 90kW and 100kW wave-diesel system requires the diesel generators to remain on 98% of the year, while the 200kW wave-diesel system requires the diesel to operate only 63% of the year, reducing emissions and noise impacts. The fuel delivery requirement for the 200kW wave-diesel system is 2 per year, while both the 100kW and 90kW wave-diesel systems require 4 fuel deliveries per year. The emissions rate of the 200kW and 90kW wave-diesel system is 271 gCO_2/kWh and 518gCO_2/kWh respectively. For these factors, the 90kW wave-diesel system has approximately double the diesel generation requirements and impacts of the 200kW wave-diesel system.

For the low, average and high fuel cost scenarios, the range of allowable LCOE values of the wave-diesel system are 0.62-0.73$/kWh, 0.51-0.60$/kWh and 0.39-0.46$/kWh. The 200kW wave-diesel system results in 19,800$/$kW_{installed}$ with an average fuel cost of 1.6$/L and the 90kW wave-diesel system results in 25,400$/$kW_{installed}$.

The allowable cost values based on utilized wave generation at the community distribution system results in ranges from 0.65$/kWh to 0.64$/kWh. The utilization is lowest for the 200kW WEC system at 78%. The smaller WEC capacities have higher utilization at 94%, further reducing diesel use and the related diesel costs. These additional cost savings influence the rising allowable cost trend for decreasing WEC capacity. By comparison to hydro system costs, a similar trend occurs, increasing installed costs for decreasing hydro capacity. A similar cost trend may occur for wave systems.

Systems A-E achieves fuel use reductions from 78%- 88%. The 100kW diesel generators are required to supplement wave and hydro generation throughout the year as the capacity factor drops from 25% to a 7.6%-13% capacity factor. The 250kW diesel generator capacity factor drops drastically from 31% (diesel-only system) to 1.7%-3.25%, utilized during periods of wave and hydro unavailability. The average diesel fuel efficiency drops marginally from 3.1kWh/L (diesel-only system) to 2.9-3.0 kWh/L.

Systems A to C require 1 annual fuel delivery and Systems D and E require 2 fuel deliveries, down from the baseline 6 deliveries of diesel-only system. Diesel hours of operation range from 22% to 40%. Systems A and B result in nearly 50% less fuel deliveries and diesel ON hours than the 225kW hydro-diesel system with 3 fuel deliveries and 45% diesel ON hours. System A has the lowest emissions rate of all hybrid-diesel systems at 106 gCO_2/kWh.

5.0 Proposed Wave and Hydro Integration Plan

This chapter focusses on interpreting the results of Chapter 4 to provide a high-level summary of the technical and economic analysis of each hybrid diesel system that is accessible to readers of any technical expertise. Decision criteria highlight the key findings of the work and relate project development, required capital investments, purchase agreements and CO_2 emissions targets.

The diesel generation strategy plans for a diesel power station upgrade. The power station is the location of interconnection to the community distribution system, connecting generation to electric loads. Upgrading the station is the proposed first step of capital investments of the integration planning process. BC Hydro estimated the capital cost of upgrading the diesel facilities at $3.7M. This $3.7M is not part of the allowable cost formulations as the investment does not result in diesel cost savings. Instead, this is considered a sunk cost financed by capital improvement funds, subsidies or infrastructure funds for existing facilities.

The integration planning includes the interconnection of future renewable energy generators. There may be requirements for upgrades in communications, data acquisition, diesel fuel storage and metering systems. There may also be requirements to upgrade or replace electrical equipment such as conduit, transformers, safety equipment, etc. Civil and Geotechnical plans should be evaluated based on proposed future interconnections and facility upgrades.

Once diesel facility upgrades are complete, facility management should re-measure diesel fuel efficiency and capacity factors on an annual basis. Once renewable energy generation systems are interconnected, the evaluation of diesel offsets is to be based on the most current diesel data.

Table 5-1: Diesel System Integration Plan

Diesel Generation Strategy	Diesel power station upgrade. Plan for interconnection of future generators. Plan to re-evaluate power station electrical and civil design to accommodate system upgrades.	**0-3 years** **N/A** **25% CF – 100kW Diesel** **31% CF – 250kW Diesel**
Wave Technology Development and Market Changes	N/A	-
Hydro Technology Development and Market Changes	N/A	-
Capital Investment Cost	Engineering, Procurement, and Construction	Up to $3.7M
Avoided Diesel Fuel Cost		N/A
Annual Fuel Use Reduction		N/A
CO2 Emissions Rate Intensity		858 gCO2/kWh
Diesel Fuel Efficiency		3.1kWh/L
All values based on average resource year and average fuel rate		

The 'moderate renewable' integration plan builds from the diesel generation strategy. This is the proposed second step of capital investments of the integration plan. The 225kW hydro system will be selected to develop a hydro-diesel system. The hydro system will be 90% of diesel rated capacity. While the energy model predicts only a 2% capacity factor for the 250kW diesel, the essential service of this generator is for back-up supply if the hydro system is unavailable during the winter season. Smaller diesel generators will be considered to coordinate efficient diesel operations with the 100kW generator during Quarter 2 and Quarter 3.

Under the 'moderate renewable' integration plan, renewable generation will constitute, on average, 65% of annual demand. If utility management facilitates a hydro construction contract for design, construction and operations, it should be less than or equal to $3.83M, based on $17,000/kWinstalled allowable cost. If utility management seeks to offer the hydro project to an IPP, the PPA contract value should be less than or equal to 0.68$/kWh. The average number of days with diesel operations will be 165, reduced from 365. Diesel emissions are projected to be reduced by 66%.

Table 5-2: Moderate Renewable Integration Plan

Renewable Supply Mix	**Hydro System – To be installed**	**225 kW (90% of 250kW Diesel Capacity)**
Diesel Generation Strategy	Diesel power plant upgraded. Plan for additional small to medium sized generators to supplement hydro generation. 250kW diesel required for back-up supply during winter months	31% CF – 100kW Diesel 2% CF – 250kW Diesel
Renewable Percentage of Electric Sales		Range: 63% - 92% Average = 65%
Development Time Horizon	Hydro	3-5 years
Hydro Technology Development and Market	Hydro systems are a mature technology. Numerous commercial technology solutions. Bid process to determine Lowest Cost Engineering, Procurement, and Construction	-
Allowable Total Cost	Utility Owned and Managed Project	Up to \$3.83M
Avoided Diesel Fuel Cost: Utility PPA value	Utility PPA value to Hydro IPP	Up to 0.68\$/kWh
Annual Fuel Use Reduction		66%
CO2 Emissions Rate Intensity		293 gCO2/kWh
Diesel Fuel Efficiency		3.16 kWh/L
All values based on average resource year and average fuel rate		

The 'high renewable' integration plan builds on the 'moderate renewable' integration plan. In this third phase of capital investments, a 90kW WEC system will be installed. It is assumed the diesel system will be upgraded and the hydro system will be installed. As many wave technologies are pre-commercial, either a demonstration project will be pursued or utility management will wait for commercial wave technologies. Either option may not be viable for 10 or more years. Pre-development work will be needed to investigate permitting, increase understanding of WEC types, lead times for significant equipment, ongoing WEC resource monitoring, etc.

Once the wave system is installed, total renewable energy supply will be 126% of the 250kW diesel capacity. The 250kW diesel generator will continue to serve as back-up supply. The 100kW diesel generator will reduce output from a 31% to a 13% capacity factor. On average, up to 79% of electric sales will come from both hydro and wave generation. The average number of days with diesel operations will be 144, reduced from 165 with the hydro-diesel system. Diesel emissions could be reduced by 78%, an increase from 66% with the hydro-diesel system.

The allowable installed cost for a 225kW hydro system plus a 90kW WEC system is $14,200/kWinstalled. This value allocates $3.19M to the hydro system and $1.28M to the wave system. For the hydro-diesel system scenario, the installed cost for the 225kW hydro is up to $3.83M, greater than the allowable cost of $3.19M. If utility management facilitates a wave generation construction contract for design, construction and operations, allowable costs for the WEC system should be re-assessed after the development of the second phase hydro-diesel system.

If utility management seeks to offer the wave project to an IPP, the PPA contract value should be less than or equal to 0.66$/kWh, to be re-assessed after development of the hydro-diesel system. The most challenging situation is if there is a Hydro IPP controlling hydro services to the community utility. Integration of a wave generation system will severely impact hydro generation sales. Utility management will need to offer a different revenue source such as standby services to reduce lost hydro revenues. If utility management owns and operates diesel and hydro systems, competition with a wave IPP will be reduced. Competition will be eliminated if utility management owns and operates (through service contracts) all generation sources.

Table 5-3: High Renewable Integration Plan

Renewable Supply Mix	**Wave System: To be installed** **Hydro System: Installed**	**90 kW** **225 kW** **(126% of 250kW Diesel Capacity)**
Diesel Generation Strategy	Require small to medium sized generators as back-up to hydro and wave generation. 250kW diesel required for back-up supply during winter months	13% CF – 100kW Diesel 3.3% CF – 250kW Diesel
Renewable Percentage of Electric Sales		Up to 79%
Development Time Horizon	Wave Demonstration Project Commercial Wave Project	10+ years
Wave Technology Development and Market Changes	Research and development to commercialization.	-
Hydro Technology	Installed	-
Allowable Total Investment Cost	Utility Owned and Managed Project	Up to $1.28M
Allowable Cost (Utility)	Utility PPA value	Up to 0.66$/kWh
Allowable Cost (IPP)	Cost for IPP to develop	Up to 0.60$/kWh
	Competition occurs if separate PPA exist with Hydro IPP and WEC IPP Utility offers rate for stand-by service to Hydro IPP	58% utilized hydro generation 93% utilized Wave generation
Annual Fuel Use Reduction		78%
CO2 Emissions Rate Intensity		193 gCO2/kWh
Diesel Fuel Efficiency		2.89 kWh/L
All values based on average resource year and average fuel rate		

6.0 Conclusions

The main objective of this research was to develop an evaluation methodology to determine diesel mitigation impacts and the allowable costs of renewable energy supply integrated into an existing diesel generation system. The real-world application to the case study community of Hot Springs Cove on the Vancouver Island Coast represented a single analysis that can be applied to any remote community that is planning to change existing electric supply.

The electric supply model, RCOM was developed in GAMS and was a linear mixed integer mathematical program. The model was based on engineering design, mathematical formulations and synthesis of community data. Candidate energy system designs included: diesel only systems, hydro-diesel systems, wave-diesel systems, and hydro-wave-diesel systems. Each system scenario represented a fixed capacity of wave or hydro.

RCOM optimized each system scenario for lowest cost operations. The objective functions and constraints of RCOM were technical-economic relationships. Operations were ruled by: an energy balance equation for generation and demand, the generator models to emulate the equipment specifications of the prescribed wave and hydro technologies, and the specifications of the diesel technology. Additional constraints included a 95% availability factor for both wave and hydro that required diesel to meet electric demand at minimum 5% of the time. A diesel cycling constraint was also applied, where diesel has a minimum run-time of four hours before it was allowed to switch off.

The allowable cost of renewable energy supply was based on modeled avoided diesel costs comprised of: diesel fuel, diesel variable O&M, diesel overhaul costs, and diesel barge (fuel delivery) costs. These avoided cost LCOE values could potentially be the basis for electric supply owners to determine rates for Power Purchase Agreements. This methodology upheld utility responsibilities to not impact approved electric rates charged to utility customers. For community managed electric utility systems, evaluation of electric supply alternatives that reduce reliance on diesel fuel use have value in hedging against fluctuating fuel prices and the environmental risks of delivering and burning diesel fuel in the community.

RCOM model results found diesel generators were required for all systems. The 250kWdiesel generator provided back-up power during times of scheduled and unscheduled hydro or wave outages. For all systems, the 250kW diesel generator capacity factor dropped from 31% with diesel-only systems to 1.7%-3.25% for wave-hydro-diesel systems, 3%-6% for wave-diesel systems and 2-3% for hydro-diesel systems. Wave generation effectively reduced the requirement of a winter diesel generator for winter demand. The 100kW diesel generator supplemented both wave and hydro generation for all systems and the capacity factor rose from 25% with the diesel-only system, to 44% for the 90kW wave-diesel system and rose to 28-31% for the hydro-diesel systems. The wave-hydro-diesel systems reduced the 100kW diesel generator utilization to a capacity factor range of 7.6%-13%.

The hydro-diesel system had high capital and operational costs as specified by the hydro contractor and resulted in no cost savings with respect to the diesel-only system. Hydro generation reduced diesel use and associated costs by: $4.66M-4.59M based on diesel fuel cost of 2$/L, $3.82M-$3.77M based on diesel fuel cost of 1.6$/L and $2.97M-$2.94M based on diesel fuel cost of 1.2$/L. Diesel avoided costs equated to an allowable LCOE value of 0.68$/kWh for all hydro systems. Allowable installed costs for each system ranged from $17,000/kWinstalled to $11,600/kWinstalled for the 325kW hydro system. By comparison to the specified costs of the hydro contractor, the actual installed costs for incrementally larger hydro capacities did not increase linearly with increasing capacity. Many design factors remained constant with increasing hydro capacity.

For hydro system performance, the 225kW system was a good match to community electric demand. Hydro minimum constraints for shut down and start-up operations were 5% and 10% of rated hydro capacity. Increasing hydro capacity increased the minimum capacity operations and resulted in longer shutdown periods.

The 200kW-90kW wave-diesel systems allowable costs for wave generation were: 0.62-0.73$/kWh or 24,200-31,100 $/$kW_{installed}$ based on diesel fuel cost of 2$/L, 0.51-0.60$/kWh or 19,800-25,400$/$kW_{installed}$ based on diesel fuel cost of 1.6$/L, and 0.39-0.46$/kWh or 15,300-19,700$/$kW_{installed}$ based on diesel fuel cost of 1.2$/L. The allowed costs for utilized wave generation ranged from 0.63$/kWh to 0.65$/kWh.

Larger (200-180kW) wave-diesel systems, (225-325kW) hydro-diesel systems and all wave-hydro-diesel systems significantly reduced diesel operations and fuel use. Hydro-diesel systems reduced fuel use and emissions by 65%-66% and fuel deliveries were reduced to 3 (50% of the diesel-only system). The large wave-diesel systems reduced fuel use and emissions by 64%-68% and fuel deliveries were reduced to 2-3 (less than 50% of the diesel-only system). For all wave-hydro-diesel systems, fuel use was reduced by 78%-88% and fuel deliveries were reduced to 1-2. For all these systems, diesel operational hours ranged from 22%-45%.

Overall, the allowable LCOE costs of utilized hydro and wave systems ranged from 0.68$/kWh for all hydro scenarios and 0.63$/kWh to 0.65$/kWh for all wave scenarios. Diesel fuel use reduction was 64%-68% for all wave-diesel and hydro-diesel systems and provided similar diesel mitigation and allowable costs. There are other important factors to consider in electric system planning. Reliability and GHG emissions targets may take precedence in investment plans.

The proposed integration plan consisted of three capital investment stages. The first stage was to upgrade the diesel generation facility, including future renewable energy system interconnections. The scope of this work may cost up to $3.7M, based on a quotation from BC Hydro. Funding sources assigned to existing facility operations, maintenance and upgrades were applicable and are not included in the allowable cost accounting.

The second phase capital investment was to integrate a 225kW hydro system into the existing diesel system. The allowable cost for the hydro system development, construction and operations was $3.83M. If utility management chose not to own and operate the hydro system, a PPA of 0.68$/kWh may be offered to a hydro IPP. On average, 65% of electric sales would be generated from the hydro system. Emissions and diesel fuel use would be reduced by 66%.

The third phase of capital investments was to integrate a 90kW wave system into the existing hydro and diesel system. Allowable costs were up to $1.28M for development, construction and operations of the wave system. If utility management chose not to own and operate the wave system, a PPA of 0.66$/kWh may be offered to a wave IPP. The costs for the IPP were based on total wave generation with an allowable cost of 0.60$/kWh. Hydro generation utilization was reduced to 58%, displaced by wave generation. Involvement of IPPs creates competition with additional sources of renewable energy.

The integration plan achieved lower emissions intensity from the BAU system of 858 gCO2/kWh to 193 gCO2/kWh of the wave-hydro-diesel system. The new challenge identified in the integration plan for high renewable integration was the competition of renewable energy sales of wave and hydro generation. In this scenario, due to the RCOM economic values of no cost wave generation, hydro generation was rolled back. From a technical perspective, the hydro system had a reservoir to store the hydro resource and supplement wave generation as needed. To achieve 78% diesel mitigation, other PPA rates for other system attributes may need to be developed such as storage systems or on-demand capacity, to not penalize initial power purchase agreements.

The development of wave and hydro systems for the community would likely be eligible for government grants or subsidies. The allowable costs of proposed systems would be useful information for government agencies to have when making granting decisions. Grants or subsidies could be sized to ensure the net value of the project achieved allowable cost benchmarks while enabling high diesel mitigation operations.

There are several important and value-added efforts that can build on this research. While the analysis exploited several years of hydrological resource data to inform the hydro generation side of the Hot Springs Cove analyses, the wave resource could also be measured over several years. A wave resource database would determine average wave power densities over a 10, 20, or 30-year period. Estimating the impact of climate change on wave resource variability would provide a better forecast of expected wave power densities over a project lifetime.

This analysis relied on a single year of community energy consumption data recorded between the years 2014-2015. The aggregate load did not include any composition breakdown; for example, residential, commercial, school buildings, heating, hot water heaters, or appliances. Data on load control constraints and any representation of the expected long-term variation (year-to-year) was not included either.

Further analysis could incorporate more communities. Variable community sizes, locations, utility management models and electric costs impact allowable costs for other renewable technologies. Integration planning could be developed for a regional electric utility that is planning to move towards uniform electric charges and rates for all communities. For hydro system analyses, increasing reservoir storage capacity could be examined.

As capital expenditures and operational expenditures are yet to be determined for wave energy, the present analysis determined the *allowable costs* for wave systems. Future work should develop a detailed wave engineering design and an environmental assessment. Detailed design would define all equipment, mapping, civil work and material quantities that would accurately measure system electrical losses and capital cost estimates. Operational costs could be estimated by identifying equipment lifetime and replacement costs and system monitoring equipment.

7.0 Works Cited

[1] M. Solano-Peralta, X. Vallve, T. Couture, J. Glassmire, P. Lilienthal, E. Sanders and C. Colson, "Renewable energies for remote areas and islands (remote)," International Energy Agency - RETD, 2012.

[2] J. Royer, "Status of remote/off-grid communities in Canada," Natural Resource Canada, Government of Canada, 2011.

[3] Canada Energy Regulator, "Market Snapshot: Explaining the high cost of power in northern Canada," 16 February 2017. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2017/market-snapshot-explaining-high-cost-power-in-northern-canada.html. [Accessed 24 3 2021].

[4] Quilliq Energy Corporation, "2018/19 General Rate Application," October 2017. [Online]. Available: https://www.qec.nu.ca/sites/default/files/2018-2019_qec_general_rate_application.pdf. [Accessed 24 3 2021].

[5] Canada Energy Regulator, "Canada's Renewable Power Landscape 2017 – Energy Market Analysis," 29 September 2020. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/electricity/report/2017-canadian-renewable-power/canadas-renewable-power-landscape-2017-energy-market-analysis-ghg-emission.html. [Accessed 24 3 2021].

[6] Quilliq Energy Corporation, "Customer Rates," [Online]. Available: https://www.qec.nu.ca/customer-care/accounts-and-billing/customer-rates. [Accessed 25 March 2021].

[7] Northwest Territories Power Corporation, "Rate Regulation," June 2016. [Online]. Available: https://www.ntpc.com/about-ntpc/rate-regulation. [Accessed 24 3 2021].

[8] Ontario Energy Board, "Priority transmission projects," 29 July 2016. [Online]. Available: https://www.oeb.ca/industry/policy-initiatives-and-consultations/priority-transmission-projects#pickle. [Accessed 24 4 2021].

[9] Natural Resources Canada, "Charting the course - Canada's marine renewable energy technology roadmap," October 2011. [Online]. Available: http://www.publications.gc.ca/site/eng/407077/publication.html. [Accessed 25 March 2021].

[10] BC Hydro, "BC Hydro 2018 Carbon Neutral Action Report," May 2019. [Online]. Available: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/environmental-reports/2018-carbon-neutral-action-report.pdf. [Accessed 25 March 2021].

[11] Standing Senate Committee on energy, the environment and natural resources, "Powering Canada's territories," Senate of Canada, Canada, 2015.

[12] Sigma Engineering Ltd., "Energy overview study of remote communities in Canada," Energy Mines and Resources Canada, 1985.

[13] Northwest Territories Public Utilities Board, "What is a General Rate Application?," [Online]. Available: https://www.nwtpublicutilitiesboard.ca/sites/default/files/general-rate-

application.pdf. [Accessed 25 March 2021].

[14] Quilliq Energy Corporation, "Commercial and Institutional Power Producer Program," May 2020. [Online]. Available: https://www.qec.nu.ca/customer-care/generating-power/commercial-and-institutional-power-producer-program. [Accessed 25 March 2021].

[15] Northwest Territories Power Corporation, "Adding Renewables to Electricity Grids," February 2018. [Online]. Available: https://www.ntpc.com/docs/default-source/default-document-library/community-capacity-for-integrating-renewables-(february-2018).pdf?sfvrsn=2. [Accessed 25 March 2021].

[16] BC Hydro, "Independent projects history & maps," 1 October 2020. [Online]. Available: https://www.bchydro.com/work-with-us/selling-clean-energy/meeting-energy-needs/how-power-is-acquired.html. [Accessed 25 March 2021].

[17] Hydro One, "Renewable Energy," [Online]. Available: https://www.hydroone.com/abouthydroone/CorporateInformation/Documents/2019%20Reindeer%20Renewable%20Energy%20Program%20Remotes.pdf. [Accessed 25 March 2021].

[18] S. Boronowski, "Integration of wave and tidal power into the Haida Gwaii electrical grid," Univeristy of Victoria, 2009.

[19] L. Mofor and P. Journeay - Kaler, "Pacific Lighthouses: Hybrid power systems," International Renewable Energy Agency, 2013.

[20] C. Barley, "Dissertation: Modeling and optimization of dispatch strategies for remote hybrid power systems," Colorado State University, Fort Collins, 1996.

[21] BC Hydro, "Resource options update: results summary," 2016.

[22] J. Khan and G. S. Bhuyan, "Ocean energy: global technology development status," International Energy Agency- Ocean Energy Systems, 2009.

[23] BC Hydro Remote Community Electrification, "Community electricity plan for refuge cove," BC Hydro, 2013.

[24] Aboriginal Affairs and Northern Development Canada, "Hesquiaht First Nation Registered Population," [Online]. Available: http://fnp-ppn.aandc-aadnc.gc.ca/fnp/Main/Search/FNRegPopulation.aspx?BAND_NUMBER=661&lang=eng. [Accessed 2015].

[25] Five Nations Energy Inc., "FNEI Rate 2016 Rate Application," [Online]. Available: https://www.fivenations.ca/index.php/regulatory/regulatory-2. [Accessed 04 October 2020].

[26] The Weather Network, "Estevan Point, BC," [Online]. Available: http://legacyweb.theweathernetwork.com/statistics/temperature/cl1032730/cabc0090. [Accessed 2015].

[27] G. Sentlinger, "Hydrological Analysis of Ahtaapq Creek," Aquarius R&D Inc., 2016.

[28] C. E. Hiles, B. J. Buckham, P. Wild and B. Robertson, "Wave energy resources near Hot Springs Cove, Canada," *Renewable Energy,* no. 71, pp. 598-608, 2014.

[29] B. R. Robertson, C. E. Hiles and B. J. Buckham, "Characterizing the near shore wave energy resource on the west coast of Vancouver Island, Canada," *Renewable Energy,* vol. 71, pp. 665-678, 2014.

[30] L. H. Holthuijsen, Waves in oceanic and coastal waters, Cambridge: Univerisity Press, 2010.

[31] J. J. Grainger and W. D. Stevenson, Jr., Power Systems Analysis, McGraw-Hill, Inc., 1994.

[32] National Renewable Energy Laboratory, "Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective," National Renewable Energy Laboratory, Golden, 2017.

[33] S. M. M. U. B. H. M. Short, "NREL is a national laboratory of the U.S. Department of Energy, Office of Energy," National Renewable Energy Laboratory, Golden, 2011.

[34] W. Short, D. J. Packey and T. Holt, "A manual for the economic evaluation of energy efficiency and renewable energy technologies," National Reneable Energy Laboratory, 1995.

[35] K. Darrow, R. Tidball, J. Wang and A. Hampson, "Catalog of CHP technologies Section 2. Technology characterization - reciprocating internal combustion engines," US Environmental Protection Agency, 2015.

[36] British Columbia Provincial Government, "Provincial Greenhouse Gas Inventory Report," 2012. [Online]. Available: http://www2.gov.bc.ca/assets/gov/environment/climate-change/reports-and-data. [Accessed 2013].

[37] Scheinder Electric, "Low Voltage Distribution Transformers, Three Phase," [Online]. Available: https://www.schneider-electric.us/en/. [Accessed December 2018].

[38] H. Bailey, J. P. Ortiz, B. J. Buckham, B. Robertson and R. S. Nicoll, "A Methodology for wave-to-wire WEC simulations," in *Proceedings of the 2nd Marine Energy Technology Symposium*, Seattle, 2014.

[39] Statistics Canada, "Consumer Price Index: Annual review, 2017," [Online]. Available: https://www150.statcan.gc.ca. [Accessed December 2018].

[40] J. Chozas, J. Kofoed and N. Jensen, "User guide - COE calculation tool for wave energy converters," Department of Civil Engineering, Aalborg University, Aalborg, 2014.

[41] Ocean Energy Systems, "International levelised cost of energy for ocean energy technologies," Ocean Energy Systems, International Energy Agency, Lisbon, 2015.

[42] Ministry of Forests, Lands and Natural Resource Operations, "Water sustainability fees, rentals and charges tariff regulation," Executive Council, Province of British Columbia, Victoria, 2016.

[43] Q. Paris, Economic Foundations of Symmetric Programming, New York: Cambridge University Press, 2011.

[44] Natural Resources Canada, "The Atlas of Canada - Remote Communities Energy Database," [Online]. Available: http://atlas.gc.ca/rced-bdece/en/index.html. [Accessed 04 December 2017].

Appendix A.Diesel System Costs

Diesel fuel costs and delivery dates for Hesquiaht in 2015

Delivery Number	Date	Fuel (L)	Fuel Unit Cost ($/L)
1	Unknown	49,744	1.39
2	2015-03-12	47,218	1.46
3	2015-05-20	49,289	1.49
4	2015-07-08	45,600	1.49
5	2015-10-14	49,357	1.44
6	2015-12-05	49,601	1.39
Total		290,812	Average = 1.46
Average Cost (2018$)			1.60

Diesel fuel use in Hesquiaht from May to November 2015

2015	Generator (L)	Band Office (L)	Backhoe (L)	Lodge (L)	Fisheries Truck (L)	Fisheries Project (L)
May	47500	-	-	-	80	-
June	21109	400	98	200	-	-
July	15585	-	43	-	-	-
August	19375	-	45	-	84	414
September	29861	400	-	-	-	-
October	20175	-	-	-	-	-
November	30929	300	97	-	-	-
Total	**184,534**	**1,100**	**283**	**200**	**164**	**414**

Diesel operational costs ($2015)

Generator Major Overhauls and Replacement. 250 kW Generator after 15,000 hours	$50,000.00	250 kW operating cost: 5.00 ($/hr)
Generator Major Overhauls and Replacement. 100 kW Generator after 20,000 hours	$25,000.00	100 kW operating cost: 1.88 ($/hr)
Fixed O&M (salary): $ 55,000.00		

Diesel generation operational costs ($2018)

Fuel Cost	$Average\ C_{Fuel} = 1.6\ \$/L$ $High\ C_{Fuel} = 2\ \$/L$ $Low\ C_{Fuel} = 1.2\ \$/L$
Operations and Maintenance Costs	$C_{Diesel\ O\&M} = C_{Oil} \cdot P_D(t) + \quad C_{Fixed\ O\&M}$ $C_{Oil} = 0.005\ \$/kWh$ $C_{Fixed\ O\&M} = 57{,}200\ \$/yr$
Overhaul Costs	$C_{Overhaul,100kW} = 2\ \$/h$ $C_{Overhaul,250kW} = 5.20\ \$/h$
Barge Costs	$C_{Barge} = 3{,}500\ \$/delivery$

Diesel system total cost formulation

Total Cost: Diesel-Only System	$\boldsymbol{TC = C_{Fuel,PV} + C_{Diesel\ O\&M,PV} + C_{Overhaul,PV} + C_{Barge,PV}}$
$C_{Fuel,PV} = \sum_{N=1}^{Lifetime} \left\{ \sum_{t=1}^{365\cdot 24} C_{Fuel} \cdot V_{Fuel}(t) \right\} \frac{(1+i)^N}{(1+d)^N}$	
$C_{Overhaul,PV} = \sum_{N=1}^{Lifetime} \left\{ \sum_{t=0}^{365\cdot 24} C_{Overhaul} \cdot X_D(t) \right\} \frac{(1+i)^N}{(1+d)^N}$	
$C_{Barge,PV} = \sum_{N=1}^{Lifetime} \left\{ \sum_{t=1}^{365\cdot 24} C_{Barge} \cdot X_{Barge}(t) \right\} \frac{(1+i)^N}{(1+d)^N}$	
$C_{Diesel\ O\&M,PV} = \sum_{N=1}^{Lifetime} \left\{ \sum_{t=0}^{365\cdot 24} C_{Oil} \cdot P_D(t) + C_{Fixed\ O\&M} \right\} \frac{(1+i)^N}{(1+d)^N}$	

Appendix B. Hydro System Data and Costs

Equations and definitions for hydro power generation

Penstock Losses	$\boldsymbol{H_{Net}} = H_{Gross} - H_{Loss}$
Hydro Turbine efficiency	$\eta_{Turbine}(x) = 5.87x^5 - 19.2x^4 + 24.0x^3 - 14.6x^2 + 4.44x + 0.27$, x = % of Q_D (refer to Figure 2-18)
Powerhouse Station Load Losses	Cooling, electric fans (summer), Heating, electric heaters (winter), Lights and power electronics (all year) $\eta_{Power\ house} = 99\%$
Transformer Losses	Based on Capacity 300 kVA transformer coil and core losses $\eta_{transformer} = 98.8\%$
Transmission Losses	Transmission losses and interconnection into community bus losses $\eta_{transmission} = 97.6\%$
Total Electrical Efficiency	$\eta_{Total} =$ $\eta_{Turbine} \cdot \eta_{Powerhouse} \cdot \eta_{transformer} \cdot \eta_{transmission}$
Hydro Power Definition	$P_H = \frac{H_{Net} \cdot \rho_{water} \cdot \eta_{Total} \cdot Q_{Turbine} \cdot g}{1000W/kW}$ $\rho_{water} = 1000\ kg/m^3,\ g = 9.81\ m/s^2$
Annual Unavailability	Unavailability is the hydro station downtime for servicing and unplanned outages Unavailability = 5% (Availability = 95%) 440 hours per year, 18.3 days per year 110 hours per quarter, 4.6 days per quarter

Hydro system capital costs

Feasibility and preliminary design	$860,000
Access roads and barge landing	$292,000
Civil contractor overhead	$212,000
Intake civil	$860,000
Penstock civil	$1,086,000
Tributary taps	$219,000
Powerhouse civil (including switchyard)	$279,000
Turbine, generator and auxiliary components	$465,000 (225kW) $490,000 (275kW) $516,000 (325kW)
Powerline engineering and construction	$421,000
Electrical equipment supply and install	$445,000
Engineering, management & environmental	$1,543,000
Other capital costs	$12,000
Contingency	$960,000
Tax	$77,000
Total	**$7.73M (225kW)** **$7.76M (275kW)** **$7.78M (325kW)**

Hydro system operational costs

Environmental / Hydrology Monitoring	\$22,800
Insurance	\$6,700
Land Lease	\$1,440
Management Fees	\$15,600
Miscellaneous/Contingency	\$5,200
O&M Salary and Training	\$39,000
Vehicle Expenses	\$2,100
Repairs and Maintenance	\$10,400
Taxes, Property	\$15,900
Total Hydro Fixed Cost	$C_{fixed\ Hydro}$ **= \$119,200/yr**
Water rental: Capacity	$C_{rental\ cap}$ **= 2.6\$/kW/yr**
Water rental: Output	$C_{rental\ variable}$ **= 1.4\$/MWh/yr**

Hydro-diesel system total cost formulation.

Total Cost: Hydro-Diesel System	$TC = C_{Fuel,PV} + C_{Diesel\ O\&M,PV} + C_{Overhaul,PV} + C_{Barge,PV} + C_{Hydro\ O\&M,PV} + C_{Hydro\ Capital}$
$$C_{Hydro\ O\&M} = \sum_{t=0}^{365\cdot 24} C_{rental\ variable} \cdot P_H(t) + C_{rental\ cap} + C_{fixed\ Hydro}$$	
$$C_{Hydro\ O\&M,PV} = \sum_{N=1}^{Lifetime} \{C_{Hydro\ O\&M}\} \frac{(1+i)^N}{(1+d)^N}$$	

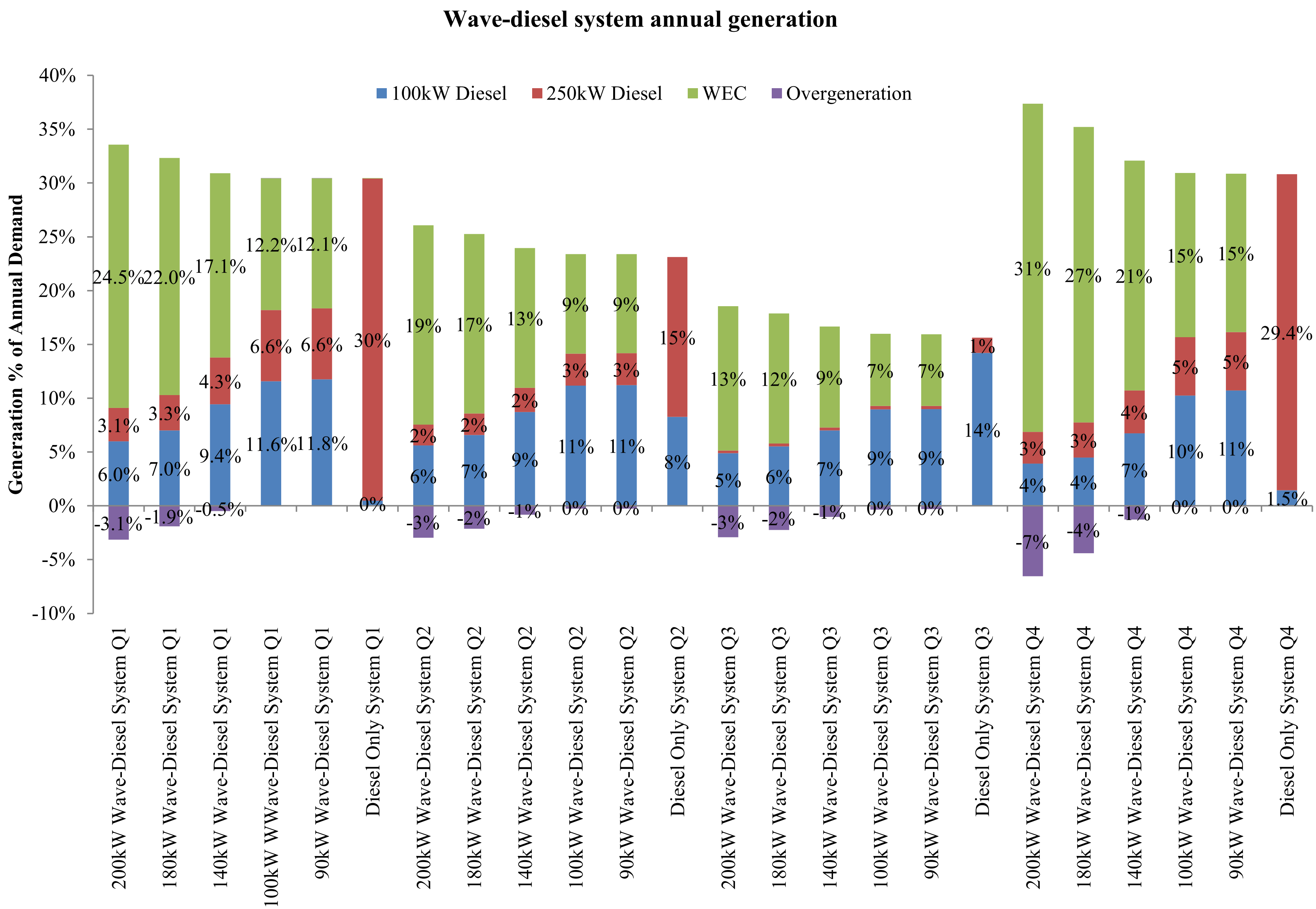
Appendix C.Wave Energy Converter Data

SurfPower efficiency matrix

Wave energy Period (Te)

Significant Wave Height (Hs)

Peak Period	7.2	8.3	9.4	10.5	11.6	12.7	13.8	14.9	16	17.2
Energy Period	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
0.25										
0.75		0.14	0.10	0.06	0.07	0.05				
1.25	0.29	0.31	0.24	0.20	0.17	0.13				
1.75	0.34	0.30	0.25	0.22	0.17	0.14	0.12			
2.25	0.32	0.27	0.22	0.20	0.16	0.14	0.12	0.10		
2.75	0.32	0.26	0.22	0.18	0.14	0.11	0.10	0.08	0.08	
3.25		0.23	0.18	0.16	0.13	0.11	0.09	0.08		
3.75		0.21	0.17	0.14	0.12	0.10	0.09	0.07		
4.25			0.15	0.13	0.10	0.09	0.07	0.07		
4.75			0.15	0.12	0.09	0.09	0.07	0.06	0.05	
5.25				0.11	0.09	0.07	0.06	0.05	0.05	
5.75				0.09	0.08	0.07	0.06	0.05	0.04	0.04
6.25					0.07	0.06	0.05	0.04	0.04	0.03
6.75					0.06		0.05	0.04	0.03	


Wave-diesel system annual generation
100kW Diesel
250kW Diesel
WEC
Overgeneration
Generaation % of Annual Demand
40%
35%
30%
25%
20%
15%
10%
5%
0%
-5%
-10%
24.5%
22.0%
17.1%
12.2%
12.1%
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9%
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7%
10%
11%
1.5%
-3.1%
-1.9%
-0.5%
-3%
-2%
-1%
0%
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-3%
-2%
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0%
0%
-7%
-4%
-1%
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0%
200kW Wave-Diesel System Q1
180kW Wave-Diesel System Q1
140kW Wave-Diesel System Q1
100kW WWave-Diesel System Q1
90kW Wave-Diesel System Q1
Diesel Only System Q1
200kW Wave-Diesel System Q2
180kW Wave-Diesel System Q2
140kW Wave-Diesel System Q2
100kW Wave-Diesel System Q2
90kW Wave-Diesel System Q2
Diesel Only System Q2
200kW Wave-Diesel System Q3
180kW Wave-Diesel System Q3
140kW Wave-Diesel System Q3
100kW Wave-Diesel System Q3
90kW Wave-Diesel System Q3
Diesel Only System Q3
200kW Wave-Diesel System Q4
180kW Wave-Diesel System Q4
140kW Wave-Diesel System Q4
100kW Wave-Diesel System Q4
90kW Wave-Diesel System Q4
Diesel Only System Q4

Appendix D. Wave-Hydro-Diesel Results