13th EWTEC 2019 Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Wave and hydro integration for remote communities: a break-even analysis

Bryson Robertson, Jessica Bekker, Bradley Buckham

Abstract— **North American remote communities suffer from costs of energy reaching $1.00/kWh, are in most cases entirely reliant on diesel and are often cited as potential 'break-in' markets for wave energy projects. However, wave energy integration is complicated by the supply-demand dynamics, the availability of other commercially ready renewable options and hidden costs that arise when the intermittent renewable is buffered.**

This study utilizes the Remote Community Optimization Model (RCOM) to study the full system dynamics for Hot Springs Cove; a remote community on the West Coast of Canada. The RCOM model formulates the community's energy system operation as an optimization problem, and for a given system design determines the least cost manner in which the generation options are deployed to meet demand hour-by-hour. The diesel only option resulted in LCOE at $0.76/kWh. The development of a small scale hydro-electricity system, 225kW rated power, reduces the community's fuel costs by ~$5.2M over the 30 yr project lifetime. However, these savings are less than the associated capital required to build the hydro-system, and the associated LCOE increased to $1.36/kWh. Based on a 'break-even' costs analysis, adding a wave energy converter to the hydro-diesel hybrid energy system was found to be economically viable if the wave supplied power can be delivered for less than $0.39/kWh for a 200kW wave device or $0.46/kWh for a 100kW device. The opportunity to incorporate wave power is driven primarily by the costs associated with inefficient operation of the diesel generators at low output, and the fixed (i.e. unavoidable) annual operating and maintenance costs for diesel systems. While remote communities' high LCOE is often cited as a rationale for wave energy integration, this work quantifies the merit order for renewable generation options and helps identify the cost reductions that are actually possible.

Keywords— **renewable energy integration, wave energy, hydroelectric power, levelized cost of energy (LCOE), micro-grid, remote communities.**

I. INTRODUCTION

GLOBALLY, many remote communities suffer from exorbitant electricity costs, a reliance on fossil fuel sources, and ageing energy infrastructure.

Electricity costs, up to 10x utility costs, severely handicaps the communities ability to provide reliable services and to seize on economic development opportunities. This results in migration away from historically, and culturally, significant community locations [1]–[3]. Additionally, the reliance on fossil fuel based generation – generally diesel – is often at odds with the communities' cultural view points on the interactions between people and place. Finally, the coupled effects of ageing infrastructure and diesel reliance conspire to place these communities as some of the least resilient to the economic and environmental change [4]. With this in mind, many of these communities are actively transitioning their electricity systems to renewable energy resources to provide a sustainable electricity future, opportunities for economic growth and, hopefully, a harbinger for global change.

While commercial wave and tidal energy projects are still nascent, it is paramount to ensure that; 1) as these communities transition to renewables, the electricity systems they are designing allow for significant wave and tidal resources to contribute to a decarbonisation strategy, and 2) that technology and project developers' present efforts are guided by an understanding of the appropriate technology scale (kW) and the economic break-even points for marine energy penetration.

On the west coast of Canada, the dependence of remote communities on diesel-based electricity generation is in direct conflict with their wealth of proximate, raw renewable energy resources [5]. Dominant amongst these renewable resources are hydro, wave and tidal energy. This study focusses on the remote community of Hot Springs Cove on Vancouver Island, Canada. Hot Springs Cove is currently developing a small storage hydro system, yet continues to be intrigued by the opportunities associated with the local wave energy resource. As such, this study assesses the temporal compatibility of local demand with a combination of micro-hydro and wave supplied power; the efficiency of the technology choice and scale; and, the system-wide economic break-even point for introducing wave energy, based on diesel mitigation.

Paper ID number: 1741; Conference track: Economical, social, legal and political aspects of ocean energy.

B. Robertson is with Pacific Marine Energy Centre, Civil and Construction Engineering, Ocean State University, Corvallis, Oregon, USA (email: bryson.robertson@oregonstate.edu).

J. Bekker and B. Buckham are with Mechanical Engineering, University of Victoria, BC (email: jbekker@uvic.ca, bbuckham@uvic.ca).

II. Background

A. Hot Springs Cove, Canada

Hot Springs Cove is a remote First Nations community on the west coast of Vancouver Island, Canada. The community is located at 49°22'N, 126°16W and is only accessible by boat or seaplane. Currently, the community consists of ~ 123 people, 3 administrative and community buildings and 30 residential homes.

As with many remote First Nations communities, Hot Springs Cove suffers from a high cost of energy. The community has been very actively promoting its vision for a renewable energy future and associated increased economic opportunities. In 2014, Hot Springs Cove installed electrical meters to record community electricity load data at 15min resolution (shown in Fig. 1 for 2015). The largest demand occurs during winter and peaks at 193.5 kW, while summer load averages just 50 kW.

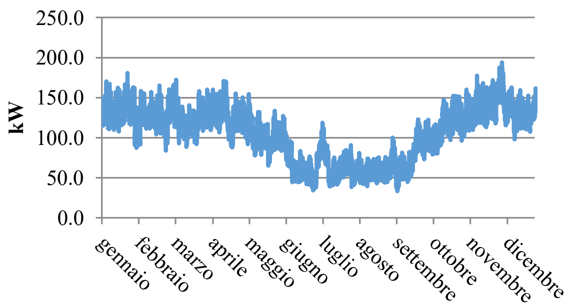

Fig. 1. Electrical demand for Hot Springs Cove (2015).

B. Existing Electrical Generation

Any future hybrid energy system needs to maximize the benefit of existing infrastructure, while minimizing the total fuel costs and related emissions. The current energy system at Hot Springs Cove consists of two (2) 250 kW generators and two (2) 100kW generators – as shown in Fig. 2. The larger 250kW units are designed to meet winter peak loads, while the smaller 100kW units are specified for summer operation. The duplication is for redundancy and reliability concerns.

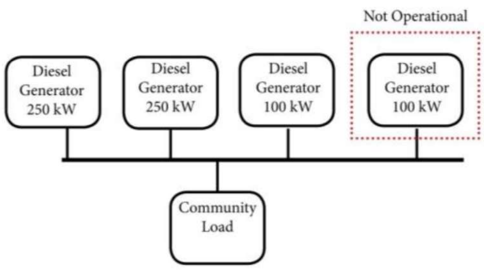

Fig. 2. HSC existing diesel generation.

C. Renewable Resource Options

As with many high-latitude coastal communities, Hot Springs Cove has a limited suite of renewable resource opportunities to draw from. Dominate amongst the options are traditional small scale hydroelectric (micro-hydro) generation and wave energy generation.

1) Hydroelectric Resource

Hot Springs Cove benefits from its proximity to Ahtaapq Creek. The creek is ~2km from the community and offers an opportunity to develop a limited storage hydro generation project. The creek flow rate in 2006 is shown in Fig. 3. 2006 represents an average year for creek mean annual discharge. The seasonal complementarity between the flow rates in Ahtaapq Creek and the community load profile is immediately evident; both peak in the winter with limited demand/availability during summer months. It is important to note that while the seasonal complementarity exists, there are extended periods during winter months with very little flow; primarily driven by short duration freezing events.

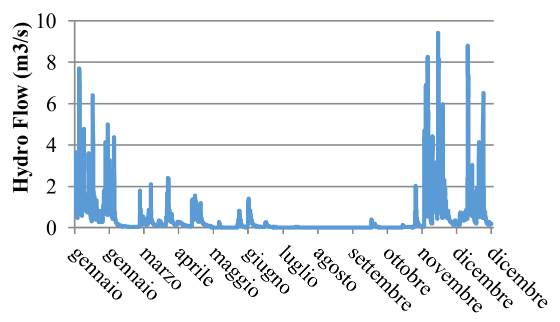

Fig. 3. Ahtaapq creek annual flow rates.

2) Wave Energy Resource

Numerous studies have been conducted on assessing the future prospects of wave energy on the west coast of Canada [6]–[8]. For Hot Springs Cove, a location ~2km from shore and in 40m of water was identified based on a Simulation WAves Nearshore (SWAN) model [9].

Fig. 4 shows the variation in the significant wave height (H_s) and energy period (T_e). The site features a mean annual significant wave height of 1.9m, a maximum significant wave height of ~5m and a minimum of ~1m (the 0m value on Jan 1st is SWAN model spin-up and not real). The wave energy period is reasonably variable (between 6 – 14 sec.) and a mean energy period of 9.5 sec.

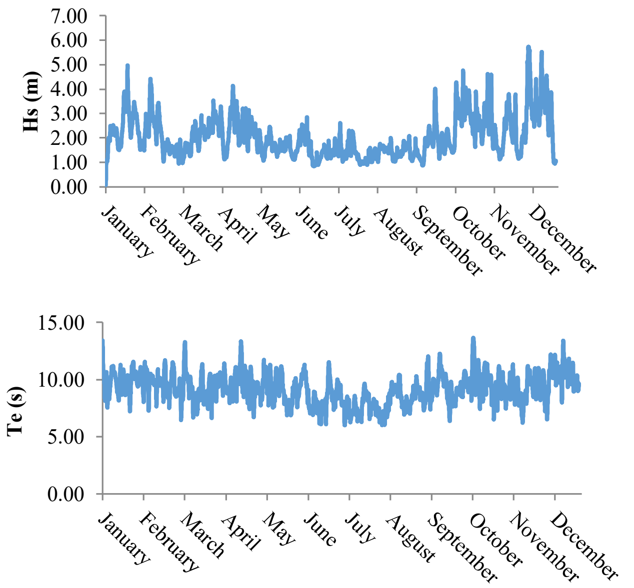

Fig. 4. a) Significant wave height and b) wave energy period at Hot Springs Cove.

III. Remote Community Optimization Model (RCOM)

RCOM is a research code, built on the General Algebraic Modelling System (GAMS) software platform [10] and completes economic and technical assessments for the hybrid energy systems in rural and remote communities. RCOM formulates the hourly resolved supply-demand energy balance problem as a linear, mixed integer programming problem. The RCOM tool takes in community and resource input data and technical descriptions of technology performance and cost metrics, and then determines the optimal generation scheme, at hourly resolution, to meet the community demand over a defined project lifetime. A schematic of possible hybrid energy systems at Hot Springs Cove is presented in Fig. 5.

RCOM is a cost-minimization optimization, yet is not a capacity expansion model. Capacities of each technology are determine *a priori* and RCOM determines the optimal dispatch of each generator to minimize costs. As such, comparisons between different energy systems and installed capacities is completed via a scenario-based study.

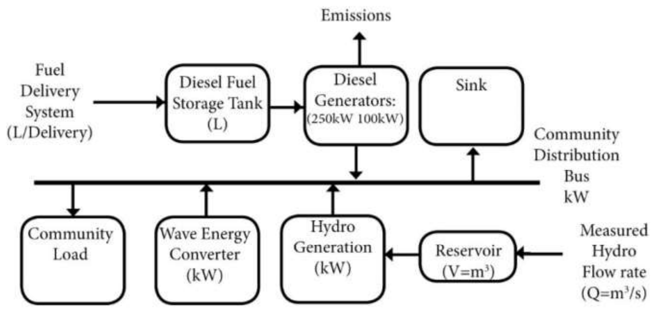

Fig. 5. Complete hybrid energy system options for Hot Springs Cove. Each energy system includes/disregards certain generators from system as described in TABLE 4.

D. RCOM Technology Characterization

For each technology option, RCOM inputs capital, fixed and variable operating costs, emissions intensity, and resource availability. The following sections detail the technology representations and associated modelling constraints.

1) Diesel Generation Technology and Constraints

Within the RCOM model, the diesel fuel use for the 250kW and 100kW generators was linearized based on both kWh generated and hours 'on'. See Table 1.

TABLE 1
DIESEL GENERATOR FUEL CONSUMPTION

Rated Capacity	Minimum Generation	Fuel Consumption (L/hr)
250 kW	50 kW	$0.25P_D(t) + 5.5X_D(t)$
100 kW	20 kW	$0.24P_D(t) + 3.6X_D(t)$

where $P_D(t)$ is the power is each hour time step, and $X_D(t)$ is a binary value indicating if the generator is on/off.

Minimum generation was set to 20% of rated capacity and a minimum of 4hr 'up' time enforced to eliminate cycling impacts on the equipment. No minimum 'down' time was included. CO_2 emissions were determined to be 5.0 and 3.5 g/kWh for the 250kW and 100kW generators respectively. Additional fuel deliveries were at unit volume of 49,4000L/delivery (via barge from another community).

The diesel system generation costs are detailed in Table 2 and the total costs (TC) formulated in (1). Note the present value (PV) costs are detailed in (1); assuming a 30-yr project lifespan, a discount rate of 10%, and an inflation rate of 1.6%:

$$TC_{diesel,PV} = C_{Fuel,PV} + C_{Diesel\ O\&M,PV} + C_{Overhaul,PV} + C_{Barge,PV} \quad (1)$$

TABLE 2
DIESEL SYSTEM GENERATION COSTS

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

2) *Hydroelectric Technology and Constraints*

Hydro generation is defined by the incoming creek flow rate, storage reservoirs size, and the desired turbine capacity. The incoming creeks flow rates have been previously defined, and the reserve storage opportunity is limited to 6000m^3. Additionally, in order to maintain the ecological biodiversity in the creek, an inflow stream requirement (IFR) is 0.011m^3/s. The IFR represents the minimum constant flow rate that must be maintained in the creek.

The investigated hydro system has a capacity of 225kW and a maximum volume flow of 0.125 m^3/s. Turbine generation shutdown and start-up generation is assumed to be 5% and 10% of rated capacity respectively.

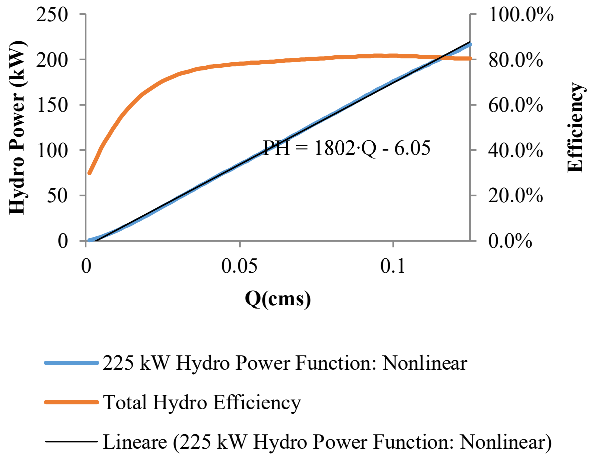

Fig. 6. 225kW Hydro-electric generation power relationship.

Fig. 6 illustrates the total efficiencies and power output for the 225kW hydroelectric generation system. The generation system includes turbine efficiency losses, power station losses, and transmission losses – hence only realises a total peak efficiency of 80%. Finally, the hydro system is given a 95% availability factor. To account for this availability factor, the RCOM model randomly assigns 5% of all hours to have zero hydro-electricity output (within the optimization framework).

The costs associated with hydroelectric plant design, construction, permitting are formulated in (2) and detailed in Table 3. Note that the water rental costs have both a capacity (C_{hydro_cap}) and a generation cost (C_{hydro_gen}).

The fixed costs (design, turbine and generator, construction, environmental monitoring, land lease, insurance, etc costs) – based on Canyon Hydro quotations - and variable operation and maintenance costs (water rentals, management frees, vehicles, repairs and maintenance) – based on Barkley Group experience.

$$TC_{hydro,PV} = C_{hydro\_cptl} + C_{hydro_{fix},PV} + C_{hydro_{cap},PV} + C_{hydro_{gen},PV} \quad (2)$$

TABLE 3
HYDRO SYSTEM GENERATION COSTS

ITEMS	COSTS
Capital Construction Costs	$C_{hydro\_cptl} = \$\,7.73M$
Fixed Operating Costs	$C_{hydro\_fix} = 119{,}200\ \$/yr$
Water Rental Costs	$C_{hydro\_cap} = 2.6\frac{\$}{kW}/yr$ $C_{hydro\_gen} = 1.4\frac{\$}{mWh}/yr$

3) *Wave Energy Technology and Constraints*

For this study, the wave energy converter (WEC) technology of choice was the Seawood Designs 'SurfPower' system [11], [12]. Fig. 7 provide an overview of the system, and additional details on the numerical modelling can be found in [13].

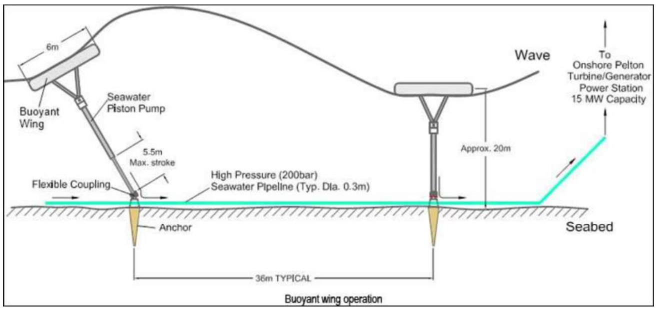

Fig. 7. Seawood Designs 'Surfpower' WEC.

As with many renewable energy technologies, the rated power of the WECs are in flux. The power production potential is relative to the wave-perpendicular width of the device, the efficiency of conversion from 'wave-to-wire', the wave climate and the Power-Take-Off (PTO). The sea state dependent power (P_w) is calculated using (3):

$$P_w = \eta_{WEC}\rho H_s^2 T_e L \quad (3)$$

Where η_{WEC} is the efficiency of the WEC (Fig. 8), ρ is seawater density (1025kg/m^3), and L is the wave-perpendicular width of the WEC. The device output (P_w) is capped at the rated capacity.

Two WEC width and capacity scenarios are investigated; 24m/200kW and 12m/100kW. Whilst the rated power will not scale exactly with device width, the assumption provide an illustrative example of appropriate scale for integration. These values correspond to ~200% and 100% of mean annual electrical demand. Fig. 9 shows the annual power production from a 200kW WEC installed at the chosen location off Hot Springs Cove.

Peak Period (Tp)	7.2	8.3	9.4	10.5	11.6	12.7	13.8	14.9	16	17.2
Energy Period (Te)	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
Significant Wave Height (He) 0.25										
0.75		0.14	0.1	0.06	0.07	0.05				
1.25	0.29	0.31	0.24	0.2	0.17	0.13				
1.75	0.34	0.3	0.25	0.22	0.17	0.14	0.12			
2.25	0.32	0.27	0.22	0.2	0.16	0.14	0.12	0.1		
2.75	0.32	0.26	0.22	0.18	0.14	0.11	0.1	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	0.1	0.09	0.07		
4.25			0.15	0.13	0.1	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	

Fig. 8. WEC Efficiency Matrix.

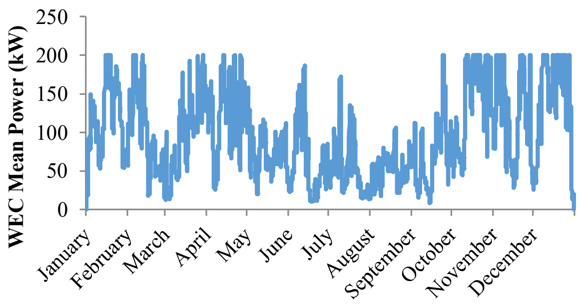

Fig. 9. 200kW WEC power generation at Hot Spring Cove.

Given the nascent nature of the WEC industry, costs are uncertain. A break-even cost analysis is utilized for WEC generation system costs to identify the allowable $/kWh and $/kW for the community to benefit from wave energy, yet have no impact of their costs of energy.

Finally, the wave energy system is given a 95% availability factor to mimic the hydroelectric facility.

E. *Economic Analysis*

For this analyses, the Levelized Cost of Energy (LCOE - $/kWh) and the cost of installed capacity ($/kW) will be the primary economic metrics of comparison. The LCOE can be determined by utilizing a Capital Recovery Factor (CRF) calculated using (4):

$$CRF = d\frac{(1+d)^N}{(1+d)^N - 1} \qquad (4)$$

where d is the discount rate (10%) and N is the assumed project lifetime (30 yrs). The LCOE can then be calculated as:

$$LCOE = \frac{TC_{system} \cdot CRF}{Annual\ Demand} \qquad (4)$$

where TC_{system} is the total costs of the hybrid energy system in question.

Note that TC_{system} includes upfront capital costs for construction (hydroelectric) and lifetime operating costs (fuel, oil, water lease, maintenance, etc.).

Wave energy systems have no capital or operating expenses included. The 'break-even' allowable wave energy system costs are based on diesel energy system cost savings per kWh generated. This is calculated by (5):

$$LCOE_{allow} = \frac{(TC_{system} - TC_{diesel}) \cdot CRF}{Wave\ Generation} \qquad (5)$$

Finally, the cost of installed capacity are specific to the energy system in question. The diesel system has been installed and therefore has zero installed capacity cost. The hydroelectricity system installed capacity cost is $\frac{7.73M}{225\ kW} = \$\,34{,}400/kW$.

IV. Results

The results will be presented based on both hybrid energy systems and scenarios of installed capacities within each system. TABLE 4 provides an overview of the systems and scenarios to be analysed.

TABLE 4
OVERVIEW OF ENERGY SYSTEMS AND SCENARIOS

System	Scenario Generation Capacities
Diesel System	- Diesel: 100kW & 2x 250kW
Hydro-Diesel System	- Diesel: 100kW & 2x 250kW - Hydro: 225kW
Wave-Diesel System	- Diesel: 100kW & 2x 250kW - Wave: 200kW or 100kW
Wave-Hydro-Diesel System	- Diesel: 100kW & 2x 250kW - Hydro: 225kW - Wave: 200kW (Sys. A) / 100kW (Sys. D)

F. *Diesel System*

The costs and operational characteristics of the existing diesel system serve as the comparison point for all future energy systems.

Fig. 10 shows the seasonal and capacity rating distribution of diesel generation. The 250kW generator primarily functions for winter peaks loads, while the 100kW generator is dispatched more during lower summer loads. Over the year, the 250kW and 100kW generators have capacity factors (CF) of 31% and 25% respectively. Finally, the diesel energy system emits 780 tonnes/yr of CO_2

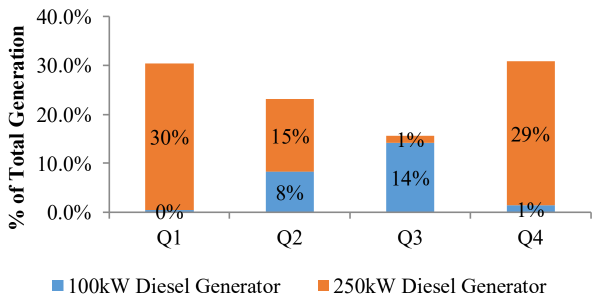

Fig. 10. Seasonal distribution of diesel generation.

The total cost of running the diesel energy system is $6.44M, it generates 909 MWh, and has an LCOE of $0.75/kWh. Diesel fuel costs dominate the economics, accounting for 80% of total annual costs.

G. *Hydro-Diesel System*

Fig. 11 illustrates the generation penetration rates over the year at Hot Springs Cove. Based on an average rainfall year (MAD = 0.39 m^3/s), hydro can provide 65% of total generation over the year. The CF of the 250kW diesel generator is reduced to just 2%, yet is still required in all seasons. The 100kW generator CF increases to 31%.

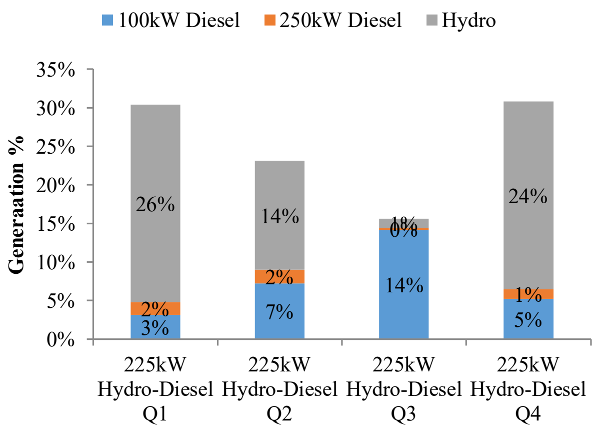

Fig. 11. Hydro-Diesel System generation.

The integration of hydroelectricity into the energy system saves ~ 193,000 L of diesel fuel; a 66% reduction and the associated 66% reduction in carbon dioxide emissions (final emissions = ~260 tonnes/yr). This also reduces the number of fuel deliveries/barges from 6/yr to just 2 deliveries. The hydro-diesel system saves $324,000/yr in direct fuel and delivery costs. Over the 30yr project lifespan, this accounts for $5.23M of savings.

However, the LCOE for the hydro-diesel system is $1.36/kWh; an 80% increase over the baseline diesel only system. This is primarily driven by the $7.73M capital cost of developing the hydroelectric system – an upfront cost that is greater than the total diesel saving over the 30 yr lifetime.

H. *Wave-Diesel System*

The analysis of the wave-diesel system is based on operational and economic implications of installing differing levels of WEC capacity (detailed in TABLE 4).

Fig. 12 shows the generation from a 200kW and 100kW WEC. Wave energy in the diesel energy system accounts for 43% to 71% of total annual energy demand for the 100kW and 200kW WECs respectively. The CFs of the 250kW generator drops to just 6% and 3%, while the 100kW generator is more effective and has a CF of 44% and 21% respectively.

The 200kW generator reduces fuel consumption by 68%, but also generates excess electricity energy; up to 16% of annual demand. The 100kW generator reduces fuel consumption by 40% and only generates 3% excess energy during the non-peak seasons. The CO_2 final emissions for the 200kW and 100kW devices are 246 and 467 tonnes/yr respectively. Financially, the 200kW will save $3.96M over a 30 yr project, while the 100kW will save $2.32M.

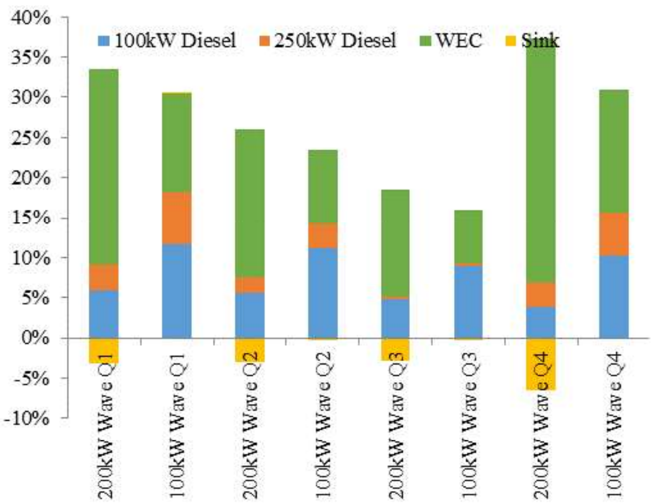

Fig. 12. Wave-Diesel System Generation.

Using (5), the allowable LCOE for a wave energy system can be calculated. For the 200kW and 100kW WEC systems, the allowable LCOEs are $0.39/kWh and $0.46/kWh. The values reflect the allowable costs for variable renewables and the need for dispatchable generators. The increased allowable LCOE for the 100kW WEC is due to the higher utilization and reduced excess generation.

Finally, the breakeven installed costs for the 200kW and 100kW WEC are $20,000/kW and 25,000/kW. These are both lower than the $35,000/kW required for the hydroelectric system.

I. *Wave-Hydro-Diesel System*

Wave energy conversion projects are still pre-commercial, so it is important to ensure that future wave projects will be complimentary with energy systems that are getting built now. Hot Springs Cove is moving forward with the 225kW hydroelectric facility, so it is important to understand how a wave project will impact the performance of a hydro-diesel system. Two scenarios are investigated; a 200kW WEC (System A) and a 100kW WEC (System D) addition.

Figure 13 shows the generation mix for each season. Overall, zero-carbon generation (e.g. 225kW hydro + 200kW wave) accounts for 89% of total generation; a significant penetration. Yet this requires zero-carbon generation capacity that is ~ 218% higher than peak demand. Interestingly, both systems still require the

250kW and 100kW diesel systems to ensure 100% reliability. The diesel generator CF's are shown in Table 3.

TABLE 5
DIESEL GENERATION CAPACITY FACTORS

DIESEL CF	200KW WEC (SYSTEM A)	100KW WEC (SYSTEM D)
250 kW Diesel	1%	8%
100 kW Diesel	3%	13%

System A has significant over generation (~16%) with the majority of this occurring during the fall months; a period of high rainfall and wave conditions (no provisions for energy storage is included in these scenarios). These system scenarios, as expected, have the most significant influence on total emissions, with a 78% - 88% reduction.

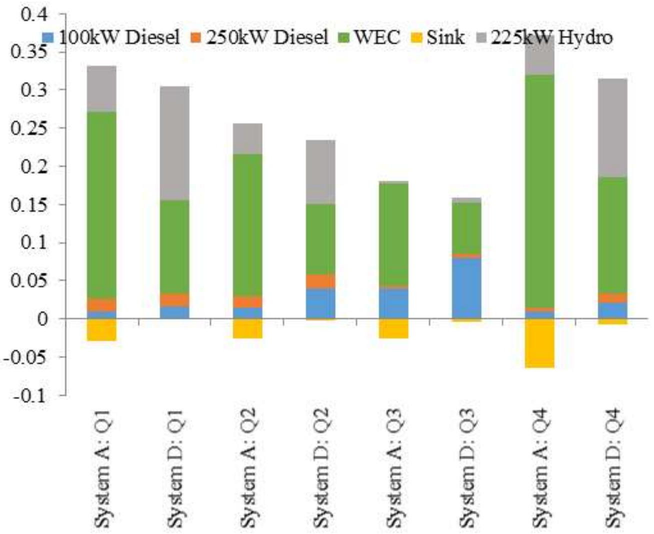

Figure 13. Wave-Hydro-Diesel System generation.

The 200kW scenario results in $5.1M in fuel savings, while the 100kW system account for $4.5M in savings. However, System A has a total cost of ~$14.1M and System D has a total cost of $13.6M; significant numbers when compared against the $6.4M cost to continue to operate the existing diesel system.

V. RESULTS DISCUSSION

The presented results provide a host of interesting implication for the integration of renewable energy resources into remote, diesel reliant energy systems.

The existing diesel energy system at Hot Springs Cove supplies them with reliable electricity. However, the costs, emissions, noise impacts, and dependence on marine transported diesel fuel are risks and limit their ability for economic development. Annually, the community burns 293,00L of fuel, emits 780 tonnes of CO_2 and requires 6 deliveries of fuel. The resulting LCOE is $0.75/kWh; fuel costs account for ~ 80% of this. It is important to note that these costs do not account for capital previously invested to purchase and install the diesel generation systems.

The development of a 225kW hydroelectric system significantly reduces the community's fuel consumption, emissions and fuel delivery reliance. Fuel consumption falls by 193,000L, emissions are reduced by 66%, and only 2 annual fuel deliveries are required. However, the capital costs to design, permit and construct the hydroelectric scheme are significant ($7.73M). So while the hydroelectric system is able to save $5.23M over the next 30 years, the development of the hydro-diesel energy system actually increases the LCOE by 80%; to $1.36/kWh. However, the construction of energy systems in these remote communities has often been heavily subsidized through federal government funding. The concept of extended the national grid to Hot Springs Cove has been frequently been investigated and current capital cost estimates vary between $11.2M - $16.9M; this costs overshadow the much smaller costs associated with the hydro-electric system.

The wave-diesel energy system results in similar fuel, emissions and fuel delivery reductions to the hydro-electric system. The similarity between wave and coastal hydroelectric generation is expected when assessing the similarity of the annual resource profile. For the investigated 200kW and 100kW WECs, these values are 201,000L/534 tonnes/4 deliveries and 118,000L/313 tones/2 deliveries respectively. Based on the break-even cost analysis, the 200kW and 100kW LCOE's need to be below $0.39/kWh and $0.46kWh respectively. The most significant difference is the excess generation associated with the 200kW WEC; ~16% of annual demand. The hydro-electric system has a buffering ability due to the water (energy) storage associated with the upstream reservoir. This could be replicated with the addition of battery storage to the wave energy system.

Finally, the wave-hydro-diesel system. The addition of a 200kW and 100kW WEC to the hydro-diesel system increase the total renewable energy penetration to 89% and 80% respectively. These WEC capacities reduce diesel fuel consumption and associated emissions by 87% - 80% and the fuel deliveries to just 1/yr. However, despite adding 200% renewable capacity (when compared against peak loads), the system still requires both the 250kW and 100kW diesel generators to maintain system reliability. These scenarios further reinforce the impact of over generation from the 200kW WEC; impacts that could be mitigated by the addition of storage or installing a smaller-scale WEC.

Building on the presented work, there are a host of additional factors that would provide import contextual information when assessing this research.

First, for this assessment, a year with an average Mean Annual Discharge (MAD) in Ahtaapq Creek is used. This choice has significant influence on the timing and total water (energy) budget the hydro-electricity system is able to use in the simulation. It would important to investigate the impact of higher and lower water years on the energy system performance. This could be expanded to active/inactive wave energy resource years.

Second, temporal coherence. The MAD data for Ahtaapq Creek is from 2006, the community demand from 2015 and the wave data from 2011. While all these datasets are representative of the 'average' conditions, the lack of temporal coherence means that the impacts of infrequent events will not be captured. For example, large winter high atmospheric pressure events will results in increased demand, but will also reduce stream flow (due to freezing) and reduced wave heights. During these time, the reliability of the energy system will rely on the diesel systems exclusively.

Third, these results are location specific. Whilst this research does provide important results for integrating variable renewable resources into remote community electrical grids, they are not universally applicable or accurate. The impacts could be significantly better, or worse, in differing communities, with differing renewable and demand profiles.

Finally, energy storage is not included in these analyses for a number of reasons. The RCOM architecture is not conducive for accurately representing storage performance (energy vs. capacity, charge & discharge rates, round trip efficiency) and cost (degradation and lifetime expectancy) uncertainties. Additionally, if storage was to be included in a break even analysis, then the avoided costs identified would have to be split between the WEC and the battery storage – not a simple task and introduces additional uncertainty for investors and future system operators.

VI. Conclusion

Remote communities suffer from high costs of energy and are often cited as potential 'break-in' markets for wave energy projects. These references often cite existing LCOE, do so in the absence of other renewable energy options, and without accounting the full dynamics of the electricity system. This study utilizes the Remote Community Optimization Model (RCOM) to study the full system dynamics for Hot Springs Cove; a remote community on the West Coast of Canada.

The RCOM models quantified the total system costs of business-as-usual diesel-based generation at $0.76/kWh. The development of a small scale hydro-electricity system, 225kW rated power, reduces the communities fuel costs by ~$5.2M over the 30 yr. project lifetime. However, these savings are less than the associated capital required to build the hydro-system ($7.7M), and the associated LCOE is increased to $1.36/kWh.

Based on a 'break-even' costs analysis, wave energy conversation is cost optimal if it can be installed for $0.39/kWh and $0.46/kWh; for a 200kW and 100kW system respectively. This is reduced LCOE opportunity is driven primarily by the system dynamics associated with variable renewable generation in a diesel-based system. These include the costs associated with: 1) minimum generation times for diesel generation (4hr 'on'), and 2) annual fixed operating and maintenance costs for diesel systems. While lower LCOE that often cited, this research provides a robust methodology to quantify the merit order for generation in remote communities and help clearly identify the cost reductions necessary.

Acknowledgement

The authors would like to acknowledge Barkley Project Group for partially funding this research, provide invaluable community demand data, and helping scope the research goals for the community.

References

[1] R. Kempener, O. L. d'Ortigue, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, "Off-grid renewable energy systems: Status and methodological issues," *Abu Dhabi*, 2015.

[2] Y. Kuang *et al.*, "A review of renewable energy utilization in islands," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 504–513, 2016.

[3] M. Previsic and R. Bedard, "Yakutat Conceptual Design, Performance, Cost and Economic, Wave Power Feasibility Study," *Electr. Power Res. Inst.*, vol. 43, p. 43, 2009.

[4] B. Walker, "Administrative order No. 289: Establishing Alaska Climate Change Strategy." State of Alaska, 2017.

[5] J. Royer, "Status of remote/off-grid communities in Canada," *Nautral Resour. Canada, Gov. Canada*, 2011.

[6] B. Robertson, C. Hiles, and B. Buckham, "Characterizing the near shore wave energy resource on the west coast of Vancouver Island, Canada," *Renew. Energy*, vol. 71, pp. 665–678, 2014.

[7] G. Reikard, B. Robertson, B. Buckham, J.-R. Bidlot, and C. Hiles, "Simulating and forecasting ocean wave energy in western Canada," *Ocean Eng.*, vol. 103, pp. 223–236, 2015.

[8] I. Moazzen, B. Robertson, P. Wild, A. Rowe, and B. Buckham, "Impacts of large-scale wave integration into a transmission-constrained grid," *Renew. Energy*, vol. 88, pp. 408–417, 2016.

[9] B. Robertson, C. Hiles, E. Luczko, and B. Buckham, "Quantifying wave power and wave energy converter array production potential," *Int. J. Mar. Energy*, vol. 14, 2016.

[10] G. D. Corporation, "General Algebraic Modeling System (GAMS), rel. 24.2. 1." GAMS Development Corporation Washington, DC, 2013.

[11] H. Bailey, J. Ortiz, B. Robertson, B. Buckham, and R. Nicoll, "A Methodology for Wave-To-Wire WEC Simulations," *Mar. Renew. Energy Technol. Symp.*, pp. 1–15, 2014.

[12] H. Bailey, B. Robertson, and B. Buckham, "Variability and stochastic simulation of power from wave energy converter arrays," *Renew. Energy*, vol. 115, 2018.

[13] H. Bailey, B. R. D. Robertson, and B. J. Buckham, "Wave-to-wire simulation of a floating oscillating water column wave energy converter," *Ocean Eng.*, vol. 125, 2016.